REHABILITATION OF MINED-OUT DUNE LAND AT TRONOX KZN SANDS FOR SUGARCANE PRODUCTION

By

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LIST OF ABBREVIATIONS

0 P	No phosphorus fertilizer
0.5 P	Phosphorus fertilizer at half the recommended rate
1 P	Phosphors fertilizer at recommended rate
ABM	Aboveground biomass
Al	Aluminium
BMP	Bulk mixing plant
°C	Degrees Celcius
C	Carbon
C:N	Carbon to nitrogen
Ca	Calcium
Cl	Chloride
CEC	Cation exchange capacity
cm	Centimetre
CO_2	Carbon dioxide
CPC	Central processing plant
Cu	Copper
dS/m	Desi-siemens per meter
EC	Electrical conductivity
EMP	Exchangeable magnesium percentage
ESP	Exchangeable sodium percentage
FAS	Fertiliser Advisory Service
FC	Filtercake
Fe	Iron
FI_{PAR}	Fractional interception of photosynthetic active radiation
G	Gram
H	Hydrogen
HMS	Heavy minerals concentrate
IF	Inorganic fertilizer
ISCW	Institute for Soil, Climate and Water

K	Potassium
kg/ha	Kilograms per hectare
kPa	Kilopascal
$LSD_{0.05}$	Least significant difference at 5% confidence level
m^2	Square meters
Mg	Magnesium
mg/kg	Milligrams per kilogram
mm	Millimetre
Mn	Manganese
MPa	Megapascal
MWD	Mean weight diameter
N	Nitrogen
NF	No fertilizer
ns	Not significant
Na	Sodium
NH_4	Ammonium
NO_3	Nitrate
O_2	Oxygen
P	Phosphorus
PDI	Phosphorus desorption index
pH	Measure of acidity/alkalinity
PWP	Primary wet plant
RBM	Root biomass
PR	Penetration resistance
RS	Reconstituted soil
RSF	Residue storage facility
RSR	Root to shoot ratio
S	Sulphur
SASA	South African Sugar Association
SASRI	South African Sugarcane Research Institute
SD	Stalk diameter

SEM	Standard error of mean
Si	Silicon
SL	Stalk length
SO4	Sulphate
SWC	Soil water content
t/ha/annum	Tonnes per hectare per annum
t/ha	Tonnes per hectare
t/ha/month	Tonnes per hectare per month
US	Unmined soil
µgCO2-C/g/day	Microgram carbon dioxide carbon per gram per day
TN	Tiller number
TVD	Top visible dewlap
WPBM	Whole plant biomass
Zn	Zinc

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DECLARATION

I, Corlina Margaretha van Jaarsveld, do hereby declare that the thesis hereby submitted by me for the Philosophiae Doctorate Degree in Agronomy at the University of the Free State is my own original independent work and that I have not previously submitted the same work for a qualification at another university.

I further cede copyright of the thesis in favour of the University of the Free State.

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Corlina Margaretha van Jaarsveld Date

ABSTRACT

Titanium-rich minerals were extracted from the soil of the Hillendale mine near Empangeni in the KwaZulu Natal province of South Africa (28° 50’ S and 31° 56’E) *by using a hydraulic open-cast procedure. A mechanical process was employed to separate the heavy minerals from the sand and slimes (silt and clay fractions combined) in the soil. The mining process resulted in a physical and chemical disturbance of the soil and the mining company (Tronox KZN Sands) has a legal obligation to rehabilitate the post-mined soil back to sustainable sugarcane production. The sand and slimes fractions (void of heavy minerals) were mixed together to a ratio of 70:30 sand:slimes to create a reconstituted soil. The reconstituted soil was subsequently deposited on sand to a depth of 1.8 m. The objective of this study was to test specific soil amendments for their potential to improve the reconstituted soil physically and chemically for successful sugarcane production. These amendments included gypsum, filtercake and inorganic phosphorus (P).*

Waterlogging was a constraint that affected the tested amendments under field conditions. Data collected from field experiments revealed that waterlogging affected sugarcane growth both directly and indirectly. The most noteworthy effect of waterlogging on sugarcane was iron (Fe) toxicity which was observed in treatments where filtercake was applied in the plant crop. Iron toxicity is a rare phenomenon in sugarcane production. In addition, magnesium (Mg)-related dispersion was identified in the reconstituted soil which increased soil erodibility. It was also noted that the reconstituted soil had high potential for hardsetting and compaction.

The reconstituted soil lacks structure. Hence, gypsum, as a source of calcium (Ca), was tested as a potential flocculent to improve soil structure in both field and pot experiments. The gypsum application rate varied from 0 and 16 t/ha. Gypsum successfully improved the Ca:Mg ratio of the soil to the ideal range for optimum crop growth of 1.5 to 4.5 or higher. Improvement of the Ca:Mg ratio is important in counteracting Mg-related dispersion. Gypsum application however did not significantly improve mean weight diameter (a parameter associated with soil structure) and sugarcane growth and yield relative to the control treatment without gypsum.

Organic matter has the potential to improve soils both physically and chemically. Filtercake (FC), an organic waste product from the sugar milling process, was tested as a potential organic amendment of the soil at rates that varied from 0 to 100 t/ha. Applying FC at a rate of 100 t/ha was very effective in increasing the electrical conductivity (EC) of the soil and in increasing the P content of the soil. However, FC application in the field was associated with negative effects on sugarcane growth including nitrogen (N) immobilization and Fe toxicity (as already mentioned). Yet, in the corresponding pot experiment, where waterlogging and N immobilization were absent or minimal, sugarcane growth was not significantly improved where FC was applied compared to the control treatment without FC. Mean weight diameter was also not significant improved by FC *application in the field. Thus, FC did not appear to be a suitable amendment in this study and might have to be replaced by a different source of organic matter.*

The post-mined soil was low in P which is an essential plant nutrient and therefore the effect of inorganic P application was tested in the field and in pots. Inorganic P application rates varied between 0 and 70 kg/ha in these two experiments. Sugarcane growth and nutrient uptake was significantly improved by inorganic P application in the plant crop of the field experiment. In the first ratoon crop, waterlogging was likely responsible for reduced sugarcane growth and nutrient uptake. In the pot experiment, application of inorganic P was associated with increased aboveground, root and whole plant biomass. Inorganic P application also significantly improved uptake of P and Ca.

When pooling the data for the three pot experiments (which was done in similar soil and over similar period of time), it revealed that sugarcane whole plant biomass (WPBM) had a significant and positive relationship ($p<0.01$) with inorganic Ca ($r^2 = 0.63$), P ($r^2 = 0.66$) and K ($r^2 = 0.62$), as well as the Ca:Mg ratio of the soil ($r^2 = 0.58$). Whole plant biomass also correlated negatively ($p<0.01$) with the Mg:K ratio in the soil ($r^2 = -0.48$). The minimum inorganic Ca, P and K application rates and Ca:Mg ratio for optimum WPBM, as extrapolated from the data, were 608 kg/ha, 74 kg/ha, 287 kg/ha and 0.9, respectively. These application rates will have to be tested under field conditions.

The results of this study confirmed that amending the reconstituted soil both physically and chemically is imperative for successful sugarcane production. More research is required to fine-tune the amendments tested in this study in order to sustain sugarcane production in the reconstituted soil in the long run. Soil erosion, waterlogging, hardsetting, compaction, nutrient deficiencies or toxicities and poor yield can be expected if the soil is not rehabilitated successfully. One of the most important aspects of the soil rehabilitation at Hillendale will be to improve soil structure which in turn will improve water drainage. With improved water drainage, the risk for sugarcane production being compromised by the above mentioned constraints will be reduced. Recommendations were made with regards to management of the reconstituted soil and for future research at Hillendale.

Key Words: Soil amendments; gypsum; filtercake; organic matter; inorganic phosphorus

CHAPTER 1

GENERAL INTRODUCTION

1.1 INTRODUCTION

The mining of the dune land by Tronox KZN Sands at Hillendale near Empangeni entails hydraulic excavation with the aim of extracting titanium-rich heavy minerals from sand. Hydraulic excavation involves applying water under high pressure to the sand based mineral deposits to produce slurry. This slurry is pumped to a primary wet plant where the heavy mineral concentrate is separated from the sand and slimes. The heavy mineral concentrate is then transported to the central processing facility (CPC) near Empangeni for further processing, while the sand and slimes are mixed together to create a reconstituted soil which is pumped to the restoration area. Thus, the natural soil profile is completely destroyed during the mining operation. This kind of mining also destroys the soil's mineral nutrient balance for plant growth (Golder Associates, 2004).

The land being mined by Tronox KZN Sands was previously under commercial sugarcane production. As part of the mineral rights agreement, Tronox KZN Sands has to rehabilitate mined-out land back to be able to support commercial sugarcane production. The restoration process involves back-filling and re-shaping the mined out land with the reconstituted soil (void of heavy minerals) and covering the backfilled-land with a layer of topsoil (which has been removed and stored before mining). Subsequently, the re-constructed soil will be subjected to suitable fertility restoration procedures aimed at creating soil physical and chemical properties that are conducive to sustainable production of sugarcane. This study was aimed at identifying and evaluating suitable restoration methods for bringing the land back into sugarcane production.

1.2 BACKGROUND

1.2.1 Description of Hillendale area

1.2.1.1 Location, size and climate

The Hillendale mine, the location of this study, is situated at 28° 50' S and 31° 56'E on the north coast of the KwaZulu Natal (KZN) Province of South Africa and comprises an area of 287.8 ha in size (Snyman 2001). It is situated about 9 km south east of the town of Empangeni and is bordered by the uMhlatuze River in the northwest (Figure 1.1).

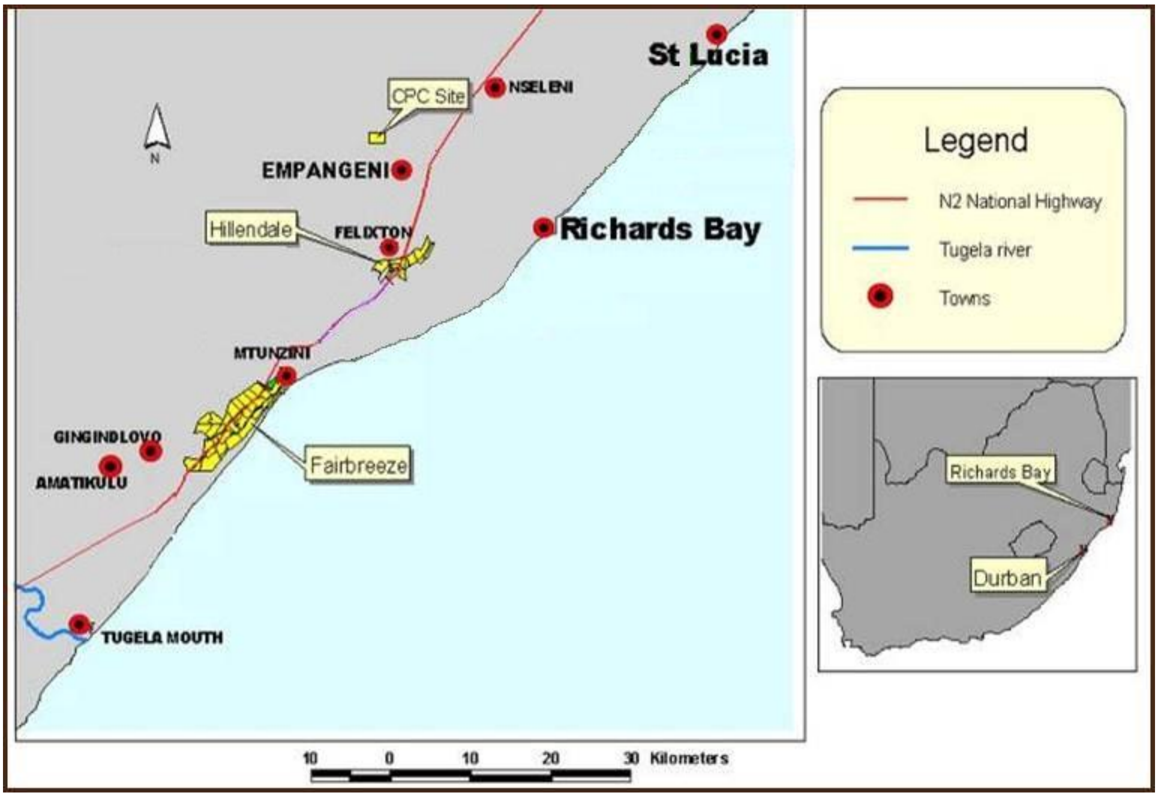

Figure 1.1: The location of the Hillendale mine.

The area has a sub-tropical to tropical climate with hot and humid summers and warm to cool winters with no frost. The mean annual temperature is 21.8°C and the mean annual rainfall is 1324 mm. The rainfall is well distributed throughout the year (Table 1.1). Sugarcane was the only crop grown at Hillendale prior to mining (Snyman, 2001). Sugarcane is also the predominant crop grown in the area, with smaller areas under *Eucalyptus* plantations and sub-tropical fruit production.

Table 1.1: The long-term rainfall and temperature of the Hillendale area (from Snyman, 2001).

Month	Average monthly rainfall (mm)	Average monthly maximum temperature (°C)	Average monthly minimum temperature (°C)
Jan	152.5	30.0	21.1
Feb	163.9	29.6	21.0
Mar	152.7	29.3	20.3
Apr	104.7	27.3	17.9
May	96.2	25.1	14.7
Jun	70.7	23.4	11.7
Jul	64.7	23.4	11.4
Aug	61.8	24.0	13.5
Sep	90.5	25.4	15.7
Oct	115.2	26.1	16.9
Nov	120.8	27.6	18.3
Dec	130.2	29.5	20.3
	Total: 1323.9	*Average: 26.7*	*Average: 16.9*

1.2.1.2 Topography and geology

Snyman (2001) described the pre-mining topography at Hillendale as having gentle eastern slopes (with an average slope of 10%). Such gentle slopes are ideal for crop cultivation and mechanisation. The eastern slopes varied between 40 and 80 m above sea level. The western slopes (which were about 40 m above sea level) on the property were much steeper (average 30%) and therefore limiting for mechanical operations. The western slopes bordered the uMlathuze flood plain.

The geology of Hillendale falls almost entirely under the Berea Formation. A small part of Hillendale includes the uMhlatuze flood plain where the parent material is alluvium (Snyman, 2001).

1.2.2 Mining history of Hillendale

The heavy mineral deposits at Hillendale were 'discovered' in the late 1980s by G. Blendolf and M. Oldenburg (Cocks, 2012, pers. comm.). Shell South Africa and Rhoex Ltd. formed a joint venture and acquired the land in the early 1990s. In 1994 they sold the land to IHM Heavy Minerals Ltd. (Cocks, 2012, pers. comm.). Mining related activities at Hillendale were initiated in 1995 with a detailed feasibility study by IHM Heavy Minerals Ltd. which later changed its name to Kumba Resources Ltd. (Kotzé et al., 2006). In February 2001, an Australian company, Ticor Ltd., bought 40% shares in the business from Kumba Resources and subsequently took over the management of the mine (Kotzé et al., 2006). The actual mining at Hillendale started in April 2001. In 2005, Ticor sold back its shares to Kumba Resources which subsequently relisted their mineral sands business under the name Exxaro Sands (Pty) Ltd. (Exxaro KZN Sands, s.a., Kotzé et al., 2006) which included Exxaro KZN Sands. On the 15th of June 2012, the majority share in Exxaro KZN Sands was transferred to Tronox and the company renamed Tronox KZN Sands. Tronox KZN Sands is a subsidiary of the global company Tronox (Cocks, 2012, pers comm).

Tronox KZN Sands consists of the Hillendale mine, the Central Processing Complex (CPC) outside Empangeni and the Fairbreeze mineral reserves (situated 24 km from the Hillendale mine). Mining operations at the Fairbreeze mineral reserve had not yet started at the time of writing this thesis (Cocks, 2012, pers comm).

1.2.3 Hillendale mineral deposits

The heavy mineral deposits (also called mineral sands) which are mined at Hillendale originate from the weathering of igneous rocks such as granite and basalt.

The mineral-rich material was carried from inland by rivers and deposited along old coastal regions. Ocean currents gradually shifted the deposits southward. Deposition by wind also resulted in high concentration of the minerals in certain areas (Cocks, 2012, pers. comm.).

The minerals deposits at Hillendale contain titanium-rich ilmenite, zircon, rutile and leucoxene (Table 1.2) among others. In total, Tronox KZN Sands has ilmenite reserves of more than 25.6 million tons (Exxaro KZN Sands, s.a.). These mineral sand reserves are some of the richest in the world (Exxaro KZN Sands, s.a.). Other important producers of mineral sands include Australia, the USA, Canada and India (Kotzé et al., 2006).

Table 1.2: Name plate capacities of the Hillendale mine (from Kotzé et al., 2006).

Product	Capacity (tons per annum)
TiO_2 slag	250 000
Low manganese pig iron (LMPI)	145 000
Ilmenite	550 000
Zircon	60 000
Rutile	30 000
Leucoxene	5 000

The products mined at Hillendale have a wide spectrum of uses as illustrated in Figure 1.2. Ilmenite is smelted in two furnaces to produce slag rich in titanium oxide (TiO_2) (also called titania slag) and low manganese pig iron (LMPI). The slag is mainly used as a source of titanium oxide pigment for the paper, paint and plastic industries. Titanium oxide is also used in cosmetics and sunscreen preparations (Exxaro KZN Sands, s.a). Low manganese pig iron (LMPI) is used in the high quality engineering casting business. Titanium rich rutile mineral is also beneficiated from the mine, and is used in the manufacturing of welding rods and for the production of titanium metal and titanium oxide pigment. Titanium metal is extensively used in aeroplanes and spacecraft because of its strength and light weight. It is also used in the medical field for implants and artificial limbs. Zircon (zirconium silicate) is used in a wide range of industrial and domestic products including ceramics, tiles, sanitary ware, refractories, television screens and computers (Exxaro KZN Sands, s.a).

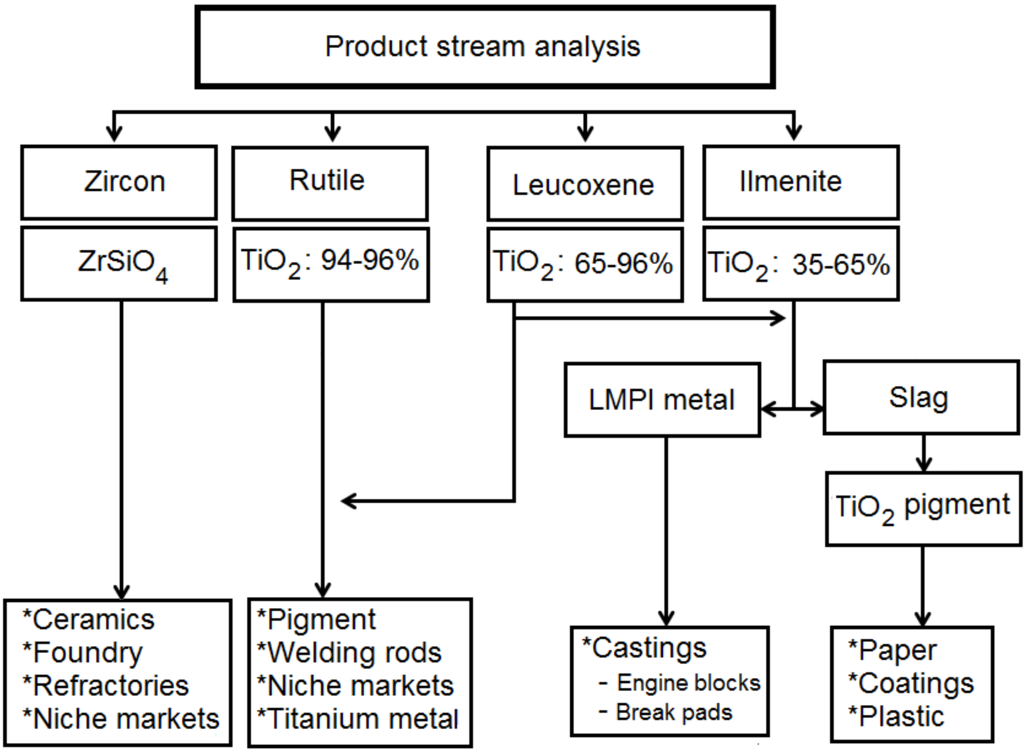

Figure 1.2: The uses and end-products of the minerals mined at Hillendale (from Cocks, 2012, pers. comm.).

1.3 PROBLEM STATEMENT

Soil structure is known to be a pertinent factor in the functioning of a soil and its ability to support plant and animal life. In a structured soil, primary soil particles combine to form secondary units or aggregates (Bronick and Lal, 2005). The mining procedure at the Hillendale mine results in a destruction of the soil structure and changes in chemical composition that renders the soil less suitable for profitable crop production.

Without soil amendments that will restore the soil structure of the reconstituted soil, there is a potential for a number of crop production constraints to develop. These include restricted seedling emergence and root growth, reduced water infiltration, increased soil erosion, waterlogging and limited aeration (Hillel, 1982, Bronick and Lal, 2005). The restoration of a stable structure of the soil will therefore be a very important aspect of the Hillendale rehabilitation program. Furthermore, the reconstituted soil will need chemical amendments to restore deficiencies and possible imbalances caused by the mining process.

1.4 OBJECTIVES OF STUDY

The overall objective of this study was to amend the reconstituted soil physically and chemically to such a level that it has the ability to support profitable sugarcane production. Specific objectives were to:

i) Give a review of the mining and rehabilitation processes at the Hillendale mine.

ii) Test gypsum as a an amendment for improving the structure of the reconstituted and sugarcane growth thereon.

iii) Test filtercake as a potential organic amendment for improving the structure of the reconstituted soil and sugarcane growth thereon.

iv) Evaluate different inorganic phosphorus application rates for restoring the P levels of the reconstituted soil and to supply adequate P for sugarcane growth.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The review chapter has four sections. The first section entails a description of the mining and rehabilitation processes at the Hillendale mine with reference to pre-mining surveys and studies at Hillendale. Since the improvement of soil structure is one of the central aspects of this study, the second section deals with soil structure and the factors that influence it. The third section of the review is dedicated to giving a background of soil amendments tested in this study. And finally, the fourth section discusses the biology, physiology and husbandry of sugarcane since sugarcane is the crop that will be re-established in the rehabilitated soil.

2.2 MINING AND REHABILITATION PROCEDURES AT HILLENDALE

2.2.1 Mining process

A mining feasibility study conducted at Hillendale mine revealed that hydraulic mining would be the most cost effective way of mining (SRK Consulting, s.a.). The hydraulic mining method makes use of water monitors (guns) which emit a jet of water under high pressure onto a soil face to undermine it, thus causing it to collapse (Figure 2.1). More water is used to break up the soil material into slurry. The slurry (also called run of mine) flows down trenches under gravity to sumps (launders) from where it is pumped to the primary wet plant (PWP). Generally, the depth of mining is between 10 and 40 m below the original topographical surface (Kotze et al., s.a.). The water used at Hillendale comes from the adjacent uMhlatuze river. Four monitors can be operated at Hillendale simultaneously with each gun having a capacity of 250 – 350 tons of water per hour (Cocks, 2012, pers. comm.).

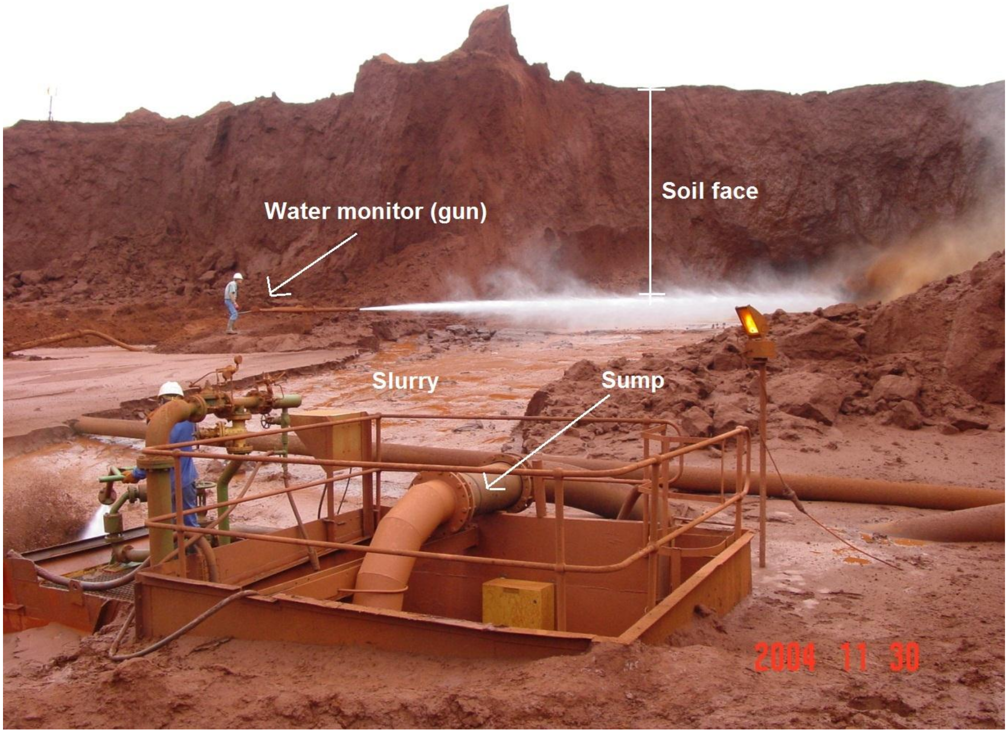

Figure 2.1: The mining procedure: Water under high pressure is sprayed on the soil face to create slurry which flows to a sump. From the sump the slurry is pumped to the primary wet plant.

At the primary wet plant, the larger material (called 'over-size') is removed first with a large trommel screen which works like a giant sieve, removing larger rocks, pebbles and agglomerates (Figure 2.2). The remaining "undersize" material is de-slimed with hydrocyclones which make use of high centrifugal forces to separate the lighter slimes ("slimes" consist of a mixture of fine silt and clay particles all smaller than 45µm fraction) from the heavier sand and heavy minerals fraction (Cocks, 2012, per. comm.).

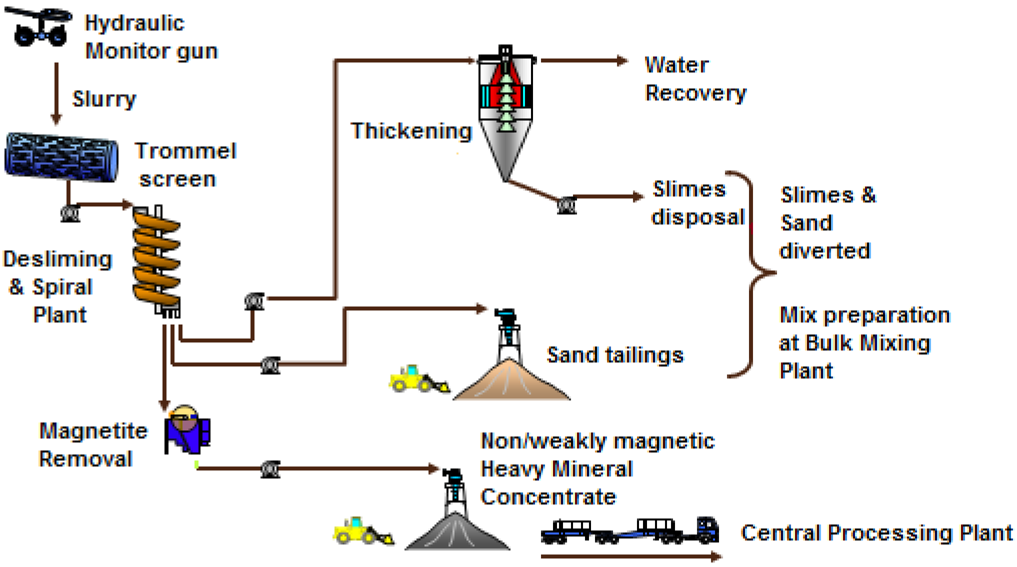

Figure 2.2: Illustration of the various processes at the Hillendale mine.

The lighter silica sand is separated from heavy minerals in a spiral plant. The spiral plant makes use of “cork-screw” shaped banks of spirals which allow for gravitational forces to be used to separate dense heavy minerals from the lighter silica sand particles. The spirals provide for a surface where water elutriates and entrains the particles and the density differences cause the particles to position themselves according to their density (Cocks, 2012, pers. comm.).

Most of the slimes fraction from the de-sliming cyclone stage is pumped to the residue storage facility (RSF, or also known as slimes dam), after being flocculated and de-watered with a thickener (Figure 2.3).

Figure 2.3: The residue storage facility (RSF) which contains slimes (slit and clay). The RSF covers an area of about 130 ha.

The thickener is an anionic polyacrylamide which is added at low concentration to flocculate the slimes. The flocculation and subsequent de-watering process allows the majority of the water to be recycled and re-used in the mining process (Cocks, 2012, pers. comm.). The flocculant is the only chemical that is added in the mining and processing operations, and is not harmful to the environment (Seybold, 1994). The sand tailings from the primary wet plant are returned to the mined-out land and stacked to re-build the dunes in a process called backfilling.

Magnetic material in the heavy minerals concentrate (HMC) is separated from non- and weakly magnetic material using low intensity magnetic separators (Cocks, 2012, pers. comm.) at the primary wet plant. The magnetic material (magnetite) is returned to mine as part of the back-filled sand tailings material, while the non and weakly magnetic material is transported by truck to the central processing plant (CPC) near Empangeni for further processing (Figure 2.4).

Figure 2.4: A photograph of the primary wet plant (PWP) with non- and low magnetic heavy minerals concentrate (HMC) seen in the foreground. This material is transported by truck to the central processing plant (CPC) near Empangeni for further processing.

The primary wet plant has a capacity of 816 000 tons run of mine (slurry) per month and 876 000 tons HMC per annum (SRK Consulting, s.a.). At full capacity, about 155 000 tons per month of slimes is pumped to the RSF which has an active area of 130 ha.

2.2.2 Rehabilitation process

The rehabilitation process starts with backfilling the mine void with sand to the original landscape using cyclones (Kotzé et al., s.a.) (Figure 2.5). The shaped sand dunes are then capped with a hydraulically transported mixture of 70% sand and 30% slimes (reconstituted soil) to a depth of 1.5 m (Cocks, 2012, pers. comm.) (Figure 2.6). The mixing of the sand and slimes takes place in a bulk mixing plant (BMP) (Figure 2.7). The amount of sand entering the bulk mixing plant is controlled with a belt scale, while the amount of slimes is controlled with a flow meter (Hattingh et al., 2007a). The relative amounts of silt and clay in the slimes cannot be controlled by the metallurgical process and are a function of the fines fraction characteristics of the mined ore body (Cocks, 2012, pers. comm.).

Figure 2.5: A photograph of a cyclone in action. Cyclones are used for backfilling the post-mined areas with sand.

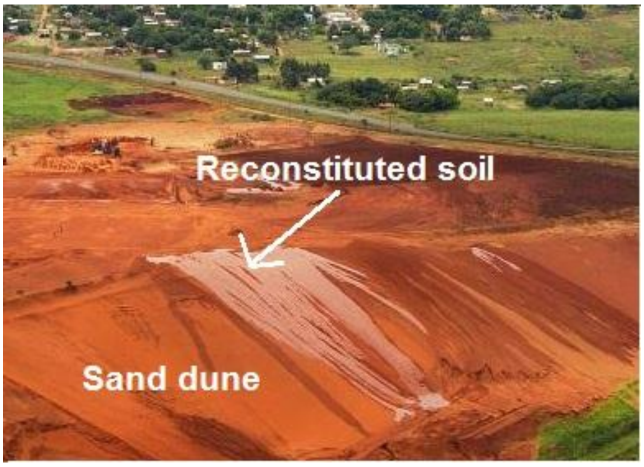

Figure 2.6: A reconstructed sand dune being covered with reconstituted soil.

Figure 2.7: A photograph of the bulk mixing plant (BMP). Sand is being fed on a conveyer belt into the plant where it is mixed with slimes. The resultant mixture is known as the reconstituted soil.

Initially the reconstituted soil was simply left to dry until at least the top 30 cm or so was dry enough for planting crops. In 2011, Exxaro KZN Sands introduced various mechanical soil preparation techniques (like rotovating and deep ripping), to aerate and dry out the soil quicker and more efficiently before re-establishing vegetation (Cocks, 2012, pers. comm.).

The mining operations at Hillendale were originally planned to terminate in 2010, however termination has been extended until 2013. It is envisioned that the rehabilitation at Hillendale will be complete in 2019 (Cocks, 2012, pers. comm.). The final phase of the rehabilitation will involve the rehabilitation of the RSF to support sugarcane production. The RSF rehabilitation however does not fall within the scope of this study.

2.2.3 Pre-mining and initial rehabilitation studies

2.2.3.1 Pre-mining soil survey

A detailed survey of the pre-mining soil at Hillendale was conducted by Snyman (2001). The survey showed that 78% (223.90 ha) of the soil belonged to the Hutton soil form (Table 2.1), while the remainder of the soil consisted of Clovelly (2%), Griffin (2%), Dundee and Katspruit (combined 4%) soil forms. The study area also included buildings and a small area with post-mined soil (9%), since mining had already started a few months prior to the survey.

According to Snyman (2001), the pre-mined soil at Hillendale was predominantly sandy with a generally low base-status (Table 2.1), characteristic of dystrophic or well weathered soils. The soil P was low to medium, while the K, Ca and Mg were low. The soil pH was low and so was the electrical conductivity of the soil, showing that there was no salt contamination in the soil. However, a low EC can cause soil dispersion (Shainberg et al., 1989). Nonetheless, Snyman (2001) gave no indication that soil dispersion was observed in the soil. The exchangeable sodium percentage (ESP) was also low, which shows that the soils were not sodic. Soil erosion hazard was classified as high. Calculating the Ca:Mg and Mg:K ratios from the data provided by Snyman (2001) revealed that the Ca:Mg ratio was within the ideal range (1.5 – 4.5) for optimum crop production in both the A and B horizons, while the Mg:K ratio was lower than the ideal range (3 – 4) in the A-horizon and slightly higher in the B-horizon than the ideal range of 3 – 4 (Buys, 1986).

Table 2.1: Average values or descriptions of selected soil parameters of samples taken from the Hutton soil form before mining (Snyman, 2001).

Analytical property	A horizon	B horizon
Sand (%)	89.02	76.45
Slimes[1] (%)	3.66	3.25
Clay (%)	5.56	18.24
Soil organic matter (%)	0.52	0.36
pH (H_2O)	5.25	5.35
Na (mg/kg)	5.98	6.04
K (mg/kg)	18.69	22.97
Ca (mg/kg)	54.51	144.04
Mg (mg/kg)	8.51	5.24
S-value (cmol(+)/kg)	0.43	1.05
CEC (cmol(+)/kg)	5.37	6.82
P (mg/kg) (Bray method)	20.07	10.47
Electrical conductivity (dS/m)	0.17	0.11
Ca:Mg ratio	3.89	2.95
Mg:K ratio	1.46	4.15
ESP	0.66	0.36
Structure	Single grain	Apedal
Soil effective depth (cm)	150	
Total available moisture (mm)	146	
Profile infiltration	High	
Wetness hazard	None	
Soil erosion hazard	High	

[1] A mixture of fine silt and clay particles all smaller than 45µm fraction

Snyman (2001) classified the agricultural potential of the pre-mining soil at Hillendale according to the soil characteristics, climate and terrain as follows:

- 87.8 ha or 30.5% as having a high potential
- 159.5 ha or 55.0% as having moderate to high potential, and
- 30.3 ha or 10.5% as having sub-marginal potential.

Based on information obtained from the soil survey of Hillendale mine site, Snyman (2001) made the following recommendations:

- That the mining area be landscaped back to its original land form
- That the mined material (void of heavy minerals) be used to back-fill the mined out land
- That the mined material be covered with a layer of uncontaminated topsoil (which is removed and stockpiled before mining)

Snyman (2001) further suggested an assessment of changes in the physical and chemical properties of the post-mined material and the associated effects on the agricultural potential of the soil compared to the pre-mining conditions.

2.2.3.2 Pilot experiment

A report by Golder Associates (2004) makes reference to a pilot experiment that was done in 1995 to determine the ability of the post-mined soil to support sugarcane growth (Fortman, 1998). In this simple experiment, sugarcane was grown in a pit filled with sand tailings (soil minus heavy minerals and containing an average of 10% slimes) to a depth of 5 m. No topsoil was returned to the plot. Sugarcane was also grown in an adjacent plot in undisturbed soil which contained 18% slimes on average. Both plots were fertilized according to a chemical analysis of the respective soils. During the second season, the sugarcane in the post-mined soil produced much lower yield (18 t/ha) than the control plot (51 t/ha). Since drought was experienced during the experimental period, the low yield in the sand tailings plot was explained by the low water retention of the soil. Thus a recommendation was made by Golder Associates (2004) to cap the sand tailings with a mixture of sand and slimes. The water retention of this mixture (reconstituted soil) should have similar water retention to the pre-mined soil. Samples from pre- and post-mined soils were taken (Table 2.2) by Golder Associates (2004) as part of the quest to determine the qualities of a suitable reconstituted soil (Table 2.3).

Table 2.2: Details of pre- and post-mining material (from Golder Associates, 2004).

Sample	Detail of soil sample
001	Soil samples of pre mined red Hutton soil at incremental depths of 300mm up to 1.8m, typical sugarcane profile
002	Soil samples of pre-mined yellow Clovelly soil at incremental depths of 300 mm up to 1.8 m, typical sugarcane profile
003	Yellow post mining material, >45 micron, unrehabilitated
004	Red post mining material, >45 micron, unrehabilitated
005	Turf (from Arcadia and Katspruit soil forms)
006	Slimes
007	Topsoil stockpile

Table 2.3: Analytical properties of pre- and post-mined soils (from Golder Associates, 2004).

Parameter	Standard	Soil samples						
		001	002	003	004	005	006	007
Bulk density	1275kg/m^3	1275kg/m^3	1275kg/m^3	1275kg/m^3	1275kg/m^3	1275kg/m^3	1275kg/m^3	1275kg/m^3
Permeability	10-20mm/h @ Bulk Density of 1275kg/m^3	10 mm/h	8 mm/h	15 mm/h	12 mm/h	3 mm/h	1 mm/h	9 mm/h
Clay content	> 2%	15%	13%	2%	1%	34%	17%	9%
Clay minerals	1:1 (Kaolinite), 2:1 (smectite, vermiculite) clay minerals	Kaolinite	Kaolinite	Kaolinite	Kaolinite	Smectite	Kaolinite	Kaolinite
Void ratio	>0.2	0.4	0.6	0.7	0.8	0.2	0.6	0.5
Soil structure		Single grain	Single grain	Single grain	Single grain	Massive	Single grain	Single grain
Soil texture		Sandy	Sandy	Sandy	Sandy	Clay	Sandy	Sandy
pH	5.3 – 7.2	5.2	5.6	5.1	4.9	7.6	7.1	6.3
Cation exchange capacity	> 2cmol+/kg	4cmol+/kg	3cmol+/kg	1 cmol+/kg	0.2 cmol+/kg	35 cmol+/kg	3 cmol+/kg	4 cmol+/kg
Ca+Mg:K Ratio	10 -20	10	8	34	286	17	7	6
N, P, K	15, 5, 75 mg/kg	3, 2, 80	1, 5, 20	0.2, 0.01, 4	0.1, 0.1, 2	34, 13, 178	6, 3, 89	1, 5, 28
Ca, Mg, SO$_4$	200 – 3000, 50-500, <100mg/kg	78, 12, 14	65, 10, 9	16, 4, 1	21, 6, 3	890, 121, 15	340, 21, 9	88, 9, 4
Cl, Co, B, Fe, Mn, Z, Mo, Si	<1mg/kg	<1	<1	<1	<1	<1	<1	<1
Salinity (EC mS/m)	<450mS/m	56	154	29	35	231	188	144
ESP	<15%	<15	<15	<15	<15	<15	>15	<15
Organic C content	>0.1%	0.3	0.4	0.03	0.06	0.3	0.01	0.1
Root depth (mm)		350	450					

It is unfortunate that the report by Golder Associates (2004) did not indicate the silt and sand content of the soil samples. Nonetheless the report stated that the pre-mined Hutton and Clovelly soils had a sandy loam texture. This is in agreement with the results of the texture of the Hutton subsoils as described by Snyman (2001). It was reasoned that the reconstituted soil should have a similar texture to the pre-mined soils since texture is a major factor in determining soil water retention (Rowell, 1994). Golder Associates (2004) thus recommended that the sand and slimes tailings be mixed in such a way that the resultant reconstituted soil contains approximately 70% sand, 15% silt and 15% clay.

Although the importance of water retention in crop growth is not disputed, the effect of soil drainage was never considered in this work. Overlaying one soil with another with different texture effectively creates a duplex soil. Such duplex (or texture-contrast) soils have a wide range of potential problems including waterlogging, crusting, erosion, increased manganese levels and poor crop establishment (Hardie et al., 2012 and references therein). This is even more concerning if taken into account that the reconstituted soil is deposited as slurry (which implies a water saturated soil) onto the sand.

Golder Associates (2004) used the Soil Water Balance (SWB) model to calculate the minimum soil depth that would supply adequate water during periods of low rainfall (which was taken as 699 mm/year based on long-term weather data) and concluded that this depth was 2 m. In later work, the recommended soil depth was changed to a minimum of 1.25 m by Hattingh et al. (2007b). However, it was not clear how Hattingh et al. (2007b) determined the depth. The reconstituted soil used in this study was deposited to a depth of 1.8 m.

Following the baseline study report by Golder Associates (2004), a number of options were evaluated to determine the most efficient and cost effective way to mix sand and slimes (Hattingh et al., 2007a). A decision was taken that the bulk mixing using dry sand and wet slimes was the most suitable method of reconstituting a post-mining soil. A pilot bulk mixing plant for sand and wet slimes was thus built, which was replaced in 2008 with the bulk mixing plant that has been in use since then (Cocks, 2012, pers. comm.).

2.2.3.3 Post-mined soil profile description

In 2008, a soil survey was conducted by Snyman (2008) which mainly focused on describing pre-mined soils for the Port Durnford mine project. However he did include the description of a reconstituted soil profile at Hillendale. Snyman (2008) pointed out (regarding the reconstituted soil at Hillendale) that the "natural macrostructure (previously single grain and apedal) has been destroyed with massive large blocky and massive stratified structure now being dominant." He noted that the texture in the soil was variable and that hardsetting was observed. Snyman (2008) recommended that the soil mixing must be done more homogeneously and that organic matter be added to the soil. He suggested a reconstituted soil depth of 2 m.

2.2.3.4 Other field experiments

From 2007 to 2010, the University of Zululand undertook a number of field experiments aimed at evaluating a number of soil amendments for their ability to improve the physical and chemical properties of the reconstituted soil (Van Jaarsveld and Zharare, 2010).

The most important findings of the experiments were:

i) Where the reconstituted soil was deposited to the depth of 1.8 m, the soil remained very wet throughout the experimental period. The poor drainage in the soil was attributed to two factors: Firstly, the interface between the reconstituted soil and the sand underneath it created a barrier for water flow. This phenomenon is due to differences in the hydraulic conductivity between the two soil textures (Gardner 1968; Hillel, 1982). Secondly, magnesium related dispersion was identified in the soil and this would have lowered the hydraulic conductivity of the soil.

ii) High manganese levels were observed in sugarcane leaves. This was explained by poor aeration in the reconstituted soil.

iii) Erosion potential of the soil was expected to be high because of the poor drainage and magnesium related dispersion.

iv) The addition of gypsum improved the Ca:Mg ratio of the soil and significantly improved aggregate stability. Gypsum was thus considered a potential soil amendment.

v) In an experiment where a legume (*Desmodium intortum*) and a grass (*Chloris guayana*) were planted alone or in combination, aggregate stability was significantly improved where the legume and grass were grown together, compared to where they were grown separately.

vi) Sugarcane yield was higher in a reconstituted soil with a thickness of 1.8 m than with a thickness of 0.5 m.

vii) There was significant spacial variation in particle size distribution in the reconstituted soil.

2.3 SOIL STRUCTURE

Soil structure has important effects on soil fertility. It determines soil water movement and retention, erosion, crusting, nutrient recycling, root penetration and crop yield (Bronick and Lal, 2005). A well-structured soil is characterized by the presence of stable aggregates. Aggregates are formed when primary soil particles combine with organic and inorganic substances to form secondary particles (Bronick and Lal, 2005).

2.3.1 Factors Influencing soil structure

Soil aggregation is a dynamic process with soil clumps continually being formed or disrupted. Soil aggregation depends on factors like the environment, soil management practices, plant properties, soil mineral composition, soil texture, organic matter content, soil forming processes, microbial activities, exchangeable ions, nutrient reserves and moisture availability (Kay, 1998).

2.3.1.1 Organic matter

Organic matter is central to the formation and stability of soil aggregates. The addition of organic matter to a soil in the form of manure, mulch and compost often has a positive effect on soil structure (Pagliai et al., 2004; Bronick and Lal, 2005). This positive effect can be partly attributed to the increase in microbial activity after organic matter addition, which in turn affects aggregation (Schlecht-Pietschet et al., 1994; Ros et al., 2003). The role of organic matter is mainly by binding soil particles together or by forming complexes with soil minerals (Tisdall and Oades, 1982).

Organic matter appears to be especially important in the stability of larger aggregates (>250 µm) by binding soil particles together (Tisdall and Oades, 1982). The stability of microaggregates (<250 µm) is not influenced by organic matter (Tisdall and Oades, 1982). Tisdall and Oades (1982) who reviewed the effect of organic matter on soil aggregation divided organic binding agents into three groups, namely transient, temporary and persistent.

Transient binding agents consist of organic matter which is decomposed quickly in soils. Polysaccharides are the most important binding agent in this group and are produced by plant roots and micro-organisms. Since transient binding agents are quickly decomposed, their effect of aggregate stability is only temporary. The effect of polysaccharides appears to be only on aggregates which are smaller than 50 µm diameter. The effect of polysaccharides is also less in soils with high organic matter.

The effect of temporary binding agents may last for months or even years in soils. Temporary binding sites include plant roots and fungal hyphae, especially hyphae of vesicular-arbuscular (VA) mycorrhizae.

Fungi hyphae are described as a ‘sticky string bag’ because of its ability to entangle particles and cement them together (Oades and Waters, 1991). Hyphae are effective in binding soil particles, even when they are not alive (Tisdall and Oades, 1982). Arbuscular mycorrhizal fungi (AMF) produce a substance called glomalin which plays an important role in stabilizing aggregates (Wright and Upadhyaya, 1998; Rillig et al., 2002; Rillig, 2004). Glomalin is a glycoprotein which coats the mycorrhizal hyphae (Nichols, 2008). It is extremely resistant to microbial decay and very effective in binding soil particles together.

Persistent binding agents include complexes formed between degraded and stable organic matter and amorphous soil silicates. The organic component in aggregates probably acts like a nucleus with the inorganic component surrounding the nucleus (Tisdall and Oades, 1982).

2.3.1.2 Plant roots

The effect of plant roots on aggregation (as was also discussed in the previous section) is both direct in that they enmesh soil particles, but also indirectly by releasing organic substances into the soil and by supporting soil microorganisms (Tisdall and Oades, 1982). The decomposition of dead roots also promotes aggregation (Six et al., 2004).

Different root systems affect aggregation differently. Fibrous root systems, such as those of grasses, produce high levels of aggregation (Chan and Heenan, 1996). This can be explained by the ability of such root systems to produce large amounts of organic matter that decompose slowly (Brady and Weil, 1999).

Root penetration has been reported to decrease the proportion of relatively unstable macroaggregates, but to increase the proportion of relatively stable microaggregates (Carter et al., 1994).

2.3.1.3 Microorganisms

Microorganisms are pertinent to soil aggregation (Six et al., 2004). Aggregate stability has been shown to correlate with microbial biomass (Haynes and Beare, 1997). As already discussed previously, both bacteria and fungi produce various substances which promote aggregation (Tisdall and Oades, 1982, Chenu, 1989; Oades, 1993; Nichols, 2008). Fungi hyphae are also able to entangle particles and cement them together (Oades and Waters, 1991).

2.3.1.4 Clay mineralogy

An increase in clay surface area and cation exchange capacity (CEC) generally increases the rate and stability of aggregation (Bronick and Lal, 2005). Kaolinite, which is a 1:1 clay, has a low CEC and surface area and tends to decrease aggregate stability. Smectite and other 2:1 clays have a high CEC and surface area which results in high aggregation (Seta and Karathanasis, 1996; Six et al., 2004).

2.3.1.5 Chemical composition

Soil dispersion, which disrupts soil aggregates, is promoted by the presence of monovalent ions like Na^+ and NH_4^+, while flocculation is promoted by polyvalent ions like Ca^{2+}, Fe^{3+} and Al^{3+} (Hillel, 1998; Bronick and Lal, 2005). Although Mg^{2+} is a divalent ion, high Mg^{2+} concentrations in a soil can lead to dispersion (Mullins et al., 1990). A high soil pH, low electrolyte concentration and a fully hydrated soil, as well as mechanical agitation also promote dispersion (Mullins et al., 1990; Hillel, 1998). Soil pH also affects aggregation indirectly by influencing plant growth, metal ion solubility and microbial activity (Haynes and Naidu, 1998).

Aggregation is promoted by the precipitation of (hydr)oxides, phosphates and carbonates. Polyvalent ions like Si^{4+}, Fe^{3+}, Al^{3+} and Ca^{2+} stimulate precipitation of these compounds, which in turn act as binding agents for primary particles (Bronick and Lal, 2005). In oxide-rich soils, oxides are known to be the dominant binding agent (Oades and Waters, 1991; Rhoton et al., 1998).

2.4 GYPSUM

Gypsum contains calcium which acts as a flocculant in soil, thereby promoting good soil structure. Gypsum ($CaSO_4$) is therefore often used to improve soil structure in degraded soils (Mengel and Kirkby, 1987; Mullins et al., 1990; Bronick and Lal, 2005). A previous study identified gypsum as a potential amendment for improving the soil structure of the post-mined soil at Hillendale (Van Jaarsveld and Zharare, 2010).

2.4.1 Process and characteristics of soil dispersion

During the process of soil dispersion, fine particles, such as clay, forms a stable suspension in or throughout the soil solution, with the concomitant breakdown of soil aggregates (Van der Watt and Van Rooyen, 1990). The destruction of soil aggregates in turn results in surface crusts, low soil water infiltration, increased run-off and erosion and poor root growth and plant establishment (Shainberg et al., 1989). Dispersed soils are also more prone to hardsetting during which the soil spontaneously increases in density and hardens (Mullins et al., 1990).

On a chemical level, soil dispersion involves the repulsion of clay particles. Clay particles are surrounded by a negative electrical field and during dispersion these fields increase in magnitude resulting in clay particles moving further apart. The size of the electrical field is increased by the presence of highly hydrated monovalent cations, such as Na^+, K^+ and NH_4^+, as well as Mg^{2+} (Shainberg et al., 1989; Bronick and Lal, 2005). The Mg^{2+} ion causes dispersion because of its relatively thick hydration radius (Keren, 1991). The size of the electrical field is also increased by an increase in pH and by a low electrolyte concentration in the soil solution (Shainberg et al., 1989).

The potential for soil dispersion is greatest when sodium (Na^+) ions are in excess of other cations. The concentration of Na ions relative to other ions in the soil can be expressed by two related parameters, the sodium adsorption ratio (SAR) and the sodium exchangeable percentage (ESP). Electrolyte concentration is measured by the electrical conductivity (EC) with distilled water having an EC of 0 dS/m. Traditionally it was accepted that sodium dispersion occurs in soils when the ESP exceeds 15 % (Rowell, 1994). Yet the effect of the relative Na concentration on soil dispersion cannot be separated from the effect of electrolyte concentration. Even soils with a low ESP can be dispersed with water having a low EC (Shainberg et al., 1989). The EC of the soil solution at the soil surface is mainly determined by the applied water (which is often rain water with a low EC), while the EC of the soil solution further down the soil profile is mainly determined by the dissolution rate of the soil constituents (Shainberg et al., 1989).

Abrol et al. (1988) described sodic soils (dispersed soils resulting from a high soil Na concentration) as follows: "Under field conditions after irrigation or rainfall, sodic soils typically have convex surfaces. The soil a few centimeters below the surface may be saturated with water while at the same time the surface is dry and hard. Upon dehydration cracks of 1-2 cm across and several centimeters deep form and close when wetted. The cracks, generally, appear at the same place on the surface each time the soil dries unless it has been disturbed mechanically."

Magnesium has also been implicated in soil dispersion. Soil dispersion by Mg is more complex and appears to be restricted to very specific conditions in the soil that was well summarized by Fenton and Conyers (2002). Both Mg and Na dispersion had been demonstrated on soils with a wide variety of clay mineralogy (including smectite and kaolinite rich soils) (Shainberg et al., 1989; Dontsova and Norton, 1999) and wide range of clay contents (Miller et al., 1998; Dontsova and Norton, 1999).

Soil dispersion can also be caused mechanically by agitation of soil particles. Mechanical dispersion is caused, for example, when raindrops hit the soil surface that result in the dislodging of clay particles and clogging of the soil pores (Shainberg et al., 1989; Mullins et al., 1990).

In contrast to dispersion, flocculation reduces repulsion between clay particles and enhances aggregation (Mullins et al., 1990). Polyvalent ions like Ca^{2+}, Fe^{3+} and Al^{3+} promotes flocculation (Hillel, 1998; Bronick and Lal, 2005). Shainberg et al. (1989) stated that gypsum, as a source of Ca, "directly prevents swelling and dispersion, and indirectly increases porosity, structural stability, hydraulic properties, soil tilth, drainage and leaching, and reduces dry soil strength." It is against this background that gypsum was evaluated for its effect on poorly structured reconstituted soil of a backfilled land.

2.4.2 Gypsum uses, sources and solubility

Gypsum, viz. calcium sulfate dihydrate ($CaSO_4.2H_20$), is a relatively common mineral that has a number of agricultural uses, both as nutritional source of Ca and S and as a soil conditioner (Shainberg et al., 1989). Gypsum also has a number of commercial uses including wallboard and as a cement additive. Sources of gypsum are either natural deposits, which are obtained by mining, or as a by-product from industrial processes (Shainberg et al., 1989). Phosphogypsum (gypsum containing low quantities of phosphorus) is one such by-product that is produced in large quantities during the production of phosphoric acid (Shainberg et al., 1989).

The solubility of gypsum in aqueous solution is relatively low, yet high enough to contribute to the ionic strength (electrolyte concentration) of watery solutions (Shainberg et al., 1989). The solubility of gypsum is slightly higher than that of lime ($CaCO_3$), but lower than $CaCl_2$ and $Ca(NO_3)_2$ (Shainberg et al., 1989). The relatively low solubility of gypsum allows a slow release of Ca ions over a long period of time. Calcium ions from gypsum can easily exchange other cations on the exchange complex, thereby releasing these ions into the soil solution (Shainberg et al., 1989). Particle size of gypsum is an important aspect that influences solubility. The smaller the particle size of gypsum, the better the solubility (Shainberg et al., 1989).

2.4.3 Effects of gypsum on soils and plants

2.4.3.1 Soil flocculation

The flocculation effect of gypsum on soils is by two mechanisms (Shainberg et al., 1989; Miller et al. 1998). Firstly, gypsum has an ionic strength effect (increases the electrolyte concentration). Secondly, the Ca^{2+} ions that are released when gypsum is dissolved are able to displace Na^+ and Mg^{2+} ions on the exchange complex. Miller et al. (1998) suggested that the flocculation by gypsum is mainly by its effect on ionic strength and to a lesser degree by cation displacement.

2.4.3.2 Crust formation and soil strength

Mitchell et al. (2000) were able to demonstrate a decrease in soil crust strength by 14 % in an experiment where gypsum was applied to the soil surface and irrigated with saline water. Radcliffe et al. (1986) reported that there was no decrease in penetration resistance[1] in bare soil treated with gypsum as compared to soil under alfalfa and peach trees treated with gypsum. It was suggested that gypsum stimulated root growth in this study and that the subsequent formation of root channels lowered the penetration resistance. Sumner et al. (1990) showed a

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[1] Penetration resistance is a parameter of soil strength or hardness. Penetration resistance generally increases with increase in bulk density or compaction and sand percentage and decreases with increase in soil water content (Aggarwal et al., 2006 and references therein).

decrease in the penetration resistance of subsoil hardpans following gypsum application in a field study under peaches, cotton and alfalfa.

2.4.3.3 Hydraulic conductivity

The hydraulic conductivity of dispersed soils is increased by gypsum application (Shainberg et al., 1982; Shainberg et al., 1989). Sahin and Anapali (2005) were able to demonstrate that either mixing gypsum into the soil surface or adding it to the leaching water in the laboratory significantly ($p<0.01$) increased the hydraulic conductivity of a sodic soil.

2.4.3.4 Water infiltration and soil loss

When three sandy soils were tested in a rain-simulator experiment, infiltration rates increased by 2 to 4 times in gypsum treated soils, as compared to the same soils without gypsum (Miller et al., 1998). In the same experiment, soil loss in the run-off was also reduced in all three soils when gypsum was added. Miller et al. (1998) explained the effect of gypsum in the experiment as an ionic strength effect, pointing out that the electrical conductivity of the water used in the simulator was low enough to cause dispersion of the clay fraction.

In a laboratory experiment with a sandy clay loam soil that easily forms crusts in the field, adding $NaNO_3$ in a rain simulator test resulted in soil sealing and a concomitant decrease in infiltration rates. When gypsum was added to the same soil, no run-off occurred until 4 cm of water was applied, but a high infiltration rate was maintained throughout the rain simulation run. When both $NaNO_3$ and gypsum were applied to the soil, the soil behaved the same as when only gypsum was applied. Soil loss from the experiment showed similar results, with the Na-treated soil showing a large soil loss, compared to the control, and the gypsum alone or gypsum and $NaNO_3$ combination treatments showing low soil loss (Miller et al., 1998).

In another laboratory experiment, Miller et al. (1998) demonstrated that when gypsum was added to the water used in a rain simulator, as compared to where deionized water alone was applied, run-off was lower where gypsum was added in both soils tested. Similar results, as discussed above, were also obtained by Miller et al. (1998) in field experiments with gypsum.

A study by Dontsova and Norton (1999) showed that in soils treated with Ca, final infiltration rates were double that of the same soil treated with Mg and that the total infiltration was increased by 20 to 100 % by Ca application. Soil loss was also less in the Ca treated soil as compared to the Mg treated soil. Ben-Hur et al. (1992) demonstrated that spreading 5 t/ha phosphogypsum on the soil surface decreased soil loss sharply in a dispersive soil and moderately in a non-dispersive soil.

2.4.3.5 Aggregate stability and soil structure

Baldock et al. (1994, as cited in Amézketa, 1999), made the observation that while gypsum did not improve macro-aggregate stability, it did improve microaggregate stability significantly. A 46% increase in aggregate stability was observed where gypsum was applied to the soil surface (Mitchell et al., 2000). Gypsum application was able to increase structure and yield in a sodic soil, while in Mg-dispersed soil, only structure was improved (Grierson, 1978 as cited in Mullins et al., 1990). Dontsova and Norton (1999) were able to show that aggregate destruction was greater in soils treated with Mg than in soil treated with Ca.

2.4.3.6 Plant growth

In a soil with subsoil acidity, adding 10 t/ha gypsum and 25 t/ha lime was able to increase maize yield by 25 % for 11 seasons. In comparison, lime applied alone had minimal effects on acidity below the depth of incorporation (Farina et al., 2000a). Gypsum is also known to stimulate root growth in soil with subsoil acidity by decreasing the Al levels in the affected soil (Shainberg et al., 1989, Farina et al., 2000b). Gypsum treatment of a sandy loam soil in a field experiment showed that emergence of cotton nearly doubled in the first 5 days of planting compared to the untreated soil (Miller et al., 1998). Kumar et al. (1999), who studied the effect of gypsum on a sodic soil under sugarcane, reported an increase in sugarcane yield and juice extraction percentage where gypsum was added to irrigation water. Adding gypsum to saline-sodic and sodic irrigation waters resulted in an increase in cane and sucrose yields as compared to where gypsum was omitted (Choudhary et al., 2004). Where gypsum was used to amend a sodic bentonite mine spoil, perennial grass biomass and canopy cover increased drastically (150% and 140%, respectively) (Schuman et al., 1994). Mitchell at al. (2000) did not observe an increase in yield or crop stand in their gypsum experiment, in spite of an increase in aggregate stability and decrease in crust strength where gypsum was added.

2.4.3.7 Plant nutrients

Increases in yield due to gypsum application can sometimes be explained by a nutritional effect of Ca and S rather than an effect on the soil (Toma et al., 1999), including in sugarcane (Breithaupt et al., 1991). Viator et al. (2002) showed no increase in cane and sucrose yields in an experiment where gypsum was added to a silty clay loam soil, although it was not clear if the soil was dispersed or deficient in S.

As can be expected, leaf Ca and S are increased in the second and sometimes already in the first year after gypsum application in several crops including apple, coffee, maize, cotton, peanuts and alfalfa (Shainberg et al., 1989 and references therein) as well as in sugarcane (Breithaupt et al., 1991). Leaf Mg, and sometimes also leaf K, was simultaneously depressed by the application of gypsum in these crops (Shainberg et al., 1989, and references therein), but not in sugarcane (Breithaupt et al., 1991). Viator et al. (2002) showed that gypsum application increased sugarcane leaf concentrations of Ca, S, Mn and Zn with no effect of leaf N, P, K, Mg, Cu and Fe concentrations.

Calcium is known to exchange Mg from the clay exchange complex in the soil and Mg is known to accumulate lower down in the soil profile following gypsum application (Shainberg et al., 1989; Farina et al., 2000b). Mays and Mortvedt (1986) reported a decrease of maize yield with high phosphogypsum applications and attributed it to a Ca induced Mg deficiency. Although gypsum can cause leaching of K, the behavior of soil K however also depends on the location. South African soils appear to have a greater affinity for K than for Mg and hence little K mobilization takes place in our soils when gypsum is added (Shainberg et al., 1989).

Gypsum application is known to result in increased Mn uptake by plants, but the reason for this is not understood yet (Shainberg et al., 1989). Gypsum is known to decrease both the exchangeable Al and Al saturation down the whole soil profile, making it a useful amendment on acid soils with high Al concentrations (Shainberg et al., 1989; Farina et al., 2000b). Sulfate ions are not easily leached from the soil profile, following gypsum application, but soil NO_3^- is (Souza and Ritchey, 1986 as cited in Shainberg et al., 1989). Favaretto et al. (2006) indicated that gypsum application failed to decrease NO_3^- concentrations in run-off. In the same study, water extractable P in the run-off sediment was increased by gypsum application by 50% compared with the Mg treated soil.

2.4.4 Longevity and effectiveness of gypsum response

It was reported that cation imbalances can result from heavy gypsum applications in some sandy soils. Suggestions were made that in such soils more frequent, but smaller applications of gypsum might be more efficacious (Miller at al., 1998). Loveday (1981), as cited in Mullins et al. (1990), pointed out that, during drought, the effect of gypsum might be less, because the increased seedling emergence could result in less water availability in the soil later in the season. Shainberg et al. (1989), on the other hand, reported a greater gypsum response in times of water stress and attributed it to the presence of deeper roots that extracted water from deeper in the profile where gypsum was added.

Other factors that could influence the response to gypsum are high organic matter levels, covered soils, direct seed drilling, neutral pH, low concentrations of organic matter molecules adsorbed on clay particles, severe drying and the presence of calcium carbonate (Mullins et al., 1990 and references therein).

The effects of gypsum application to ameliorate subsoil acidity could still be seen 16 years after application in one study (Toma et al., 1999) and 10 years in another study (Farina et al., 2000b). In the latter study, gypsum continued to move down in the profile up to the eighth season where it reached a final depth of about 0.75 m.

Gypsum application did not result in changes in plant growth until the second or third year in a study by Schuman et al. (1994) on sodic bentonic mine spoils in the USA. Interestingly, South African and Georgian soils often show a delayed response to gypsum, as compared to, for example Brazilian soils. This delayed response was explained by the relatively slow movement of water through the soil profile in South African soils as compared to the extremely fast drainage in Brazilian soils (Shainberg et al., 1989).

2.4.5 Basic cation ratios in soils

The use of so-called ‘balanced’ Ca, Mg and K ratios as a basis for fertilizer recommendations is a controversial issue (example Sawyer, 2003; Kopittke and Menzies, 2007; Rehm, 2009). Cation ratios have been a topic of much scrutiny over the years. Relatively recently, Kopittke and Menzies (2007) reviewed the concept and concluded that “within the ranges commonly found in soils, the chemical, physical and biological fertility of a soil is generally not influenced by the ratios of Ca, Mg and K". They indicated that the Ca:Mg ratio of soils are usually within the range of 0.25:1 to 31:1.

Several studies suggested that the Ca:Mg ratios are not of importance in a number of crops including alfalfa, barley, wheat, canola, lupine and maize as long as neither of the two nutrients are deficient (for example Hunter, 1949; McLean and Carbonell, 1972; Liebhardt, 1981; Western Australian No-Tillage Farmers Association, 2005 as cited in Kopittke and Menzies, 2007).

Yet there is also evidence to suggest otherwise. The Ca:Mg ratio has been used as a tool to predict the erodibility of the soil (Dontsova and Norton, 1999) and has been suggested as a criterion to identify Mg dispersion (Fenton and Conyers, 2002). The effect of Mg on soil dispersion was also recognized by Rengasamy (1983), Curtin et al. (1994), Keren (1991) and Zhang and Norton (2002). It is well recorded that Ca has an antagonistic effect on Mg and that high soil Ca can result in Mg deficiency in plants (Shainberg et al., 1989; Marschner, 1995). Likewise, high applications of Mg can result in decreased uptake of Ca (Mengel and Kirkby, 1987). It is also reported that uptake of Ca can be depressed by high levels of K (Mengel and Kirkby, 1987).

In their review on the importance of cation ratios in soils, Koppitke and Menzies (2007) did not indicate the range of Mg:K ratios typically found in soils. They did refer to two studies where the Mg:K ratios were lower than 1:1 with no effect on tomato yield (Bear et al., 1951) or sorghum growth (Ologunde and Sorensen, 1982). MacLean et al. (1983) were able to show that Mg:K ratios varying between 0.6:1 and 3.6:1 did not have a significant effect on maize, soybeans, wheat and alfalfa yield. In contrast, it is also reported that Mg and K have an antagonistic relationship, with high applications of the one leading to deficiencies of the other (Mengel and Kirkby, 1987; Marshner, 1995, Hannan, 2011).

2.5 SOIL ORGANIC MATTER

2.5.1 Nature and composition of soil organic matter

Soil organic matter (SOM) can be defined as any material originally produced by living organisms that is returned to the soil and undergoes decomposition (Bot and Benites, 2005). Organic matter (OM) in soil originates mostly from plant tissue (Prasad and Power, 1997; Bot and Benites, 2005). Plant residues typically contain between 60 and 90% water with the rest being dry matter. The dry matter, in turn, contains about 40% C and 40% O with less than 10% H and other elements like S, N, P, K, Ca and Mg (Prasad and Power, 1997). The total breakdown of organic matter (called mineralization) results in the release of mineral nutrients into the soil that will in turn contribute to soil fertility (Bot and Benites, 2005). The OM content of soil varies from about 0.2% in desert soils to more than 80% in some organic soils (Magdoff and Weil, 2004). The OM content of cultivated mineral soils has been reported to be between 1 and 4% (Magdoff and Weil, 2004) or as high as 30% (Prasad and Power, 1997; Bot and Benites, 2005).

The decomposition of plant and animal residues by soil microorganisms results in the formation of compounds that can roughly be divided into the so-called active organic fraction (10 to 40% of total SOM) and the resistant or stable organic fraction (40 to 60% of total SOM) (Bot and Benites, 2005). The active organic fraction is characterized by substances that are easily decomposed and forms the main food supply for many soil organisms (Bot and Benites, 2005; Coyne and Thompson, 2006). Proteins, amino acids, sugars and starches all form part of the active fraction and they are collectively known as non-humic substances (Bot and Benites, 2005; Coyne and Thompson, 2006). The stable organic fraction is also collectively known as humus or humic substances and does not have a consistent identifiable chemical composition (Coyne and Thompson, 2006). Because of the complex chemical nature of these substances, they are very resistant to microbial breakdown and they remain in the soil for a long time (Bot and Benites, 2005). Humic substances are typically dark in colour and when present in large quantities in soils results in dark-coloured soil.

2.5.2 Importance of soil organic matter

Soil organic matter, and in particular, humus has the following functions in soil:

i. When SOM is mineralized it releases N, P and S and many other nutrients into the soil that are essential to plants (Coyne and Thompson, 2006).

ii. Soil organic matter makes an important contribution to the cation exchange capacity of a soil, especially in sandy soils (Magdoff and Weil, 2004; Coyne and Thompson, 2006). The retention of cations on the exchange sites of SOM prevents these ions from leaching out of the root zone.

iii. Soil organic matter is able to interact with metal ions, oxides, hydroxides, mineral and organic compounds including toxic substances, pollutants and herbicides. The effect of harmful substances in the environment is reduced in this way. The addition of SOM also affects the mobility and solubility of metals that can be either beneficial or harmful for plant growth, depending on the metal and its concentration (Magdoff and Weil, 2004).

iv. Soil organic matter acts like a glue that binds soil particles together into aggregates thereby improving both aggregation and aggregate stability (Tisdall and Oades, 1982), especially in soils low in clay (Magdoff and Weil., 2004). It also improves aggregate stability by forming chemical bonds with clay and iron hydroxides in the soil (Anderson et al., 1998a). The presence of more stable aggregates in a soil increases the resistance of the soil against dispersion and surface crusting and hence also improves resistance against soil erosion (Pagliai et al., 2004; Coyne and Thompson, 2006; Tejada and Gonzalez, 2007).

v. In addition to aggregate stability, SOM also improves several other physical properties in soils. It increases the water-holding capacity of soil. This is possible firstly because SOM retains water directly and secondly because SOM improves soil structure and porosity that in turn improves the water holding capacity of the soil (Celik et al., 2004; Coyne and Thompson, 2006). Better porosity furthermore results in better soil water drainage (Coyne and Thompson, 2006). Soil organic matter also lowers bulk density (Tejada and Gonzalez, 2007; Celik et al., 2010) and increases friability (tendency of soil clods to easily crumble into their natural aggregates) (Magdoff and Weil, 2004). Soils with good friability are easier to cultivate. Soil high in OM has a higher temperature (because of its dark colour) and is well buffered against temperature fluctuations (because of its higher water retention) (Coyne and Thompson, 2006).

vi. Soil organic matter acts as a food source for soil microorganisms, as well as larger soil organisms like earthworms. When OM is added to a soil it enhances both the diversity of microorganism species, as well as the microbial biomass. The microbial biomass is therefore usually proportional to the amount of OM in the soil. Soil microorganisms in turn are directly or indirectly responsible for many important processes in a soil including the formation of humus and mineralization of SOM, stabilizing of soil aggregates, production of plant growth regulators, competition with plant pathogens and pesticide degradation (Magdoff and Weil, 2004).

vii. Humic substances can directly affect plant growth. Humic and fulvic acid, for example, can enhance plant growth directly through physiological and nutritional effects. Some of these substances also function as natural plant hormones (Bot and Benites, 2005).

2.5.3 Factors affecting soil organic matter content

2.5.3.1 Soil water content

On the one hand, soil organic matter tends to be higher in areas with higher rainfall because more vigorous plant growth results in more residues being produced (Bot and Benites, 2005). On the other hand, conditions of prolonged waterlogging in soils results in an oxygen poor environment that slows down decomposition and ultimately results in an accumulation of SOM (Ross, 1989). Since O_2 is used as an electron acceptor in aerobic respiration, the lack of O_2 in waterlogged soils favors anaerobic respiration that uses alternative electron acceptors. The end-products of anaerobic respiration include a wide range of substances of which many are detrimental to plant growth. The electron transfer reactions (or redox reactions) in O_2 poor soils follow a specific sequence as the O_2 concentration decreases. First NO_3^- is used as an electron acceptor, resulting in a loss of N from the soil in the form of N_2 gas. This process is called denitrification. After this Mn^{4+} is reduced to Mn^{2+}, then Fe^{3+} is reduced to Fe^{2+} and so forth (Brady and Weil, 2004). Waterlogged soils are therefore often associated with N deficiencies and Mn and Fe toxicities (Ross, 1989, Prasad and Power, 1997).

2.5.3.2 Temperature

Decomposition of SOM takes place faster at higher temperatures (Prasad and Power, 1997; Bot and Benites, 2005). Soil organic matter tends to accumulate at the bottom of hills, because the soil water content tends to be higher there and because of the effect of gravity. In the southern hemisphere, SOM is often higher on north-facing slopes, because of higher temperature (Bot and Benites, 2005; Coyne and Thompson, 2006).

2.5.3.3 Clay content and type

Prasad and Power (1997) reported that the OM of clayey soils is two to four times higher than in sandy soils. There are a number of reasons for this. Firstly, the better aeration in sandy soils results in a quick and complete decomposition of SOM as compared to clayey soils (Prasad and Power, 1997). Secondly, clay particles tend to form bonds with OM that retards decomposition. And lastly, soil with high clay content has a higher potential for aggregate formation. The OM inside aggregates is physically protected against microbial breakdown (Bot and Benites, 2005). Soil rich in 2:1 type clays tends to have a higher SOM content than soils rich in 1:1 type clays (Prasad and Power, 1997).

2.5.3.4 Quantity and quality of added organic residues

The rate at which SOM accumulates depends largely on both the quantity and quality of the added material (Bot and Benites, 2005). Plant and animal residues show much variety in their chemical composition, and hence vary in the ease with which they are decomposed (Ross, 1989). Organic residues containing large quantities of soluble compounds such as sugars, amino acids, as well as proteins and carbohydrates are easily decomposed (Ross, 1989). The presence of lignin, polyphenols, lipids and chitin in the residues slows down decomposition (Ross, 1989; Bot and Benites, 2005).

The carbon to nitrogen (C:N) ratio of organic residues is important. When residues with a high (25 – 45) C:N ratio are added to a soil, there is a sudden increase in microbial activity. Microbes require N to decompose organic matter and the availability of inorganic N in the soil will be temporarily restricted until the decomposition process is completed. This period of limited N availability in the soil is known as N immobilization (Ross, 1989). The N deficiencies that result from N immobilization can have a negative effect on plant growth (Prasad and Power, 1997). Grass residues typically have a high C:N ratio, while residues from leguminous crops have a low C:N ratio. Nitrogen immobilization is less or absent when residues with a low C:N ratio are added to a soil (Prasad and Power, 1997). Residues with a high C:N ratio favors humus formation with a concomitant improvement of soil structure, while residues with a low C:N ratio favor a quick release of mineral N into the soil (Bot and Benites, 2005). In addition to producing residues with high C:N ratios, grasses also have intensive root systems that are known to produce large amounts of residues. It is not surprising then that soil under pasture (grass) typically contains more SOM than, for example, soil under forest (Stevenson and Cole, 1999).

2.5.3.5 Human activities

Certain human activities, particularly agricultural practices, can affect the SOM content. Any activity that removes vegetation or residues from the soil has a negative effect on SOM levels. This includes deforestation, burning of vegetation and crop residues, overgrazing and removal of crop residues from the field (Bot and Benites, 2005). When soil is ploughed during tillage, the soil is aerated which results in faster decomposition of the SOM (Prasad and Power, 1997; Stevenson and Cole, 1999). The use of certain fertilizers and pesticides can boost microbial activity that in turn increases the decomposition of SOM (Stevenson and Cole, 1999; Bot and Benites, 2005). Activities like composting, manuring, and practices that leave plant residues on the soil surface can also increase the OM content of the soil (Stevenson and Cole, 1999; Rivero et al., 2004; Bot and Benites, 2005).

2.5.4 Use of filtercake as an organic amendment

2.5.4.1 Origin and composition of filtercake

Filtercake (FC) (also known as mud press, milo or smuts) is a waste product of sugarcane milling. In this process, sugar containing juice is separated from the solid organic material by a filtration (Dee et al., 2002), and a solid cake called FC accumulates on the filters. The chemical composition of FC depends on the type of milling process, the presence of fly ash, the cane variety and the amount of soil and extraneous material in the cane that is milled (Anon., 2003). Filtercake contains N, P, K, Ca and Mg and other nutrients plus various organic compounds such as starch, sugars, wax, protein, gums and pectin. The mineral content of FC is however variable (Table 2.4).

Table 2.4: Variation in chemical composition (on a dry weight basis) of filtercake (FC) as determined by the milling process (from Anon., 2003).

Constituent	Value
Total C (%) (mainly sugar, fibre, waxes)	30 to 45
Total N (%) (as protein)	1.0 to 2.0
C:N ratio	20 to 35
P (%)	0.5 to 2.5
K (%)	0.2 to 0.3
Ca (%)	1.0 to 5.0
Mg (%)	0.2 to 1.0
S (%)	0.1 to 0.2
Si (%)	1.0 to 4.0
Zn (ppm)	75 to 200
Cu (ppm)	40 to 90

Some sugarcane mills mix fly ash (another by-product of sugarcane milling) into the FC that reduces the nutrient value of the end-product (Table 2.5) (Anon., 2003). Dee et al. (2002) reported a pH value for FC of 6.85 and for fly ash of 7.69. The water content of fresh FC is typically between 65 to 75%, but in the field it dries out to between 50 and 60% water (Anon., 2003).

Table 2.5: Typical chemical composition (on a dry weight basis) of filtercake (FC), fly ash and a mixture of FC and fly ash (from Anon., 2003).

Material	N	P	K	Ca	Mg
	%				
FC only	1.60	1.00	0.30	1.75	0.46
FC + fly ash	0.84	0.60	0.30	1.05	0.40
Fly ash only	0.11	0.18	0.70	0.30	0.34

2.5.4.2 Availability and application rate of filtercake

Large quantities of FC (400 000 to 500 000 tons/annum) are normally available from sugar mills (Anon., 2003). However, due to the weight of FC, it is expensive to transport and its use as an organic amendment is normally limited to areas close to sugar mills (Dee et al., 2002).

Filtercake is equivalent to a 5:3:1 inorganic fertilizer mixture and it normally contains sufficient P for the plant, first and second ratoon crops. However, the chemical composition of FC is rarely completely suitable for sugarcane production. Hence, it is usually necessary to apply inorganic fertilizer in combination with the FC to balance nutrients. The availability of N contained in FC depends on the C:N ratio. If the C:N ratio is higher than 30, then N will not be immediately available for plant growth. On the other hand if FC is composted to a C:N ratio of less than 20, then up to 70 % of the N will be immediately available for plant growth (Anon., 2003).

Farmers are generally advised to apply fresh FC at a rate of 30 t/ha in the planting furrow, since this application rate is considered adequate to supply the required N and P. Additional K application is advised. However, the application rate of FC is also dependent on the type of soil and the C:N ratio of the FC (Anon., 2003).

2.5.4.3 Effect of filtercake application on soil quality and sugarcane growth

The main benefit of FC application appears to be its effects on soil structure and the water infiltration rate of the soil (Roth, 1971; Henry and Rhebergen, 1994; Anon., 2003; Van Antwerpen et al., 2003). In addition, it increases soil water retention, water infiltration and the cation exchange capacity (CEC); lowers the bulk density and increases the rooting depth (Meyer et al., 1992; Anon., 2003). In saline-sodic soils, it has been used successfully to leach excessive amounts of Na from the soil (Henry and Rhebergen, 1994; Anon., 2003). Sugarcane yield is known to increase following FC application, but the sucrose yield can be lowered due to delayed ripening that in turn results from the gradual release of soil N (Anon., 2003). A study by Gilbert et al. (2008) on a sandy soil showed that both cane yield and sucrose yield were improved more when 224 t/ha FC was applied alone as compared to when inorganic fertilizer was applied alone. This was especially evident from the results obtained for the second ratoon harvesting. Gilbert et al. (2008) explained the effect of FC as due to increased water holding capacity and nutrient availability.

Application of FC has been reported to be effective to increase the organic matter content of the soil (Dee et al., 2002). Van Antwerpen et al. (2003) reported that plant available P, K, Ca and Mg were more than doubled where FC was applied as compared to where it was omitted. They also reported that the biological properties of the soil (including microbial biomass, basal respiration and the metabolic quotient) were more favorable where organic matter was applied as compared to the control.

2.6 PHOSPHORUS

2.6.1 Role of phosphorus in plants

Phosphorus is a component of adenosine triphosphate (ATP), which stores and transfers energy for metabolic processes in plants. Phosphorus is also a component of deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) and is involved in plant reproduction and cell division. It is a constituent of phospholipids which are important for cell membrane integrity and function (Plaster, 2009). Phosphorus promotes early root formation and growth (Fertilizer Industry Federation of Australia, 2000). In addition, P increases plant resistance to cold and diseases, hastens crop maturity, aids in flowering and fruiting and improves the quality of grains and fruits (Plaster, 2009; Fertilizer Industry Federation of Australia, 2000).

2.6.2 Phosphorus deficiency in plants

Phosphorus deficiency results in stunted growth and delayed maturity in plants (Stevenson and Cole, 1999). In cereals, as well as sugarcane, tillering is reduced (Mengel and Kirkby, 1987; SASA, 1998; Fertilizer Industry Federation of Australia, 2000). Since P is easily translocated from older to newer tissues, deficiency symptoms first appear on the lower parts of plants (Fertilizer Industry Federation of Australia, 2000). Anthocyanin accumulation in mature leaves is typical of P deficiency in plants and results in tissues being abnormally dark green with red and purple hues (Taiz and Zeiger, 1991). The leaves may be malformed with necrotic (areas where tissues had died) spots and the leaves may eventually turn brown and die (Taiz and Zeiger, 1991). A study by Mollier and Pellerin (1999) on maize revealed that P starvation resulted in an initial stimulation of root growth, followed by a strong reduction in root growth thereafter. They postulated that P deficiency affects root growth by affecting the carbon partitioning to roots and shoots, with an increase in carbon partitioning to roots during the early stages of P deprivation.

2.6.3 Phosphorus availability in soils

Since elemental P is very reactive chemically, it is only found in combinations with other elements in nature. Soil P is provided by the weathering of minerals like apatite. When P is released into the soil solution by weathering, orthophosphate ions ($H_2PO_4^-$ and HPO_4^{2-}) are formed. Plants absorb mainly orthophosphate to supply in their P needs, but orthophosphate is available only in small quantities in the soil solution (Fertilizer Industry Federation of Australia, 2000). The P in soil solution is subject to many reactions that lower its solubility and therefore its availability to plants. These reactions are generally referred to as P fixation or sorption (Brady and Weil, 2008). Based on this, soil P is often divided into three fractions or pools: i) phosphate in soil solution; ii) phosphate in the labile pool and iii) phosphate of the non-labile pool (Mengel and Kirkby, 1987; Fertilizer Industry Federation of Australia, 2000). The first pool refers to soluble P in the soil solution. The second pool (labile pool) refers to the P that has formed compounds with Ca, Fe, Al, Mg and Mn or that is adsorbed on the reactive surfaces of certain clay minerals (Fertilizer Industry Federation of Australia, 2000). The labile pool is in rapid equilibrium with the soil solution (Mengel and Kirkby, 1987). Insoluble P represents the third pool and includes aged and well crystallized precipitates of Fe, Al, Mg, Ca and Mn, as well as P that have penetrated particles (occluded phosphates) and stable organic P (Fertilizer Industry Federation of Australia, 2000).

Phosphorus removed from the soil solution by plant roots needs to be replaced from the labile pool on a continuous basis. Phosphorus in the soil solution may be replaced as often as two or three times a day (Fertilizer Industry Federation of Australia, 2000). The P concentration in the solution depends, therefore, on the quantity of P in the labile pool, but also on the ease with which the P is released (desorbed) from the labile pool. The ease with which labile P is released or desorbed is an indication of the buffer capacity (resistance against change) of the soil. The buffering capacity is useful in understanding both the effectiveness of P fertilizer application and the replenishment of P in the soil solution after plant uptake (Holford, 1997).

The contribution of P associated with organic matter to plant available P is still little understood. It is reported that soil organic matter contains between 25 and 90 % of all soil P (Plaster, 2009). The organic forms of P includes mainly phosphorylated sugars and alcohols (comprising about 10 to 50% of the total organic P), as well as nucleic acids and phospholipids (Mengel and Kirkby, 1987; Brady and Weil, 2008). Although plants can, to a very limited extent, absorb organic forms of P, most organic P needs to be mineralized before being available to plants. The rate of mineralization depends on a number of factors which include soil temperature, moisture content and pH (Fertilizer Industry Federation of Australia, 2000). Mineralized organic P has been shown to be the most important source of P in highly weathered soils where P fixation is very prominent (Brady and Weil, 2004).

2.6.4 Factors influencing phosphorus availability

2.6.4.1 Phosphorus sorption and fixation

The amount of P that is fixed is determined by a number of factors which include type and amount of clay, pH and the amount of organic matter present.

i. Clay content and type

Some clay minerals fix more P than others. Iron and aluminium (Al) oxides and hydroxides (typical of highly weathered soils) and amorphous clay and humus-Al complexes (typical of soils formed from volcanic ash) have a high P fixing ability (Fertilizer Industry Federation of Australia, 2000). Kaolinite has a higher fixing ability than other layer silicate clays (Brady and Weil, 2008). The higher the clay content of the soil, the more P will be fixed (Fertilizer Industry Federation of Australia, 2000).

ii. Soil pH

Phosphorus fixation is more prominent at a very low and very high soil pH and generally P is most available for uptake at a pH of between 6 and 7. When the soil pH is low, P reacts with Fe and Al, reducing its availability. Similarly, when the soil pH is high P reacts with Ca to form insoluble calcium phosphate (Brady and Weil, 2008).

iii. Organic matter content

The presence of organic matter in soils reduces P fixation in several ways. This is because fixation sites on clays become occupied by large organic molecules and organic acids (produced by plant roots) which can prevent adsorption of P (Brady and Weil, 2008).

2.6.4.2 Time and placement of phosphorus fertilizer

The chances for P fixation are increased the longer the soil is in contact with the added P. This factor is even more critical in high fixing soils (Fertilizer Industry Federation of Australia, 2000).

Soil P has limited mobility and tends to remain close to the place of placement. Phosphorus leaching is therefore only significant in very sandy soils. Because of limited mobility, phosphorus fertilizer must be placed as close as possible to the root zone (Fertilizer Industry Federation of Australia, 2000; Brady and Weil, 2008).

2.6.4.3 Water and oxygen content of soils

The effect of waterlogging on plant available P in soils is complex. It is well established that waterlogging can increase the soluble P fraction of the soil (Savant and Ellis, 1964; De Mello et al., 1998; Zhang et al., 2003). Although different mechanisms have been suggested, this increase in soluble P is believed to be mainly by dissociation of iron phosphates due to the lowered redox potential in a waterlogged soil (Savant and Ellis, 1964; Zhang et al., 2003), as well as the liberation of sorbed, precipitated and occluded forms of P (Zhang et al., 2003). However, increased availability of P due to waterlogging is often only temporary. During prolonged waterlogging the liberated P is either re-adsorbed or precipitated and therefore not available to plants (Zhang et al., 2003). Even during periods when P availability increases during waterlogging, it does not necessarily mean that plant roots are able to absorb it. In an oxygen poor environment root respiration is impaired, which in turn affects the ability of the roots to absorb nutrients (Fertilizer Industry Federation of Australia, 2000; Board, 2008). Some plants can overcome this by producing aerenchyma tissue in their stems that can transport O_2 to the roots during flooding (Parent et al., 2008). It is known that some sugarcane cultivars are also able to produce aerenchyma tissue that increases their resistance against waterlogging (Glaz and Morris, 2010). Microbial activity (important for mineralization of phosphorus), is also inhibited during waterlogging which also lowers the availability of P to plants (Fertilizer Industry Federation of Australia, 2000; Plaster, 2009).

2.6.4.4 Soil compaction

Phosphorus uptake is limited in compacted soil, since soil compaction reduces root growth and therefore nutrient uptake (Fertilizer Industry Federation of Australia, 2000).

2.6.4.5 Temperature

Low temperature affects P uptake negatively, because it slows down root growth and respiration, microbial activity and P diffusion (Fertilizer Industry Federation of Australia, 2000; Plaster, 2009).

2.6.4.6 Mycorrhizal infection

Infection of plant roots, including sugarcane, with vesicular arbuscular mycorrhizae increases P uptake (Sanders and Tinker, 1973; Kelly et al., 1997). Mycorrhizae hyphae act like an extension of the plant root system enabling the exploration of a larger soil volume for P and other nutrients (Clark and Zeto, 1996).

2.6.5 Measurement of soil phosphorus

There are various methods available to extract P from soils for measurement of plant available P. Because P compounds are sparingly soluble in water it is seldom used as an extractant, since very small amounts of P is extracted in this way. More commonly used extractants include hydrochloric acid and ammonium fluoride (Bray method), sodium bicarbonate (Olsen method), ammonium carbonate, ammonium fluoride and ammonium EDTA (Ambic method) and sulphuric acid (Truog method). Plant available P can also be measured using anion exchange resin. The suitability of a particular method depends on the soil pH and soil type (Buys, 1986). Hendry et al. (1993) evaluated four extraction procedures for P in a range of soils cultivated by the South African and Swaziland sugar industry. They concluded that the Truog method is the most suitable for these soils. Earlier work done by Du Toit (1957) and Du Toit et al. (1962) on the Truog method and the P requirement of sugarcane form the basis of current P fertilizer recommendations by the Fertiliser Advisory Service (FAS) of the South African Sugarcane Research Institute (SASRI). The FAS routinely use the Truog method to test soil samples for P content. Based on the results of the Truog method, P can be applied at rates ranging from 0 to 80 kg/ha P (FAS, 2004). Phosphorus threshold values are 31 mg/kg P for plant cane and 11 mg/kg P for ratoon cane (SASA, 2000).

Although the Truog method is widely used for sugarcane production, it is sometimes not adequate to predict P fertilizer requirements. For example, research conducted by Meyer and Dicks (1979) showed that due to the effect of P sorption and fixation in some soils, applying P simply based on the Truog method is not sufficient for optimum sugarcane growth. They suggested using the phosphorus desorption index (PDI) method (Reeve and Sumner, 1970) as a supplementary method in P fertilizer recommendations. Thus, the FAS incorporates both P extraction and P sorption in their P fertilizer recommendations (FAS, 2004). A PDI of smaller than 0.2 is regarded as a sign of a high P fixing ability in a soil, while a PDI value of between 0.2 and 0.4 is regarded as moderately P fixing. In both strongly and moderately P-fixing soils, the recommended P application rate is adjusted to compensate for P fixation. In soils with a low P fixing ability (PDI values greater than 0.4), the P fertilizer recommendation is based on the Truog extraction only. Bainbridge et al. (1995) evaluated fifty topsoils in the KwaZulu-Natal province for their P fixing abilities. They concluded that high sorbing soils were mostly found in high rainfall areas with acidic soils. Soils with low sorbing abilities were more characteristic of lower rainfall and coastal areas. They also showed that P sorption is dependent on the clay content and clay type, with clayey soils and 1:1 clays having the highest P sorption.

2.7 SUGARCANE

2.7.1 Sugarcane production in South Africa

In South Africa sugarcane is produced in KwaZulu-Natal and in Mpumalanga (Smith, 2006). From 1996 to 2010 the annual sugar production in South Africa varied between 2.1 and 2.7 million tons per annum. The average yield of harvested cane in South Africa varied between 60 t/ha and 75 t/ha over the same period (Tongaat Hulett Sugar, 2011). Smith (2006) indicated that the potential annual cane yield for the North Coast (which includes the study area) is 9 tons per 100 mm of water per hectare. When considering the long-term average annual rainfall of the area of 1323 mm (Snyman, 2001), the potential cane yield for the North Coast area calculates to 119 t/ha/annum.

2.7.2 Sugarcane biology and physiology

Sugarcane (*Saccharum officinarum*) is a perennial member of the grass family (Poaceae) and as a crop provides about 65% of the sugar produced in the world (SASA, 2005).

2.7.2.1 Sugarcane roots

The first roots that develop from buds on the setts (stem cuttings) are called sett roots (Smith et al., 2005). They are fine and highly branched. The sett roots are gradually replaced with shoot roots which form the main root system of the plant. Different kinds of shoot roots are identified which function to anchor the plant and absorb water and nutrients. Some shoot roots can penetrate to a depth of more than

6 m with root activity below a depth of 2 m (Smith et al., 2005). However, about 50% of the root biomass is found in the top 20 cm of soil and 85% in the top 60 cm (Blackburn, 1984, as cited in Smith et al., 2005).

Smith et al. (2005) reported that the size and distribution of the sugarcane root system is very dependent on soil water content. Continuous drier soil conditions lead to a deeper root system, while the presence of a continuous high water table results in a shallow root system. Sugarcane having shallow root systems due to a high water table can benefit from the water source, however they are at risk of water stress if the soil suddenly dries out (Smith et al., 2005 and references therein). After harvesting (ratooning) the root system dies back partially and is partially replaced by new growth (Smith et al., 2005).

2.7.2.2 Sugarcane leaves and inflorescences

The sugarcane leaf consists of a lower leaf sheath, which surrounds the stem and an upper leaf blade. The leaves have an alternate arrangement on the stem and after the 14th leaf is formed all leaves are similar in size. Dead sugarcane leaves are referred to as trash (SASA, 2005).

Sugarcane, like other tropical grasses, is a C4 plant which is characterized by a highly efficient photosynthetic pathway. The photosynthetic efficiency of individual leaves depends on the size and the age of the leaves. Old leaves contribute less to photosynthesis than younger fully expanded leaves and most of the photosynthate stored in the stems comes from the fully expanded leaves (SASA, 2005).

The sugarcane inflorescence morphology is similar to that of other grasses with the inconspicuous flowers carried in a tassel. In South Africa sugarcane only produces seed under controlled conditions in greenhouses (SASA, 2005).

Floral initiation is dependent on day-length and sugarcane typically flowers from June onwards. Lower night temperatures in the absence of water stress can also initiate flowering. During flowering vegetative growth stops and an ageing process starts during which the leaves stop photosynthesizing. Flowering is important in the sense that it induces ripening (accumulation of sucrose in stems). However, the sucrose content will eventually decline as senescence of the stem progresses (SASA, 2005).

2.7.2.3 Sugarcane stems

The primary stem (which develops from the stem cutting or sett) contains buds at its base from which secondary stems develop. This process is called tillering. Each of the tillers themselves can give rise to new tillers. Tillering continues until environmental factors such as space or light become limiting. Each tiller is supported by its own root system (SASA, 2005).

The sugarcane plant contains between 10 and 14% sucrose which is stored in the vacuole of stem cells. The length of the internodes of the stems is generally a function of the growth rate which is in turn affected by climatic and cultural factors. Sugarcane production is aimed at producing stems with long and thick internodes, because then more sucrose can be stored in the stem. Long internodes are produced under conditions of rapid growth as in hot and wet summers (SASA, 2005). Stem elongation is also determined by light intensity and day length (SASA, 2005).

Ripening, during which sucrose accumulates in stems, is initiated when vegetative growth ceases. Ripening can be triggered by environmental factors like lower temperatures, lower humidity and shorter daylength (which normally lead to flowering). Nitrogen starvation, water stress and chemical ripeners can also induce ripening. The sucrose content is usually at its lowest between January and March and at its highest in September to October (SASA, 2005). Sugarcane harvesting is ideally done when the sucrose content of the stems is at their peak.

2.7.3 Sugarcane husbandry

Commercial sugarcane is propagated vegetatively by sections of immature stems, known as setts, seedcane or seed pieces. The setts are allowed to grow into mature cane which is then cut at or below ground level. The remaining root system will produce new growth which is known as ratooning (SASA, 2005). The first crop harvested is called plant cane and the successive crops as first, second etc. ratoons. Usually sugarcane is ratooned five or six times, but can be ratooned as many as ten times before being replaced with new cane (Smith, 2006). Sugarcane is typically planted or ratooned in spring which allows for maximum use of temperature and radiation during summer (SASA, 2005).

2.7.3.1 Climate and soil requirements

Sugarcane is cultivated in tropical and sub-tropical latitudes (SASA, 2005). The rainfall requirement for sugarcane production is 850 – 1500 mm over the growing season (Smith, 2006). In South Africa, rainfall is the main factor that can limit sugarcane yield. When water is not a limiting factor, sugarcane yields are influenced by temperature and radiation (SASA, 2005). Sugarcane can be grown as a dry-land crop or under irrigation (SASA, 2005; Smith, 2006).

The growing season must be long and warm. An optimum mean daily temperature is 22 - 30°C. During ripening, cooler temperatures (10 – 20°C) are required to reduce vegetative growth and increase the sucrose content. Sugarcane is sensitive to frost. Temperatures should not be lower than 5 °C in winter and the mean annual temperature must be above 18°C. Since sugarcane is a C4 plant it has a high solar radiance requirement. The maximum altitude for sugarcane production is 1200 m above sea level (Smith, 2006).

Sugarcane is not very specific in its soil requirements, but soil should be a minimum of 1 m deep and provide good drainage with the water table 1.5 to 2.0 m below the soil surface (Smith, 2006).

2.7.3.2 Planting methods

Setts are usually planted by hand in rows with a spacing that varies between 1 m and 1.4 m (Smith, 2006). The best planting time for sugarcane in coastal lowlands is from early August to the end of October (Smith, 2006). Seed cane is planted at a rate of 8 to 9 t/ha and setts are placed with a 30% overlap in the furrows (Smith, 2006). The planting depth is about 10 cm (Smith, 2006).

2.7.3.3 Fertilizer requirement

The Fertiliser Advisory Service (FAS) of the South African Sugarcane Research Institute make fertilizer recommendations (Table 2.6) to farmers based on a number of soil and climatic factors as well as water supply (rain-fed or irrigated), crop cycle (plant crop or ratoon) and rooting depth (SASA, 2005).

Table 2.6: Typical recommended nitrogen (N), phosphorus (P) and potassium (K) application rates for sugarcane production (SASA, 2005).

Nutrient	**Typical application rate** **------------------kg/ha-----------------**
Nitrogen (N)	60 – 140 (plant cane) 100 – 180 (ratoon cane)
Phosphorus (P) (Truog method)	0 – 60 (plant cane) 20 – 30 (ratoon cane)
Potassium (K)	0 – 200 (plant cane) 0 – 200 (ratoon cane)

2.7.3.4 Sugarcane harvesting

After cutting of the stems at the base, the sugarcane trash (leaves and tops) can be burnt or left on the land (known as trashing). The time from planting or ratooning to harvesting depends on the climate (Smith, 2006), cultivar and a number of other factors, like incidence of disease, drought etc. (SASA, 2005). In hotter climates cane is usually cut every 12 to 14 months and in cooler climates every 22 months (Smith, 2006). The harvested sugarcane stalks are transported by truck to the nearest sugar mill for sugar extraction.

2.8 CONCLUSIONS

The review highlighted some of challenges in restoring the post-mined soil to a level that is suitable for crop production. A lack of soil structure is a potentially serious constraint in crop production and thus the formation and stability of aggregates is a crucial aspect of successful rehabilitation of the reconstituted soil. It is hoped to improve soil structure through flocculation, by using gypsum, and to bind soil particles together by using filtercake. The P content of the post-mined soil is low and since P is an essential nutrient for plant growth, a lack of P supply to plants will result in poor sugarcane yields. However, the interaction of P with soil is complex and simply applying P at recommended rates might not be sufficient to supply adequate P. The rehabilitation of the reconstituted soil could be complicated by the fact that a duplex soil profile is created and by the presence of Mg-related dispersion in the soil.

CHAPTER 3

EFFECT OF GYPSUM APPLICATION ON PROPERTIES OF A RECONSTITUTED SOIL AT HILLENDALE MINE AND RESULTING SUGARCANE GROWTH TREREON

ABSTRACT - *The reconstituted soil of the back-filled land at the Hillendale mine needs to be rehabilitated back to sugarcane production. Thus this study was conducted which examined the effects of gypsum on stabilizing the reconstituted soil for sugarcane production. Gypsum was applied at rates of 0, 3.2, 6.4, 9.6, 12.8 and 16 t/ha to sugarcane growing under rain-fed conditions in the reconstituted soil with a mixture of 70:30 sand:slimes (silt and clay fraction combined). Nitrogen and P were applied according to the soil analysis, while K was applied at a rate that aimed to establish a Mg:K ratio of a 3:1 in the soil. Gypsum released Ca that displaced exchangeable Mg from the soil and improved the Ca:Mg ratio towards the ideal 1.5:1 ratio, but appeared to have little effect on the electrolyte concentration. Sugarcane growth was not significantly influenced by gypsum application. The absence of a significant gypsum application response with regards to sugarcane growth is difficult to explain. It is possible that the effect of gypsum was masked by the complex interaction amongst Ca, K and Mg ions in the soil or by the poor water drainage of the soil. Actual yield compared well with those predicted by the Canesim model for all treatments in the first ratoon crop, but were lower than the simulated yield in the second ratoon crop, likely because of late fertilizer application. Applying gypsum that coincides with fertilizer K will probably be required to improve both cation ratios to their optimum ranges.*

3.1 INTRODUCTION

Soil dispersion is the disruption of soil aggregates emanating from clay particles repelling each other, resulting in a gel-like condition. By contrast, in a flocculated soil, clay particles adhere to each other in clumps, creating pores between them that allow water to pass through. Soil dispersion is generally promoted by the presence of monovalent ions like Na^+, K^+ and NH_4^+, while flocculation is promoted by polyvalent ions like Ca^{2+}, Fe^{3+} and Al^{3+} (Hillel, 1998; Bronick and Lal, 2005), but not Mg^{2+}. Of the three polyvalent cations, Ca^{2+} is well tolerated by plants when supplied in excess. Thus, gypsum ($CaSO_4$), a sparingly soluble source of Ca^{2+}, is often used to improve soil structure in degraded/dispersed soils, by acting as a flocculant (Mengel and Kirkby, 1987; Mullins et al., 1990; Bronick and Lal, 2005). In addition, gypsum also contributes to the electrolyte concentration of the soil solution, which also counteracts soil dispersion (Shainberg et al., 1989). Dispersed/degraded soils treated with gypsum typically show improved water infiltration, aggregate stability, penetration resistance, hydraulic conductivity, as well as a reduction in soil loss and crusting (Shainberg et al., 1982; Radcliffe et al., 1986; Shainberg et al. 1989; Sumner et al., 1990; Miller et al., 1998; Mitchell et al, 2000; Sahin and Anapali, 2005). Not surprisingly, gypsum has often been shown to increase yield in degraded soils under several crops, including sugarcane (Miller et al., 1998; Schuman et al., 1994; Kumar et al., 1999; Choudhary et al., 2004).

Not all polyvalent ions can mitigate soil dispersion. Even though Mg^{2+} is a divalent ion, high Mg^{2+} concentrations in a soil can lead to dispersion (Mullins et al., 1990, Keren, 1991; Tisdall and Oades, 1982). Fortunately this effect of Mg can be countered by gypsum, whose Ca has been shown to displace Mg in Mg-dispersed soils with concomitant improvement in soil physical properties (Mullins et al., 1990; Dontsova and Norton, 1999).

The reconstituted soil at the Hillendale mine, the site of this study, has previously been shown to lack structure, and to show Mg-related dispersion (Van Jaarsveld and Zharare, 2010). Hence, an experiment was conducted in this study to examine the effect of gypsum on the reconstituted soil and its subsequent ability to support sugarcane growth under field conditions.

3.2. MATERIAL AND METHODS

3.2.1 Trial site

The experiment was conducted on a mined-out area on the Hillendale premises that was back-filled with a 70:30 sand-slimes (silt + clay fraction) mixture to a depth of 1.8 m. Cracks present in the soil, both on the surface and below (Figure 3.1) were often observed. Because of these cracks, the soil hydraulic conductivity (using a double ring infiltrometer) could not be measured.

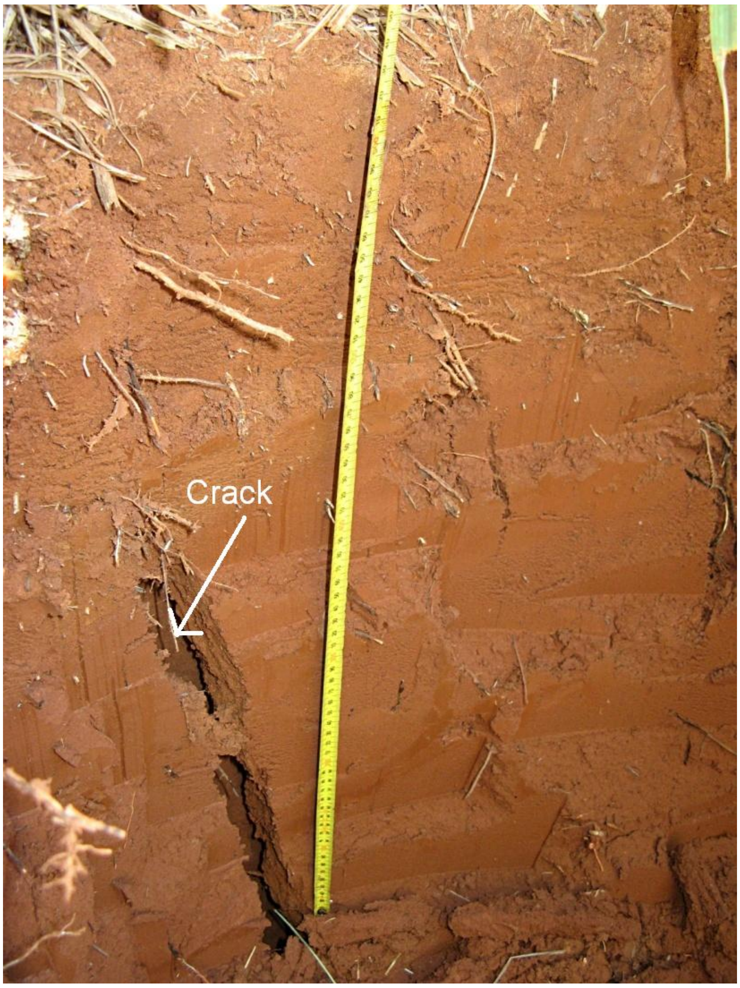

Figure 3.1: A typical profile of the reconstituted soil to a depth of ± 50 cm. Note discontinuous cracks in the soil profile.

3.2.2 Treatments and experimental design

Six gypsum application rates (0, 3.2, 4.6, 9.6, 12.8 and 16 t/ha) were laid out in a complete randomized block design with four replicates in 100 m^2 plots. Sugarcane cultivar N41, which is well suited for production under dry-land cultivation in the area (SASA, 2003), was planted with in an inter-row spacing of 1 m.

The Ca:Mg and Mg:K ratios (Buys, 1986) in the soil were used for basing gypsum and K application rate treatments. Potassium was applied as KCl salt at a rate of 3.9 t/ha in all six treatments. This rate was required to improve the Mg:K ratio of the soil to 3:1. Gypsum was applied by broadcasting over the soil surface and incorporating it into the soil (Figure 3.2) before planting.

Figure 3.2: A photograph showing the site of the experiment shortly after gypsum was incorporated into the soil.

Urea and single superphosphate were applied at rates equivalent to 92 kg/ha N and 68 kg/ha P, respectively, based on the soil analysis and recommendations made by the Fertilizer Advisory Service of the South African Sugarcane Research Institute (FAS) on all plots. Fertilization done in 2009 and in 2010 was based on the FAS recommendation alone.

The sugarcane was planted on 17 February 2009 and grown under rain-fed conditions. Seven months after planting the first sugarcane harvesting was done (14 September 2009). Harvesting was done at in September to coincide with the time of peak sucrose content (SASA, 2005). The first-ratoon crop was harvested on 15 November 2010 (fourteen months after ratooning). Final harvesting for this experiment (second-ratoon crop) was done on 20 June 2011 (7 months after the first ratoon). It was decided to terminate the experiment at this time, because of technical contraints. No trashing was done during the experiment. Rainfall was recorded at the Hillendale premises during the experiment (Table 3.1).

Table 3.1: Monthly rainfall as recorded from the start of the experiment until termination.

Year	Month	Total rainfall (mm)	Year	Month	Total rainfall (mm)
2009	February	33.2	2010	May	64.9
2009	March	31.1	2010	June	18.1
2009	April	27.4	2010	July	44.8
2009	May	26.8	2010	August	30.0
2009	June	22.5	2010	September	30.3
2009	July	17.9	2010	October	85.5
2009	August	139.9	2010	November	100.4
2009	September	33.3	2010	December	94.6
2009	October	98.7	2011	January	208.2
2009	November	138.5	2011	February	72.8
2009	December	62.7	2011	March	118.3
2010	January	103.5	2011	April	136.8
2010	February	85.6	2011	May	42.2
2010	March	159.07	2011	June	55.4
2010	April	70.6			

3.2.3 Data collection

3.2.3.1 Soil physical parameters

3.2.3.1.1 Particle size distribution

In July 2010 three soil samples were taken from each plot to a depth of 20 cm. Samples from each plot were combined to obtain a composite sample per plot. Sampling depth was limited to 20 cm, since the soil was too wet for deeper sampling. Particle size distribution (PSD) of the composite samples was determined by sieve and hydrometer method (Non-affiliated Soil Analysis Work Committee, 1990).

3.2.3.1.2 Soil water content

Soil water content (SWC) was measured weekly using a Sentek Diviner 2000 portable soil moisture probe at 10 cm intervals to a depth of 150 cm from February 2009 and until July 2010. Calculation of soil water content was done using the Sentek default calibration equation for sand, loam and clay loam (Sentek Sensor Technologies, 2001). At each sampling time, one set of readings was taken per plot. The Diviner instrument was stolen from the Hillendale premises in August 2009, and was replaced in the same month. Although the replacement Diviner instrument was calibrated as the first one, data for the two instruments could not be compared.

Based on the readings of the Diviner instrument, the average SWC of the reconstituted soil layer was calculated for three depth zones: 0 to 50 cm, 50 to 100 cm and 100 to 150 cm by dividing the sum of the SWC of the relevant depth zone by 5 (the number of 10 cm intervals). Note that no data is available for the month of August 2009 when the instrument was stolen.

The actual SWC, as measured with the Diviner instrument, was compared to theoretical calculation of field capacity and soil saturation. Field capacity is the SWC where all the free water had drained away under gravity. Saturation is the SWC where all the soil pores are filled with water (Coyne and Thompson, 2006). Calculation of the average field capacity and saturation was done as suggested by Schultze et al. (1985), Van Rensburg (1988), Van Antwerpen et al. (1994) and Meyer and Van Antwerpen (1995). Calculations were based on the average silt-plus-clay content of all plots, as well as a dry bulk density of 1.40 g/cm^3.

3.2.3.1.3 Penetration resistance

The penetration resistance (PR) was measured in June 2009 using a Geotron hand penetrometer Model G94 at 1 cm intervals down to a maximum depth of 80 cm. Three readings were taken in the rows and three readings between rows (inter-row). Soil water content was determined with the Diviner instrument as discussed in section 3.2.3.1.2 on the same day as the measurement of PR. The PR was corrected for the soil moisture content as suggested by Van Antwerpen et al. (2007), and the average PR was calculated for each 10 cm increment down to a depth of 80 cm by dividing the sum of the PR measurements for each 10 cm increment by 10. The PR was measured again in July 2010, but only for two pre-selected treatments (0 and 9.6 t/ha). The 0 t/ha gypsum treatment was selected because it was the control treatment and the 9.6 t/ha gypsum treatment was selected because the sugarcane in this treatment yielded the highest in the plant crop.

3.2.3.1.4 Aggregate stability

Three soil samples were collected in August 2010 from randomly selected locations within each plot from all treatments to a depth of 20 cm. The three samples were combined to create one composite sample per plot. Aggregate stability was determined for three size fractions (2 – 5 mm, 1 - 2 mm and 0.5 – 1 mm) by wet sieving using the method described by Haynes (1993). Because of the sandy texture of the soil, the sieving time was reduced from 30 minutes to 5 minutes. Aggregate stability is expressed as the mean weight diameter (MWD). The MWD is calculated as the sum of the mass fraction of soil remaining on each sieve after sieving, multiplied by the mean aperture of the adjacent mesh (Le Bissonnais, 1996).

3.2.3.2 Soil chemical parameters

3.2.3.2.1 Soil fertility status

In July 2008 (prior to the start of the experiment), soil augering was done on the experimental area at 10 randomly selected locations to a depth of 20 cm. The soil from all ten locations was mixed to obtain a composite sample. In June 2009 and July 2010 a composite soil sample, comprising of three subsamples, was collected for chemical analyses from each plot to depth of 20 cm. The 2009 samples, but not the 2010 samples for each treatment were combined to obtain one sample per treatment. Most of the soil chemical analyses were done using standard methods described by the Non-affiliated Soil Analysis Work Committee (1990): pH (water), organic C (Walkley-Black), extractable P (Truog), and exchangeable K, Ca and Mg (NH_4OAc). Inorganic S was extracted also with NH_4OAc (Bardsley and Lancaster, 1960) while Cu, Fe, Mn and Zn were extracted with EDTA- $(NH_4)_2$ CO_3. (Trierweiler and Lindsay, 1969). The P was determined with colorimetry, and K, Ca, Mg, S, Cu, Fe, Mn and Zn with atomic absorption spectrometry.

3.2.3.2.2 Magnesium-related dispersion

Soil samples were collected in February 2011 (24 months after application) to a depth of 20 cm from each plot from two pre-selected gypsum application treatments (0 t/ha and 16 t/ha). These two treatments were selected because they represented the control (where no gypsum was added) and the highest gypsum application rate, respectively. The four samples were then combined to obtain a composite sample for each of the two pre-selected treatments. The samples were tested for salinity and sodicity following the method of the Non-affiliated Soil Analysis Work Committee (1990) and the magnesium dispersion was interpreted according to Fenton and Conyers (2002).

3.2.3.3 Soil microbiological parameters

In September 2008, prior to the start of the experiment, 10 soil samples were collected randomly to a depth from the experimental area to a depth 10 cm and mixed to obtain one sample. In subsequent years, three samples per plot were taken in September 2009 and in February 2011 to a depth of 10 cm from plots of two selected treatments (0 and 16 t/ha gypsum treatments). These two treatments were selected because they represented extremes. The three samples were mixed to obtain one composite sample per plot. Microbial biomass and basal respiration were estimated for the composite samples using the fumigation-extraction method as described by Vance et al. (1987). Organic C content was determined by a dichromate wet oxidation procedure (Sahrawat, 1982). The microbial quotient was calculated as the ratio of microbial biomass C to soil organic C, and the metabolic quotient as the ratio of basal respiration CO_2-C produced per unit of microbial biomass-C.

3.2.3.4 Sugarcane growth response

3.2.3.4.1 Fractional light interception

A ceptometer (SF-80 model, Decagon Devices, Pullman, WA, USA) was used to measure the fractional interception of photosynthetically active radiation (FI_{PAR}). Ten PAR readings each below and above the green sugarcane canopy were taken weekly at midday on a day with clear skies in each plot. In the plant crop, the readings were taken at 87, 106, 128, 136, 142, 162, 176 and 183 days after planting. In the first ratoon crop, the readings were taken at 122, 142, 175, 210, 220, 261 and 266 days after ratooning. The FI_{PAR} values were calculated as one minus the ratio of below to above canopy PAR readings.

3.2.3.4.2 Foliar nutrient content

The prescribed time for taking foliar samples in the coastal lowland areas is between 4 and 7 months of age (SASA, 2005). Youngest mature leaves (or also called top visible dewlap leaves) were collected in May 2009 (approximately 4 months after planting) from all treatments from sugarcane plants in each plot, but not from plants on the sides of plots. Sampling was done again in June 2010 (approximately 4 months after ratooning) from two selected treatments (0 and 9.6 t/ha) only. In both cases the mid-ribs of the leaves were removed and the leaf blades washed. The leaf blades were then analyzed by the FAS laboratory for their mineral content (P, K, Ca, Mg, S, Si, Zn, Cu, Mn and Fe) using an X-ray fluorescence analysis, and for N using near-infrared spectroscopy.

3.2.3.4.3 Cane, sucrose and aboveground biomass yields

At harvesting (14 September 2009, 15 November 2010 and 20 June 2011), sugarcane was collected from a net plot of 16 m^2 in each treatment plot and weighed to determine the cane yield. The cane yield was calculated by extrapolating the stalk fresh mass of the 16 m^2 samples to t/ha. The tiller number, stalk length and stalk diameter were however determined from 1 m^2 subsamples of the 16 m^2 net plot. The stalks of the 1m^2 subsamples were shredded and analyzed for their sucrose content (Buchanan and Brokensha, 1974; SASTA, 1985) and the sucrose yield was extrapolated to t/ha. Leaves and shredded stalks of the 1 m^2 subsamples were subsequently dried at 80°C for 48 hours and weighed to determine aboveground mass (ABM). The actual cane and sucrose yield obtained was compared with simulated cane and sucrose yield using the Canesim model (Singels and Donaldson, 2000) (Table 3.2).

Table 3.2: A summary of the inputs used in the Canesim model (Singels and Donaldson, 2000) for the gypsum experiment.

Input	Comment
Effective rooting depth	Taken as 1.8 m (depth of reconstituted soil layer).
Clay content	Obtained from soil texture data
Start and end dates	As given in section 3.2.3.1.2
Weather data (rainfall, temperature and humidity)	Obtained from Hillendale and Empangeni weather stations
Water supply	Rainfed
Cultivar	N41
Row spacing	1 m
Growth cycle	Plant/ratoon
Trash layer	None
Drainage constant	Taken as slow (0.05 fraction/day)
Initial soil water content	Obtained from soil water data collected with Diviner instrument. Soil water content was extrapolated to a depth of 1.8 m to correspond with effective rooting depth.

3.2.4 Statistical analysis

All statistical analyses were performed using GenStat12 (VSN International, 2009) software. Where possible, means were separated by LSD (least significant difference) at 5% significance level.

3.3 RESULTS AND DISCUSSION

3.3.1 Soil physical parameters

3.3.1.1 Particle size distribution

The average slimes content varied amongst the treatments from 31.5% in the 3.2 t/ha gypsum treatment to 39.5% in the 9.6 t/ha gypsum treatment, but there were no significant differences amongst treatments in the slimes content (Table 3.3). On average, the slimes content of all the samples was 34.5%, which was slightly higher than the target value of 30%. The clay and silt content also did not differ significantly amongst treatments. It needs to be emphasized that particle size distribution was only determined from soil samples taken to a depth of 20 cm and therefore represented that soil layer only.

Table 3.3: Particle size distribution of soil taken to a depth of 20 cm in the gypsum treatment plots. Values are the average of 4 replicates and the values in brackets show standard error of mean (SEM).

Gypsum application rate	Clay	Silt	Slimes (silt + clay)	Sand
---------t/ha---------	-------------------------------	%	---------------------------	
0	28.25	6.00	34.25	64.50
	(±3.54)	(±0.82)	(±4.11)	(±3.57)
3.2	25.00	6.50	31.50	66.00
	(±2.00)	(±0.50)	(±1.50)	(±0.00)
6.4	27.50	7.25	34.75	63.25
	(±3.38)	(±0.48)	(±3.71)	(±2.81)
9.6	32.50	7.00	39.50	60.50
	(±2.60)	(±0.58)	(±3.01)	(±3.01)
12.8	26.50	6.75	33.25	64.25
	(±3.52)	(±0.48)	(±3.97)	(±2.84)
16	28.25	5.50	33.75	66.00
	(±1.70)	(±0.65)	(±2.14)	(±2.12)
Average	*28.00*	*6.50*	*34.50*	*64.08*
$LSD_{0.05}$	ns[1]	ns[1]	ns[1]	ns[1]

[1] ns = Not significant

3.3.1.2 Soil water content

3.3.1.2.1 February 2009 to July 2009

For the measurements done from February 2009 to July 2009 (with the first Diviner instrument), there were significant interactions ($p<0.05$) between measuring time, and soil depth (Figure 3.3), and between soil depth and gypsum application rate (Figure 3.4). Over this period, the SWC was consistently highest in the deepest soil zone (100 – 150 cm depth zone) and decreased significantly with decreasing soil depth (Figure 3.3) over the entire period. At all three soil depths, the SWC decreased significantly with time. From the inception of the experiment the greatest decrease occurred in the 50 – 100 cm soil depth zone. In the 0 - 50 cm and 50 - 100 cm depth zones, the decrease in SWC with time were somewhat linear. In the 100 - 150 depth zone which had the most stable SWC, the decrease was curvilinear, being slow at first between February 2009 and May 2009, and steepening after May 2009. The average SWC in this interaction ranged from 39.1% in the 100 – 150 cm depth zone in February 2009 to 6.9% in the 0 – 50 cm depth zone in July 2009.

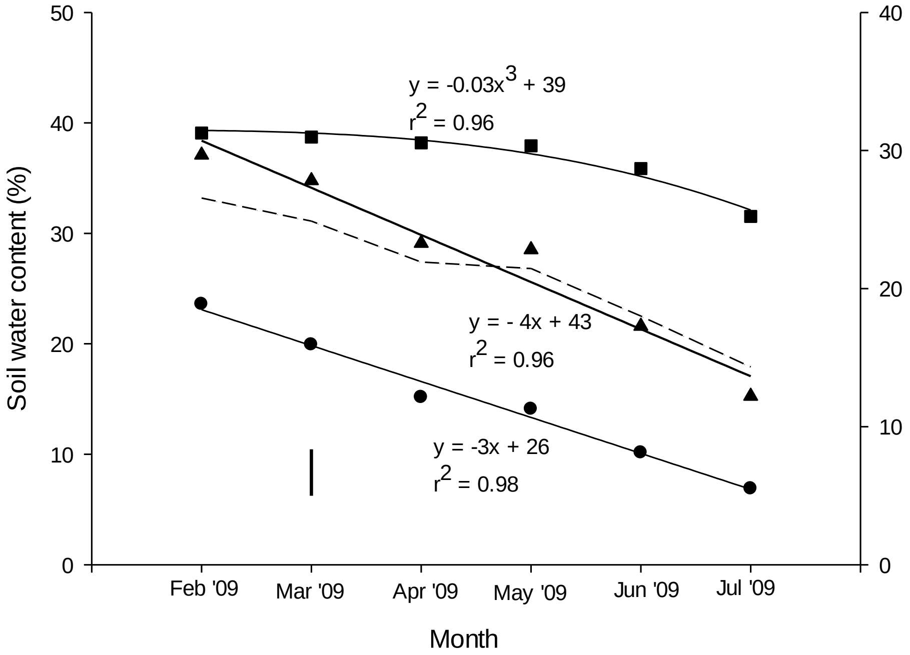

Figure 3.3: Change in soil water content (SWC) for the 0 – 50 cm depth zone (-●-), 50 – 100 cm depth zone (-▲-) and 100 - 150 cm depth zone (-■-) during the period of February 2009 to July 2009 as an average of gypsum application rate. The dotted line shows the average monthly rainfall and the vertical bar represents $LSD_{0.05}$ for the interaction.

Although the rainfall corresponded well with the SWC (Figure 3.3), the total monthly rainfall did not correlate significantly ($r^2 = 0.70$) with the average monthly soil water content during the period of February 2009 to July 2009. It needs to be considered though that the data set was small. The fact that the rainfall corresponded well with the SWC shows that during this period most of the rainwater was able to infiltrate into the soil.

If it is assumed that the slimes content and bulk density remained uniform down the soil profile, a theoretical calculation of field capacity and saturation gave values of 26% and 34%, respectively (Schultze et al., 1985; Van Rensburg, 1988, Van Antwerpen et al., 1994; Meyer and Van Antwerpen, 1995). In the 50 – 100 and 100 - 150 cm depth zones, the SWC was above field capacity (26%) and saturation (34%) for at least a part of the period over which the SWC was measured. Since water cannot be held above saturation this could indicate that the slimes content was higher in these depth zones than in the top 20 cm of soil. Water held above the field capacity of a soil is a sign of poor drainage, since all free water should be drained away under gravity when there is no drainage limitation. This was visually confirmed by the wetness of the soil observed in a profile pit. A drainage limitation was also reported in the reconstituted soil used in a previous study at Hillendale (Van

Jaarsveld and Zharare, 2010). In addition, the fact that water was held above field capacity could also show that the slimes content was higher in these depth zones than in the top 20 cm of soil.

Gypsum application did not influence the SWC down the soil profile, but there were significant variation in SWC among the gypsum treatments within each of the depth zones (Figure 3.4). However, the influence of gypsum on the SWC was variable. For the 0 – 50 cm depth zone, the 6.4 t/ha gypsum treatment had the highest SWC (18.3%). In the 50 – 100 cm depth zone the highest SWC (30.9%) was obtained from the 16 t/ha gypsum treatment which was significantly higher than the SWC in the 9.6 t/ha gypsum treatment (24.4%). The reason for this difference is not known. None of the differences amongst the gypsum treatments were significant in the 100 – 150 cm depth zone, but the 16 t/ha gypsum treatment had the highest SWC (38.9%).

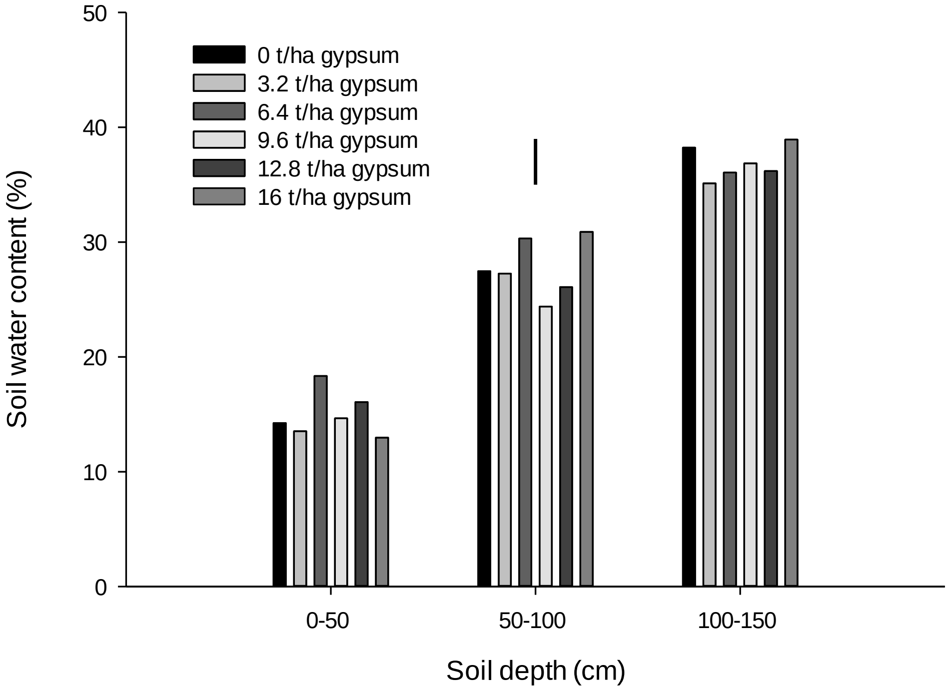

Figure 3.4: Effect of gypsum application on soil water content (SWC) as an average for the period from February 2009 to July 2009. The vertical bar represents $LSD_{0.05}$.

3.3.1.2.2 September 2009 to July 2010

For the SWC measurements taken from September 2009 to July 2010, significant interactions ($p<0.05$) were observed between gypsum application rate and the soil depth (Figure 3.5) and also between the measuring time and soil depth (Figure 3.6). Similar to the measurements done between February 2009 and July 2009, there was a significant increase in SWC with an increase in soil depth (Figure 3.5). The SWC varied from 6.0% in the 0 – 50 cm depth zone to 28.6% in the 100 – 150 cm depth zone. The 0 and 16 t/ha gypsum treatments had higher SWC in both the 50 – 100 and 100 – 150 cm depth zones as compared to the other gypsum treatments (with most of the differences significant, $p<0.05$). The fact that the 0 t/ha gypsum treatment had a higher SWC than most of the treatments where gypsum was added could be an indication that gypsum application lowered the SWC. The reason for the relatively high SWC in the 16 t/ha gypsum treatment could not be determined. In both the 50 – 100 and 100 – 150 cm depth zones, the SWC was lowest in the 3.2 t/ha gypsum treatment.

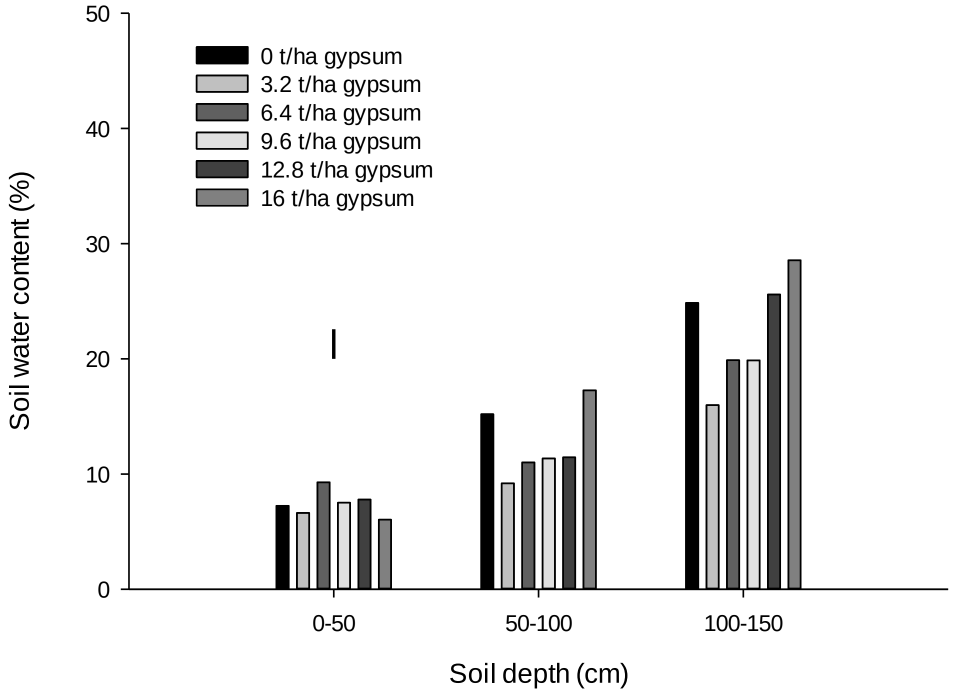

Figure 3.5: Effect of gypsum application on soil water content (SWC) as an average of the measuring period from September 2009 to July 2010. The vertical bar represents $LSD_{0.05}$ for the interaction.

Similarly to measurements taken in the period from February 2009 to July 2009, the SWC was consistently highest in 100 - 150 cm depth zone and lowest in the 0 - 50 cm depth zone

(Figure 3.6). In all three depth zones, a significant increase in SWC was observed from September 2009 to December 2009. The increase was greatest in the 100 - 150 cm depth zone. This increase coincided with high rainfall during this period (Table 3.2), but was possibly partially attributed to a slight increase in electrolyte concentration since fertilizer was applied during this period. However, with an even higher rainfall recorded in March 2010, there was a downward trend in the SWC from December 2009 to August 2010. The highest SWC (37.2%) was measured during November 2009 in the 100 – 150 cm depth zone and the lowest SWC (3.6%) was measured during September 2009 in the 0 – 50 cm depth zone. The monthly average SWC did not correlate significantly ($r^2 = 0.45$) with total monthly rainfall. During this measuring period, the SWC in the 100 – 150 cm depth zone exceeded the calculated field capacity and saturation of the soil. An explanation for this phenomenon was given in section 3.3.1.2.1.

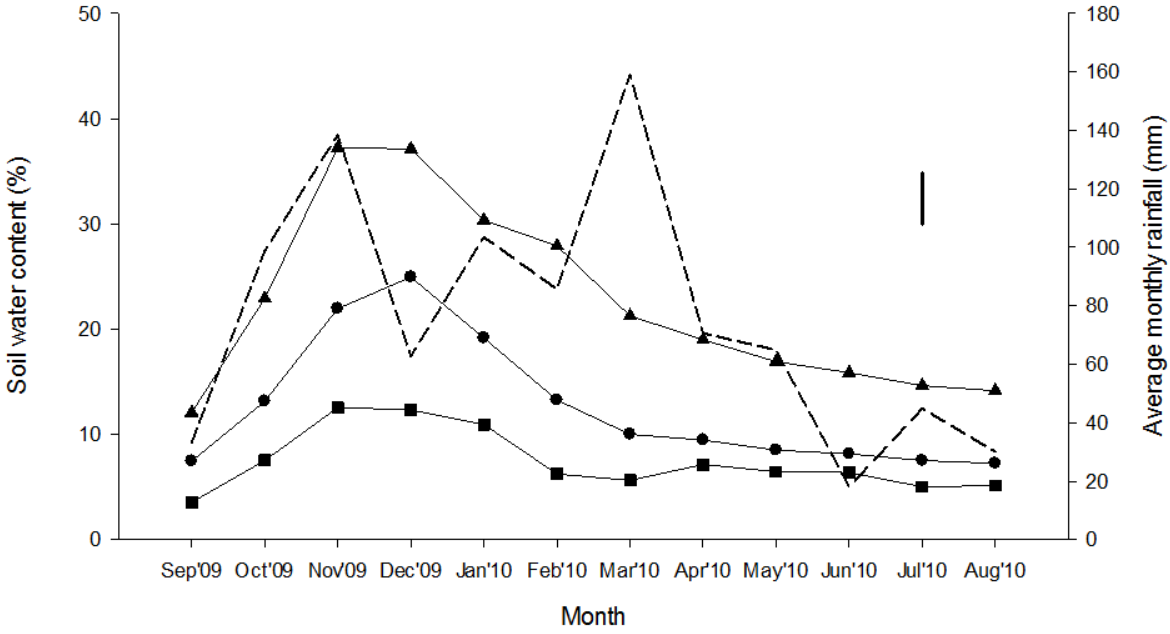

Figure 3.6: Change in soil water content (SWC) for the 0 – 50 cm depth zone (-■-), 50 – 100 cm depth zone (-●-) and 100 - 150 cm depth zone (-▲-) during the period of September 2009 to August 2010 as an average of gypsum application rate. The dotted line shows the average monthly rainfall and the vertical bar represents $LSD_{0.05}$ for the interaction.

3.3.1.3 Penetration resistance

3.3.1.3.1 In and between rows

Four months after planting of sugarcane the penetration resistance (PR) was significantly ($p<0.05$) higher (201.3 kPa) in the rows than between the rows (122.4 kPa). It is possible that some compaction resulted in the rows following the disturbance of the soil with planting in June 2009. The soil between the rows was not disturbed at planting.

3.3.1.3.2 Change with soil depth

In June 2009 the PR changed significantly ($p<0.05$) with soil depth (Figure 3.7). The PR was lowest at 10 cm soil depth (59.3 kPa). From 10 to 20 cm soil depth the PR increased approximately four-fold to a value of 213.3 kPa and then progressively and significantly declined as the soil depth increased from 20 to 50 cm. Before planting the soil was turned by hand to incorporate the gypsum and this disturbance of the soil could have caused compaction and hence explain the higher PR in the 20 cm depth four months after planting. At soil depth greater than 50 cm, the PR gradually increased with increasing soil depth to 285.0 kPa at 80 cm soil depth which was approximately six-fold higher than at 10 cm soil depth. The PR has been shown to increase over depth in many studies which was not related to changes in soil texture or bulk density (for example Radcliffe et al., 1986; Van Antwerpen and Meyer, 1997; Vanags et al., 2006). However, neither the particle size distribution nor the bulk density was determined at these depths in the reconstituted soil.

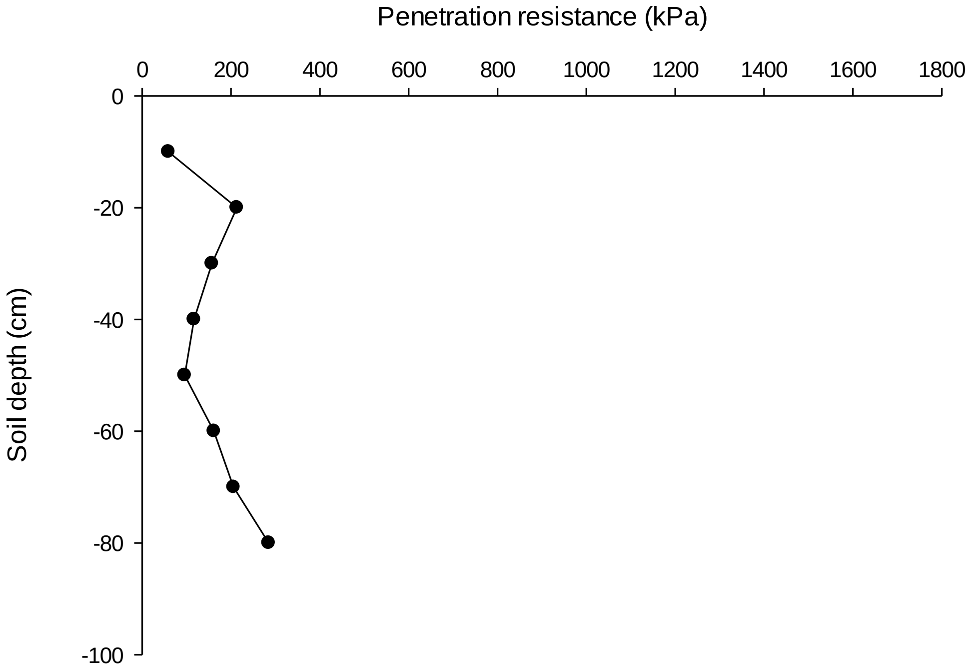

Figure 3.7: Change in penetration resistance with soil depth four months after planting. The horizontal bar represents $LSD_{0.05}$.

3.3.1.3.3 Effect of gypsum application

The application of gypsum at different rates had a significant ($p<0.05$) effect on PR in June 2009 (Table 3.4) as calculated as an average of soil depth. Five months after planting, the 12.8 t/ha gypsum treatment had the highest PR (169.0 kPa) among the treatments, whilst the values were markedly lower for the 3.2 t/ha, 9.6 t/ha and 16 t/ha gypsum treatments. The PR was also relatively high in the 0 t/ha gypsum treatment (150.4 kPa). Gypsum has been shown to lower PR (Radcliffe et al., 1986), while K is known to cause dispersion when present in large quantities (Auerswald et al, 1996; Chen et al, 1983). Van Antwerpen and Meyer (1997) attributed the increase in soil strength in their study to an increase in soil K content. In the present study, where K was applied in the absence of gypsum (0 t/ha gypsum treatment), the PR was higher (150.4 kPa) than most of the treatments (although not significantly). The effects of bulk density, particle size distribution and dispersion/flocculation on PR were difficult to separate in this experiment. It is possible that the measured values were the result of both physical (bulk density and particle size distribution) and chemical (dispersion/flocculation) effects. Spatial variation in bulk density/particle size distribution could have been induced unintentionally as the experimental area was filled up with reconstituted soil that varied in either of the two physical parameters. It is unfortunate that there is no data on the variation of bulk density and soil Ca, Mg and K content over depth which may have been more helpful in explaining the measured PR. The slimes content did not correlate significantly with PR to a depth of 20 cm.

In July 2010, the PR for the two pre-selected treatments did not differ significantly (Table 3.4). However, 17 months after planting the PR was higher (338.7 kPa) in the 0 t/ha gypsum treatment than in the 9.6 t/ha gypsum treatment (274.0 kPa). Gypsum in known to lower PR (Sumner et al., 1990) and could offer an explanation for the lower PR observed in the 9.6 t/ha gypsum treatment.

Table 3.4: Effect of gypsum application rate on penetration resistance 5 months (June 2009) and 17 months (July 2010) after planting as an average of soil depth. Values are the average of 64 replicates and averages with different letters within a column differ significantly ($p<0.05$).

Gypsum application rate (t/ha)	Penetration resistance (kPa)	
	2009	**2010**
0	150.38^{ab}	338.72
3.2	93.21^{b}	-
6.4	114.33^{ab}	-
9.6	88.56^{b}	274.03
12.8	168.95^{a}	-
16	94.62^{b}	-
Average	*119.47*	*306.38*
$LSD_{0.05}$	62.58	ns[1]

[1] ns: Not significant

3.3.1.3.4 Change with time

The PR for the 0 and 9.6 t/ha gypsum treatments, significantly ($p<0.05$) increased from an average of 119.5 kPa in June 2009 to an average of 306.4 kPa in July 2010. Compaction was unlikely (except at planting) and the increase in PR might therefore indicate hardsetting which is characterized by a spontaneous increase in bulk density. However, all PR values in this study were well below the critical value of 2800 kPa for sugarcane (Swinford and Boevey, 1984), which indicates there was little possibility of root growth being negatively affected by soil hardness.

3.3.1.4 Aggregate stability

The aggregate stability, expressed by the mean weight diameter (MWD), was not significantly affected by gypsum application, although it was highest (0.13 mm) in the 9.6 t/ha gypsum treatment (Table 3.5). Soil from the 3.2 t/ha gypsum treatment had a MWD of only 0.03 mm. The MWD values of below 0.4 mm are indicative of very unstable aggregates (Le Bissonnais, 1996). Since all MWD values in this experiment were well below 0.4 mm, it was concluded that the reconstituted soil was highly unstable and sensitive to erosion at the time of taking the samples.

It should also be noted that a study by De-Campos et al. (2009) indicated that aggregate stability was affected negatively by waterlogging. Although the soil dried out significantly over time, it is possible that the initial high water content of the soil negatively influenced aggregate stability. There is also a possibility that the aggregate stability would have improved over time. Aging was recognized by Amézketa (1999) as a factor that influences aggregate stability. In a previous study (Van Jaarsveld and Zharare, 2010), the MWD was significantly higher (0.24 mm) where gypsum was applied to a reconstituted soil at a rate of 5 t/ha than where gypsum application was omitted (0.15 mm) after a period of 37 months under sugarcane. The MWD in the present study correlated significantly with clay content (r^2=0.68, p<0.01), but not with soil Ca content, Mg content or organic matter content or any other soil parameter measured.

Table 3.5: Effect of gypsum application on mean weight diameter of soil aggregates taken to a soil depth of 20 cm at 18 months (August 2010) after planting. Values are the average of 4 replicates and values in brackets show standard error of mean (SEM).

Gypsum application rate ------------t/ha----------	Mean weight diameter -------------mm-------------
0	0.07 (±0.02)
3.2	0.03 (±0.002)
6.4	0.06 (±0.02)
9.6	0.13 (±0.03)
12.8	0.07 (±0.03)
16	0.08 (±0.01)
Average	*0.07*
$LSD_{0.05}$	ns[1]

[1] ns = Not significant

3.3.2 Soil chemical parameters

3.3.2.1 Soil fertility status

3.3.2.1.1 Change over time

According to the analyses of the soil samples collected from 2008 to 2010, the soil P which ranged from 3.4 to 6.6 mg/kg appeared to be low in the reconstituted soil (Table 3.6) when compared to the threshold value of 31 mg/kg for plant cane and 11 mg/kg for ratoons (FAS, 2004). All other soil nutrients were above their respective threshold values (where available). The soil pH, which varied from 6.5 to 6.8, was within the optimum range (5.3 to 8.0) for sugarcane production (FAS, 2004). The results also indicate that it is unlikely that gypsum would have had a nutritional effect, since the reconstituted soil was not deficient in Ca or S in 2008. As expected, the soil Ca, P and K increased from 2008 to 2010 due to application of fertilizers containing these elements. It is interesting to note that in spite of the exceptionally high application rate of K (3.9 t/ha KCl), the soil K did not increase drastically. The decrease in Mg from 678 mg/kg in 2008 to 534 mg/kg in 2010 is likely to be a result of displacement by Ca (Shainberg et al., 1989) and K. The Ca:Mg ratio increased over time and was on average within the ideal range (Buys, 1986) in 2010. It is interesting that although K was applied at a rate that theoretically would have been sufficient to correct the Mg:K ratio to the optimum range, the ratio was not corrected, but nonetheless improved over time. A very small increase (0.02%) in organic matter content was observed.

Table 3.6: Summary of changes in soil chemical parameters over time for all treatments in the reconstituted soil.

Soil chemical parameter	Threshold value /optimum range	July 2008 (composite sample)	June 2009	July 2010
pH (H_2O)	5.3 – 8.0[1]	6.80	6.48	6.61
Organic matter (%)	-	0.20	-	0.22
P (mg/kg)	31[2](plant cane) 11[2] (ratoons)	5.20	3.35	6.60
K (mg/kg)	112[2]	77.30	138.73	166.37
Ca (mg/kg)	200[2]	524.50	999.00	1198.81
Mg (mg/kg)	25[2]	678.00	698.33	534.27
Ca:Mg ratio[3]	1.5 – 4.5[4]	0.47	0.88	1.82
Mg:K ratio[3]	3 – 4[4]	29.26	17.26	12.78
S (mg/kg)	15	29.20	-	-
Mn (mg/kg)	-	3.20	-	1.99
Fe (mg/kg)	-	2.50	-	2.54
Cu (mg/kg)	-	0.70	-	-
Number of samples (N)[5]		1	6	24

[1]After SASA (2005); [2]After FAS (2004); [3]Calculated from the cmol(+)/kg soil concentrations; [4]After Buys (1986); [5]Note the unequal data sets between years

3.3.2.1.2 Effect of gypsum application

Of the soil parameters measured in the 2010 samples that were taken to 20 cm depth, only soil Ca, Mg and Fe varied significantly among the gypsum application rates (Table 3.7). All the other soil parameters measured was not significantly affected by gypsum application at 17 months after planting. Soil organic matter varied from 0.1 to 0.6%. The relatively large SOM content in the 0 t/ha treatment is likely the result of a sampling error. Generally, the Ca content of the soil increased as the gypsum application rate increased. Only the soil Ca content in the 9.6 t/ha gypsum treatment (1082 mg/kg) was slightly lower (but not significant) than that in the 6.4 t/ha gypsum treatment (1200 mg/kg). The Ca content showed an inverse relationship with the Mg content of the soil ($r^2 = -0.63$, $p<0.01$). It is known that soil Ca has an antagonistic effect on the soil Mg (Shainberg et al., 1989; Farina et al., 2000b). The soil Mg content, however, remained high, even at the highest gypsum application rate. The Ca:Mg ratio was the lowest where gypsum was not applied and generally increased with increasing gypsum application to a ratio of 5.4 for the highest rate (16 t/ha). However, the increase was not always significant with each increment in gypsum application, and in the case of the gypsum rate increment from 6.4 t/ha to 9.6 t/ha there was a small and non-significant decrease in the Ca:Mg ratio from 1.3 to 1.2.

Buys (1986) indicated that the ideal soil Ca:Mg ratio is between 1.5 and 4.5 for crop production, whereas Fenton and Conyers (2002) indicated that a Ca:Mg ratio below 1.0 satisfies the criteria for Mg dispersion. Theoretically, an application of about 14 t/ha gypsum in the present study should have increased the Ca:Mg ratio in the reconstituted soil to 1.5.

The results from the soil analysis, however, indicated that a Ca:Mg ratio of 1.5 was reached at a lower gypsum application rate of 12.8 t/ha. It is possible that the Ca:Mg ratio was also influenced by the application of single superphosphate, which also contains Ca (Buys, 1986). An application rate of 16 t/ha increased the Ca:Mg ratio to a value of 5.4, which was higher than the upper limit of the optimum range (4.5). The effectiveness of gypsum to improve the Ca:Mg ratio in the reconstituted soil is encouraging. The displacement of Mg by Ca did not appear to affect the Mg:K ratio (as is evident from Table 3.7). Applying gypsum together with K will probably be required to improve both cation ratios to their optimum ranges. It is noted that there was not a single treatment in this experiment where both the Ca:Mg and Mg:K ratios were corrected to their respective ideal ranges.

The soil Fe content was lowest in the 3.2 t/ha gypsum treatment (2.0 mg/kg) and highest in the 12.8 t/ha and 16 t/ha gypsum treatments (3.0 mg/kg). Soil Ca content correlated significantly with soil Fe content ($r^2 = 0.51$, $p < 0.05$) and Ca therefore appears to have displaced Fe. It is known that Ca and Fe have an antagonistic relationship (Mengel and Kirkby, 1987). The exchangeable Mn correlated well with soil pH ($r^2 = -0.68$, $p < 0.01$) showing that Mn availability was determined by pH.

Table 3.7: Effect of gypsum application on chemical parameters 17 months (July 2010) after planting. Soil samples were taken to a soil depth of 20 cm. Values are the average of 4 replicates and averages with different letters within a column differ significantly ($p<0.05$).

Gypsum application	**pH (H_2O)**	**Organic matter**	**P**	**K**	**Ca**	**Mg**	**Ca:Mg**[3]	**Mg:K**[3]	**Fe**	**Mn**
-----t/ha-----		**-----%-----**	**-------------------------mg/kg----------------------------**						**-------mg/kg--------**	
0	6.85	0.60	6.85	211.85	639.38^{a}	702.50^{ac}	0.56^{a}	13.85	2.50	2.23
3.2	6.65	0.12	7.08	120.65	786.03^{a}	612.50^{acd}	0.79^{a}	16.46	2.00^{a}	1.65
6.4	6.68	0.15	6.53	162.43	1199.98^{ab}	567.50^{acd}	1.28^{a}	13.91	2.50	1.93
9.6	6.45	0.10	6.83	226.48	1081.93^{a}	535.00^{ad}	1.23^{a}	9.47	2.25^{a}	2.25
12.8	6.30	0.17	5.73	123.65	1264.80^{ab}	490.00^{ad}	1.62^{a}	15.69	3.00^{b}	2.08
16	6.75	0.15	6.58	153.15	2220.78^{b}	298.10^{bd}	5.44^{b}	7.32	3.00^{b}	1.80
Average	*6.61*	*0.22*	*6.60*	*166.37*	*1198.81*	*534.27*	*1.82*	*12.78*	*2.54*	*1.99*
Threshold value/ optimum range	5.3 – 8.0[1]		11[2]	112[2]	200[2]	25[2]	1.5 – 4.5[4]	3 – 4[4]		
LSD$_{0.05}$	ns[5]	ns[5]	ns[5]	ns[5]	778.1	122.10	2.33	ns[5]	0.58	ns[5]

[1] After SASA (2000); [2] After FAS (2004); [3] Calculated from cmol(+)/kg soil concentrations; [4] After Buys (1986); [5] ns = Not significant

3.3.2.2 Magnesium-related dispersion

The salinity and sodicity tests done on soil samples collected in February 2011 (24 months after planting) from the 0 and 16 t/ha gypsum treatments showed Mg-related dispersion was present where gypsum was not applied (Table 3.8). The 0 t/ha gypsum treatment satisfied enough of the criteria that this soil qualifies for Mg-related dispersion. For example, the soil in the 0 t/ha gypsum treatment had a high exchangeable Mg percentage (EMP = 51.85%), a low electrical conductivity (EC = 0.13 dS/m), a low exchangeable sodium percentage (ESP = 2.82%) and a low Ca:Mg ratio (0.79). Addition of gypsum at a rate of 16 t/ha was able to overcome magnesium dispersion, specifically by increasing the Ca:Mg ratio to 1.32. This Ca:Mg ratio was however considerably lower than the value of 5.44 (Table 3.7) obtained from routine soil analyses. Since a composite sample was analyzed for each treatment in the Mg dispersion test, it might not have been as representative as the four replicate samples that were collected and analyzed separately for soil fertility status (as discussed in section 3.3.2.1.2). Nonetheless, in both cases, Mg dispersion was present in the 0 t/ha gypsum treatment and absent in the 16 t/ha gypsum treatment. The EC (as an indication of electrolyte concentration) increased from 0.13 dS/m in the 0 t/ha gypsum treatment to 0.36 dS/m in the 16 t/ha gypsum treatment, but the range was still below the required value of 1.28 dS/m to prevent dispersion (Table 3.8). Therefore dispersion caused by a low electrolyte concentration remained a possibility in the reconstituted soil.

Table 3.8 Criteria used for establishing the magnesium-related dispersion potential of a reconstituted soil 24 months after planting of soil samples taken to a depth of 20 cm. For Mg dispersion to be present criteria 1, 2, 3, 4 and/or 5 must be met.

Criteria	Critical value for Mg dispersion[1]	Gypsum treatment	
		0 t/ha	16 t/ha
1. EMP[2] (%)	>30	51.85	40.50
2. EC (dS/m)	<1.28	0.13	0.36
3. Ca:Mg ratio	<1	0.79	1.32
4. ESP (%)	<4	2.82	4.69
5. ESP + 0.1EMP[2] (%)	>6	8.01	8.74
Dispersed		Yes	No

[1]After Fenton and Conyers (2002) and all except EC (saturated paste) are based on cmol(+)/kg soil concentrations; [2]EMP = Exchangeable magnesium percentage

The cation exchange capacity (CEC) values were 9.2 cmol(+)/kg in the 0 t/ha gypsum treatment and 8.74 cmol(+)/kg in the 16 t/ha gypsum treatment. These values are typical for soils dominated by the clay mineral kaolinite (Van der Watt and Van Rooyen, 1990). This corroborated with the results of clay analysis done by Golder Associates (2004), which also showed that the Hillendale soils are dominated by kaolinite. Kaolinite is a non-swelling clay and is therefore not associated with cracks in soils (Rowell, 1994). However, deep cracks were observed in the reconstituted soil (Figure 3.8) and are believed to be a result of soil dispersion (Abrol et al., 1988).

Figure 3.8: Photographs showing deep cracks in the reconstituted soil.

3.3.3 Soil microbiological parameters

It is assumed that when micro-organisms are stressed that they produce more CO_2-C per unit microbial biomass per unit time and therefore the microbial quotient increases (Anderson and Domsch, 1993). A metabolic quotient of greater than 10 μgC/g soil and a microbial quotient of smaller than 0.2 shows that soil microorganisms were under stress from a lack of N (Van Antwerpen et al., 2009).

In the composite sample collected prior to the start of the experiment, the metabolic quotient was 5.64 μgCO_2-C/g/day (showing no N stress), but the microbial quotient was 0.04 (showing N stress) (Table 3.9). Thus, there is a contradiction in the data. Most metabolic and microbial quotient values recorded in 2009 and 2011 (7 and 24 months after planting, respectively) indicate N stress in both the 0 and 16 kg/ha gypsum treatments. Carter (1986) conducted a study on the effect of gypsum and lime on microbial biomass in a sodic soil. The results indicated that gypsum application had a direct and negative effect on microbial activity. In a study on the effect of gypsum and organic material on saline and sodic soils, Wong et al. (2009), showed that gypsum application decreased microbial respiration. In the present study, the 0 t/ha and 16 t/ha gypsum treatments did not differ significantly in metabolic and microbial quotients, but the 16 t/ha gypsum treatment had a higher metabolic quotient (indication of stress) than the 0 t/ha gypsum treatment in both 2009 and 2011. There was no significant change in the metabolic and microbial quotients from 2009 to 2011.

Table 3.9: Metabolic and microbial quotients of a composite soil sample taken to a depth of 10 cm before the start of the experiment (September 2008), and for the 0 and 16 t/ha gypsum treatments 12 months after planting (September 2009) and 24 months after planting (February 2011). Values in brackets show standard error of mean (SEM).

Sample identification	September 2008	September 2009	February 2011
	Metabolic quotient **------------------------------------μgCO_2-C/g/day-----------------------------------**		
Composite sample	5.64	-	-
0 t/ha gypsum	-	8.70 (±3.74)	10.76 (±2.99)
16 t/ha gypsum	-	19.47 (±9.72)	16.02 (±3.29)
Average		*14.09*	*13.39*
N	1	4	4
p<0.05		ns[1]	ns[1]
	Microbial quotient		
Composite sample	0.04	-	-
0 t/ha gypsum	-	0.04 (±0.01)	0.04 (±0.01)
16 t/ha gypsum	-	0.05 (±0.01)	0.04 (±0.02)
Average		*0.04*	*0.04*
N	1	4	4
p<0.05		ns[1]	ns[1]

[1] ns = Not significant

3.3.4 Sugarcane growth response

3.3.4.1 Fractional light interception

3.3.4.1.1 Effect of gypsum application

The sugarcane in the 9.6 t/ha treatment showed an average fractional interception of photosynthetically active radiation (FI_{PAR}) of 0.85, which was significantly higher than all the other treatments during the measuring period (Table 3.10). Sugarcane growth was therefore more vigorous in the 9.6 t/ha gypsum treatment as compared to the other treatments in the planted crop. In the first ratoon crop, none of the FI_{PAR} differences amongst the treatments were significant.

Table 3.10: Effect of gypsum application on the fractional interception of photosynthetically active radiation (F_{IPAR}) for the plant (2009) and first ratoon crops (2010). Averages with different letters within a column differ significantly (p<0.05).

Gypsum application (t/ha)	FI_{PAR} Plant crop (2009)	FI_{PAR} First ratoon (2010)
0	0.80^a	0.92
3.2	0.80^a	0.91
6.4	0.79^a	0.92
9.6	0.85^b	0.91
12.9	0.81^a	0.92
16	0.80^a	0.92
Average	*0.81*	*0.92*
N	28	28
$LSD_{0.05}$	0.04	ns[1]

[1] ns = Not significant

3.3.4.1.2 Over time for plant and first ratoon crops

In the plant crop FI_{PAR} increased significantly from 0.75 at 87 days after planting to 0.80 at 128 days after planting (Figure 3.9). This was followed by a significant decrease in FI_{PAR} to176 days after planting. Finally, FI_{PAR} decreased again from 0.82 to 0.78. The decrease in FI_{PAR} in the plant crop after 128 days after planting and again after 176 days after planting showed that the plants were stressed. Canopy development is influenced by cultivar, planting or ratooning date, row spacing, planting density and the environment (Smit et al., 2004; Singels et al., 2005). Of the environmental factors temperature and stress (like drought and nutrient deficiencies) are important in affecting FI_{PAR} (Singels et al., 2005). During stress plants can shed or roll their leaves resulting in lower light interception by the canopy. When comparing the FI_{PAR} data for the plant crop with the actual SWC for the same period, it does not show a clear relationship (Figure 3.10). In addition, the Canesim model does not predict any stress during this period and it is thus not possible to determine the cause of the decrease in FI_{PAR} after either 128 days or 162 days after planting.

In the ratoon crop, the FI_{PAR} increased gradually during the measuring period up to a final value of 0.97 (Figure 3.9). There was no indication for the FI_{PAR} data of the ratoon crop that the plants were stressed.

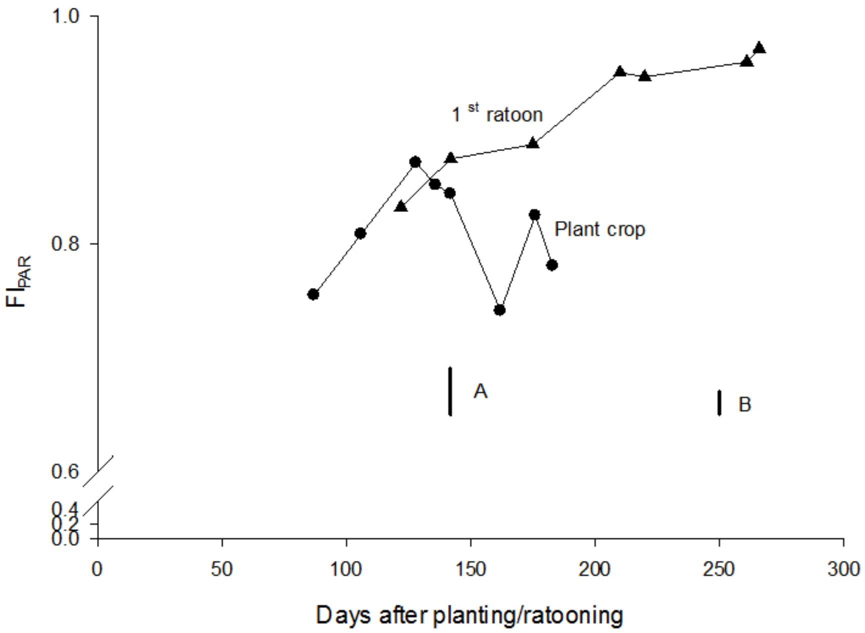

Figure 3.9: Change in fractional interception for photosynthetically active radiation (FI_{PAR}) over time of the plant crop (2009) (-●-) and first ratoon crop (2010) (-▲-). The short measuring time in the plant crop was due to harvesting at 209 days after planting. Vertical bars show $LSD_{0.05}$ (A = plant crop and B = first ratoon crop).

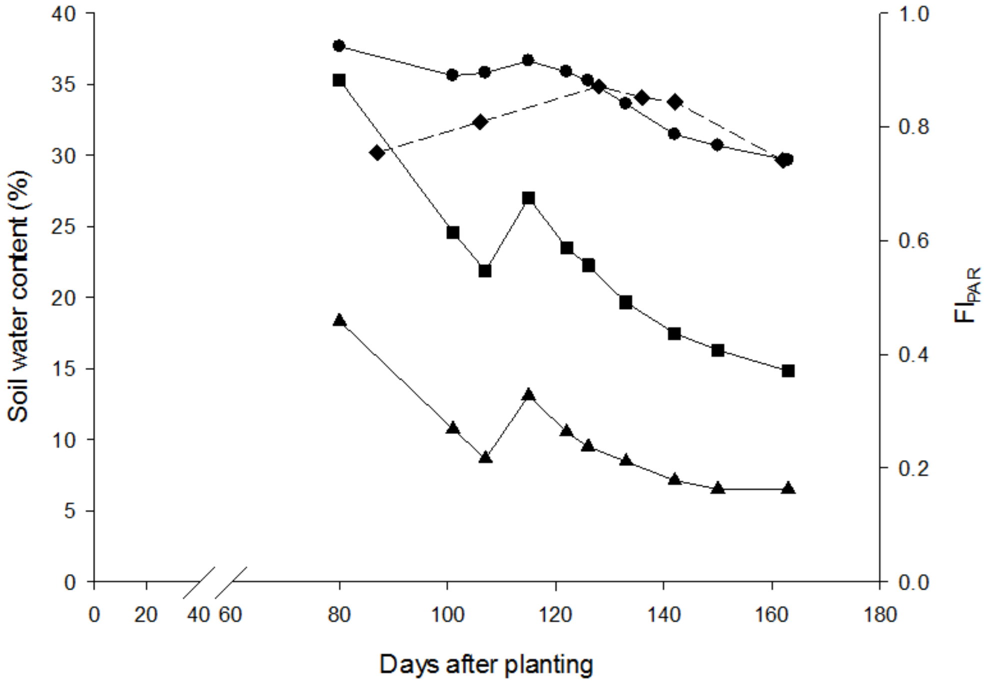

Figure 3.10: Relationship between the measured soil water content (SWC) for three depth zones (0 – 50 cm depth = -▲-; 50 -100 cm depth = -■-; 1000 – 150 cm depth = -●-) and the fraction interception of photosynthetically active radiation (FI$_{PAR}$) (dotted line) of the plant crop.

3.3.4.2 Foliar nutrient content

3.3.4.2.1 Deficiencies and toxicities

On average, there were no deficiencies observed, except for P in the first ratoon crop which had a P content of 0.18% compared to the threshold of 0.19% (Table 3.11). In spite of the high K application rate, the foliar K was not exceptionally higher than the threshold for foliar K. This, as was already pointed out in section 3.3.2.1.1, could be an indication that K displaced Mg. Both the foliar Mn and Fe contents were considerably higher than the threshold values (15 and 17 mg/kg, respectively) in both sampling events. Toxicity levels for foliar Mn and Fe have not been determined for sugarcane and it is not certain if these high levels of the two nutrients were toxic. All other nutrients measured appeared to be adequate (on average) for sugarcane growth.

Table 3.11: Summary of the average foliar nutrient content for all treatments during the experiment.

Foliar nutrient	Threshold value[1]	Plant crop (2009)	First ratoon crop (2010)
N (%)	1.90 (plant) 1.80 (ratoon)	2.32	1.88
P (%)	0.19	0.19	0.18
K (%)	1.05	1.52	1.15
Ca (%)	0.15	0.32	0.36
Mg (%)	0.08	0.15	0.33
S (%)	0.12	0.24	0.16
Si (%)	0.75	1.32	0.82
Zn (mg/kg)	13.00	17.57	17.00
Cu (mg/kg)	3.00	6.00	6.00
Mn (mg/kg)	15.00	132.61	89.63
Fe (mg/kg)	75.00	190.28	202.38
Number of samples (N)[2]	-	24	8

[1]After FAS (2004); [2]Note the unequal data sets between years

3.3.4.2.2 Plant crop in 2009

The foliar mineral contents of the plant crop reflected neither deficiencies nor toxicities for essential nutrients generally associated with sugarcane production (Table 3.12). However, gypsum application had a significant effect on the foliar Mg and Zn content. The differences for other foliar nutrients contents were small and not significant amongst gypsum application treatments. An antagonism between Ca and Mg was reflected by the negative correlation between leaf Ca and leaf Mg (r^2 =-0.59; $p<0.05$) (Shainberg et al., 1989).

The results for foliar Zn content were variable. The 6.4 t/ha gypsum treatment showed the lowest foliar Zn content and the 9.6 t/ha and 16 t/ha gypsum treatments the highest foliar Zn content. Shainberg et al. (1989) reported that soil Zn was moderately displaced by the Ca from gypsum, although the results were inconsistent. The Zn content of the soil was, however, not determined in this study and it is not clear from the observed results if Ca indeed displaced Zn. The leaf Mg and leaf K showed a significant negative correlation (r^2 = -0.56, $p<0.01$). Soil Mg and soil K are known to have an antagonistic effect on the uptake of each other (Mengel and Kirkby, 1987) and probably explains the observed negative correlation between the two nutrients in the leaves. Application of gypsum is known to enhance uptake of Mn (Shainberg et al., 1989), yet no significant interaction between Ca and Mn were observed in the foliar data of the plant crop.

Table 3.12: Effect of gypsum application on the foliar nutrient content 4 months after planting of the plant crop (2009). Values are average of 4 replicates and averages with different letters within a column differ significantly ($p<0.05$).

Gypsum application	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**Si**	**Zn**	**Mn**	**Cu**	**Fe**
t/ha	**%**							**mg/kg**			
0	2.43	0.20	1.46	0.31	0.17^{a}	0.24	1.28	17.75^{af}	157.25	6.00	187.75
3.2	2.26	0.19	1.52	0.32	0.15^{b}	0.24	1.58	17.00^{ace}	135.50	6.00	188.50
6.4	2.39	0.19	1.56	0.32	0.14^{b}	0.23	1.25	16.67^{be}	121.00	6.00	211.00
9.6	2.25	0.19	1.46	0.32	0.15^{b}	0.25	1.37	18.00^{adf}	132.75	6.00	180.75
12.8	2.31	0.19	1.60	0.32	0.14^{b}	0.24	1.22	17.75^{af}	120.50	6.00	179.75
16	2.31	0.19	1.51	0.33	0.14^{b}	0.24	1.20	18.00^{adf}	125.75	6.00	198.75
Average	*2.32*	*0.19*	*1.52*	*0.32*	*0.15*	*0.24*	*1.32*	*17.57*	*132.61*	*6.00*	*190.22*
Threshold value[1]	1.90	0.19	1.05	0.15	0.08	0.12	0.75	13.00	15.00	3.00	75.00
$LSD_{0.05}$	ns[2]	ns[2]	ns[2]	ns[2]	0.04	ns[2]	ns[2]	0.97	ns[2]	ns[2]	ns[2]

[1] After FAS (2004); [2] ns = Not significant

Table 3.13: Effect of 0 and 9.6 t/ha gypsum treatments on the foliar nutrient content 4 months after ratooning of the first ratoon crop (2010). Values are average of 4 replicates and values in brackets show standard error of mean (SEM).

Gypsum application	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**Si**	**Zn**	**Mn**	**Cu**	**Fe**
t/ha	**%**							**mg/kg**			
0	1.85	0.19	1.14	0.35	0.20	0.16	0.91	17.25	83.00	6.00	213.50
	(±0.15)	(±0.01)	(±0.12)	(±0.19)	(±0.01)	(±0.01)	(±0.18)	(±0.75)	(±11.66)	(±0.00)	(±22.11)
9.6	1.91	0.18	1.17	0.36	0.19	0.16	0.74	16.75	96.25	6.00	191.25
	(±0.07)	(±0.003)	(±0.07)	(±0.14)	(±0.02)	(±0.01)	(±0.14)	(±0.48)	(±6.25)	(±0.00)	(±47.43)
Average	*1.88*	*0.19*	*1.15*	*0.36*	*0.20*	*0.16*	*0.82*	*17.00*	*89.63*	*6.00*	*202.38*
Threshold value[1]	1.80	0.19	1.05	0.15	0.08	0.12	0.75	13.00	15.00	3.00	75.00
Significance ($p<0.05$)	ns[2]	ns[2]	ns[2]	ns[2]	ns[2]	ns[2]	ns[2]	ns[2]	ns[2]	ns[2]	ns[2]

[1] After FAS (2004); [2] ns = Not significant

Table 3.14: Comparison of the foliar nutrient content of the plant and first ratoon crops of the 0 and 9.6 t/ha gypsum treatments. Values are the average of 24 replicates and averages with different letters within a column differ significantly ($p<0.05$). Values in brackets show standard error of mean (SEM).

Crop	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**Si**	**Zn**	**Mn**	**Cu**	**Fe**
	%							**mg/kg**			
Plant	2.34^{a}	0.20^{a}	1.46^{a}	0.32^{a}	0.16^{a}	0.24^{a}	1.32^{a}	17.88	145.00^{a}	6.00	184.25
	(±0.05)	(±0.003)	(±0.03)	(±0.003)	(±0.01)	(±0.01)	(±0.10)	(±0.23)	(±7.44)	(±0.00)	(±8.89)
First ratoon	1.88^{b}	0.18^{b}	1.15^{b}	0.36^{b}	0.20^{b}	0.16^{b}	0.82^{b}	17.00	89.63^{b}	6.00	202.38
	(±0.08)	(±0.003)	(±0.06)	(±0.01)	(±0.01)	(±0.01)	(±0.11)	(±0.42)	(±6.62)	(±0.00)	(±24.59)
Average	*2.11*	*0.19*	*1.307*	*0.34*	*0.18*	*0.20*	*1.07*	*17.44*	*117.31*	*6.00*	*193.31*
Threshold value[1]	1.90 (plant) 1.80 (ratoon)	0.19	1.05	0.15	0.08	0.12	0.75	13.00	15.00	3.00	75.00
Significance	$p<0.05$	$p<0.05$	$p<0.05$	$p<0.05$	$p<0.05$	$p<0.05$	$p<0.05$	ns[2]	$p<0.05$	ns[2]	ns[2]

[1] After FAS (2004); [2] ns = Not significant

3.3.4.2.3 First ratoon crop in 2010

No significant effects manifested in the mineral contents of the first ratoon crop due to the 0 and 9.6 t/ha gypsum treatments (Table 3.13). The foliar P and Si were below their respective threshold values for unlimited growth of sugarcane in the 9.6 t/ha gypsum treatment. No nutrient deficiencies or toxicities were observed in the foliar data of the first ratoon crop.

3.3.4.2.4 Comparison of plant and first ratoon crops

A comparison of the foliar mineral contents of the plant and ratoon crops of the 0 t/ha and 9.6 t/ha gypsum treatments showed that the N, P, K, S, Si and Mn content was significantly ($p<0.05$) lower in the first ratoon crop than in the plant crop (Table 3.14). The foliar Ca and Mg content showed the opposite trend. Differences for the foliar Zn, Cu and Fe content were not significant between the plant and first ratoon crops.

3.3.4.3 Cane, sucrose and aboveground biomass yields

3.3.4.3.1 Cane yield

In the plant crop of 2009, the 9.6 t/ha gypsum treatment gave a cane yield of 5.15 t/ha/month which was significantly higher than the cane yield of 3.13 t/ha/month recorded in the 12.8 t/ha gypsum treatment (Figure 3.11). However, the cane yield did not differ significantly amongst any of the other gypsum treatments in the plant crop. For the plant crop, the slimes content of the soil correlated positively with cane yield ($r^2 =0.54$, $p<0.01$), which explains the measured difference in the cane yield between the 9.6 t/ha gypsum treatment (which had the highest average slimes content) and 12.8 t/ha gypsum treatment (which had a relatively low slimes content). Sugarcane plants in the 9.6 t/ha gypsum treatment had more tillers (TN) and longer stalks (SL) than sugarcane plants in the other treatments, although the differences were not significant (Table 3.15). It is not possible to explain the effect of slimes on sugarcane growth in the plant crop with the available data. A complete set of soil chemical data in 2009 could have helped to explain the observed results.

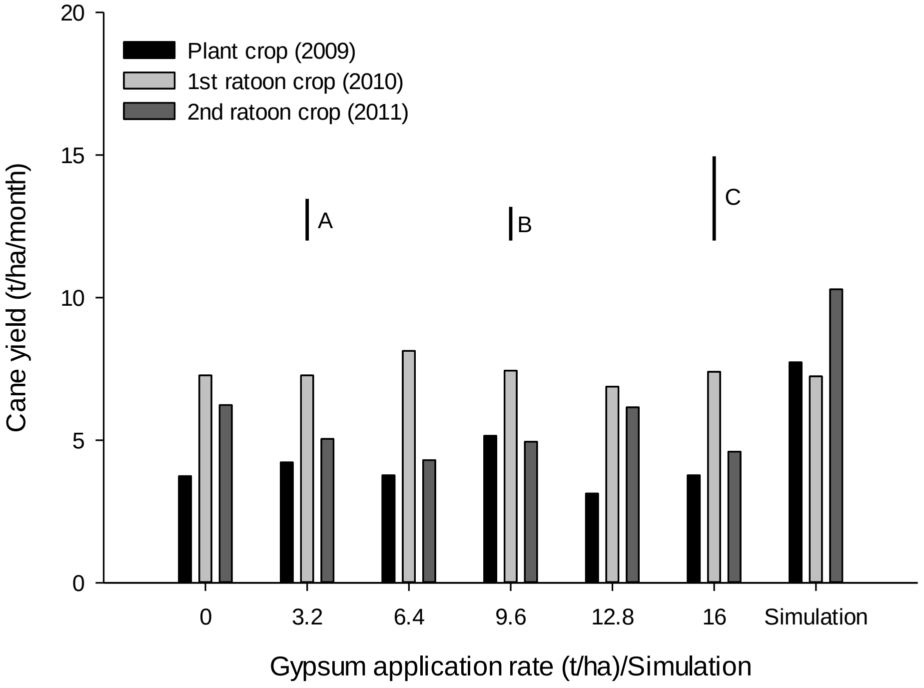

Figure 3.11: Effect of gypsum application on actual cane yield during the experiment and simulated yield with Canesim model. Vertical bars show $LSD_{0.05}$ (A = plant crop, B = 1stratoon crop and C = 2ndratoon crop).

Table 3.15: Effect of gypsum application on tiller number (TN), stalk length (SL), stalk diameter (SD) for the plant crop. Values are the average of 4 replicates and values in brackets show standard error of mean (SEM).

Gypsum application	Tiller number (TN)	Stalk length (SL)	Stalk diameter (SD)
-----t/ha----	-----per m^2------	---------------------cm---------------------	
0	19.78 (±0.60)	39.63 (±7.31)	2.17 (±0.03)
3.2	18.25 (±0.47)	49.71 (±6.76)	2.17 (±0.08)
6.4	18.47 (±0.87)	49.75 (±7.04)	2.10 (±0.03)
9.6	20.22 (±1.19)	58.99 (±4.45)	2.08 (±0.04)
12.8	19.00 (±0.97)	43.51 (±10.35)	2.12 (±0.05)
16	17.03 (±0.52)	47.01 (±4.66)	2.20 (±0.03)
Average	*18.79*	*48.10*	*2.14*
$LSD_{0.05}$	ns[1]	ns[1]	ns[1]

[1] ns = Not significant

For the plant crop, all gypsum treatments gave lower cane yields than the corresponding cane yield simulated by the Canesim model (Figure 3.11). The model predicted a period of waterlogging stress from planting until 94 days after planting. However, the simulated SWC was consistently lower than the actual SWC as measured with the Diviner instrument. For example, the average SWC predicted by the Canesim model for March 2009 was 329 mm while the actual SWC for the same month was 505 mm. It is therefore assumed that the model underestimated the waterlogging stress in the plant crop which explains the relatively low actual cane yield in all treatments relative to the simulated cane yield.

Mengel and Kirkby (1987) reported that under oxidizing conditions in the soil, Fe^{3+} precipitates on the plant root surfaces as iron oxide giving the roots a red brown colour. When oxygen is limiting in the soil, iron sulfide (FeS) is precipitated on the root surfaces giving the roots a black colour. Sumner (2011) reported that such roots are not efficient in absorbing nutrients which results in yield decline. Live black roots were indeed observed on the sugarcane during the experiment (Figure 3.12), which confirmed low oxygen levels in the reconstituted soil.

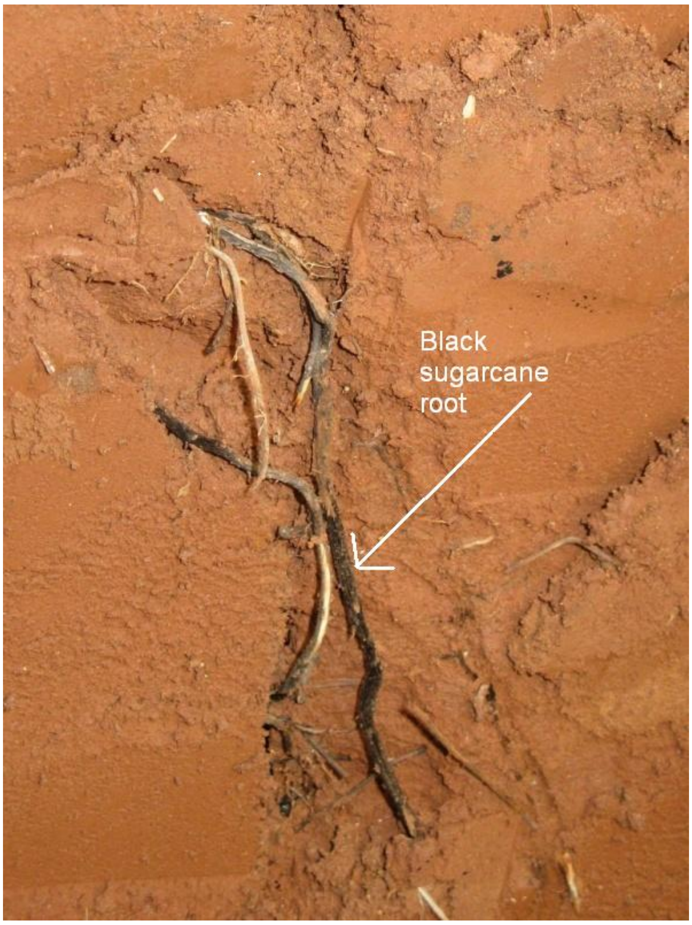

Figure 3.12: Photograph taken at termination of the experiment which shows black sugarcane roots. Such roots are indicative of waterlogging.

The application of gypsum did not have a significant effect on cane yield in the first ratoon crop of 2010. The cane yield varied from 7.27 to 8.13 t/ha/month. The actual cane yield was similar to the simulated cane yield. The Canesim model predicted drought during the growth period of the first ratoon crop. However, the actual SWC was higher than the simulated SWC and it is not certain to which degree the plants suffered from drought, if at all.

In the second ratoon crop of 2011 there was also no significant effect of gypsum application on the cane yield which varied from 4.30 to 6.23 t/ha/month. The simulated yield was considerably higher than the actual cane yield. Fertilizer was applied late for this ratoon crop and it could be that nutrient deficiencies resulted in the relatively low yields. The Canesim model did not predict waterlogging or water stress for the second ratoon crop.

3.3.4.3.2 Sucrose yield

The general trend for sucrose yield was similar to that of cane yield (Figure 3.13). For the plant crop the 9.6 t/ha gypsum treatment gave the highest sucrose yield (0.53 t/ha/month) and the 12.8 t/ha gypsum treatment the lowest sucrose yield (0.27 t/ha/month). This was the only significant difference as far as sucrose yield is concerned. Sucrose yield of the plant crop correlated significantly ($r^2 = 0.54$, $p < 0.01$) with the slimes content of the soil. The lowest (1.14 t/ha/month) and highest (1.34 t/ha/month) sucrose yields of the second ratoon crop were measured in the 12.8 and 6.4 t/ha gypsum treatments, respectively. Conversely, the lowest (0.39 t/ha/month) and highest (0.57 t/ha/month) sucrose yields were recorded in the 6.4 and 12.8 t/ha gypsum treatment, respectively.

The simulated sucrose yield was higher than the corresponding actual sucrose yields in the plant crop, which was already explained in the previous section. In the first ratoon crop, the actual sucrose yields were considerably higher than the simulated sucrose yield, which is encouraging. But in the second ratoon crop, the actual sucrose yields were considerably lower than the simulated sucrose yield, which could be from nutrient deficiencies, as explained earlier.

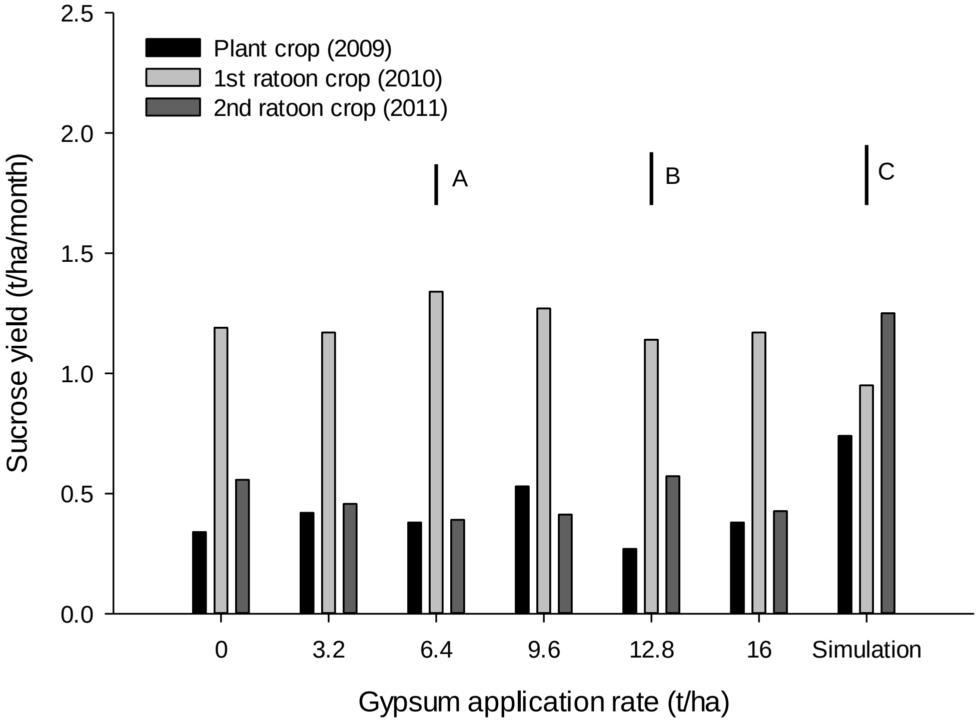

Figure 3.13: Effect of gypsum application on actual sucrose yield during experiment and simulated sucrose yield with Canesim model. Vertical bars show $LSD_{0.05}$ (A = plant crop, B = 1st ratoon crop and C = 2nd ratoon crop).

3.3.4.3.3 Aboveground biomass yield

The aboveground biomass (ABM) yield showed a similar trend to the cane and sucrose yields (Figure 3.14). On average for the gypsum treatments, the ABM yield varied from 0.7 t/ha/month for the plant crop to 3.6 t/ha/month for the first ratoon crop. Worth noting in this data set is the fact that the ABM yield was apparently not affected by nutrient stress to the same extent as the cane and sucrose yields, as reflected by relatively small decrease in ABM yield between the first and second ratoon crops.

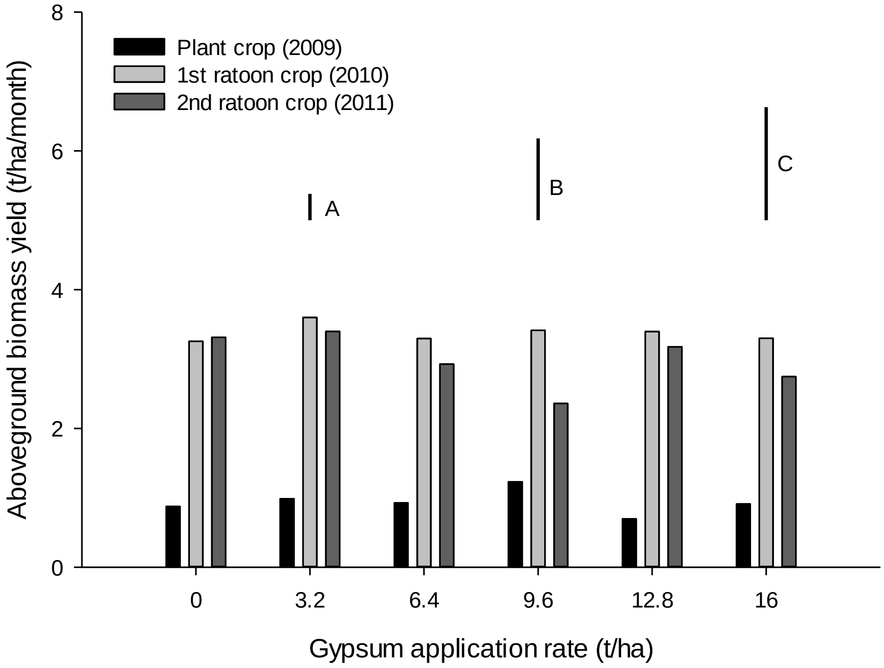

Figure 3.14: The effect of gypsum application on the aboveground biomass (ABM) yield during experiment. Vertical bars show LSD$_{0.05}$ (A = plant crop, B = 1stratoon crop and C = 2ndratoon crop).

3.3.4.3.4 Comparison of plant, first and second ratoon crop yields

Significant differences in cane, sucrose and ABM yield were observed between the plant, first and second ratoon crops (Table 3.16). Sugarcane performed best in the first ratoon crop with sucrose, cane and ABM yields of 1.22, 7.40 and 3.38 t/ha/month, respectively. The relatively large decrease in sucrose yield from the first to the second ratoon could be explained, at least in part, by the fact the harvesting was done in June, which is not a peak time for sucrose content (SASA, 2005).

Table 3.16: Comparison of sucrose, cane and aboveground biomass (ABM) yields of plant, first and second ratoon crops. Values are the average of 4 replicates and averages with different letters within a column differ significantly (p<0.05).

Crop	Sucrose yield	Cane yield	ABM yield
	--------------------------t/ha/month-----------------------		
Plant crop	0.39^a	3.97^a	0.94^a
First ratoon	1.22^b	7.40^b	3.38^b
Second ratoon	0.46^a	5.17^c	2.99^b
Average	*0.80*	*5.68*	*2.16*
LSD$_{0.05}$	0.46	2.14	1.44

The results presented in this experiment show that the cane and sucrose yield was affected by the slimes content of the reconstituted soil as reflected by the positive correlations between the slimes content and cane and sucrose yield. This effect of slimes on sugarcane growth however, could not be explained. The significant effect of slimes on sugarcane growth was absent in the first and second ratoon crops.

The addition of gypsum did not have a direct effect on sugarcane growth or aggregate stability (as measured by the MWD) in this experiment. Mitchell et al. (2000) also did not find an increase in winter cover crop yield in their study where gypsum was applied in spite of an increase in aggregate stability and a decrease in crust strength. In a previous three year field experiment conducted at Hillendale, application of 5 t/ha gypsum also did not significantly improve sugarcane yield relative to the control without gypsum (Van Jaarsveld and Zharare, 2010), but MWD was significantly improved. In the current experiment, however, the MWD could have been negatively affected by the high SWC (De-Campos et al., 2009) and by the relatively short time (16 months) between planting and soil sampling for aggregate stability (Amézketa, 1999), as was also pointed out previously. Gypsum application did succeed in improving the Ca:Mg ratio of the soil and also increased the EC of the reconstituted soil (although the EC remained low) in this experiment.

The failure of gypsum to improve sugarcane growth is difficult to explain. It is possible that the effect of gypsum was masked by the complex interactions of Ca, K and Mg ions in the soil or by the poor water drainage of the soil. A better understanding of Ca, K and Mg interactions is necessary to determine the optimum application rates for gypsum and/or K. In addition, the application of KCl at a rate of 3.9 t/ha as was used in this experiment could have environmental (Van Antwerpen and Meyer, 1997) and cost implications. More work on the role of K in dispersion of the reconstituted soil is therefore especially important. It was noted, however that the high K application rate did not result in an exceptionally high soil or foliar K content. When comparing the actual cane and sucrose yields of the first ratoon crop with the simulated cane and sucrose yields, the results seem to indicate that satisfactory yields can be achieved without the addition of gypsum. However more work is required in this regard before such a conclusion can be finalized. It must also be considered that this study was conducted over a relatively short period of time and on level soil. The benefit of gypsum might only be fully observed over a longer period of time and when the potential for soil erosion is higher.

3.4 CONCLUSIONS

The addition of gypsum did not improve soil structure or sugarcane performance in this experiment. Gypsum application increased the Ca:Mg ratio, but the electrolyte concentration remained low even at the highest gypsum application rate. Based on the results of this experiment alone, gypsum does not appear to be a suitable soil amendment for the reconstituted soil, but more work will be required to confirm this statement. It is possible that the effect of gypsum was masked by factors like the relatively short period over which the experiment was conducted, the poor drainage of the soil and ion interactions.

CHAPTER 4

EFFECT OF FILTERCAKE APPLICATION ON PROPERTIES OF A RECONSTITUTED SOIL AT HILLENDALE MINE AND RESULTING SUGARCANE GROWTH THEREON

ABSTRACT - A field experiment was conducted on back-filled land at the Hillendale mine to test the effect of filtercake (FC) application, a locally available source of organic matter, on the physical and chemical properties of a reconstituted soil and sugarcane growth thereon. Five treatments were evaluated including FC applied at 10, 30 and 100 t/ha, respectively. These three FC treatments were balanced with inorganic fertilizer to provide optimum amounts of N, P and K for sugarcane growth based on the fertility status of the reconstituted soil. In the two remaining treatments in the reconstituted soil, inorganic fertilizer was applied alone (without FC) at the recommended rate and at three times the recommended rate also based on the fertility status of the reconstituted soil. Sugarcane was also grown in an adjacent unmined area in disturbed soil used for cropping. The cane yield in the plant crop was lower in treatments where FC was applied as compared to the other treatments, including in the unmined soil. However cane yield was not improved by applying inorganic fertilizer at three times the recommended rate as compared to applying it at the normal recommended rate in the plant and first ratoon crop. The addition of FC at a rate of 100 t/ha was very effective in overcoming Mg-related dispersion, but the addition of FC did not improve aggregate stability. Filtercake application is likely to have resulted in N immobilization in the FC treatments in the plant crop, as reflected by low foliar N levels and visual N deficiency symptoms early in the experiment. High levels of foliar Fe in the plant crop were observed for sugarcane grown in the reconstituted soil. The cane and aboveground biomass (ABM) yield of the plant crop showed a significant and negative correlation with foliar Fe content (r^2 = -0.82 and r^2 = -0.88, respectively, $p<0.05$), confirming Fe toxicity. Iron toxicity is likely to be the result of O_2 deprivation in the reconstituted soil. There was however a significant increase in yield in the first ratoon crop compared to the plant crop. Sugarcane grown in the unmined soil had a significantly higher yield than sugarcane grown in the reconstituted soil in the first ratoon crop, but there were no significant differences in yield amongst treatments in the reconstituted soil.

4.1 INTRODUCTION

The objective of the study at Hillendale mine was to evaluate options for rehabilitating a post-mining reconstituted soil to support sugarcane production at levels similar to or better than those before mining was done. Because of the mining method employed at Hillendale mine, the reconstituted soil after mining on the backfilled land lacks soil structure (Van Jaarsveld and Zhahare, 2010). Soil structure is an important factor in the ability of a soil to support plant growth. A well-structured soil is characterized by the presence of water stable aggregates (Bronick and Lal, 2005). In the presence of water stable aggregates, water and air are able to move unhindered in a soil thereby creating a soil environment where roots receive adequate oxygen and water (Coyne and Thompson, 2006). Soil organic matter is one of the most important factors that influences the formation and stability of soil aggregates (Tisdall and Oades, 1982).

Soil erodibility is strongly linked to aggregate stability (Cerdá, 1998; Bryan, 2000; Cantón, et al, 2009). Stronger aggregates can resist raindrop impact better. Since aggregate stability is positively affected by organic matter, clay soil, which contain more organic matter than sandy soils have more resistance against erosion. In sandy soils, organic matter is quickly mineralized, and hence sandy soils are more sensitive to soil erosion than clay soils. Also, soils containing 2:1 clay minerals typically contain more organic matter than soils with 1:1 clay minerals (Prasad and Power, 1997). In addition to aggregate stability, soils with structure are also characterized by higher infiltration rates, which reduce run-off and in turn reduce erosion (Brady and Weil, 2004).

The effect of organic matter on aggregation is both direct and indirect. It affects aggregation directly by binding soil particles together like glue (Bronick and Lal, 2005) and by forming chemical bonds with clay and iron hydroxides in the soil (Anderson et al., 1998a). The addition of organic matter affects aggregation indirectly by increasing microbial activity, which in turn also has a positive effect on aggregation (Schlecht-Pietschet et al., 1994; Ros et al., 2003). Soil organic matter also has many other benefits to soils that could further improve plant growth (Magdoff and Weil, 2004; Coyne and Thompson, 2006). An experiment was therefore conducted to test the effect of a locally available source of organic matter, namely filtercake (FC), on the physical, chemical and microbiological properties of a reconstituted soil, and the growth of sugarcane on this soil at the Hillendale rehabilitation site.

4.2. MATERIAL AND METHODS

4.2.1 Trial site

The experiment was conducted under rain-fed conditions at Hillendale mine on a post-mined reconstituted soil (RS), which consisted of 70:30 sand-slimes (silt plus clay fraction) mixture to a depth of 1.8 m. Soil of an adjacent unmined land (US) was included against which the effects of the treatments on the reconstituted soil were compared. This area, which was situated on the uMhlatuze floodplain, but still within the Hillendale boundaries, consisted of unmined soil used for cropping. The soil (Figure 4.1) was characterized by a sandy soil top layer (0 - 30 cm); overlaying a black, clayey layer (30 - 50 cm) which in turn overlaid a sandy layer (50 – 100 cm).

Figure 4.1: A typical profile of disturbed soil to a depth of ± 100 cm in the unmined area.

4.2.2 Treatments and experimental design

Five amendment treatments were applied on the RS, laid out in a complete randomized block design with four replicates in 10 m x 10 m plots. In three of the treatments, FC was applied at rates of 10, 30 or 100 t/ha in combination with inorganic fertilizer. In the other two treatments, inorganic fertilizer (IF) was applied without FC. On the US sugarcane was planted in six replicate plots (10 m x 10 m) with inorganic fertilizers. Details on the application of the FC and inorganic fertilizer are given in the next section.

4.2.3 Filtercake and fertilizer application

Filtercake was obtained from the nearby Felixton sugarcane mill. Composite samples of the FC were sent to South African Sugarcane Research Institute Fertilizer Advisory Service (FAS) laboratory in Mt Edgecombe and Agricultural Research Council Institute for Soil, Climate and Water (ISCW) laboratory in Pretoria to determine their chemical composition. The FAS analysis was based on methodology described by Beater (1962) and Meyer et al. (1997). The ISCW analysis was conducted using methodologies described by Zasoski and Burau (1977), Jimenez and Ladha (1993) and Handreck and Black (1994). The results of the analyses (Table 4.1) were used to calculate the amount of inorganic fertilizer (Table 4.2) that would be required to balance the N, P and K so that the total amount of these nutrients applied would be equal to that of the FAS recommendation (based on the fertility status of the RS) for all three FC treatments. Calculation of the fertilizer requirement for the three FC treatments was based on the results of the FAS analysis, because the results corresponded better with those reported in literature (Anon, 2003). The FC was broadcast and incorporated manually into the soil to a depth of approximately 15 cm prior to planting.

Table 4.1: Chemical composition of composite filtercake samples analyzed by ISCW and FAS laboratories.

Parameter	ISCW	FAS
pH	5.98	-
Electrical conductivity (mS/m)	146	-
C (%)	3.18	-
N (%)	0.06	0.36
C:N	53	-
P (%)	0.49	0.39
K (%)	0.47	0.28
Ca (%)	1.76	1.30
Mg (%)	0.65	0.42
Ca:Mg	2.71	3.09

As mentioned in section 4.2.2, two treatments (IF and 3 x IF) involved the application of N, P and K inorganic fertilizers only (Table 4.2). In the case of the IF treatment, the inorganic fertilizers for N, P and K were applied at planting at the recommended rates made by FAS based on the fertility status of the RS. For the 3 x IF treatment, also based on the fertility status of the RS, the inorganic fertilizers for N, P and K was applied at planting at three times the FAS recommended rates. In the US, N, P and K were applied as inorganic fertilizers at planting at the FAS recommended rates based on the fertility status of the soil.

During the experiment, severe N deficiencies were visually observed in treatments where FC was applied. A decision was therefore taken to apply additional N in these treatments. This second N application was aimed at balancing the N that was already applied as inorganic N so that the total inorganic N application would be more or less equal to the FAS recommended rate of 100 t/ha N (Table 4.2). The second N application was done on 15 April 2010, namely 7 months after planting.

Table 4.2: Filtercake and fertilizer application during the experiment.

Treatment	FC application	1st N application	2nd N application	P application	K application
	-----t/ha-----	-------------------------------kg/ha----------------------------			
10 t/ha FC	10	82	16.5	40.5	161
30 t/ha FC	30	46	46	1.5	133
100 t/ha FC	100	0	101	0	35
3 x IF	0	300	0	180	525
IF	0	100	0	60	175
US	0	100	0	70	175
Recommended rate for RS	-	100	0	60	175
Recommended rate for US	-	100	0	70	175

In the treatments on the RS, N was applied as urea, P as single superphosphate and K as KCl. For the US, the N, P and K were applied as 650 kg/ha of a compound fertilizer 2:3:4 (30). In addition, 2.9 t/ha calcitic lime was broadcast and incorporated into the soil of the unmined area prior to planting to correct the pH from 5.0 to 5.3. Fertilizer application for the first ratoon crop was according to the FAS recommended rate for all treatments.

4.2.4 Plant management

Sugarcane cultivar N41, which is well suited for production under dry-land cultivation in the area (SASA, 2003), was planted in 1 m inter-row spacing in all plots. Planting was done on 2 September 2009 and harvesting of the plant crop was done on 16 November 2010 (14 months after planting). The final harvesting (first ratoon) occurred on 20 June 2011 (7 months after ratooning).

4.2.5 Data collection

Data collection was similar to that of the gypsum field experiment (section 3.2.3), but sampling and measurement was done at different times (Table 4.3). In addition, rainfall data was collected on the Hillendale mine premises during the experiment (Table 4.4).

Table 4.3: Summary of the sampling times and treatments measured during the filtercake field experiment. Details can be found in the listed sections as they are similar to that of the gypsum field experiment.

Section for details	Sampling time	Treatments measured	Comments
3.2.3.1 Soil physical parameters			
3.2.3.1.1 Particle size analysis	Jul 2010	All	
3.2.3.1.2 Soil water content	Sep 2009 to Jul 2010	All	Measured weekly
3.2.3.1.3 Penetration resistance	Jun 2009	All	Measured before the start of experiment
	Jul 2010	100 t/ha FC, IF, US	Treatments represented extremes.
3.2.3.1.4 Aggregate stability	Aug 2010	All	
3.2.3.2 Soil chemical parameters			
3.2.3.2.1 Soil fertility status	Jul 2008	Composite, RS and US sample	Taken before start of experiment
	Jul 2010	All	
3.2.3.2.2 Magnesium related dispersion	Feb 2011	Composite, RS and US sample	Samples taken from non-amended soil inside experimental areas
	Feb 2011	100 t/ha FC, IF and US	Treatments represented extremes.
3.2.3.3 Soil microbiological parameters	Sep 2008	Composite, RS only	
	Jul 2008	Composite, US only	
	40, 163, 210, 317, 537 days after planting	100 t/ha FC, IF, 3 x IF	Treatments represented extremes. Days were randomly selected.
	537 days after planting	US only	

Table 4.3: A summary of the sampling times and treatments measured during the filtercake field experiment (cont.).

Section for details	Sampling time	Treatments measured	Comments
3.2.3.4 Sugarcane growth response			
3.2.3.4.1 Fractional light interception	134, 154, 187, 222, 232, 273 days after planting	All	Days were randomly selected.
3.2.3.4.2 Foliar nutrient content	Feb 2010 (5 months after planting)	All	
	Jun 2010 (9 month after planting)	100 t/ha FC, IF, US	
3.2.3.4.3 Cane, sucrose and aboveground bio-mass (ABM) yield	Nov 2010	All	
	Jun 2011	All	

Table 4.4: Monthly rainfall as recorded from the start of the experiment until termination.

Year	Month	Total rainfall (mm)	Year	Month	Total rainfall (mm)
2009	September	33.3	2010	August	30.0
2009	October	98.7	2010	September	30.3
2009	November	138.5	2010	October	85.5
2009	December	62.7	2010	November	100.4
2010	January	103.5	2010	December	94.6
2010	February	85.6	2011	January	208.2
2010	March	159.07	2011	February	72.8
2010	April	70.6	2011	March	118.3
2010	May	64.9	2011	April	136.8
2010	June	18.1	2011	May	42.2
2010	July	44.8	2011	June	55.4

4.2.6 Statistical analysis

All statistical analyses were performed using GenStat12 software (VSN International, 2009). Where possible, means were separated by LSD (least significant difference) at 5 % significance level.

4.3. RESULTS AND DISCUSSION

4.3.1. Soil physical parameters

4.3.1.1 Particle size distribution

The slimes (silt + clay) content of the treatments in the RS (taken to a depth of 20 cm) varied from 18% to 25.5% with no significant differences amongst treatments (Table 4.5). However, clay content varied significantly ($p<0.05$) among treatments with the IF treatment having the highest clay content of 20.8% and the 100 t/ha FC treatment the lowest clay content of 14.8%. These differences in clay content were induced unintentionally when the experimental area was filled up with RS. Yet, there were no significant correlations between clay content of the soil and any soil chemical or plant growth parameter measured in this experiment. The influence of the variation in clay content on the soil chemical properties and sugarcane growth was therefore considered negligible.

The average slimes content of the samples in the RS was 23.2%, which was markedly lower than the target value of 30%, but was close to the average silt-plus-clay content (23.3%.) of the plots in the US. However, it needs to be emphasized that the particle size distribution was only done for the top 20 cm of soil. The variation in texture deeper down in the soil profile is therefore not known.

Table 4.5: Particle size distribution of soil taken to depth of 20 cm in the filtercake and/or fertilizer treatment plots. Values are the means of 4 replicates and averages with different letters within a column differ significant ($p<0.05$).

Treatment	Clay	Silt	Slimes (clay + slit)	Sand
	-----------------------------	------------------------------%------------------------------		------------------------------
10 t/ha FC	17.00^{acd}	6.75	23.75	78.00
30 t/ha FC	19.50^{abc}	4.75	24.25	73.75
100 t/ha FC	14.75^{ad}	3.25	18.00	80.00
3xIF	16.25^{acd}	8.00	24.25	76.25
IF	20.75^{bcd}	4.75	25.50	74.50
US	17.17^{acd}	6.17	23.33	76.67
Average	*17.54*	5.65	*23.19*	*76.53*
$LSD_{0.05}$	3.24	ns[1]	ns[1]	ns[1]

[1]ns = Not significant

4.3.1.2 Soil water content

Soil water content (SWC) showed significant measuring time x soil depth (Figure 4.2) and soil depth x FC and/or fertilizer application (Figure 4.3) interactions. The average SWC for the three depth zones varied between 10.6% and 45.1%. During the experimental period it was highest in the 100 - 150 cm depth zone and the lowest in the 0 – 50 cm depth zone (Figure 4.2). There was an initial rapid increase in SWC at all three depth zones between September and October 2009 to a plateau that lasted until December 2009 for the 0 – 100 cm depth zone and January 2010 for 100 - 150 cm depth zone. Soil water tended to decline more rapidly in the 0 - 50 cm and 50 - 100 cm depth zones from December 2009 to February 2010. At soil depth 100 - 150 cm, there was a tendency for the SWC to decline gradually from March 2010 onwards. In the 50 - 100 cm depth zone, there was a dip in SWC in February 2010 that was followed by a rise in March 2010. The initial increase in SWC from September to October 2009 could be explained by the addition of fertilizer in September 2009 that would have increased the electrolyte concentration and therefore the water intake and retention. The trend observed for SWC in this interaction was similar to that observed in the gypsum field experiment (Figure 3.6). There was no significant correlation between rainfall received and SWC of the three soil depth intervals during the experimental period (0 – 50 cm: $r^2 = 0.37$; 50 – 100 cm: $r^2 = 0.45$ and 100 – 150 cm: $r^2 = 0.58$).

If it is assumed that the clay content remained uniform down the RS profile, a theoretical calculation of field capacity and saturation gave values of 20% and 30%, respectively (Schultze et al., 1985; Van Rensburg, 1988; Van Antwerpen et al. (1994); Meyer and Van Antwerpen, 1995). In the 100 - 150 cm zone, the average SWC during the measuring period in the RS was 40.3%, which was higher than the calculated saturation (30%). The SWC was higher than field capacity in the RS, at least temporarily, in all three depth zones and the average monthly SWC varied between 18.4% and 37.0% during the measuring period (data not shown). A similar explanation of the observed high SWC as given in section 3.3.1.2.1 is applicable and is likely the result of poor water drainage.

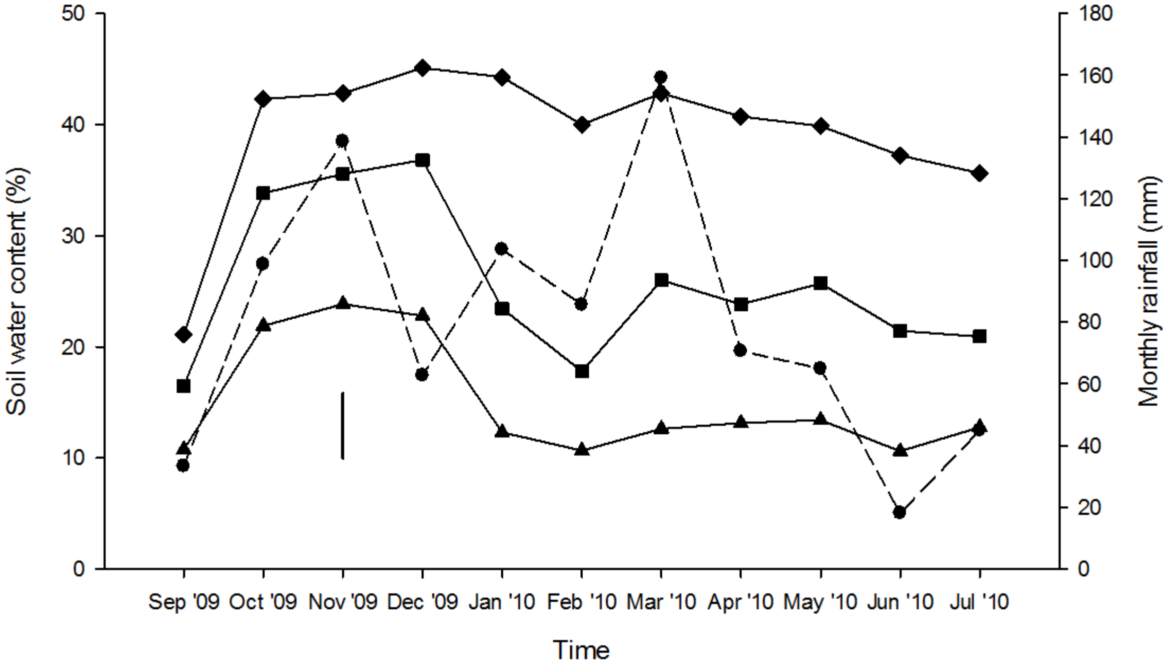

Figure 4.2: Change in soil water content (SWC) for the 0 – 50 cm depth zone (-▲-), 50 – 100 cm depth zone (-■-) and 100 - 150 cm depth zone (-♦-) during the period of September 2009 to August 2010 as an average of filtercake (FC) and/or fertilizer application. The dotted line (-•-) shows the average monthly rainfall, and the vertical bar represents $LSD_{0.05}$ for the interaction.

The SWC was higher in treatments in which FC was incorporated compared to treatments without FC application (Figure 4.3), with the 100 t/ha FC treatment having the highest SWC. Filtercake is known to increase soil water retention (Henry and Rhebergen, 1994; Anon., 2003) and was likely the reason for the higher SWC in treatments where FC was applied. The soil in the unmined land had the lowest SWC of all treatments in all depth zones with the 0 – 50 cm depth zone having a SWC of only 5.8%. In the 100 – 150 cm zone, the SWC was very similar for all treatments in the RS and also in the US. The relatively high SWC in this depth zone of the RS could be an indication that the clay content was higher in this zone. Saturation and field capacity was not calculated for the RS, since the soil was not homogenous down the soil profile (see Figure 4.1) and the particle size distribution below 20 cm soil depth was not determined.

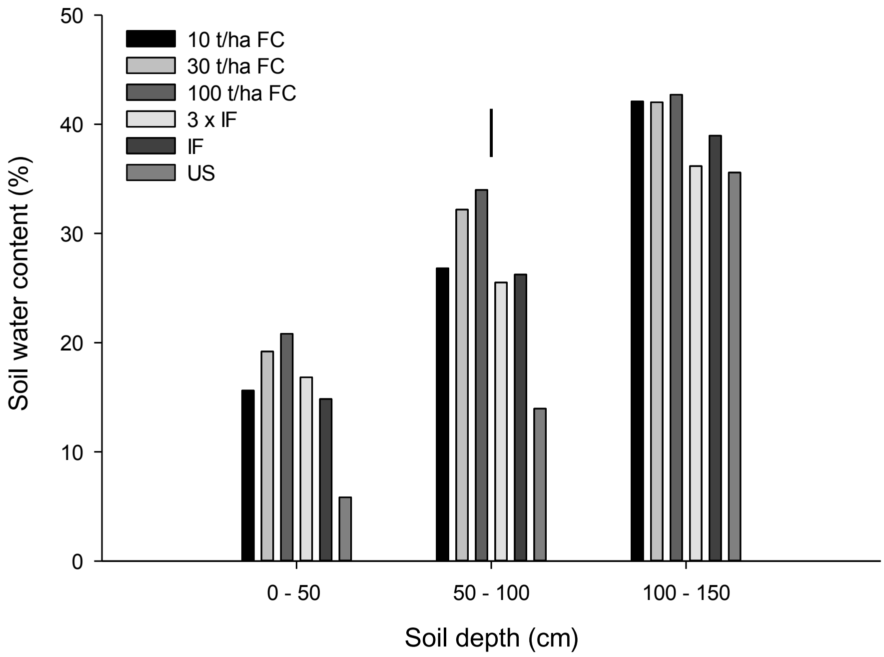

Figure 4.3: Effect of filtercake and/or fertilizer application on soil water content (SWC) as an average of measuring period from September 2009 to July 2010. The vertical bar represents LSD$_{0.05}$.

4.3.1.3 Penetration resistance

4.3.1.3.1 Before start of experiment

As expected, in June 2009 prior to the start of the experiment, there were no significant differences between the treatment plots of the RS in penetration resistance (PR). In the RS the average PR at 10 cm depth was 53.7 kPa after which it decreased to 4.7 kPa at 30 cm soil depth (Figure 4.4). From 40 cm depth the PR increased steadily and significantly down the soil profile to a final PR of 165.2 kPa at 80 cm depth. Increases in PR down the soil profile are common in other studies (for example Radcliffe at al., 1986; Van Antwerpen and Meyer, 1997; Vanags et al., 2006). The same phenomenon was also noted in the gypsum field experiment (section 3.3.1.3.2).

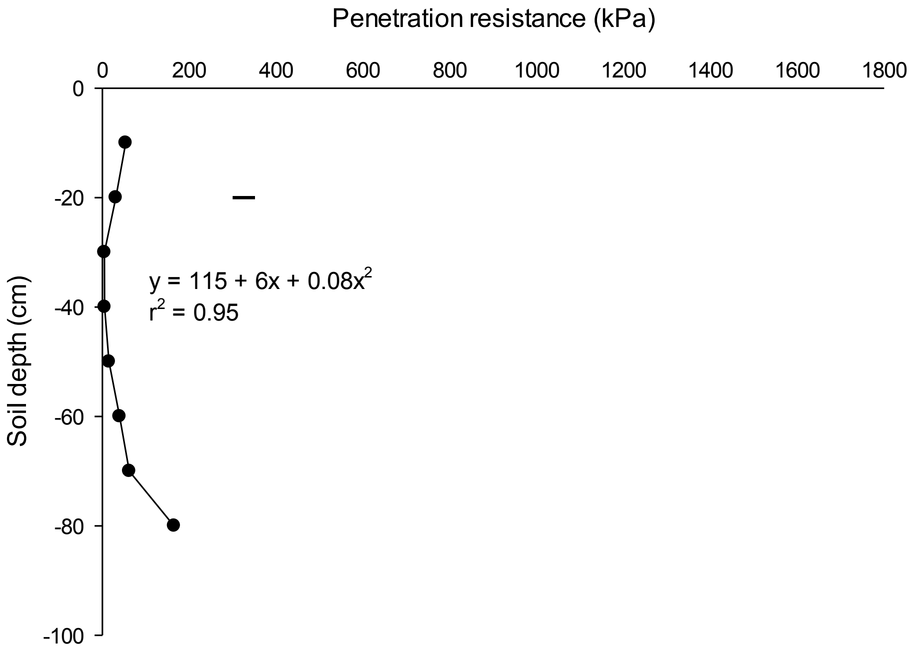

Figure 4.4: Change in penetration resistance (PR) with soil depth for all treatments in the RS before the start of the experiment. The horizontal bar represents the $LSD_{0.05}$.

4.3.1.3.2 During plant crop growth

A significant soil depth x FC and/or fertilizer application interaction on PR was observed in July 2010 during the plant crop growth (Figure 4.5). The US showed a sharp increase in PR from 148 kPa at 30 cm soil depth to 1672.1 kPa at 80 cm soil depth. Unfortunately, the previous cultivation history of the US is not known and compaction imposed by previous tillage operations could have resulted in this increase. In addition, the soil profile also showed a drastic change in texture below 30 cm soil depth (Figure 4.1). In the RS, a student t-test between the 100 t/ha FC and IF treatments revealed that the IF treatment had a significantly higher average PR (194.6 kPa) than the 100 t/ha FC treatment (124.4 kPa). Organic amendments are known to decrease PR, even below the depth of incorporation (Celik et al., 2010), as was also the case in this experiment. This effect is partly attributed to the ability of organic matter to lower the bulk density of the soil (Celik et al., 2010). It is also possible that the higher SWC in the 100 t/ha FC treatment (as discussed in section 4.3.1.2) contributed to its lower PR. Differences in PR between row and interrow were not significant. In both the 2009 and 2010 data, there was no indication of compaction or hardsetting in the RS with all values being well below 2800 kPa, the critical PR value for root growth for sugarcane (Swinford and Boevey, 1984). In the unmined land a number of individual PR readings did exceed 2800 kPa, but the average values were still below 2800 kPa.

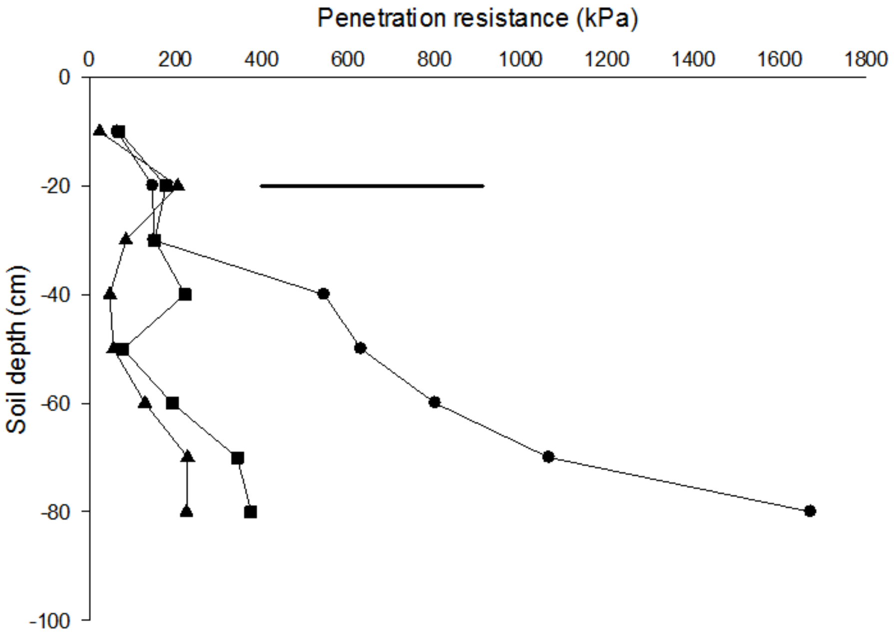

Figure 4.5: Change in penetration resistance (PR) with soil depth for the unmined soil (US) (-●-) and the reconstituted soil (RS) (100 t/ha FC treatment, -▲- and 3 x IF treatment, -■-) 10 months after planting. The horizontal bar shows the LSD$_{0.05}$ for the interaction.

4.3.1.3.3 Change with time

When comparing the 100 t/ha FC and IF treatments in the RS before the start of the experiment and during plant crop growth in 2010, the results indicate a significant increase in PR from 75.6 kPa in 2009 to 149.6 kPa in 2010. This increase could be the result of compaction or the start of hardsetting.

4.3.1.4 Aggregate stability

In the US, the aggregate stability expressed as the mean weight diameter (MWD) was 0.67 mm. A MWD value of 0.67 mm is classified according to Le Bissonnais (1996) as being unstable and inclined to form crusts. Values for the RS were significantly lower than in the US and varied between 0.06 and 0.20 mm (Table 4.6). A MWD of below 0.40 mm is classified as very unstable and showing systematic crust formation (Le Bissonnais, 1996). At the time of taking the samples in August 2010 during plant crop growth, both the RS and the US were therefore sensitive to erosion. The addition of FC to the RS even at the highest application rate did not result in stable aggregates, although the MWD was higher (but not significant) in the 100 t/ha FC treatment than in the other treatments. In a study by Celik et al. (2010), who tested different organic amendments, the MWD diameter was significantly higher after 8 years in treatments with organic matter than in the control without such amendments. In another similar study, aggregate stability increased after four years of adding organic matter (Tejada and Gonzalez, 2007). Aging has been identified as a critical factor that influences aggregate stability (Amézketa, 1999), and hence it is possible that the fourteen months of running this experiment was not long enough for significant improvement in aggregate stability.

Table 4.6: Effect of filtercake and/or fertilizer application on the mean weight diameter of soil aggregates taken to a depth of 20 cm at 11 months (August 2010) after planting. Averages with different letters within a column differ significantly ($p<0.05$).

Treatment	Mean weight diameter --------mm--------	Number of samples (N)
10 t/ha FC	0.09^a	4
30 t/ha FC	0.18^a	4
100 t/ha FC	0.20^a	4
3xIF	0.06^a	4
IF	0.09^a	4
US	0.67^b	6
Average	*0.25*	-
$LSD_{0.05}$	0.20	-

De-Campos et al. (2009) have reported that waterlogging negatively affects aggregate stability. In this experiment, the MWD diameter correlated negatively ($p<0.01$) with the SWC in the 0 - 50 cm (r^2 = -0.56; $p<0.01$) and 50 - 100 cm (r^2 = -0.58; $p<0.01$) depth zones, which confirms observations made by De-Compos et al. (2009). The MWD correlated with soil pH (r^2 = -0.66, $p<0.01$), showing that aggregate stability increased as the soil pH decreased. A low soil pH has been shown to promote flocculation (Shainberg et al., 1989), which possibly explains this correlation in the present study. The MWD also correlated negatively with the soil K and Mg content (r^2 = -0.66 and r^2 = -0.70, $p<0.01$, respectively). Potassium and Mg ions are among the factors that cause soil dispersion (Shainberg et al., 1989, Bronick and Lal, 2005), which explains the negative correlations between these ions and MWD in this study. Conversely, Ca, Fe and Mn ions are associated with soil flocculation (Bronick and Lal, 2005). In this study, as expected, soil Fe and Mn correlated positively with MWD (r^2 = 0.67 and r^2 = 0.68, $p<0.01$, respectively). It also showed a positive correlation with the Ca:Mg ratio (r^2 = 0.67, $p<0.01$). The MWD correlated negatively with the Mg:K ratio (r^2 = -0.63, $p<0.01$), which shows that the aggregate stability was higher when the Mg:K ratio was lower.

4.3.2 Soil chemical parameters

4.3.2.1 Soil fertility status

4.3.2.1.1 Change over time

The addition of lime to the US prior to planting was effective in improving the pH from 5.0 to 5.4 (Table 4.7), which is within the advised range (5.3 – 8.0) for optimum sugarcane growth (SASA, 2005). Similarly, the pH of the RS was within the optimum range with a value of 7.5, both before and during the experiment. Both P and K were below their threshold values for optimum sugarcane growth of 31 and 112 mg/kg, respectively, in the RS and the US (FAS, 2004). The addition of calcitic lime to the US, which contains Ca, was effective in improving the Ca:Mg ratio from 0.7 to 1.5. In the RS the Ca:Mg ratio remained low and varied between 0.6 and 0.7. The addition of FC and/or K fertilizer improved the Mg:K ratio in both the RS and in the US, but this cation ratio still remained higher than the ideal range (3 to 4) for optimum crop growth (Buys, 1986). Both Mn and Fe decreased in the US from 2008 to 2010, but remained much higher than in the RS. The Mn in the RS remained stable at 2.1 mg/kg, while the Fe increased slightly from 2.4 mg/kg in 2008 to 2.9 mg/kg in 2010. In spite of the addition of FC, sampling done in July 2008 and July 2010 showed that the organic matter content did not increase in the RS. In the US, the organic matter content decreased markedly from 1.1% to 0.4%. Although the soil disturbance at planting could have resulted in a decrease in SOM (Both and Benites, 2005), this decrease was very drastic and might have been the result of a sampling error. The S was sufficient for sugarcane in the RS in 2008 with a value of 27.6 mg/kg. Unfortunately S was not determined in the US, and hence, there is no comparable data for the US. It is important to point out that the soil fertility status of the US and RS, as discussed here, only represents the top 20 cm of these soils.

Table 4.7: Summary of the changes in soil chemical parameters over time from samples to a depth of 20 cm of the reconstituted soil (RS) (average of all treatments) and unmined soil (US).

Soil chemical parameter	Threshold value/optimum range	RS: July 2008	RS: July 2010	US: July 2008	US: July 2010
pH (H_2O)	5.3 – 8.0[1]	7.5	7.5	5.0	5.4
Organic matter (%)	-	0.2	0.2	1.1	0.4
P (mg/kg)	31[2]	9.5	25.1	5.3	8.3
K (mg/kg)	112[2]	62.3	88.3	50.5	52.6
Ca (mg/kg)	200[2]	564.0	591.9	307.9	529.8
Mg (mg/kg)	25[2]	572.0	567.4	253.3	211.6
Ca:Mg ratio[3]	1.5 – 4.5[4]	0.6	0.7	0.7	1.5
Mg:K ratio[3]	3 – 4[4]	29.31	20.74	15.97	12.90
S (mg/kg)	15	27.6	-	-	-
Mn (mg/kg)	-	2.1	2.1	89.0	33.1
Fe (mg/kg)	-	2.4	2.9	270.0	157.7
Number of samples (N)[5]	-	1	20	1	6

[1]After SASA (2005); [2]After FAS (2004); [3]Calculated from the cmol(+)/kg soil concentrations; [4]After Buys (1986); [5]Note the unequal data sets between years

4.3.2.1.2 Effect of filtercake and/or fertilizer application

The soil pH was significantly lower in the US (5.38) relative to the treatments in the RS where the pH varied from 7.05 to 8.03 (Table 4.8). In this study pH was the highest in the 100 t/ha FC treatment, followed by the 30 t/ha FC treatment and then the 10 t/ha treatment, although the differences were not significant. The pH was also lower, but not significant, in the 3 x IF and IF treatments than in the FC treatments. These variations in pH among the treatments in the RS and the differences between the US and the RS probably reflect differences in SWC and O_2 levels. Kirk et al. (1990), as cited in Marschner (1995), indicated that waterlogging increases soil pH. This explanation is confirmed by the positive correlations obtained in the present experiment between soil pH and SWC in the 0 - 50 cm depth zone ($r^2 = 0.68$, $p<0.01$).

Table 4.8: Effect of filtercake and/or fertilizer application on soil chemical properties 10 months (July 2010) after planting. Soil samples were taken to a depth of 20 cm. Averages with different letters within a column differ significantly ($p<0.05$).

Treatment	pH (H_2O)	Organic matter	P	K	Ca	Mg	Ca:Mg[3]	Mg:K[3]	Fe	Mn	Number of samples (N)
		%	----------------------------	mg/kg	----------------------------				-------mg/kg	---------	
10 t/ha FC	7.40^{a}	0.18	12.75^{a}	91.88^{a}	575.50	620.00^{a}	0.58^{a}	21.79^{a}	3.00^{a}	2.08^{a}	4
30 t/ha FC	7.70^{a}	0.20	20.83^{a}	80.25^{a}	611.40	541.85^{a}	0.77^{a}	21.52^{a}	3.00^{a}	1.85^{a}	4
100 t/ha FC	8.03^{a}	0.20	73.73^{b}	92.13^{a}	715.10	537.50^{a}	0.82^{a}	18.79^{a}	3.00^{a}	1.95^{a}	4
3 x IF	7.30^{a}	0.20	11.63^{a}	80.55^{a}	580.30	515.00^{a}	0.70^{a}	20.96^{a}	2.50^{a}	2.38^{a}	4
IF	7.05^{a}	0.13	6.53^{a}	96.85^{a}	477.45	622.73^{a}	0.47^{a}	20.65^{a}	3.00^{a}	2.05^{a}	4
US	5.38^{b}	0.44	8.27^{a}	52.58^{b}	529.87	211.58^{b}	1.53^{b}	12.90^{b}	157.67^{b}	33.07^{b}	6
Average	*7.01*	*0.23*	*21.21*	*80.08*	*577.62*	*485.30*	*0.87*	*18.93*	*38.62*	*9.22*	-
Threshold value/ optimum range	5.3 – 8.0[1]	-	31[2]	112[2]	200[2]	25[2]	1.5 – 4.5[4]	3 – 4[4]	-	-	-
$LSD_{0.05}$	0.86	ns[5]	20.34	17.36	ns[5]	114.80	0.57	4.09	50.79	10.27	-

[1] After SASA (2005); [2] After FAS (2004); [3] Calculated from the cmol(+)/kg soil concentrations; [4] After Buys (1986); [5] ns = Not significant

The low pH in the US probably contributed to the high Mn and Fe contents in this soil, as compared to the RS where the pH was higher (Table 4.8), since the solubility of both Mn and Fe is increased by a low soil pH (Mengel and Kirkby, 1987). This effect of pH on Mn and Fe is confirmed by significant ($p<0.01$) correlations between pH and Mn and Fe (r^2 = - 0.84 for both Mn and Fe).

Addition of FC to the RS at 100 t/ha significantly improved the P status of the soil where the resultant soil P tested 73.7 mg/kg, compared to the IF treatment where the soil P tested 6.5 mg/kg (Table 4.8). This was confirmed by the positive correlation between the FC application rate and soil P (r^2 = 0.87, $p<0.01$). This correlation also shows that FC was mineralized in the soil. Soil P was higher (but not significant) in the 3 x IF treatment (11.6 mg/kg) compared to the IF treatment. The soil K was significantly lower in the US than in any treatment in the RS. Differences in soil K amongst treatments in the RS were not significant and all values were lower than the recommended K value of 112 mg/kg (FAS, 2004). This shows that neither adding FC nor applying inorganic K, even at a high rate, improved the plant available K to the recommended level in the RS. The low K in all samples could point to K being easily leached from both the RS and the US. Potassium leaching is common in sandy soils and soils rich in kaolinite (Mengel and Kirkby, 1987), which both applies to RS and US (Snyman, 2001). The soil Mg was significantly lower in the US than in any treatments in the RS (Table 4.8), which reflected the lower initial Mg content in the US compared to the RS (Table 4.7). The soil Mg correlated negatively with the soil Mn and Fe (r^2 = -0.78 and r^2 = -80, respectively, $p<0.01$) which probably reflects the antagonistic effects of Mn and Fe on Mg (Mengel and Kirkby, 1987; Marschner, 1995). A similar explanation probably accounts for the lower Mg content in the samples of June 2010.

The Ca:Mg ratio of 1.53 in the US (Table 4.8) was within the ideal range for crop production (1.5 to 4.5), according to Buys (1986). This cation ratio was significantly ($p<0.05$) lower in the RS and hence lower than the ideal range (Table 4.7). In the RS the 100 t/ha FC treatment had the highest Ca:Mg ratio (0.82) amongst the treatments, but not significantly so. The Mg:K ratios in the RS varied from 18.8 (100 t/ha FC) to 21.8 (10 t/ha FC) and fell not in the ideal range according to Buys (1986). However this cation ratio was significantly ($p<0.05$) lower in the US, namely 12.9. Differences amongst treatments concerning organic matter were not significant. This was contrary to expectation that the addition of as much as 100 t/ha FC, would not increase the organic matter content. Probably the high temperatures experienced in the coastal region of Kwazulu-Natal resulted in a fast breakdown of organic matter in the RS (Bot and Benites, 2005).

4.3.2.2 Magnesium-related dispersion

The samples collected in February 2011 from the non-amended RS and the US revealed that in both cases the soils were dispersed (Table 4.9). For example, the RS and US satisfied respectively 80% and 100% of the five criteria applied as they had a higher exchangeable Mg percentage (EMP), lower electrical conductivity (EC), lower Ca:Mg ratio (only US), lower exchangeable sodium percentage (ESP) and higher ESP-plus-EMP than the stipulated criteria. Thus it appears that dispersion is common to pre- and post-mined soils at Hillendale (Van Jaarsveld and Zharare, 2010). Deep cracks similar to those described in section 3.2.1 were observed in this experiment, which indicated soil dispersion.

Table 4.9: Criteria used for establishing the magnesium-related dispersion potential of composite soil samples taken to a depth of 20 cm of non-amended reconstituted soil (RS) and unmined soil (US) 17 months after planting. For Mg dispersion to be present criteria 1, 2, 3, 4 and/or 5 must be met.

Criteria	Critical value for Mg dispersion[1]	RS	US
1. EMP[2] (%)	>30	53.62	46.15
2. EC (dS/m)	<1.28	0.47	0.18
3. Ca:Mg ratio	<1	0.50	0.57
4. ESP (%)	<4	5.69	2.70
5. ESP + 0.1EMP[2] (%)	>6	11.05	7.32
Dispersed		Yes	Yes

[1] After Fenton and Conyers (2002) and all except EC (saturated paste) are based on cmol(+)/kg soil concentrations; [2] EMP = Exchangeable magnesium percentage

The addition of 100 t/ha FC was able to overcome Mg-related dispersion in the RS by lowering the EMP and increasing the Ca:Mg ratio and the EC (Table 4.10). In contrast, addition of inorganic fertilizer did little to alleviate Mg-related dispersion. The addition of lime at the start of the experiment was able to increase the Ca:Mg ratio in the US, thereby counteracting dispersion, but the EC remained low.

Table 4.10: Criteria used for establishing the magnesium-related dispersion potential of filtercake and/or fertilizer treated soil samples taken to a depth of 20 cm at 17 months after planting. For Mg dispersion to be present criteria 1, 2, 3, 4 and/or 5 must be met.

Criteria	Critical value for Mg dispersion[1]	Treatment		
		100 t/ha FC	IF	US
1. EMP[2] (%)	>30	24.63	54.66	32.46
2. EC (dS/m)	<1.28	2.55	0.46	0.21
3. Ca:Mg ratio	<1	2.0	0.25	1.33
4. ESP (%)	<4	1.56	7.28	2.43
5. ESP + 0.1EMP[2] (%)	>6	4.02	12.74	5.68
Dispersed		No	Yes	No

[1] After Fenton and Conyers (2002) and all except EC (saturated paste) are based on cmol(+)/kg soil concentrations; [2] EMP = Exchangeable magnesium percentage

4.3.3 Soil microbiological parameters

4.3.3.1 Effect of filtercake and/or fertilizer application

The metabolic quotient for the US (23.8 µgCO_2-C/g/day) was 9.2 fold that of the RS (2.6 µgCO_2-C/g/day), but the microbial quotient of the RS (0.05) was 16.7 fold that of the US (0.003) before the start of the experiment (Table 4.11). According to Van Antwerpen et al. (2009) a metabolic quotient of greater than 10 µg C/g soil/day and a microbial quotient of smaller than 0.2 show that the soil microorganisms were under stress from a lack of N. Most of the metabolic and microbial quotient values recorded before the start of the experiment (Table 4.11) or during the experiment (Table 4.12) are indicative of N stress, but more severely so in the US. It could not be shown from the available data that the addition of FC significantly improved the metabolic and microbial quotients relative to the treatments without FC. It is possible that sampling was not done often enough to detect the effect of FC on the metabolic and microbial quotients, since these quotients varied over time (as discussed in section 4.3.3.2).

Table 4.11: Metabolic and microbial quotients of composite soil samples taken to a depth of 10 cm from the reconstituted soil (RS) and unmined soil (US) before the start of the experiment.

Source of sample	Metabolic quotient ---µgCO_2-C/g/day---	Microbial quotient
RS	2.59	0.05
US	23.84	0.003
Number of samples (N)	1	1

Table 4.12: Effect of filtercake and/or fertilizer application on metabolic and microbial quotients of soil samples taken to a depth of 10 cm during growth of the first ratoon crop. Values with different letters within a column differ significantly (p<0.05).

Treatment	Metabolic quotient -----µgCO$_2$-C/g/day---	Microbial quotient	Number of samples (N)
100 t/ha	27.85^a	0.01	4
3 x IF	16.63^a	0.03	4
IF	17.32^a	0.03	4
US	93.31^b	0.008	3
Average	*35.14*	*0.02*	-
LSD$_{0.05}$	28.13	ns[1]	-

[1] ns: Not significant

4.3.3.2 Change over time

There were large variations in the metabolic and microbial quotients over time (Figure 4.6). The metabolic quotient ranged between 9.41 to 35.14 µgCO$_2$-C/g/day and the microbial quotient from 0.02 to 0.06. Unfortunately, these variations could not be explained from available data, including temperature. More regular sampling could possibly have helped to explain the data.

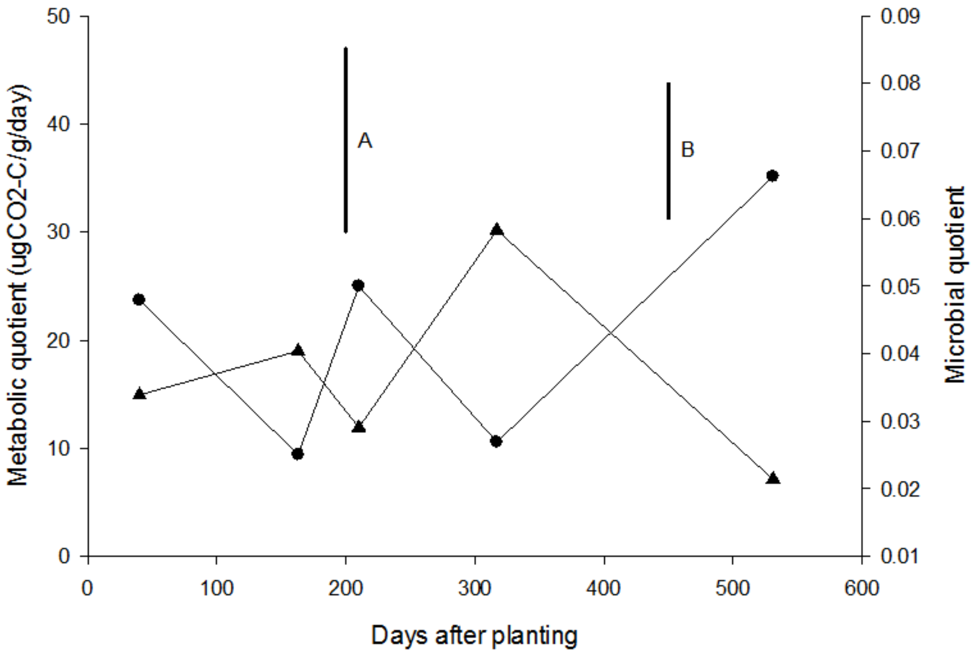

Figure 4.6: Change in metabolic (-•-) and microbial quotient (-▲-) over time. Values are means of the 100 t/ha FC, 3 x IF, and IF treatments. Vertical bars show LSD$_{0.05}$ (A = metablic quotient; B = microbial quotient).

4.3.4 Sugarcane growth response

4.3.4.1 Fractional light interception

As can be expected the fractional interception of photosynthetically active radiation (FI_{PAR}) increased significantly over time as the plants increased in size (Figure 4.7). This parameter increased from 0.4 at 234 days after planting to 0.8 at 273 days after planting. There was no indication of stress during this period.

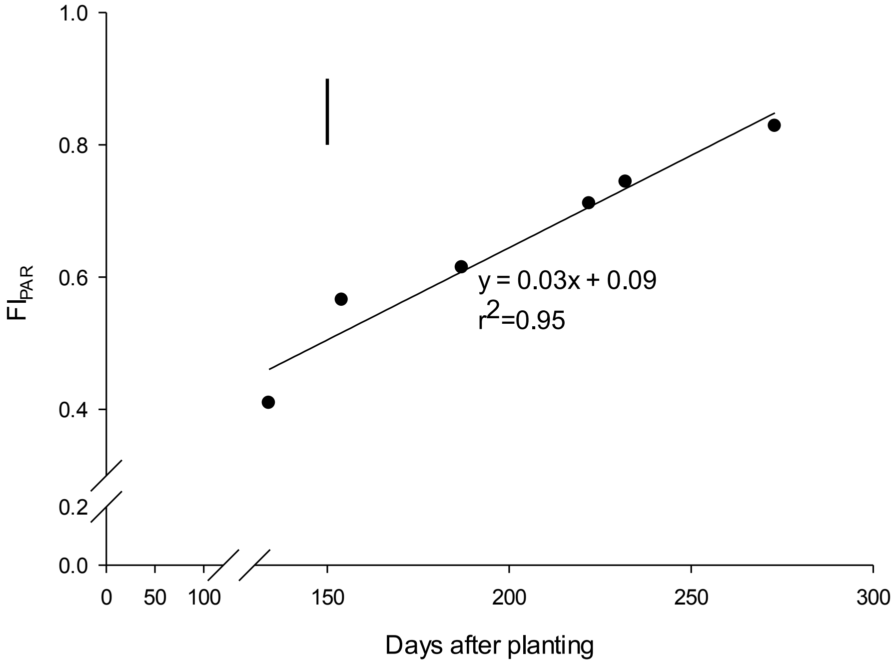

Figure 4.7: Change in fractional interception of photosynthetically active radiation (FI_{PAR}) for all treatments of the plant crop from 137 to 273 days after planting. Vertical bar shows $LSD_{0.05}$.

Significant FC and/or fertilizer application effects were observed for FI_{PAR} (Table 4.13). The 100 t/ha FC treatment had a significantly lower FI_{PAR} than the other treatments. This high FC application may have induced an acute N deficiency which resulted in stunted growth and hence the low FI_{PAR}. Thus, treatments where FC was applied showed a lower FI_{PAR} in comparison to treatments in which FC was not applied.

Table 4.13: Effect of filtercake and/or fertilizer application on the fractional interception of photosynthetically active radiation (FI_{PAR}) during the measuring period. Values with different letters within a column differ significantly ($p<0.05$).

Treatment	FI_{PAR}
10 t/ha FC	0.56^{aceg}
30 t/ha FC	0.63^{acg}
100 t/ha FC	0.35^{be}
3xIF	0.79^{ah}
IF	0.74^{af}
US	0.76^{ad}
Average	*0.64*
Number of samples (N)	24
$LSD_{0.05}$	0.13

4.3.4.2 Foliar nutrient content

4.3.4.2.1 Deficiencies and toxicities

There were large differences in leaf N between samples taken from the plant crop in February 2010 and June 2010 (1.58% and 2.14%) from that grown in the RS (Table 4.14). In the US, differences were smaller. All leaf samples taken from the RS in February 2010 contained N levels that were below the level (1.9%) considered adequate for sugarcane (FAS, 2004). Note that the N applied as urea in the RS for the establishment of the plant crop was split in two equal applications, which is the common practice. The first application of urea was at planting. At the time the first leaf samples were taken in February 2010 (five months after planting), the second application of urea had not been done, and therefore explains the low foliar N in most of these treatments. In the second set of leaf samples, which were taken in June 2010 (nine months after planting) after the second urea application had been done, the leaf N levels were within the optimal range for sugarcane growth in all treatments. The leaf P levels of the plants grown in the RS were 0.19% and 0.22% for the February 2010 and June 2010 samples, respectively, (Table 4.14). These levels indicated adequate P nutrition for sugarcane. Marginal phosphorus deficiency was noted in June 2010 leaf samples for US where the P content was 0.17% and this was probably the result of low soil P content in this soil (Table 4.8). No deficiencies of other nutrients were observed in this study. Both Mn and Fe were markedly higher in the second sampling (February 2010) than in the first sampling (June 2010).

The foliar Mn in the US, which varied from 59.6 to 302.3 mg/kg was considerably higher than the threshold value (15 mg/kg) for Mn in both February 2010 and June 2010 leaf samples. Likewise, the foliar Fe in the RS was also higher than the threshold for Fe (75 mg/kg), especially in samples taken in June 2010 where the Fe content was 304.5 mg/kg.

Brown spots indicative of Fe toxicity (Mengel and Kirkby, 1987; Marschner, 1995), were visible on the leaves of the plants growing in the RS (Figure 4.8).

Figure 4.8: A photograph of a sugarcane leaf showing brown spots.

Table 4.14: Summary of average foliar nutrient content during the experiment reconstituted soil (RS) and the unmined soil (US). Data for the RS in February 2010 were averages for all treatments, while data for June 2010 were averages for the 100 t/ha FC, IF and US treatments only.

Nutrient	Threshold value[1]	RS: Feb 2010	RS: June 2010	US: Feb 2010	US: June 2010
N (%)	1.90	1.58	2.14	2.06	1.99
P (%)	0.19	0.19	0.22	0.21	0.17
K (%)	1.05	1.06	1.29	1.24	1.08
Ca (%)	0.15	0.34	0.22	0.33	0.34
Mg (%)	0.08	0.17	0.13	0.14	0.14
S (%)	0.12	0.14	0.15	0.19	0.15
Si (%)	0.75	1.15	-	1.49	2.14
Zn (mg/kg)	13.00	16.33	35.57	18.33	18.33
Cu (mg/kg)	3.00	6.00	6.57	6.00	6.00
Mn (mg/kg)	15.00	59.61	98.00	251.33	302.33
Fe (mg/kg)	75.00	174.67	304.51	154.67	194.33
Number of samples (N)[2]	-	20	8	6	3

[1] After FAS (2004); [2] Note the unequal data sets between years

4.3.4.2.2 Plant crop in February 2010

Both the foliar Zn and Mn were significantly higher in plants grown in the US compared to plants grown in the RS (Table 4.15), probably due to the low pH of the soil (Table 4.7). Zinc uptake by plants increased with a decreasing soil pH (Mengel and Kirkby, 1987). In the February 2010 foliar analysis data, the leaf Mn and Zn correlated significantly ($p<0.01$) with soil pH ($r^2 = -0.81$ and $r^2 = -0.64$, respectively). Differences in foliar Zn and Mn for plants in the RS were not significant.

The foliar N was highest (2.1%) for plants grown in the US. In the RS soil, N was higher (but not significant) in the treatments where only inorganic fertilizer was applied compared to the treatments where FC was applied. In the 100 t/ha FC treatment, no inorganic N was applied during the first N application at planting (Table 4.9), since the FC theoretically contained sufficient N for sugarcane growth. The fact that plants in this particular treatment showed N deficiency is assumed to be a sign of N immobilization. Nitrogen immobilization was expected because of the high C:N ratio (Table 4.1) of the FC. Symptoms of N deficiency were visible in these plants (Figure 4.9). Nitrogen immobilization could also have been a contributing factor to the low foliar N contents in the 10 t/ha and 30 t/ha treatments which also showed visual N deficiency. In the 3 x IF treatment, more than the recommended amount of N had been applied at the time of taking the samples, and yet the foliar analysis showed that N was deficient (this deficiency was however not visually observed). Clearly, only an insufficient fraction of the applied N in this case was available for plant uptake. The reason for the N deficiency in the 3 x IF treatment is not certain, but leaching cannot be ruled out. In leaf samples taken in February 2010, there were no significant differences in foliar P, K, Ca, Mg, S, Si, Cu and Fe amongst FC and/or fertilizer treatments.

Figure 4.9: A photograph taken on the 8th of April 2010 (218 days after planting) showing severe N deficiencies in sugarcane in a 100 t/ha FC treatment plot. In the background is a 3 x IF treatment plot in which sugarcane did not show visual signs of N deficiency.

Table 4.15: Effect of filtercake and/or fertilizer application on the foliar nutrient content 5 months after planting of the plant crop in February 2010. Averages with different letters within a column differ significantly ($p<0.05$).

Treatment	N	P	K	Ca	Mg	S	Si	Zn	Mn	Cu	Fe	Number of samples (N)
	%							mg/kg				
10 t/ha FC	1.41a	0.18	1.01	0.34	0.17	0.12	0.97	16.25^{a}	57.25^{a}	6.00	194.25	4
30 t/ha FC	1.62a	0.18	1.01	0.35	0.17	0.12	1.00	16.33^{a}	62.67^{a}	6.00	154.00	4
100 t/ha FC	1.45a	0.17	1.04	0.33	0.14	0.12	1.37	16.25^{a}	49.25^{a}	6.00	201.25	4
3 x IF	1.70ab	0.19	1.11	0.35	0.18	0.15	1.14	16.33^{a}	63.67^{a}	6.00	134.67	4
IF	1.77ab	0.20	1.12	0.36	0.18	0.18	1.25	16.50^{a}	67.00^{a}	6.00	174.00	4
US	2.06b	0.21	1.24	0.33	0.14	0.19	1.49	18.33^{b}	251.33^{b}	6.00	154.67	6
Average	*1.70*	*0.19*	*1.10*	*0.34*	*0.16*	*0.15*	*1.24*	*16.83*	*107.54*	*6.00*	*169.67*	-
Threshold value[1]	1.90	0.19	1.05	0.15	0.08	0.12	0.75	13.00	15.00	3.00	75.00	-
LSD$_{0.05}$	0.45	ns[2]	ns[2]	ns[2]	ns[2]	ns[2]	ns[2]	1.40	57.47	ns[2]	ns[2]	-

[1] After FAS (2004); [2] ns = Not significant

4.3.4.2.3 Plant crop in June 2010

Foliar K was lowest in the US (1.08%) relative to the treatments in the RS (Table 4.16). This phenomenon could have been the result of low K content in the US. Both the foliar Ca and Mn contents were highest in the US when compared to the treatments in the RS. The foliar Ca content correlated negatively (r^2 = -0.73, $p<0.05$) with the foliar Fe content. Competitive suppression of Fe on Ca uptake has been noted previously (Mengel and Kirby, 1987). The high foliar Mn in the US could be expected under conditions of low soil pH (Mengel and Kirbky, 1987) in this soil.

Leaf Fe was highest in the 100 t/ha FC treatment (329 mg/kg), followed by the IF treatment (272 mg/kg). The lowest foliar Fe content was in the US (194 mg/kg). Since microbes in the soil use organic matter as substrate for respiration it is not surprising that an increase in organic matter can result in an increase in the availability of Fe in O_2 poor soils (Russell, 1973). Iron can be used as alternative electron acceptors in anaerobic respiration (Brady and Weil, 2004). The addition of FC at 100 t/ha could therefore have caused the observed higher foliar Fe content compared to treatments where no FC was added. Poor water drainage in the RS is believed to have resulted in an O_2 poor environment, which may have necessitated the use of Fe by microbes as an alternative electron acceptor. The foliar Fe correlated positively with the SWC in the 0 - 50 cm (r^2 = 0.58, $p<0.01$) and 50 - 100 cm (r^2 = 0.54, $p<0.05$) depth zones which also supports this hypothesis. An O_2 poor environment was however not expected in the US and therefore the foliar Fe content was relatively normal in this treatment. There were no significant differences amongst fertilizer application treatments for the foliar P, Mg, S, Zn and Cu in the June 2010 samples.

Table 4.16: Effect of filtercake and/or fertilizer application on the foliar nutrient content 9 months after planting of the plant crop (June 2010). Values are the average of 4 replicates and averages with different letters within in column differ significantly ($p<0.05$).

Treatment	N	P	K	Ca	Mg	S	Zn	Mn	Cu	Fe	Number of samples (N)
	%						mg/kg				
100 t/ha FC	2.33	0.26	1.25^{a}	0.23^{a}	0.14	0.16	26.75	100.25^{a}	7.25	329.00^{a}	4
IF	1.89	0.16	1.34^{a}	0.21^{a}	0.13	0.13	47.33	95.00^{a}	5.67	272.00^{b}	4
US	*1.99*	*0.17*	*1.08^{b}*	*0.34^{b}*	*0.14*	*0.15*	*18.33*	*302.33^{b}*	*6.00*	*194.33^{c}*	6
Average	*2.10*	*0.20*	*1.22*	*0.26*	*0.14*	*0.15*	*30.40*	*159.30*	*6.40*	*271.50*	-
Threshold value[1]	1.80	0.19	1.05	0.15	0.08	0.12	13.00	15.00	3.00	75.00	-
$LSD_{0.05}$	ns[2]	ns[2]	0.10	0.04	ns[2]	ns[2]	ns[2]	44.83	ns[2]	37.34	-

[1] After FAS (2004); [2] ns = Not significant

Table 4.17: Comparison of February and June 2010 foliar nutrient contents of the plant crop. Values are average of 24 replicates and averages with different letters within in column differ significantly ($p<0.05$). Values in brackets show standard error of mean (SEM).

Sampling time	N	P	K	Ca	Mg	S	Zn	Mn	Cu	Fe
	%						mg/kg			
Feb 2010	1.87	0.20	1.15	0.34^{a}	0.15^{a}	0.17	17.31	151.08	6.00	172.46^{a}
	(±0.10)	(±0.01)	(±0.05)	(±0.01)	(±0.006)	(±0.01)	(±0.36)	(±28.79)	(±0.00)	(±12.92)
Jun 2010	2.10	0.20	1.22	0.26^{b}	0.14^{b}	0.15	30.40	159.30	6.40	271.50^{b}
	(±0.11)	(±0.02)	(±0.04)	(±0.02)	(±0.005)	(±0.01)	(±7.28)	(±31.59)	(±0.37)	(±19.42)
Average	*1.97*	*0.20*	*1.18*	*0.30*	*0.15*	*0.16*	*23.00*	*154.65*	*6.17*	*215.52*
Threshold value[1]	1.90 (plant) 1.80 (ratoon)	0.19	1.05	0.15	0.08	0.12	13.00	15.00	3.00	75.00
Significance	ns[2]	ns[2]	ns[2]	$p<0.05$	$p<0.05$	ns[2]	ns[2]	ns[2]	ns[2]	ns[2]

[1] After FAS (2004); [2] ns = Not significant

4.3.4.2.4 Comparison of February 2010 and June 2010 data

As already pointed out, Ca and Fe have an antagonistic adsorption effects in soils (Mengel and Kirkby, 1987). This could explain why the foliar Ca decreased from February 2010 to June 2010, while the foliar Fe showed the opposite response (Table 4.17). The reason for the lower foliar Mg in the June 2010 samples than in the February 2010 samples were not certain, but it possibly corresponded to a decrease in soil Mg (Table 4.8) in the RS. The foliar N, P, K, S, Zn, Mn and Cu did not change significantly between the two sampling times tested. What should be noted is the increase in foliar P in 100 t/ha FC treatment from 0.17% in February 2010 to 0.26% in June 2010. This shows that P contained in the FC was not yet mineralized in February 2010, but was available for plant uptake at the time of the June 2010 analysis.

4.3.4.3 Cane, sucrose and aboveground biomass yields

4.3.4.3.1 Cane yield

Plants grown in US showed the highest cane yield (6.43 t/ha/month) and the 100 t/ha FC treatment the lowest cane yield (1.87 t/ha/month) in the plant crop (Figure 4.10). Nitrogen deficiencies which occurred early in the experiment in plants grown in the RS, could have reduced the yield. However foliar N content in leaves sampled in February 2010 (which showed a low foliar N for plants in the RS) did not correlate significantly with the cane yield. The Canesim model predicted periods of waterlogging induced stress from 29 to 103 days after planting. As was the case with the gypsum field experiment (section 3.3.4.3.1), the actual SWC, as measured with the Diviner instrument, was consistently higher than the SWC predicted with Canesim. It is assumed then that the effect of waterlogging was more severe than the model predicted in the plant crop, and probably explains the lower actual yield in all treatments in RS than the predicted yield. Yield simulations were not done in the US, because complete soil data was not available for this soil.

The cane yield of the plant crop correlated significantly with a number of parameters, including SWC (0 – 50 cm depth zone), MWD, soil Ca:Mg ratio, foliar Mn and foliar Fe (Table 4.18). A more detailed analysis showed a linear or curvilinear relationship between cane yield and these parameters (Figures 4.11 to 4.13). The relationships indicated that poor aeration in the RS (which was likely the result of soil dispersion and poor drainage) resulted in Fe toxicity that in turn had a negative effect on the cane yield. It is known that soil Mn and Fe are antagonistic and high soil Fe content can result in reduced uptake of Mn (Mengel and Kirkby, 1987). This relationship was also reflected by the significant negative correlation between foliar Fe and foliar Mn ($r^2 = -0.80$, $p<0.01$). However, the foliar Mn for plants in the RS was still much higher than the threshold value of 15 mg/kg and the reason for the positive correlation between cane yield and foliar Mn is therefore specific for the given situation. Applying inorganic fertilizer at three times the recommended rate did not significantly improve cane yield as compared to applying it at the normal recommended rate.

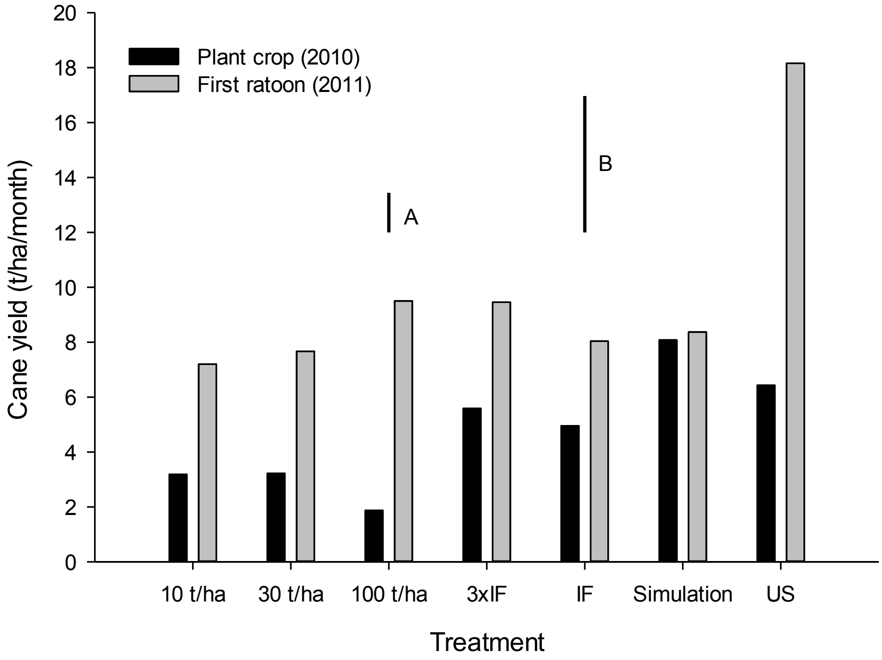

Figure 4.10: Effect of filtercake and/or fertilizer application on actual cane yield in reconstituted soil (RS) and unmined soil (US) during the experiment and simulated cane yield with Canesim model. Vertical bars show LSD$_{0.05}$ (A = plant crop, B = 1st ratoon crop).

Table 4.18: Correlation coefficients (r^2-values) resulting from correlations of cane, sucrose and aboveground biomass (ABM) yields with soil water content (SWC), mean weight diameter of soil aggregates (MWD), soil Ca:Mg ratio, soil Mg:K ratio and foliar Mn and Fe of the plant crop.

	Cane yield	Sucrose yield	ABM yield
SWC (0 – 50 cm)	-0.55^{2}	-0.40^{1}	-0.60^{2}
MWD	0.50^{2}	0.31^{ns}	0.61^{2}
Soil Ca:Mg	0.53^{2}	0.33^{ns}	0.59^{2}
Soil Mg:K	-0.37^{ns}	-0.14^{ns}	-0.54^{1}
Foliar Mn[4]	0.70^{2}	0.47^{ns}	0.79^{2}
Foliar Fe[4]	-0.51^{1}	0.47^{ns}	-0.56^{1}

^{1} = Significant, $p<0.05$; ^{2} = Significant $p<0.01$; ^{ns} = Not significant; [4]Foliar data for February 2010 and June 2010 were combined for this analysis

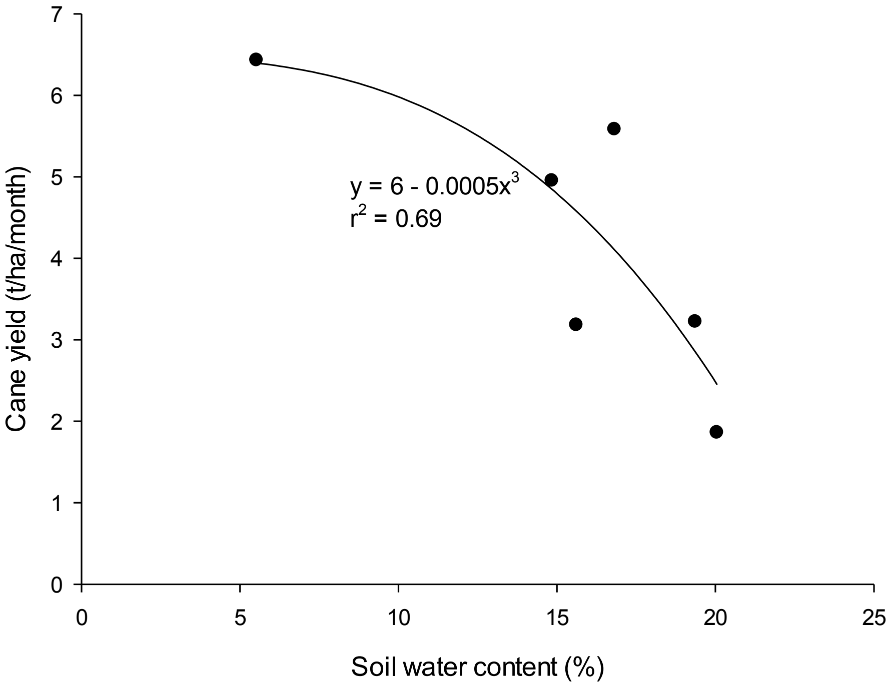

Figure 4.11: Effect of soil water content (SWC) (0 – 50 cm depth zone) on the cane yield for the plant crop. Data points represent averages.

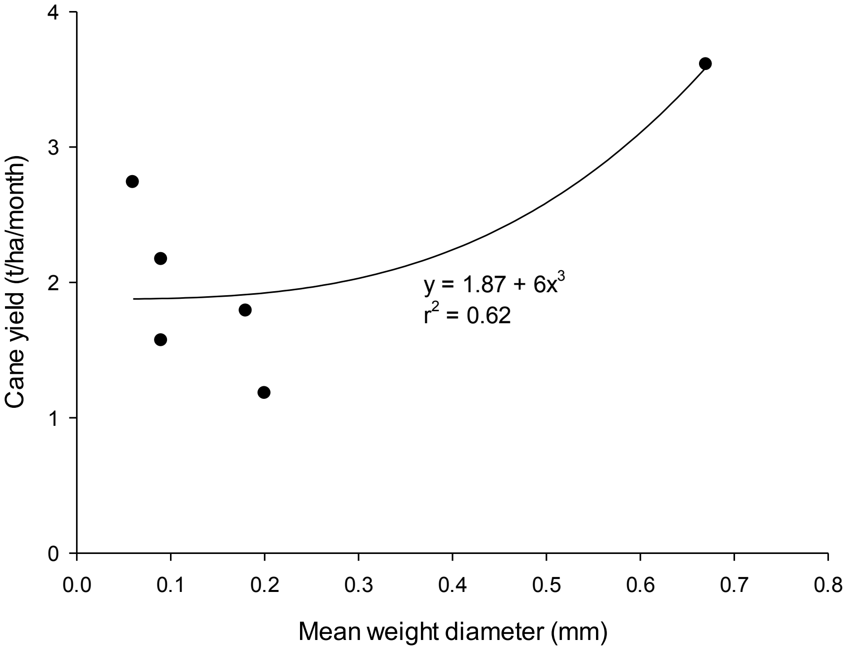

Figure 4.12: Effect of mean weight diameter (MWD) on the cane yield of the plant crop. Data points represent averages.

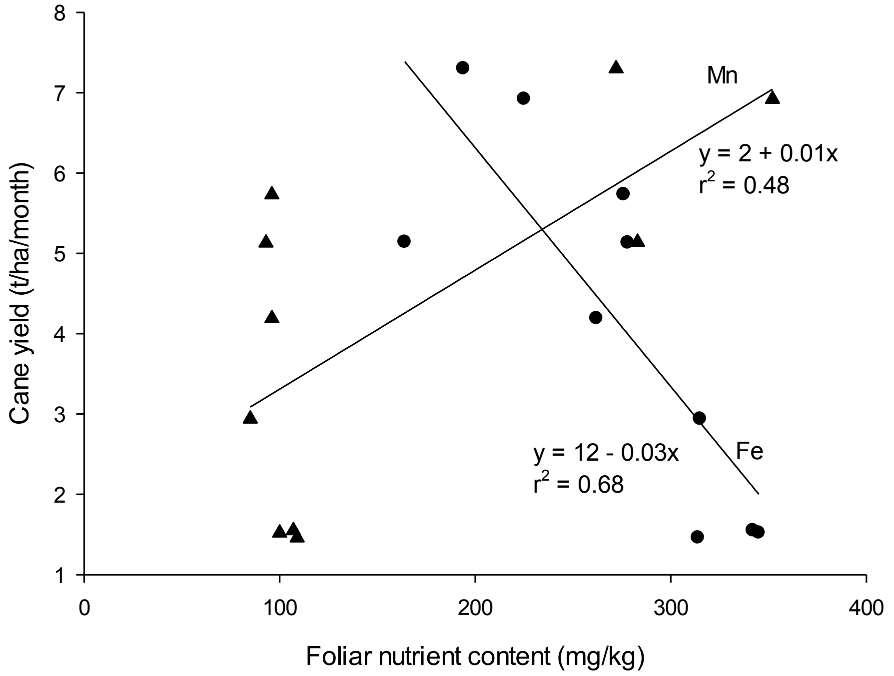

Figure 4.13: Effect of foliar manganese (Mn) (-▲-) and iron (Fe) (-•-) on the cane yield of the plant crop. Data points represent raw data.

Cane yield in the first ratoon crop of the RS did not differ significantly between the treatments, and the actual yield compared well with the simulated yield (Figure 4.10). The Canesim model predicted very short periods of waterlogging induced stress during the first ratoon period that were also less in severity than those of the plant crop. Furthermore, no drought was predicted by the model for the first ratoon period. The cane yield in the US (18.2 t/ha/month) was significantly and markedly higher than in the RS (<9.5 t/ha/month). The six plots in the US were situated very close to a water canal. About two months before harvesting, the canal overflowed its banks because of an obstruction to its water flow upstream which resulted in the six plots being temporarily flooded. Unfortunately it could not be determined how this flooding affected the yield which could have been either positively or negatively.

4.3.4.3.2 Sucrose yield

The trends in the response of the sucrose yield to treatments were very similar to those for the cane yield in both the plant and first ratoon crops (Figure 4.14). Sucrose yield in the plant crop varied between 0.9 t/ha/month in the 3 x IF treatment to 0.3 t/ha/month in the 100 t/ha FC treatment. For the plant crop, the sucrose yield of all treatments was lower in the RS than the sucrose yield predicted with the Canesim model, possibly because the model underestimated the effect of waterlogging. As with the cane yield, it is assumed that the sucrose yield in the plant crop was affected by the initial N deficiencies. The sucrose yield of the plant crop did not correlate well with SWC (0 – 50 cm depth zone), MWD, soil Ca:Mg, soil Mg:K or foliar Fe and Mn (Table 4.18).

In the ratoon crop, the sucrose yield of the treatments in the RS corresponded well with the simulated yield. The sucrose yield did not differ significant amongst FC and /or fertilizer application treatments in the RS. As was also the case with the cane yield, the sucrose yield of the plants in the US was considerably higher than in the RS.

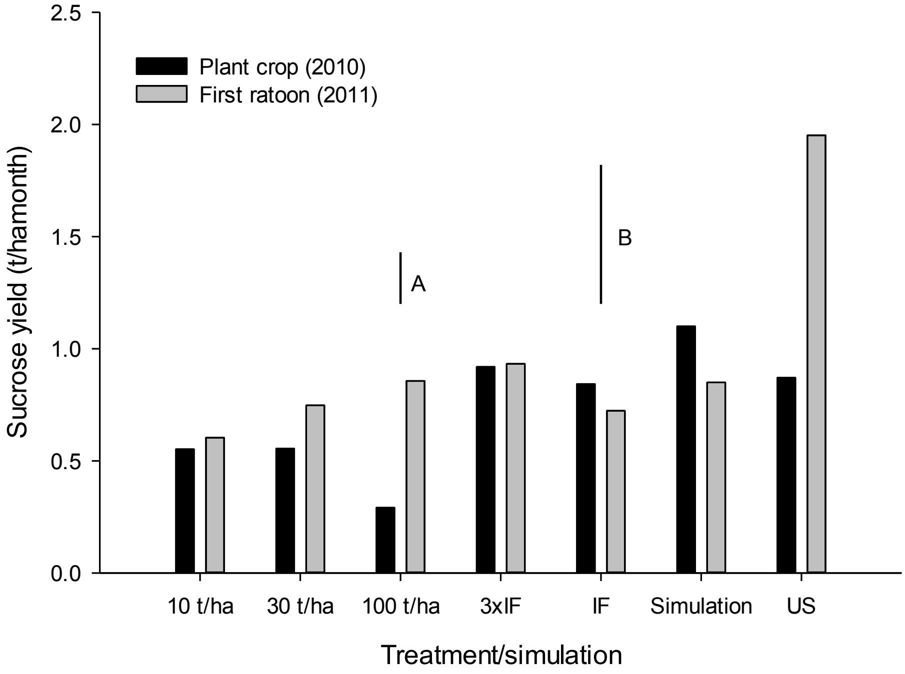

Figure 4.14: Effect of filtercake and/or fertilizer application on actual sucrose yield in the reconstituted soil (RS) and unmined soil (US) during the experiment and simulated sucrose yield with Canesim model. Vertical bars show $\mathbf{LSD_{0.05}}$ (A = plant crop, B = $\mathbf{1^{st}}$ratoon crop).

4.3.4.3.3 Aboveground biomass yield

The ABM yield in the plant crop was highest in the US (Figure 4.15). As with the sucrose and cane yields, the ABM yield was lowest in the 100 t/ha FC treatment. The ABM yield correlated significantly with SWC (0 – 50 cm zone), MWD, soil Ca:Mg, soil Mg:K ratio, foliar Mn and foliar Fe (Table 4.18). The relationships between ABM yield and SWC, MWD and foliar Mn and Fe were similar to that of cane yield (Figures 4.11 to 4.13) and data was thus not shown. Aboveground biomass yield was therefore also negatively affected by Fe toxicity resulting from poor aeration in the RS. As with cane yield, ABM yield showed a positive correlation with foliar Mn content. The relationship between ABM yield and the soil Ca:Mg and Mg:K ratios were linear (Figures 4.16 and 4.17).

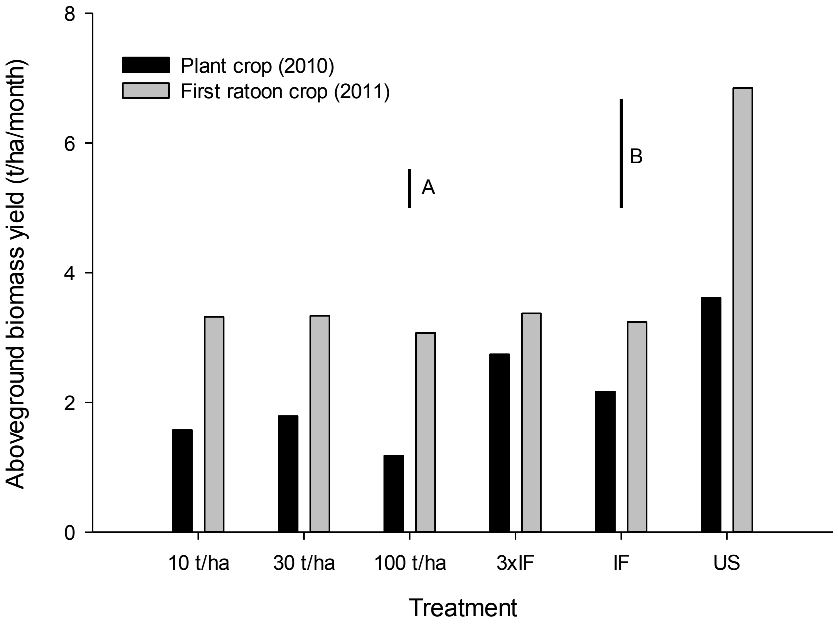

Figure 4.15: Effect of filtercake and/or fertilizer application on the aboveground (ABM) yield in the reconstituted soil (RS) and unmined soil (US). Vertical bars show $LSD_{0.05}$ (A = plant crop, B = 1st ratoon crop).

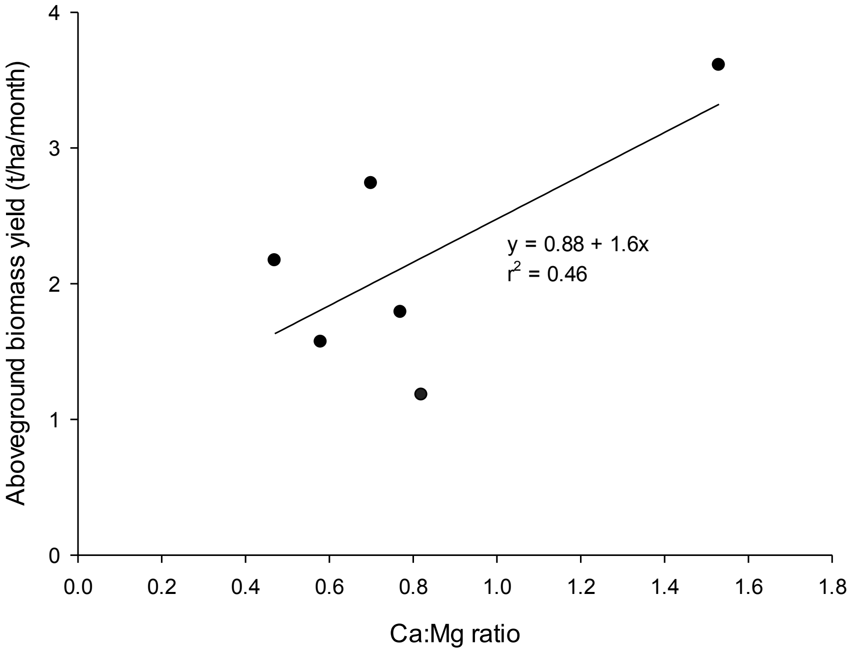

Figure 4.16: Effect of soil Ca:Mg ratio on the cane yield of the plant crop. Data points represent averages.

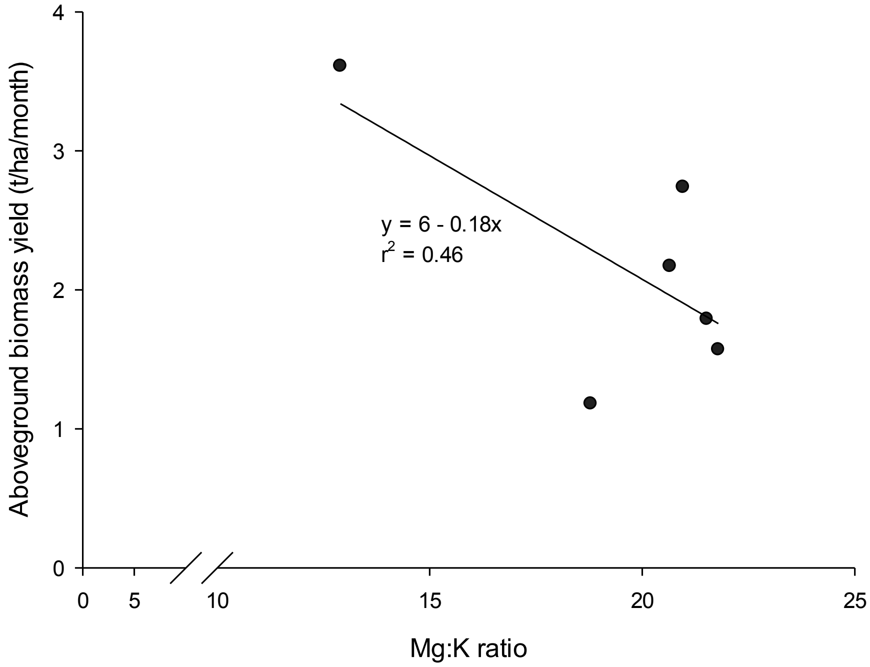

Figure 4.17: Effect of soil Mg:K ratio on the aboveground (ABM) yield of the plant crop. Data points represent averages.

4.3.4.3.4 Comparison of plant and first ratoon crop yields

The cane, sucrose and ABM yields were significantly higher in the first ratoon crop than in the plant crop (Table 4.19). In the US alone, the differences in the cane, sucrose and ABM yields were 183, 124 and 90%, respectively. Variety N41 is known for the tendency of its yield to improve with ratoons (SASA, 2003). It is interesting that in section 3.3.4.3.4 reporting the effects of gypsum application, a significant decline in yields where observed from the first to the second ratoon crop. This decline was explained by the late application of fertilizer. In the current experiment, fertilizer was also applied late, yet the yield increased.

Table 4.19: Comparison of sucrose, cane and aboveground biomass (ABM) yields of plant and first ratoon crops. Averages with different letters within columns differ significantly ($p<0.05$). Values in brackets show standard error of mean (SEM).

Year	Cane yield	Sucrose yield	ABM yield
	------------------------t/ha/month		----------------------
Plant crop	1.88^{a} (±0.37)	0.27^{a} (±0.05)	0.96^{a} (±0.19)
First ratoon	5.27^{b} (±1.05)	0.64^{b} (±0.13)	1.86^{b} (±0.37)
Average	*5.04*	*0.52*	*1.73*
Significance	$p<0.05$	$p<0.05$	$p<0.05$

4.3.4.3.5 Tiller number, stalk length and stalk diameter

Stalk length (SL) correlated significantly with cane ($r^2 = 0.86$, $p<0.01$) sucrose ($r^2 = 0.90$, $p<0.01$), and ABM ($r^2 = 0.62$, $p<0.01$) yields. However, neither tiller number (TN) nor stalk diameter (SD) correlated significantly with any of these yields. The plant crop grown in US had higher TN, SL and SD than any of the treatments in the RS (Table 4.20). The plant crop in the 100 t/ha FC treatment also had a relatively high TN (14.23 per m^2) and SD (2.3 cm) in comparison to the other treatments in the RS, but had the lowest SL (75.9 cm). It is concluded then that SL, rather than TN and SD, was the most important contributor to the observed differences amongst treatments in cane, sucrose, and ABM yield in the plant crop.

Table 4.20: Effect of filtercake and/or fertilizer application on tiller number, stalk length and stalk diameter for the plant crop. Values with different letters within a column differ significantly ($p<0.05$).

Treatment	Tiller number	Stalk length	Stalk diameter	Number of samples (N)
	----per m^2----	------------------cm	-----------------	
10 t/ha FC	12.50^{abcd}	160.22^{ab}	2.10^{acd}	4
30 t/ha FC	10.09^{acd}	182.36^{b}	2.03^{ac}	4
100 t/ha FC	14.23^{bcd}	75.89^{a}	2.32^{abd}	4
3 x IF	12.69^{abcd}	215.86^{b}	2.06^{acd}	4
IF	11.34^{abc}	192.99^{b}	2.12^{acd}	4
US	14.74^{bd}	219.14^{b}	2.38^{bcd}	6
Average	*12.76*	*177.85*	*2.18*	-
$LSD_{0.05}$	2.34	60.97	1.80	-

The first ratoon crop in the US had a significantly higher SL than the first ratoon crop in the RS (Table 4.21). On average, the SL of these plants in the US was 154.0 cm, while in the RS it varied from 57.5 to 67.1 cm. There were no significant differences amongst the treatments with regards to SD. The 10 t/ha FC treatment had the highest TN (18.50 per m^2) but the lowest SL (574.89 mm) and SD (19.81 mm) of all treatments. The reason for this is not known. Stalk length correlated significantly ($p<0.01$) with cane, sucrose and ABM yield ($r^2 = 0.88$, $r^2 = 0.89$ and $r^2 = 0.87$, respectively). The TN did not correlate significantly with any of these yields.

Table 4.21: Effect of filtercake and/or fertilizer application on tiller number (TN), stalk length (SD) and stalk diameter (SD) of the first ratoon crop. Averages with different letters within a column differ significantly ($p<0.05$).

Treatment	Tiller number (TN)	Stalk length (SL)	Stalk diameter (SD)	Number of samples (N)
	------per m^2--------	---------------------cm---------------------		
10 t/ha FC	18.50^{a}	57.49^{a}	1.98	4
30 t/ha FC	12.50^{b}	65.51^{a}	2.10	4
100 t/ha FC	14.00^{b}	53.61^{a}	2.12	4
3 x IF	14.00^{b}	67.05^{a}	2.43	4
IF	12.67^{b}	60.54^{a}	2.66	4
US	16.17^{ab}	154.02^{b}	2.23	6
Average	*14.84*	*83.22*	*2.09*	-
$LSD_{0.05}$	4.09	19.20	ns[1]	-

[1] ns: Not significant

When comparing the sugarcane yield recorded in this experiment to that of the simulated yield with the Canesim model, the postulated benefit of FC in the RS could not be demonstrated due to an acute induced N deficiency. However, the experiment probably not run for a long enough time for the FC to have a significant effect on sugarcane growth. The FC also appeared to be mineralized quickly in the RS, which might require more frequent FC applications. Despite this, FC was effective in overcoming Mg-related dispersion when added at a rate of 100 t/ha. The downside of FC application appeared to be immobilization of N. However, this can be prevented by supplying additional N with the FC or by using a source of organic matter with a higher C:N ratio (Barbarick, 2011).

It was clear from the results that waterlogging in the RS had a negative effect on sugarcane growth. The addition of FC to the waterlogged RS was even more detrimental by causing Fe toxicity. Applying organic matter to RS with high water content should therefore be avoided.

4.4 CONCLUSIONS

The addition of FC to the RS did not significantly improve sugarcane yield as compared to treatments in which inorganic fertilizer was applied alone. Applying inorganic fertilizer at three times the recommended rate also did not significantly improve yield, relative to applying it at the recommended rate. The performance of the plant crop in the RS was poorer in treatments in which FC was applied in the RS than in the US due to N immobilization and Fe toxicity. The non-amended RS showed Mg-related dispersion, but the addition of FC at a rate of 100 t/ha was able to overcome Mg-related dispersion. Aggregate stability was not significantly higher in any of the FC treatments as compared to the other treatments in the RS.

CHAPTER 5

EFFFECT OF INORGANIC PHOSPHORUS APPLICATION ON PROPERTIES OF A RECONSTITUTED SOIL AT HILLENDALE MINE AND RESULTING SUGARCANE GROWTH THEREON

ABSTRACT - *A field experiment was conducted on a reconstituted soil at the Hillendale mine to test the effect of inorganic phosphorus (P) application and its availability to the plant, first and second ratoon sugarcane crop. Four treatments were evaluated including treatments where P fertilizer was either omitted, applied at half the recommended rate or applied equal to the recommended rate according to chemical analysis of the soil. In the fourth treatment no fertilizer was applied at all, whereas nitrogen (N) and potassium (K) were applied at recommended rates in the first three treatments. Fertilizer application had a highly significant effect on cane, sucrose and aboveground biomass (ABM) yield. The application of P resulted in improved uptake of N, P, K, calcium (Ca), sulphur (S) and magnesium (Mg) in the plant crop. In the first ratoon crop, cane, sucrose and ABM yield correlated significantly and negatively with soil water content and positively with foliar N, P and K. All these three nutrients were deficient in the treatment where N, P and K were applied at the recommended rate. Waterlogging was likely responsible for limiting the uptake of these nutrients that in turn affected sugarcane growth negatively. Thus, applying fertilizer at recommended rates was not adequate for optimal sugarcane growth in the reconstituted soil under waterlogged conditions in this experiment. In the second ratoon crop, cane, sucrose and ABM yield was also relatively low likely because of waterlogging and nutrient deficiencies.*

5.1 INTRODUCTION

At the Hillendale mine, the site of this study, the soil analysis done of post-mined soil has revealed low levels of P (Golder Associates, 2004). A chemical analysis of the non-amended soil used in field experiments of which results were discussed in previous chapters also revealed low levels of P. This study was therefore conducted at Hillendale on the reconstituted post-mined soil to investigate the availability of P for sugarcane growth.

Phosphorus is an essential element for plant growth and is an integral component of several important compounds in plant cells (Taiz and Zeiger, 1991). It is often regarded as the second most limiting plant nutrient in soils, after nitrogen (Salisbury and Ross, 1992). Even when present in a soil, P may not be available to plants, because of fixation (sorption). When P is fixed, it is tightly bound to mineral surfaces, especially at both high and low pH extremes, leading to restricted P mobility in the soil (Fertilizer Industry Federation of Australia, 2000; Brady and Weil, 2008). In addition, when soluble P is added to soil in fertilizers, it reacts and combines with many components in soil such as Al, Fe and Mn in acid soils and Ca in alkaline soil, forming complex insoluble components (Fertilizer Industry Federation of Australia, 2000; Brady and Weil, 2008). The availability of soil P is therefore very dependent on soil reaction and mineralogy.

In the South African sugarcane industry, the extractable soil P is typically determined with the Truog extraction method which also forms the basis of P fertilizer recommendations (Hendry et al., 1993; FAS, 2004). Recommendation for P application, as based on the Truog method, can vary between 0 and 80 kg/ha P (FAS, 2004). In addition to the Truog extraction method, the phosphorus desorption index (PDI) is used to recognize soils with a high P fixing ability. In such soils, additional P application is advised to compensate for P fixation (Reeve and Sumner, 1970; Meyer and Dicks, 1979; FAS, 2004). Soils with a low P fixing ability have PDI values greater than 0.4 (FAS, 2004).

Whilst P application must be done, the applications must be balanced, since both low and extremely high levels of soil P can limit growth (Mengel and Kirby, 1987).

5.2 MATERIAL AND METHODS

5.2.1 Treatments and experimental design

The P experiment was conducted on a mined-out area that was back-filled with a 70:30 sand-slimes (silt + clay fraction) mixture to a depth of 1.8 m. There were four fertilizer application treatments laid out in a complete randomized block design with four replicates and a plot size of 10 m x 8 m. In one treatment no fertilizer was applied (‘NF treatment’). In the other three treatments P was either omitted (‘0 P treatment’) or applied as single superphosphate (10,5% P) at half the recommended rate (‘0.5 P treatment’) or at the recommended rate (‘1 P treatment’). Potassium and N and were applied in the 0 P, 0.5 P and 1 P treatments either as the compound fertilizer 2:0:3 (49) or separately as potassium chloride (50% K) and urea (46% N) or limestone ammonium nitrate (28% N) also at recommended rates. The recommended rates by Fertiliser Advisory Service (FAS) of the South African Sugarcane Research Institute (SASRI) as based on soil analysis were 100 kg/ha N, 70 kg/ha P and 175 kg/ha K. All fertilizer was band placed at planting and top-dressed in the first and second ratoon crops. The treatments for the plant, first ratoon and second ratoon crops were the same.

5.2.2 Plant management

Sugarcane cultivar N41, which is well suited for dry-land cultivation in the area (SASA, 2003), was planted in 1 m inter-row spacing on 20 February 2009. The first sugarcane harvesting was done on 15 September 2009 (seven months after planting) and the first-ratoon crop harvested on 22 November 2010 (fourteen months after ratooning). The experiment was terminated with the final harvesting (second-ratoon crop) on 20 June 2011 (seven months after the first ratoon). No trashing was done at harvest.

5.2.3 Data collection

Rainfall data was collected on the Hillendale mine premises during the experiment (Table 5.1). Data collection was similar to that of the gypsum field experiment (section 3.2.3), but sampling was done at different times (Table 5.2). The phosphorus desorption index (PDI) was determined from the composite soil sample collected in July 2008 for its soil fertility status (Table 5.2, section 3.2.3.2.1) using the method of Reeve and Sumner (1970).

Table 5.1: Monthly rainfall as recorded from the start of the experiment until termination.

Year	Month	Total rainfall (mm)	Year	Month	Total rainfall (mm)
2009	February	33.2	2010	May	64.9
2009	March	31.1	2010	June	18.1
2009	April	27.4	2010	July	44.8
2009	May	26.8	2010	August	30.0
2009	June	22.5	2010	September	30.3
2009	July	17.9	2010	October	85.5
2009	August	139.9	2010	November	100.4
2009	September	33.3	2010	December	94.6
2009	October	98.7	2011	January	208.2
2009	November	138.5	2011	February	72.8
2009	December	62.7	2011	March	118.3
2010	January	103.5	2011	April	136.8
2010	February	85.6	2011	May	42.2
2010	March	159.07	2011	June	55.4
2010	April	70.6			

Table 5.2: Summary of the sampling times and treatments measured during the phosphorus field experiment. Details can be found in the listed sections as they are similar to that of the gypsum field experiment.

Section for details	Sampling time	Treatments measured	Comments
3.2.3.1 Soil physical parameters			
3.2.3.1.1 Particle size analysis	Jul 2010	All	
3.2.3.1.2 Soil water content	Sep 2009 to Jul 2010	All	Measured weekly. Since the Diviner instrument was stolen the measurements were divided into two periods – as measured with original and replacement instrument, respectively.
3.2.3.1.3 Penetration resistance	Jun 2009	All	Measured before the start of experiment
	Jul 2010	NF and 1 P	Treatments represented extremes.
3.2.3.1.4 Aggregate stability	Aug 2010	All	
3.2.3.2 Soil chemical parameters			
3.2.3.2.1 Soil fertility status	Jul 2008	Composite sample	Sample taken before start of experiment
	Jun 2009	Composite sample from 0P, 0.5 P and 1P treatments	Samples taken for fertilizer purposes.
	Jul 2010	All	
3.2.3.2.2 Magnesium related dispersion	Feb 2011	NF and 1 P, as well a composite sample from non-amended soil in the experimental area.	Treatments represented extremes.
3.2.3.3 Soil microbiological parameters	Sep 2008	Composite sample only	Sample taken before start of experiment
	Sep 2009	NF and 1 P	Treatments represented extremes.
	Feb 2011	NF and 1 P	Treatments represented extremes.

Table 5.2: A summary of the sampling and measurements taken during the experiment (cont.).

Section for details	Sampling time	Treatments measured	Comments
3.2.3.4 Sugarcane growth response			
3.2.3.4.1 Fractional light interception	Plant crop: 125, 133,139,159,173 and 190 days after planting	All	Days were randomly selected.
	First ratoon crop: 121, 174, 209, 219 and 260 days after planting	All	Days were randomly selected.
3.2.3.4.2 Foliar nutrient content	May 2009 (4 months after planting)	All	
	Feb 2010 (5 months after ratooning)	All	
	Jun 2010 (8 months after ratooning)	NF and 1 P	Treatments represented extremes.
3.2.3.4.3 Cane yield	Sep 2009	1P	Only plants of 1 P treatment were large enough for sampling
	Nov 2010	All	
	Jun 2011	All	
3.2.3.4.3 Sucrose yield	Sep 2009	1P	Only plants of 1 P treatment were large enough for sampling
	Nov 2010	All	
	Jun 2011	All	
3.2.3.4.3 Aboveground biomass (ABM) yield	Sep 2009	All	
	Nov 2010 Jun 2011	All	
3.2.3.4.3 Tiller number, stalk length and stalk diameter	Nov 2010	All	
	Jun 2011	0 P, 0.5 P and 1 P	Because of small plant size, stalk length and stalk diameter were not determined in NF treatment

5.2.4 Statistical analysis

All statistical analyses were performed using GenStat12 software (VSN International, 2009). Where possible, means were separated by LSD (least significant difference) at 5 % significance level.

5.3. RESULTS AND DISCUSSION

5.3.1 Soil physical parameters

5.3.1.1 Particle size distribution

The slimes content varied between 17.3% and 22.0% with an average of 19.3% in the top 20 cm of soil (Table 5.3). This was markedly lower than the target value of 30%. The slimes content was slightly higher in the NF and 0.5 P treatments than in the 1P treatment, but not significantly so. Also, neither the clay contents nor the silt contents differed significantly among treatments.

Table 5.3: Particle size distribution of soil taken to a depth of 20 cm in the fertilizer treatment plots. Values are the average of 4 replicates and values in brackets indicate the standard error of mean (SEM).

Fertilizer application	Clay	Silt	Slimes (slit + clay)	Sand
	--------	--------	--------%--------	--------
NF	16.25 (±0.95)	5.75 (±0.85)	22.00 (±1.73)	78.00 (±1.73)
0 P	12.25 (±2.06)	5.00 (±0.41)	17.25 (±1.93)	82.50 (±1.71)
0.5 P	15.00 (±0.82)	5.00 (±1.00)	20.00 (±1.29)	78.00 (±1.29)
1 P	12.75 (±2.39)	5.00 (±0.58)	17.75 (±2.87)	82.25 (±2.87)
Average	*14.06*	*5.19*	*19.25*	*80.19*
$LSD_{0.05}$	ns[1]	ns[1]	ns[1]	ns[1]

[1] ns = Not significant

5.3.1.2 Soil water content

5.3.1.2.1 February 2009 to July 2009

A significant measuring time x soil depth interaction was observed (Figure 5.1). The general trend was similar to that observed in the gypsum field experiment for the same period (as discussed in section 3.3.1.2.1) in that the soil water content (SWC) decreased linearly in all three depth zones over time and that the SWC was progressively higher with an increase in soil depth. The SWC followed the same pattern as the rainfall, although the correlation between SWC and the average monthly rainfall was not significant (r^2 = 0.44). The SWC in this interaction varied between 11.4% and 40.0%. Drying occurred at a faster rate in the 0 – 50 cm depth zone than in the other two zones. This shows that most water lost during this period occurred close to soil surface.

Assuming uniform slimes content in the reconstituted soil profile, a theoretical calculation of field capacity and saturation (Schultze et al., 1985; Van Rensburg, 1988; Van Antwerpen (1994); Meyer and Van Antwerpen, 1995) gave values of 18 and 28%, respectively. As was the case in the other field experiments (sections 3.3.1.2 and 4.3.1.2), the SWC exceeded saturation in many cases. This indicates that the slimes content in these zones was higher than in the top 20 cm of soil (as was also pointed out in previous chapters). Also, for most of this measuring period (with the exception of the period between May 2009 and July 2009 in the 0 – 50 cm depth zone), the SWC in all three depth zones was higher than field capacity, which indicates a draining limitation in the soil or that the slimes content was higher in these zones than in the top 20 cm of soil or both. A similar drainage limitation in the reconstituted soil has been reported in a previous study at Hillendale (Van Jaarsveld and Zharare, 2010). Visual observation of the soil during the experiment confirmed that it was indeed very wet. The SWC did not differ significantly amongst treatments in this measuring period (February 2009 to July 2009).

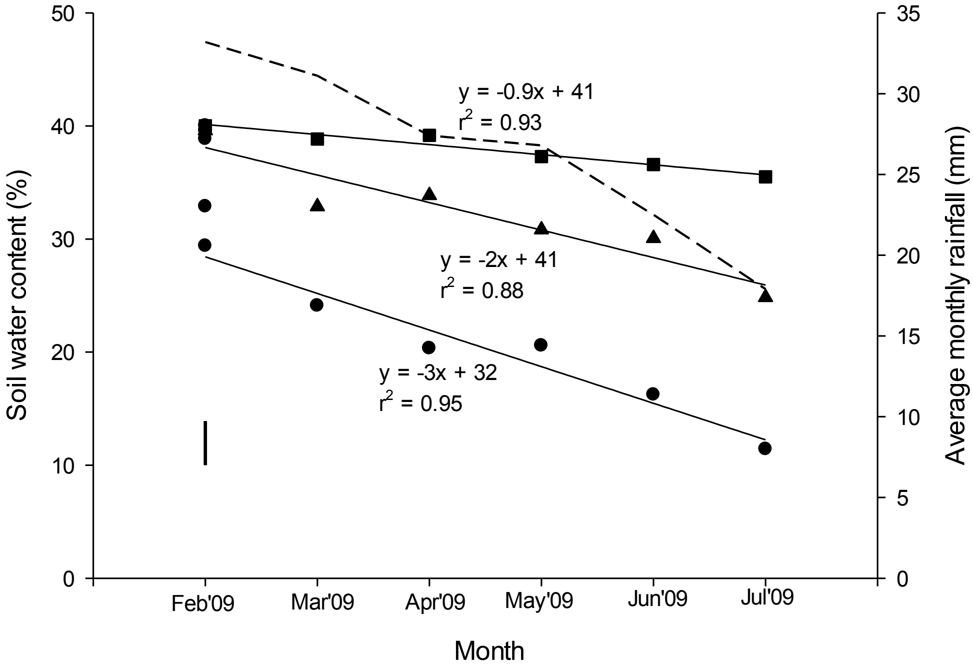

Figure 5.1: Change in soil water content (SWC) for the 0 – 50 cm depth zone (-●-), 50 – 100 cm depth zone (-▲-) and 100 - 150 cm depth zone (-■-) during the period of February 2009 to July 2009 as an average of fertilizer application rate. The dotted line shows the average monthly rainfall and vertical bar represents $LSD_{0.05}$ for the interaction.

5.3.1.2.2 September 2009 to July 2010

For the above period, significant measuring time x soil depth and fertilizer application x soil depth interactions were observed with SWC (Figure 5.2). In measurements taken after July 2010 with the replacement probe, the SWC was also lowest in the 0 – 50 cm depth zone (average 16.2%) and highest in the 100 – 150 cm zone (average 37.2%). The SWC showed a similar trend to that of the other field experiments for the same period (sections 3.3.1.2 and 4.3.1.2) with low correlation with average monthly rainfall ($r^2 = 0.26$). Similar to the previous measuring period, much of the water in this period was held above the estimated field capacity (18%) and saturation (28%) values.

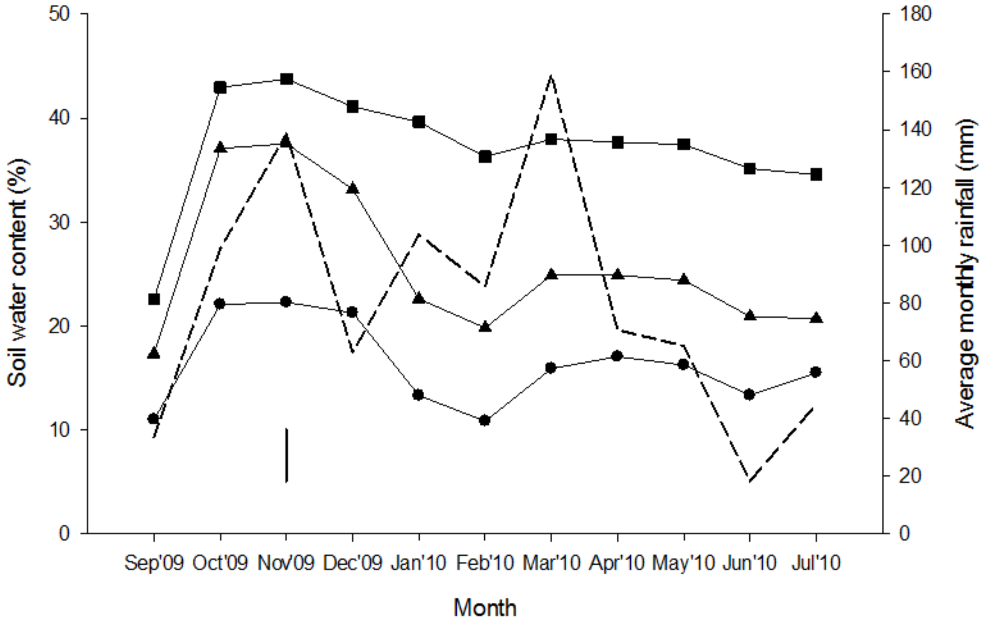

Figure 5.2: Change in soil water content (SWC) for the 0 – 50 cm depth zone (-●-), 50 – 100 cm depth zone (-▲-) and 100 - 150 cm depth zone (-■-) during the period of September 2009 to July 2010 as an average of fertilizer application rate. The dotted line shows the average monthly rainfall and vertical bar represents $LSD_{0.05}$ for the interaction.

The significant soil depth x fertilizer application interaction with regards to SWC also showed an increase in SWC with increase in soil depth (Figure 5.3). Most of the differences amongst treatments were not significant, but the SWC was relatively high in the NF treatment in all three depth zones which ranged on average from 18.9% to 42.5%. Poor growth in the NF treatment could have resulted in a poor transpiration rate that in turn could have resulted in little water being removed from the soil by plant roots, thus resulting in a relatively high SWC. In the 0 – 50 cm and 50 - 100 cm depth zones the SWC was also relatively high in the 0.5 P treatment. The reason for this is not certain, but it is possible that the slimes content could have been higher in this treatment below a depth of 20 cm relative to the other treatments. The SWC in the top 20 cm of soil did not correlate significantly with the slimes content of the soil (which was also sampled to a depth of 20 cm).

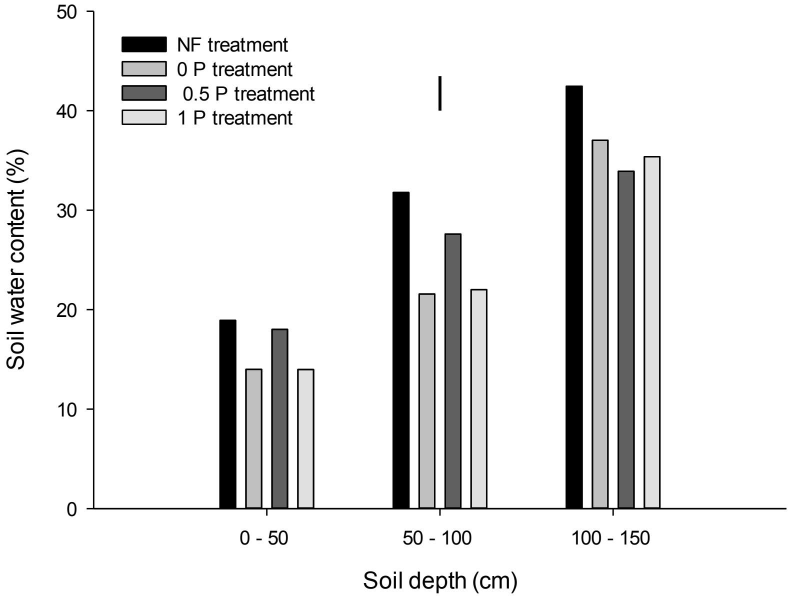

Figure 5.3: Effect of fertilizer application on the average soil water content (SWC) as an average for the measuring period from September 2009 to July 2010. Vertical bar represents $LSD_{0.05}$ for the interaction.

5.3.1.3 Penetration resistance

5.3.1.3.1 Effect of fertilizer application

In 2009, the PR was significantly higher in the 1 P treatment (159.9 kPa) than in the NF (73.3 kPa) and 0.5 P (58.6 kPa) treatment (Table 5.4) when calculated as an average of soil depth. A correlation analysis revealed a negative and significant correlation between the PR (to a depth of 20 cm) and the slimes content of the soil (r^2 = -0.56, $p<0.01$). This shows that the PR was a function of soil texture, at least to a depth of 20 cm. In 2010, the two pre-selected treatments (NF and 1 P) also differed significantly ($p<0.05$) with the 1 P treatment again having the highest PR, but the correlation between PR and slimes was not significant.

Table 5.4: Effect of fertilizer application on penetration resistance (PR) 5 months after planting of the plant crop (2009) and 17 months after planting of the first ratoon crop (2010) as an average of soil depth. Values are the average of 64 replicates and averages with different letters within a column differ significantly. Values in brackets show the standard error of mean (SEM).

Fertilizer application	Penetration resistance (kPa)	
	Plant crop (2009)	First ratoon crop (2010)
NF	73.28[a]	91.65[a] (±13.95)
0 P	117.77[ab]	-
0.5 P	58.59[a]	-
1 P	159.86[b]	254.3613[b] (±38.16)
Average	*102.38*	*173.01*
$LSD_{0.05}$	65.9	$p<0.05$

5.3.1.3.2 Change with soil depth

In 2009, the PR changed significantly with soil depth (Figure 5.4). The PR was relatively high in the top 20 cm of soil, which corresponds with the sugarcane planting depth and was likely caused by compaction. From a depth of 40 cm, the PR increased steadily. An increase in PR over soil depth has also been observed in the other field experiments (sections 3.3.1.3 and 4.3.1.3). In 2010, the PR for the two pre-selected treatments did not differ significantly over soil depth, but showed a similar trend as in 2009. The highest average PR in 2009 was 190.3 kPa, and in 2010 295.4 kPa.

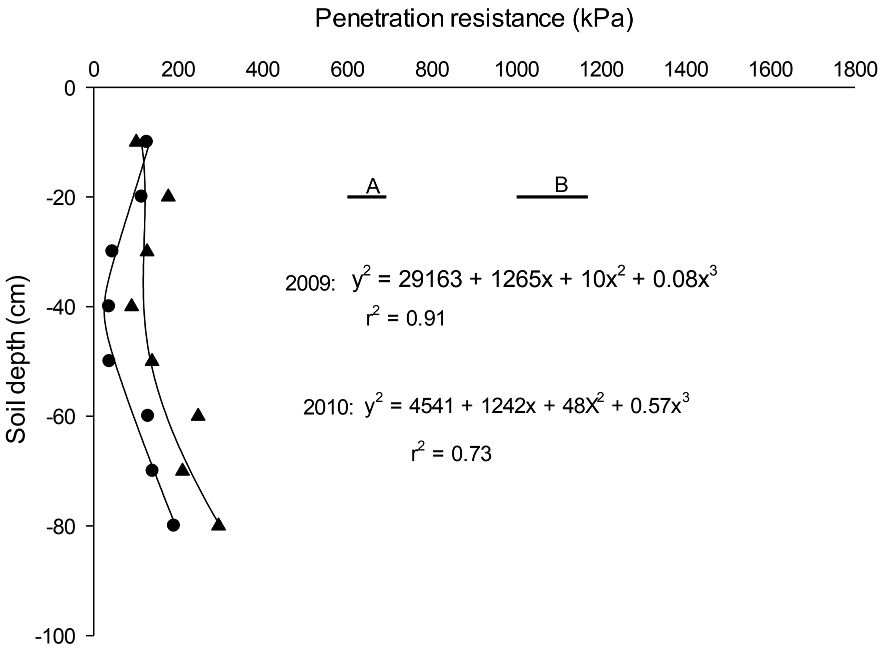

Figure 5.4: Change in penetration resistance (PR) with soil depth for all treatments 5 months after planting of the plant crop (2009) (-●-) and for the NF and 1 P treatments 17 months after planting in the first ratoon crop (2010) (-▲-). Horizontal bars represent $LSD_{0.05}$ (A = 2009 and B = 2010).

5.3.1.3.3 In and between rows

In 2009, the PR in the row was an average of 138.4 kPa that was significantly ($p<0.05$) higher than in the inter-row where the PR was 66.4 kPa. This difference was likely due to compaction in the rows caused by disturbance of the soil at planting. The pattern was the opposite in the two pre-selected treatments in 2010 with PR being 152.0 kPa in the rows and 194.0 kPa in the inter-rows (significant, $p<0.05$). It was not possible to establish why the trend reversed from 2009 to 2010.

5.3.1.3.4 Change with time

The PR increased significantly from 109.2 kPa in 2009 to 173.0 kPa in 2010 (comparing the NF and 1 P treatments only). This increase in PR could indicate that a small degree of either hardsetting or compaction had taken place. An increase in PR over time was also observed in the gypsum (section 3.3.1.3) and FC field experiments (section 4.3.1.3.3). Nonetheless, all PR values recorded in this experiment were well below the critical PR value for sugarcane growth of 2800 kPa (Swinford and Boevey, 1984).

5.3.1.4 Aggregate stability

The aggregate stability, as expressed by the mean weight diameter (MWD) did not differ significantly among the treatments, but was highest in the 1 P treatment (Table 5.5) with a value of 0.10 mm. All treatments had MWD values of below 0.4 mm, which is classified as very unstable and inclined to form crusts (Le Bissonais, 1996). The soil, at the time of sampling, was therefore very sensitive to erosion. The MWD did not correlate significantly with any other parameter in this experiment.

Table 5.5: Effect of fertilizer application on the mean weight diameter (MWD) of soil aggregates taken to a soil depth of 20 cm at 18 months (August 2010) after planting. Values are the average of 4 replicates and values in brackets show standard error of mean (SEM).

Fertilizer application	Mean weight diameter ------mm------
NF	0.07 (±0.03)
0 P	0.07 (±0.01)
0.5 P	0.07 (±0.01)
1 P	0.10 (±0.04)
Average	*0.07*
$LSD_{0.05}$	ns[1]

[1] ns = Not significant

5.3.2 Soil chemical parameters

5.3.2.1 Soil fertility status

5.3.2.1.1 Change over time

The soil pH remained within the optimum range for sugarcane growth (SASA, 2000) in all analyses (Table 5.6) and varied between 6.8 and 6.9. Organic matter content remained more or less the same in the 2008 and 2010 analysis. Before the start of the experiment and in the 2010 analysis, the P content was lower than the critical value for sugarcane growth (SASA, 2000) with a value of 6.6 mg/kg. The soil P was sufficient for sugarcane growth (SASA, 2000) in the 2009 analysis with a value of 19.7 mg/kg. The phosphorus desorption index (PDI) was high, showing that the reconstituted soil had a low P-fixing ability (FAS, 2004). Soil K remained low throughout the experimental period, but was the highest in the final analysis with a content of 82.8 mg/kg. The soil Ca and Mg were high throughout the experimental period, but their values were highest in 2009. The Ca:Mg ratio was also at its highest in 2009 (0.9), but it was lower than the optimum range (3 to 4) for crop growth (Buys, 1986) in all analyses. The Mg:K ratio was high in all three sampling events, but the lowest in the 2010 analysis. Both the soil Mn and Fe were at their highest in the final analysis with contents of 2.3 and 4.9 mg/kg, respectively.

Table 5.6: Summary of changes in soil chemical parameters over time for all treatments as taken from soil samples to a depth of 20 cm from the reconstituted soil.

Soil chemical parameter	Optimum range/threshold values	July 2008 (composite sample)	June 2009	July 2010
pH (H_2O)	5.3 – 8.0[1]	6.90	6.77	6.87
Organic matter (%)	-	0.20	-	0.18
P (mg/kg)	31[1](plant cane) 11[1] (ratoons)	6.30	19.67	6.59
PDI	-	0.60	-	-
K (mg/kg)	112[1]	61.30	70.67	82.78
Ca (mg/kg)	200[1]	372.90	916.67	413.00
Mg (mg/kg)	25[1]	512.00	636.67	515.86
S (mg/kg)	15	15.40	-	-
Ca:Mg ratio[2]	1.5 – 4.5[3]	0.44	0.91	0.51
Mg:K ratio[2]	3 – 4[3]	26.25	23.81	20.88
Mn (mg/kg)	-	1.60	-	2.29
Fe (mg/kg)	-	4.40	-	4.94
Cu (mg/kg)	-	0.50	-	-
Number of samples (N)[4]	-	1	3	16

[1] After SASA (2000); [2]Calculated from the cmol(+)/kg soil concentrations; [3]After Buys (1986); [4]Note the unequal data sets between years

5.3.2.1.2 Effect of fertilizer application

It is known that waterlogging results in an increase in soil pH, with the exception of alkaline soils where a decrease in pH occurs (Mengel and Kirkby, 1987). Lu et al. (2004, as cited in Parent et al., 2008), explained this increase by the ‘trapping’ of CO_2 in the soil that subsequently results in the formation of bicarbonate ions and a concomitant increase in soil pH. The CO_2 involved comes from plant root and microbe respiration. In the NF treatment, pH remained almost unchanged during the experiment (Table 5.7), probably because plant growth was very poor in this treatment (as discussed in section 5.3.4.3), which may have resulted in very little release of CO_2. At 17 months after planting, the pH of the 0 P and 0.5 P treatments, where plant growth was better than in the NF treatment, was higher than in the NF treatment. The soil pH was lowest in the 1 P treatment (significant, $p<0.05$, between the 1 P and 0 P treatments), which was characterized by relatively vigorous sugarcane growth. It is possible that the overriding factor in influencing pH in this treatment was the release of protons by the roots (Rowell, 1994), which resulted in the lowest pH of all treatments. In addition, the SWC was relatively low in the 1 P treatment, which could have allowed some CO_2 to escape. In the filtercake field experiment (section 4.3.2.1.2) a significant correlation between SWC and soil pH was observed and this was explained by the effect of waterlogging on soil pH (Kirk et al., 1990, as cited in Marschner, 1995). However, a significant relationship between SWC and pH was not observed in this experiment.

Soil P was higher in the 1P treatment than in the other treatments, but the difference was not significant (Table 5.7). The soil P varied from 5.6 mg/kg (in the 0 P treatment) to 8.0 mg/kg (in the 1 P treatment). Soil P for all treatments was lower than the threshold value of 11 mg/kg. The low soil P, even in the 1 P treatment, together with the fact that soil P did not correlate significantly (r^2 = 0.43) with the P application rate, showed that some of the P applied was not available for plant uptake. Correlations between soil P and other soil parameters measured in this study was not significant with the exception of the Mg:K ratio (r^2 = - 0.67, $p<0.01$). It is not certain how soil P affected the Mg:K ratio. In this experiment, the Mg:K ratio was highest in the NF treatment (27.2) and lowest in the 1 P treatment (15.9) (Table 5.7). The Mg:K ratio was also likely influenced by the fact that no K fertilizer was applied in the NF treatment while it was applied in the other three treatments.

Soil pH correlated negatively (significant, $p<0.01$) with the soil Fe and Mn (r^2 = -0.72 and r^2 = -0.77, respectively). It is known that Fe and Mn availability in soils is determined both by pH and O_2 levels in the soil (Marschner, 1995). A high SWC in soil is usually associated with low O_2 levels. The soil Mn and Fe did not correlate with the SWC in the 0 – 50 cm zone. This shows that, at least in the top 20 cm of soil, the Fe and Mn availability was determined by pH and not by a lack of O_2 in the soil.

Fertilizer application did not have a significant effect on soil organic matter and the nutrients K, Ca, Mg, Fe, Mn, or the Ca:Mg ratio.

Table 5.7: Effect of fertilizer application on soil chemical parameters 17 months (July 2010) after planting. Soil samples were taken to a depth of 20 cm. Values are the average of 4 replicates and averages with different letters within a column differ significantly ($p<0.05$).

Fertilizer application t/ha	pH (H_2O)	Organic matter %	P	K	Ca	Mg	Ca:Mg[3]	Mg:K[3]	Fe	Mn
			---------------------------mg/kg			-----------------------------			---------mg/kg	------------
NF	6.95^{ab}	0.20	6.58	69.28	422.63	590.00	0.44	27.24^{b}	3.25	1.15
0 P	7.15^{a}	0.10	5.60	71.90	410.93	506.60	0.50	22.46^{ab}	3.75	1.60
0.5 P	7.00^{ab}	0.20	6.90	106.30	403.08	555.00	0.45	17.88^{a}	3.75	2.08
1 P	6.38^{b}	0.20	8.00	83.65	415.40	411.83	0.65	15.94^{a}	9.00	4.35
Average	*6.87*	*0.18*	*6.59*	*82.78*	*413.01*	*515.86*	*0.51*	*20.88*	*4.94*	*2.29*
Threshold value/ optimum range	5.3 – 8.0[1]	*6.87*	11[2]	112[2]	200[2]	25[2]	1.5 – 4.5[4]	3 – 4[4]		
$LSD_{0.05}$	0.52	ns [5]	ns[5]	ns[5]	ns[5]	ns[5]	ns[5]	6.72	ns[5]	ns[5]

[1]After SASA (2005); [2]After FAS (2004); [3]Calculated from the cmol(+)/kg soil concentrations; [4]After Buys (1986); [5]ns = Not significant

5.3.2.2 Magnesium related dispersion

Magnesium related dispersion was indicated in all three samples tested (Table 5.8). Although P application has been shown to improve the Ca:Mg ratio (as discussed earlier), this effect was not evident in the Mg-related dispersion data. The EC was very low for all treatments. A low EC in itself can also result in soil dispersion (Shainberg et al., 1989). The addition of fertilizer was expected to improve the EC, yet there was no indication from the data that the addition of fertilizer in the 1 P treatment improved the EC as compared to the two samples taken from soil where no fertilizer was added (NF and non-amended soil). Deep cracks in the soil, indicative of soil dispersion were observed in this experiment. The cracks were similar to those described in section 3.2.1.

Table 5.8: Criteria used for establishing the magnesium-related dispersion potential of a composite sample (non-amended soil) and the NF and 1P treatments 24 months after planting. Soil samples were taken to a depth of 20 cm. For Mg dispersion to be present criteria 1, 2, 3, 4 and/or 5 must be met.

Criteria	Critical value for Mg dispersion[1]	Composite sample (non-amended soil)	NF treatment	1 P treatment
1. EMP[2] (%)	>30	54.12	59.44	53.97
2. EC (dS/m)	<1.28	0.23	0.22	0.16
3. Ca;Mg ratio	<1	0.5	0.33	0.45
4. ESP (%)	<4	5.96	7.23	3.15
5. ESP + 0.1EMP[2] (%)	>6	11.37	13.17	8.55
Dispersed		Yes	Yes	Yes

[1] After Fenton and Conyers (2002) and all except EC (saturated paste) are based on cmol(+)/kg soil concentrations; [2]EMP = Exchangeable magnesium percentage

5.3.3 Soil microbiological parameters

All the metabolic and microbial quotient values recorded before the start of treatments during the experiment (Table 5.9) were indicative of N stress (Van Antwerpen et al., 2009), although there was an improvement at the end of the experiment for these two parameters. Although the metabolic quotient was higher in the 1 P treatment (7.7 µgCO_2-C/g/day) than in the NF treatment (5.2 µgCO_2-C/g/day), the difference was not significant. The microbial quotient was the same (0.04) in both treatments. The metabolic and microbial quotients did not correlate significantly with any of the soil parameters measured in this study.

Table 5.9: Metabolic and microbial quotients of a composite soil sample taken to a depth of 10 cm before the start of the experiment (September 2008), and for the NF and 1 P treatments 24 months after planting (February 2011). Values in brackets show standard error of mean (SEM).

Sample identification	Metabolic quotient (μgCO$_2$-C/g/day)	
	September 2008	**February 2011**
Composite sample	28.97	-
NF	-	7.71 (±4.89)
1 P	-	5.22 (±1.77)
Average	-	*6.47*
Number of samples (N)	1	4
p<0.05	-	ns[1]
	Microbial quotient	
Composite sample	0.02	-
NF	-	0.04 (±0.01)
1 P	-	0.04 (±0.01)
Average	-	*0.04*
Number of samples (N)	1	4
p<0.05	-	ns[1]

[1] ns = Not significant

5.3.4 Sugarcane growth response

5.3.4.1 Fractional light interception

5.3.4.1.1 Effect of fertilizer application

The FI$_{PAR}$ was highest in the 1 P treatment, followed by the 0.5 P treatment and the 0 P treatment and the lowest in the NF treatment for both 2009 and 2010 (Table 5.10). This was in agreement with the visual observation of poor plant growth where no fertilizer was added but increased growth with increase in P fertilizer application rate (Figure 5.5).

Table 5.10: Effect of fertilizer application on the fractional interception of photosynthetic active radiation (FI$_{PAR}$) for the plant (2009) and first ratoon (2010) crops. Values are the average of 24 replicates and averages with different letters within a column differ significantly (p<0.05).

Fertilizer application	FI$_{PAR}$	
	Plant crop (2009)	**First ratoon crop (2010)**
NF	0.35^{a}	0.35^{a}
0 P	0.58^{bc}	0.74^{b}
0.5 P	0.66^{bc}	0.78^{b}
1 P	0.85^{bd}	0.95^{c}
Average	*0.61*	*0.70*
LSD$_{0.05}$	0.07	0.12

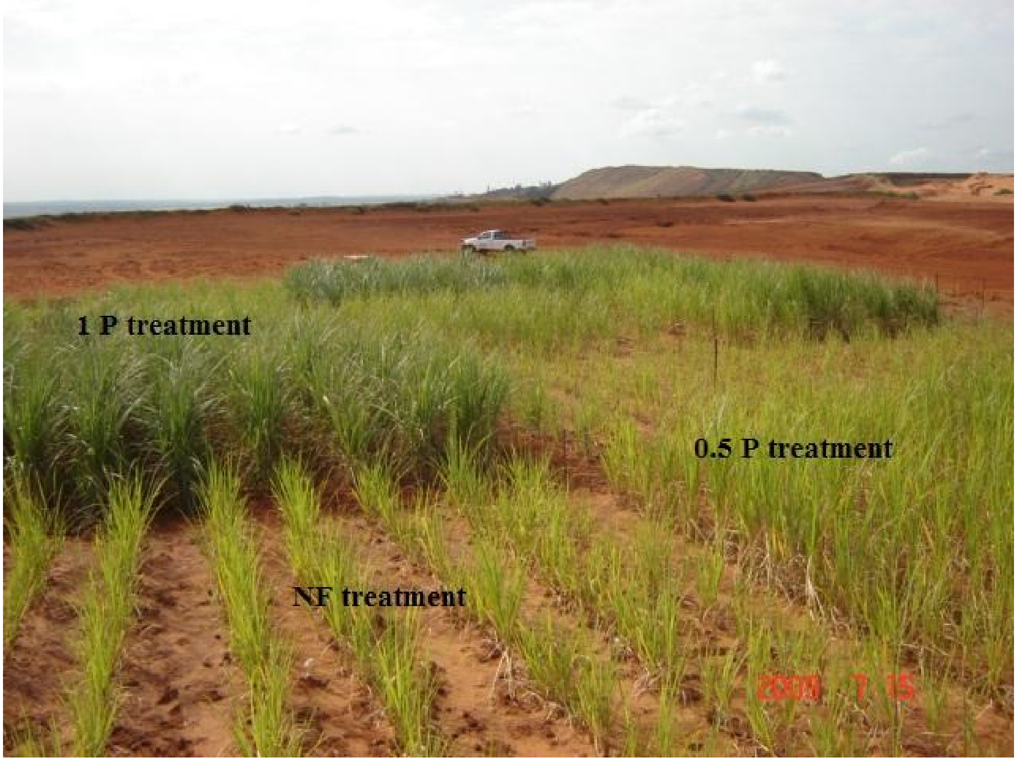

Figure 5.5: A photograph of the sugarcane plant crop taken 146 days after planting (16 July 2009). Note the distinct differences in plant size amongst the NF, 0.5 P and 1 P treatments.

5.3.4.1.2 Change over time for plant and first ratoon crops

The FI_{PAR} for the plant crop showed a downward trend over time, although the decrease was not significant while the FI_{PAR} in the first ratoon crop increased over time, but not significantly so (Figure 5.6). The decrease in FI_{PAR} in the plant crop is probably indicative of plant stress (Smit et al., 2004; Singels et al., 2005). This observation is based on the fact that the Canesim model predicted drought during the same period that the FI_{PAR} measurements were taken. During most of the FI_{PAR} measuring period (125 to 190 days after planting), very little rain fell. Furthermore, the measurements were taken at a time (23 June 2009 to 8 August 2009) when the soil had already dried out considerably (Figure 5.1). As the soil dried out over time, the plants suffered from water stress and the FI_{PAR} decreased accordingly (Figure 5.7). Then, on the 1st of August 2009 (162 days after planting), 26 mm of rain fell. This increased the SWC drastically and enabled the plants to recover to some extent – hence the increase in FI_{PAR} after 162 days after planting. Note that most of the water in 0 – 50 cm depth zone is below the calculated field capacity of 18% (section 5.3.1.2.1). It is likely that most water taken up from sugarcane was from this depth zone (SASA, 2005). The reason for the small increase in FI_{PAR} from 130 to 139 days after planting is not known and is probably not related to SWC. The correlation between the FI_{PAR} and predicted SWC was however not significant, probably because of the small dataset.

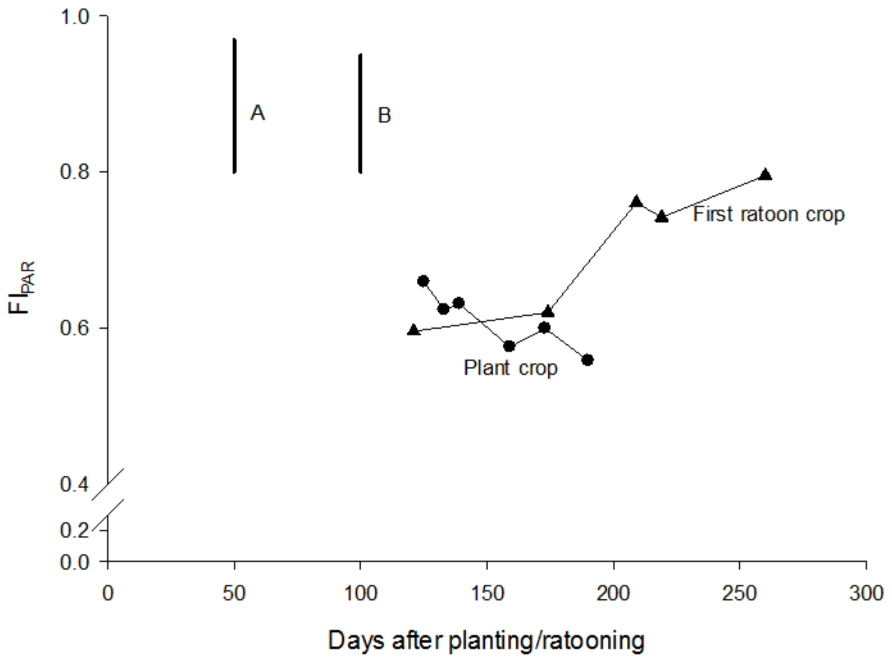

Figure 5.6: Change in fractional interception of photosynthetically active radiation (FI_{PAR}) over time of the plant crop (2009) and first ratoon crop (2010). The short measuring time in the plant crop was due to harvesting at 207 days after planting. Vertical bars show $LSD_{0.05}$ (A = plant crop and B = first ratoon crop).

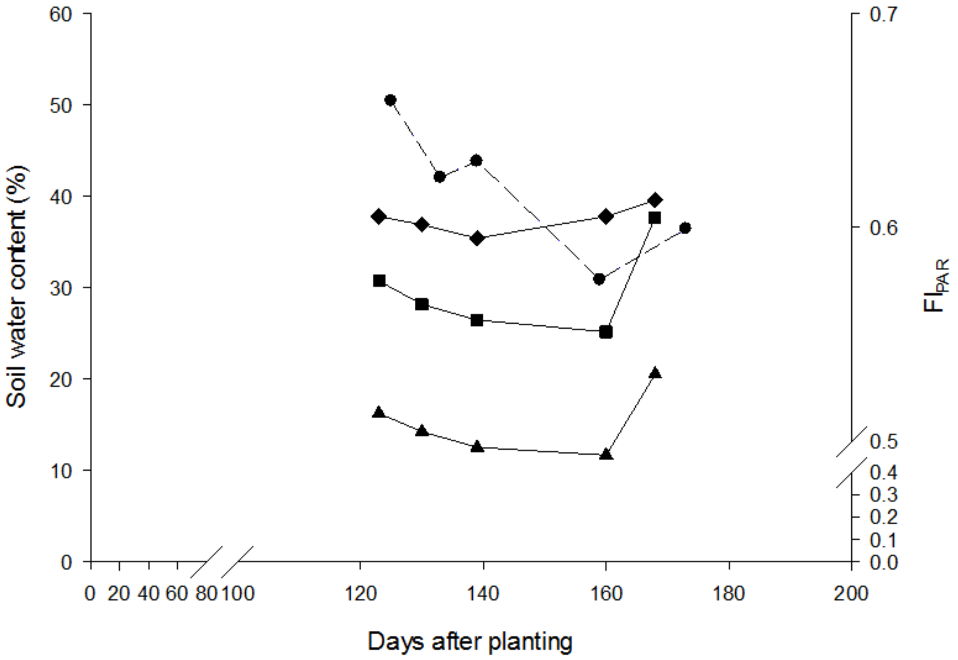

Figure 5.7: Comparison of soil water content (SWC) for 0 – 50 cm depth zone (-▲-), 50 – 100 cm depth zone (-■-) and 100 – 150 cm depth zone (-♦) with the fractional interception of photosynthetically active radiation (FI_{PAR}) (dotted line) of the plant crop.

In the first ratoon crop there was a gradual increase in SWC in all three depth zones (Figure 5.8). The fact the FI_{PAR} increased over the same period of time shows that the plants did not experience drought or waterlogging stress. However, the SWC reached a point where it probably became too high (211 days after planting) and the plants experienced waterlogging-related stress. This is indicted by the decrease in FI_{PAR} between 211 and 219 days after planting. After 211 days from planting, the SWC began to decrease, which allowed the plants to recover and hence the increase in FI_{PAR} observed after 219 days after planting. Correlation between SWC and FI_{PAR} in the first ratoon crop (2010) was not significant.

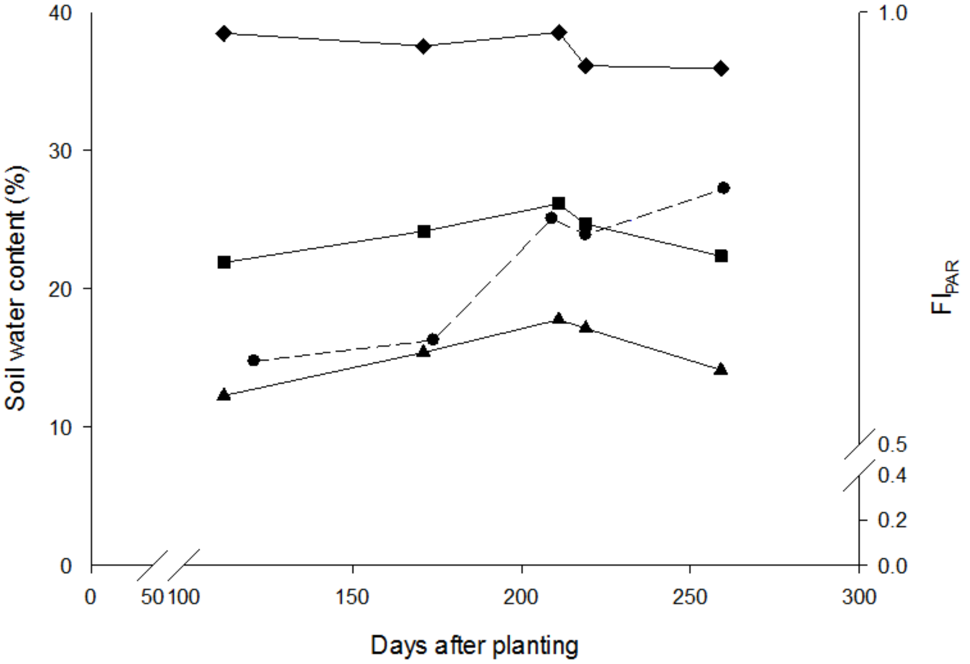

Figure 5.8: Comparison of soil water content (SWC) for 0 – 50 cm depth zone (-▲-), 50 – 100 cm depth zone (-■-) and 100 – 150 cm depth zone (-♦) with the fractional interception of photosynthetically active radiation (FI_{PAR}) (dotted line) of the first ratoon crop.

The Canesim model predicted drought during this period, but there is no indication that the plants were stressed from the FI_{PAR} data. Possibly the plants had adequate water available during this time, since the actual SWC was higher than the predicted SWC.

5.3.4.2 Foliar nutrient content

5.3.4.2.1 Deficiencies and toxicities

Leaf N, P and K were sufficient in samples taken in 2009, but deficient in all samples analyzed in 2010 (Table 5.11). Leaf Ca, Mg, Si, Zn, Mn and Cu were adequate for sugarcane growth (FAS, 2004). Sulfur was only deficient in leaf samples taken in February 2010. The foliar Fe was considerably higher than the threshold value for adequacy, especially in the June 2010 analysis. The foliar Fe was lowest in February 2010 and the highest in June 2010.

Table 5.11: Summary of average foliar nutrient content for all treatments during the experiment.

Nutrient	Threshold value[1]	Plant crop	First ratoon crop	
		May 2009	February 2010	June 2010
N (%)	1.90 (plant) 1.80 (ratoon)	1.93	1.31	1.18
P (%)	0.19	0.22	0.15	0.13
K (%)	1.05	1.31	0.98	0.99
Ca (%)	0.15	0.28	0.31	0.23
Mg (%)	0.08	0.15	0.11	0.10
S (%)	0.12	0.20	0.09	0.12
Si (%)	0.75	1.17	1.71	-
Zn (mg/kg)	13.00	17.31	15.44	18.71
Cu (mg/kg)	3.00	6	5.88	4.71
Mn (mg/kg)	15.00	114.19	61.63	76.00
Fe (mg/kg)	75.00	241.00	180.25	472.71
Number of samples (N)[2]	-	12	16	8

[1]After FAS (2004); [2]Note the unequal data sets between years

5.3.4.2.2 Plant crop in May 2009

As can be expected, the foliar P was highest in the 1 P treatment with a content of 0.35 % (Table 5.12). The 0 P, 0.5 P and 1 P treatments did not differ significantly amongst each other in their foliar P content. In the NF and 0 P treatments, the foliar P content was lower than the threshold value of 0.19%. P application rate correlated significantly with the foliar P content (r^2 = 0.81, p<0.01) and a linear relationship between these two parameters were observed (Figure 5.9).

Table 5.12: The effect of fertilizer application rate on the foliar nutrient content in plant crop (May 2009). Values are average of 4 replicates and averages with different letters within a column differ significantly.

Fertilizer application t/ha	N	P	K	Ca	Mg	S	Si	Zn	Mn	Cu	Fe
	%							mg/kg			
NF	1.36^{acd}	0.18^{a}	1.23^{a}	0.26^{a}	0.14	-	-	-	-	-	-
0 P	1.61^{abc}	0.16^{a}	1.31^{ab}	0.30^{b}	0.15	0.16^{a}	1.11	17.25	71.75^{a}	6.00	195.25^{b}
0.5 P	2.09^{bd}	0.19^{a}	1.35^{b}	0.31^{b}	0.16	0.21^{b}	1.40	17.75	87.50^{b}	6.00	336.50^{a}
1 P	2.49^{bd}	0.35^{b}	1.38^{b}	0.31^{b}	0.17	0.23^{b}	1.35	16.75	128.25^{b}	6.00	222.50^{b}
Average	*1.89*	*0.22*	*1.32*	*0.29*	*0.15*	*0.20*	*1.28*	*17.25*	*95.83*	*6.00*	*251.42*
Threshold value[1]	1.90	0.19	1.05	0.15	0.08	0.12	0.75	13.00	15.00	3.00	75.00
$\text{LSD}_{0.05}$	0.33	0.07	0.09	0.04	ns[2]	0.04	ns[2]	ns[2]	38.88	ns[2]	104.5

[1] After FAS (2004); [2]ns = Not significant

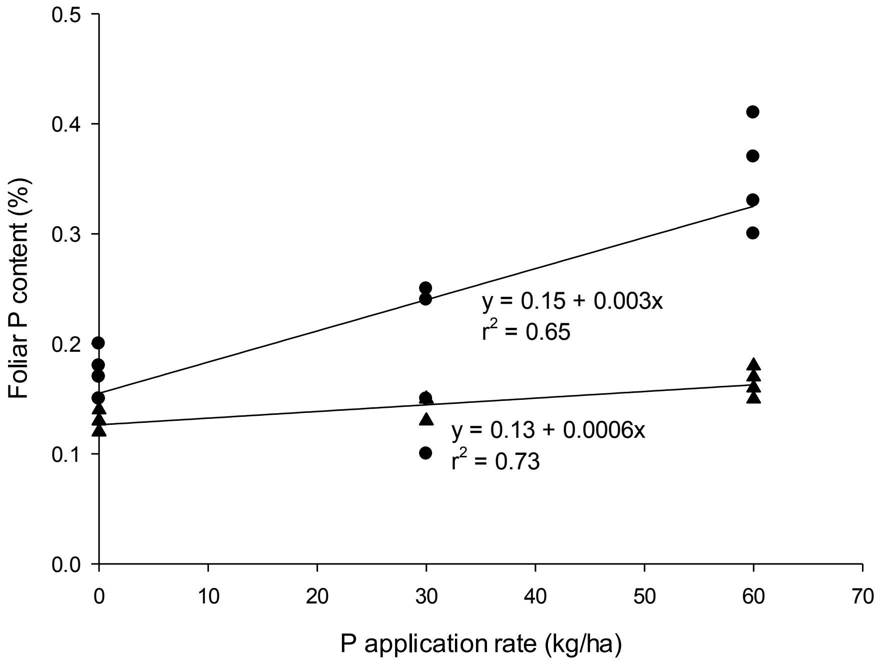

Figure 5.9: Effect of inorganic phosphorus (P) application rate on the foliar phosphorus (P) content in the plant crop (-●-) and February 2010 analysis of the first ratoon crop (-▲-). Data points show raw data.

The 1 P treatment had the highest foliar N content of all treatments namely 2.5% (Table 5.12). Foliar N was deficient in the NF and 0 P treatments where the foliar N content was 1.4% and 1.6%, respectively. The foliar Ca was lowest in the NF treatment (0.26%) relative to the other treatments where it varied between 0.30% and 0.31%. Phosphorus application is known to promote root growth (Fertilizer Industry Federation of Australia, 2000). A study by Akram et al. (2007) showed that application of P improved crop growth, yield and nutrient uptake in sorghum. It was therefore possible that root growth was best in the highest P application rate in this study, which resulted in better absorption of nutrients. This was indeed confirmed by the positive correlations between the P application rate and foliar N (r^2 = 0.90, $p<0.01$), K (r^2 = 0.62, $p<0.05$), Ca (r^2 = 0.50, $p<0.05$), Mg (r^2 = 0.58, $p<0.05$), S (r^2 = 0.77, $p<0.01$) and Mn (r^2 = 0.73, $p<0.01$). In addition, foliar P correlated significantly with foliar N (r^2 = 0.75, $p<0.01$), S (r^2 = 0.68, $p<0.05$) and Mn (r^2 = 0.74, $p<0.01$).

Foliar S, Mn and Fe were not determined for the NF treatment in this analysis, but the foliar S and Mn were lowest in the 0 P treatment and highest in the 1 P treatment. The foliar Fe was highest in the 0.5 P treatment (336.5 mg/kg), relative to the 0 P and 1 P treatments. The reason for the relatively high foliar Fe content in the 0.5 P treatment is not known. The foliar Fe content did not correlate significantly with soil pH or with SWC in this experiment. Foliar K, Mg, Si, Zn and Cu were not significantly affected by fertilizer application treatments.

5.3.4.2.3 First ratoon crop in February 2010

Foliar N, P, K, Ca, Mn, S and Mg did not vary significantly among fertilizer application treatments. Generally the foliar N, P, K, Ca, S and Mg increased with fertilizer application (Table 5.13). As explained before, this was likely the result of root growth simulation by P application, which led to better nutrient uptake. The foliar P correlated positively and significantly ($p<0.01$) with all these nutrients in the leaves which supports the explanation (data not shown). The foliar P also correlated significantly with foliar Zn and Si. In spite of the increase with P application, several nutrients were deficient including N and P (all treatments) and K and S (all treatments except the 1 P treatment). Deficiencies for N and P were not expected in the 1 P treatment, where fertilizer application was at the recommended rate and also not for K in the 0 P or 0.5 P treatments. At the time of taking these samples (February 2010) the Canesim model predicted water stress. However, it is not certain if the plants actually suffered from drought at this time, since the actual SWC (as measured with the Diviner Instrument), was consistently higher than the water content predicted by Canesim. It seems likely that the plants suffered from waterlogging induced stress earlier in the growth period. The Canesim model indeed predicted such stress from 62 to 83 days after planting. Considering that the actual water content was higher than the predicted SWC it can be assumed that the waterlogging stress period was both longer and more severe than predicted by Canesim and that affected root growth to such an extent that uptake of nutrient later in the growth season was impaired. Black roots, indicative of waterlogging (Mengel and Kirky, 1987; Sumner, 2011), was (as also discussed in section 3.3.4.3.1) observed on the roots systems of the sugarcane plants in this experiment which also supports this hypothesis. Furthermore, Sumner (2011) pointed out that such root are inefficient at absorbing nutrients. The relatively small effect of P application on foliar P content in the first ratoon crop can also be seen elsewhere (Figure 5.9).

It has been shown that waterlogging can result in deficiencies of several essential nutrients (N, P, K, Mn, Cu and Zn) in plants (Ponnamperuma, 1972; Steffens et al., 2005). Correlations between foliar N and P and SWC (taken a long-term average) in this experiment were however not significant. It needs to be pointed out though that the availability of P in waterlogged soils is complex and might not be explained by a simple correlation analysis. Furthermore, using the long-term average SWC for correlations might also not be accurate. In the case of N, leaching could also have affected its availability to roots and in turn could have masked the effect of waterlogging. The foliar K, Ca and S (of the February 2010 analysis) did show negative and significant ($p<0.05$) correlations with the long-term average SWC in the 50 – 100 cm and 100 – 150 cm depth zones (Table 5.14).

The foliar Mn was significantly ($p<0.01$) lower in the 0 P treatment than in the other treatments. Manganese uptake, like Fe uptake, is influenced by soil pH and soil O_2 levels (Marschner, 1995), but in this study the foliar Mn did not correlate significantly with soil pH or with SWC. Thus the reason for the observed foliar Mn values could not be explained. There was no significant fertilizer application effect for foliar Fe, Si, Zn or Cu in this dataset. As in the May 2009 dataset, the foliar Fe did not correlate significantly with soil pH or SWC.

In the combined foliar data for the two analyses done in 2010, there emerged a negative correlation between foliar Ca and foliar Fe (r^2 =-0.53, $p<0.01$). This was expected since Fe is known to have an antagonistic effect on Ca uptake (Mengel and Kirkby, 1987).

Table 5.13: Effect of fertilizer application on the foliar nutrient content 5 months after ratooning of the first ratoon crop (February 2010). Values are average of 4 replicates and averages with different letters within a column differ significantly ($p<0.05$).

Treatment	N	P	K	Ca	Mg	S	Si	Zn	Mn	Cu	Fe
t/ha	--%---							---------------------------mg/kg------------------------			
NF	1.01^{b}	0.13^{a}	0.88^{b}	0.29^{a}	0.10^{a}	0.04^{df}	1.73	15.00	69.00^{b}	5.75	192.25
0 P	1.46^{a}	0.13^{a}	1.00^{ab}	0.31^{a}	0.11^{ab}	0.08^{aef}	1.91	15.25	47.50^{a}	6.00	172.75
0.5 P	1.38^{a}	0.14^{a}	1.04^{a}	0.31^{a}	0.11^{ab}	0.09^{abcef}	1.70	15.25	56.75^{ab}	5.75	173.25
1 P	1.60^{a}	0.17^{b}	1.08^{a}	0.34^{b}	0.12^{b}	0.13^{bde}	1.49	16.25	73.25^{b}	6.00	182.75
Average	*1.36*	*0.14*	*1.00*	*0.31*	*0.11*	*0.09*	*1.71*	*15.44*	*61.63*	*5.88*	*180.25*
Threshold value[1]	1.80	0.19	1.05	0.15	0.08	0.12	0.75	13.00	15.00	3.00	75.00
$LSD_{0.05}$	0.23	0.02	0.09	0.02	0.02	0.03	ns[2]	ns[2]	12.58	ns[2]	ns[2]

[1]After FAS (2004); ns[2] = Not significant

Table 5.14: Correlation coefficients (r^2-values) resulting from correlations of soil water content (SWC) (at two depth zones) with foliar K, Ca and S in the February 2010 analysis.

	SWC (50 – 100 cm depth)	SWC (100 – 150 cm depth)
Foliar K	-0.59[1]	-0.57[1]
Foliar Ca	-0.61[1]	-0.63[2]
Foliar S	-0.51[1]	-0.53[1]

[1] = significant, $p<0.05$; [2] = significant, $p<0.01$

5.3.4.2.4. First ratoon crop in June 2009 for the NF and 1 P treatments

Contrary to expectation, the foliar P and Mg had higher values in the NF treatment (Table 5.15). Foliar K was highest (significant, $p<0.05$) in the 1 P treatment. Both the foliar P and K were lower than their respective threshold values. Other nutrients did not differ significantly between the 1 P and NF treatments. In this analysis, foliar P did not correlate significantly with any of the other foliar nutrients.

5.3.4.2.5 Comparison of May 2009, February 2010 and June 2010 data

When comparing the 1 P and NF treatments for the May 2009, February 2010 and June 2010 analyses, most foliar nutrients were higher in the 2009 analysis than in the 2010 analyses (Table 5.16). These nutrients included N, P, K, Mg, S, Mn and Cu. The foliar N, P and K were above their respective thresholds for optimum sugarcane growth in the 2009 foliar analysis, but deficient in the two foliar analyses done in 2010. The foliar Ca and Fe showed an antagonistic relationship as was already pointed out earlier. Foliar Fe was at its lowest in the analysis done in February 2010. It is noteworthy that during February 2010, the SWC was relatively low (Figure 5.2) and this could have contributed to the low foliar Fe content. Zinc was lowest in analysis done in February 2009.

Table 5.15: Effect of fertilizer application on the foliar nutrient content 8 months after ratooning of the NF and 1 P treatments in the first ratoon crop (June 2010). Values are average of 4 replicates and values with different letters within columns differ significantly ($p<0.05$).

Fertilizer application	N	P	K	Ca	Mg	S	Si	Zn	Mn	Cu	Fe
	----------%						-----------	----------mg/kg			----------
NF	1.12	0.14^{a}	0.93^{a}	0.23	0.10^{a}	0.09	1.82	17.50	75.75	4.75	455.75
1 P	1.20	0.12^{b}	1.02^{b}	0.26	0.09^{b}	0.12	-	19.00	73.25	4.75	421.75
Average	*1.16*	*0.13*	*0.97*	*0.24*	*0.10*	*0.11*	-	*18.25*	*74.50*	*4.75*	*438.75*
Threshold value^{1}	1.90	0.19	1.05	0.15	0.08	0.12	0.75	13.00	15.00	3.00	75.00
Significance	ns^{2}	$p<0.05$	$p<0.05$	ns^{2}	$p<0.01$	ns^{2}	-	ns^{2}	ns^{2}	ns^{2}	ns^{2}

[1] After FAS (2004); [2] ns = Not significant

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Table 5.16: Comparison of the plant crop (May 2009) and first ratoon crop (February 2010 and June 2010) foliar nutrient content. Values are average of 16 replicates and averages with different letters within a column differ significantly ($p<0.05$).

Crop	N	P	K	Ca	Mg	S	Si	Zn	Mn	Cu	Fe
	----------%						-----------	----------mg/kg			----------
Plant (May'09)	1.93^{a}	0.27^{a}	1.31^{a}	0.28^{ab}	0.15^{a}	0.23^{a}	1.35^{a}	16.75^{ab}	128.25^{a}	6.00^{a}	222.50^{a}
First ratoon (Feb'10)	1.31^{b}	0.15^{b}	0.98^{b}	0.31^{a}	0.11^{b}	0.09^{b}	1.61^{b}	15.63^{a}	71.13^{b}	5.88^{a}	187.50^{a}
First ratoon (Jun'10)	1.18^{b}	0.13^{b}	1.00^{b}	0.23^{b}	0.10^{b}	0.12^{b}	-	18.71^{b}	76.00^{b}	4.71^{b}	472.71^{b}
Average	*1.48*	*0.18*	*1.10*	*0.28*	*0.12*	*0.13*	*1.52*	*17.00*	*84.95*	*5.47*	*299.95*
Threshold value^{1}	1.90	0.19	1.05	0.15	0.08	0.12	0.75	13.00	15.00	3.00	75.00
LSD$_{0.05}$/Significance	0.46	0.07	0.11	0.04	0.02	0.05	$p<0.05$	1.76	24.30	0.50	201.10

[1] After FAS (2004)

5.3.4.3. Cane, sucrose and aboveground biomass yields

5.3.4.3.1 Cane yield

In the plant crop the cane yield was determined for the 1 P treatment only. The actual cane yield for this treatment was 3.8 t/ha/month which was considerably lower than the simulated cane yield of 7.6 t/ha/month (Figure 5.10). The Canesim model predicted both waterlogging and water stress in the plant crop. The actual SWC was consistently higher than the SWC predicted by Canesim. It is therefore possible that the effect of waterlogging induced stress was worse than that predicted by Canesim. This could in turn explain why the actual cane yield was lower than the predicted cane yield. Similar results were obtained in the gypsum field experiment where sugarcane was grown in a similar soil over a similar period of time as in this experiment (section 3.3.4.3.1). In the plant crop, the cane yield of the 1 P treatment did not correlate significantly with SWC or any of the foliar nutrients.

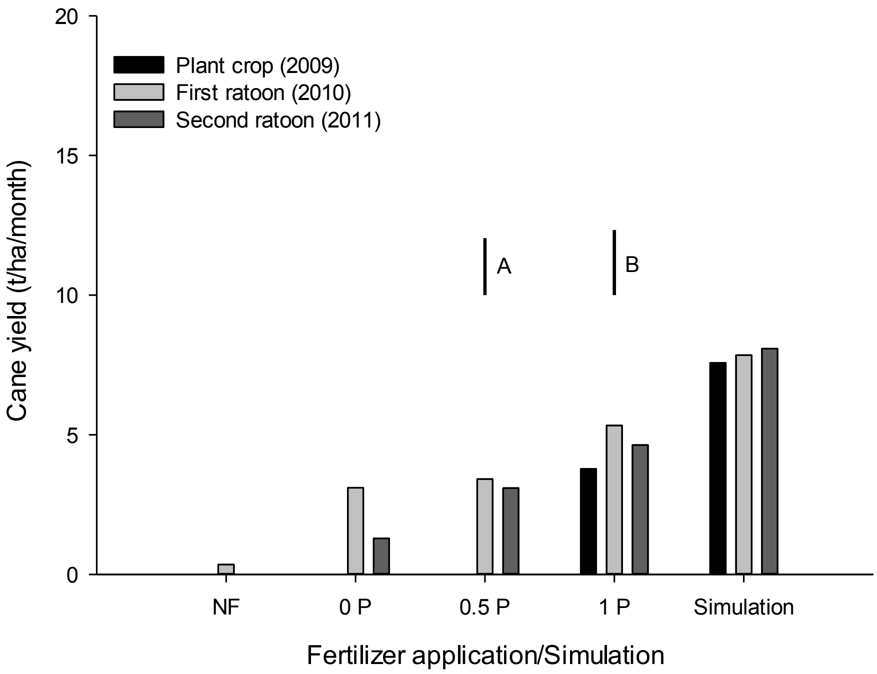

Figure 5.10: Effect of fertilizer application on the actual cane yield during the experiment and simulated yield with the Canesim model. Vertical bars show LSD$_{0.05}$ (A = 1st ratoon crop, B = 2nd ratoon crop).

The 1 P treatment had the highest cane yield in the first ratoon crop (5.3 t/ha/month) and the NF treatment the lowest cane yield (0.4 t/ha/month). The 0 P and 0.5 P treatments had cane yields of 3.1 and 3.4 t/ha/month, respectively, which did not differ significantly from each other. Treatment differences in cane yield were supported by visual differences in plant size amongst treatments (Figure 5.5). All treatments, including the 1 P treatment (which received optimum fertilization), had considerably lower cane yields than that predicted for the first ratoon crop. As pointed out earlier, it is possible that the Canesim model underestimated the effect of waterlogging. In addition, nutrient deficiencies were observed in the plant crop (section 5.3.4.2.3). Both these factors could have resulted in the relatively low actual cane yield. The effect of SWC and nutrient content on the cane yield of the first ratoon crop was confirmed by significant correlations. The cane yield of the first ratoon crop correlated significantly and negatively with the SWC of the 50 – 100 cm and 100 – 150 cm depth zones as recorded for this growth period (r^2 = -0.59 and r^2 = -0.61, $p<0.01$, respectively) (Table 5.17). However, these correlations need to be viewed with caution since the long-term average SWC was used in the calculation. When the foliar data for February 2010 and June 2010 were combined there were positive correlations between cane, sucrose and ABM yield and foliar N, K and S (Table 5.18). These nutrients were also deficient or at least marginal in these foliar analyses, including the 1 P treatment (Table 5.13 and 5.15). A more detailed analysis of the effect of SWC on yield revealed a linear relationship between the two parameters (Figure 5.11). The relationship between foliar N, K and S and cane yield was also linear or curvilinear (Figures 5.12 to 5.14). Similar results were obtained for sucrose and aboveground (ABM) yield (data not shown). In the combined data set yield did not correlate significantly with foliar P, however the foliar P correlated significantly ($p<0.01$) with cane yield (r^2 = 0.73) in the February 2010 data set.

In the second ratoon crop, the simulated cane yield was higher than the actual cane yield. Fertilizer was applied late in the second ratoon crop and could have affected the cane yield. In addition, the Canesim model predicted waterlogging stress from ratooning until 98 days after ratooning. The waterlogging stress was assumed to be worse than predicted by Canesim (as was also pointed out above) and thus it is likely that the plants suffered from waterlogging stress.

Table 5.17: Correlation coefficients (r^2-values) resulting from correlations of soil water content (SWC) (at two depth zones) with sucrose, cane and aboveground biomass (ABM) yield in the first ratoon crop.

	SWC (50 - 100 cm)	SWC (100 – 150 cm)
Cane yield	-0.59[1]	-0.61[1]
Sucrose yield	-0.58[1]	-0.62[1]
ABM yield	-0.58[1]	-0.56[1]

[1] = Significant $p<0.01$

Table 5.18: Correlation coefficients (r^2-values) resulting from correlations of foliar N, K and S with sucrose, cane and aboveground biomass (ABM) yield of the first ratoon crop. The February and June 2010 analysis were combined for these correlations.

	Foliar N	Foliar K	Foliar S
Sucrose yield	0.60[1]	0.71[1]	0.65[1]
Cane yield	0.60[1]	0.72[1]	0.66[1]
ABM yield	0.61[1]	0.71[1]	0.67[1]

[1] = Significant $p<0.01$

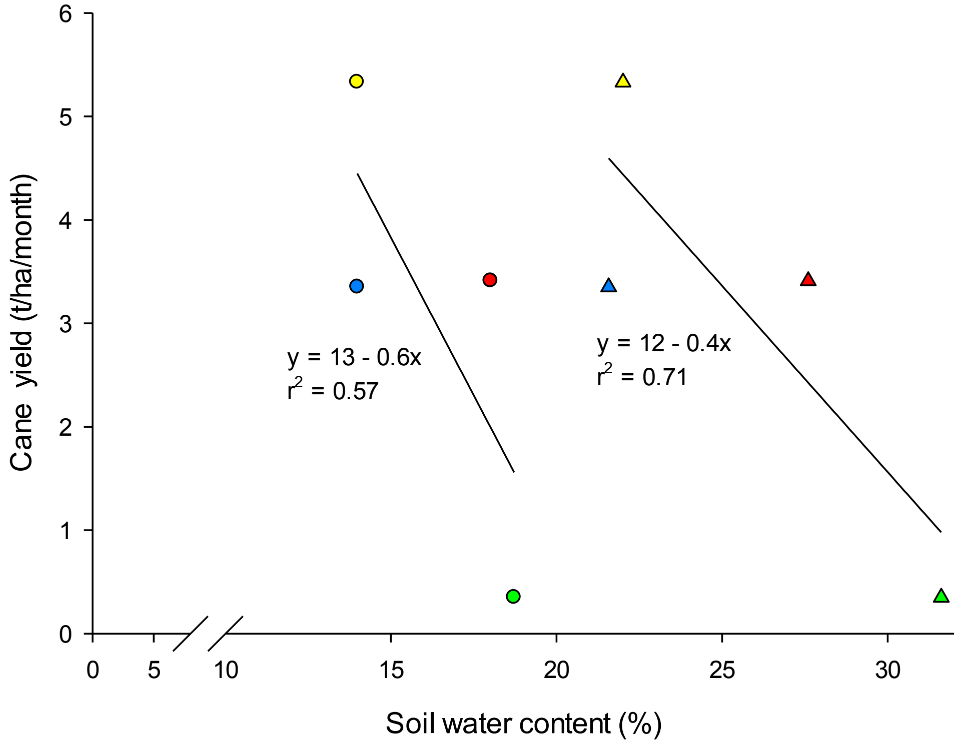

Figure 5.11: Effect of soil water content (SWC) of the 0 – 50 cm depth zone (-▲-) and the 50 – 100 cm depth zone (-●-) on cane yield of the first ratoon crop. Data points represent averages and green indicates the NF treatment, blue the 0 P treatment, red the 0.5 P treatment and yellow the 1 P treatment.

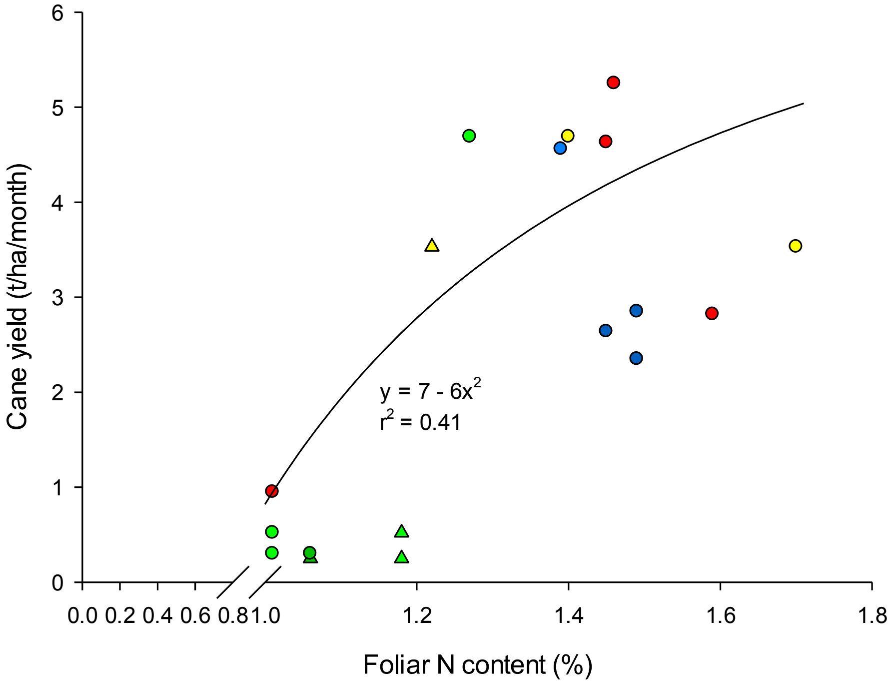

Figure 5.12: Effect of foliar nitrogen (N) content on the February 2010 (-•-) and June 2010 (-▲-) analysis on the cane yield of the first ratoon crop. Data points show raw data and green indicates the NF treatment, blue the 0 P treatment, red the 0.5 P treatment and yellow the 1 P treatment.

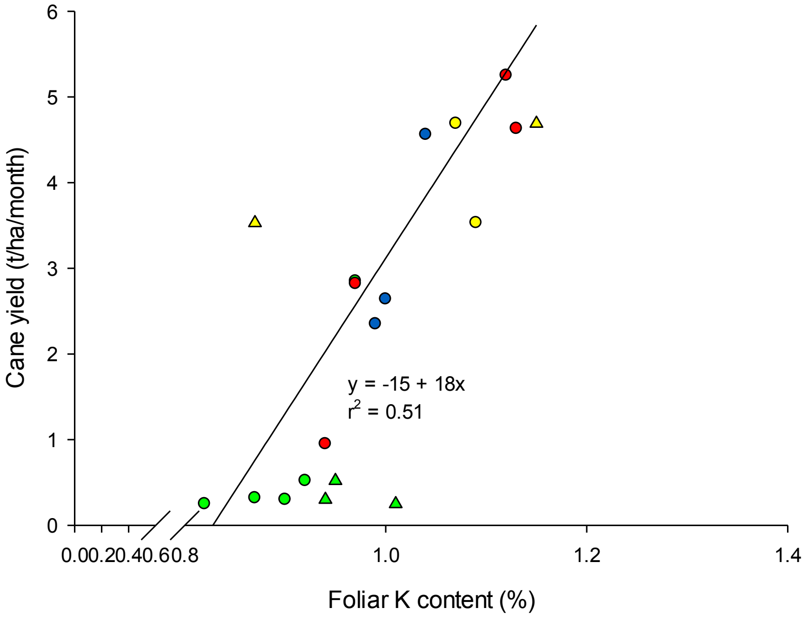

Figure 5.13: Effect of foliar potassium (K) content of the February 2010 (-•-) and June 2010 (-▲-) analysis on the cane yield of the first ratoon crop. Data points show raw data and green indicates the NF treatment, blue the 0 P treatment, red the 0.5 P treatment and yellow the 1 P treatment.

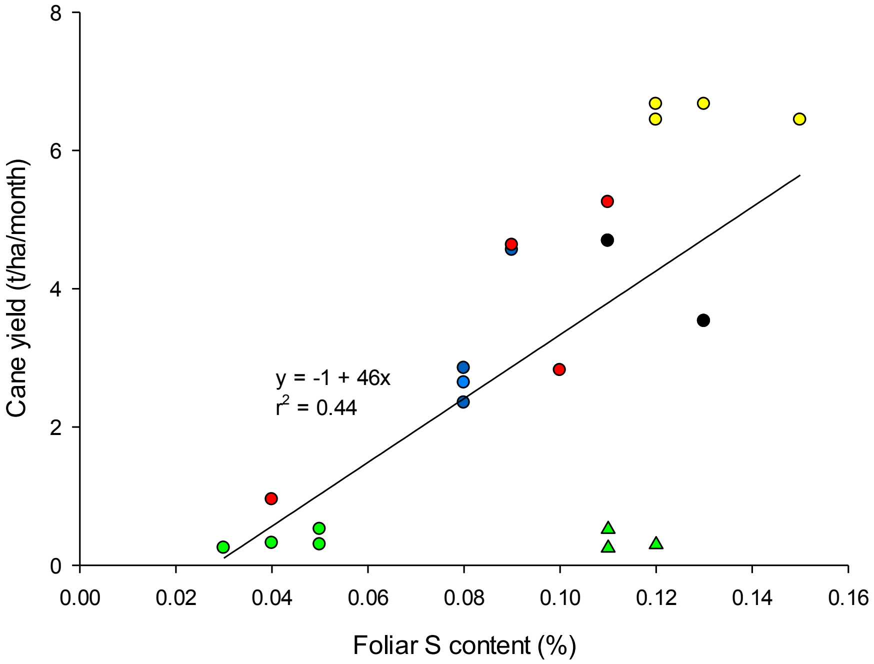

Figure 5.14: Effect of foliar sulphur (S) content of the February 2010 (-●-) and June 2010 (-▲-) analysis on the cane yield of the first ratoon crop. Data points show raw data and green indicates the NF treatment, blue the 0 P treatment, red the 0.5 P treatment and yellow the 1 P treatment.

5.3.4.3.2 Sucrose yield

The sucrose yield showed similar trend to the cane yield (Figure 5.15). The average sucrose yield varied between 0.06 t/ha month in the NF treatment of the first ratoon crop to 0.9 t/ha/month in the 1 P treatment of the same crop. It is assumed that the relatively low sucrose yield, as compared to the simulated sucrose yield was caused by waterlogging and nutrient deficiencies. As for cane yield, correlations supported this assumption (Tables 5.17 and 5.18).

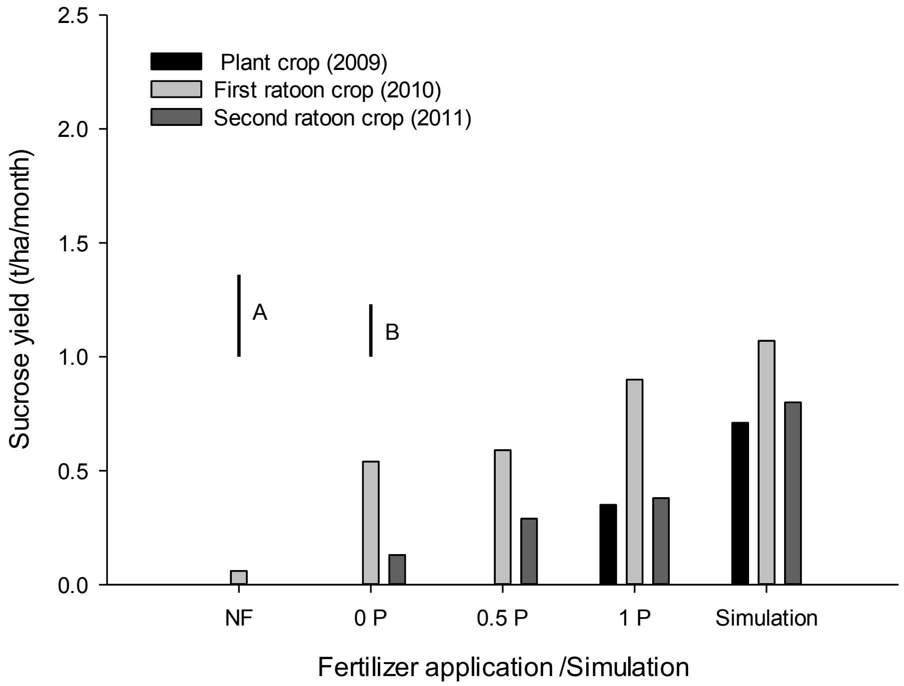

Figure 5.15: Effect of fertilizer application on the actual sucrose yield during the experiment and simulated yield with the Canesim model. Vertical bars show LSD$_{0.05}$ (A = 1st ratoon crop, B = 2nd ratoon crop).

5.3.4.3.3 Aboveground biomass yield

As with the cane and sucrose yield, the ABM yield increased with an increase in fertilizer application with the highest ABM yield in the 1 P treatment (Figure 5.16). The results also confirmed the relative differences in plant size amongst the treatments which was visually observed. The lowest average ABM yield (NF treatment of the plant crop) was 0.2 t/ha/month and the highest average ABM yield (1P treatment of the first ratoon crop) was 2.7 t/ha/month. Significant and negative correlations between ABM yield and SWC were observed (Table 5.17), while correlations between ABM yield and foliar N, K and S content were significant and positive (Table 5.18). Aboveground biomass yield also correlated significantly and positively ($p<0.05$) with foliar P (r^2 = 0.83), Ca (r^2 = 0.55) and Mn (r^2 = 0.82). A linear relationship was observed between P application rate and ABM yield (Figure 5.17). Where no P was applied, ABM was higher in the plant crop, but ABM was higher in the first ratoon crop at P application of 30 and 60 kg/ha.

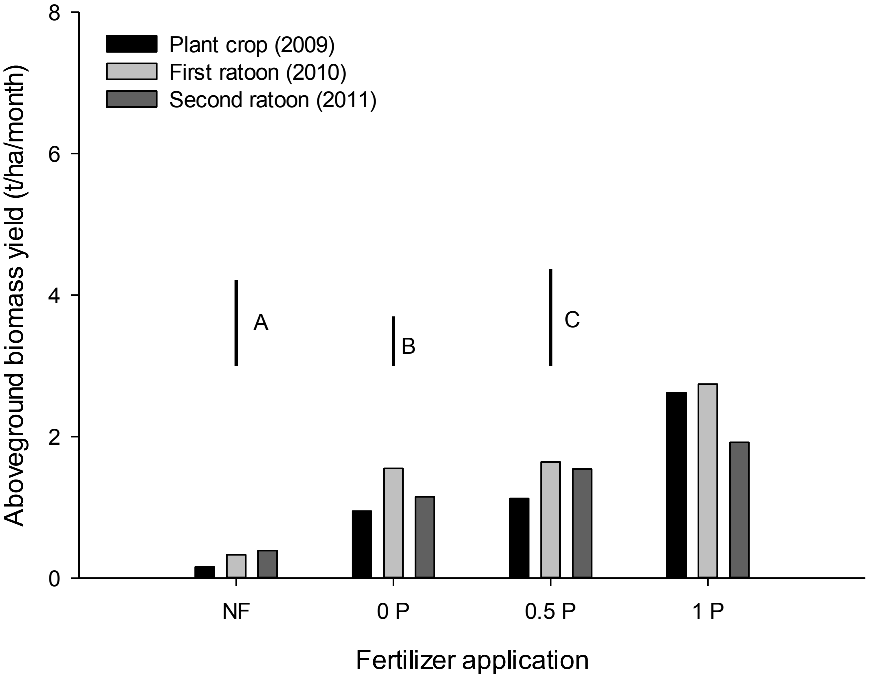

Figure 5.16: Effect of fertilizer application on the aboveground biomass (ABM) yield during the experiment. Vertical bars show LSD$_{0.05}$ (A = plant crop, B = 1stratoon crop and C = 2ndratoon crop).

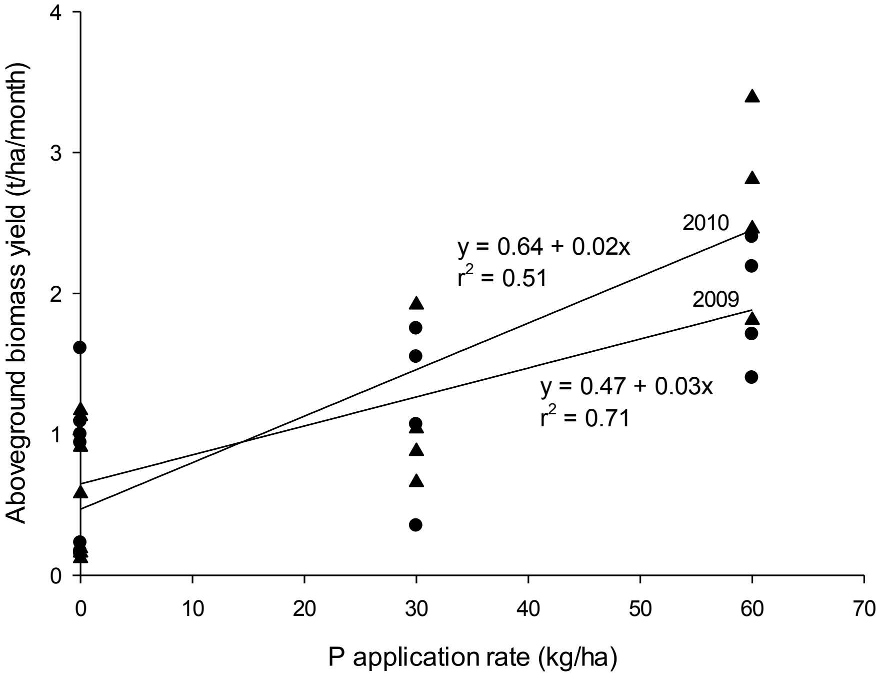

Figure 5.17: Effect of inorganic phosphorus (P) application on the aboveground biomass (ABM) yield of the plant crop (-•-) (2009) and the first ratoon crop (-▲-) (2010). Data points show raw data.

5.3.4.3.4 Comparison of plant, first and second ratoon yields

The sucrose yield decreased significantly from 2010 to 2011 (Table 5.19). This decrease can be partly explained by the fact that harvesting was done in 2011 at a time when the sucrose yield is not at its peak (SASA, 2005). There were no significant changes in the cane or ABM yield over time. The relatively stable cane and ABM yields in this experiment was in contrast to the cane and ABM yields of the gypsum and filtercake field experiments where the first ratoon crop had significantly higher cane and ABM yields than the plant crop (Tables 3.16 and 4.19).

Table 5.19: Comparison of sucrose, cane and aboveground biomass (ABM) yield of the plant, first and second ratoon crops. Averages with different letters within columns differ significantly. Values in brackets show standard error of mean (SEM).

Crop	Sucrose yield	Cane yield	ABM yield
	------------------------t/ha/month	----------------------------	----------------------------
Plant	-	-	1.21 (±0.25)
First ratoon	0.52^{a} (±0.09)	3.04 (±0.55)	1.26 (±0.24)
Second ratoon	0.26^{b} (±0.48)	3.00 (±0.56)	1.42 (±0.27)
Average	*0.41*	*3.02*	*1.30*
N	12	12	16
Significance	$p<0.05$	ns[1]	ns[1]

[1] ns = Not significant

5.3.4.3.5 Tiller number, stalk length and stalk diameter

For the first ratoon crop, differences in tiller number (TN) among treatments were not significant (Table 5.20). Significant differences amongst treatments were observed for the stalk length (SL) and stalk diameter (SD). The NF treatment had lowest SL of 49.9 cm and SD of 1.5 cm of all treatments. The SL was highest in the 1 P treatment (201.5 cm), but SD was similar for the 0 P, 0.5 P and 1 P treatments.

Table 5.20: Effect of fertilizer application on the tiller number (TN), stalk length (SL) and stalk diameter (SD) of the first ratoon crop. Values are the average of 4 replicates and averages with different letters within a column differ significantly (p<0.05).

Fertilizer application	Tiller number (TN)	Stalk length (SL)	Stalk diameter (SD)
	----per m^2----	------------------------cm	------------------
NF	10.98	49.91^{a}	1.49^{a}
0 P	11.17	149.00^{bc}	1.86^{b}
0.5 P	10.70	163.54^{b}	1.89^{b}
1 P	10.18	201.54^{bd}	1.87^{b}
Average	*10.76*	*139.65*	*1.76*
$LSD_{0.05}$	ns[1]	47.56	0.17

[1] ns = Not significant

The SL and SD all showed significant ($p<0.01$) and positive correlations with sucrose, cane and ABM yield (Table 5.21). These correlations were the highest between cane, sucrose and ABM yield and SL. Correlations between cane, sucrose and ABM yield and TN were not significant. The observed differences in sugarcane yield amongst treatments in this experiment were therefore determined mostly by SL and to a lesser extent by SD. Although P is known to promote tillering in grasses (Mengel and Kirkby, 1987; SASA, 1998; Fertilizer Industry Federation of Australia, 2000), it did not affect tillering in this experiment (Table 5.22).

Table 5.21: Correlation coefficients (r^2-values) resulting from correlations of stalk length (SL) and stalk diameter (SD) with sucrose, cane and aboveground biomass yield of the first ratoon crop.

	Stalk length (SL)	Stalk diameter (SD)
Sucrose yield	0.75[2]	0.52[2]
Cane yield	0.82[2]	0.71[2]
ABM yield	0.55[1]	0.51[1]

[1] Significant $p<0.05$; [2] Significant $p<0.01$

For the second ratoon crop, SL and SD were not determined for the NF treatment, because of the small size of the plants. There were no significant treatment effect of TN, SL or SD, but the SL and SD did increase progressively from the 0 P to the 1P treatment (Table 5.22). The SL of the 1 P treatment was 643.1 cm and the SD 2.5 cm.

Table 5.22: Effect of fertilizer application on the tiller number (TN), stalk length (SL) and stalk diameter (SD) of the second ratoon crop. Values are the average of 4 replicates and values in brackets show standard error of mean (SEM).

Fertilizer application	Tiller number (TN)	Stalk length (SL)	Stalk diameter (SD)
	----per m^2----	-------------------cm-------------------	
NF	-	-	-
0 P	9.44 (±1.69)	46.378 (±15.95)	1.95 (±0.08)
0.5 P	6.32 (±2.42)	50.15 (±10.49)	2.01 (±0.03)
1 P	9.44 (±1.18)	64.31 (±6.08)	3.14 (±1.11)
Average		*55.06*	*2.46*
$LSD_{0.05}$	ns[1]	ns[1]	ns[1]

[1] ns = Not significant

In 2011, the cane and sucrose yield correlated significantly ($r^2 = 0.94$ and $r^2 = 0.93$, $p<0.01$) with SD. Cane and sucrose yield was not significantly affected by TN or SL. The ABM yield did not correlate significantly with the TN, SL or SD.

As can be expected, sugarcane growth was positively affected by N, P and K application. Application of P improved uptake of N, P, K, Ca, S and Mg, probably by stimulating root growth. Nutrient deficiencies were not observed in the plant crop where N, P and K was applied at the recommended rate (1 P treatment), yet the actual cane and sucrose yield was lower than the predicted cane and sucrose yield in this treatment. It is possible that the lower than expected yield in the 1 P treatment of plant crop was the result of both waterlogging and water stress. In contrast, in the first ratoon crop, N, P and K deficiencies reduced sugarcane growth in the 1 P treatment. Although a direct link between waterlogging and N, P and K uptake could not be shown, it is nonetheless assumed that waterlogging did affect the uptake of these nutrients by sugarcane by affecting the ability of the root systems to absorb nutrients. A significant and negative relationship between foliar K content and SWC in the 50 – 100 cm ($r^2 = -0.59$) and 100 - 150 cm ($r^2 = -0.57$) depth zones was observed in the first ratoon crop. The application of inorganic fertilizer at recommended rates alone was therefore not sufficient to support optimal sugarcane growth in the first ratoon crop in the reconstituted soil in this experiment. It is difficult to explain why nutrient deficiencies did not occur in the plant crop, since waterlogging was also present. A possible explanation could be that root development was better in the first ratoon crop and that more roots therefore penetrated deeper into the soil profile where the soil was wetter.

In the second ratoon crop, cane and sucrose yield was also relatively low (in comparison with the simulated yields) and this was likely the result of waterlogging and nutrient deficiencies, since fertilizer was applied late.

5.4 CONCLUSIONS

Application of inorganic P increased the uptake of N, P, K, Ca, S and Mg by sugarcane roots in the plant crop. Drought, waterlogging and nutrient deficiencies (including P) were factors that likely influenced sugarcane growth in this experiment. Waterlogging affected growth both directly and indirectly by influencing the uptake of nutrients.

CHAPTER 6

EFFECT OF GYPSUM, FILTERCAKE AND INORGANIC PHOSPHORUS APPLICATION ON PROPERTIES OF A RECONSTITUTED SOIL AND RESULTING SUGARCANE GROWTH THEREON IN A GREENHOUSE

ABSTRACT - *Three experiments were conducted simultaneously to test effects of gypsum, filtercake (FC) and inorganic P on a reconstituted soil and resulting sugarcane growth in a greenhouse. Experiment 1 tested the effects of six gypsum rates, namely 0, 2.4, 4.8, 7.2, 9.6 and 12 t/ha. Potassium was applied in all gypsum treatments at the rate required to correct the Mg:K ratio to 3:1. Phosphorus and N were applied at recommended rates in all the gypsum treatments. Experiment 2 tested the effect of three filtercake application rates (10, 30 and 100 t/ha) under a basal application of P and N at recommended rates based on the soil tests. There were two additional treatments in which inorganic fertilizer was applied without filtercake at the recommended rate or at three times the recommended rate. Experiment 3 included treatments where inorganic P was applied at the recommended rate, or at half the recommended rate or not applied at all. In all P treatments, N and K were applied at recommended rates. There was an additional control treatment in which no fertilizer was applied. Gypsum application significantly improved both the Ca:Mg and Mg:K ratios in the soil in Experiment 1. However, gypsum application did not significantly affect the foliar nutrient content, aboveground (ABM) or root biomass (RBM). The 12 t/ha gypsum treatment had a significantly higher whole plant biomass (WPBM) than the control (0 t/ha gypsum treatment). Applying filtercake at a rate of 100 t/ha in Experiment 2 resulted in a drastic increase in soil P and also in significant improvement of the Ca:Mg ratio of the soil, but did not result in higher ABM, RBM or WPBM compared to control treatment without FC. In the treatment where fertilizer was applied at three times the recommended rate, the Mg:K ratio was improved the most and the ABM, RBM and WPBM were higher than in the other treatments. Application of P fertilizer resulted in a greater uptake of P and Ca by sugarcane in Experiment 3. As expected, ABM, RBM and WPBM was highest where fertilizer was applied at the recommended rate in this experiment. The ABM, RBM and WPBM were significantly and negatively affected by the Mg:K ratio in Experiment 3 (r^2 = - 0.62, r^2 = -0.69 and r^2 = -0.76, respectively). When the data of the three experiments were pooled into one data set it revealed that WPBM correlated significantly ($p<0.01$) and positively with inorganic Ca (r^2 = 0.63), P (r^2 =*

0.66) and K application (r^2 = 0.62) as well as the Ca:Mg ratio of the soil (r^2 = 0.58). Whole plant biomass correlated negatively with the Mg:K ratio of the soil (r^2 = -0.48, $p<0.01$). Interpolation of regression graphs indicated minimum Ca, P and K application rates for optimum WPBM of 608 kg/ha (2.6 t/ha gypsum) 74 kg/ha (704 kg/ha single superphosphate) and 287 kg/ha (574 kg/ha KCl), respectively.

6.1 INTRODUCTION

Hydraulic mining is employed at the Hillendale mine to create slurry of the top 40 m of soil which is then pumped to a separation plant. Titanium-rich minerals are removed from the soil using a mechanical process. The end result of this process is the complete separation of the sand and slimes (silt and clay combined) fractions of the soil. The sand and slimes are subsequently mixed to a ratio of 70:30 to create a so-called reconstituted soil. The post-mined (or reconstituted) soil at Hillendale is characterized by a lack of soil structure and low P and organic matter content (Golder Associates, 2004). The rehabilitation of this soil requires it to be suitable for sustainable sugarcane production.

Three potential soil amendments for the post-mined soil have been tested, all in the field (as discussed in Chapters 3, 4 and 5) and under controlled conditions, namely gypsum, filtercake and inorganic phosphorus. Gypsum, as a source of calcium, is a flocculant and promotes aggregation (Shainberg et al., 1989; Mitchell et al., 2000) as well as other physical properties in soils (Radcliffe et al., 1986; Shainberg et al., 1989; Miller et al., 1998; Mitchell et al., 2000). Filtercake, a locally available waste product from the sugarcane milling process, was tested as a source of organic matter. The addition of organic matter to soils improves aggregation and aggregate stability (Tisdall and Oades, 1982; Anderson et al., 1998a;). Soil organic matter also improves the chemical properties of soils (Coyne and Thomson, 2006) and promotes microbial activity (Magdoff and Weil, 2004). Phosphorus is an essential nutrient for plant growth (Mengel and Kirkby, 1987).

6.2 MATERIAL AND METHODS

6.2.1 Treatments

6.2.1.1 Experiment 1: Gypsum application

The treatments evaluated were 0, 2.4, 4.8, 7.2, 9.6 and 12 t/ha gypsum. Nitrogen and P were applied at rates of 145 kg/ha (as urea) and 70 kg/ha P (as single superphosphate), respectively, were applied as recommended by the Fertiliser Advisory Service (FAS) of the South African Sugarcane Research Institute (SASRI) according to the soil chemical analysis. Potassium was applied at a rate of 1.2 t/ha (in the form of KCl) in all treatments. This rate was based on the amount of K required to decrease the Mg:K ratio of the soil to the recommended ratio of 3 (Buys, 1986). The gypsum and KCl were mixed into the soil, while the superphosphate was applied at planting by placing it just below the sugarcane cutting. Half of the urea was dissolved in water and applied at planting. The other half of the urea, also dissolved in water, was applied approximately one month after planting. The experimental layout was a complete randomized design replicated four times.

6.2.1.2 Experiment 2: Filtercake application

Five treatments were evaluated in this experiment which had a similar experimental design and number of replicates as Experiment 1. In three of the treatments FC was applied at rates of 10, 30 and 100 t/ha. The FC was obtained from the nearby Felixton Sugar Mill. A composite sample of the FC was analyzed for its chemical composition prior to the start of the experiment according to Meyer et al. (1997) and Beater (1962). The results of the analysis showed that the N, P, K, Ca and Mg content of the sample was 0.07%, 0.97%, 0.46%, 2.80% and 0.64%, respectively (Table 6.1).

Table 6.1: Amount of organic N, P, K, Ca and Mg supplied by filtercake in Experiment 2.

Treatment	Organic N		Organic P		Organic K		Organic Ca		Organic Mg	
	%	kg/ha	%	kg/ha	%	kg/ha	%	kg/ha	%	kg/ha
10 t/ha FC	0.07	7	0.97	97	0.46	46	2.80	280	0.64	64
30 t/ha FC	0.21	21	0.97	291	0.46	138	2.80	840	0.64	192
100 t/ha FC	0.70	70	0.97	970	0.46	460	2.80	2800	0.64	640
3 x IF	0	0	0	0	0	0	0	0	0	0
IF	0	0	0	0	0	0	0	0	0	0

The pH of the sample was 8.57. Where FC was applied the amount of N, P and K were balanced with inorganic fertilizer in order to apply a total amount of N, P and K equal to the FAS recommendation. In the other two treatments, N, P and K was applied at the FAS recommended rate (“IF” treatment) and at three times the FAS recommended rate (“3 x IF” treatment). The FAS recommended rate for N, P and K was 145 kg/ha N, 70 kg/ha P and 80 kg/ha K, which was applied (alone or in combination with FC) as urea, single superphospate and KCl, respectively. The FC and KCl were mixed into the soil, while the superphospate and urea were applied similar to the gypsum experiment.

6.2.1.3 Experiment 3: Inorganic phosphorus application

Four treatments were evaluated including P applied at the FAS recommended rate (“1 P” treatment), at half the FAS recommended rate (“0.5 P” treatment) or no P applied (“0 P” treatment). In the 1 P treatment, P was applied at a rate of 70 kg/ha and in the 0.5 P treatment at 35 kg/ha P. Single superphosphate was used as the source of P. In the 0 P, 0.5 P and 1P treatments, N and K was applied at the FAS recommended rates of 145 kg/ha N (as urea) and 80 kg/ha K (as KCl). The N, P and K fertilizer was applied in a similar way as in Experiment 1. In the fourth treatment, no fertilizer was applied at all. Each of the treatments was replicated five times in a complete randomized design.

6.2.2 Establishment of treatments

A reconstituted soil with the 70:30 sand:slimes ratio was used. Before the start of the experiments four random soil samples of the soil were analyzed for their chemical composition and particle size distribution using standard methodology (Non-affiliated Soil Analysis Work Committee, 1990). Soil chemical parameters analyzed included pH (water), P (Truog method), exchangeable K, Ca, Mg, (NH_4OAc) and organic carbon (Walkley-Black). The P was determined with colorimetry, and K, Ca, Mg with atomic absorption spectrometry. Subsequent fertilizer application was based on the average of the results of the four samples. Particle size distribution of the samples was determined by sieving and the hydrometer method (Non-affiliated Soil Analysis Work Committee, 1990). The average sand content of the four samples was 71.5 % and the average slimes content 28.5 %.

The soil was air dried and the amendment material thoroughly mixed with soil as per treatments in each of the three experiments and filling up the pots. Each of the 20 L pots used was filled with 26.6 kg of the amended soil for each of the treatments. Cuttings of sugarcane variety N41 was germinated in a commercial seedling mix and one healthy germinated cutting was transplanted to each pot. The experiments commenced on 21 February 2011 and were terminated on 6 July 2011 (135 days after planting) and were conducted in a greenhouse.

6.2.3 Water application

The determination of field capacity, wilting point and saturation of the soil was based on the particle size analysis (section 3.2.3.1.2) according to Schultze et al. (1985), Van Rensburg (1988), Van Antwerpen et al. (1994) and Meyer and Van Antwerpen (1995). An automated drip irrigation system was used to daily supply an amount of water that did not exceed the field capacity of the treatment with the lowest water requirement (in other words the minimum amount of water). One pot per treatment was weighed weekly and the water needed to 'top up' to field capacity was applied by hand. Since the experiment was run over a relatively short period of time it was assumed that the weight of the plants was negligible.

6.2.4 Data collection

6.2.4.1 Clay estimate

A soil sample was collected from each pot at termination of the experiments (135 days after planting) and the clay content of the samples was estimated using NIR spectroscopy (Johnson et al., 1987). The amount of clay in the slimes of the reconstituted soil cannot be directly controlled by the bulk mixing plant. Thus, the clay estimate was used to determine if any significant differences in clay content existed among treatments within an experiment. If any significant difference in clay content did occur, then it could have been a factor that affected soil physical and chemical properties and hence sugarcane growth.

6.2.4.2 Soil fertility status

At termination of experiments (135 days after planting), soil samples were collected from each pot and analyzed for their chemical soil fertility status similar to the soil samples collected before the start of the experiment.

6.2.4.3 Sugarcane foliar analysis

Leaves blades where collected at 135 days after planting from the primary stem of each plant and analyzed for their P, K, Ca, Mg, S, Si, Zn, Cu, Mn and Fe content using X-ray fluorescence analysis and for N content using near-infrared spectroscopy. In some cases, the leaf material was not adequate to determine all the nutrients. In these cases, only the macronutrients were determined. Since all the leaves on a plant were harvested, it was not possible to compare the values with the foliar nutrient thresholds for sugarcane because these thresholds are based on the nutrient status of the first mature (TVD) leaf only.

6.2.4.4 Sugarcane growth response

At 135 days after planting the height of the primary stem of each plant up to the first mature leaf (top visible dewlap leaf) were measured (referred to as TVD height). The number of tillers per pot was counted. The aboveground parts (stems and leaves) and roots of each plant were harvested separately and dried for 48 hours at

80 °C and weighed to determine the aboveground biomass (ABM) and root biomass (RBM). The whole plant biomass (WPBM) and root to shoot ratio (RSR) were calculated from the ABM and RBM.

6.2.5 Data analysis

The data for each experiment was analyzed separately, but also pooled and analyzed as one data set. In latter case, only WPBM was used as a sugarcane growth parameter, since it was considered the most important of these parameters. All statistical analysis was performed using GenStat12 (VSN International, 2009) software. Where possible, means were separated by LSD (least significant difference) at 5% significance level.

6.3 RESULTS AND DISCUSSION

6.3.1 Experiment 1: Gypsum application

6.3.1.1 Clay content

The average clay estimate of the samples collected at termination of the gypsum experiment was 14.5% and ranged between 11.9% and 17.8% for the gypsum application treatment with no significant variation among treatments (Table 6.2). The clay estimate did not correlate significantly with any soil or sugarcane growth parameter measured in this study.

Table 6.2: Clay estimate of soil samples collected from pots of different gypsum treatments of Experiment 1 at termination (135 days after planting). Values are the average of 4 replicates and values in brackets show standard error of mean (SEM).

Gypsum application rate --------t/ha-----	Clay estimate ------------%-----------
0	12.58 (±0.83)
2.4	17.75 (±3.90)
4.8	11.85 (±5.10)
7.2	14.28 (±4.97)
9.6	15.78 (±4.80)
12	14.80 (±2.77)
Average	14.50
$LSD_{0.05}$	ns[1]

[1] ns = Not significant

6.3.1.2 Soil fertility status

6.3.1.2.1 Change over time

The soil pH, P, K, Ca and Mg content and Ca:Mg and Mg:K ratios changed significantly ($p<0.05\%$) over time (Table 6.3). The average pH (water) remained within the ideal range (5.3 – 8.0) for sugarcane growth (SASA, 2005) both before and at termination of the experiment (135 days after planting), but was at its highest (6.6) at termination. The average soil P was below the threshold value for sugarcane growth (FAS, 2004) in both analyses but it increased from 7.8 mg/kg (before the experiment) to 24.0 mg/kg (at termination). The soil K was 762.7 mg/kg at termination of the experiment which was considerably higher than the sugarcane threshold of 200 mg/kg (FAS, 2004). The high K application at the beginning of the experiment was probably responsible for the high average soil K content at termination. Both the average soil Ca and Mg were high before the start of the experiment and were even higher at termination of the experiment. Although an increase was expected in soil Ca, because of gypsum application, an increase was not expected in the case of Mg. It is not known why Mg increased in this experiment. The soil Mg at the end of the experiment was 1239.6 mg/kg, as compared to the threshold for optimum sugarcane growth of 25 mg/kg (FAS, 2004). The Ca:Mg ratio was low initially (0.7), but was within the ideal range for crop production (Buys, 1986) at termination with an average of 1.6. The Mg:K ratio was 14.6 before the experiment started and 5.6 when the experiment ended. Both these values were higher than the ideal range for crop growth of 3 to 4 (Buys, 1986).

The organic matter content was very low (0.08%) before the start of the experiment. Three of the four samples analyzed contained no organic matter. The low organic matter content was likely the result of the soil disturbance during the mining process. Soil samples taken from the Hutton soil before mining, which was the dominant pre-mining soil type, showed soil organic matter content of 0.52% in the A horizon, and 0.36% in the B horizon (Table 2.1).

Table 6.3: Summary of the changes in soil fertility status for all treatments before and at 135 days after planting in Experiment 1. Averages with different letters within rows differ significantly ($p<0.05$). Values in brackets show standard error of mean (SEM).

Soil chemical parameter	Optimum/threshold values	Initial	Termination	Significance
pH (H_2O)	5.3 – 8.0[1]	5.97^a (±0.08)	6.62^b (±0.05)	$p<0.05$
Organic matter (%)	-	0.08	-	
P (mg/kg)	31[2]	7.80^a (±0.83)	23.96^b (±2.21)	$p<0.05$
K (mg/kg)	112[2]	107.50^a (±2.50)	762.67^b (±26.60)	$p<0.05$
Ca (mg/kg)	200*	546.25^a (±15.86)	3237.93^b (±318.13)	$p<0.05$
Mg (mg/kg)	25[2]	490.00^a (±15.14)	1239.58^b (±81.02)	$p<0.05$
Ca:Mg ratio[3]	1.5 – 4.5[4]	0.68^a (±0.01)	1.61^b (±0.15)	$p<0.05$
Mg:K ratio[3]	3 – 4[4]	14.62^a (±0.46)	5.26^b (±0.38)	$p<0.05$
Mn (mg/kg)	-	2.4	-	-
Fe (mg/kg)	-	5.8	-	-
Number of samples (N)[5]	-	4	24	-

[1]After SASA (2000); [2]After FAS (2004); [3]Calculated from the cmol(+)/kg soil concentrations; [4]After Buys (1986); [5]Note the unequal data sets between years

6.3.1.2.2 Effect of gypsum application

The application of gypsum had significant effects on soil Ca and Mg contents and the Ca:Mg and Mg:K ratios (Table 6.4). Gypsum application correlated significantly with the soil Ca ($r^2 = 0.88$, $p<0.01$) and the Ca:Mg ratio ($r^2 = 0.76$, $p<0.01$), with the 0 t/ha gypsum treatment having the lowest soil Ca content (807.6 mg/kg) and Ca:Mg ratio (0.59). Theoretically, an amount of 8.6 t/ha gypsum should have been enough to increase the Ca:Mg ratio to 1.5. Yet, this ratio was reached at a lower application rate. It needs to be noted however, that single superphosphate which was also applied in this experiment, contains 20% Ca and could also have affected the Ca:Mg ratio. Similarly, an application rate of 1248 kg/ha K should have been sufficient to lower the Mg:K ratio to 3, yet it remained higher than 4 in all treatments, except in the 0 t/ha and 7.2 t/ha gypsum treatments.

Table 6.4: Effect of gypsum application on soil chemical parameters 135 days after planting in Experiment 1. Values are the average of 4 replicates and averages with different letters within a column differ significantly.

Gypsum application	pH (H_2O)	P	K	Ca	Mg	Ca:Mg[3]	Mg:K[3]
-----t/ha----		-------------------------mg/kg----------------------------					
0	6.43	21.30	711.25	807.60^{ac}	845.00^{acdef}	0.59^{acd}	3.76^{a}
2.4	6.55	26.83	862.25	2532.50^{bc}	1512.50^{bcef}	1.04^{abc}	5.57^{abcd}
4.8	6.63	32.08	775.50	3287.50^{bc}	1262.50^{abefcd}	1.59^{bcd}	5.21^{abcd}
7.2	6.55	17.13	690.75	2792.50^{bc}	787.50 ^{abde}	2.31^{bd}	3.62^{abc}
9.6	6.70	24.75	829.25	5252.50^{bcd}	1455.00^{bcdf}	2.26^{bd}	5.63^{abcd}
12	6.90	21.68	707.00	4755.00^{bcd}	1575.00^{bcdf}	1.86^{bd}	7.79^{bd}
Average	*6.63*	*23.96*	*762.67*	*3237.93*	*1239.58*	*1.61*	*5.27*
Threshold value/ optimum range	5.3 – 8.0[1]	31[2]	112[2]	200[2]	25[2]	1.5 – 4.5[4]	3 – 4[4]
$LSD_{0.05}$	ns[5]	ns[5]	ns[5]	91.60	102.30	0.05	4.73

[1] After SASA (2000); [2] After FAS (2004); [3] Calculated form the cmol(+)/kg soil concentrations; [4] After Buys (1986); [5] ns = Not significant

6.3.1.3 Sugarcane foliar analysis

The foliar K and Mg content were significantly affected by gypsum application (Table 6.5). The average foliar K varied between 1.1% (in the 9.6 t/ha treatment) and 1.2% (in the 0 t/ha gypsum treatment). Since this was a very narrow range, the effect of gypsum application on foliar K could be considered negligible. The same is true about the foliar Mg content where the difference between the highest and lowest average foliar Mg content was only 0.04%. Gypsum application did not have a significant effect on any of the other foliar nutrients measured.

The gypsum application rate correlated significantly with the foliar Ca content (r^2 = 0.53, $p<0.01$), but the gypsum application rate did not correlate with any other foliar nutrient.

Table 6.5: Effect of gypsum application on the foliar nutrient content 135 days after planting in Experiment 1. Values are average of 4 replicates and averages with different letters within a column differ significantly (p<005).

Gypsum application	N	P	K	Ca	Mg	S	Si	Zn	Mn	Cu	Fe
t/ha	%							mg/kg			
0	0.66	0.10	1.21^{a}	0.32	0.16^{acd}	0.08	1.12	11.00	220.00	4.00	121.25
2.4	0.70	0.12	1.16^{ab}	0.35	0.12^{bc}	0.08	1.41	13.75	205.00	5.00	154.25
4.8	0.73	0.12	1.20^{ab}	0.33	0.13^{bcd}	0.08	1.16	14.00	164.25	5.00	193.75
7.2	0.59	0.12	1.16^{ab}	0.36	0.12^{bc}	0.09	1.54	13.75	199.25	5.00	158.75
9.6	0.73	0.12	1.11^{b}	0.36	0.12^{bc}	0.09	1.51	14.00	184.75	5.00	159.50
12	0.54	0.10	1.19a	0.36	0.15^{ad}	0.09	1.58	13.33	233.33	5.00	173.00
Average	0.66	0.11	*1.17*	0.35	*0.13*	0.08	1.38	13.30	199.67	4.83	159.52
LSD$_{0.05}$	ns[1]	ns[1]	0.06	ns[1]	0.02	ns[1]	ns[1]	ns[1]	ns[1]	ns[1]	ns[1]

[1] ns = Not significant

6.3.1.4 Sugarcane growth response

As illustrated in Figure 6.1, gypsum application did not have a significant effect on any of the sugarcane growth parameters measured in this experiment. The WPBM ranged from 341.8 g to 392.5 g (Table 6.6). The average tiller number, TVD height and RSR were 5.58, 559.6 mm and 0.7 respectively. It should be noted that in spite of the increase in foliar Ca with an increase in gypsum application (Table 6.5), the foliar Ca did not correlate significantly with any of the sugarcane growth parameters measured. The tiller number, TVD height, ABM, RBM, WPBM and RSR did not correlated significantly with any other foliar nutrient or soil parameters measured in this experiment.

Table 6.6: Effect of gypsum application on the sugarcane tiller number, TVD (top visible dewlap) leaf height, aboveground biomass (ABM), root biomass (RBM), whole plant biomass (WPBM) and root to shoot ratio (RSR) 135 days after planting in Experiment 1. Values in brackets show standard error of mean (SEM).

Gypsum application rate	Tiller number	TVD height	ABM	RBM	WPBM	RSR
-----t/ha-----		---mm---	---------------------g-----------------------			
0	5.50 (±0.29)	729.00 (±71.64)	204.73 (±19.42)	136.65 (±12.56)	344.29 (±26.58	0.68 (±0.11)
2.4	5.25 (±0.75)	850.75 (±41.03)	237.73 (±5.71)	152.89 (±18.01)	386.79 (±12.05	0.66 (±0.09)
4.8	5.75 (±0.25)	(±644.50 (±50.23)	220.63 (±24.25)	165.29 (±17.52)	387.72 (±19.81	0.80 (±0.18)
7.2	5.25 (±0.25)	764.75 (±34.86)	221.58 (±12.17)	154.58 (±17.91)	376.16 (±24.62	0.70 (±0.08)
9.6	5.50 (±0.29)	751.00 (±49.20)	202.35 (±14.1)	137.83 (±30.23)	341.77 (±29.80	0.70 (±0.17)
12	6.25 (±0.63)	817.50 (±89.59)	237.78 (±29.59)	157.53 (±4.87)	392.47 (±42.50)	0.70 (±0.11)
Average	*5.58*	*759.58*	*220.80*	*150.17*	*371.77*	*0.71*
$LSD_{0.05}$	ns[1]	ns[1]	ns[1]	ns[1]	ns[1]	ns[1]

[1] ns = Not significant

Figure 6.1: A photograph of the plants of the various gypsum treatments taken 135 days after planting in Experiment 1. Note that there were no significant differences for ABM among the treatments.

6.3.2 Experiment 2: Filtercake application

6.3.2.1 Clay content

The clay estimate of soil samples collected at termination of the experiment in Experiment 2 varied from 21.9% to 27.5%, with an average of 23.6%. The FC treatments did not differ significantly with regards to the clay estimate (Table 6.7).

Table 6.7: Clay estimate of soil samples collected from pots of different filtercake/fertilizer treatments of Experiment 2 at termination (135 days after planting). Values are the average of 4 replicates and values in brackets show standard error of mean (SEM).

Filtercake/ fertilizer application	Clay estimate ----------%---------
10 t/ha	24.83 (±1.55)
30 t/ha	22.30 (±2.01)
100 t/ha	21.98 (±1.67)
3I x F	27.50 (±2.08)
IF	21.83 (±2.48)
Average	*23.58*
$LSD_{0.05}$	ns[1]

[1] ns = not significant

6.3.2.2 Soil fertility status

6.3.2.2.1 Change over time

The FC used in Experiment 2 had a pH of 8.57. This probably explains the significantly ($p<0.05$) higher average pH (6.7) 135 days after planting, compared to the pH before the experiment started (6.0) (Table 6.8). Also, a significant and positive correlation between soil pH and FC application rate was observed ($r^2 = 0.63$, $p<0.01$). However, the average soil pH remained within the optimum range for sugarcane growth of 5.3 to 8.0 (FAS, 2004) (Table 6.8). The average soil P and K was low before the experiment started (7.8 mg/kg and 107.5 mg/kg, respectively), but was higher than (or just below) their respective thresholds for sugarcane 135 days after planting (FAS, 2004). The increase for both P and K was however not significant. The soil Ca and Mg were both high before the experiment and was at their highest (significant, $p<0.05$) 135 days after planting. At termination of the experiment (135 days after planting) the average Ca content was 972.6 mg/kg and the average Mg 1029.1 mg/kg. The average Ca:Mg ratio decreased (significant, $p<0.05$) and the average Mg:K ratio increased (not significant) from the initial (before the experiment) to the final (at termination of the experiment) soil analysis.

Table 6.8: Summary of the changes in soil fertility status for all treatments before and at 135 days after planting in Experiment 2. Values with different letters within rows differ significantly ($p<0.05$). Values in brackets show standard error of mean (SEM).

Soil chemical parameter	Optimum/ threshold values	Initial	Termination	Significance
pH (H_2O)	5.3 – 8.0[1]	5.97^{a} (±0.08)	6.69^{b} (±0.73)	$p<0.05$
Organic matter (%)	-	0.08	-	
P (mg/kg)	31[2]	7.80 (±2.29)	29.71 (±7.73)	ns[6]
K (mg/kg)	112[2]	107.50 (±2.50)	158.75 (±26.24)	ns[6]
Ca (mg/kg)	200[2]	546.25^{a} (±15.86)	972.59^{b} (±72.30)	$p<0.05$
Mg (mg/kg)	25[2]	490.00 (±15.14)	1029.05 (±58.23)	$p<0.05$
Ca:Mg ratio[3]	1.5 – 4.5[4]	0.68^{a} (±0.01)	0.57^{b} (±0.02)	$p<0.05$
Mg:K ratio[3]	3 – 4[4]	14.63 (±0.46)	28.84 (±3.35)	ns[6]
Mn (mg/kg)	-	2.4 (±0.58)	-	
Fe (mg/kg)	-	5.8 (±1.18)	-	
Number of samples (N)[5]	-	4	24	

[1]After SASA (2000); [2]After FAS (2004); [3]Calculated from the cmol(+)/kg soil concentrations; [4]After Buys (1986); [5]Note the unequal data sets between years; [6]ns = Not significant

6.3.2.2.2 Effect of filtercake/fertilizer application

There was a significant effect of filtercake/fertilizer application on soil P, K, Ca and Ca:Mg ratio and Mg;K ratio (Table 6.9), but not on pH and Mg content. The soil P increased with an increase in FC application. In the 100 t/ha FC treatment, the soil P values were higher than 80 mg/kg which was excessive. It has been reported that excessively high levels of P in the root medium can depress growth, probably because of associated deficiencies of Zn, Fe and Cu (Loneragan and Asher, 1976 as cited in Mengel and Kirkby, 1987). This drastic increase in soil P also shows that P was mineralized from FC. The soil P was higher (significant, $p<0.05$) in the 3 x IF treatment (67.4 mg/kg) than in the IF treatment (6.5 mg/kg), because of the higher P application in the 3 x IF treatment.

As expected, the soil K was higher (but not significantly so) in the 3 x IF treatment than in the IF treatment, since more inorganic K was applied in the 3 x IF treatment than in the IF treatment. The soil K was significantly ($p<0.01$) higher in the 3 x IF treatment (328.5 mg/kg) than in the 10, 30 and 100 t/ha FC treatments (151.4 mg/kg, 65.3 mg/kg and 104.0 mg/kg, respectively). The addition of FC did not result in a higher K content in the soil relative to the control treatment (IF treatment). This could be an indication that K mineralization of the FC was slow.

The soil Ca correlated with the FC application rate (r^2 = 0.68, $p<0.01$) and is probably the result of Ca contained in FC (Table 6.9). The Ca:Mg ratio increased with FC application rate, which was supported by a positive correlation coefficient between the Ca:Mg ratio and the FC application rate (r^2 = 0.86, $p<0.01$). However, the 100 t/ha FC treatment was the only treatment in Experiment 2 where the Ca:Mg ratio was higher at termination of the experiment compared to the initial Ca:Mg ratio. There is no indication from the results of this particular experiment that the addition of single superphosphate, which contains 20% Ca, affected the Ca:Mg ratio of the soil, since it was 0.52 in both the IF and 3 x IF treatments (where the single superphospate application rate was tripled compared to the IF treatment).

The Mg:K ratio was lowest (significant, $p<0.05$) in the 3 x IF treatment, with a value of 8.2. In the other treatments, the Mg:K ratio varied between 22.6 (IF treatment) and 46.6 (10 t/ha FC treatment). The 3 x IF treatment was the only treatment where the Mg:K ratio was lower (and thus improved) at the end than at the beginning of the experiment. In all the other treatments it was highest at termination of the experiment. This was also reflected by the positive correlation coefficient between the FC application rate and Mg:K ratio (r^2 = 0.53, $p<0.05$). The mineralization rate of the FC was not known, but is assumed that the relative release of K, Ca and Mg from the FC affected the cation ratios of the soil. It was already pointed out that little K was apparently released from FC, which could have contributed to the observed decline of the Mg:K ratio in treatments where FC was applied.

Table 6.9: Effect of filtercake and/or fertilizer application on soil chemical parameters 135 days after planting in Experiment 2. Values are the average of 4 replicates and values with different letters within a column differ significantly.

Filtercake/ fertilizer application	pH (H_2O)	P	K	Ca	Mg	Ca:Mg^3	Mg:K^3
		----------------------------mg/kg----------------------------					
10 t/ha FC	6.60	11.35^{ad}	151.38^{a}	911.18^{a}	1065.00	0.52^{a}	23.44^{ae}
30 t/ha FC	6.73	52.27^{bc}	65.25^{a}	857.68^{a}	950.00	0.55^{a}	46.61^{b}
100 t/ha FC	7.00	>80	103.90^{a}	1350.55^{b}	1157.50	0.71^{b}	36.64^{bc}
3xIF	6.57	67.35^{bd}	328.53^{b}	690.17^{a}	803.33	0.52^{a}	8.19^{d}
IF	6.50	6.53^{abcd}	196.60^{ab}	986.17^{ab}	1141.00	0.52^{a}	22.58^{e}
Average	*6.69*	*29.71*	*158.75*	*972.59*	*1029.05*	*0.57*	*28.84*
Threshold value/ optimum range	5.3 – 8.0^1	31^2	112^2	200^2	25^2	1.5 – 1.4^4	3 – 4^4
$LSD_{0.05}$	ns^5	16.40	121.40	382.40	ns^5	0.08	9.19

[1] After SASA (2000); [2] After FAS (2004); [3] Calculated form the cmol(+)/kg soil concentrations; [4] After Buys (1986); [5] ns = Not significant

6.3.2.3 Sugarcane foliar analysis

Filtercake is known to be a source of several nutrients, including N, P, K, Ca, Mg, S, Si Zn and Cu (Anon., 2003). This could explain why most of these nutrients (K and Ca being the exception) were taken up in larger quantities by plants where FC was applied at a rate of 10 t/ha compared to the IF treatment where no FC was applied (Table 6.10). However, most of these nutrients were present in larger quantities in plants of the 10 t/ha FC treatment, compared to the 30 t/ha FC treatment. Filtercake mineralization rates could have been different between these two treatments. It is not possible to explain why the 100 t/ha FC treatment had the highest soil Ca content, yet the foliar Ca content did not vary significantly among treatments. The 3 x IF treatment had 0.2 mg/kg higher foliar N content than the IF treatment (Table 6.10). This was expected because of the higher N application in the 3 x IF treatment. The average foliar N of the FC treatments ranged from 0.7 mg/kg to 0.8 mg/kg with no significant difference among the treatments. There were no visual signs of N deficiency and at termination of the experiment the foliar N was higher in the FC treatments than in the IF treatment (with most of the differences among treatments being significant). Differences in foliar P, K, Ca, Mg, Cu, Mn and Fe among treatments were not significant. It is important to point out that although the addition of FC increased the soil P drastically, uptake of P was similar in all treatments in Experiment 2.

Table 6.10: Effect of filtercake and/or fertilizer application on the foliar nutrient content 135 days after planting in Experiment 2. Values are the average of 4 replicates and averages with different letters within a column differ significantly ($p<0.05$).

Filtercake/ fertilizer application	N	P	K	Ca	Mg	S[2]	Si[2]	Zn[2]	Mn[2]	Cu[2]	Fe[2]
	%							mg/kg			
10 t/ha FC	0.79^{a}	0.14	1.01	0.32	0.16	0.10^{a}	1.79^{ab}	15.68^{a}	205.67	216.33	5.00
30 t/ha FC	0.76^{a}	0.11	1.04	0.31	0.13	0.08^{b}	2.27^{a}	13.00^{b}	120.00	151.00	5.00
100 t/ha FC	0.70^{ab}	0.10	1.09	0.25	0.15	-	-	-	-	-	-
3xIF	0.74^{a}	0.11	1.01	0.31	0.15	0.07^{b}	1.23^{b}	13.00^{b}	168.00	147.00	5.00
IF	0.53^{b}	0.12	1.03	0.34	0.14	0.06^{b}	1.54^{b}	13.33^{b}	194.00	144.33	5.00
Average	*0.71*	*0.11*	*1.04*	*0.30*	*0.14*	*0.08*	*1.70*	*13.90*	*177.50*	*167.80*	*5.00*
$LSD_{0.05}$	0.16	ns[1]	ns[1]	ns[1]	ns[1]	0.02	0.37	1.05	ns[1]	ns[1]	ns[1]

[1] ns = Not significant; [2] Micronutrients and S could not be determined in the 100 t/ha FC treatment because of inadequate leaf material due to small plant size.

6.3.2.4 Sugarcane growth response

The TVD height, ABM, RBM and WPBM differed significantly among FC/fertilizer treatments, but the tiller number and RSR did not show significant differences among treatments (Table 6.11). The ABM, RBM and WPBM were significantly higher in the 3 x IF treatment relative to the treatments where FC was applied (Figure 6.2). Since the plants in the FC treatments did not significantly outperform the plants of the IF treatment (which is the control treatment), the addition of FC did not succeed in improving sugarcane growth in this particular experiment.

Nitrogen immobilization was expected in treatments where FC was applied, since FC is known to have a high C:N ratio (Anon., 2003). If N immobilization had occurred it would have had a negative effect of sugarcane growth where FC was applied relative to the IF treatment where no FC was applied. Although the ABM, RBM and WPBM was consistently lower in the FC treatments than the IF treatment in the present experiment, the differences were not significant. Nitrogen immobilization, if it did occur at all, therefore had an insignificant effect on growth in Experiment 2. The 100 t/ha FC treatment had the highest TVD height of all treatments.

Table 6.11: Effect of filtercake (FC) and/or fertilizer application on the sugarcane tiller number, TVD (top visible dewlap) leaf height, aboveground biomass (ABM), root biomass (RBM), whole plant biomass (WPBM) and root to shoot ratio (RSR) 135 days after planting in Experiment 2. Averages with different letters within a column differ significantly (p<0.05).

Filtercake/ fertilizer application	**Tiller number**	**TVD height**	**ABM**	**RBM**	**WPBM**	**RSR**
		--mm---	**----------------------g------------------------**			
10 t/ha FC	4.33	780.67^{a}	171.35	84.02^{a}	252.19^{a}	0.50
30 t/ha FC	4.75	773.00^{a}	147.83	79.84^{a}	233.12^{ac}	0.67
100 t/ha FC	5.25	915.75^{b}	188.85	101.61^{a}	312.23^{d}	0.51
3xIF	5.67	800.33^{ab}	211.17	159.32^{b}	370.49^{bd}	0.78
IF	7.00	705.33^{a}	182.07	116.25^{ab}	298.32^{ae}	0.64
Average	*5.35*	*800.82*	*178.43*	*106.15*	*293.27*	*0.61*
Number of samples (N)	4	*4*	*4*	*3*	*3*	*3*
$LSD_{0.05}$	ns[1]	130.30	ns[1]	47.60	62.09	ns[1]

[1]ns = Not significant

Figure 6.2: A photograph taken of plants of the filtercake/fertilizer treatments at 135 days after planting in Experiments 2. Note the larger plant size in the 3 x IF treatment.

The ABM, RBM and WPBM correlated significantly and positively with the soil K, inorganic P application rate and negatively with Mg:K ratio (Table 6.12). Correlation coefficients between ABM, RBM and WPBM with inorganic N application rates were not significant. None of the sugarcane growth parameters measured in this experiment correlated significantly with any of the foliar nutrients.

Sugarcane growth parameters in Experiment 2 did not correlate significantly with organic application rates of N, P, K and Ca. Although the foliar nutrients content of many nutrients were higher in the 10 t/ha FC treatment than the IF treatment (as discussed in section 6.3.2.3), it could be that the uptake of these nutrients was insufficient to affect sugarcane growth significantly.

Table 6.12: Correlation coefficients (r^2-values) resulting from correlations of aboveground biomass (ABM), root biomass (RBM) and whole plant biomass (WPBM) with soil K, inorganic P application and the Mg:K ratio in Experiment 2.

	ABM	RBM	WPBM
Soil K	0.35^{ns}	0.66^{2}	0.59^{2}
Inorganic P application	0.45^{ns}	0.73^{2}	0.73^{2}
Mg:K	-0.51^{1}	-0.69^{2}	-0.70^{2}

^{1} = Significant $p < 0.05$; ^{2} = Significant $p < 0.01$; ^{ns} = Not significant

6.3.3 Experiment 3: Inorganic phosphorus

6.3.3.1 Clay content

The estimated clay content did not vary significantly among treatments (Table 6.13) and did not correlate significantly with soil chemical or sugarcane growth parameters measured in this experiment. The highest clay estimate was in the NF treatment (22.4%) and the lowest in the 0.5 P treatment (19.5%).

Table 6.13: Clay estimate of soil samples collected from pots of different fertilizer treatments of Experiment 3 at termination (135 days after planting). Values are the average of 4 replicates and values in brackets show standard error of mean (SEM).

Fertilizer application	Clay estimate
	--------%--------
NF	22.40 (±2.49)
0P	20.18 (±3.47)
0.5P	19.50 (±2.90)
1P	20.50 (±0.93)
Average	20.56
LSD $_{0.05}$	ns^1

^{1}ns = Not significant

6.3.3.2 Soil fertility status

6.3.3.2.1 Change over time

The soil pH and Ca, Mg content of the soil was higher 135 days after planting than before the experiment started (Table 6.14). The average Ca:Mg ratio decreased significantly from 0.7 (before the experiment) to 0.5 (at termination of the experiment). As mentioned in Experiments 1 and 2, a sampling error could have resulted in a higher Ca:Mg ratio before the experiment. The pH was within the optimum range for sugarcane growth (FAS, 2004) in both analyses. The soil P and K content and Mg:K ratio did not change significantly in the analyses done before the experiment and at termination of the experiment. At termination of the experiment, the soil P was still, on average, 25.7 mg/kg lower than the threshold value for sugarcane growth of 31 mg/kg. This was because P was only applied at the recommended rate in one of the treatments (1 P treatment). Both the average

Ca:Mg and Mg:K ratios were below their respective optimum ranges (1.5 – 4.5 and 3 – 4, respectively) for optimum crop growth (Buys, 1986) before and at termination of the experiment.

Table 6.14: Summary of the changes in soil fertility status for all treatments before and at 135 days after planting in Experiment 3. Values with different letters within rows differ significantly (p<0.05). Values in brackets show standard error of mean (SEM).

Soil chemical parameter	Optimum/threshold values	Initial	Termination	Significance
pH (H_2O)	5.3 – 8.0[1]	5.97^a (±0.08)	6.37^b (±0.03)	$p<0.05$
Organic matter (%)	-	0.08	-	
P (mg/kg)	31[2]	7.80 (±4.57)	5.33 (±5.76)	ns[6]
K (mg/kg)	112[2]	107.50 (±5.00)	147.91 (±44.76)	ns[6]
Ca (mg/kg)	200[2]	546.25^a (±15.86)	674.18^b (±24.31)	$p<0.05$
Mg (mg/kg)	25[2]	490.00^a (±15.14)	826.50^b (±20.29)	$p<0.05$
Ca:Mg ratio[3]	1.5 – 4.5[4]	0.68^a (±0.02)	0.50^b (±0.05)	$p<0.05$
Mg:K ratio[3]	3 - 4[4]	14.62 (±0.46)	19.15 (±4.72)	ns[6]
Mn (mg/kg)	-	2.4	-	
Fe (mg/kg)	-	5.8	-	
Number of samples (N)[5]	-	4	20	

[1]After SASA (2000); [2]After FAS (2004); [3]Calculated form the cmol(+)/kg soil concentrations; [4]After Buys (1986); [5]Note the unequal data sets between years; [6]ns = Not significant

6.3.3.2.2 Effect of inorganic phosphorus application

Although the soil P did not differ significantly among treatments, it did increase with an increased fertilizer application (Table 6.15). The soil P varied from 2.14 mg/kg (in the NF treatment) to 9.28 mg/kg (in the 1 P treatment). In all four treatments, the soil P was lower than the threshold value for sugarcane growth of 31 mg/kg P.

The soil K was the lowest (99.6 mg/kg) in the NF treatment and the highest in the 0 P treatment (187.6 mg/kg). It is possible that the K that was applied in the 0 P treatment was taken up poorly because of poor growth and remained in the soil. The Mg:K ratio followed the same pattern as the soil K with the highest average in the NF treatment (23.9 mg/kg).

The soil Ca, Mg and the Ca:Mg ratio increased with an increase in fertilizer application. Single superphosphate contains calcium and this is likely why the Ca content increased with an increase in P application rate, which was supported by the positive correlation between the P application rate and the Ca:Mg ratio ($r^2 = 0.59$, $p<0.01$). The soil Ca and Mg showed a positive relationship ($r^2 = 0.77$, $p<0.01$). The foliar P content, but not soil P content correlated better with P application rate ($r^2 = 0.78$, $p<0.01$).

Table 6.15: Effect of fertilizer application on soil chemical parameters 135 days after planting in Experiment 3. Values are the average of 4 replicates and averages with different letters within a column differ significantly.

Fertilizer application	**pH (H_2O)**	**P**	**K**	**Ca**	**Mg**	**Ca:Mg**[3]	**Mg:K**[3]
			------------------------mg/kg-------------------------				
NF	6.36	2.14	99.60^{a}	549.12^{acd}	742.00^{a}	0.45^{a}	23.86^{a}
0P	6.30	3.48	187.58^{b}	645.38^{abc}	812.00^{ab}	0.49^{ab}	14.39^{b}
0.5P	6.32	6.44	150.94^{ab}	722.24^{bcd}	862.00^{b}	0.51^{b}	19.23^{ab}
1P	6.48	9.28	153.50^{ab}	779.96^{bd}	890.00^{b}	0.54^{b}	19.12^{ab}
Average	*6.37*	*5.34*	*147.91*	*674.18*	*826.50*	*0.50*	*19.15*
Threshold value/ optimum range	5.3 – 8.0[1]	31[2]	112[2]	200[2]	25[2]	1.5 – 1.4[4]	3 – 4[4]
$LSD_{0.05}$	ns[5]	ns[5]	45.37	91.60	102.30	0.05	4.73

[1] After SASA (2000); [2] After FAS (2004); [3] Calculated form the cmol(+)/kg soil concentrations; [4] After Buys (1986); [5] ns = Not significant

6.3.3.3 Sugarcane foliar analysis

The foliar P and Ca were lowest in the 0 P and NF treatments (significant, $p<0.05$) (Table 6.16). The foliar Fe was significantly lower in the 0.5 P treatment (171.5 mg/kg) than in the 1 P treatment (219.0 mg/kg). The reason for this is not known. The foliar N, K, Mg, S, Si, Mn, Cu and Zn did not vary significantly among the fertilizer application treatments.

Table 6.16: Effect of fertilizer application on the foliar nutrient content 135 days after planting in Experiment 3. Values are average of 5 replicates and averages with different letters within a column differ significantly.

Fertilizer application	N	P	K	Ca	Mg	S[2]	Si[2]	Zn[2]	Mn[2]	Cu[2]	Fe[2]
	%						mg/kg				
NF	0.73	0.06^{a}	1.29	0.20^{a}	0.20	-	-	-	-	-	-
0P	0.57	0.05^{ab}	1.18	0.19^{ab}	0.17	-	-	-	-	-	-
0.5P	0.66	0.11^{b}	1.04	0.31^{b}	0.14	8.25	111.50	13.75	157.75	5.00	171.50^{a}
1P	0.65	0.11^{b}	1.03	0.33^{b}	0.14	7.80	147.40	13.40	150.80	5.20	219.00^{b}
Average	*0.65*	*0.08*	*1.14*	*0.26*	*0.17*	*8.00*	*131.44*	*13.56*	*153.89*	*5.11*	*197.89*
LSD$_{0.05}$	ns[1]	0.03	ns[1]	0.05	ns[1]	ns[1]	ns[1]	ns[1]	ns[1]	ns[1]	$p<0.05$

[1] ns = Not significant; [2] Micronutrients and S could not be determined in the 100 t/ha FC treatment because of inadequate leaf material due to small plant size.

6.3.3.4 Sugarcane growth response

Sugarcane growth in terms of the ABM, RBM and WPBM, TVD height and tiller number was best in the 1 P treatment (Table 6.17). The NF and 0 P treatments had lowest values for these parameters (Figure 6.3). The RSR did not differ significantly among fertilizer treatments. Phosphorus application is known to stimulate root growth and plant growth in general (Buys, 1986; Fertilizer Industry Federation of Australia, 2000; Chandrasekaran et al., 2010) and could offer an explanation as to why sugarcane growth was better in the 1 P treatment where P was applied at a higher rate than in the other treatments. Correlations between P application rate and ABM, RBM, TVD height and tiller number was significant and positive, which supports this explanation (Table 6.18). Because P application improves root growth it is also associated with improved uptake of N, P and K (Akram et al., 2007). In the current experiment, P application rate correlated positively and significantly ($p<0.01$) with the foliar P, as well as Ca content ($r^2 = 0.83$ and $r^2= 0.78$, respectively). The foliar P and Ca, in turn, also correlated significantly and positively with the tiller number, TVD height ABM, RBM and WPBM. The significant correlation of Ca with these sugarcane growth parameters thus shows that Ca did have a nutritional effect in this particular experiment. It is possible that the high Mg content of the soil in the NF and 0 P treatments (where no Ca was applied in any form) suppressed the uptake of Ca by the sugarcane plants (Mengel and Kirkby 1987). In the 0.5 P and 1 P treatments, Ca was applied in the form of single superphosphate that could have increased the uptake of Ca. In Experiment 3, the foliar N and K did not correlate significantly with any of the sugarcane growth parameters measured.

Table 6.17: Effect of fertilizer application on the sugarcane tiller number, TVD (top visible dewlap) leaf height, aboveground biomass (ABM), root biomass (RBM), whole plant biomass (WPBM) and root to shoot ratio (RSR) 135 days after planting in Experiment 3. Averages with different letters within a column differ significantly ($p<0.05$).

Fertilizer application	Tiller number	TVD height	ABM	RBM	WPBM	RSR
		---mm---	-----------------------g---------------------			
NF	1.80^{a}	457.00^{a}	53.54^{a}	52.08^{a}	108.18^{a}	0.95
0P	3.00^{ab}	394.40^{ab}	45.44^{ab}	46.69^{ab}	93.66^{a}	0.99
0.5P	5.40^{b}	641.40^{b}	146.34^{b}	124.24^{b}	275.21^{b}	0.83
1P	5.40^{b}	680.20^{b}	173.40^{b}	147.59^{b}	328.72^{c}	0.82
Average	*3.90*	*543.25*	*104.68*	*89.11*	*193.15*	*0.90*
N	4	4	4	3	3	3
$LSD_{0.05}$	1.22	104.70	53.49	30.36	58.62	ns[1]

[1] ns = Not significant

Figure 6.3: A photograph taken of plants of the fertilizer application treatments at 135 days after planting in Experiment 3. Note the smaller plant size in the NF and 0 P treatments.

Table 6.18: Correlation coefficients (r^2-values) resulting from correlations of sugarcane tiller number, TVD (top visible dewlap) leaf height, aboveground biomass (ABM), root biomass (RBM) and whole plant biomass (WPBM) with soil and foliar Ca, P application and foliar P 135 days after planting in Experiment 3.

	Tiller number	TVD height	ABM	RBM	WPBM
Soil Ca	0.60^2	0.67^2	0.53^1	0.63^1	0.66^1
Foliar Ca	0.73^2	0.73^2	0.74^2	0.86^2	0.89^2
P application	0.77^2	0.81^2	0.81^2	0.92^2	0.94^2
Foliar P	0.66^2	0.68^2	0.76^2	0.80^2	0.81^2

^{1} = Significant $p < 0.05$; ^{2} = Significant $p < 0.01$

6.3.4 Pooled data of experiments 1, 2 and 3

6.3.4.1 Effect of inorganic calcium application on whole plant biomass

A significant and positive correlation ($r^2 = 0.63$, $p < 0.01$) was observed between inorganic Ca application and whole plant biomass (WPBM). The interpolation from the regression graph of the relationship between Ca supply and relative WPBM indicated that the critical level for deficiency (95% of the maximum) was 608 kg/ha (Figure 6.4). The critical level for excess (95% of maximum) was 2920 kg/ha Ca. The inorganic Ca application rate correlated significantly with the leaf Ca ($r^2 = 0.50$, $p<0.01$) and the leaf Ca in turn correlated significantly with WPBM ($r^2 = 0.74$, $p<0.01$) which shows that Ca did have a nutritional effect. The initial Ca content of the soil was 546.3 mg/kg which was considerably higher than the threshold for Ca for optimum sugarcane growth of 200 mg/kg (FAS, 2004). It is possible that the high Ca:Mg ratio in the soil reduced the uptake of Mg, since Mg has an antagonistic effect on the uptake of Ca (Mengel and Kirkby, 1987) and that adding extra Ca (in the form of gypsum and/or single superphosphate) allowed better uptake of Ca. The possibility of Ca also having a physical effect on the soil cannot be excluded, but could not be proven with the available data.

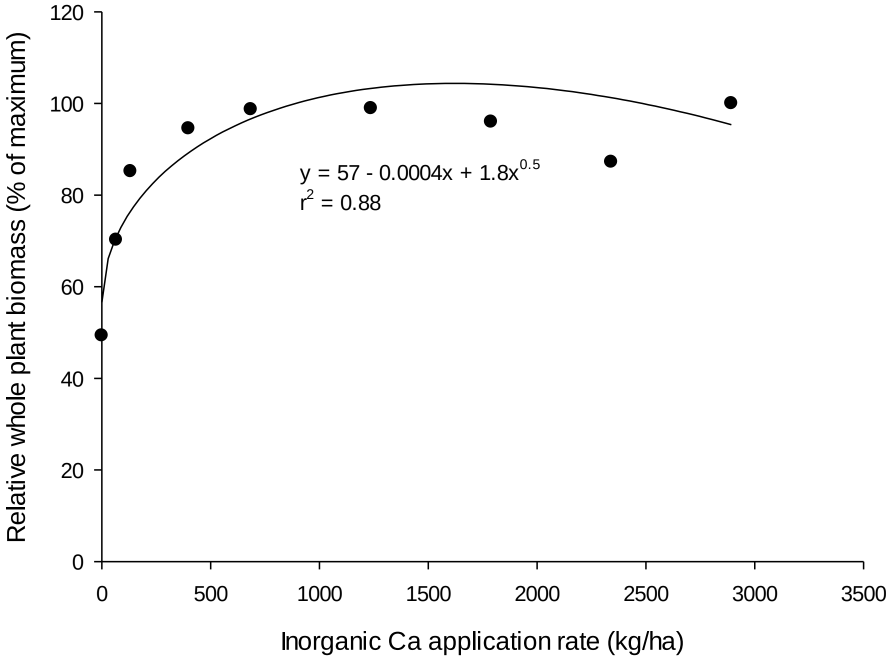

Figure 6.4: Effect of inorganic calcium (Ca) application on the relative whole plant biomass (WPBM) in the pooled data. Data points represent averages.

6.3.4.2 Effect of inorganic phosphorus application on whole plant biomass

The relationship between inorganic P application and WPBM was positive and significant ($r^2 = 0.66$, $p<0.01$). In addition, WPBM showed a positive correlation with foliar P ($r^2 = 0.58$, $p<0.01$). The optimum range for inorganic P application, as obtained through interpolation of the regression graph (95% of maximum), was between 74 kg/ha and 230 kg/ha P (Figure 6.5). It should be noted that only four P application rates were used to construct the graph and that there was a large gap between the 70 kg/ha and 210 kg/ha P application rates.

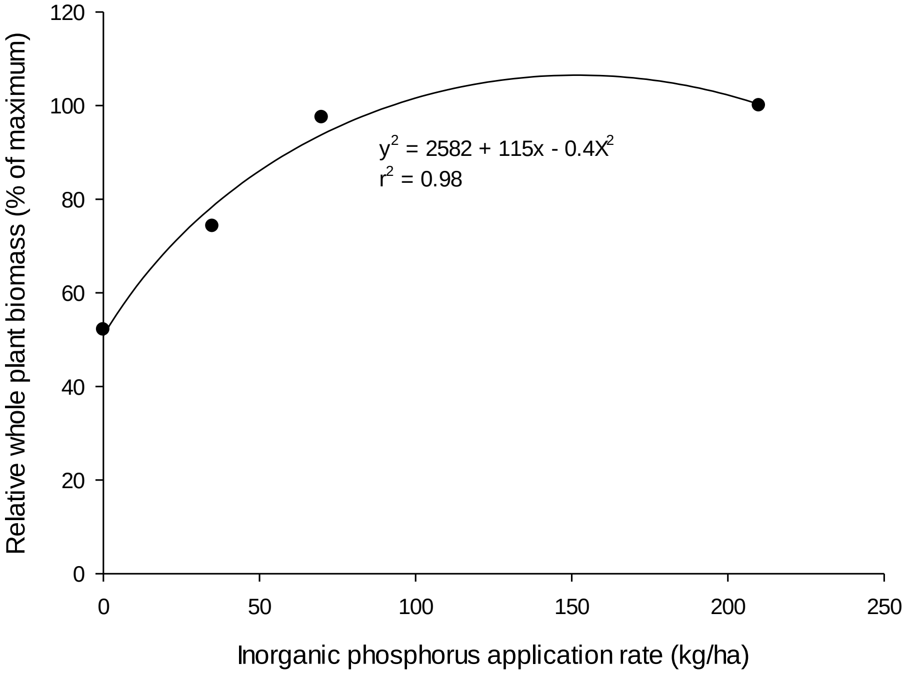

Figure 6.5: Effect of inorganic phosphorus (P) application on the relative whole plant biomass (WPBM) in the pooled data. Data points represent averages.

6.3.4.3 Effect of inorganic potassium application on whole plant biomass

Whole plant biomass correlated significantly with the inorganic K application rate ($r^2 = 0.62$, $p<0.01$). A quadratic relationship was indicated by the regression between the relative whole plant biomass and the inorganic K application rate (Figure 6.6). Interpolation of the regression graph revealed an optimum range for inorganic K application rate (95% of maximum) of between 287 kg/ha and 1378 kg/ha K. It should be noted that there was a large gap between the 240 and 1240 kg/ha K application rates. Unlike foliar Ca and P, the foliar K did not correlate significantly with WPBM ($r^2 = 0.06$). It seems unlikely therefore that application of inorganic K had a nutritional effect on sugarcane growth in the pot experiments.

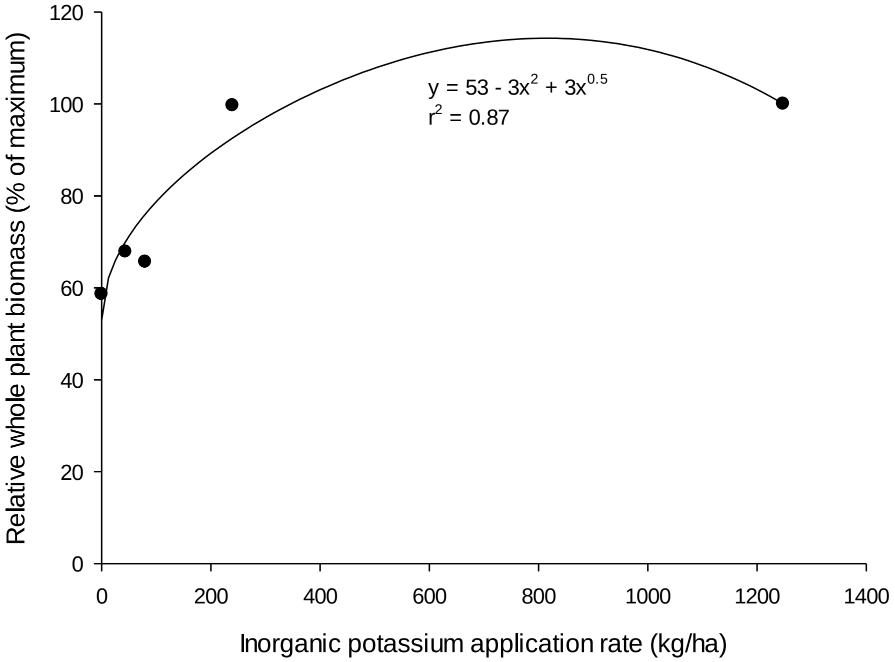

Figure 6.6: Effect of inorganic potassium (K) application on the relative whole plant biomass (WPBM) in the pooled data. Data points represent averages.

6.3.4.4 Effect of N, K, P and Ca application on the Ca:Mg and Mg:K ratios

As expected, the application of inorganic N did not influence the Ca:Mg and Mg:K ratios in the pooled data set. The application of inorganic P, K and Ca had a significant and positive relationship with the Ca:Mg ratio and a significant and negative relationship with the Mg:K ratio (Table 6.19). The fact that K application affected the Ca:Mg ratio, could indicate that it lowered the exchangeable Mg and thereby possibly promoted flocculation in the soil. Phosphorus application also reduced the Mg:K ratio in the P field experiment (section 3.3.2.1.2). The mechanism for this interaction is not known and appears to be restricted to lower application rates of P, since it was not observed in other field or pot experiments where the application rate of P was at the recommended rate or higher.

Table 6.19: Correlation coefficients (r^2-values) resulting from correlations of the Ca:Mg and Mg:K ratios with the inorganic P, K and Ca application rates in the pooled data set.

	Ca:Mg	Mg:K
Inorganic P application	0.26^1	-0.57^2
Inorganic Ca application^3	0.88^2	-0.55^2
Inorganic K application	0.76^2	-0.75^2

^{1} = Significant p <0.05; ^{2} = Significant p<0.01; ^{3}Includes the Ca contained in single superphophate

6.3.4.5 Effect of Ca:Mg and Mg:K ratios on whole plant biomass

There were significant (p<0.01) correlations for WPBM with the Ca:Mg and Mg:K ratios (r^2 = 0.51 and r^2 = -0.67, respectively). Quadratic and linear relationships were observed between the Ca:Mg and Mg:K ratios and WPBM, respectively (Figures 6.7 and 6.8). Interpolation of the regression graph between the Ca:Mg ratio and the relative WPBM revealed an optimum range (90% of maximum) for the Ca:Mg ratio of between 0.92 and 1.87. It is possible that the effect of the Mg:K ratio on WPBM was more the fact that it lowered the exchangeable Mg which improved flocculation in the soil rather than promoting uptake of K and thereby stimulating plant growth. Foliar K did not correlate significantly with WPBM (as pointed out in section 6.3.4.3), which supports this hypothesis.

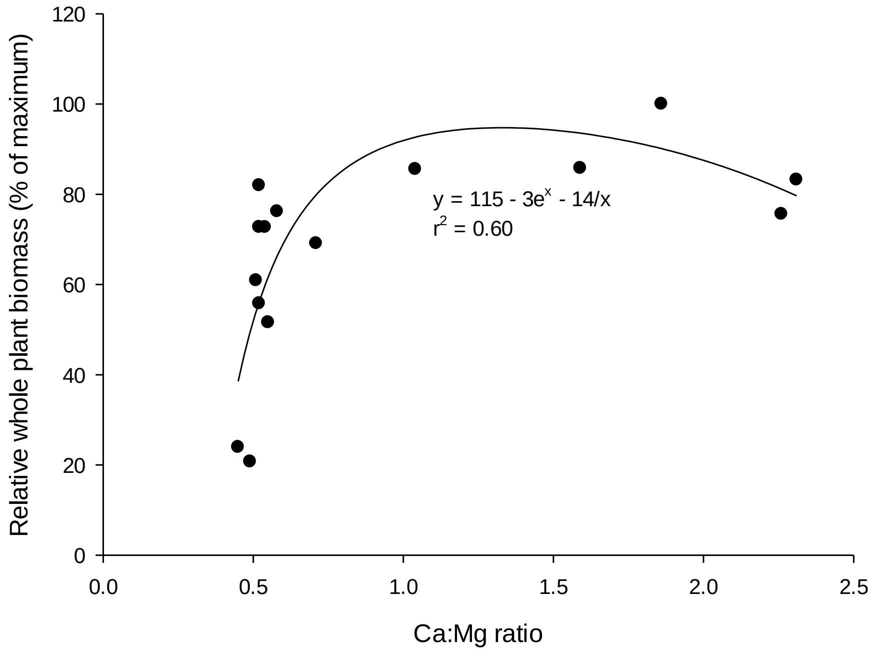

Figure 6.7: Effect of Ca:Mg ratio on the relative whole plant biomass (WPBM) in the pooled data. Data points represent averages.

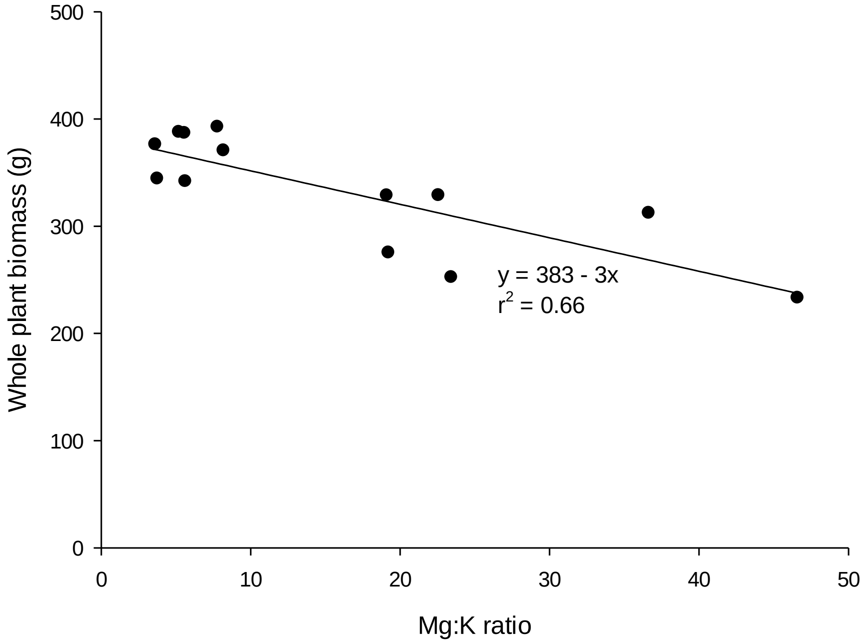

Figure 6.8: Effect of Mg:K ratio on whole plant biomass (WPBM) in the pooled data. Two treatments, namely the NF and 0 P treatments, were left out of the regression since they were outliers. Data points represent averages.

The results of the pooled data made it possible to identify a number of factors that significantly affected WPBM namely inorganic Ca, P and K application and the Ca:Mg and Mg:K ratios (Table 6.20). The Ca:Mg ratio in turn was significantly influenced by the application of inorganic K and Ca. The Mg:K ratio was significantly influenced by the application of inorganic P, K and Ca. Since P and Ca are essential nutrients for plant growth, it also had a direct effect on WPBM in these experiments, which should not be ignored. There was no indication from the pooled data that K had a direct effect of sugarcane growth.

The correlation coefficients between N application rate and WPBM was significant but small (r^2 = 0.38, $p<0.01$, respectively), and the effect of N application on sugarcane biomass was thus considered negligible.

Analysis of the pooled data set showed that the addition of gypsum, filtercake or inorganic fertilizer (N, P and K) at three times the recommended rate did not significantly improve WPBM relative to the two treatments where fertilizer was applied at the recommended rate (IF and 1 P treatments). Not applying any fertilizer or applying no P, as in the NF and 0 P treatments, did however result in significantly lower WPBM of plants compared to plants of the IF and 1 P treatments.

The IF and 1 P treatments, where N, P and K were applied at similar rates had remarkably similar WPBM values (328.7 g and 328.5 g, respectively) and also very similar Ca:Mg (0.52 and 0.54, respectively) and Mg:K (22.6 and 19.1, respectively) ratios. The effect of gypsum on the Ca:Mg and Mg:K ratios can be clearly seen in comparison to ratios in treatments where gypsum was not supplied. In treatments where gypsum was applied, the Ca:Mg ratio was consistently higher than 1 and the Mg:K ratio lower than 8. The Ca:Mg ratio of treatments where gypsum was not applied varied from 0.5 to 0.7 and the Mg:K ratio from 8.1 to 46.6.

Calcium and K are known to have an antagonistic relationship with Mg (Mengel and Kirkby,1987) and no Mg fertilizer was added to the soil, therefore a decrease, rather than an increase was expected in treatments where Ca and/or K was applied. The increase in soil Mg observed in these three pot experiments was thus not expected and needs further investigation. In the gypsum (Table 3.6) and filtercake (Table 4.7) field experiments, the soil Mg was, on average, lower in the July 2010 analyses than before the experiments started and in the inorganic P experiment (Table 5.6) it was very similar in both analyses.

It is unfortunate that a distinction could not be made in these experiments between the nutritional and physical soil effects of Ca. This could have been avoided by doing a simple turbidity test at the end of the experiment. Such a test could have shown differences (if any) in the level of dispersion/flocculation of the soil of different treatments.

Table 6.20: Summary of the effect of inorganic N, P, K and Ca application on the Ca:Mg and Mg:K ratios and whole plant biomass (WPBM) in Experiments 1, 2 and 3 at 135 days after planting.

Experiment	Treatment	Inorganic N application rate	Inorganic P application rate	Inorganic K application rate	Inorganic Ca application rate	Ca:Mg ratio	Mg:K ratio	WPBM
		-----kg/ha-----						-----g-----
1	0 t/ha gypsum	145	70	1248	133	0.59	3.76	344.29
	2.4 t/ha gypsum	145	70	1248	685	1.04	5.57	386.79
	4.8 t/ha gypsum	145	70	1248	1237	1.59	5.21	387.72
	7.2 t/ha gypsum	145	70	1248	1789	2.31	3.62	376.16
	9.6 t/ha gypsum	145	70	1248	2341	2.26	5.63	341.77
	12 t/ha gypsum	145	70	1248	2893	1.86	7.79	392.47
2	10 t/ha FC	139.47	0	44	0	0.52	23.44	252.19
	30 t/ha FC	128.41	0	0	0	0.55	46.61	233.13
	100 t/ha FC	89.7	0	0	0	0.71	36.64	312.23
	3 x IF	453	210	240	399	0.52	8.19	370.49
	IF	145	70	80	133	0.52	22.58	328.72
3	NF	0	0	0	0	0.45	23.86	108.18
	0 P	145	0	80	0	0.49	14.39	93.66
	0.5 P	145	35	80	66.5	0.51	19.22	275.21
	1 P	145	70	80	133	0.54	19.12	328.54
Average	-	-	-	-	-	*0.95*	*16.59*	*299.24*
$LSD_{0.05}$	-	-	-	-	-	0.34	5.15	65.07

6.4 CONCLUSIONS

Whole plant biomass of sugarcane was significantly influenced by the Ca:Mg ratio, the Mg:K ratio and inorganic Ca, P and K. The minimum Ca, P and K application rates for optimum WPBM was 608, 74 and 287 kg/ha, respectively. The optimum application rate for K was higher than its recommended rate for the reconstituted soil. The Ca:Mg ratio range for optimum WPBM was 0.92 to 1.87. The addition of FC did not significantly improve sugarcane growth in comparison to the control treatments (IF and 1 P treatments). It is evident from these results that specific fertility intervention would be essential for successful sugarcane production on mined Hillendale soils.

CHAPTER 7

GENERAL DISCUSSION AND RECOMMENDATIONS

7.1 RATIONALE FOR STUDY

The dune land being mined by Tronox KZN Sands at Hillendale for the extraction of titanium and other heavy minerals was previously under commercial sugarcane production. The mining entails the hydraulic extraction of the dune land which destroys the native soil profile completely. Tronox KZN Sands is however obliged for rehabilitation of the mined-out land to conditions where it is again suitable for the production of sugarcane commercially. This involves the backfilling and reshaping of the mined-out land with reconstituted soil (void of heavy minerals) before covering it with stored topsoil (removed before mining). Additionally, it is required to amend the reconstituted soil physically and chemically to support profitable sugarcane production. Soil amendments applied for this purpose are *inter alia* gypsum, filtercake and inorganic phosphorus.

7.2 POTENTIAL SOIL REHABILITATION CONSTRAINTS

Before the effects of the soil amendments tested in this study is discussed, it is necessary to give a description of the potential constraints associated with the reconstituted soil. These constraints became evident from data collected and observations made while conducting the experiments. If these issues are not addressed effectively, it is possible that sugarcane might not be grown successfully in the long run on the reconstituted soil.

7.2.1 Waterlogging

Waterlogging was a serious concern in the reconstituted soil. Visual observation of the reconstituted soil confirmed that it remained extremely wet over time; even after several months of being deposited (sections 3.3.1.2.2, 4.3.1.2 and 5.3.1.2.2). The main cause of the waterlogging is likely the fact that the reconstituted soil was deposited over sand, thus forming a duplex soil. Differences in hydraulic conductivity between the two soil layers prevented the waterfront from moving across the interface between these two soil layers of different texture, resulting in water accumulating in the reconstituted soil. This phenomenon is characteristic of a duplex soil and was described, for example, by Gardner (1968), Hillel (1982) and Young et al. (2006).The recommendation made from the initial rehabilitation work carried out by Golder Associates (2004) was based on the assumption that the soil would dry out after deposition and that soil water retention would be the most limiting factor in subsequent sugarcane growth. Although water retention is very important in ensuring adequate water supply to plants, the poor drainage potential of the re-constructed soil profile was not taken into account in this initial work. The waterlogging caused by the drainage limitation was possibly exacerbated by the dispersive nature of the reconstituted soil and the fact that the soil was deposited as slurry, which was saturated with water.

Waterlogging affected sugarcane growth both directly and indirectly. Negative and significant correlation of cane, sucrose and aboveground biomass (ABM) yield with soil water content (SWC) gave evidence of the direct effect of waterlogging on sugarcane growth in the field experiments that tested filtercake (FC) (Table 4.18) and inorganic P (Table 5.17). Black sugarcane roots (Figure 3.12), which were observed in all three field experiments, was also proof of an oxygen poor soil environment. The black colour is caused by deposition of FeS that precipitates on the root surfaces of plants growing in oxygen poor soils (Mengel and Kirkby, 1987).

Iron toxicity and nutrient deficiencies were also associated with the waterlogging in this study. The addition of organic matter (in the form of FC) to the oxygen poor reconstituted soil forced soil microorganisms to use an electron acceptor other than oxygen to oxidize organic matter (Russell, 1973). As a result Fe^{3+} was used an electron acceptor, which in turn released Fe^{2+} into the root zone. High levels of Fe^{2+} is toxic to plants (Mengel and Kirkby,1987) and negative and significant correlations of cane and ABM yield with foliar Fe were observed in the plant crop of the FC field experiment (Table 4.18). Iron toxicity is very rare in sugarcane, as reflected by the lack of literature on this topic. This in turn could be an indication of a serious problem with the reconstituted soil and the need to improve the structure and drainage of the soil. It is possible that the addition of any form of organic matter to a waterlogged reconstituted soil could lead to Fe toxicity.

Negative and significant correlations were recorded between foliar K, Ca and S and the long-term average SWC of the 50 – 100 and 100 – 150 cm depth zones in the first ratoon crop of the inorganic P field experiment (Table 5.14). This gave indication that waterlogging affected nutrient uptake. The possibility of waterlogging also affecting uptake of N and P cannot be excluded in this experiment, but could not be directly shown from the data. Foliar N, P, K and S were low or marginal in both first ratoon foliar analyses, including the treatment where N, P and K were applied at the recommended rates (1 P treatment) (Tables 6.13 and 6.15).

7.2.2 Soil erosion

The non-amended reconstituted soil was highly erodible. Magnesium-related dispersion was identified repeatedly in soil samples before amendments were added (Tables 3.8, 4.9 and 5.8). The unmined soil (US) which was used as a control treatment in the FC field experiment was also initially dispersed (Table 4.9). Soil dispersion was visually confirmed in the reconstituted soil (Figure 3.8). Since water infiltration is typically low in dispersed soils (Abrol et al., 1988, Dontsova and Norton, 1999), run-off is increased which in turn leads to increased soil erosion (Dontsova and Norton, 1999).

Low electrolyte concentration is another factor that can cause soil dispersion (Shainberg et al., 1989). In most of the soil samples analysed, the EC was considerably lower than the threshold EC of 1.28 dS/m for Mg-related dispersion (Fenton and Conyers, 2002), even after amendments were added. Such low electrolyte concentrations could have been a factor that caused soil dispersion by itself.

The risk of soil erosion in the reconstituted soil was probably also increased by low organic matter (OM) content. Organic matter in soil is important in aggregate stability (Tisdall and Oades, 1982), which in turn is an important factor that influences soil erodiblity (Pagliai et al., 2004; Coyne and Thompson, 2006; Tejada and Gonzalez, 2007). Aggregate stability was indeed very low in this study with averages in mean weight diameter (MWD) for treatments ranging between 0.07 mm and 0.13 mm at eighteen months after planting in the gypsum (Table 3.5) and inorganic P (Table 5.5) field experiments. Mean weight diameter in the reconstituted soil of the FC field experiment varied between 0.06 mm and 0.18 mm at eleven months after planting (Table 4.6). In contrast, the unmined soil had an average MWD of 0.67 mm.

The post-mined soil profile created at Hillendale is that of a duplex soil, since the reconstituted soil layer had a very different texture to that of the sand underneath it. Hardie et al., 2012 pointed out that duplex soil can be associated with a high erosion potential, because of their poor drainage. The duplex nature of the reconstructed soil profile is thus a further factor that could have increased the risk of soil erosion.

7.2.3 Hardsetting and compaction

Hardsetting is defined as the spontaneous process by which soil structure collapses after wetting followed by hardening of the soil without restructuring during drying (Mullins et al., 1990; Anderson et al., 1998b). Hardsetting is more likely to occur in soils with high silt and sand content, soils with non-swelling clays, dispersed soils and soils low in OM content. Characteristics of these soils include poor aeration and movement of water into and through the soil, increased runoff and erosion and poor root penetration (Anderson et al., 1998b).

In agriculture systems, compaction is often caused by pressure exerted by farm machinery. Compaction has the same negative effects on soil as hardsetting. The amount of compaction that can occur in a soil is a function of soil water content and moist soils are very vulnerable to compaction (Hillel, 1982). Dispersed soils are also prone to compaction (Davies and Lacey, 2010).

It is clear from the discussion above that the reconstituted soil at Hillendale is vulnerable to both hardsetting and compaction. Penetration resistance was used in this study to measure soil hardness, which can be the result of either hardsetting or compaction. Average penetration resistance values measured in the reconstituted soil were all well below the critical value of 2800 kPa for sugarcane production (Swinford and Boevey, 1984). However, there was a significant ($p<0.05$) increase in penetration resistance over time in all field experiments conducted in this study. For example, in the gypsum field experiment, the average PR increased from 119.5 kPa in 2009 to 306.4 kPa in 2010. Both hardsetting and compaction are potential constraints to successful sugarcane production in the reconstituted soil, although they did not have significant influence on sugarcane growth in this particular study. It also needs to be considered that the reconstituted soil remained very wet throughout the experimental time and it is uncertain how the soil will react in terms of hardsetting if it does dry out.

7.3 STRATEGIES FOR MINIMIZING SOIL CONSTRAINTS

7.3.1 Waterlogging and soil erosion

Since the non-amended reconstituted soil is very unstable, every possible precaution needs to be taken against erosion. Some strategies against erosion include contour tillage, strip tillage, no-till or minimum tillage, permanently having the soil covered with crops or residues, increasing water infiltration and reducing run-off (Directorate Agricultural Information Services, 2008).

Improving the soil structure is imperative to combatting both waterlogging (Gardner, 1996) and erosion (Brady and Weil, 2004). As far as soil structure is concerned, alleviating soil dispersion is very important. Organic matter is a well-known amendment for dispersed soils (for example Abrol et al., 1988; Clark et al., 2007; Davies and Lacey, 2010; Carrow and Duncan, 2012), making an increase in OM content all the more important in the rehabilitation of the reconstituted soil at Hillendale. Carrow and Duncan (2012) reported that organic amendments often enhanced the effectiveness of gypsum on sodic soils. The same could be true about Mg-related dispersed soils, and needs further investigation.

Increasing the electrolyte concentration of the soil is also an important aspect in stabilizing the soil. Application of FC at 100 t/ha increased EC to 2.6 dS/m and was by far the most effective among all treatments tested for their effect on EC in this study. Including an amendment that will increase the EC to a minimum of 1.28 dS/m (as indicated by Fenton and Conyers, 2002 as a criteria for Mg-related dispersion) needs to be incorporated into the rehabilitation program.

It needs to be pointed out that as long as the reconstituted soil is deposited on sand, the soil will retain its duplex nature. However, improving drainage in the reconstituted soil and depositing the reconstituted soil layer with adequate thickness could go a long way in ensuring that sugarcane can be grown sustainably. Insertion of sub-surface drainage pipes could help to drain excess water and thus to prevent waterlogging. It is also important to consider that in years of low rainfall, the reconstituted soil layer could act like a water reservoir and could be an advantage in crop production. Irrigation is not advised until the reconstituted soil is stabilized.

7.3.2 Compaction and hardsetting

Since the reconstituted soil is at risk to both hardsetting and compaction, it is advised to measure the penetration resistance at least annually over a period of several years. Soil water content is a very important factor that influences compaction (Hamsa and Anderson, 2005) and it could therefore be worthwhile to determine the ideal SWC for tillage in the reconstituted soil.

A review on soil compaction by Hamsa and Anderson (2005) suggested that soil compaction can be avoided in several ways. As already pointed out, tilling the soil at a water content that will result in minimum compaction is important. Pressure caused by machinery should be limited by decreasing axle load and/or increasing the contact area of wheels with the soil. Decreasing the number of tillage operations by using a no-till or minimum tillage system can be an effective way to reduce compaction. Using a so-called controlled traffic system where traffic is confined to certain areas will limit compaction to certain areas in the field. Increasing the organic matter content will stabilize the soil structure and decrease soil bulk density and soil strength. Growing plants with strong deep root systems can penetrate compacted soils. Finally, Hamsa and Anderson (2005) suggested using gypsum to improve the soil’s resistance (through improved soil structure) to compaction.

Hardsetting can be alleviated or avoided by adding organic matter to the soil, overcoming soil dispersion, avoiding having bare soils, growing crops with fibrous root systems, increasing electrolyte concentration in the soil and applying gypsum (Anderson et al., 1998b).

7.4 RESPONSE OF RECONSTITUTED SOIL TO AMENDMENTS

As mentioned, gypsum, filtercake and inorganic phosphorus were used as amendments to rehabilitate the reconstituted soil back to profitable sugarcane production.

7.4.1 Gypsum

7.4.1.1 Soil water content

There are indications from the data that gypsum application affected the soil water content (SWC). The SWC was significantly higher in two depth zones in the 0 t/ha and 16 t/ha gypsum treatments compared to the other gypsum treatments during the September 2009 to July 2010 measuring period (Figure 3.5). It is possible that gypsum lowered the SWC where gypsum was applied, yet it could not be explained why the soil of the 16 t/ha gypsum treatment had a relatively high SWC. Also, the gypsum and inorganic P field experiments were run simultaneously and yet the SWC in the three depth zones of the gypsum field experiment in July 2010, for example, (Figure 3.6) was considerably lower than in July 2010 in the inorganic P field experiment (Figure 5.2).

7.4.1.2 Aggregate stability

Aggregate stability, as measured by the mean weight diameter (MWD), was not significantly improved by gypsum application in the field. In a previous study at Hillendale (Van Jaarsveld and Zharare, 2010), applying gypsum at a rate of 5 t/ha resulted in a MWD of 0.24 mm after 37 months, while in the control treatment it was significantly ($p<0.05$) lower (0.07 mm). In the present study, MWD was determined 18 months after applying gypsum and varied from 0.03 to 0.13 mm. Time therefore could have been a factor that also influenced the aggregate stability in the field experiment. This confirms a report by Amézketa (1999), who indicated aging as a factor that influence aggregate stability. Waterlogging is another factor that could have affected the MWD negatively in the gypsum field experiment (De-Campos et al., 2009).

7.4.1.3 Ratios of cations

The ability of gypsum to improve the Ca:Mg ratio is important in overcoming Mg-related dispersion in the reconstituted soil, which is one of the criteria used in characterizing Mg-related dispersion (Fenton and Conyers, 2002). Gypsum application was very successful in improving the Ca:Mg ratio in both the field and pot experiments. The Ca:Mg ratios in the field experiment varied from 0.6 (0 t/ha gypsum treatment) to 5.4 (in the 16t/ha gypsum treatment) (Table 3.7). In the gypsum pot experiment (Experiment 1), the Ca:Mg ratio in the 0 t/ha gypsum treatment was 0.6 (Table 6.4). The 9.6 t/ha gypsum treatment had the highest Ca:Mg ratio in this experiment, namely 2.3. According to Buys (1986) the ideal Ca:Mg ratio for optimum crop production is between 1.5 and 4.5. Application of inorganic Ca had the ability to improve the Mg:K ratio, as was reflected from the pot experiment data (Table 6.19).

The use of gypsum as a soil amendment certainly needs further investigation, because of its ability to improve cation ratios in the soil, even if it may not increase sugarcane yield. However, the interaction between Ca, Mg and K in the soil is complex and future work should focus on understanding their separate and combined effects on dispersion/flocculation of the reconstituted soil. Competitive interaction between these ions could also affect their uptake by plants and hence affect crop growth (Mengel and Kirkby, 1987; Marschner, 1995). It is especially important to test the effect of K on the soil, since a high application of K could be detrimental to soil structure (Shainberg et al., 1989; Auerswald et al., 1996; Bronick and Lal, 2005) and can become an environmental issue if it accumulates in the soil (Van Antwerpen and Meyer, 1997).

Although optimum ranges for Ca and K were identified in the pot experiments (608 to 2920 kg/ha and 287 to 1378 kg/ha, respectively), these application rates will have to be confirmed under field conditions.

7.4.1.4 Sugarcane growth

In the pooled data of the pot experiments, the Ca application rate correlated significantly and positively with whole plant biomass (WPBM) ($r^2 = 0.63$, $p<0.01$). It was however not clear if this effect was purely nutritional (caused by increased uptake of Ca by plants) or also by a physical effect on the soil. It is therefore important to make a distinction between the nutritional and soil physical effect of Ca and K when conducting future experiments. Gypsum application did not significantly improve cane, sucrose or ABM yield in the gypsum field experiment.

7.4.2 Filtercake

The most promising effect of FC in this study was its ability to overcome Mg-related dispersion. Addition of FC at a rate of 100 t/ha improved all the criteria associated with Mg-related dispersion (Table 4.10). In this regard, the ability of FC at 100 t/ha to improve the electrical conductivity (EC) of the soil is especially significant, since, as discussed in section 7.2.2, a low EC can result in soil dispersion (Shainberg et al., 1989).

The application of FC at 100 t/ha was most efficient (relative to the other treatments in the FC field and pot experiments) in increasing the P content of the soil (Tables 4.8 and 6.9). In the 2010 foliar analysis, the foliar P content was also higher in the 100 t/ha FC treatment (but not significant) than in the other treatments (Table 4.16).

The addition of FC did not significantly improve aggregate stability or sugarcane growth in the field, possibly because of confounding factors. As with gypsum, the effect of FC was probably masked by a number of factors. Firstly, waterlogging caused iron toxicity in the field which affected sugarcane growth negatively. Secondly, waterlogging could have had a negative effect on aggregate stability (De-Campos et al., 2009). Thirdly, the aggregate stability was measured only 11 months after applying FC which might not have been long enough for FC to have an effect (Amézketa, 1999). Lastly, the high C:N ratio of the FC caused nitrogen immobilization in the field which also affected sugarcane growth negatively. However, even in the FC pot experiment, where waterlogging and N immobilization was absent or minimal, the sugarcane growth was still not significantly higher than the control treatment. Hence, FC did not give the expected response in this study.

Filtercake was used in this study as a source of organic matter. However, the soil can be organically amended by other organic sources (like compost) or by green manuring. There is need to determine the most efficient and cost-effective way to amend the soil organically. In a previous study at Hillendale (Van Jaarsveld and Zharare, 2010), growing a legume and grass together as a green manure, significantly increased aggregate stability in comparison to the control at 15 months after planting. The use of a green manuring as an organic amendment is thus worth pursuing further in future.

Before mining, the average OM content of the Hutton soils (which dominated Hillendale prior to mining) was 0.5% with an average slimes content of 9.2% (Snyman, 2001) (Table 2.1). The average OM content of the reconstituted soil measured in July 2010 from samples collected from the three field experiments was 0.2% with an average slimes content of 25.6%. The South African Sugar Association Experiment Station (1999) reported that Hutton soils of the coastal lowlands, which include the study area, typically have moderate levels of organic matter (2 – 4%). These soils are known to be loamy sands or sandy loams (South African Sugar Association Experiment Station, 1999), which is similar to the texture of the reconstituted soil (Golder Associates, 2004). It should thus be possible to increase the OM content of the reconstituted soil considerably. A minimum OM content of 1% should be a reasonable goal in the reconstituted soil.

Adding organic matter to a soil with high water content is however not advisable. It will increase the water retention and could result in toxicities. The possibility of drying out the reconstituted soil in some way before crops are grown or the installation of a sub-surface drainage system are issues that will have to be investigated further. It is advisable to use a source of organic matter with a low C:N ratio to prevent N immobilization. If using an organic matter source with a high C:N ratio, adding inorganic N to the soil to prevent N immobilization might be required (Barbarick, 2011).

Soil tillage will need to be done in a way that will disturb the soil as little as possible once organic matter has been added or a crop is growing. Every time the soil is disturbed, the organic matter content will decrease due to mineralization (Bot and Benites, 2005). Increasing SOM content is a slow process and could take several years (Snapp and Grandy, 2011) and is unlikely to be achieved by a single application of compost or green manure and even less so if the soil is regularly disturbed. In this regard sugarcane is a good crop to grow since it is normally ratooned for several years before replanting.

Organic matter has the potential to improve soil structure and soil fertility and to combat dispersion, compaction and hardsetting. Thus, of all amendments, increasing the OM content of the reconstituted soil is considered the most important and should be treated as such.

7.4.3 Inorganic phosphorus

Cane, sucrose and aboveground biomass (ABM) yield increased significantly with an increase in P application rate in the plant crop of the inorganic P field experiment. Uptake of N, P, K, Ca, Mg and S were significantly improved by inorganic P application in the same crop. There was no indication of P or other nutrient deficiencies in the plant crop. Applying inorganic P at the recommended rate in the first ratoon crop was not adequate for optimum sugarcane growth, possibly because of the effect of waterlogging.

It was assumed that application of inorganic P stimulated root growth in the field which in turn improved uptake of nutrients in the plant crop. This assumption was confirmed by data collected in the inorganic P pot experiment (Experiment 3) which showed a highly significant correlation ($p<0.01$) between P application rate and root biomass (RBM) ($r^2 = 0.92$). In this experiment, it was also shown the application of P significantly ($p<0.01$) increased uptake of P and Ca ($r^2 = 0.83$ and $r^2 = 0.78$, respectively). Furthermore, P application significant improved ABM ($r^2 = 0.81$, $p<0.01$) and WPBM ($r^2 = 0.94$).

Application of inorganic P had a significant ($p<0.01$) negative relationship with the Mg:K ratio in the P field experiment ($r^2 = -\ 0.67$), as well as in the pooled data of the pot experiments ($r^2 = -0.57$). The mechanism for this interaction is not known.

Applying P in the field experiments at the recommended rate had variable results and there seems to be a possibility that P will have to be applied at a higher rate. In the pooled data of the pot experiments, however, the minimum P application rate for optimum WPBM (74 kg/ha) was similar to the recommended rate of 70 kg/ha P. More work is therefore needed to determine the optimum P application rate under field conditions. It needs to be considered that waterlogging affects P availability in soils and that the optimum P application rate might be different at different water contents in the soil.

7.4.4 Cation ratios and sugarcane growth

The importance of cation ratios in crop production is a controversial issue. Some studies have suggested that they have significant effect on soil quality and hence crop growth, while others have shown no effect (Koppitke and Menzies, 2007 and references therein). Even in this study the effect of the Ca:Mg and Mg:K ratios on sugarcane growth and yield was variable. The pooled data of the pot experiments showed a positive correlation of WPBM with the Ca:Mg ratio ($r^2 = 0.51$, $p<0.01$) and a negative correlation with the Mg:K ratio ($r^2 = -0.67$, $p<0.01$). The data indicated that the optimum Ca:Mg ratio, in terms of WPBM, was 0.9 which was lower than the ideal range of crop production of 1.5 to 4.5 (Buys,1986) for optimum crop production. In the filtercake field experiment, the Ca:Mg ratio correlated significantly ($p<0.01$) and positively with cane and ABM yield ($r^2 = 0.53$ and $r^2 = 0.59$, respectively). The Mg:K ratio showed a significant and negative relationship with ABM yield ($r^2 = -0.54$, $p<0.05$). However, in both the gypsum and inorganic P field experiments, cane, sucrose and ABM yield were not significantly affected by the Ca:Mg and Mg:K ratios.

7.5 CONCLUSIONS

The ultimate goal of the rehabilitation program at Hillendale is to successfully re-establish sugarcane production in the reconstituted soil. However, long-term sustainable sugarcane production might be compromised if the potential constraints of waterlogging, erosion, hardsetting and compaction are not addressed. The results of this study showed that successful sugarcane production will not be possible without amending the soil physically and chemically. Yet many questions remain unanswered regarding the amendments tested in this study and this work is by no means complete. However, the results obtained in this study can provide a valuable basis for future research and ultimately contribute to the successful rehabilitation of the reconstituted soil at Hillendale.

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