THE ROLE OF LIVING PLANT ROOTS AND CATTLE MANURE AS A SOIL AMENDMENT IN THE ALLEVIATION OF COMPACTED COAL MINE SOILS

By

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Submitted in partial fulfilment of the requirements for the degree

MSc (Agric): Pasture Science

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DECLARATION

I, Poloko Emmanuel Mosebi, declare that the dissertation hereby submitted by me for the MSc (Agric) degree at the University of Pretoria is my own independent work and has not previously been submitted by me for a degree at this or any other University.

Signed____

Poloko Emmanuel Mosebi

April 2010

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ABSTRACT

The role of living plant roots and cattle manure as a soil amendment in the alleviation of compacted coal mine soils

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In South Africa, most of the surface coal mines are situated on the Highveld of the Mpumalanga Province. The mining industry plays a vital role and contributes to the economy of the country. Very often the mining activities change the physical nature of the soil which results in soil compaction. In mine soils, compaction is of great importance in plant growth and the environment because its high levels may adversely result in the degradation of soil structure, reduced nutrient distribution and reduced root growth, which eventually decreases plant growth. To ensure a productive vegetation, compacted mine soils has to be ameliorated effectively. A combination of practices is suggested to alleviate soil compaction, but some of them are costly and not ecologically stable particularly the use of conventional methods. Therefore, the challenge is to use the potential practices to ameliorate compacted soils. The proposed investigations, which are envisaged to solve harmful effects of soil compaction on plant growth, include biological activities, achieved through appropriate application of cattle manure and planting of pasture species. A review on literature, some studies indicate that the application of organic manure amendments such as cattle manure may overcome the negative effects of compaction, due to the beneficial effects on soil physical, chemical and biological properties in the zone of incorporation. Other studies has shown that pastures are linked with improvements in soil structure, soil organic matter content, rooting depths, consequently, reductions in bulk density. The focus of this study were to monitor the root biomass of irrigated Tall Fescue (*F. arundinacea* cv Dovey) and dryland Smuts Fingergrass (*D. eriantha* cv Irene) on mine soils, and to describe soil bulk density and soil nutrient concentrations in such soils. This study were also determining the effects of incorporating cattle manure into compacted (mine soils) and non compacted (agricultural soils) and evaluating its effects on the seedling growth rate, dry matter and root biomass production of Tall Fescue and Smuts Fingergrass. In addition, the influence of different rates of cattle manure on soil bulk density and nutrient concentration in such compacted soil was also measured. These parameters are relevant to the sustainable rehabilitation of mine soils. Based on the results obtained in this study, it was concluded that the use of two grass species, Tall Fescue and Smuts Fingergrass, with vigorous root systems have extended their roots in compacted mine soil layers over two growing seasons. Other results have demonstrated that application of cattle manure revealed a significant decrease in soil bulk density of compacted mine soils planted to Tall Fescue and Smuts Fingergrass. The bulk density was at a minimum in the 80 tha^{-1} cattle manure-treated plots and followed by the 40 tha^{-1} cattle manure treatment, and the maximum bulk density was recorded for the control treatment (0 tha^{-1}). The application of cattle manure resulted in a large input of nutrients to the soil as compared to untreated control and significantly increased Tall Fescue and Smuts Fingergrass growth and production. This research has illustrated that use of plant roots and cattle manure as soil organic amendments to reduce soil compaction may be environmentally and economically beneficial leading to a more sustainable agricultural system.

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Chapter 1

A review on the plant root development and cattle manure amendments in compaction alleviation of mine soils

1. Introduction

In South Africa, most of the coal mines are currently situated on the Highveld of the Mpumalanga Province. The mining industry plays a vital role in the economy of the country. However, the mining activities often change the physical state of soil resources which result in certain environmental challenges, with respect to soil degradation (Truter, 2007). Surveys have indicated that of the approximately 40 000 ha, which have been disturbed by surface coal mining in the past 30-35 years, approximately 30 000 ha of reclaimed land is severely compacted and only about 10 000 ha has a satisfactory effective soil depth (Rethman, 2006).

One of the factors leading to soil degradation is compaction. Soil compaction in surface coal mining operations has an impact on plant growth and yield through increased bulk density or strength of soil, commonly known as mechanical impedance. Mechanical impedance of soil is an important constraint to root and shoot growth, decreasing oxygen availability and altering both water storage and availability. Furthermore, there is a reduction in size and continuity of soil macro-pores through which roots preferably grow, leading to slower root elongation, poor root density and reduced soil volume (Thom *et al*., 1997).

In mine soils, compaction has been registered to have had a strong influence on the landscape and plant growth. Pasture species vary considerably in their tolerance of soil compaction. The roots of grass species can penetrate into rigid pores smaller than their nominal diameter and through this radial expansion they reduce soil compaction (Osmont *et al*., 2007). Roots grow by a process of cell division in the apical meristem, just behind the tip and cell expansion, in a zone just behind the apex. Water influx into cells generates turgor pressure, which provides the driving force for elongation and development of roots (Clark *et al*., 2003).

The roots of grass species exert a growth pressure in order to displace soil particles, overcome friction and elongate through the soil, consequently weakening and loosening compacted soil particles (Motavalli *et al*., 2003). In dense soil, with voids such as cracks, grass species having lateral roots which rapidly penetrate, thereby increasing their capacity to exploit soil resources. In non-tilled soil layers roots are predominantly vertical following vertical earthworms' channels and cracks through compacted profiles (Clark *et al*, 2003). The architecture and spatial arrangement of root systems, contribute to the characteristics of pastures subjected to a complex soil structure of compacted layers (Osmont *et al*., 2007).

As has already been noted, mine soils are seriously impacted by compaction, resulting in serious degradation of physical soil parameters. Application of cattle manure has a potentially very important role to play as on amendment to alleviate compaction. The addition of cattle manure to soil provides several potential benefits by improving soil structure, fertility and increasing soil organic matter (McAndrews *et al.*, 2006). Mine soils treated with such organic amendments have a greater resilience (do not compact easily) and a greater resistance to re-compaction. They also exhibit systems of ecosystem recovery which are not evident in reclamation areas receiving only mechanical/physical/chemical amelioration (Rethman, 2006).

Tripathi and Singh, (2004) also reported that the application of manure improved soil physical properties, organic matter content and nutrient capacity of the soil and increased plant growth. Addition of manure as an amendedment improved bulk density, soil crusting, porosity, aggregation, infiltration, hydraulic conductivity, water holding capacity, field capacity, plant-available water and permanent wilting point (Hamza & Anderson, 2005). With low organic matter levels mine soils are subject to compaction. Rethman, (2006) also emphasized the role of green manuring, organic amendments and restorative pastures to restore and maintain organic matter levels in mine soils over the long term.

2. Soil compaction

Plant growth is restricted when the uptake of water, oxygen and nutrients is less than the demand of the plant. One of the factors leading to limitation of supply from the soil to the root system is soil compaction (Nadian *et al*., 1998). Soil compaction is perceived as a major threat to long-term survival of plants on mine soils in the Mpumalanga Highveld. Soil compaction is defined as a change in soil volume leading to increased soil bulk density (Marshall & Holmes 1988; Thom *et al*., 1997). Soil compaction reduces air volume, and causes re-arrangement of soil particles which are packed closer together, thereby increasing soil strength (Thom *et al*., 1997). The increase in bulk density and strength of soil are commonly known as mechanical impedance, reducing permeability and diffusivity of water and air (Mulholland *et al*., 1996).

Cook *et al*., (1996) also reported that soil compaction, by increasing mechanical impedance, creates unfavourable growing conditions for roots as supplies of oxygen, water, and nutrients are reduced. It has been suggested by many researchers that increasing the soil bulk densities from 1.3 to 1.7 Mgm^{-3}, or a penetration resistance from 3.0 to 5.0 MPa, may limit root development and decrease plant growth (Bengough & Mullins 1990a; Kuznetsova 1990). In a study of the effects of soil bulk density on root and shoot growth of different ryegrass lines, it was reported that the growth of perennial ryegrasses was affected by increasing soil bulk density from 1.1 to 1.4 Mgm^{-3} (Thom *et al*., 1997). On the surface mine soils in the Mpumalanga Highveld, compaction is a threat to these soils and plant productivity, and the degree of compaction on these sites varied between 1.8 and 1.9 gcm^{-3} at 0-20 and 20-40 cm respectively (Rethman, 2006).

2.1 Causes of soil compaction

Compaction can occur both naturally, by settling or slumping of soil, and because of the activities of humans as well as trampling by animals (Kozlowski, 1999). When it is very wet, loose soils may be compressed as a result of settling and or slumping. Settling is associated with drying and wetting, resulting to shrinkage and swelling of soil that leads to closer packing of soil aggregates (Koolen & Kuipers, 1983). Slumping follows weakening of soil aggregates as a result of wetting and disintegration at contact points, allowing closer packing (Mullins, 1991). Most commonly, soils are severely compacted by tillage tools, trampling by animals, pedestrian traffic and heavy machinery.

2.1.1 Tillage tools

Soils may be compacted by tillage tools that operate below the soil surface. Some of the soil is pushed ahead of the moving tool against the resistance of the soil body; hence, the soil becomes compacted (Hillel, 1982). Wiermann *et al*., (2000) studied the long-term effect of reduced tillage on soil strength properties on a silty loam soil. They found that the repeated deep impact of tillage tools in conventionally treated plots resulted in a permanent destruction of newly formed soil aggregates. This led to a relatively weak soil structure of the tilled horizons.

The effects of traditional tillage, minimum tillage, and no-tillage on soil water, soil organic matter and soil compaction were investigated by Benito *et al.,* (1999). It was found that soil compaction was less in traditional tillage, but there was more compaction in the subsoil after harvesting, thus resulting in less soil compaction than in the no-tillage treatment. Li HongWen *et al.,* (2000) reported that when farm operations are performed when soil is wet, it could increase soil compaction significantly. Random traffic can also severely compact the soil, reduce infiltration and increase energy consumption. Rethman, (2006) also reported that even agricultural equipment, used in post-mining land use systems, can cause re-compaction, especially if land is cultivated when the soil moisture content is conducive to compaction and when soil organic matter and aggregation (structure) are sub-optimal.

2.1.2 Animal trampling

Most of the soil compaction in intensive agriculture is caused by the external load on soil from farm machinery or livestock. This causes considerable damage to the structure of the tilled soil and the subsoil (Defossez & Richard, 2002). Trampling of a dry soil by livestock may compact the surface layer and disrupt soil aggregation while trampling of moist soil deformed the aggregates and created a flat, relatively impermeable layer comprised of dense and unstable clods (Warren *et al.,* 1987).

The intensification of dairy farming has also been found to have a deleterious effect on soil quality, particularly in terms of compaction by trampling, which results in losses of production, pasture quality and hydraulic conductivity (Mitchell & Berry, 2001). One of the most important soil properties vulnerable to animal trampling is bulk density and penetration resistance, which is highly sensitive to animal trampling. Mapfumo *et al.,* (1999) reported that the surface (0-2.5 cm) bulk density and penetration resistance was significantly greater under heavily grazed than under medium and lightly grazed area.

Soil compaction induced by trampling related to the soil depth. The depth of trampling-induced soil compaction varies depending on animal weight and soil moisture and could range from 5 to 20 cm. Ferrero & Lipiec, (2000), reported that most compaction effects were limited to the surface and intermediate depths of about 20 cm, while Vzzotto *et al.,* (2000) reported that animal trampling increased soil density in the first 5 cm soil depth and Terashima *et al.*, (1999) reported that trampling affected soil properties to a depth of 20 cm, with the greatest effect in the top 5 cm. Usman, (1994) suggested that trampling produced dense zones, which reduced water infiltration at a depth of 7.5 cm.

2.1.3 Pedestrian traffic and number of passes

The use of recreational parks and forests increases soil compaction, destroys ground cover, decreases infiltration of water, and increases runoff and soil erosion. Kozlowski (1999) reported that in the Rocky Mountain National Park camp grounds the soil from heavily used sites had an average bulk density of 55.3% higher than soil from lightly used sites. The compacting effect of intensive use was more pronounced in the 0-5 cm soil layer on lightly and moderately used sites, while it was also found to a depth of 13 cm on heavily used sites (Dotzenko *et al*., 1967).

Subsoil compaction may be induced by repeated traffic and the effects can persist for a very long time (Balbuena *et al.*, 2000). In highly weathered soils, there are changes in soil physical properties in which compaction may not increase the strength but may reduce the porosity, thus restricting water supply to the root surface (Rengasamy, 2000). Alakukku, (1996) reported that in both clay and organic soil, the penetrometer resistance was 22-26% greater; the soil moisture water content was lower, and the soil structure more massive in plots with repeated traffic than in the control plots.

Intensity of trafficking (number of passes) plays an important role in soil compaction because deformations can increase with the number of passes (Bakker & Davis, 1995). Experimental findings have shown that all soil parameters become less favourable after the passage of a tractor and that a number of passes on the same tramlines of a light tractor, can do as much or even greater damage than a heavier tractor with fewer passes (Chygarev & Lodyata, 2000).

Seker & Isildar, (2000) reported that the number of tractor passes increased soil bulk density and compaction, and decreased total porosity, void ratio, air porosity and drainage porosity. These findings were also supported by Balbuena *et al*., (2000) who reported that 10 passes significantly affected soil properties of the surface layer to 50 cm depth compared to the 1 pass and no-traffic control treatments. The negative effects of the number of passes on soil compaction was also explained by Mosaddeghi *et al*., (2000) who showed that increasing the number of passes counterbalanced the effect of manure in ameliorating soil compaction.

2.1.4 Heavy machinery

Tillage and traffic using heavy machines can also induce subsoil compaction in different soil types (Mosaddeghi *et al.*, 2000). The depth of the compaction varies widely from 10 to 60 cm but it is more obvious in topsoil around 10 cm (Flowers & Lal, 1998). Balbuena *et al.*, (2000) reported that penetrometer reading increments between 16 and 76% can occur in the first 40 cm of the surface layer and bulk density can also increase but increases were limited to a 15 cm depth. However, in a grassland situation differences between heavy and light loads in the shallower depth range (topsoil) were not found (Jorajuria & Draghi, 2000).

Heavy machine loads play an important role in soil compaction. Rethman, (2006) reported that in the Mpumalanga Highveld the use of heavy earth moving equipment is the primary causes of soil compaction. Wingate-Hill & Jakobson, (1982) indicated that under heavy traffic loads some soils become compacted to a depth of 1 m and sometimes more. However, the highest degree of compaction typically occurs in the top 30 cm of the soil profile, which normally contains most of the root mass. Kozlowski, (1999) reported that vehicles exert three major compacting forces on soils: the normal vertical force due to the dynamic load of the wheels, shear stress caused by slippage of wheels, and vibration of engines through the tyres. Most soils become compacted during the first few passes of a vehicle. Subsequent passes generally have little additional effect but the impact varies with the load and soil strength (Shetron *et al.*, 1988).

Horn *et al.*, (2001) reported that wheel load and tyre type also increases soil bulk density and influences soil compaction. Almost all tyres significantly increase soil compaction in the wheel track, while only some of them increase soil compaction near the track. Febo & Planeta, (2000) reported that wider wheels fitted with radial tyres reduce soil compaction as compared to those with metal tracks and diagonal-ply tyres which usually destroy the layers of soil structure. However, tyre ground pressure values vary significantly between different machines with trailers, and slurry tankers exerting the highest ground pressures (Pagliai & Jones, 2002). Rethman, (2006) also reported that the compaction is a function of applied pressure and aggravated by size of loads, use of wheeled (tyres) vehicles and number of passes (traffic) over reclamation areas.

2.2 Effects of soil compaction

2.2.1 Soil parameters

Soil compaction resulted in increased soil strength and soil density (Dollhopf & Postle, 1988). Soil strength is the resistance of a soil to deformation or fracture (Hillel, 1980). It is an indication of the resistance that a soil will provide against the growth of plant roots. However, if a soil has few pores that are adequate in size for root penetration, then roots can displace soil back when they enlarge during growth. This is acceptable for low strength soils, but root growth is essentially stopped in high strength soils (Conrad *et al.*, 2002).

Bengough & Mullins, (1990b) reported that as a root enters a soil of high strength, its rate of elongation declines while radial expansion increases behind the root tip. The lowered rate of root elongation reflects a decreased rate of cell division in the meristem together with a decrease in cell elongation. Kozlowski, (1999) stated that severe compaction of soil not only shortens and thickens roots but also may alter their branching patterns. In general, the roots growing in compacted soil become more branched and form more lateral roots. Some species form a mat of proliferated short roots at a shallow soil depth.

In mine soils, Rethman, (2006) found that the two most common physical parameters affected by compaction are bulk density (BD) and soil strength, both of which increase dramatically under the impact of heavy machinery. This impact is often reflected in the breakdown of soil structure which in turn has strong influence on proportions of macro-pores, micro-pores and aeration porosity. Kozlowski & Pallardy, (1997) also reported that compacted profile layers resulted from surface pressure applied to the soil breaking the bonds of aggregating agents that hold soil particles together into structural units. Subsequently, the particles become reoriented into a configuration that has a higher bulk density (BD) (mass per unit volume) and soil strength.

Rethman, (2006) also reported that within the soil profile the physical impacts of compaction often results in slow percolation or drainage which can have the effect of causing periodic waterlogging and poor aeration in the plough layer. In extreme cases, such poor drainage or percolation might also reduce replenishment of water in the sub-soil or of ground water reserves. Where there is preponderance of very fine pores as in dense compacted horizons, water is strongly adsorbed and the utilization of such soil water is poor.

2.2.2 Water relations

In practice, however the Mpumalanga Highveld is characterized by rainfall distribution (over the year) and variability (from year to year) which can result in drought stress both within and between seasons (Rethman, 2006). The effects of soil compaction on plant growth are seriously increased under drought stress. Plant growth is strongly influenced by soil moisture (Sharp *et al*., 1988). Decreased soil moisture can result in various responses, such as decreased cellular growth, suppressed leaf expansion, stomatal closure, a reduction in the rate of photosynthesis, and the accumulation of various osmolytes within cells (Taiz & Zeiger, 2002). Nonami & Boyer, (1990) reported that in soybean (*Glycine max*) hypocotyls, growth was suppressed due to water stress, whereby a reduction in the surrounding water potential affected the turgor pressure of elongating cells, and this reduction causes a change in the elongation rate of the cells.

The growth rate of roots is regulated by a combination of the expansion and the production of cells (Beemster & Baskin, 1998). Moreover, cell expansion appears to be more sensitive in general to water stress. The rate of root elongation decreased where the root tip experienced low water potential resulted in the suppression of cell expansion (Hsiao, 1973). Hsiao & Xu, (2000) reported that when water potential is suddenly reduced in roots, osmotic adjustment occurs rapidly to allow partial turgor recovery, re-establishment of water potential gradient for water uptake and the loosening ability of the cell wall, increases. These adjustments permit root to resume growth under low water potential.

Water deficiency results in the growth of leaves to be readily inhibited. Osmotic adjustment of leaves occurs slowly when the water potential is reduced to a similar magnitude to that of roots. Additionally, the cell wall loosening ability does not increase substantially. It does, however, decrease leading to marked growth inhibition (Hsiao & Xu, 2000). Hsiao & Xu, (2000) further stated that the growth of both roots and leaves are hydraulically isolated from the vascular system. This isolation protects the roots from low water potential in the mature xylem and facilitates the continued growth. The water potential of the leaf growth region is barely affected by soil water removal through transpiration. Furthermore, leaf water potential would be low and subjected to further reductions by high evaporative demand.

Chaves *et al.,* (2002) reported that water stress has a negative impact on carbon assimilates of the leaf. Carbon assimilation decreases as a consequence of limitations to carbon dioxide diffusion in the leaf, diversion of carbon allocation to non-photosynthetic organs and changes in leaf biochemistry result in the down-regulation of photosynthesis. This resulted from stomatal closure which restricts water losses. Stomatal control of water losses has been identified as an early event in plant response to water deficit leading to a limitation of carbon uptake by leaves (Cornic & Massacci, 1996). Stomata close in response to either a decline in leaf turgor or water potential. Stomatal responses are often linked to soil moisture content. This suggests that stomata are responding to chemical signals like abscisic acid (ABA) produced by dehydrating roots (Chaves *et al.*, 2002).

Rethman *et al.,* (1997) studied the influence of soil water availability on the above and below ground phytomass of five sub-tropical grass species. Species evaluated included *Cenchrus ciliaris* cv. Molopo, *Digitaria eriantha:eriantha* cv. Irene, *Eragrostis curvula* cv. Common, *Panicum coloratum* cv. Selection 75 and *P. maximum* cv. Gatton. They found that in terms of above ground production *C.ciliaris* recorded the highest yield 15% more than *E.curvula,* 21% more than *P.maximum*, 40% more than *D.eriantha* and 59% more than *P.coloratum* and was the least sensitive to soil water availability. In contrast, *C.ciliaris* and *E.curvula* recorded dramatically lower below ground phytomasses 66% and 73% respectively than *P.maximum*, which had the best root development.

The effects of soil compaction on plant growth are very complex in mine soils. The major reasons for this reduction in plant productivity include the water balance and nutrient usage in such soils, and the major mechanical resistance to root penetration or root growth offered by the high soil strength and bulk densities in compacted soils. Where pasture/forage crops have been established on compacted soils it is common to find that, apart from depressed yields, these crops are also characterized by a poorer cover. The same is true of annual row crops where drastic reductions in crop productivity, make qualification for mine closure or bond release virtually impossible on many sites. In forestry production; poor survival, establishment, low tree heights and an overall reduction in stem values are common where compaction has impacted on the environment (Rethman, 2006).

2.2.3 Mineral nutrition

Severe soil compaction decreases root absorption of major mineral nutrients, especially N, P and K. (Kozlowski, 1999). Mineral uptake per plant is reduced because the growth of roots is inhibited by greater soil resistance to root penetration. When roots fail to explore a large volume of soil resources, mineral nutrients become positionally unavailable (Wolkowski, 1990).

2.2.3.1 Nitrogen

Root development is extremely sensitive to variations in nutrient supply. Nitrogen is absorbed by the roots in the form of nitrate (Zhang *et al*., 1999). The processes by which nitrate is absorbed depending on its availability and distribution, can have both positive and negative effects on the development and growth of lateral roots. (Zhang *et al*., 1999) reported that when *Arabidopsis* roots were exposed to a locally concentrated supply of nitrates there was no increase in lateral root numbers within the nitrate rich zone, but there was a localized increase in the mean rate of lateral root elongation, which was attributable to a corresponding increase in the rate of cell production in the lateral root meristem.

However, severe compaction decreased the rates of nitrate supply to the roots, causing a systemic inhibitory effect on lateral root development (Zhang *et al*., 1999). Li *et al.,* (2007) reported that compaction limits nitrogen (N) supply thereby causing reduced plant growth and morphological changes such as slowing of root growth relative to shoot growth. Breland & Hansen, (1996) identified that soil compaction reduced nitrogen (N) mineralization and N availability. Because of the possible creation of anaerobiosis under compacted soil conditions, more N is generally lost from the soil system.

Denitrification is generally thought to be the most likely process of N loss from compacted soil condition (Ponder *et al*., 2003). The amount of N loss may vary widely among soils and ecosystems and the loss may be attributed to both denitrification and leaching. In a laboratory study by Torbert & Wood, (1992) on the effects of soil compaction on microbial activity and N losses, they found that greater N losses were observed with increasing bulk density, most likely due to denitrification and leaching. In another study of compaction effects on nitrogen mineralization and microbial biomass using N labeled clover, it is found that after 98 days, the net mineralization of clover N was reduced by 18% in the compacted pots compared with the non-compacted pots. The soil was uniformly compacted to a bulk density of 1.8 g dry soil cm^{-3} which was 9.3 kg of dry soil per pot using a drop hammer. The non-compacted pots were not compacted and its bulk density was 1.3 g dry soil cm^{-3} using 6.7 kg of dry soil per pot (Breland & Hansen, 1996).

2.2.3.2 Phosphorus

Soil compaction also affects the phosphorus (P) supply to plants. This is mainly dependent upon the soil's initial degree of compactness, as well as its moisture status and level of plant available P (Cornish *et al.*, 1984). A reduced root system is likely to affect the ability of plants to take up water and nutrients. In particular, it may reduce the uptake of the less mobile nutrients, such as P (Kristoffersen, 2005). Since soil compaction normally restricts root penetration, it is expected that a reduced root system would lead to lower plant uptake of phosphorus.

Prummel, (1975) reported that restricted root growth due to poor soil structure limited the plant uptake of phosphate, especially at low phosphate availability. Lipiec & Stepniewski, (1995) showed a significant reduction in the P uptake by spring barley in strongly compacted soil, and related it to differences in the configuration of the root system. In another study, Kristoffersen, (2005) reported that the root length was drastically reduced by increased soil compaction and the P uptake per unit root length of roots decreased with increasing level of soil compaction.

However a certain amount of compaction, such as that caused by normal tillage operations, may be beneficial for nutrient uptake as it increases the contact between soil particles and roots, and may lead to a more rapid exchange of ions between the soil matrix and roots (Arvidsson, 1999). It may also lead to higher concentrations of P within the root depletion zone due to higher soil density (Nadian *et al.*, 1996). Thicker roots may also be able to take up more P per unit root length, because of increased maximal influx with increased root diameter (Peterson & Barber, 1981).

2.2.3.3 Potassium

Potassium (K) is one of the major nutrients, essential for root growth and development. The availability of potassium to the plant is highly variable, due to complex soil dynamics, which are strongly influenced by root-soil interactions (Grabov *et al.*, 2006). In accordance with its availability to plants, soil potassium is found in different pools, such as soil solution and exchangeable K (Syers, 1998). Yanai *et al.*, (1996) reported that severe compaction reduced the exchange of potassium in the soil solution. The release of exchangeable K is often slower in compacted soil, resulting in a decrease rate of K acquisition by plants roots (Johnston, 2005).

Potassium status may further deteriorate with the increasing soil bulk density and soil strength, which interfere with potassium uptake (Qi & Spalding, 2004). Plant roots can experience transient shortages of potassium because of spatial heterogeneity and temporal variations in the availability of this nutrient. The main source of soil heterogeneity is soil compaction, which often suppresses roots growth and inhibits the K transport activity, which creates zones with reduced nutrient content (Grabov *et al.*, 2006). However in less compacted soils contact between roots and K may occur, because of root growth into the area where the nutrient is located and transport of a nutrient to the root surface through the soil (Jungk & Claassen, 1997).

In a greenhouse study conducted by Kuchenbuch *et al.*, (1986) it was found that less soil compaction is associated with higher volumetric water content and therefore tends to facilitate K transport to the root surface. However, the dense soil may also cause a reduction in the root length and so the higher bulk density does not necessarily result in increased K accumulation (Seiffert *et al.*, 1995). Oliveira *et al.*, (2004) reported that K translocation through the soil to the root surface is facilitated by diffusion and mass flow. Diffusion is the dominant mechanism of K delivery to the root surface and constitutes up to 96% of total soil K transport. In dry soils, bulk density content is normally higher and, therefore, K delivery was found to be low, from the restricted mass flow and diffusion (Vetterlein & Jahn, 2004).

2.3 Alleviation of soil compaction

Compaction is one of the most important soil quality indicators reflecting the potential for environmental damage and the physical state of the soil resources (Birkas *et al.,* 2004). A combination of practices is suggested to alleviate soil compaction. These practices include conservation tillage and biological activities. Managing soil compaction by conservation tillage can be achieved through appropriate application of some of the following techniques: mechanical soil loosening such as deep ripping, controlled traffic and reducing soil disturbances by strip, shallow tillage or no-till. Biological effects involve incorporating organic materials and growing soil loosening crops by rotating cash crops and pastures with strong tap roots capable of penetrating and breaking down compacted soils.

2.3.1 Conservation tillage

2.3.1.1 Deep ripping

Deep ripping or deep cultivation is an important practice to alleviate soil compaction, destroying hard pans and ameliorating hard setting soils (Laker, 2001; Hamza & Anderson, 2005). Henderson, (1991) reported that deep ripping of compacted, sandy soil increased dry matter at flowering of field peas (*Pisum species*) and lupins (*Lupinus species*) and their yield increased on ripped soils by 64 and 84%, compared to undisturbed soils. In another study of compacted soils, it was found that grain yields were increased slightly more on the compacted loamy sand soil than on the sandy loam soil due to deep ripping and gypsum application (Hamza & Anderson, 2003).

Deep ripping has an influence on the soil-water relations, especially infiltration rate of compacted soils. Hamza & Anderson, (2002) found that deep ripping alone increased the infiltration rate in the first three years but the effect did not last into the fourth year. In fact the effect of ripping on water infiltration began to decline sharply in the second year. It was suggested that the decrease in the infiltration rate with time for the ripped, treatments indicates that large soil voids created by ripping, filled gradually with fine particles and colloids and the soil became compacted again. Hall *et al.,* (1994) also reported that the effect of deep ripping on soil-water relations declines after the first year and yield increases associated with deep ripping did not persist in the second year of the experiment, presumably due to re-compaction.

Ripping soil alleviates compaction and increases yields more efficiently by removing the causes of compaction. Ellis, (1990) reported that grain yields showed little response to deep ripping in wheeled treatments even though penetrometer resistance showed a marked decrease, but a significant increase in grain yield occurred where both the compacted layer and wheel traffic were removed. Kayombo & Lal, (1993) suggested that the alleviation of soil compaction can be achieved by the use of mechanical loosening techniques such as deep ripping and subsoiling to remove soil compaction. They added that the effect of mechanical loosening tends to work more effectively if the field traffic is controlled.

2.3.1.2 Controlled traffic

Soil compaction may be the most devastating effect of vehicle traffic. The option for overall reduction of vehicle traffic in the field is to consider a form of controlled traffic (Raper, 2005). Controlled traffic is a system which restricts soil compaction to the traffic lanes to maintain a zone more favourable for plant growth (Braunack *et al.*, 1995). Williford, (1980) found significantly increased cotton yields in a Tunica clay in Mississippi over a 5 year period from controlled traffic plots. Controlled traffic slows down the effect of re-compaction on tilled soil (Busscher *et al.*, 2000), significantly increases soil water infiltration, improves soil structure, increases soil moisture and reduces run-off (Li YuXia *et al.*, 2001).

Controlled wheel traffic has effects on soil strength. Liebig *et al.,* (1993) found that soil strength in the trafficked inter-row was 56% greater than the non-trafficked inter-row and 104% greater than the row on a silty clay loam. Alakukku, (1998) also reported that soil penetrometer resistance was greater in compacted than control plots in the 35-49 cm layer of a clay loam and the 25–35 cm layer of a silt soil. This was found when comparing compacted soil by three passes of high axle load traffic and un-compacted (no traffic) silt and clay loam soils. The subsoil structure was also more massive and homogeneous in compacted than in control plots.

Controlled traffic has been shown to have lower energy requirements as compared to other tillage techniques (Coates & Thacker, 1990). Williams *et al.,* (1991) reported that controlled traffic used up to 79% less energy to perform a tillage activity such as discing. The same results were supported by Nikolic *et al.,* (2001) who estimated the saving energy of 20-25%. Coates, (1997) also reported that the second best tillage, as far as energy is concerned, is reduced (minimum) tillage, which has been shown to offer significant energy savings over conventional systems.

Raper *et al*., (1998) compared the effect of controlled traffic on soil compaction with trafficked areas and the subsequent effect on crop root penetration on sandy loam. They found that traffic decreased the total estimated soil volume suitable for root growth. Bulinski & Niemczyk, (2001) also reported that the volumetric density of soil sampled from the traffic lanes in a controlled traffic system was higher by 15–39% as compared with trafficked areas. Similar results were also reported by Panayiotopoulos *et al.* (1994) who found that controlled traffic resulted in better root growth and lower resistance to penetration.

2.3.1.3 Reducing soil disturbances by tillage systems

Traffic on loose soil causes a significant increase in soil compaction. The main function of tillage systems is to alleviate subsoil compaction. Botta *et al*., (2004) emphasized primary and secondary tillage to be applied to reduce soil disturbances. Primary tillage increases the volume of soil accessible by plant roots, so one of its objectives is to increase the void ratio of soil. Secondary tillage decreases the size of soil aggregates. Busscher *et al.,* (2006) reported that tillage systems, especially primary tillage, helps to alleviate plant water stress by making more of the profile available for root exploration and water extraction. A significant decrease in soil compaction and higher pasture yields, measured as dry matter production, were observed when the secondary system was performed by tractor equipped with larger sized radial tyres (Botta *et al*., 2004).

The techniques commonly utilized for control and management of topsoil and subsoil compaction are subsoiling and chiseling. Balbuena *et al.,* (1998) reported that subsoiling and chiseling applied at depth of 280-450 mm are utilized for controlling subsoil compaction and to increase crop yields. In a study of deep tillage and traffic effects on subsoil compaction and sunflower (*Helianthus annus L.*) yields, Botta *et al*., (2006) found that the total cross-sectional area loosened by the chisel was 14% more than the subsoiler and even though the chisel efficiency was 85% less than the subsoiler.

Raper *et al*., (1994) compared various cotton tillage systems on a sandy loam soil, including annual subsoiling at 0.4 and 0.5 m depth. They found that the positive effects of controlling traffic were significant when in-row subsoiling was used as an annual tillage treatment. In addition to the environmental benefit of maintaining surface residues and alleviating soil compaction, they found that strip tillage, involving in-row subsoiling to 0.4 m depth, decreased cone index directly beneath the row, decreased topsoil bulk density, increased soil water content, decreased energy usage and increased yields.

2.3.2 Biological effects

2.3.2.1 Addition of organic manure

Application of organic manure such as cattle manure, may overcome the negative effects of compaction due to the beneficial effects on soil physical, chemical and biological properties in the zone of incorporation (Motavalli *et al*., 2003). An increase in soil organic matter from organic manure is a desirable aim as it is associated with better soil physical properties such as greater aggregate stability, reduced bulk density, improved water holding capacity at low suctions and enhanced porosity (Moreno *et al*., 2006). Carter, (2002) suggested that maintaining an adequate amount of organic matter in the soil not only stabilizes soil structure and makes it more resistant to degradation, but also decreases bulk density and soil strength. Zhang, (1994) emphasized that mixing organic matter with soil reduced soil bulk density and improved porosity. Similarly Martin & Stephens, (2001) indicated that organic materials possess lower bulk density and greater porosity than that of mineral soils.

The addition of organic matter to topsoil through incorporation of plant residues or manure application has been widely studied by many researchers (Soane, 1990; Zhang, 1994; Hamza & Anderson, 2003). Fettell, (2000) reported that manure as a source of organic matter is a beneficial practice in improving soil physical properties in compacted soils. Reddy, (1991) observed a decrease of 0.02 Mg m^{-3} in bulk density and 11.8 kPa in soil strength while the infiltration rate increased by 0.4 cm h^{-1} on a sandy loam soil due to the application of 10 t ha^{-1} of green leaf manure.

Organic matter influences soil structure and compatibility through different mechanisms such as binding of soil aggregate particles (Zhang & Hartge, 1992). Puget *et al*., (1999) confirmed that stable aggregates were enriched and formed around young decomposing soil organic matter. The type of organic matter is also important. Readily oxidisable soil organic matter seems to be more relevant in determining mechanical behaviour of the soil (Ball *et al.,* 2000). On the other hand, the less humified organic matter has a greater effect in increasing aggregate porosity resulting in the decrease of aggregate tensile strength (Zhang, 1994).

Matsi *et al*, (2003) have shown that the application of cattle manure can increase the soil available macronutrients N, P, and K. Nitrogen is a primary plant nutrient (especially for grasses) and exists as plant available nitrogen in the form of ammonium or nitrate. Nitrogen applied to grasses before they begin flowering stimulates tillering, while nitrogen applied during or after flowering stimulates stem and leaf growth (Whitehead, 2000). Phosphorus is critical for early root growth, for seed production, and for effective nitrogen fixation by legume nodules. Potassium is important during the growing season. It increases the ability of plants to survive winter conditions, by stimulating root growth and reducing water loss through stomata or leaf pores (Horne, 1992).

2.3.2.2 Soil loosening deep-rooted crops

Subsoil compaction may reduce the availability and uptake of water and plant nutrients thereby lowering crop yields. Amongst the management options for alleviating subsoil compaction is the selection of crop rotations with deep-rooted crops (Motavalli *et al*., 2003). Ishaq *et al*., (2001) reported that plant species that have the ability to penetrate soils with high strength usually possess a deep tap root system. Incorporating such species in rotation is desirable to minimize the risks of subsoil compaction. Jayawardane & Chan, (1994) suggested that on soils such as vertisols with high shrink swell potential, strong rooted crops such as safflower (*Carthamus spp*.) could be used as a biological soil loosening treatment through a deep soil profile.

It has been suggested that genetic improvement for root growth in soils with hard layers, could potentially reduce subsoil compaction (Hamza & Anderson, 2005). Busscher *et al.,* (2000) reported that soybean (*Soja spp*.) CV PI 416937 possesses a superior genetic capability over CV Essex, to produce more root growth in soils with high penetration resistance. Rosolem & Takahashi, (1998) studied the effects of soil sub-surface compaction on root growth and nutrient uptake by soybean grown on sandy loam soils. They reported that sub-surface compaction led to an increase in root growth with a corresponding decrease in the compacted layer. There was no effect of subsoil compaction on total root length or surface area, soybean growth or nutrition.

Changes in root diameter loosen and break down any compacted soil layer around them. Hamza *et al*., (2001) using a computer assisted tomography technique, showed that radish (*Raphanus spp*.) and lupin (*Lupinus spp*.) roots exhibit a temporary decrease in diameter after transpiration commences followed by a significant temporary increase.

This fluctuation in diameter destabilizes soil and loosens the compaction. Cochrane and Aylmore, (1994) studied the effects of plant roots on soil structure. They found that legumes are more effective for loosening soil structure aggregates than non-legumes, and lupins were reported to be the most efficient species.

2.3.3 Alleviation of compaction in mine soils by using cattle manure and pasture grasses

2.3.3.1 Cattle manure

Organic matter levels are generally very low in mine soils. This may be ascribed to the loss of organic matter from the A-horizon because of compaction and re-compaction, high bulk densities and soil strength, hard setting and surface crusting. These, in turn, result in poor structure, aggregate stability, porosity, infiltration, drainage, water retention, an increase in runoff and erosion, poor aeration, drainage and root penetration (Rethman, 2006). The application of cattle manure has often been reported to increase plant growth and improve physical properties of the soil. Hati *et al*., (2006) reported that the application of animal manures improved physical properties of the soil, which promoted higher nutrient and water uptake by plant roots and increased plant growth. Zhang *et al*., (2006) also found that cattle manure application improved the physical properties of the soil, which promoted better rooting as well as higher nutrient and water uptake by Bromegrass and Oat production. Rethman, (2006) also emphasized the role of green manuring, organic amendments and restorative pastures to restore and maintain organic matter levels in mine soils over the long term.

2.3.3.2 Pasture grasses

In South Africa surveys on reclaimed areas have revealed that compaction has imposed severe restrictions on the effective rooting depths of most reconstructed soils. Successful strategies to achieve alleviation of compaction will probably include the selection of species which are not only adapted to local climatic conditions and satisfy the defined objectives of post-mining land use but will also be able to tolerate high bulk densities or better still alleviate such conditions and penetrate dense compacted layers, in combination with mechanical, chemical and other biological methods of alleviation, or amelioration of compaction (Rethman, 2006).

Tall Fescue (*Festuca arundinacea*) is an important temperate perennial grass, which it is widely used for both forage and turf purposes (Sleper & West, 1996). Compared with other cool-season turfgrass cultivars, Tall Fescue is reported to have good high temperature tolerance and drought resistance. Major components of drought resistance are the development of a deep and viable root system (Carrow, 1996; Dane *et al.,* 2006). Sheffer *et al.*, (1987) reported that Tall Fescue is better able to avoid drought than other turfgrasses such as perennial ryegrass (*Lolium perenne* L.) or Kentucky bluegrass (*Poa pratensis* L.). They indicated that variations in turfgrass drought resistance have been attributed mainly to differences in total root length density and rooting depth.

Salt stress is also a major factor reducing plant productivity. The detrimental effects of salinity on turfgrass growth include osmotic stress, ion toxicity and nutritional disturbances (Cheeseman, 1988). Salt tolerant plants have the ability to minimize these detrimental effects by producing an extensive root system and having salt secreting glands on the leaf surface (Poljakoff-Mayber, 1988). Alshammary *et al.*, (2004) studied the growth responses of four turfgrass species to salinity. They found that the growth of Tall Fescue roots was less adversely affected by salinity than that of shoots, leading to a significant shift in the root to shoot ratio in favour of the root. Tall Fescue also had a higher root to shoot ratio than Kentucky bluegrass at 4.7 and 9.4 dSm^{-1} salinity levels.

Tall Fescue is long-lived and often survives for 6-10 years or more, penetrating moist soils to a depth of 150 cm and tolerating contaminated soils (Walsh, 1995). Aprill & Sims, (1995) have suggested the use of such grasses for the treatment of hydrocarbon-contaminated sites. Horst *et al.*, (2000) compared the growth and development of Smooth

Bromegrass and Tall Fescue in 2,4,6-trinitrotoluene (TNT)-contaminated soil. They reported that the shoot dry weight of Tall Fescue was 50% greater than that of Smooth Bromegrass. Tall Fescue roots were also significantly longer than those of Smooth Bromegrass, at all concentrations of TNT.

Smuts Fingergrass *(Digitaria eriantha)* is a subtropical species widely spread in southern Africa. Smuts Fingergrass is now widespread in grazing areas throughout the world's humid tropics and subtropics, including South-East Asia (Smith & Valenzuela, 2002). It is a palatable, good quality summer growing perennial grass suited to a range of soils, very persistent and productive species (Buckley, 1959). In agreement with other investigations, *D. eriantha* showed its adaptation to the environment of the north-west slopes in southern Queensland by tolerating regular and severe night frosts over a season of 4-5 months (Strickland, 1974). Its persistence and competitive ability, particularly in low nitrogen soil, may be due to non-symbiotic N fixation in its rhizosphere (Tow & White, 1976).

Rethman & Tanner, (1993) studied the influence of the level of soil fertility on the botanical composition of pastures established on rehabilitated strip-mined land in South Africa. They found that over an experimental period of five years (1987-1992) the annual *Eragrostis tef* and weakly perennial *Chloris gayana* species disappeared completely, irrespective of the level of fertility, whereas the perennial Smuts Fingergrass (*Digitaria eriantha*) persisted as dominant species irrespective of soil acidity, phosphorus or potassium status.

In other investigations it was found that *D. eriantha* can establish well in degraded areas. It is better adapted to low fertile soils and is tolerant of soil aluminum, which is often present in acidic tropical soils. It tolerates soil pH (H_2O) from 4.5 to 8.0 and drought (Smith & Valenzuela, 2002). Snyman, (2003) studied revegetation of bare patches in a semi-arid rangeland of South Africa. He reported that regardless of cultivation treatment, or soil form, *D. eriantha* had the best survival after 10 years and had even spread into adjacent areas. Tow *et al.*, (1997) reported that *D. eriantha* indicated good adaptation to the poor physical conditions and extremes of moisture supply encountered in solodic soil profiles by producing the high yields of both shoot and root.

High summer temperatures can often have an adverse effect on growth of temperate species. Since *D. eriantha* is a subtropical grass, its better growth and water-use efficiency at higher temperature regimes (between 35-38ºC) was predictable (Tow, 1993). Tow *et al.*, (1997) also compared the effects of environmental factors on the performance of *D. eriantha* and *Medicago sativa* in monocultures and as a mixture. The results of the experiment confirmed the field observations that Smuts Fingergrass and lucerne had complementary temperature responses, and thus complementary seasonal growth patterns, Smuts Fingergrass being favoured by summer temperatures and lucerne by spring temperatures.

On post-mining environments the following effects of pastures have been recorded and most of these are linked with the impact of soil compaction; improvements in soil structure / aggregation, soil organic matter content, rooting depths, microbial and micro-fauna, infiltration rates and reduced erosion, hydraulic conductivity, water holding capacity and aeration, consequently, reductions in bulk density, surface crusting and hard setting (Rethman, 2006).

3. Conclusions

Surface mining activities contribute to environmental damage and change the physical state of soil leading to harmful effects of soil compaction on plant growth. In mine soils, compaction restricts the establishment and growth of plants by decreasing the development of roots to acquire nutrients and water. The capacity of roots to penetrate soils decreases with increasing soil strength and bulk density. Soil of high strength reduces root elongation. Root and shoot masses, root system surface areas and root diameters decrease with increasing soil bulk density.

It was found that compaction can occur naturally by settling of soil, and because of the activities of humans. In mine soils, most commonly, soils are severely compacted by heavy machinery. From surveys it has been reported that in the Mpumalanga Highveld the use of heavy earth moving equipment is the primary causes of soil compaction. Other studies indicated that under heavy traffic loads some soils become compacted to a depth of 1 m and sometimes more. However, the highest degree of compaction typically occurs in the top 30 cm of the soil profile, which normally contains most of the root mass.

A combination of practices is suggested to alleviate soil compaction. These practices include conservation tillage and biological activities, achieved through appropriate application of some of the following techniques; mechanical soil loosening such as deep ripping, controlled traffic, reducing soil disturbances by strip, shallow tillage or no-till, incorporating organic materials and growing soil loosening crops by rotating cash crops and pastures plants with strong tap roots capable to penetrate and break down compacted soils.

In mine soils, the proposed investigations, which are envisaged to solve harmful effects of soil compaction on plant growth, include planting of pasture species and application of cattle manure. Pastures are linked with improvements in soil structure, soil organic matter content, rooting depths, consequently, reductions in bulk density. The application of cattle manure has often been reported to increase plant growth and improve physical properties of the soil.

4. References

ALAKUKKU, L., 1996. Persistence of soil compaction due to high axle load traffic I. Short-term effect on the properties of clay and organic soils. *Soil Tillage Res*. **37**: 211-222.

ALAKUKKU, L., 1998. Properties of compacted fine-textured soils as affected by crop rotation and reduced tillage. *Soil Tillage Res*. **47**: 83-89.

ALSHAMMARY, S. F., QIAN, Y. L. & WALLNER, S. J. 2004. Growth response of four turfgrass species to salinity. *Agric. Water Manag*. **66**: 97-111.

APRILL, W. & SIMS, R.C., 1995. Evaluation of the use of prairie grasses for stimulating polycyclic aromatic hydrocarbon treatments in soil. *Chemosp*. **20**: 253-265.

ARVIDSSON J., 1999. Nutrient uptake and growth of barley as affected by soil compaction. *Plant Soil* **208**: 9-19.

BAKKER, D. M. & DAVIS, R. J., 1995. Soil deformation observations in a Vertisol under field traffic. *Aust. J. Soil Res*. **33**: 817-832.

BALBUENA, H. R., ARAGO'N, A., Mc DONAGH, P., CLAVERIE, J. & TERMINIELLO, A., 1998. Effect of three different tillage systems on penetration resistance and bulk density. In: Proceedings of the IV CADIR (Argentine Congress on Agricultural Engineering), **1**:197-202.

BALBUENA, R. H., TERMINIELLO, A. M., CLAVERIE, J. A., CASADO, J. P. & MARLATS, R., 2000. Soil compaction by forestry harvester operation. Evolution of physical properties. *Revista Bra. Eng. Agric. Amb.* **4**: 453-459.

BALL, B. C., CAMPBELL, D. J. & HUNTER, E. A., 2000. Soil compactibility in relation to physical and organic properties at 156 sites in UK. *Soil Tillage Res*. **57**: 83-91.

BEEMSTER, G. T. S. & BASKIN, T. I., 1998. Analysis of cell division and elongation underlying the developmental acceleration of root growth in *Arabidopsis thaliana*. *Plant Physiol.* **116**: 1515-1526.

BENGOUGH, A. G. & MULLINS, C. E., 1990a. Penetrometer resistance, root penetration resistance and root elongation rate in sandy loam soils. *Plant Soil.* **131**: 59-66.

BENGOUGH, A. G. & MULLINS, C. E., 1990b. Mechanical impedance to root growth: A review of experimental techniques and root growth responses. *J. Soil Sci.* **40**: 341-358.

BENITO, A., SOMBRERO, A. & ESCRIBANO, C., 1999. The effect of conservation tillage on soil properties. *Agric. Rev. Agro*. **68**: 538-541.

BIRKAS, M., JOLANKAI, M., GYURICZA, C. & PERCZE, A., 2004. Tillage effects on compaction, earthworms and other soil quality indicators in Hungary. *Soil & Tillage Res*. **78**: 185-196.

BOTTA, G., JORAJURIA, D., BALBUENA, R. & ROSATTO, H., 2004. Mechanical and cropping behavior of direct drilled soil under different traffic intensities: Effect on soybean (*Glycine max* L.) yields. *Soil Till. Res*. **78**: 53-58.

BOTTA, G. F., JORAJURIA, D., BALBUENA, R., RESSIA, M., FERRERO, C., ROSATTO, H. & TOURN, M., 2006. Deep tillage and traffic effects on subsoil compaction and sunflower (*Helianthus annus* L.) yields. *Soil & Tillage Res*. **91**: 164-172.

BRELAND, T. A. & HANSEN, S., 1996. Nitrogen mineralization and microbial biomass as affected by soil compaction. *Soil Biol. Biochem*. **28**: 655-663.

BRAUNACK, M. V., McPHEE, J. E. & REID, D. J., 1995. Controlled traffic to increase productivity of irrigated row crops in the semi-arid tropics. *Aust. J. Exp. Agric.* **35**: 503-513.

BUCKLEY, K.S., 1959. Plant testing for soil conservation at Inverell, *Soil Cons. J. NSW* **15**: 308-313.

BULINSKI, J. & NIEMCZYK, H., 2001. Effect of method of agricultural outfit running on the field on soil properties and sugar beet yielding. *Ann. Warsaw Agric. Univ. Agric. Eng*. **41**: 39-44.

BUSSCHER, W. J., LIPIEC, J., BAUER, P. J. & CARTER, T.E., 2000. Improved root penetration of soil hard layers by a selected genotype. *Commun. Soil Sci. Plant Anal.* **31**: 3089-3101.

BUSSCHER, W. J., BAUER, P. J. & FREDERICK, J. R., 2006. Deep tillage management for high strength southeastern USA Coastal Plain soils. *Soil & Tillage Res*. **85**: 178-185

CARROW, R. N., 1996. Drought avoidance characteristics of diverse Tall Fescue cultivars. *Crop Sci*. **36**: 371-377.

CARTER, M. R., 2002. Soil quality for sustainable land management: Organic matter and aggregation interactions that maintain soil functions. *Agronomy J*. **94**: 38-47.

CHAVES, M. M., PERIERA, J. S., MAROCO, J., RODRIGUES, M. L., RICARDO, C. P. P., OSORIO, M. L., CARVALHO, I., FARIA, T. & PINHEIRO, C., 2002. How plants cope with water stress in the field, photosynthesis and growth. *Ann of Bot*. **89**: 907-916.

CHEESEMAN, J. M., 1988. Mechanisms of salinity tolerance in plants. *Plant Physiol*. **87**: 745-755.

CHYGAREV, Y. & LODYATA, S., 2000. Research of tyre rigidity in terms of ecological safety of agricultural landscapes. Instytut Budownictwa, Mechanizacji i Elektryfikacji Rolnictwa, Lublin, Poland, p. 171-176.

CLARK, L.J., WHALLEY, W.R. & BARRACLOUGH, P. B., 2003. How do roots penetrate strong soil? *Plant and Soil* **255:** 93–104

COATES, W., 1997. Minimum tillage systems for irrigated cotton: Is subsoiling necessary. *Appl. Eng. Agric*. **13**: 175-179.

COATES, W. E. & THACKER, G. W., 1990. A comparison of two reduced tillage systems for cotton production. Agricultural Engineering Conference. In: Proceedings of a Conference held in Toowoomba, Queensland, Australia, 11-14 November 1990. p. 128-132.

COCHRANE, H. R. & AYLMORE, L. A. G., 1994. The effects of plant roots on soil structure. In: Proceedings of 3rd Triennial Conference ‘‘Soils 94’’. p. 207-212.

CONRAD, P. W., SWEIGARD, R. J. & YINGLING, J. C., 2002. Use of ripping to alleviate excessive compaction on reclaimed surface mined land. *Trans*. **312**: 159-165.

COOK, A., MARRIOTT, C. A., SEEL, W. & MULLINS, C. E., 1996: Effects of soil mechanical impedance on root and shoot growth of *Lolium perenne* L., *Agrostis capillaris* and *Trifolium repens* L. *J. Exper. Bot.* **47**: 1075-1084.

CORNIC, G. & MASSACCI, A., 1996. Leaf photosynthesis under drought stress. *Ann of Bot.* **89**: 887-894.

CORNISH P.S., SO H.B. & McWILLIAM J.R., 1984. Effects of soil bulk density and water regimen on root growth and uptake of phosphorus by ryegrass. *Aust. J. Agric. Res.* **35**: 631-644.

DANE, J. H., WALKER, R. H., BAHAMINYAKAMWE, L. & BELCHER, J. L., 2006. Tall Fescue and hybrid Bluegrass response to soil water matric head limits. *Agric.water manag.* **86**: 177-186.

DEFOSSEZ, P. & RICHARD, G., 2002. Models of soil compaction due to traffic and their evaluation. *Soil Tillage Res*. **67**: 41-64.

DOLLHOPF, D. J. & POSTLE, R. C., 1988. Reclamation of surface mine lands. *Trans*. **1**: 81-104.

DOTZENKO, A. K., PAPAMICHOS, N. T. & ROMINE, D. S., 1967. Effect of recreational use on soil and moisture conditions in Rocky Mountain National Park. *J. Soil Water Conserv*. **22**: 196-197.

ELLIS, T.W., 1990. Controlled traffic cropping at Roseworthy College-The first year. Agricultural Engineering Conference. Proceedings of a Conference held in Toowoomba, Australia, 11-14 November 1990. p. 25–29.

FEBO, P. & PLANETA, A., 2000. Wheels or tracks for the tractors of the future. *Macchine e Motori Agricoli*. **58**: 50-52.

FERRERO, A. & LIPIEC, J., 2000. Determining the effect of trampling on soils in hillslope woodlands. *Int. Agrophys*. **14**: 9-16.

FETTELL, N., 2000. Green or brown manure benefits two years down the track. In: Braunack, M., O'Connell, L. The 2001 Australian Grain Field Research Manual. p. 23-24.

FLOWERS, M. & LAL, R., 1998. Axle load and tillage effect on soil physical properties and soybean grain yield on a mollic ochraqualf in northwest Ohio. *Soil Tillage Res*. **48**: 21-35.

GRABOV, A., ASHLEY, M. K. & GRANT, M., 2006. Plant responses to potassium deficiencies: A role for potassium transport. *J. Exper Bot*. **57**(2): 425-436.

HALL, D. J. M., McKENZIE, D. C., MACLEOD, D. A. & TOOLT, I. D., 1994. Amelioration of a hardsetting Alfisol through deep mouldboard ploughing, gypsum application and double cropping. II. Soil water relations. *Soil Tillage Res*. **28**: 271-285.

HAMZA, M. A., ANDERSON, S. H. & AYLMORE, L. A. G., 2001. Studies of water drawdowns by single radish roots at decreasing soil water content using computer assisted tomography. *Aust. J. Soil. Res*. **39**: 1387-1396.

HAMZA, M. A. & ANDERSON, W. K., 2002. Improving soil fertility and crop yield on a clay soil in Western Australia. *Aust. J. Agric. Res*. **53**: 615-620.

HAMZA, M. A. & ANDERSON, W. K., 2003. Responses of soil properties and grain yields to deep ripping and gypsum application in a compacted loamy sand soil contrasted with a sandy clay loam soil in Western Australia. *Aust. J. Agric. Res.* **54**: 273-282.

HAMZA, M. A. & ANDERSON, W. K., 2005. Soil compaction in cropping systems: A review of the nature, causes and possible solutions. *Soil & Tillage Res.* **82**: 121-145.

HATI, K.M., MANDAL, K.G., MISRA, A.K., GHOSH, P.K. & BANDYOPADHYAY, K.K., 2006. Effect of inorganic fertilizer and farmyard manure on soil physical properties, root distribution, and water-use efficiency of soybean in Vertisols of central India. *Biores. Tech.* **97**: 2182-2188.

HENDERSON, C. W. L., 1991. Sensitivity of eight cereal and legume species to the compaction status of deep, sandy soils. *Aust. J. Exp. Agric.* **31**: 347-355.

HILLEL, D. L., 1980. Fundamentals of Soil Physics, Academic Press, San Diego, California, pp 413.

HILLEL, D. L., 1982. Introduction to Soil Physics. Academic Press, New York, pp 106.

HORN, R., WAY, T. & ROSTEK, J., 2001. Effect of repeated wheeling on stress/strain properties and ecological consequences in structured arable soils. *Revista de la Ciencia del Suelo y Nutricion Vegetal.* **1**: 34-40.

HORNE, J., 1992. Soil fertility affects pasture winter hardiness and moisture use efficiency. *Grass Forag. Sci.* **18**: 11-21.

HORST, G. L., KRISHNAN, G., DARNELL, S. & POWERS, W. L., 2000. Growth and development of Smooth Bromegrass and Tall Fescue in TNT-contaminated soil. *Environ. Pollut.* **107**: 109-116.

HSIAO, T.C., 1973. Plant response to water stress. *Plant physiol.* **24**: 519-570.

HSIAO, T. C. & XU. L., 2000. Sensitivity of growth of roots versus leaves to water stress: Biophysical analysis and relation to water transport. *J. Experiment. Bot.* **51**: 1595-1616.

ISHAQ, M., IBRAHIM, M., HASSAN, A., SAEED, M. & LAL, R., 2001. Subsoil compaction effects on crops in Punjab, Pakistan. II. Root growth and nutrient uptake of wheat and sorghum. *Soil Till. Res.* **60**: 153-161.

JAYAWARDANE, N.S. & CHAN, K.Y., 1994. The management of soil physical properties limiting crop production in Australian sodic soils-A review. *Aust. J. Soil Res.* **32**: 13-44.

JOHNSTON, A.E., 2005. Understanding potassium and its use in agriculture. Brussels: EFMA.

JORAJURIA, D. & DRAGHI, L., 2000. The management of soil physical properties limiting crop production in Australian sodic soils-A review. *Aust. J. Soil Res*. **32**: 13-44.

JUNGK, A. & CLAASSEN, N., 1997. Ion diffusion in the soil-root system. *Adv. in Agron*. **61**: 53-110.

KAYOMBO, B. & LAL, R., 1993. Tillage systems and soil compaction in Africa. *Soil Tillage Res*. **27**: 35-72.

KOOLEN, A. J. & KUIPERS, H., 1983. Agricultural Soil Mechanics. Springer, Berlin.

KOZLOWSKI, T. T., 1999. Compaction and growth of woody plants. *Scand. J. Forest Resear,* **14**: 596-619.

KOZLOWSKI, T. T. & PALLARDY, S. G., 1997. Physiology of Woody Plants. Academic Press, San Diego, CA.

KRISTOFFERSEN, A. O., 2005. Effects of soil compaction and moisture regime on the root and shoot growth and phosphorus uptake of barley plants growing on soils with varying phosphorus status. *Nutr. Cycl. in Agroecosyst*. **72**:135-146.

KUCHENBUCH, R., CLAASSEN, N. & JUNGK, A., 1986. Potassium availability in relation to soil moisture: Effect of soil-moisture on potassium diffusion, root-growth and potassium uptake of onion plants. *Plant Soil*. **95**: 221-231.

KUZNETSOVA, I. V., 1990. Optimum bulk density. *J. Soil Sci.* **5**: 43-54.

LACHNO, D. R., HARRISON-MURRAY, R. S. & AUDUS, L. J., 1982. The effects of mechanical impedance to growth on the levels of ABA and IAA in root tips of *Zea mays L. J. Exp. Bot*. **33**: 943-951.

LAKER, M.C., 2001. Soil compaction: Effects and amelioration. Proceedings of the 75th Annual Congress of the South African Sugar Technologists' Association, Durban, South Africa, 31 July 3 August 2001, p. 125-128.

LI, C., NIU, J., CHEN, F., MI, G. & ZHANG, F., 2007. Transpiration and nitrogen uptake and flow in two maize (Zea mays L.) inbred lines as affected by nitrogen supply. *Ann of Bot*. **99**: 153-60.

LIEBIG, M. A., JONES, A. J., MIELKE, L. N. & DORAN, J. W., 1993. Controlled wheel traffic effects on soil properties in ridge tillage. *Soil Sci. Soc. Am. J.* **57**: 1061-1066.

LI HONGWEN, GAO HUANWEN, CHEN JUNDA, LIWENYING & LI RUXIN, 2000. Study on controlled traffic with conservation tillage. *Trans. Chin. Soc. Agric. Eng.* **16**: 73-77.

LIPIEC, J. & STEPNIEWSKI W., 1995. Effects of soil compaction and tillage systems on uptake and losses of nutrients. *Soil Tillage Res*. **35**: 37-52.

LI YUXIA, TULLBERG, J. N. & FREEBAIRN, D. M., 2001. Traffic and residue cover effects on infiltration. *Aust. J. Soil Res*. **39**: 239-247.

MAPFUMO, E., CHANASYK, D.S., NAETH, M.A. & BARON, V.S., 1999. Soil compaction under grazing of annual and perennial forages. *Can. J. Soil Sci*. **79**: 191-199.

MARSHALL, T. J. & HOLMES, J. W., 1988. Soil physics. Cambridge, Cambridge University Press.

MARTIN, P. J. & STEPHENS, W., 2001. The potential for biomass production on restored landfill caps. In: Bullard, M.J., Christian, D.G., Knight, J.D., Lainsbury, M.A., Parker, S.R., *Asp. of Appl. Bio.*, **65**: 337-344.

MATSI, T., LITHOURGIDIS, A.S. & GAGIANAS, A.A., 2003. Effects of injected liquid cattle manure on growth and yield of winter wheat and soil characteristics. *Agron. J*. **95**: 592-596.

McANDREWS, G.M., LIEBMAN, M., CAMBARDELLA, C. A. & RICHARD. T.L., 2006. Residual effects of composted and fresh solid swine (*Sus scrofa* L.) manure on soybean [*Glycine max* (L.) Merr.] growth and yield. *Agron. J*. **98**: 873-882.

MITCHELL, F. J. & BERRY, W. A. J., 2001. The effects and management of compaction in agricultural soils. Proceedings of the Annual Congress - South African Sugar Technologists' Association, No. 75, p. 118-124.

MORENO, F., MURILLO, J. M., PELEGRIN, F. & GIRON, I. F., 2006. Long-term impact of conservation tillage on stratification ratio of soil organic carbon and loss of total and active $CaCO_3$. *Soil & Tillage Res*. **85**: 86-93.

MOSADDEGHI, M. R., HAJABBASI, M. A., HEMMAT, A. & AFYUNI, M., 2000. Soil compactibility as affected by soil moisture content and farmyard manure in central Iran. *Soil Tillage Res*. **55**: 87-97.

MOTAVALLI, P. P., STEVENS, W. E. & HARTWIG, G., 2003. Remediation of subsoil compaction and compaction effects on corn N availability by deep tillage and application of poultry manure in a sandy-textured soil. *Soil & Tillage Res.* **71**: 121-131.

MULHOLLAND, B. J., BLACK, C. R., TAYLOR, I. B., ROBERTS, J. A. & LENTON, J. R., 1996. Effect of soil compaction on barley (*Hordeum vulgare* L.) growth. I. Possible role for ABA as a root-sourced chemical signal. *J. Exp. Bot*. **47**: 539-549.

MULLINS, C. E., 1991. Physical properties of soils in urban environments. In Bullock, P. & Gregory, P. J. Soils in the Urban Environment, p. 87-118. Blackwell, London.

NADIAN, H., SMITH, S. E., ALSTON, A. M. & MURRAY, R. S., 1996. The effect of soil compaction on growth and P uptake by *Trifolium subterraneum*: Interactions with mycorrhizal colonisation. *Plant Soil.* **182**: 39-49.

NADIAN, H., SMITH, S. E., ALSTON, A. M., MURRAY, R. S. & SIEBERT, B. D., 1998. Effects of soil compaction on phosphorus uptake and growth of *Trifolium subterraneum* colonized by four species of vesicular-arbuscular mycorrhizal fungi. *New Phytol*. **139**: 155-165.

NIKOLIC, R., SAVIN, L., FURMAN, T., GLIGORIC, R. & TOMIC, M., 2001. Research of the problems of soil compaction. *Acta Techn. Agric*. **4**: 107-112.

NONAMI, H. & BOYER, J.S., 1990. Primary events regulating stem growth at low water potentials. *Plant Physiol*. **94**: 1601-1609.

OLIVEIRA, R. H., ROSOLEM, C. A. & TRIGUEIRO, R. M., 2004. Importance of mass flow and diffusion on the potassium supply to cotton plants as affected by soil water and potassium. *Rev. Bras*. **28**: 439-445.

OSMONT, K. S., SIBOUT R. & HARDTKE C. S., 2007. Hidden branches: Developments in root system architecture. *Plant Biol*. **58**: 93-113.

PAGLIAI, M. & JONES, R., 2002. Sustainable Land Management-Environmental Protection. A Soil Physical Approach. *Adva. Geoecol*. **35**: 387-396.

PANAYIOTOPOULOS, K. P., PAPADOPOULOU, C. P. & HATJIIOANNIDOU, A., 1994. Compaction and penetration resistance of an Alfisol and Entisol and their influence on root growth of maize seedlings. *Soil Tillage Res*. **31**: 323-337.

PETERSON W.R. & BARBER S.A., 1981. Soybean root morphology and K uptake. *Agron. J.* **73**: 316-319.

POLJAKOFF-MAYBER, A., 1988. Ecological-physiological studies on the responses of higher plants to salinity and drought. *Sci. Rev. Arid Zone Res*. **6**: 163-183.

PONDER, F., HUBBARD, V.C. & JORDAN, D., 2003. Effects of soil compaction, forest leaf litter and nitrogen fertilizer on two oak species and microbial activity. *Appl. Soil Ecol*. **23**: 33-41.

PRUMMEL, J., 1975. Effect of soil structure on phosphate nutrition of crop plants. *Neth. J. Agric. Sci.* **23**: 62-68.

PUGET, P., BALESDENT, J. & CHENU, C., 1999. Dynamics of soil organic matter associated with primary particle size fractions of water stable aggregates. *Euro. J. Soil Sci.* **46**: 449-459.

QI, Z., & SPALDING, E. P., 2004. Protection of plasma membrane K transport by the salt overly sensitive NaOH antiporter during salinity stress. *Plant Physiol.* **136**: 2548-2555.

RAPER, R. L., 2005. Agricultural traffic impacts on soil. *J. Terramechan.* **42**: 259-280.

RAPER, R. L., REEVES, D. W., BURT, E. C. & TORBERT, H., 1994. Conservation tillage and traffic effects on soil condition. *Trans. ASAE.* **37**(3): 763-768.

RAPER, R. L., REEVES, D. W. & BURT, E. C. 1998. Using in-row subsoiling to minimize soil compaction caused by traffic. *J. Cotton Sci.* **2**: 130-135.

REDDY, M. S., 1991. Effects of soil amendments on the hardening of red sandy loams (chalka soils) of Andhra Pradesh. *Ann. Agric.Res.* **12**: 174-176.

RENGASAMY, P., 2000. Subsoil constraints and agricultural productivity. *J. Indian Soc. Soil Sci.* **48**: 674-682.

RETHMAN, N.F.G., 2006. A review of causes, symptoms, prevention and alleviation of soil compaction on mined land. Coaltech 2020. University of Pretoria, South Africa.

RETHMAN, N. F. G. & TANNER, P.D., 1993. The influence of level of soil fertility on the botanical composition of pastures established on rehabilitated strip-mined land in South Africa. Presentation at the 10th National Meeting of the American Society for Strip Mining & Reclamation, Spokane, Washington.

RETHMAN, N. F. G., VENTER, P. S. & LINDEQUE, J. P., 1997. Influence of soil water availability on the above and below ground phytomass of five sub-tropical grass species. *Appl. Plant Scie.* **11**(1): 29-30.

ROSOLEM, C. A. & TAKAHASHI, M., 1998. Soil compaction and soybean root growth. In: Box, J.E., Root Demographics and their Efficiencies in Sustainable Agriculture, Grasslands and Forest Ecosystems. Proceedings of the 5th Symposium of the International Society of Root Research, Clemson, South Carolina, USA, p. 295-304.

SEIFFERT, S., KASELOWSKY, J., JUNGK, A. & CLAASSEN, N., 1995. Observed and calculated potassium uptake by maize as affected by soil water content and bulk density. *Agron. J.* **87**: 1070-1077.

SEKER, C. & ISILDAR, A. A., 2000. Effects of wheel traffic on porosity and compaction of soil. *Turkish J. Agric. Forestry* **24**: 71-77.

SHARP, R. E., SILK, W. K. & HSIAO, T. C., 1988. Growth of the maize primary root at low water potentials. I. Spatial distribution of expansive growth. *Plant Physiol.* **87**: 50-55.

SHEFFER, K. M., DUNN, J. H. & MINNER, D. D., 1987. Summer drought response and rooting depth of three cool-season turfgrasses. *Hort-Science.* **22**: 296-297.

SHETRON, S. G., STUROS, J. A., PADLEY, E. & TRETTINI, C., 1988. Forest soil compaction: Effect of multiple passes and loadings on wheel track surface soil bulk density. *North. J. Appl. For.* **5**: 120-123.

SLEPER, D. A. & WEST, C. P., 1996. TALL FESCUE. In: Moser, L.E., Buxton, D.R. & Casler, M.D., 1996. Cool Season Forage Grasses. Madison: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America; p. 471-502.

SMITH, J. & VALENZUELA, H., 2002. Pangolagrass.Cooperative Extension work, College of Tropical Agriculture and Human Resources, University of Hawaii at Manoa.

SOANE, B. D., 1990. The role of organic matter in soil compactibility: A review of some practical aspects. *Soil Tillage Res.* **16**: 179-201.

SNYMAN, H. A., 2003. Revegetation of bare patches in a semi-arid rangeland of South Africa: An evaluation of various techniques. *J. Arid Environ.* **55**: 417-432.

STRICKLAND, R. W., 1974. Performance of southern African *Digitaria* spp. in southern Queensland. *Australian J. Exp. Agric. & Animal Husbandry* **14**: 186-96.

SYERS, J. K., 1998. Soil and plant potassium in agriculture. York: The Fertiliser Society.

TAIZ, L. & ZEIGER, E., 2002. Plant Physiology. Sinauer Associates, Sunderland, MA, pg 591-623.

TERASHIMA, E., FUJII, E. & MISHIMA, K., 1999. Experimental studies on the effect of trampling on the root system of seedlings of Bromegrass. *Technical Bull. Faculty Horticult. Chiba Univ.* **53**: 85-92.

THOM, R. D., HOULBROOKE, J., CHAPMAN, E. R. & McLAY, C. D. A., 1997. A study of the effects of soil bulk density on root and shoot growth of different ryegrass lines. *New Zeal. J. Agric. Res.* **40**: 415-429.

TORBERT, H.A. & WOOD, C.W., 1992. Effects of soil compaction and water-filled pore space on soil microbial activity and N losses. *Comun. Soil Sci. Plant. Anal.* **23**: 1321-1331.

TOW, P. G., 1993. Persistence and water use efficiency of a tropical grass and lucerne on a solodic soil on the Far North-West Slopes of New South Wales. *Australian J. Exp. Agric.* **33:** 245-52.

TOW, P. G. & WHITE, G. J., 1976. Non-symbiotic nitrogen fixation in the rhizosphere of *Digitaria smutsii* Stent. *Plant & Soil* **45**: 637-46.

TOW, P. G., LAZENBY, A. & LOVETT, J. V., 1997. Adaptation and complementarity of *Digitaria eriantha* and *Medicago sativa* on a solodic soil in a subhumid environment with summer and winter rainfall. *Australian J. Exp. Agric.* **37**: 311-22.

TRIPATHI, R. & SINGH, A.K., 2004. Effect of water and nitrogen management on aggregate size and carbon enrichment of soil in rice-wheat cropping system. J. *Plant Nutr. Soil Sci.* **167**: 216-228.

TRUTER, W.F., 2007. Sustainable plant production on degraded soil/substrates amended with South African class F fly ash and organic materials. PhD thesis. University of Pretoria, Pretoria, South Africa.

USMAN, H., 1994. Cattle trampling and soil compaction effects on soil properties of a northeastern Nigerian sandy loam. *Arid Soil Res. Rehabilit.* **8**: 69-75.

VETTERLEIN, D. & JAHN, R., 2004. Gradients in soil solution composition between bulk soil and rhizosphere: *In situ* measurement with changing soil water content. *Plant Soil*. **258**: 307-317.

VZZOTTO, V.R., MARCHEZAN, E. & SEGABINAZZI, T., 2000. Effect of cattle trampling on lowland soil physical properties. *Ciencia Rural*. **30**: 965-969.

WALSH, R. A., 1995. *Schedonorus arundinaceus*. In: Fire Effects Information System, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. Fire Sciences Laboratory, pg. 23-26.

WARREN, S. D., THUROW, T. L., BLACKBURN, W. H. & GARZA, N. E., 1987. The influence of livestock trampling under intensive rotation grazing on soil hydrologic characteristics. *J. Range Manage*. **39**: 49-495.

WHITEHEAD, D.C., 2000. Nutrient elements in grassland soil-plant-animal relationships. CAB International Publishing. Wallingford, Oxon, UK.

WIERMANN, C., WERNER, D., HORN, R., ROSTEK, J. & WERNER, B., 2000. Stress/strain processes in a structured unsaturated silty loam Luvisol under different tillage treatment in Germany. *Soil Tillage Res*. **53**: 117-128.

WILLIAMS, D. W., CARNEGIE, E. J., ZOHNS, M. A., ANDROS, M. & KAMINAKA, M. S., 1991. Preliminary testing of the electrically powered controlled traffic farming system. Paper-American Society of Agricultural Engineers, No. 91-3047, p. 10.

WILLIFORD, J.R., 1980. A controlled-traffic system for cotton production. Trans ASAE **23**(1): 65-70.

WINGATE-HILL, R. & JAKOBSON, B. F., 1982. Increased mechanization and soil damage in forests: A review. *N Z J. For. Sci*. **12**: 380-393.

WOLKOWSKI, R. P., 1990. Relationship between wheel-traffic induced soil compaction, nutrient availability and crop growth. *J. Prod. Agric*. **3**: 460-469.

YANAI, J., LINEHAN, D. J., ROBINSON, D., YOUNG, I. M., HACKETT, C. A., KYUMA, K. & KOSAKI, T., 1996. Effects of inorganic nitrogen application on the dynamics of the soil solution composition in the root zone of maize. *Plant Soil*. **180**: 1-9.

ZHANG, H., 1994. Organic matter incorporation affects mechanical properties of soil aggregates. *Soil Tillage Res*. **31**: 263-275.

ZHANG, H. & HARTGE, K. H., 1992. Effect of differently humified organic matter on the aggregate stability by reducing aggregate wettability. *Z. Pflanzenernahr. Bodenkd*. **155**: 143-149.

ZHANG, H., JENNINGS, A., BARLOW, P.W. & FORDE, B. G., 1999. Dual pathways for regulation of root branching by nitrate. *Proc. Natl. Acad. Sci.*. **96**: 6529-6534.

ZHANG, M., GAVLAK, R., MITCHELL, A. & SPARROW, S., 2006. Solid and liquid cattle manure application in a subarctic soil: Bromegrass and oat production and soil properties. *Agron. J*. **98**: 1551-1558.

Chapter 2

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Monitoring of soil fertility, soil bulk density and root biomass of irrigated Tall Fescue (*Festuca arundinacea* cv Dovey) and dryland Smuts Fingergrass (*Digitaria eriantha* cv Irene) on mine soils subjected to different management regimes

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Abstract

Soil depth and area of rooting are important to the long-term survival of plants on mine soils. Soil compaction is perceived as a major threat to mine soils and productivity. It increases the bulk density which may limit the access of nutrients and water, thereby affecting survival and growth of plants. The objectives of the study were to monitor the root biomass of irrigated Tall Fescue (*F. arundinacea* cv Dovey) and dryland Smuts Fingergrass (*D. eriantha* cv Irene) on mine soils, and to describe soil bulk density, pH (H_2O) and soil nutrient concentrations in such soils. The study was conducted on field trials located on a surface coal mine in Mpumalanga Province in South Africa. The mine cover soil was a sandy clay with a depth of 40 cm over spoil material. The bulk density of mine soils varied from 1.80 gcm^{-3} to 1.90 gcm^{-3} at depths of 0-20 and 20-40 cm respectively. Tall Fescue was established on an area of compacted soil which had been cultivated and irrigated with poor quality mine water for three years prior to pasture establishment. The Smuts Fingergrass was planted on an adjacent area of rehabilitated dryland. The greatest root biomass of Tall Fescue was recorded in the 0-10 and 10-20 cm soil depth, followed by 20-30 and 30-40 cm soil depth. The root mass of Smuts Fingergrass was also significantly greater in 0-10 and 10-20 cm soil layers followed by 20-30 and 30-40 cm soil layers. The soil bulk density of soils planted to both grass species was lowest (1.61gcm^{-3}) in the 0-10 cm soil depth, followed by 10-20 cm, 20-30 cm and was highest (1.86gcm^{-3}) in the 30-40 cm soil depth. Root systems of both grass species were best in the upper 10 cm of the mine cover soil and declined with both depth and pH. The concentration of soil nutrients P, Na, K, Mg and Ca was greater in the 0-20 cm than in the 20-40 cm soil horizon. The development of roots into compacted soil to utilize water and nutrients is regarded as a natural process, which may alleviate compaction because of root channels and the increase in organic material in such soils.

Key words: pH (H_2O); Root biomass; Soil bulk density; Soil compaction; Soil nutrient concentrations; Smuts Fingergrass; Tall Fescue.

1. Introduction

A well developed root system is fundamental for plant growth and survival. Grass species rely on a good distribution of roots to acquire nutrients and water from the soil. While Tall Fescue (*Festuca arundinacea* cv Dovey) is planted under irrigation or under high rainfall conditions in South Africa, Smuts Fingergrass *(Digitaria eriantha* cv Irene) is planted under rainfed conditions in areas with an annual precipitation of 450-600 mm. Tall Fescue is a deep-rooted, long-lived perennial temperate grass species (Walsh, 1995). Smuts Fingergrass as a palatable good quality summer growing perennial grass suited to a range of soils, is very persistent and productive species (Buckley, 1959). One of the major constraints on root development in the soil is compaction.

Soil compaction is perceived as a major threat to agricultural soils and productivity (Nolte & Fausey, 2000). Areas of compact soil with high shear strength can be caused by agricultural machinery and surface mining activities. In South Africa, surveys have indicated that approximately 40 000 ha have been disturbed by coal surface mining in the past 30 – 35 years (Rethman, 2006). Compaction in such soils increases the bulk density and strength of soil, which are important factors affecting both shoot and root growth of plants.

It has been suggested by many researchers that soil bulk densities as low as 1.3 to 1.7 gcm^{-3}, may limit root growth and decrease plant yield (Bengough & Mullins, 1990; Kuznetsova 1990; Thom *et al*., 1997). In the study of effects of soil bulk density on ryegrass, root length and herbage yields decreased as bulk density increased from 0.9 to 1.3 Mgm^{-3} (Thom *et al*., 1997). Further effects of soil compaction are decreased root size, retarded root penetration and smaller rooting depth (Unger & Kaspar, 1994), which are among major reasons for reduced plant productivity.

Soil compaction susceptibility depends on soil texture, soil water content during of field operations and machinery loads (Hamza & Anderson, 2005; Raper 2005). When driving a vehicle on moist, arable soil, measurable compaction may be exerted to a depth of at least 30 cm at an axle load of 4 Mg (Raper, 2005). Alakukku and Elonen (1994) found that compaction of clay soil caused by axle load of 19 Mg penetrated to depth of 50 cm. In experiments, conducted by Hammel (1994), crop yields were not affected by a 10 Mg axle load in a silt loam soil, but compaction resulting from the 20 Mg axle load reduced root growth and crop growth.

Rethman, (2006) reported that the effects of soil compaction on plant growth are very complex in mine soils. Where pasture/forage crops have been established on compacted soils it is common to find that, apart from depressed yields, these crops are also characterized by a poorer cover. The major reasons for this reduction in plant productivity include the water balance and nutrient usage in such soils, and the major mechanical resistance to root penetration or root growth offered by the high soil strength and bulk densities in compacted soils. The effects of soil compaction on plant growth are seriously increased under drought stress (Sharp *et al.*, 1988). Nonami & Boyer, (1990) reported that in soybean (*Glycine max*) hypocotyls, growth was suppressed due to water stress, whereby a reduction in the surrounding water potential affected the turgor pressure of elongating cells, and this reduction causes a change in the elongation rate of the cells.

The aims of this study were to monitor the root biomass of irrigated Tall Fescue (*F. arundinacea* cv Dovey) and dryland Smuts Fingergrass (*D. eriantha* cv Irene) on compacted mine soils, and to describe pH (H_2O) and soil nutrient concentrations in such soils and the possible effects on plant growth.