SIMULATING NITROGEN DYNAMICS IN SUGARCANE CROPPING SYSTEMS USING DSSAT-CANEGRO

By

TSOELIPE SAMUEL MATLALETSA

**Submitted in partial fulfilment of the requirements for the degree M.Sc. (Agric.) Agronomy
In the Faculty of Natural and Agricultural Sciences
University of Pretoria**

**Supervisor: Dr. M. van der Laan
Co-supervisor: Prof. J.G. Annandale
Co-supervisor: Dr. N. Miles**

October 2015

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Declaration

I hereby certify that this dissertation is my own work, except where duly acknowledged. I also certify that no plagiarism was committed in writing this dissertation.

Signed ______________________

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Abstract

Sugarcane is a high-biomass producing crop and often requires substantial amounts of nitrogen (N) fertiliser to achieve optimal yields. Nitrogen fertiliser represents a significant input cost for the sugar industry. This nutrient is highly challenging to manage due to its susceptibility to various kinds of losses following application, for example, leaching and denitrification. In addition to reduced profitability, N losses potentially lead to environmental degradation, for example, through eutrophication of water bodies. As a result of the complexities of N dynamics in sugarcane cropping systems, mechanistic crop models are now more commonly being used to help understand these various N in- and outflows, and to inform better management practices. These models first require extensive calibration, testing and validation with measured data in order to gain confidence in their performance, however. In this study, a historical dataset from a fertigation trial conducted in Komatipoort, Mpumalanga, was firstly used to assess the ability of DSSAT-Canegro (with a newly included N subroutine) to simulate cane and sucrose yields as well as aboveground N mass in response to different N fertiliser rates over five consecutive seasons (2003-2007). Cane and sucrose yields, as well as aboveground N mass were adequately simulated in response to various N rates under drip irrigation. In addition to this, cane yield, aboveground N mass and soil water N concentrations were monitored for model testing purposes as part of this study in trials conducted in Pongola (irrigated), Mount Edgecombe (rainfed), and Inanda (rainfed), all in KwaZulu Natal. For the Mount Edgecombe trial, N fertiliser treatments that took soil N levels into account before deciding when to fertilise were included, and the potentially reduced leaching loads were investigated by the model. In most cases, the DSSAT-Canegro model simulated N dynamics and cane yield adequately under both irrigated

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and rainfed conditions. The model was also observed to perform well under contrasting environmental conditions, such as during periods of drought versus high rainfall. In a number of cases, significant differences in cane yield between treatments receiving different rates of N were not observed in the measured data, indicating that the crop was able to acquire sufficient N from organic matter mineralisation and fertiliser N from previous seasons' applications or the different N rates were all more than the required amount. Based on the potential implications of reduced cane yield following water stress and/or N stress, and unwanted N exports to the environment, it is concluded that DSSAT-Canegro is a useful tool to improve our knowledge of N dynamics in sugarcane ropping systems and to develop best management practices.

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INTRODUCTION

Rationale

A high demand for increased yields of agronomic crops driven by a growing world population has led to intensive use of nitrogen (N) fertilisers in agroecosystems. Nitrogen is the nutrient required in the largest quantity by crops, and because the manufacturing of nitrogenous fertilisers is energy intensive, N often represents a significant production cost in many cropping systems. Particularly in sugarcane (*Saccharum* spp. L.) cropping systems, N is required in relatively large quantities to maintain high biomass production and to attain optimum yields (Wiedenfeld, 1995). Profitability in sugarcane production is therefore closely linked to the high input costs associated with N fertilisation and the N-use efficiency of the crop.

It has been estimated that the South African sugarcane industry spends about R 440 million on N fertiliser each year ([1]Personal communication). As the South African government's Department of Energy aims to increase biofuel production in the country, the use of sugarcane as a biofuel feedstock will potentially result in expansion of lands planted to sugarcane and even higher levels of associated N fertiliser use. As with most other agronomic crops, N use efficiencies of sugarcane have been estimated to be in the region of 50% (Meyer & Wood, 1994), which is a major concern when considering the large quantities of N fertilisers being applied to sugarcane on a yearly basis. The fate of the other 50% is often unknown. Inefficient N use leads to reduced profitability for farmers and unwanted losses to the environment as a pollutant or greenhouse gas. Nitrogen fertilisers therefore represent a significant input cost for the sugar industry, and

[1] Dr Neil Miles, April 2012, SASRI

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increasing N use efficiency can result in benefits both in terms of profitability and environmental sustainability.

The losses occur mostly when N fertilisers are applied in excess of crop demand, or at inappropriate times relative to crop demand. These N losses are difficult to quantify and understand due to interacting physical, chemical and biological process that take place simultaneously. Leaching and run-off of N from sugarcane cropping systems contribute significantly to N losses and result in the pollution of groundwater and surface waters with subsequent deterioration of water quality. Gaseous losses of N through volatilisation and denitrification are also receiving heightened attention as they increase greenhouse gas concentrations in the atmosphere (Weier, 1999) and lead to terrestrial and aquatic acidification. It is therefore clear that if environmentally sustainable and profitable farming is to be realized, agronomic practices should be aimed at ensuring optimal N management that leads to high N use efficiencies.

Although a vast amount of research has been done on sugarcane N nutrition, our ability to quantify N in- and outflows in commercial production systems remains inadequate. Crop modelling is commonly used to investigate N dynamics in complex agroecosystems, but to date has only been used on a very limited scale to investigate N dynamics in South African sugarcane production systems.

Study aims and objectives

Following the recent inclusion of an N subroutine in the DSSAT-Canegro model (Van der Laan *et al*., 2011), extensive model testing is required to improve confidence in its outputs. The aim of this study is to validate the DSSAT-Canegro model for a range of cropping systems in the South African sugar industry so as to produce a robust model that can be used to investigate N dynamics more closely in future studies. A historical

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dataset from Komatipoort, and newly collected data from trials conducted in Pongola, Inanda and Mount Edgecombe was used to test the performance of DSSAT-Canegro under irrigated and rainfed conditions. Additionally, the ability of the model to simulate soil water nitrate concentrations in the solutuion, as measured from ceramic suction cups installed in selected field trials was tested, as this type of direct measurement is relatively cheap and can potentially be very useful for model calibration and validation purposes. For the Mount Edgecombe trial, monitoring and modelling were used to investigate the impact of different N fertilisation strategies on crop growth and N leaching.

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1 CHAPTER 1: LITERATURE REVIEW

1.1 Nitrogen dynamics in sugarcane cropping systems

In soil, N occurs either in organic form (plant-unavailable) as part of organic matter and crop residues, or in inorganic form (plant-available), mostly as nitrate (NO_3^-) and ammonium (NH_4^+). In agroecosystems, N can undergo a series of transformations (Figure 1.1). The nature and magnitude of these transformations is to a large extent influenced by environmental conditions and management practices, and are discussed below.

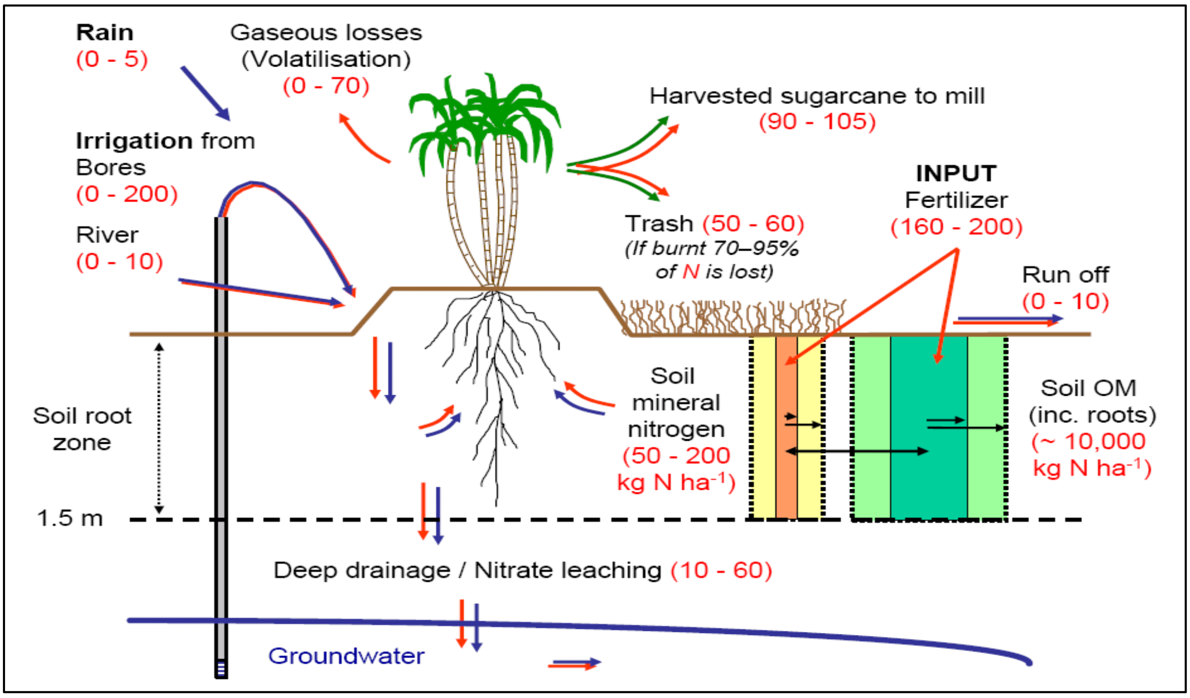

Figure 1.1 Potential nitrogen transformations in sugarcane cropping systems (Bristow, 2004)

1.1.1 Mineralisation and immobilisation

During mineralisation, organic N is converted to inorganic NH_4^+ through a process called ammonification. Depending on soil characteristics, much of this NH_4^+ may be quickly converted to NO_3^- by nitrifying bacteria through a process called nitrification (Brady &

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Weil, 1999). In contrast, immobilisation is when inorganic forms of N (NH_4^+ and NO_3^-) are converted to organic forms by soil microbes, thus making N unavailable for crop uptake. Immobilisation is therefore the reverse of mineralisation and both processes are driven by soil micro-organisms.

Soil organic matter content and the carbon (C) to N ratio (C:N ratio) of this organic matter plays a major role in determining mineralisation/immobilisation dynamics. Crop residues that contain high C:N ratios (>20:1) often promote immobilisation, whereas organic matter with low C:N ratios (<20:1) will promote mineralisation (Brady & Weil, 1999). The decomposition of fresh organic material with a high C:N ratio increases the number of heterotrophic organisms which is indicated by an increase in carbon dioxide (CO_2) evolution. During this stage, immobilisation is dominant, as the organisms compete effectively for available N.

As decomposition proceeds, the C:N ratio of the residue deceases due to decreasing C which is released during respiration. The microbial activity will eventually slow down as a result of low C supply and this will then lead to net mineralisation of N. Immobilised N, therefore, is not lost from the soil, but can be mineralised at a later stage to become available for crop uptake. Although increased immobilisation may play an important role in reducing N losses via pathways such as leaching and volatilisation, crops may suffer temporary N stress as immobilised N is unavailable for crop uptake.

Generally the C:N ratio of uncultivated topsoil is 10-12 (Brady & Weil, 1999), and this becomes higher in the subsoil as N content decreases. Mineralisation rates are strongly influenced by soil temperature, pH and water status, as well as management factors such as soil cultivation and mulching (Brady & Weil, 1999). When soil is disturbed, for example during tillage, previously occluded organic matter becomes exposed to

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microbes, oxygen (O_2) and water, and the N mineralisation rate increases as a result. In sugarcane cropping systems that are trashed, significant quantities of N can be returned to the soil via the leaf material. Soil water content determines the proportions of aerobic and anaerobic microbial activity in the soil, and aerobic conditions will normally increase mineralisation rate. Temperatures ranging between 25 and 35ºC will increase microbial activity and mineralisation rate, while soils with low pH will decrease microbial activity and therefore mineralisation rate (Brady & Weil, 1999). Schroeder *et al.* (2005) investigated the differences in mineralisation potential of different soils, observing that soil type plays an important role in determining N mineralisation rate and the amount of N released from a specific soil.

A recent study conducted in South Africa reported that approximately 2% of soil organic matter is mineralised each year from the Hutton soils of the Pongola Region in northern KwaZulu Natal (Van der Laan *et al*., 2011). According to the authors, approximately 90 kg N ha^{-1} per season is released through mineralisation of organic matter under irrigated sugarcane for either plant or ratoon crops. The authors further estimate that N made newly available through organic matter mineralisation, is potentially sufficient to meet initial crop demand for plant and ratoon crops for 55 days before fertiliser N is required. This study therefore shows that N mineralisation from soil organic matter increases crop available N, potentially reducing the quantity of fertiliser N required for sugarcane production. Meyer & Wood (1994) highlighted that although mineralisation of organic matter can play a major role in providing N required for the plant and ratoon crops, N recommendations have traditionally not adequately accounted for differences in N release when determining the N requirements of sugarcane. According to Ladha *et al*. (2005), applying fertiliser according to crop N demand, while not accounting for newly

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mineralised N, will lead to an over-supply of N in the system and subsequently result in loss of N as a pollutant.

1.1.2 Denitrification and volatilisation

Denitrification is a biochemical reaction that occurs when NO_3^- is converted to nitrite (NO_2^-) and then to nitrous oxide (N_2O), nitric oxide (NO) and dinitrogen (N_2) gasses which will be lost to the atmosphere. This reaction occurs under anaerobic soil conditions (saturated or waterlogged) when O_2 is depleted from the soil as a result of water replacing air in the soil pores. Consequently, NO_3^- and NO_2^- become the more favoured electron acceptors. Soil water status and aeration are therefore the most important factors that influence this process. Denitrification is also influenced by soil pH, since denitrifying bacteria are inactive at pH levels < 5.

In contrast, volatilisation occurs mostly when urea [$CO(NH_2)_2$] is applied to the soil surface, especially by broadcasting onto trash blankets. During the volatilisation process, $CO(NH_2)_2$ is hydrolysed to unstable carbonic acid (H_2CO_3) and eventually NH_3 and CO_2 gasses are released into the atmosphere. Unless the NH_3 reacts with water to form NH_4^+, it can escape into the atmosphere (Schumann, 2000). Numerous investigations have shown that under conducive conditions, surface application of $CO(NH_2)_2$ in sugarcane cropping systems, results in substantial loss of N through NH_3 volatilisation (Basanta *et al*., 2003; Wood *et al*., 2010). Volatilisation is largely controlled by soil pH, temperature, water status and NH_4^+ levels. Hot and humid weather, and a pH >7.5 can result in significantly high N volatilisation losses. Sufficiently large irrigation or rainfall events can lower volatilisation losses by washing $CO(NH_2)_2$ well into the soil.

Denitrification and volatilisation pathways can account for considerable amounts of N loss from soil, with each pathway potentially accounting for up to 40% loss of applied N

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fertiliser (Prasertsak *et al*., 2002; Weier, 1999; Wood, 1991). Allen *et al*. (2010) highlight that the low N use efficiencies often observed in sugarcane cropping systems may not be directly related to inability of the crop to take up N to its full potential, but should rather be attributed to these chemical reactions which result in N loss.

1.1.3 Crop nitrogen uptake

Sugarcane N uptake is believed to take place largely during the initial stages of crop development (if the N is available), with reduced N uptake during later growth stages (Muchow & Robertson, 1994). Factors including age of the crop, seasonal effects, soil water content and whether the crop is a plant or ratoon crop were found to have a major influence on N uptake (Meyer & Wood, 1994). Nitrogen uptake is also influenced by the availability and uptake of other nutrients. Early N application induces the production of tillers and ultimately millable stalks at harvest (Meyer & Wood, 1994). Muchow & Robertson (1994) observed a range in N uptake based on different N rates, and indicated that increasing N application led to lower N use efficiencies as biomass production did not increase in similar magnitude as N uptake (luxury uptake). The authors therefore found that biomass per unit N uptake, which is defined as a measure of N use efficiency, decreases with increasing N application, and therefore for the same biomass production, crop N uptake and subsequent N use efficiency can differ widely. It is therefore important to focus on optimising N use efficiencies of the crop in relation to other nutrients rather than to focus merely on maximising N use. This includes determining minimum N uptake relative to other nutrients required for optimum yield.

1.1.4 Leaching losses

In most soils, NO_3^- is usually present in much greater quantities than NH_4^+, and is highly susceptible to leaching as it is an anion and not adsorbed to soils with a high cation exchange capacity. For this reason, NO_3^- is carried with percolating water to lower levels

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of the soil profile below the root zone, where plants cannot access it. In contrast, NH_4^+ is less susceptible to leaching due to its lower concentrations and tighter adsorption to soil particles. In soils with a high anion exchange capacity (e.g. highly weathered tropical soils), the reverse will occur. Nitrogen leaching is most likely the major pathway of N loss in humid climates and under irrigated cropping systems (Prasertsak *et al*., 2002).

The amount of NO_3^- leaching below the root zone is influenced by the quantity and the type of N fertilizer used, time and frequency of application, type of crop grown and its growing period, rooting characteristics, rainfall amounts and distribution, soil hydraulic characteristics and management practices such as tillage, and whether trash is burned or retained (Rasiah *et al*., 2003). These losses can amount to 33% of applied N (Prove *et al*., 1997) or even more, depending on soil characteristics and other factors mentioned earlier. Leaching losses of up to 31% of applied N have been reported on Hutton soils under irrigated sugarcane cropping systems in South Africa (Van der Laan *et al*., 2011). These losses have a major impact on profitability of sugarcane production.

Nitrate leaching below the root zone may either be adsorbed in the subsoil, enter lateral flow that discharges into streams, enter groundwater, or denitrify below the root zone (Rasiah *et al*., 2003). When discharged into streams and groundwater, NO_3^- will eventually pollute drinking water and stimulate eutrophication in reservoirs and other water sources. Nitrate leaching, therefore, potentially has a serious impact on the environment when not carefully controlled.

1.1.5 Runoff losses

Runoff is potentially another significant pathway through which N can be lost from sugarcane fields to the environment, and normally occurs soon after N fertiliser application is followed by heavy rainfall. Studies by Thorburn *et al*. (2011) in Australia,

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show that N lost from sugarcane fields via runoff, was equivalent to 3 to 16% of applied N fertiliser. The authors concluded that although this may seem relatively little, the cumulative effects of N lost in this way will have a devastating impact on water quality in the long run, if nothing is done to minimise the impact. The long term profitability of sugarcane production is also compromised when considering the costs of N fertiliser.

1.1.6 Nitrogen fixation by legumes

It is generally accepted that legumes make substantial contributions to soil fertility in crop rotation systems through biological N fixation. It has been reported, that the failure of sugarcane to respond to high N fertiliser application rates following a legume crop, is an indication that there has already been enough N fixed by legumes, which comes available for uptake by the subsequent crop (Hemwong *et al*., 2008; Hemwong *et al*., 2009). However, the duration and magnitude of any N carry-over from legumes, and potential reductions in required rates of N fertiliser in sugarcane cropping systems, are difficult to quantify. Park *et al*. (2010) indicated that any carry-over of legume N beyond the plant crop's needs that is not accounted for during N applications on the following crop, will increase the potential for greater environmental losses of N, and reduce profitability of sugarcane systems containing legume break crops.

1.2 Modelling nitrogen dynamics in sugarcane cropping systems

1.2.1 Overview

Owing to the complexity of agricultural systems, it is often difficult to gain complete understanding of the interactions between a crop and its environment. Mechanistic crop models are useful for improving our understanding of highly complex processes occurring in agroecosystems, for example, N dynamics in sugarcane cropping systems. Adequate calibration, testing and validation exercises are, however, first required to gain confidence in the outputs of mechanistic crop models.

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Several studies which include modelling N dynamics in sugarcane cropping systems, have been conducted over the past 15 years, including one in South Africa (Garnier *et al*., 2001; Thorburn *et al*., 2005; Van der Laan *et al*., 2011). These studies involved model calibration and testing using measured data, followed by model application to improve understanding of complex natural processes that occur in the soil-plant-atmosphere system. Examples of models which are commonly used worldwide, include the Agricultural Production Systems Simulator (APSIM) (Keating *et al.*, 1999), CENTURY (Vallis *et al*., 1996), the Soil Water Balance model (SWB-Sci) (Van der Laan, 2009) and DSSAT (Daroub *et al*., 2003). Each of these models have been applied to simulate N dynamics in sugarcane cropping systems.

1.2.2 Background to the DSSAT- Canegro model with a newly included nitrogen subroutine

The stand-alone Canegro model (Inman-Bamber, 1991) was recently incorporated into the DSSAT (Decision Support System for Agrotechnology Transfer) (Tsuji *et al*., 1994) framework, through which many utilities have been added (Singles *et al*., 2008). The model simulates sugarcane growth and development using daily weather data, soil and cultivar properties, as well as management input data (Inman-Bamber, 1991). The model has the following simulation capabilities: (1) Canopy development and response to water stress, (2) radiation interception calculated from leaf area index, (3) soil water balance estimated using a cascading 'tipping-bucket' approach, (4) biomass accumulation linked to radiation interception and evapotranspiration rates, and (5) biomass partitioning to different plant components including stalk sucrose, using a source-sink approach which is affected by physiological age, temperature and water stress (Singels *et al*., 2008). Recently, N simulating capabilities have also been included

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in DSSAT-Canegro (Van der Laan *et al*., 2011). A description of the approach used to simulate N in DSSAT-Canegro is given below.

Root modelling

Although root growth modelling is based on the approach described by Singels *et al*. (2008), several modifications were made to enable carbon and N modelling in DSSAT-Canegro as described by Van der Laan *et al*. (2011). According to this approach, 4 g of sett roots per internode of plant crop is initialised before emergence takes place, and any new photosynthate is transferred to the roots. This initial root mass is converted to a root length density in the top soil layers (0 – 40 cm). Following harvest and initialization of the next ratoon crop by the model, the total root mass in the various soil layers is immediately reduced to 50% of pre-harvest root mass. The old root system then dies off rapidly at a rate of 5% per day to a depth of 0.8 m and at the normal senescence rate of 0.5% per day for roots below 0.8 m. New root formation commences for the ratoon crop while the surviving deeper roots from the previous crop are still able to extract water and N from deeper soil layers for this ratoon crop over a short period of time. Any remaining root material that has senesced is added to the root residue pool to become part of soil organic matter that will be subjected to mineralisation at a later stage.

Crop nitrogen demand and uptake

The approach used in DSSAT-Canegro for simulating crop N uptake from the soil by the roots as described by Van der Laan *et al*. (2011), is the same as that used in CERES-Maize (Jones and Kiniry 1986; Godwin and Jones 1991).This approach takes into account the quantity of inorganic N in a soil layer, root length density and the factors that influence plant available soil water. Crop N demand is then calculated by assuming different optimal N concentrations for the root, stalk and leaf components. These

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concentrations are specified for the four different growth stages used in DSSAT-Canegro, namely, leaf emergence, tillering, stalk emergence and peak stalk population (Figure 1.2).

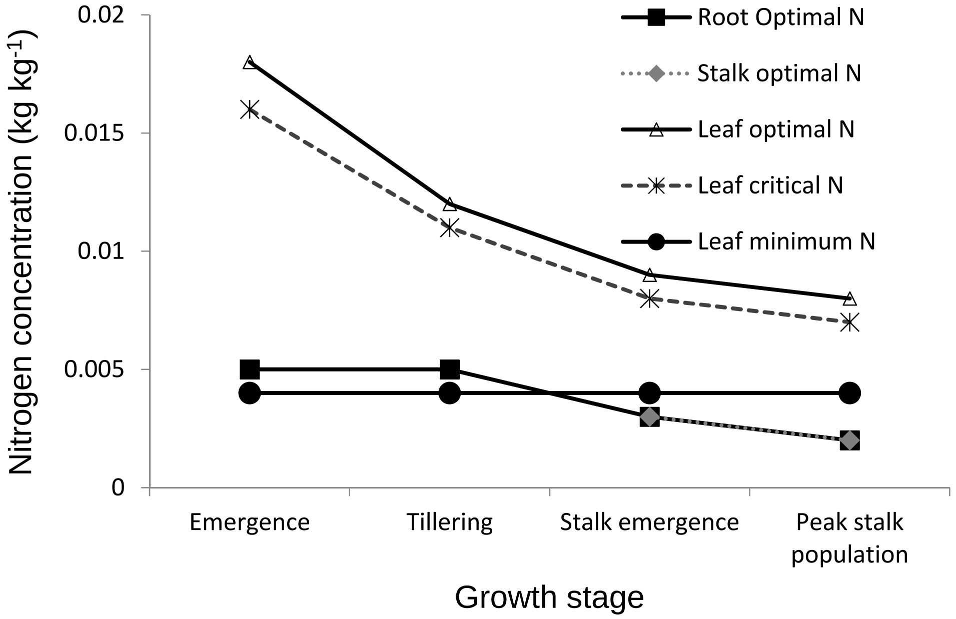

Figure 1.2 Optimal nitrogen concentrations of the leaf, stalk and root, and critical and minimum leaf nitrogen concentrations for the different growth stages as parameterised in DSSAT(Decision Support System for Agrotechnology Transfer)-Canegro (Van der Laan *et al*. 2011).

Nitrogen stress factor

Nitrogen-limited growth is simulated to take place when N concentration in the leaf is between the critical and minimum levels (Van der Laan *et al*., 2011). The approach used in the CropSyst model (Stockle *et al*., 2003) is used to calculate an N stress factor when leaf N concentration falls below the critical concentration (concentration at which the plant begins to experience N stress). This N stress factor is calculated as follows:

$$N\ Stress\ Factor = 1 - \left[1 - \frac{Leaf\ N\ Conc - Min\ N\ Conc}{Crit\ N\ Conc - Min\ N\ Conc}\right]\hat{}2$$

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The N stress factor of one (1) indicates no stress while the N stress factor of zero (0) indicates a complete stress. The N stress factor is currently only used to reduce gross photosynthesis and this indirectly represents N stress effects on other aspects of crop growth. No plant growth or dry matter accumulation is stimulated when leaf N concentration falls below the minimum N concentration.

Carbon and nitrogen transformations

The approach used to model soil C and N dynamics is based on approaches used in the CENTURY model (Gijsman *et al*., 2002) which has been incorporated into the DSSAT framework. Nitrogen mineralisation and immobilisation, volatilisation, nitrification, denitrification, urea hydrolysis as well as runoff and leaching losses, are all considered.

Soil water balance and soil temperature

A cascading, multi-layered soil profile approach is used in DSSAT, to simulate infiltration and water redistribution as described by Ritchie (1998). Air temperature and deep soil temperature as calculated from mean annual air temperature and monthly mean temperature amplitude, is used to estimate soil temperature, while accounting for the effect of albedo (fraction of solar energy reflected from earth back into the space) and solar radiation.

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2. CHAPTER 2: SIMULATION OF IRRIGATED SUGARCANE GROWTH OVER FIVE CONSECUTIVE SEASONS IN RESPONSE TO DIFFERENT NITROGEN FERTILIZER RATES

2.1 Introduction

In South Africa, approximately 24% of the total land planted to sugarcane is irrigated (Funke, 2013). As water and nitrogen (N) are closely linked because of the high solubility of NO_3^-, irrigation can play a significant role in modifying N dynamics in these systems. In some instances, N loss through leaching under irrigated sugarcane conditions has been reported to be high relative to rain-fed conditions, and this was found to occur through several mechanisms (Thorburn *et al*., 2011). Firstly, the higher potential yields of irrigated sugarcane are often associated with much higher N fertiliser applications, and this increases the potential and magnitude of N loss. Secondly, the application of irrigation water itself, especially in excess of crop demand, can promote N losses.

Robust, mechanistic crop models have the ability to help investigate and understand highly complex processes occurring in agroecosystems, including N dynamics in sugarcane cropping systems, in a better way than using measured data alone. Testing exercises should, however, be conducted to test model robustness and accuracy. In this study, DSSAT-Canegro was evaluated for its ability to simulate cane and sucrose yield and aboveground N mass in response to different N rates for five consecutive seasons, using a historical dataset from a fertigation trial conducted in Komatipoort.

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2.2 Materials and methods

2.2.1 Fertigation trial

A fertigation trial investigating sugarcane growth responses to different N fertiliser rates was conducted in Komatipoort, in Mpumalanga, South Africa (25°26'S 31°57'E and 200 m above sea level), from 2002-2007 (five cropping seasons). This area experiences a sub-tropical climate with an average annual rainfall of 596 mm and an average annual temperature of 23.2°C. Weather data used in this trial was collected from the automatic weather station (SASRI weather web) at the Komati farm.

The N32 sugarcane variety was planted on a shallow Shortlands soil (Soil Classification Working Group, 1999) under surface drip irrigation on a 12 month cropping cycle (October to October). Limestone ammonium nitrate was applied in solid form at rates of 0, 48, 96 and 144 kg N ha^{-1} per season at planting or ratooning. Irrigation rates of 6 mm were applied whenever measured soil water content reached an 8 mm deficit.

At harvest, aboveground biomass was divided into stalks, trash and leaves and samples were analysed for N content in order to determine aboveground N mass. This was done only for the second and fourth ratoon crops and for the second ratoon, the 48 kg N ha^{-1} treatment was not measured due to logistics reasons. Following pre-harvest burning, cane and sucrose yields were measured.

The DSSAT Canegro model with a newly included N subroutine as described in Chapter 1 Section 1.2, was used to simulate cane and sucrose yield, as well as aboveground N mass in response to different N rates. Measured soil characteristics, such as texture, pH, organic carbon (C), bulk density and total N for each layer of the soil profile were obtained from soil analysis results and used as parameters to initialise the model (Table 2.1). The simulation output of the model was compared with the measured data to evaluate model performance.

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Analysis of variance (ANOVA) was used to determine if there were significant differences between treatments for the measured data. Statistical criteria comprising the square of the correlation coefficient (R^2), Wilmot's index of agreement (D), root mean square error (RMSE) and mean absolute error (MAE) were used to objectively determine how adequately the model performed when comparing simulated and measured data (De Jager, 1994). The R^2 value describes the degree of correlation between measured and simulated values and the proportion of the variance in measured data explained by the model. The value ranges from 0 to 1, whereby high values indicate less error variance and normally values higher than 0.5 are considered acceptable (Van Liew *et al*., 2003). The index of agreement measures the degree of model prediction error and varies from 0 to 1, with values above 0.80 accepted as standard for good agreement between measured and simulated data (Wilmott, 1981). The RMSE and MAE are commonly used error indices in model evaluation. They indicate error or residual variance between measured and simulated values. According to Singh *et al*. (2004), RMSE and MAE values less than half the value of the standard deviations of the measured data are considered low and acceptable and either of these can be used for model evaluation. Normally, RMSE and MAE values less than 20% are considered satisfactory.

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Table 2.1 Measured and estimated soil model parameters for the fertigation trial

Soil depth (cm)	pH (H_2O)	Organic-C (%)	Total-N (%)	C:N ratio	Clay (%)	Silt (%)	Sand (%)	Bulk density (g m^{-3})	Drained upper limit (m^3 m^{-3})*	Lower limit (m^3 m^{-3})*	Saturation (m^3 m^{-3})*
0-5	6.4	1.5	0.06	14:1	30	10	60	1.5	0.323	0.217	0.400
5-15	6.4	1.1	0.06	14:1	30	15	55	1.5	0.323	0.217	0.400
15-20	6.4	0.9	0.05	14:1	35	10	55	1.6	0.302	0.206	0.403
20-40	6.4	0.84	0.05	14:1	35	10	55	1.6	0.302	0.206	0.403

*Estimated by DS

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2.3 Results

2.3.1 Cane yield

Measured cane yields for the plant crop were similar for all treatments, despite different N rates, and ranged from 134 to 140 t ha^{-1} (Figure 2.1), with no significant differences between treatments (Table 2.2). This is most likely a result of sufficiently high initial inorganic N levels in the soil at planting, plus inorganic N made available during the growing season as a result of soil organic matter mineralization to meet crop N demand for the plant crop (Figure 2.7). The lack of response to different N rates was also simulated by the model, despite slight under-estimation of cane yields (ranging from 120 to 125 t ha^{-1}). For the following four ratoon crops, clearer differences in cane yields were observed for different N rates in both measured and simulated yields, with yields increasing with increasing N application rate as expected, and also resulting in significant differences among treatments. Following a slight under-estimation of yields for the first three crops, the final two crops were well simulated by the model, with the third ratoon crop being most accurately simulated. For determining how the model performed in simulating cane yield based on statistical analysis, the model perfomed well in most cases and even better in the final ratoon crops as R^2 values above 0.80 were achieved and other statistical criteria was met (Table 2.3). This indicates that simulation accuracy improved with time. Significant differences were observed between

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some of the treatments in the final ratoon crops (Table 2.2).

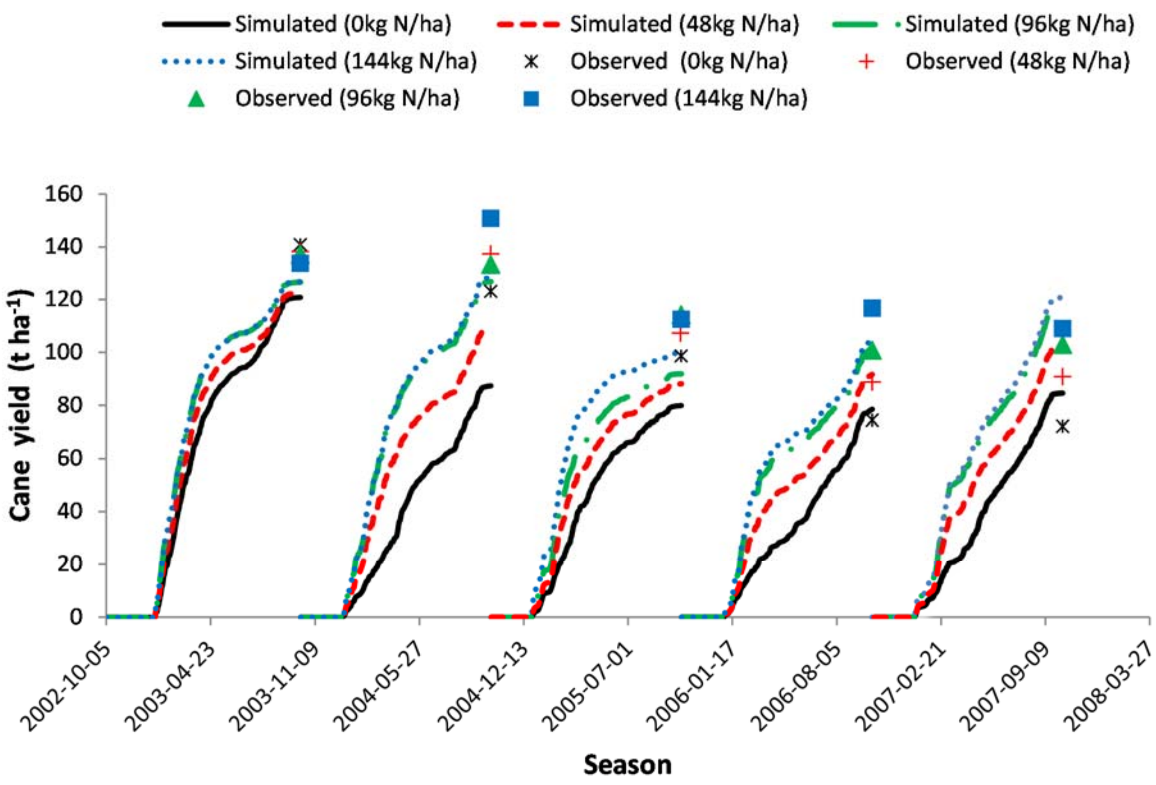

Figure 2.1 Simulated and measured cane yields at different nitrogen rates for the plant and four ratoon crops

Table 2.2 Treatment means and least significant differences (LSD) for cane yields at different nitrogen rates for the plant and ratoon crops

	Cane yield (t ha^{-1})				
N-rate (kg ha^{-1})	Plant crop	Ratoon 1	Ratoon 2	Ratoon 3	Ratoon 4
0	140.9 a	123.1 a	98.6 a	74.4 d	72.2 c
48	138.3 a	137.4 a	107.3 a	88.7 c	90.8 b
96	137.1 a	133.4 a	114.2 a	100.8 b	102.9 ab
144	133.8 a	150.8 a	112.5 a	116.7 a	109 a
LSD	11.8	29.5	16.3	11.3	17.4

LSD (P=0.05) Means with different letters differ significantly

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Table 2.3 Statistical evaluation between measured and simulated values of cane yield for the plant and four ratoon crops

Treatment	R^2	D	RMSE	MAE (%)
Plant crop				
N0	0,79	0,48	12,10	16,67
N48	0,90	0,79	18,60	12,96
N96	0,81	0,80	14,80	8,35
N144	0,92	0,83	15,32	5,58
Ratoon1				
N0	0,76	0,62	16,45	40,93
N48	0,77	0,82	13,67	26,51
N96	0,94	0,88	19,30	8,40
N144	0,72	0,76	20,20	17,53
Ratoon2				
N0	0,89	0,62	16,82	23,42
N48	0,88	0,64	13,96	21,73
N96	0,92	0,73	19,00	24,30
N144	0,78	0,87	15,93	13,61
Ratoon3				
N0	0,92	0,91	9,23	4,31
N48	0,98	0,78	7,49	2,89
N96	0,94	0,83	5,84	15,54
N144	0,87	0,62	16,51	0,74
Ratoon4				
N0	0,81	0,83	22,13	14,65
N48	0,77	0,78	17,43	11,12
N96	0,86	0,58	22,62	14,75
N144	0,92	0,77	19,22	12,91

2.3.2 Sucrose yields

Sucrose yields followed similar trends to those observed for cane yields (Figure 2.3) although this was a little more under-estimated by the model in general. The statistical criteria was not adequately met in most cases but the final two ratoon crops were well simulated by the model based on the criteria (Table 2.5). This, again indicates model improvement with time. As observed for the cane yields, significant differences between some of the treatments were also observed as sucrose yields increased with increasing N application (Table 2.4).

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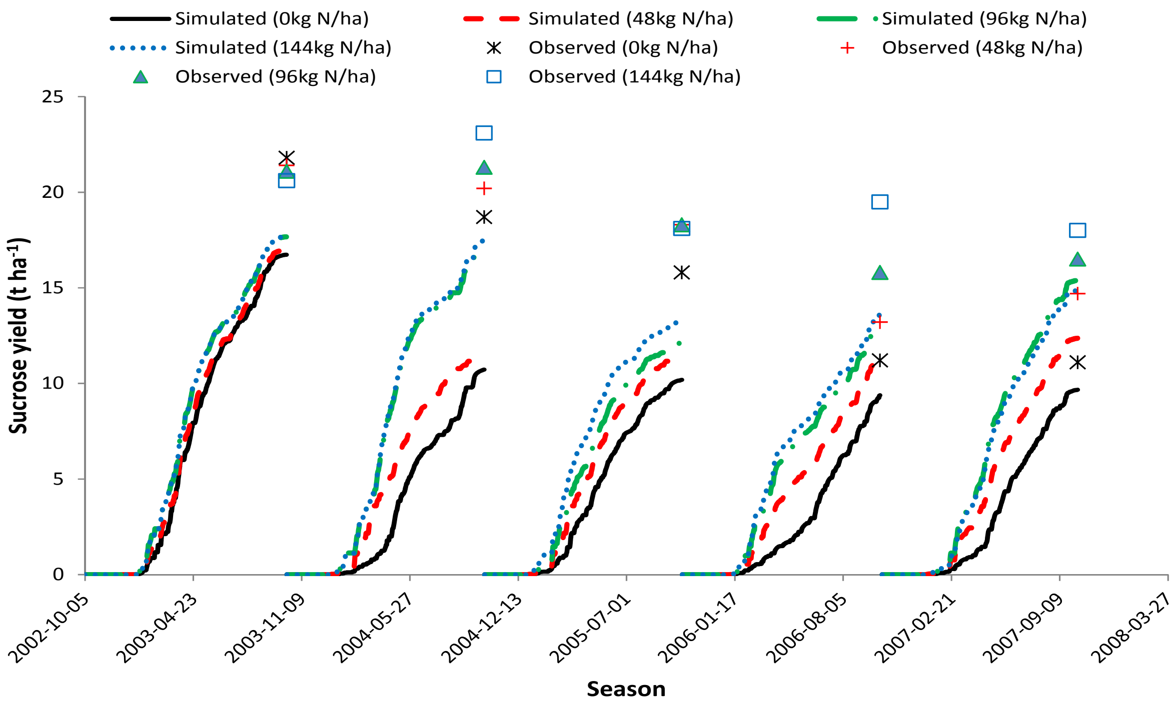

Figure 2.2 Simulated and measured sucrose yields at different nitrogen rates for the plant and four ratoon crops

Table 2.4 Treatment means and least significant differences (LSD) for sucrose yields at different nitrogen rates for the plant and ratoon crops.

	Sucrose yield (t ha^{-1})				
N-rate (kg ha^{-1})	Plant crop	Ratoon 1	Ratoon 2	Ratoon 3	Ratoon 4
0	21.8 a	18.7 b	15.8 a	11.2 d	11.1 d
48	21.4 a	20.2 ab	18.3 a	13.2 c	14.7 c
96	21.1 a	21.3 ab	18.3 a	15.8 b	16.5 ab
144	20.6 a	23.1 a	18.1 a	19.5 a	18 a
LSD	1.87	4.23	2.88	1.89	2.89

LSD (P=0.05) Means with different letters differ significantly

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Table 2.5 Statistical evaluation between measured and simulated sucrose yields for plant and four ratoon crops

Treatment	r^2	D	RMSE	MAE (%)
Plant crop				
N0	0,71	0,69	21,27	30,28
N48	0,64	0,73	18,74	25,91
N96	0,68	0,36	27,01	19,46
N144	0,73	0,48	23,00	16,42
Ratoon1				
Treatment	**r^2**	**D**	**RMSE**	**MAE (%)**
N0	0,70	0,57	16,67	40,93
N48	0,77	0,47	13,67	29,51
N96	0,60	0,72	21,30	8,40
N144	0,69	0,76	18,20	19,53
Ratoon2				
Treatment	**r^2**	**D**	**RMSE**	**MAE (%)**
N0	0,50	0,59	16,82	23,42
N48	0,65	0,64	13,96	21,73
N96	0,68	0,73	19,00	24,30
N144	0,73	0,68	15,93	13,61
Ratoon3				
Treatment	**r^2**	**D**	**RMSE**	**MAE (%)**
N0	0,72	0,79	19,23	28,31
N48	0,58	0,71	19,49	17,89
N96	0,73	0,58	25,84	15,54
N144	0,62	0,68	20,51	24,24
Ratoon4				
Treatment	**r^2**	**D**	**RMSE**	**MAE (%)**
N0	0,81	0,59	22,13	24,65
N48	0,77	0,78	17,43	28,12
N96	0,75	0,58	22,62	14,75
N144	0,62	0,77	19,22	33,91

2.3.3 Aboveground N mass

Both measured and simulated aboveground N mass increased with increasing N rate for the second and fourth ratoon crops as expected (these were the only crops for which aboveground N mass was measured) (Figure 2.3). Especially for the measured data, aboveground N mass was observed to be higher in the second ratoon than the fourth

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ratoon crop and since similar trend was also simulated by the model, it is likely that growing conditions were more favourable for the second ratoon crop. Although the model simulated the responses very well, consistent over-estimation of aboveground N mass was observed for most N rates. Statistical criteria was met for some of the treatment in both crops. Judging from the simulated net N mineralisation data (Figure 2.4), it is clear that the initially mineralised N for the plant crop was above 100 kg ha^{-1} yr^{-1} for the N0 treatment and for the following ratoon crops, ~90 kg ha^{-1} yr^{-1} of mineralised N was simulated by the model. This data corresponds very well with measured and simulated aboveground N mass in the second and fourth ratoon crops for the N0 treatment. This mainly implies that almost all mineralised N in the soil is taken up by the crop if no N fertiliser is applied and this results in the net depletion of N from the soil. Although immobilisation occurs for the N0 treatment during plant crop, no immobilisation was simulated for ratoon crops. This is contrary to all other N treatments whereby N immobilisation occurs following fertiliser application and its rate increases with increasing N application rate. This indicates that N that is extra in soil and not taken up by the crop will eventually be immobilised but can still be released again at a later stage through mineralisation.

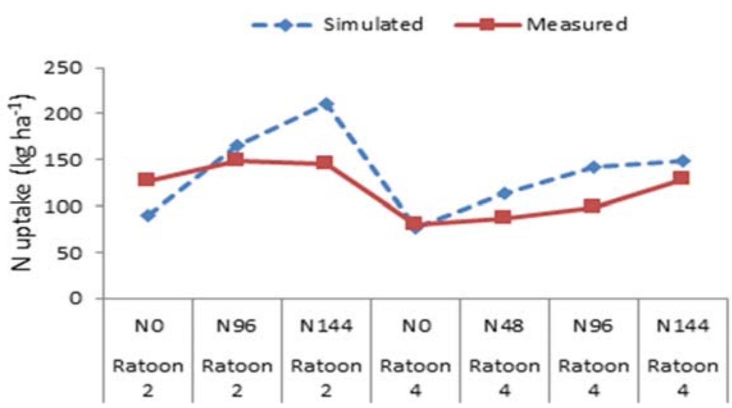

Figure 2.3 Simulated versus observed aboveground nitrogen mass at different nitrogen rates for the second and fourth ratoon crops

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Table 2.2 Statistical evaluation between measured and simulated values of aboveground nitrogen mass for the second and fourth ratoon crops

Ratoon 2				
Treatment	**R^2**	**D**	**RMSE**	**MAE (%)**
N0	72,71	70,67	22,50	19,13
N96	81,90	78,78	19,43	23,51
N144	63,11	57,05	26,32	30,80
Ratoon 4				
Treatment	**R^2**	**D**	**RMSE**	**MAE (%)**
N0	92,46	87,98	5,89	3,33
N48	71,34	69,47	18,96	27,34
N96	66,34	58,92	22,12	31,94
N144	80,12	78,95	15,34	13,4

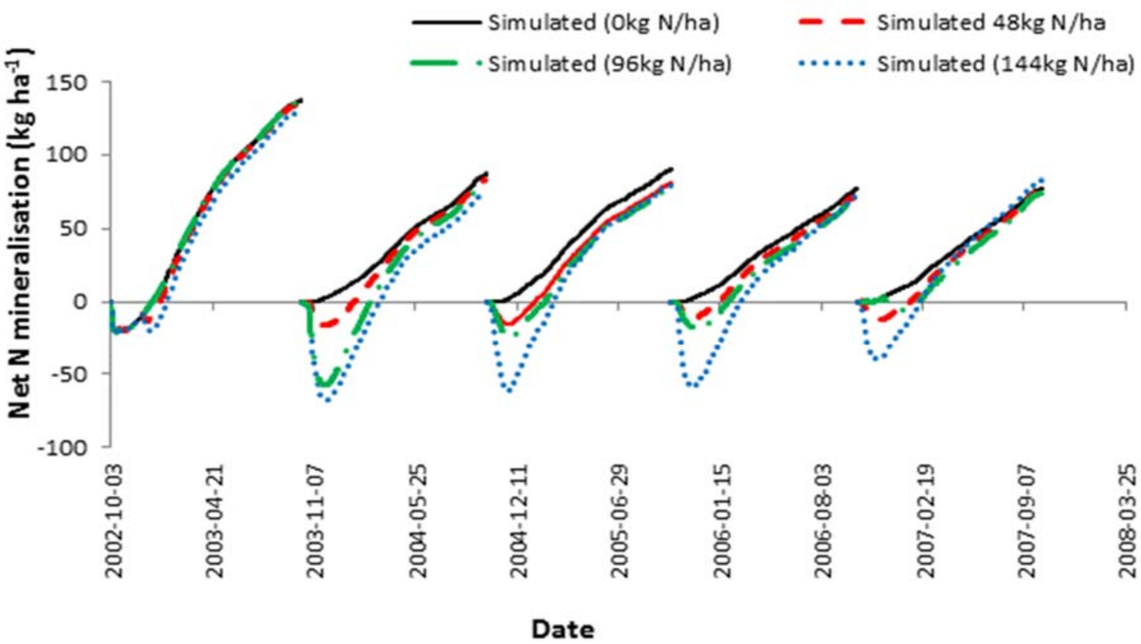

Figure 2.4 Simulated net nitrogen mineralisation at different nitrogen rates

2.4 Discussion

In most cases, DSSAT-Canegro performed reseasonably well in simulating sugarcane growth and aboveground N mass for different seasons. The model was also observed to

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be robust in estimating similar trends to the measured data, despite slight under or over-estimations in some cases.

The results of this study have shown that under certain conditions, such as when soil inorganic N levels are initially high, for example after a fallow-period when mineralized N accumulates, or for a field that has been over-fertilized in past seasons, increasing N application from 0 to 144 kg N ha^{-1} might have little or no effect on cane and sucrose yields of the plant crop. Similar results have been reported in a number of studies (Wood, 1972; Meyer and Wood, 1994; Wiedenfeld, 1995), and this has been attributed to the mineralization potential of the soil which makes sufficient inorganic N available for the plant crop, and to some extent, subsequent ratoon crops, thus resulting in minimal response. The implication of this, is that a response to N application may be more pronounced for ratoon crops as compared to the plant crop. The results have also shown that ‘mining’ of N by the crop can occur when no fertiliser is applied, since the crop takes up most mineralised N from the soil, leaving the soil depleted of N. However, when N is over-applied and not taken by the crop, immobilisation will take place, but importantly the immobilised N is not lost from the soil as it can be mineralised at a later stage.

The importance of an initialization phase during model simulation has also been revealed. While it is important to run simulations for a certain number of years, it is crucial to take into account initialization data, as the rest of the simulation output will be affected by initial conditions with which the model was initialised. It is therefore clear that when running simulation models, extensive measured data is very beneficial for calibration purposes.

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2.5 Conclusions

The DSSAT-Canegro model performed adequately in simiualting sugarcane yields and aboveground N mass in response to different N rates under a drip irrigation system in Komatipoort. This has shown that the model has the potential to guide fertilisation programmes and inform N management practices in sugarcane cropping systems. Newly mineralised N should be accounted for in fertilisation programmes, especially for the plant crop and where fields have been fallowed for certain periods or converted from virgin land. DSSAT-Canegro can potentially be used as a tool to improve understanding of N dynamics in other sugarcane cropping systems.

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3. CHAPTER 3: MODELLING NITROGEN DYNAMICS IN SUGARCANE CROPPING SYSTEMS UNDER RAINFED CONDITIONS: INANDA FIELD TRIAL

3.1 Introduction

Approximately 76% of South African sugarcane is produced under rain fed conditions (Funke, 2013). This makes the South African sugar industry highly dependent on sufficient and adequately distributed rainfall to maintain its economic viability. Significant amounts of plant available N can be lost via runoff or leaching which mostly coincides with large rainfall events. Additionally, these rainfall events can result in saturated soil conditions favouring denitrification, which also contributes to N loss to the environment. Minimising N losses should be one of the top priorities if the profitability and sustainability of sugarcane production is to be maintained.

The magnitude of N loss in sugarcane cropping systems under rain-fed conditions has been emphasised in a number of studies (Stewart *et al*., 2003; Thorburn *et al*., 2005). Thorburn *et al*. (2005) observed N leaching to be strongly correlated with rainfall received during the cropping season. High N leaching was mainly observed when high fertiliser rates (> 200 kg N ha^{-1}) were applied. The authors caution, however, that the risk of nitrate (NO_3^-) leaching from the soil profile during high rainfall events exists irrespective of N fertiliser application rate. Poor crop growth which potentially results from under-fertilising with N, can lead to reduced soil water uptake and higher volumes of deep drainage. These studies emphasise the importance of revisiting N management strategies in rain-fed systems under local conditions to better understand the fate of fertilised N.

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Although certain crop/soil N balance components such as aboveground N mass and fertiliser application rate are easily measured, measuring the quantity of N gained or lost via specific pathways such as mineralisation, denitrification, leaching and others is much more difficult. This is due to complexity of N transformations as influenced by environmental conditions and management practices. Mechanistic crop models have the potential to represent physical, chemical and biological processes occurring in the soil-plant-atmosphere continuum and the interactions thereof. Combining modelling and measurement can potentially lead to an improved understanding of N dynamics in sugarcane cropping systems and to inform optimal N management strategies. The objective of this study was to use measurements of soil water NO_3^- concentrations, as well as sugarcane aboveground N mass and yield responses to different fertiliser N application rates, to better understand N dynamics under rain fed conditions in South Africa.

3.2 Materials and methods

A trial investigating N, potassium (K) and silicon (Si) use efficiency of sugarcane was conducted at Inanda, north of Durban in Kwa-Zulu Natal, South Africa (29°37’S, 30°56’E and 556 m above sea level). Average annual rainfall for the region is 1076 mm, while the mean annual temperature is 20°C. The weather data used in this trial was collected from Inanda manual weather station (SASRI weather web). The N37 sugarcane variety was planted on Inanda soil in November 2009 on a 12 month cropping cycle for two seasons. Three N rate treatments with three replications were applied on a factorial experimental design with plot sizes of 63 m^2 and 1 m between plots. The N treatments were N0 = 0 kg N ha^{-1}, N1 = 80 kg N ha^{-1} and N2 = 160 kg N ha^{-1}. Urea was the form of N fertiliser used and was broadcasted on the soil surface.

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Ceramic suction cups (Calafrica, Nelspruit, South Africa) and wetting front detectors (WFDs) (Agriplas, South Africa) were installed at 30 and 60 cm soil depths in the plots. For WFDs, soil water samples were collected using a syringe following sufficient rainfall to enable collection of a water sample. For ceramic suction cups, a suction of 60-70 kPa was applied using a syringe, and samples were collected at regular intervals. Samples were analysed using an RQEasy Nitrate Reflectometer (Merck, Darmstadt, Germany).

A plant crop was harvested in November 2010 while the first ratoon crop was harvested in May 2012. At harvest, cane yield (t ha^{-1}) was measured and aboveground biomass samples were divided into stalks, trash and leaves and analysed for N content in order to determine aboveground N mass.

The DSSAT-Canegro model was used to simulate cane yield, aboveground N mass and soil water NO_3^- concentrations in response to different N rates. Measured soil characteristics, such as texture, pH, organic carbon (C), bulk density and total N for each layer of the soil profile were obtained from soil analysis results and used to parameterise and initialise the model (Table 3.1). Other soil characteristics such as the drained upper limit (field capacity), lower limit (permanent wilting point) and saturation volumetric water content were estimated by DSSAT using built-in pedo transfer functions for each soil layer based on measured soil characteristics. Simulated volumetric water content, measured soil layer depth and measured bulk density were used to calculate soil water NO_3^- concentration which was expressed in kg ha^{-1}. Thereafter, a comparison was made between measured and simulated soil water NO_3^- concentrations assuming that all NO_3^- was in solution.

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Table 3.1 Measured and estimated soil model parameters for the Inanda trial

Soil depth (cm)	pH (H_2O)	Organic C (%)	Total N (%)	C:N ratio	Clay (%)	Silt (%)	Sand (%)	Bulk density (g m^{-3})	Drained upper limit (m^3 m^{-3})*	Lower limit (m^3 m^{-3})*	Saturation (m^3 m^{-3})*
0-20	5.0	3.13	0.157	20:1	41	19	40	1.12	0.343	0.226	0.416
20-40	5.0	2.73	0.124	22:1	40	18	42	1.15	0.334	0.22	0.413
40-60	5.2	2.20	0.100	22:1	41	14	45	1.14	0.332	0.225	0.405
60-80	5.0	2.20	0.100	22:1	42	16	42	1.15	0.343	0.231	0.409

*Estimated by DSSAT

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Statistical criteria that were used to evaluate model performance comprised correlation coefficient (r^2), index of agreement (D), root mean square error (RMSE) and mean absolute error (MAE) as described under section 2.2 of Chapter 2.

3.3 Results

3.3.1 Cane Yields

The maximum cane yield achieved for the 2009/10 season (plant crop) was 53.8 t ha^{-1} whereas in the following 2010/11 season (first ratoon), yields up to 120 t ha^{-1} were achieved (Figure 3.1). Yields differed significantly from one another between seasons, but no yield differences were observed between different N rates in both seasons. The lower yields observed during 2009/2010 were as a result of a severe drought experienced during the growing season (rainfall data for the period shown in Figure 3.2). Therefore, the lack of differences between N rate treatments for 2009/2010 is as a result of water being the limiting factor. The reason that yields did not differ between N rate treatments in the following season (2010/2011) is likely due to high soil inorganic N being available for crop uptake due to low N uptake during previous season as well as soil organic matter mineralisation. The model simulated cane yields very well for both seasons, including the very dry 2009/10 season. Despite under-estimation of cane yield for the plant crop at the 0 kg N rate in both seasons, simulated cane yield for all three N rates was in good agreement with the measured cane yield, as evidenced in data compliance with statistical criteria (Table 3.2).

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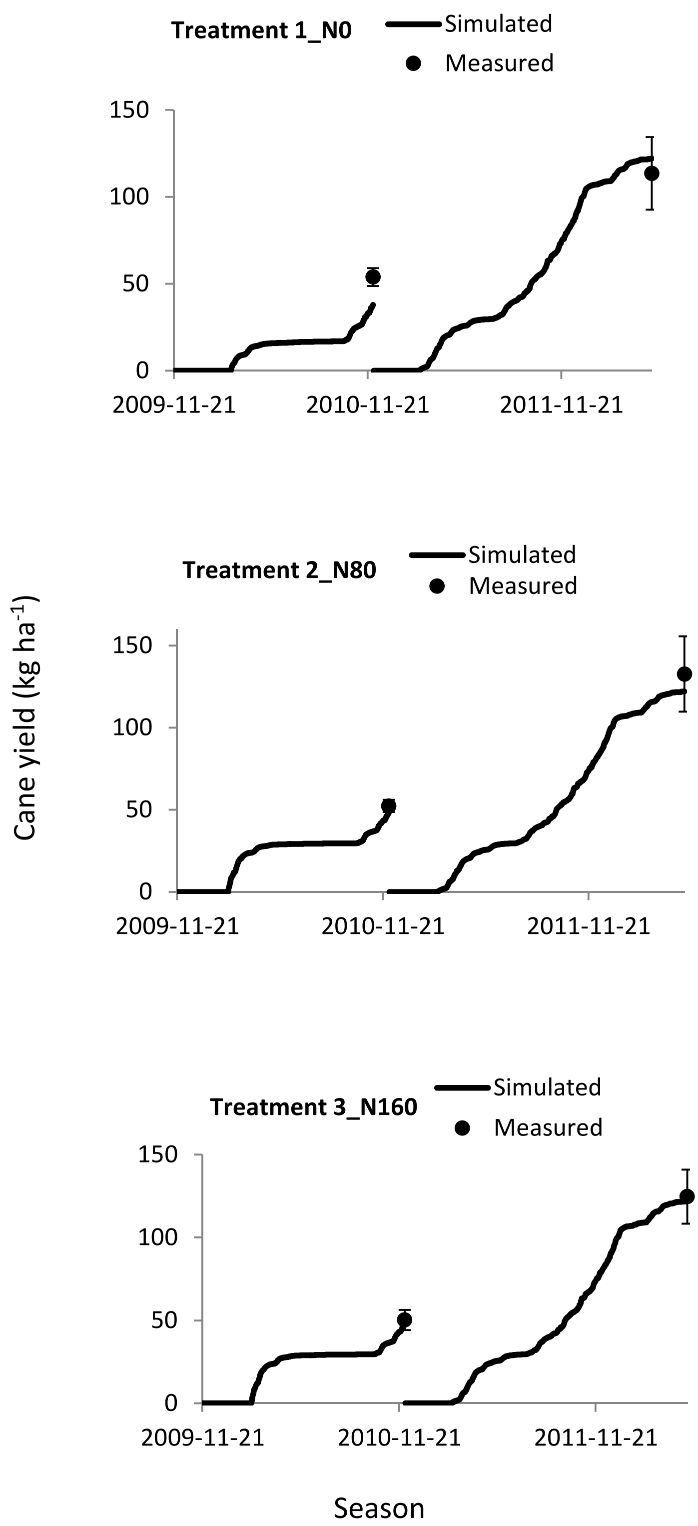

Figure 3.1 Simulated and measured cane yield for the plant and first ratoon crops in response to different nitrogen rates (N0, N80 and N160 kg ha^{-1}). Standard deviations are indicated as error bars (±)

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Table 3.2 Statistical evaluation between measured and simulated values of cane yield for the plant and the first ratoon crop

Plant crop				
Treatment	**R^2**	**D**	**RMSE**	**MAE (%)**
N0	0,40	0,44	13,7	17,7
N80	0,96	0,86	2,8	4,6
N160	0,61	0,83	3,9	6,3
Ratoon1				
Treatment	**R^2**	**D**	**RMSE**	**MAE (%)**
N0	0,77	0,83	12,9	8,9
N80	0,86	0,89	11,9	7,1
N160	0,92	0,86	9,4	5,9

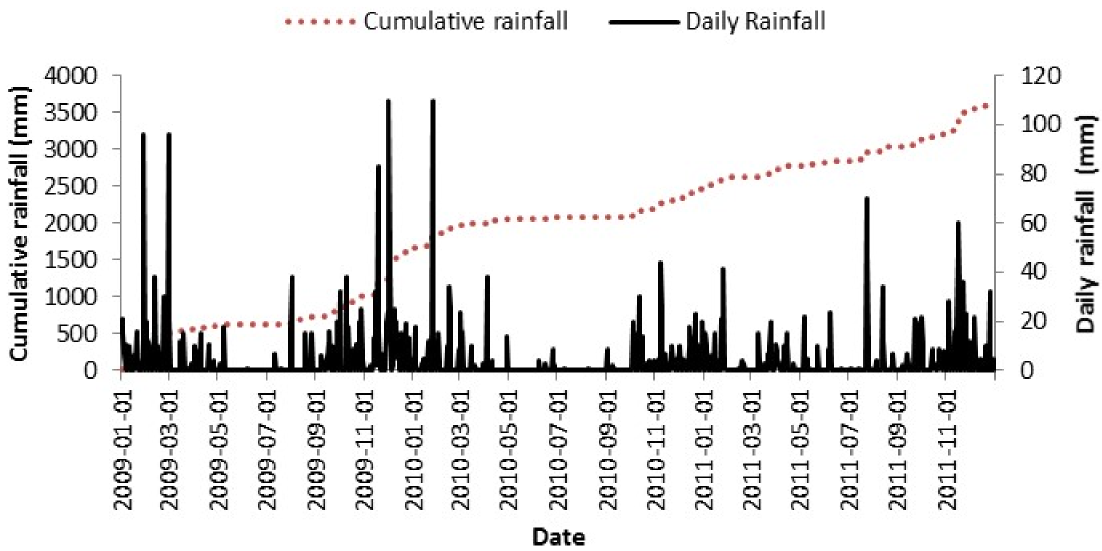

Figure 3.2 Cumulative rainfall over two consecutive seasons and actual daily rainfall at Inanda Farm

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3.3.2 Aboveground N mass

The maximum measured aboveground N mass for the 2009/2010 and 2010/2011 seasons was 178 and 294 kg ha^{-1}, respectively (Figure 3.3). Interestingly, the 0 kg ha^{-1} treatment had the highest aboveground N mass for the 2010/2011 season, while for the 2009/2010 season the 80 kg ha^{-1} treatment had the highest aboveground N mass. Despite the poor yields in 2009/2010, relatively high amounts of N were simulated to be taken up by the crop. This is because the onset of the drought was after the initial growing period during which N uptake occurs at an exponential rate. This period of drought can be clearly observed in Figure 3.2, which displays a dry period between March and October 2010.

In the 2010/2011 growing season, aboveground N mass was underestimated by the model for the 0 and 160 kg N ha^{-1} treatments. The reason for this is not clear, but this may be an indication that the crop was able to acquire N from the soil profile above the rate simulated by the model, or that unwanted N losses from the profile were overestimated by the model, resulting in N deficient conditions being simulated. However, the rest of the simulations were relatively accurate considering the acceptable statistical values that were achieved (Table 3.3). For the 2010/2011 season, two periods of exponential N uptake by the crop were simulated by the model and this is because there were shorter periods of water stress during the season which interrupted the high N uptake rate. Generally, the aboveground N mass data followed a similar trend as for cane yields.

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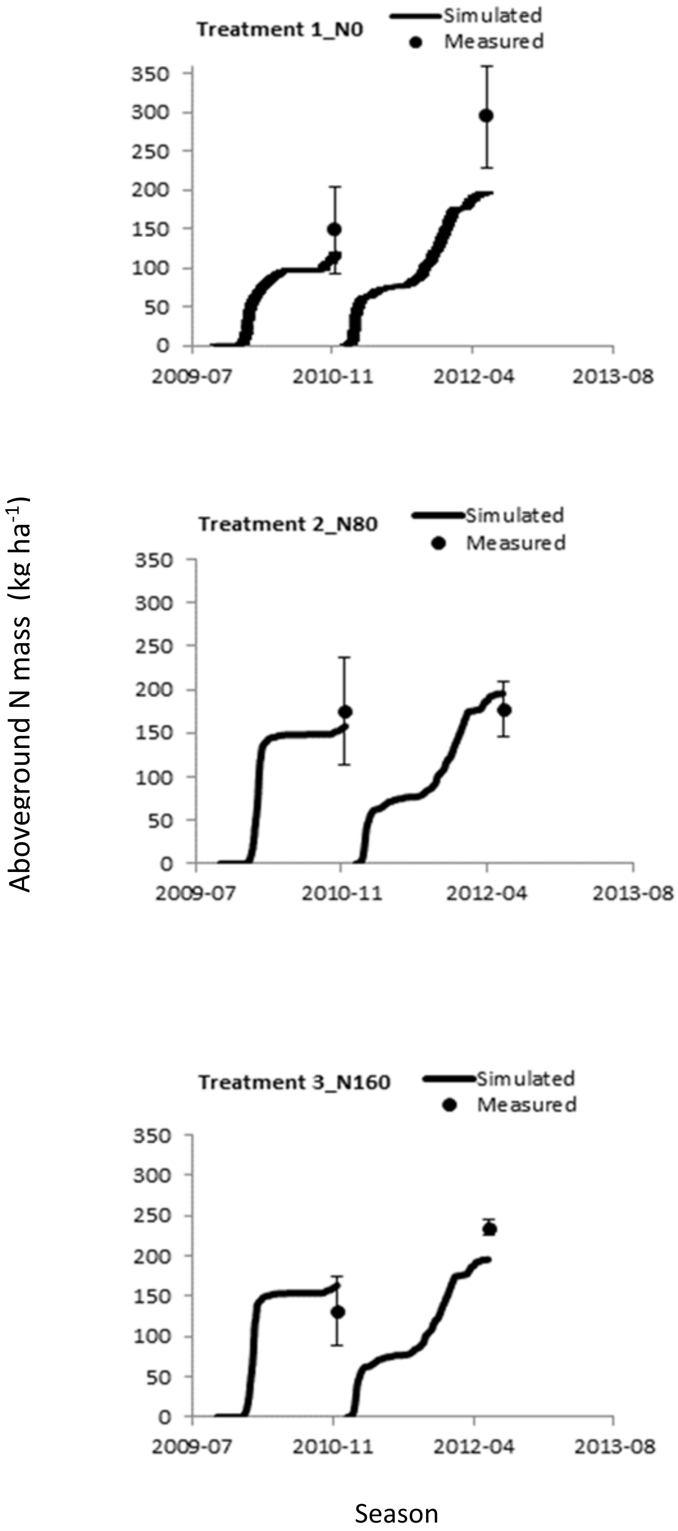

Figure 3.3 Simulated and measured aboveground nitrogen mass for the plant and first ratoon crops in response to different fertiliser nitrogen rates (N0, N80 and N160 kg ha^{-1}). Standard deviations are indicated as error bars (±)

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Table 3.3 Statistical evaluation between measured and simulated values of aboveground nitrogen mass for the plant and the first ratoon crop

Plant crop				
Treatment	**R^2**	**D**	**RMSE**	**MAE (%)**
N0	0.88	0.91	26.3	14.0
N80	0.99	0.99	13.6	5.7
N160	0.74	0.83	41.2	20.6
Ratoon 1				
Treatment	**R^2**	**D**	**RMSE**	**MAE (%)**
N0	0.07	0.41	119.7	22.2
N80	0.97	0.99	40.0	12.5
N160	0.86	0.07	36.8	10.6

3.3.3 Soil water NO_3^- concentrations

Figure 3.4 shows soil water NO_3^- concentrations measured at 30 and 60 cm depths for the three N rate treatments (N0, N80 and N160). This only represents suction cup data as the WFDs did not sample efficiently at the depths they were buried. The model estimated high soil water NO_3^- concentrations for different N rates at both the 30 and 60 cm depths. This can likely be associated with high N mineralisation (200 kg N ha^{-1}) estimated by the model (Figure 3.5). The only case in which measured soil water NO_3^- concentrations were generally higher than simulated concentrations was for the 160 kg N ha^{-1} treatment at 30 cm. Despite the over- and under-estimations by the model, the trends for the measured and simulated soil water NO_3^- concentrations were similar. These trends initially display a rapid decrease in soil water NO_3^- concentrations at the beginning of the 2009/2010 season as a result of crop N uptake, followed by a gradual increase later in the season as demand diminishes when the crop reaches maturity, but there is high N released as a result of organic matter mineralisation. Judging by the differences between soil water NO_3^- measurements made in different replicates, high

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soil spatial variability exists for this soil. Although there were plans in place to install soil water content sensors at different depths, this did not materialise, reducing our ability to interpret the soil water NO_3^- concentration data. As the WFDs did not collect water except right at the end of the season, it is likely that very few deep drainage events occurred that led to NO_3^- leaching, as was simulated by the model (Figure 3.6).

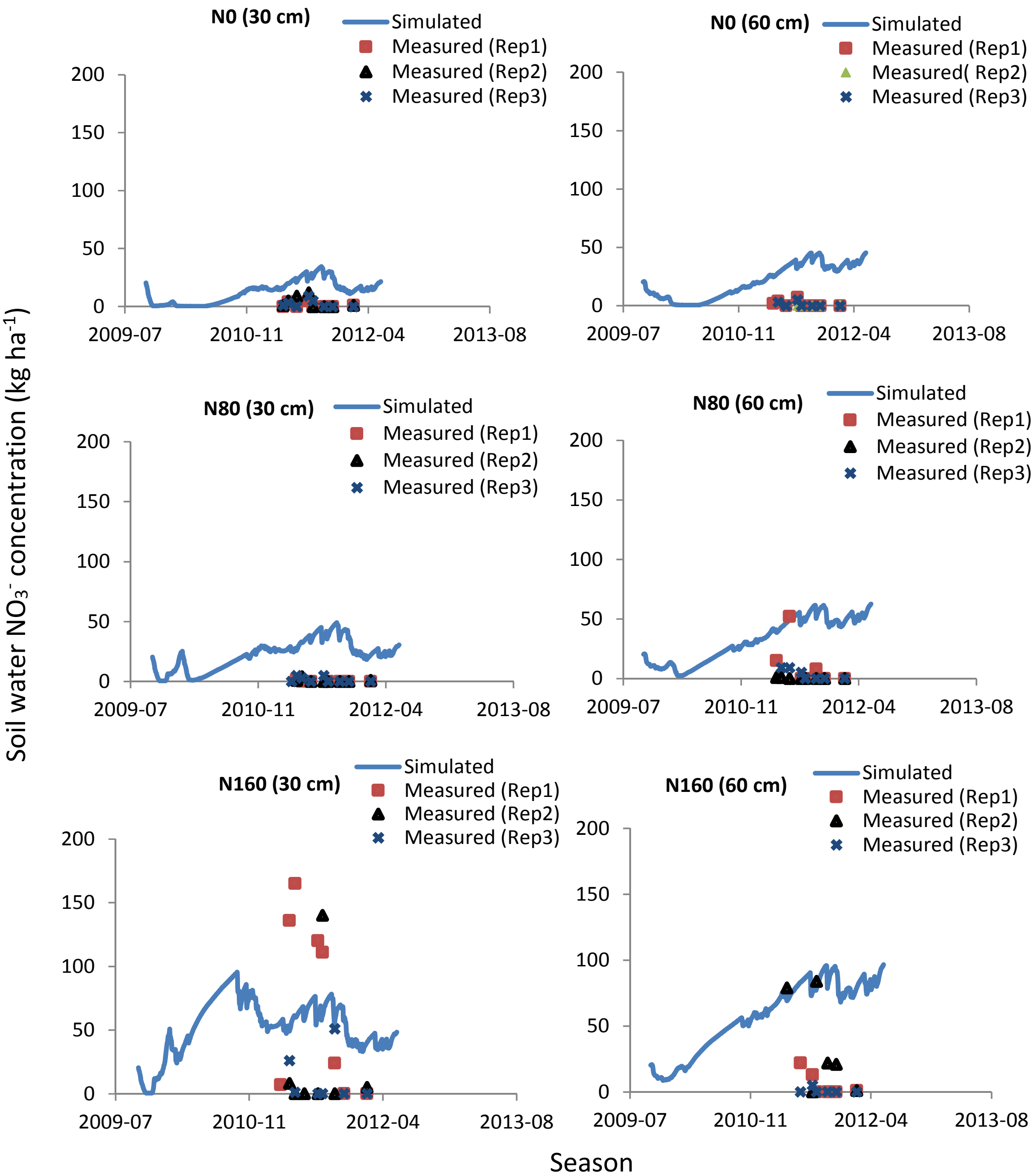

Figure 3.4 Simulated and measured soil water nitrate concentration at 30 and 60 cm depth for different nitrogen application rates (N0, N80 and N160 kg ha^{-1})

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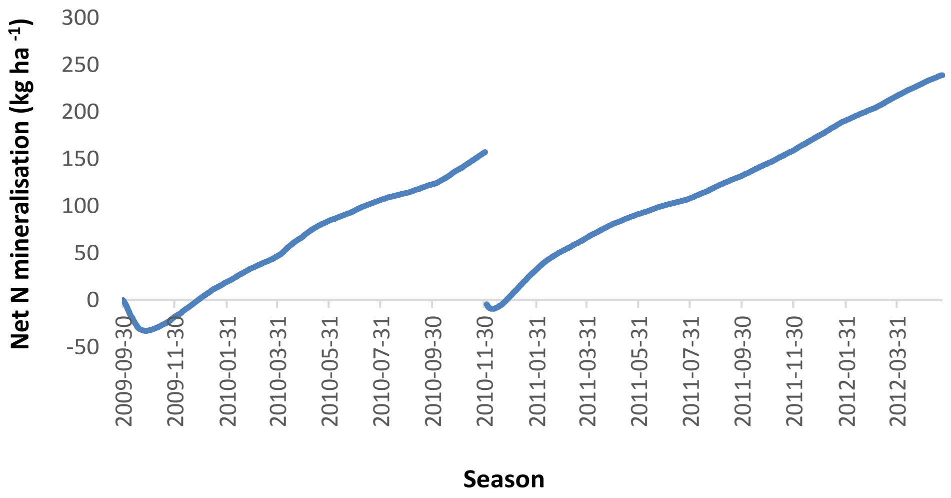

Figure 3.5 Simulated cumulative net nitrogen mineralisation during the plant and first ratoon crops at 80 kg ha^{-1} nitrogen for the Inanda soil

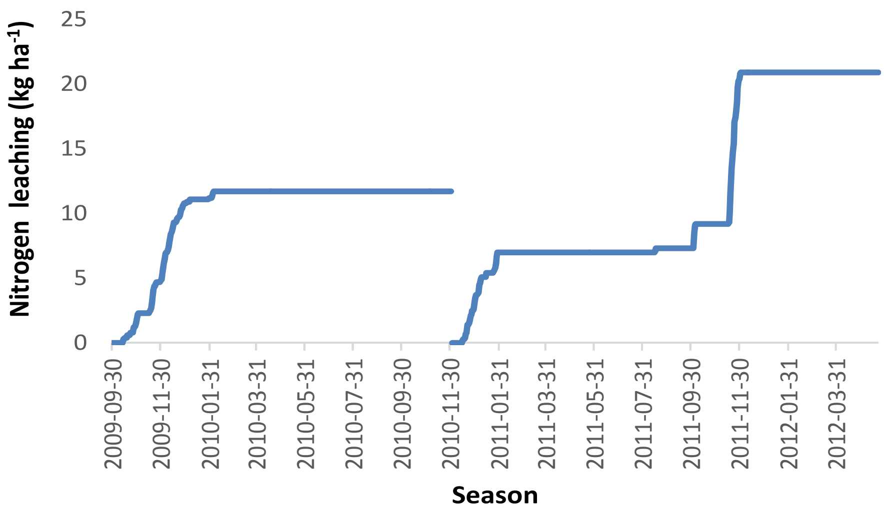

Figure 3.6 Simulated cumulative nitrogen leaching during the plant and first ratoon crops at 80 kg ha^{-1} nitrogen for the Inanda soil

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3.4 Discussion

The accurate simulation of cane yield for the dry 2009/10 season, during which yields were greatly reduced as a results of drought conditions, indicates the model is able to predict crop growth under extreme environmental conditions. This is particularly important from a climate change perspective wherein the importance of long term crop modelling can be recognised. The model estimated aboveground N mass relatively well for the Inanda trial in both seasons. Despite different N rates, similar cane yields and aboveground N mass were simulated following drought conditions encountered during the 2009/10 season. The major implication is that the crop was only able to acquire enough N for the initial growth and thereafter N uptake was reduced following the onset of drought. These observations are consistent with other findings reported by Bahrani *et al*., (2009). According to these findings the authors indicated that the increase in water stress resulted in a decrease in sugarcane response to N fertiliser.

Furthermore, it has been observed from this study that the availability of enough mineralised N and/or N left over from fertilisation in previous seasons in the soil has contributed to non-responses of cane yield and aboveground N mass to different N rates. It is clear that the amount of N taken up by the crop exceeded the amount of N fertilised in all cases. This implies that sugarcane relies on N made available through soil organic matter mineralisation and this leads to a ‘mining’ of N from the soil and rundown of soil organic matter. Although soil water NO_3^- concentration data (Figure 3.4) shows low levels of NO_3^- in the soil at different N rates, this may mean that the crop is taking up N more efficiently or more N is being lost. Despite model discrepancies in terms of over- and under-estimations of soil water NO_3^- concentrations, similar trends were observed for simulated and measured soil water NO_3^- concentration, indicating

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that the model has potential for enhancing the understanding of N dynamics in sugarcane cropping systems. Spatial variability in the soil could be part of the reason for discrepancies observed in model estimations of soil water NO_3^- concentration. The evidence for this spatial variability in the soil is clearly observed from the measured soil water NO_3^- concentration data which indicates large variances in soil water NO_3^- concentration in different parts of the field.

3.5 Conclusions

The model performed well in simulating cane yield and aboveground N mass under rainfed conditions. The model has also been observed to perform well under extreme weather conditions such as during periods of drought. Additionally, based on the implications for reduced cane yield following water stress and thus potential N stress later in the season, it can be concluded that the model has the potential for improving our knowledge of N dynamics in sugarcane cropping systems. Spatial variability in the soil can be a challenge when trying to measure soil variables for model testing purposes. A further conclusion from this study, is that data for a number of seasons is required to judge the model adequately when doing N simulations.

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4. CHAPTER 4: MODELLING NITROGEN DYNAMICS IN SUGARCANE CROPPING SYSTEMS UNDER IRRIGATED CONDITIONS: PONGOLA FIELD TRIAL

4.1 Introduction

Sugarcane cultivation in the Pongola region (northern KwaZulu-Natal) occurs exclusively under irrigation and this region contributes significantly to South Africa's overall sugarcane production. The rising costs of irrigation and fertiliser for sugarcane production remain a major challenge that faces the South African sugarcane industry as the sugarcane crop is highly dependent on both of these inputs to achieve optimum growth and yield. This necessitates a proper understanding and knowledge of sugarcane N requirements under irrigation to ensure that water and N use efficiencies of the crop are maximised. The application of this knowledge will also help to improve management to avoid unwanted N losses to the environment as a pollutant.

In sugarcane, high biomass often produced as a result of high irrigation and N in the soil, may be associated with a reduction in sugarcane quality (Meyer & Wood, 2001). Generally, increasing N application accelerates vegetative growth which result in a rapid growth rate leading to high levels of N, moisture and non-sugars within the plant and consequently lower sucrose content within the cane at harvest. It is therefore important to establish an economic balance between the quantity of N fertiliser required and the maximum amount of sugar produced, and not merely cane per unit area.

The soils found in the Pongola Region mainly include deep, red-coloured Hutton soil forms (Soil Classification Working Group, 1999). These soils were estimated to have a mineralisation potential of about 90 kg ha^{-1} of N per annum (Van der Laan *et al*., 2011). This knowledge is crucial when taking N management decisions to avoid over-

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fertilisation and to maintain sugarcane quality while reducing unwanted N losses which are detrimental to the environment.

The objective of this study was to monitor soil water NO_3^- concentrations and aboveground N mass in sugarcane cropping systems under drip irrigation in order to assess the potential of using measured soil water NO_3^- concentrations in management decisions. This data was also used to further test the DSSAT-Canegro model's ability to simulate N dynamics under drip irrigation.

4.2 Materials and methods

The trial was conducted on the SASRI Pongola Research Farm located at 27°25'S 31°35'E, 308 m above sea level and experiences a sub-tropical climate. Weather data used on this trial was collected from the automatic weather station (SASRI weather web) located at the Pongola farm. The long term average rainfall in this area is 690 mm per annum, most of which falls during the summer months. A mean temperature of 22ºC is experienced annually.

The sugarcane variety NCo376 was planted on three selected plots of about 12 m^2 each which had previously been planted to soybean (*Glycine max*). The crop was planted in April 2011 and was harvested in April 2012 and therefore had a 12 month growing period. This trial was conducted on a deep, red-Hutton soil form (Soil Classification Working Group, 1999). During planting, stalks were placed in rows and buried with soil and thereafter N fertiliser (urea) at a full rate (as recommended by SASRI's fertiliser Advisory Service) of 140 kg N ha^{-1} was applied in bands on the soil surface as one treatment and then no N was applied for the other treatment which served as a control (N0). Phosphorus (P) and potassium (K) fertilisers were also applied for both the 140 kg N ha^{-1} and 0 kg N ha^{-1} treatments in the form of superphosphate and potassium chloride

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at the rate of 150 and 100 kg ha^{-1}, respectively. In each plot, ceramic suction cups and wetting front detectors (WFDs) were installed at depths of 15, 30, 45 and 60 cm to collect soil water samples following an irrigation or rainfall event. However, the suction cups did not sample efficiently and consistently throughout the season and for this reason, data from suction cups was not used for further analysis and only WFD data was used. A technique for collecting and analysing soil water samples, as well as the calculation of soil water NO_3^- concentrations was the same as the one described in Section 3.2 of Chapter 3. In this way, soil NO_3^- concentration was constantly monitored by analysing samples collected after each irrigation application. Soil parameters as shown in Table 4.1 were used as inputs for modelling soil N processes and for calculations thereof as described in section 3.2 of Chapter 3.

At harvest, cane yield and aboveground N mass were measured. Particularly for the measurement of aboveground N mass, the same procedure as described in section 3.2 of Chapter 3 was followed.

Statistical criteria that were used to evaluate model performance for aboveground N mass simulation, comprised correlation coefficient (r^2), index of agreement (D), root mean square error (RMSE) and mean absolute error (MAE) as described under section 2.2 of Chapter 2.

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Table 4.1 Measured and estimated soil model parameters at Pongola Research Farm

Soil depth (cm)	pH (CaCl)	Organic C (%)	Total N (%)	C:N Ratio	clay	silt	sand	Bulk density (g cm^{-3})	Drained upper limit (m^3 m^{-3})*	Lower limit (m^3 m^{-3})*	Saturation (m^3 m^{-3})*
0-30	6.1	0.81	0.058	14:1	33	9	58	1.5	0.341	0.257	0.401
30-60	5.1	0.64	0.046	14:1	43	7	50	1.6	0.349	0.269	0.394
60-120	6.1	0.52	0.037	14:1	46	9	45	1.5	0.361	0.271	0.408
120-180	6.1	0.52	0.037	14:1	46	9	45	1.5	0.361	0.271	0.408

*Estimated by DSSAT

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4.3 Results

4.3.1 Cane yield

Measured cane yield was 155 and 161 t ha^{-1} for the N0 and N140 kg ha^{-1} treatments respectively (Data not shown). Satisfactory cane yield achieved for the N0 treatment compared to N140 was attributed to the previously planted soybean crop which made N available for subsequent sugarcane crop. Simulated yield was only 65 t ha^{-1} for both the N0 and the N140 kg ha^{-1} treatments. The model, therefore, tremendously under-estimated cane yield for the plant crop. The underlying reason for this under-estimation is not clear, but it is neither attributed to water stress nor N stress. Since the crop was planted in April 2011, a period nearing a cooler winter season during which a slower growth rate normally takes place, the model may have had a tendency to over-estimate the impact of this cooler period on crop development.

4.3.2 Above-ground N mass

The measured aboveground N mass of the crop for the N140 treatment was 130 kg ha^{-1} while simulated value was 105 kg ha^{-1} (Figure 4.1). For the N0 treatment, measured aboveground N mass was 120 kg ha^{-1} and the simulated aboveground N mass was 105 kg ha^{-1}. Similar to cane yield, the model under-estimated aboveground N mass, but to a much lesser extent. Similar to the over-prediction of retarded crop growth for cane yield during the cooler period, the model again over-predicted the seasonal effect on aboveground N mass. Therefore, simulated aboveground N mass appears lower than expected when impacted by seasonal conditions due to the model over-estimating the effect of these conditions. Overall, the model performed better in estimating above-ground N mass when compared to estimating cane yield. This is evidenced in the data compliance with statistical criteria, even though the criteria were not adequately met for the N140 treatment when compared to N0 treatment (Table 4.2).

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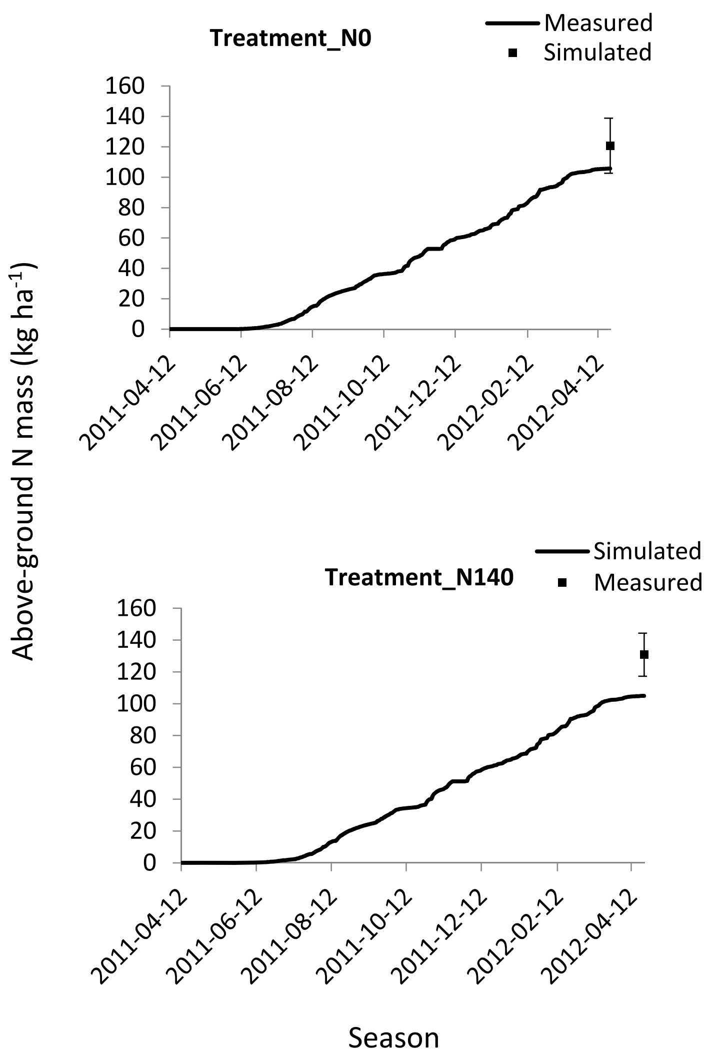

Figure 4.1 Simulated and measured aboveground nitrogen mass for the plant crop in response to nitrogen fertiliser rates of 0 and 140 kg ha^{-1}. Standard deviation is indicated as error bar

Table 4.2 Statistical evaluation between measured and simulated values for aboveground nitrogen mass

Treatment	Yield (t ha^{-1})	Aboveground N mass (kg N ha^{-1})	R^2	D	RMSE	MAE
N0	155	130	0.79	0.36	17.52	11.63
N140	161	120	0.99	0.29	27.18	16.30

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4.3.3 Soil water NO_3^- concentrations

The measured soil water NO_3^- concentrations sampled from WFDs at different soil depths (15, 30, 45 and 60 cm) clearly decreased with time over the growing season (Figure 4.2). It can be observed in this figure, that all three replications for each depth initially had high soil water NO_3^- concentrations at the beginning of the season. This was most likely caused by high mineralisation that occurred as a result of disturbing the soil during the installation of the WFDs. These concentrations decreased gradually towards the end of the growing season following N uptake by the crop, leaching and other forms of N loss. Since high N mineralization in response to soil disturbance when the instruments were installed is not simulated by the model, initial measured and simulated NO_3^- concentrations generally did not correlate well at the various soil depths. Simulated soil water NO_3^- concentrations were low at the beginning of the season and increased during the season as a result of N mineralization and low crop demand for NO_3^- initially, and then decreased towards the end of the season as crop NO_3^- uptake increased. Following an equilibration period, there was a much better correlation between measured and simulated N concentrations measurements at all depths for the second half of the season.

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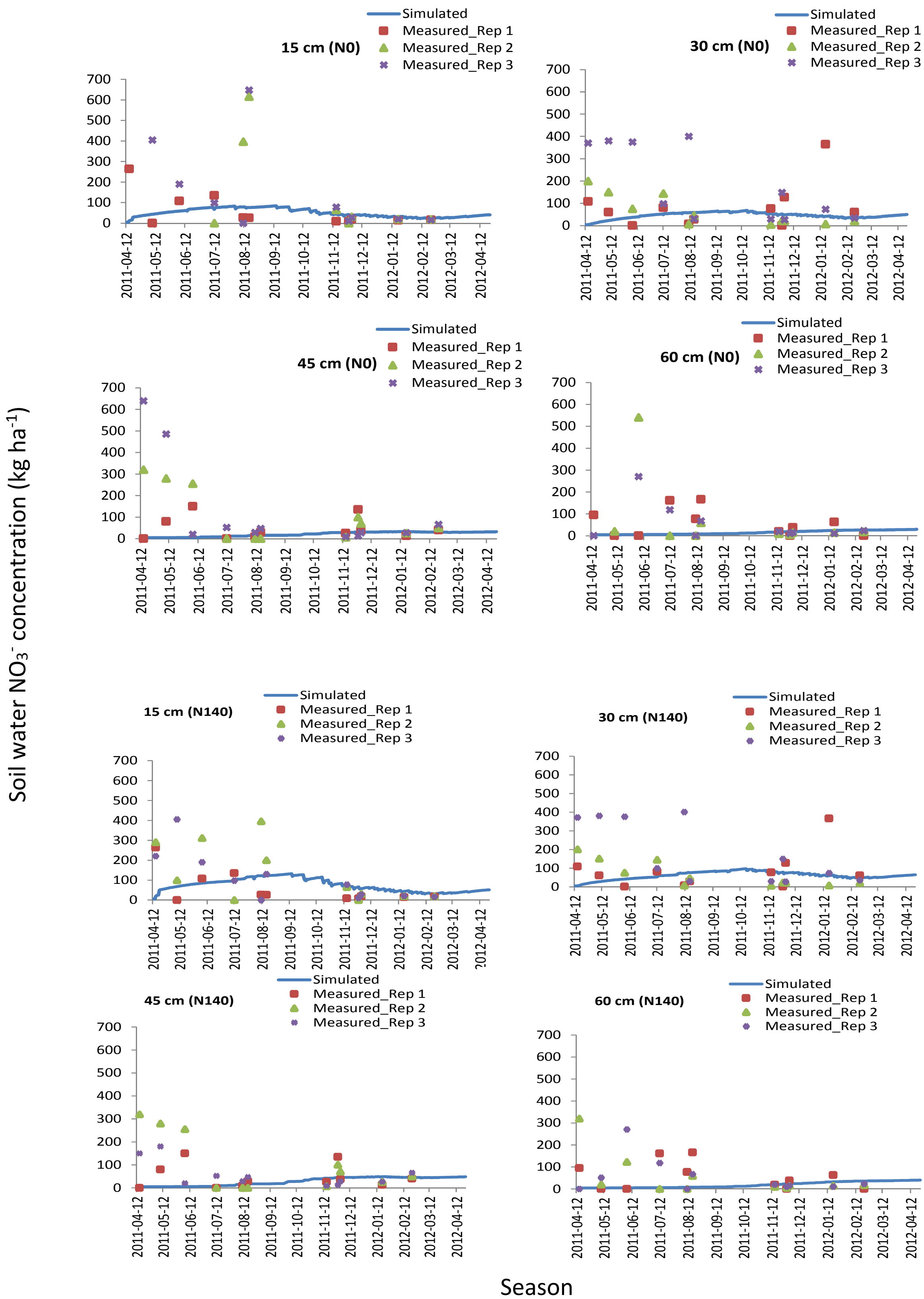

Figure 4.2 Simulated and measured soil water nitrate concentration at 15, 30, 45 and 60 cm depths for nitrogen fertiliser rates of 0 and 140 kg ha^{-1} {(data collected from WFDs)}.

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4.4 Discussion

The reason for the under-estimation of cane yield, and to some extent aboveground N mass by the model may possibly lie mainly on the temperature effects, as the model may have under-estimated growth under low seasonal temperature conditions. According to the findings reported by Donaldson *et al*., (2008), a season during which a crop is planted has a major impact on biomass accumulation, and since the Pongola trial crop was planted in the autumn (April) nearing the winter period, the model may have over-estimated the effect of these low temperature conditions which negatively affect biomass accumulation. Additionally, this has also been associated with the fraction of light intercepted by canopies and the efficiency by which radiant energy is converted into biomass (Inman-Bamber, 1994; Singels *et al*., 2005). A further explanation of these findings by Inman-Bamber, (1994) and Singles *et al*., (2005) was that a slow canopy development of the crop which starts in winter results in lower incident radiation being intercepted as compared to summer when rapid canopy development takes place, ultimately resulting in a difference in biomass accumulation between the two seasons. The growth rate of the crop is therefore very low due to a season that does not favour optimum growth conditions and also due to a lack of a well developed root system that can support rapid growth as is the case for the ratoon crops. Although DSSAT-Canegro is mechanistic and takes into account the effect of these seasonal conditions, it is not clear why it under-estimated crop growth for this season and further research on this is recommended.

The observed satisfactory cane yield achieved for the N0 treatment which was of similar magnitude as N140 treatment, indicates the benefits of rotating sugarcane with soybean crop as N is made available through legume fixation for the next crop.

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A gradual decrease in measured soil NO_3^- concentration from the beginning of the season until the lowest concentrations observed towards the end of the season, may be attributed to a number of factors. Although N uptake by the crop contributes significantly in lowering soil N concentration, N leaching and other forms of N loss such as denitrification and volatilisation (to a lesser extent) might have played a role during the initial stages of crop development and at the beginning of the season. This is because during these early stages of development, the crop does not have a well-developed root system that can take up a considerable amount of N from the soil.

The initial estimates of NO_3^- concentrations at the beginning of the season did not match measured values due to high mineralisation rates caused by the installation of WFDs in the soil and this is not simulated by the model. The model performed well in simulating NO_3^- concentration later during the season as many of the measured and simulated values were better aligned to each other.

4.5 Conclusions

The model greatly under-estimated cane yield while overall better simulation of aboveground N mass was observed. Rotating sugarcane with soybean result in more N being made available for subsequent sugarcane crop. Soil NO_3^- concentration may have not been initially well simulated due to the mineralisation pulse that occurred during WFDs installation, but simulations were better later in the season. Further research is required to better understand how modelling and measuring soil water NO_3^- concentrations can be used to guide N fertiliser management in the Pongola Region.

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5. CHAPTER 5: INVESTIGATING NITROGEN APPLICATION STRATEGIES TO MINIMISE UNWANTED LEACHING LOSSES IN RAINFED SUGARCANE CROPPING SYSTEMS

5.1 Introduction

Identifying nitrogen (N) application strategies that lead to high N use efficiencies (NUE) can play a major role in minimising unwanted N losses to the environment and thus increase profitability in rain-fed sugarcane cropping systems. Nitrogen dynamics are extremely complex which makes this essential nutrient very difficult to manage under interacting plant, soil and environmental conditions. Possible management strategies aimed at achieving high NUE while minimising N losses to the environment have been widely reported in number of studies (Meyer & Wood, 1994; Dinnes *et al*, 2002; Thorburn *et al*, 2006; Van der Laan *et al*, 2011).

Synchronising fertiliser N applications with periods of high crop N demand is one of the important strategies towards achieving high NUE. The risk of N loss is usually high when the period between N application and crop N uptake is large (Dinnes *et al*, 2002). Therefore, the timing of N application should attempt to manipulate N availability before, during and after peak crop N demand so as to ensure that the amount of inorganic N in the soil is limited at the end of the growing season and before the next crop has established an extensive root system. Another important factor in minimising N losses and related to timing, is the rate of application, and the use of split applications. Nitrogen applications in excess of crop demand will potentially result in huge amounts of N being lost to the environment. In such cases it may be crucial to split N applications in a manner that will more closely match crop N demand for each specific stage of crop

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growth. Accounting for N newly mineralised from organic matter in the soil may also be an important factor in reducing excessive N applications.

This study aims to investigate crop growth and soil water nitrate (NO_3^-) concentrations under different N application strategies in an effort to understand the fate of applied N under rain-fed sugarcane cropping systems. Measuring and Modelling are combined to enhance understanding.

5.2 Materials and methods

5.2.1 Fertilisation trial (Mount Edgecombe)

The trial was conducted in Mount Edgecombe, north of Durban in Kwa-Zulu Natal, South Africa (29°43’20’’S 31°04’29’’E and 96 m above sea level). The average annual rainfall in this area is 950 mm while the mean annual temperature is 20.5°C. Weather data was collected from the Mout Edgecombe weather station. A ratoon sugarcane variety NCo376 was previously planted on the Fernwood soil form (Soil Classification Working Group, 1999) in October 2011 and grown on a 12 month cropping cycle (October – October). The treatments and their descriptions are given in Table 5.1 below. Each treatment was replicated four times in a randomised block experimental design to account for a soil texture gradient.

Table 5.1 Nitrogen fertiliser treatment descriptions

Treatment	Description
N0	Zero N fertiliser applied
N75	75 kg N ha^{-1} limestone ammonium nitrate (LAN) applied
N150	150 kg N ha^{-1} LAN applied
N250	250 kg N ha^{-1} LAN applied
N split	75 kg N ha^{-1} LAN applied at ratooning, 75 kg ha^{-1} LAN applied later during the season
N_Mng	N applications determined by suction cup NO_3^- measurements (75 kg N ha^{-1} was applied initially and no N was applied thereafter based on suction cup NO_3^- measurements)

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Plots were 52 m^2 with a row spacing of 1.3 m. Limestone ammonium nitrate (LAN) was applied as N fertiliser by broadcasting on the soil surface according to the rates specified for each treatment as shown in Table 5.1. Phosphorus, potassium and other essential plant nutrients were applied to be non-limiting, based on soil analysis results, according to the recommended standards of FAS (Fertiliser Advisory Service) of South African Sugarcane Research Institute (SASRI).

Ceramic suction cups were installed in three replicated plots of each treatment at 30 and 60 cm soil depths and additionally at 90 cm depth for two plots. Suction pressure of approximately 60-70 kPa was applied to the suction cups using a syringe in order to draw water into the cups whenever there was enough water in the soil. Soil water samples were collected from the suction cups with a syringe following rainfall events and were taken to the laboratory for analysis of soil water NO_3 concentration using an RQEasy Nitrate Reflectometer (Merck, Darmstadt, Germany). Decagon 10HS soil water sensors linked to EM50 loggers (Decagon, Pullman, Washington) were installed in three plots receiving different N treatments to monitor soil water content on an hourly basis. Simulated volumetric water content, measured soil layer depth and measured bulk density were used to calculate measured soil water NO_3^- to be expressed in kg N ha^{-1} in order to compare between measured and simulated soil water NO_3^- concentrations assuming all NO_3^- is in the solution.

Prior to harvest of the crop in October, aboveground biomass samples were divided into stalks, trash (dead leaves) and green leaves for dry matter determination and were analysed for N content in order to determine aboveground N mass. The crop was then harvested and cane yield in terms of t ha^{-1} was measured.

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DSSAT-Canegro was used to simulate cane yield and aboveground N mass and soil N dynamics in response to different fertiliser N rates. Model parameterisation and initialisation was performed using measured data from soil analyses results obtained before the start of the experiment. The soil parameters include pH, organic carbon, total N, soil depth, bulk density, and percentage clay, silt and sand as shown in Table 5.2. The simulation output of the model was compared with the measured data to evaluate model performance. Statistical criteria that were used to evaluate model performance comprised correlation coefficient (r^2), index of agreement (D), root mean square error (RMSE) and mean absolute error (MAE) (De Jager, 1994). These criteria is described under section 2.2 of Chapter 2.

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Table 5.2 Measured and estimated soil model parameters for Mount Edgecombe trial

Soil depth (cm)	pH (CaCl)	Organic C (%)	Total N(%)	C:N ratio	Clay	Silt	Sand	Bulk density (g cm^{-3})	Drained upper limit (m^3 m^{-3})*	Lower limit (m^3 m^{-3})*	Saturation (m^3 m^{-3})*
0-20	7.6	1.37	0.098	14:1	13	8	79	1.3	0.217	0.28	0.423
20-40	7.7	1.22	0.087	14:1	13	9	79	1.3	0.208	0.122	0.417
40-60	7.8	0.85	0.061	14:1	13	7	81	1.3	0.189	0.114	0.398
60-80	7.7	0.75	0.054	14:1	15	7	79	1.3	0.195	0.121	0.387
80-100	7.7	0.75	0.054	14:1	60	10	30	1.5	0.343	0.248	0.387

*Estimated by DSSAT

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5.3 Results

5.3.1 Cane yields

Interestingly, maximum cane yields of 100 t ha^{-1} were measured for the N0, N150 and N_Mng treatments (Figure 5.1). Yields did not differ significantly between different N rate treatments (Table 5.3), and this is attributed to adequate soil N accumulated from previous fertiliser applications and N derived from organic matter mineralisation in the soil. The model consistently under-estimated cane yields for different N rates, and statistical criteria were not adequately met (Table 5.4). Despite these under-estimations by the model, simulated yields were also similar for the different N rate treatments. Simulated sugarcane growth for all treatments increased rapidly during the initial stages of crop growth followed by a slower growth rate during the mid-season and then another rapid growth rate period towards the final crop growth stage. The reason for this is most likely water-limited growth during the mid-season (Section 5.3.3, Figure 5.3). Overall, 100 t ha^{-1} cane yields are respectable for rainfed production.

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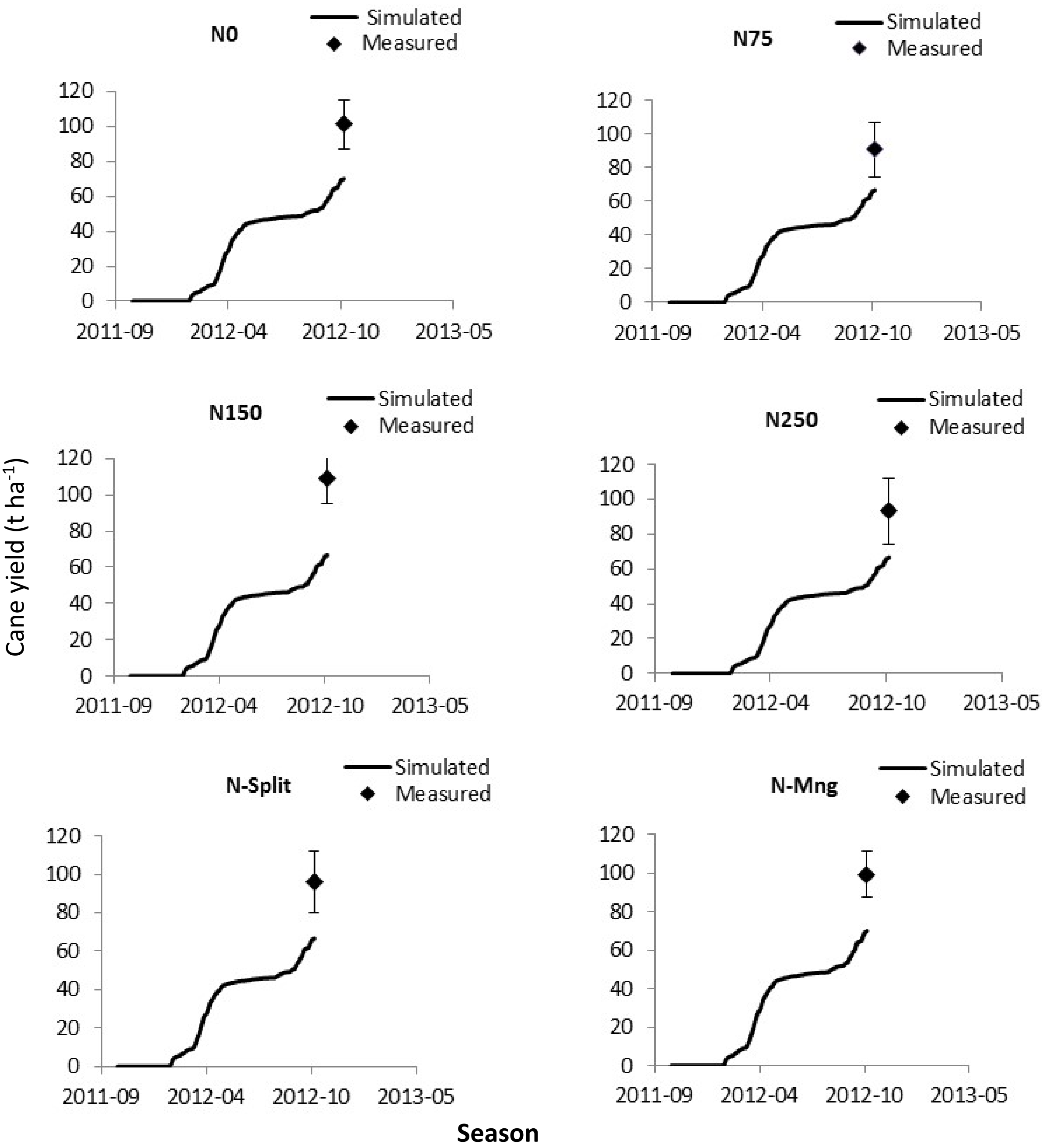

Figure 5.1 Simulated and measured cane yield for the first ratoon crop in response to different nitrogen rates and timing (N0, N75, N150, N250, N_Split and N_Mng). Standard deviations are indicated as error bars

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Table 5.3 Nitrogen fertiliser treatment means for cane yield

Treatments	Means (t ha^{-1})
N0	100.5
N75	96.4
N150	106.5
N250	90.3
N-Split	93.3
N-Mng	99.7

LSD (P=0.05): 17.01
CV (%): 11.5

Table 5.4 Statistical evaluation between measured and simulated values for cane yields

Treatment	R^2	D	RMSE (t cane ha^{-1})	MAE (%)
N0	0.56	0.67	26	19
N75	0.34	0.70	24	17
N150	0.63	0.62	28	18
N 250	0.63	0.76	19	15
N-Split	0.70	0.53	28	25
N-Management	0.17	0.51	28	19

5.3.2 Aboveground N mass

The highest aboveground N masses of 212, 218 and 227 kg ha^{-1} were measured for the N_split, N75 and N_Mng treatments, respectively (Figure 5.2) and the differences between treatments were not statistically significant except between N_split and N75 (Table 5.5). According to the model, the highest aboveground N mass was simulated for treatments N250, N_split and N150 and this was 184, 166 and 157 kg ha^{-1}, respectively. The lowest aboveground N mass was simulated for the N0 and N75 treatments. It is therefore clear that the simulated aboveground N mass increased with increasing N application rate as would be expected, but both simulated and measured values did not

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follow a similar trend probably due to spatial variability in the soil which is not accounted for by the model. However, considering statistical criteria which indicates low MAE values (<20 %) and r^2 and D values often above the 0.80 norm, the model simulated aboveground N mass relatively well (Table 5.6). This occurred despite differences in trends between measured and simulated data and despite some under-estimations observed. The model predicted that there was a very rapid rate of N uptake during the initial stage of crop development for all treatments for which there were large amounts of soil N available, but N uptake slowed down during the mid-season as result of water being a limiting factor.

According to the model, N0 and N_Mng had a similar tendency of gradual N uptake during initial stages of crop development compared to other treatments, but from the measured cane yield data, it is clear that sugarcane was still able to take up adequate N to achieve yields comparable to treatments receiving higher N rates at the beginning of the season.

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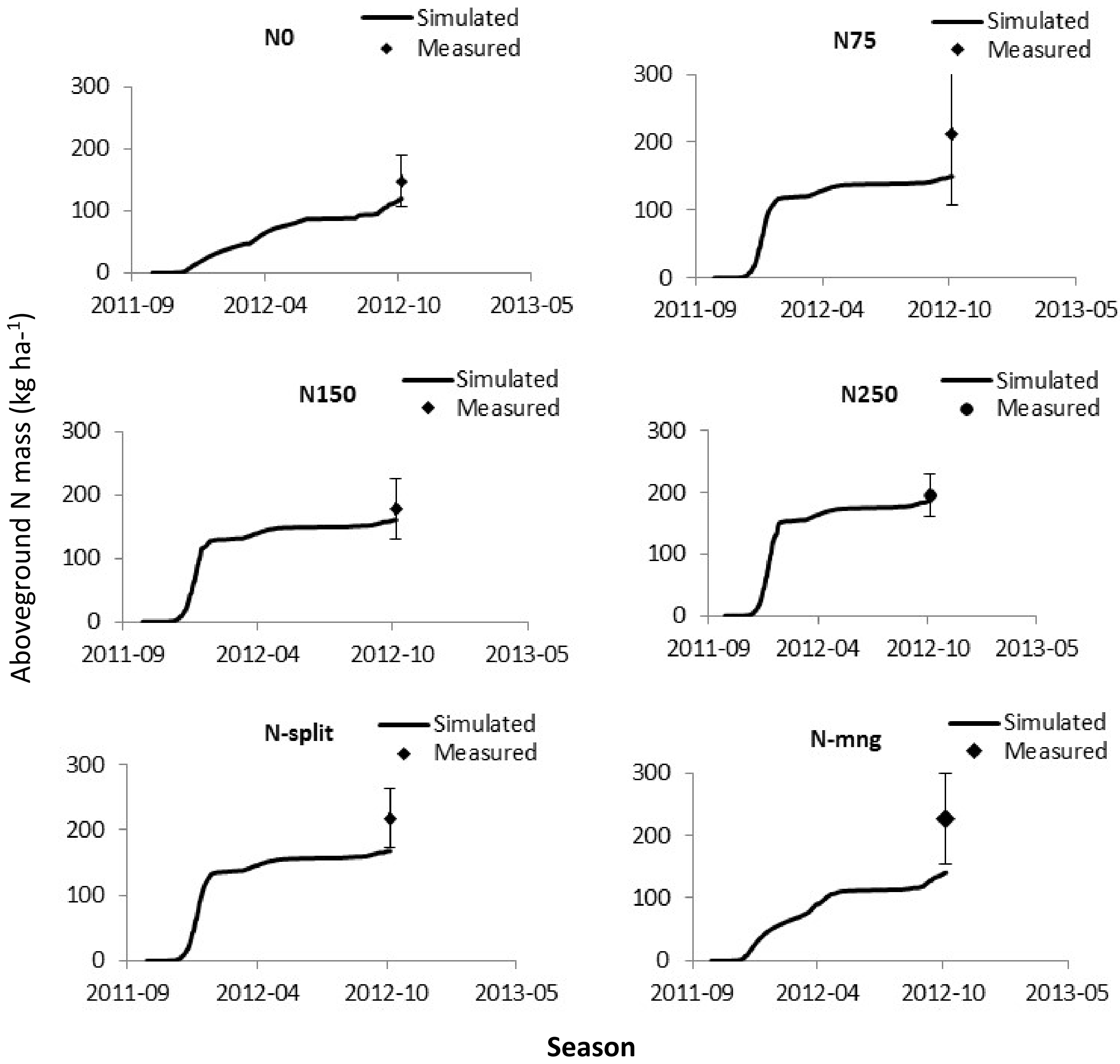

Figure 5.2 Simulated and measured aboveground nitrogen mass for the first ratoon crop in response to different nitrogen rates and timing (N0, N75, N150, N250, N_Split and N_Mng). Standard deviations are indicated as error bars

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Table 5.5 Nitrogen fertiliser treatment means for aboveground nitrogen mass

Treatments	Means (kg N ha^{-1})
N0	179.8
N75	160.7
N150	177.9
N250	195.5
N-Split	203.7
N-Mng	187.5

LSD (P=0.05): 34.73
CV (%): 12

Table 5.6 Statistical evaluation between measured and simulated values for aboveground nitrogen mass

Treatment	**R^2**	**D**	**RMSE (t cane ha^{-1})**	**MAE (%)**
N0	0.89	0.96	14	7
N75	0.94	0.90	55	16
N150	0.91	0.87	28	10
N 250	0.66	0.76	36	14
N-Split	0.78	0.78	31	11
N-Management	0.51	0.65	67	17

5.3.3 Soil profile water content

Measured soil water content for all soil depths was initially high at the beginning of the season (Figure 5.3). This was associated with high summer rainfall during January and February and a mature or recently harvested crop with a lower water demand. Following this period, the soil profile water content at 30 and 60 cm depths decreased gradually towards winter (May-July) which normally experiences lower rainfall, and it increased again as rainfall resumed in spring. Water stress was likely during the mid-season, for example, with measured values below 0.1 $m^3\ m^{-3}$ at 60 cm depth. For the 90 cm depth, a similar trend to the one observed at 30 and 60cm depths was observed.

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The model performed best at estimating soil water content at the 90 cm depth. It also did reasonably well in predicting soil water content at the 30 cm depth, while there were large differences between measured and simulated values at the 60 cm depth, especially from the mid-season onwards. Despite these discrepancies, soil water content was relatively well simulated and the trends for measured and simulated water content were very similar. The model did not predict soil water stress at any given depth, as simulated values were above 0.1 $m^3\ m^{-3}$.

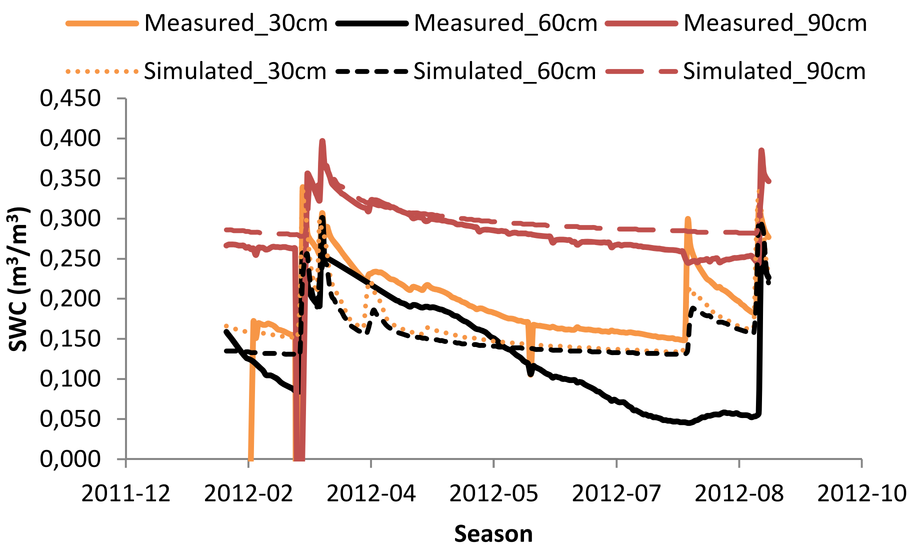

Figure 5.3 Simulated and measured soil water content at three soil depths (30, 60 and 90cm)

5.3.4 Soil water NO_3^- concentration

Despite the inconsistency of the measured data, the initial measured soil water NO_3^- concentrations appeared higher than the simulated values for most treatments except for the N0 treatment (Figure 5.4). This is likely a result of sudden increase in mineralisation following soil disturbance during the installation of sampling equipment. Thereafter the model seemed to adequately simulate soil water NO_3^- concentration in the middle of the season, following which the measured concentrations decrease more

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rapidly than was being simulated towards the end of the season for the treatments receiving higher rates of N fertiliser. Therefore, in general, simulated and measured soil water NO_3^- concentrations did not follow a similar trend. Overall, the model appeared to constantly under-estimate (specifically for N_Mng and N75 treatments) and to some extent also over-estimates (N_Split and N250) soil water NO_3^- concentration for most of the season. Some of the discrepancies between measured and simulated values can be attributed to very high spatial variability in the soil and inconsistent measurements. Nonetheless for some treatments, measured data was well aligned with the simulated data especially, for the N0, N_split and N_Mng.

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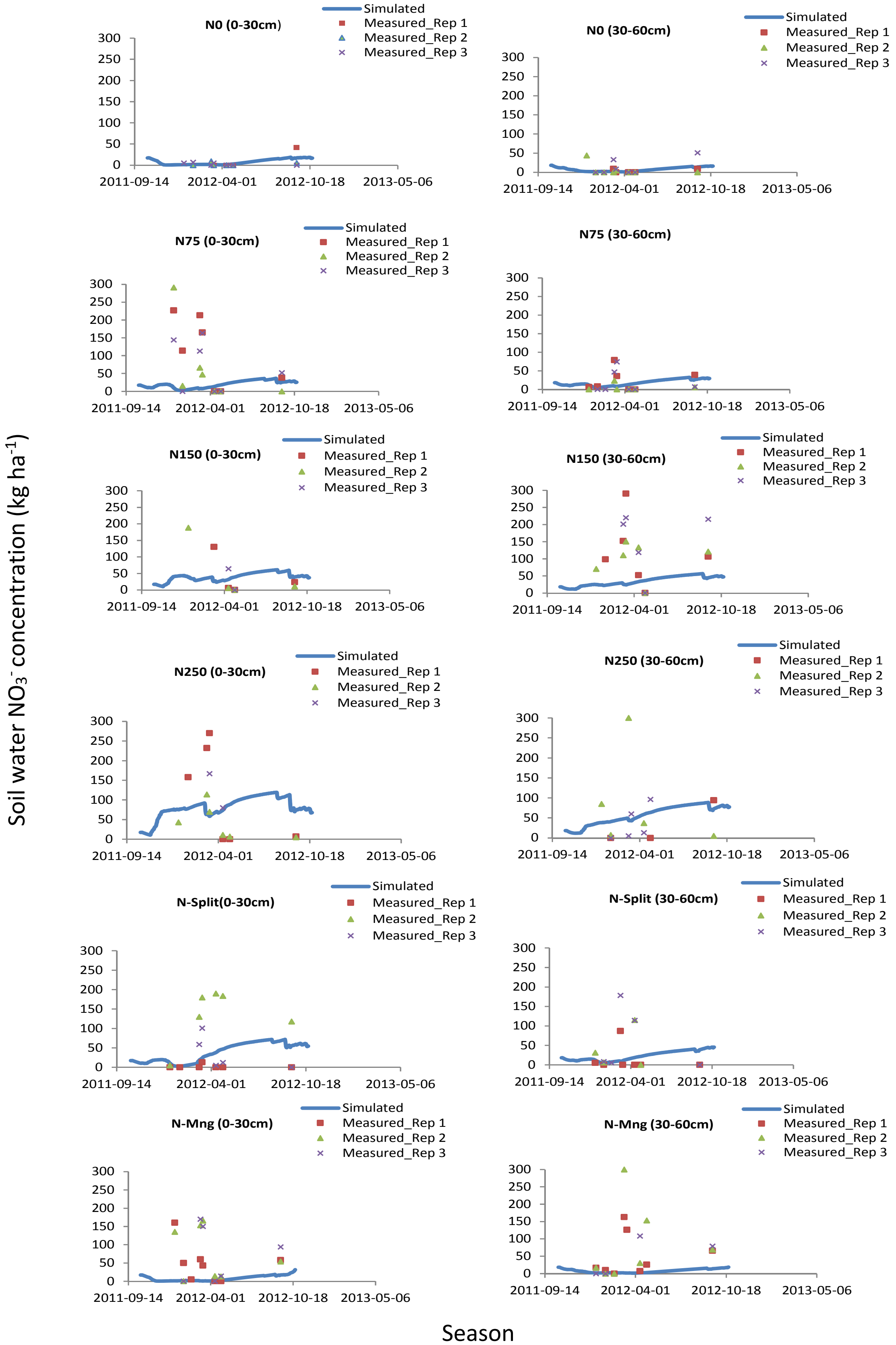

Figure 5.4 Simulated and measured soil water nitrate concentrations at 30 and 60 cm depths for different nitrogen application rate treatments

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5.4 Discussion

The model did not perform particularly well in simulating cane yields for the Mount Edgecombe field trial. The exact reason for poor performance is not clear but spatial variability in the Mount Edgecombe soil has been noted, especially in terms of clay content. Although this may not be the main reason for the under performance of the model, it may have made a major contribution to the problem, as the model assumes soil uniformity. A dry mid-season period could have also played a role. Despite a range of different N treatments that were applied, similar cane yields were observed and this may be associated with the availability of sufficient N derived from soil organic matter mineralisation and/or water being the limiting factor. However, clear differences in aboveground N mass were observed for different N rates and the model simulated this reasonably well. These findings are consistent with those reported by Muchow and Robertson (1994), whereby a range of N uptake for a similar biomass production has been reported, suggesting that an increase in N uptake did not necessarily lead to an increase in final cane yield. This is termed ‘luxury uptake’. Running a number of pre-seasons to better initialise the model for N simulations may result in more accurate simulations.

The inability to simulate measured soil water NO_3^- concentrations is disappointing. The reason for the inconsistency of the soil water NO_3^- concentration measurements may have been due to unusually high soil variability for the site. Nonetheless, large inconsistencies in soil water NO_3^- concentration measurements from this trial indicate that this measurement may be of limited use as an integral measurement for adaptive management in commercial production systems. It also appears from the model results,

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that the degree of NO_3^- leaching is higher when N application rates are higher and correlates with periods of higher rainfall.

5.5 Conclusions

The similar cane yields observed among different treatments have shown that inorganic N derived from mineralisation and past fertilisation events can be sufficient for the crop to obtain a 100 t cane ha^{-1} yield. This emphasises the importance of accounting for mineralised and residual inorganic N when determining a fertilisation programme. The highest measured aboveground N mass observed in the N_Mng, N_split and N75 treatments indicates that these treatments had high NUE which will have reduced N losses to the environment compared to treatments with higher N rate applications. The under-performance of the model in terms of simulating cane yield and soil water NO_3^- concentrations has proven the necessity of increased local calibration in some cases. However, the under-estimation of soil water NO_3^- concentration by the model may not be entirely attributed to the inaccuracy of the model itself, but rather the inconsistency resulting from the nature of the measurement. It is clear that there is also a need to select fields that are homogenous for this type of research.

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6. CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Overview

Sugarcane requires substantial amounts of N to achieve maximum yields, but this is a challenging nutrient to manage as it is highly susceptible to various types of losses which lead to environmental degradation and loss in profitability. Owing to the complexity of N dynamics in sugarcane cropping systems, mechanistic crop models are often used as an important tool to help understand these dynamics and improve management practices. In this study, the DSSAT-Canegro model with a newly included N subroutine, was tested for its capability to simulate sugarcane growth and yield under irrigated conditions using a historical dataset from a fertigation trial conducted in Komatipoort. Model performance in simulating sugarcane growth, N uptake and yield responses to different N rates under irrigated and rainfed conditions was further tested using new data collected in this study. The potential of using measured soil water NO_3^- concentrations to calibrate and test DSSAT-Canegro was also explored.

6.2 General conclusions and recommendations for simulating N dynamics in sugarcane cropping systems

Model testing using a historical dataset from the fertigation trial conducted in Komatipoort was an important exercise for initially assessing the model and to gain confidence in its output with regards to simulating aboveground variables. The model performed very well in simulating cane and sucrose yield, as well as aboveground N mass in response to different fertiliser N rates (see Chapter 3). Interestingly, for this newly converted virgin field, there were no differences in yield between the different N rate treatments for the plant crop. The reason for this is that the soil was able to supply

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enough N to match crop demand during this first season as a result of soil disturbance resulting in increased mineralisation rates and a build-up of N in this previously uncropped soil. For the final two seasons, no yield benefit was observed when applying 144 kg N ha^{-1} as opposed to 96 kg N ha^{-1}. The balance between aboveground N mass, N fertilised and mineralised N have proved that N fertiliser application is highly important to prevent 'mining' of N from the soil or excessive losses to the environment. The exercise has therefore also indicated that it is very important to always account for the newly mineralised N in the soil when planning a fertilisation programme. Good agreement between measured and simulated data indicates that this simple one-dimensional model can be used to estimate aboveground variables for a two-dimensional drip irrigation system.

The use of DSSAT Canegro to further investigate N dynamics in sugarcane cropping systems under varying environmental conditions formed an integral part of this study. Under rainfed conditions, when a severe drought was experienced in 2010, the model was observed to be robust in terms of simulating sugarcane responses accurately under these conditions (see Chapter 4). Poor crop growth and lower cane and sucrose yields were observed in the measured data and also simulated by the model. The DSSAT-Canegro model estimated much lower N uptake during the drought, representing the close link between water and N in the uptake of this nutrient. These data improve our confidence in the output of the model under extreme conditions and also emphasises the potential of the model to improve our understanding of N dynamics in sugarcane cropping systems. The accuracy of the model in simulating N responses shows its potential usefulness in assisting with the development of N fertilisation programmes.

Although the model was observed to be robust and sensitive to weather conditions, there was also a tendency for the model to exaggerate or over-estimate the impact of

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cold weather conditions on crop development in different scenarios. It is acknowledged that during low seasonal temperature conditions, the crop is expected to experience slower growth and biomass accumulation (Donaldson *et al*., 2008) (see Chapter 4). For the Pongola trial, the model appears to exaggerate the impact of low temperatures on sugarcane growth. This resulted in under-estimation of cane yield, yet aboveground N mass was still fairly well simulated. High soil water NO_3^- concentrations were observed in the beginning of the season due to soil disturbances while preparing the trial and that most likely resulted in high mineralisation and this is not simulated by the model (Chapter 5). As a result, soil water NO_3^- concentrations were more accurately simulated later in the season when the system had settled down.

For the Mount Edgecombe trial, similar cane yields observed across a range of different fertiliser N rate treatments has again indicated that sufficient N to meet crop demand resulting from mineralisation and previous N fertiliser applications may be present in the soil and should be accounted for when applying N fertiliser (see Chapter 5). Model calibration and testing requires reliable and consistent measured data. However, in this study, NO_3^- concentration data from the ceramic suction cups was not consistent and varied widely between replicates, resulting in challenges when comparing measured and simulated soil water NO_3^- concentrations. Nonetheless, the model simulated soil profile water content well which indicates its usefulness in improving the understanding of soil water N dynamics. This study has also shown that future modelling research work should focus more effort into considering spatial variability whenever simulating heterogeneous cropping systems. This can be done by finding ways of measuring and categorising spatial system characteristics in order to be incorporated and accounted for in the model.

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Nitrogen mineralisation is an important process which potentially makes considerable N available for crop uptake. When this mineralised N is accounted for in fertiliser programmes, considerable savings on N fertiliser costs can be made while also reducing susceptibility of N to losses such as leaching, denitrification and volatilisation. This will reduce environmental pollution. However, it is highly important to know N levels in the soil so that profit is not compromised. This is where quick tests such as those using suction cups and an NO_3^- reflectometer will be very useful in monitoring soil NO_3^- status. However, such tests should take into account all forms of inorganic N and not only a specific form as it is the case with the NO_3^- reflectometer. Therefore more reliable and accurate ways of measuring inorganic N levels in the soil should still be explored.

It is clear from this study that economic losses and environmental degradation resulting from injudicious management practices can be avoided if best management practices are identified and implemented in sugarcane cropping systems. Modelling has great potential in helping us to understand highly complex processes occurring in agro-ecosystems and to improve soil and crop management practices. It is recommended that whenever testing the performance of the model for simulating N dynamics and highly complex processes in this agro-ecosystem, sufficient and reliable measured data be available in order to judge the model adequately. This should be done as a result of the inconsistency of measured soil water NO_3^- concentrations observed in sugarcane cropping systems. It is further recommended that long term simulations, including adequate initialisation periods, be conducted to improve the reliability of the model and gain confidence in its output.

DSSAT-Canegro has now been tested extensively for South African sugarcane cropping systems and the model generally performed well in most cases. It is now recommended that DSSAT-Canegro be applied to improve our understanding of N dynamics in varying

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cropping systems and therefore help to guide management practices and future research.

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SUMMARY

Nitrogen is an essential nutrient required in large quantity by many crops and often represents a significant production cost in many cropping systems. Nitrogen also undergoes highly complex transformations in the soil-plant-atmosphere continuum which makes this nutrient difficult to manage. During these transformations N can be lost in many ways such as leaching, run-off, denitrification and volatilisation. This often results in environmental pollution and eutrophication of water bodies while profitability of farming is also reduced. Nitrogen losses will therefore have a devastating effect from both production and environmental perspective.

Sugarcane requires substantial amounts of N to produce high biomass and therefore achieve optimal yields. The complexity of N dynamics in sugarcane cropping systems requires better understanding with an effort to minimise N losses and mitigate environmental degradation. Mechanistic crop models are commonly being used to improve the understanding of highly complex processes including N dynamics in sugarcane cropping systems. However, these models first require extensive calibration, testing and validation with measured data in order to gain confidence in their performance. In this study, the DSSAT-Canegro model with a newly included N subroutine (Van der Laan *et al*., 2011), was first tested for its ability to simulate sugarcane growth relative to N dynamics in sugarcane cropping systems and thereafter the model was further used to explore opportunities of understanding N dynamics under different sugarcane environmental conditions

A historical dataset from a fertigation trial conducted in Komatipoort, Mpumalanga, was firstly used to assess the ability of DSSAT-Canegro to simulate cane and sucrose yields as well as aboveground N mass in response to different N rates over five consecutive

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seasons. The model performed well in simulating these aboveground variables for different seasons. Cane yield was most accurately simulated compared to sucrose yield especially for the final two ratoon crops and this reveals the importance of initialisation phase during simulation period. Aboveground N mass was also well simulated by the model, with similar trends being observed between measured and simulated data. This study has also revealed that soils that have been fallowed for a certain periods or have been converted from virgin land will have a considerable amount of N from mineralisation that occurred in the past seasons, and which will be available for crop uptake and should be accounted for in fertilisation programmes.

The model was further used to investigate sugarcane growth response to different N rates under rain-fed conditions in the Inanda and the Mount Edgecombe trials. For the Inanda trial, the model performed very well in simulating cane yield for both plant and ratoon crops. The key finding in this Inanda trial is that the model was robust enough to accurately simulate the impact of drought conditions on the plant crop whereby extremely low yields were encountered. The availability of mineralised N from the previous seasons was also observed to contribute to cane yields since there were no significant differences in yields where different N rates were applied. Although soil water NO_3^- concentrations were under-estimated by the model, similar trends were observed between simulated and measured data. For the Mount Edgecombe trial, similar cane yields observed across a range of different fertiliser N rate treatments has again indicated that sufficient N to meet crop demand resulting from mineralisation and previous N fertiliser applications may be present in the soil and should be accounted for when applying N fertiliser.

Under drip irrigated sugarcane in Pongola, the model appears to exaggerate the impact of low temperatures on sugarcane growth. This resulted in under-estimation of cane

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yield, yet aboveground N mass was still fairly well simulated. High soil water NO_3^- concentrations were observed in the beginning of the season due to soil disturbances while preparing the trial and that most likely resulted in high mineralisation and this is not simulated by the model. As a result, soil water NO_3^- concentrations were more accurately simulated later in the season when the system had settled down.

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ACKNOWLEDGEMENT

I would like to acknowledge the South African Sugarcane Research Institute, the South African Sugarcane Association and the National Research Foundation for the valuable support they provided for this research.

I thank my Co-supervisor, Dr Neil Miles for managing the Mount Edgecombe trial and making data available to us on time and for his massive support on Project 10CMO8 as a whole. I would also like to thank Dr Annette Weigel for making the Komatipoort trial data available to us and Mrs Ruth Rhodes for good collaboration on the Inanda and Pongola trials, and for providing additional data on these trials.

My gratitude also goes to Mr Matthew Jones who dedicated his time to help me overcome a number of challenges I encountered when using the DSSAT-Canegro model.

From the bottom of my heart I thank my supervisor, Dr Michael van der Laan, for his massive support and guidance throughout the entire duration of conducting this study. He played a major role in making sure that this overwhelming task of managing trials and writing a dissertation became an easy one. I also thank my co-supervisor, Prof John Annandale, who gave his time to do final check-ups to ensure that my work is of good quality.

I also thank my lady friend, Pinky, who gave me a phone call every morning to wake me up and do this important task of my dissertation. I thank her from the bottom of my heart. Finally, I would like to thank my family, my mother Disebo, and my sister Temate, for always being there for me, even in this huge study that I embarked on, they supported me every step of the way

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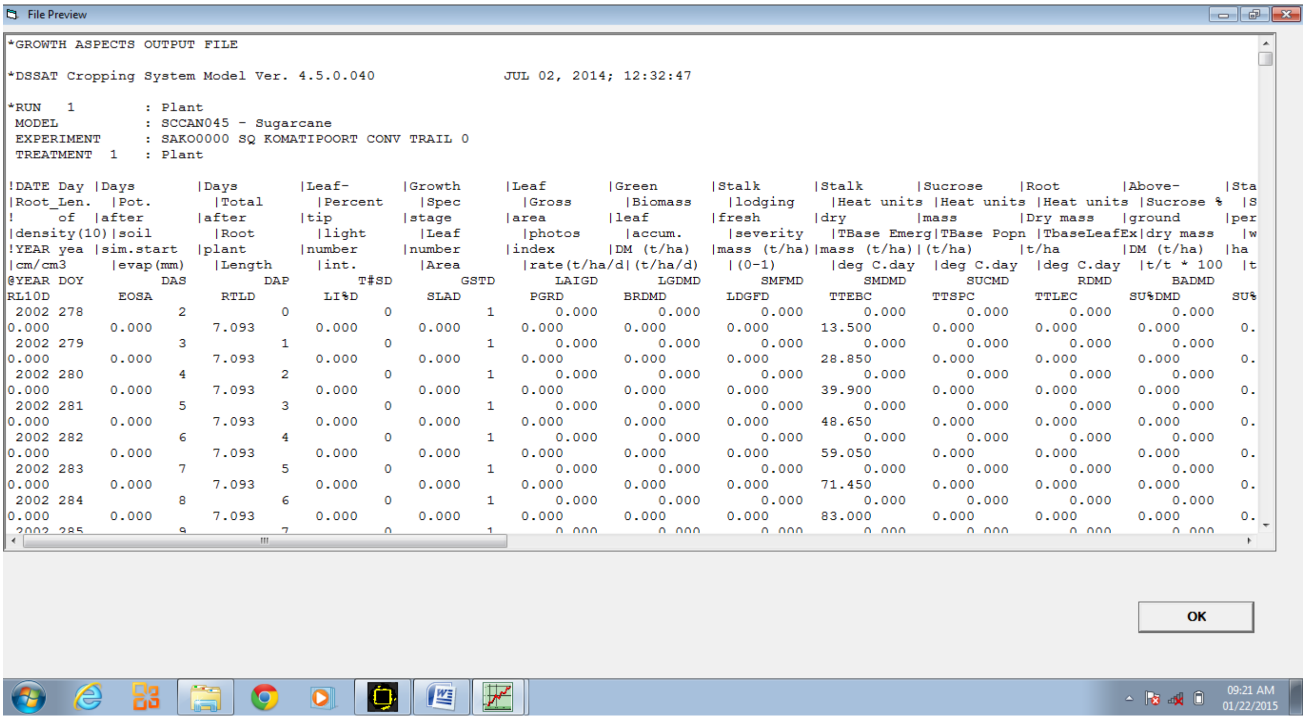
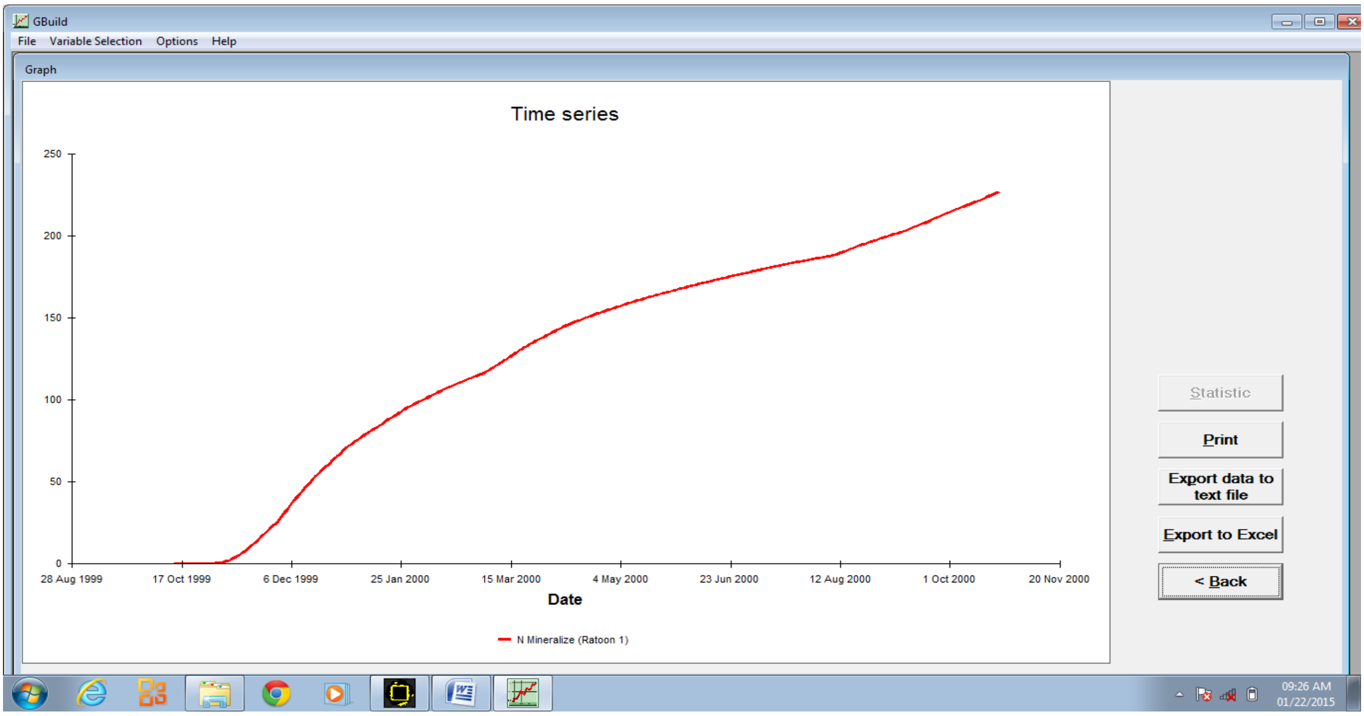
APPENDICES

Appendix A. DSSAT-Canegro Sugarcane growth simulations (A1), Cumulative N mineralisation (A2) interface screens and DSSAT interface (A3)

(A1)



(A2)



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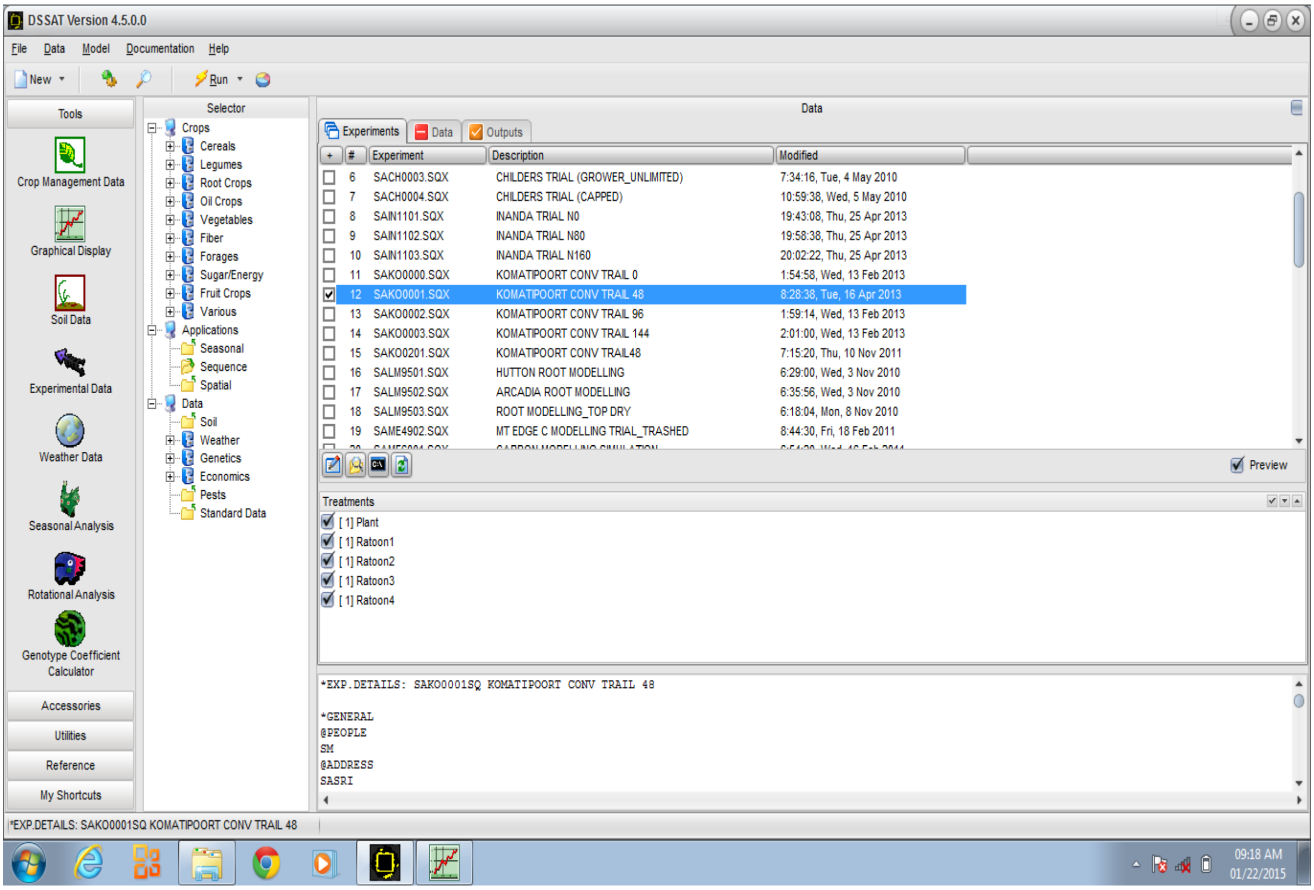
(A3)



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Appendix B. Statistical evaluation output for cane yield data for the Mount Edgecombe trial

GenStat Release 17.1 (PC/Windows 7) 08 December 2014 10:28:11
Copyright 2014, VSN International Ltd.
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GenStat Seventeenth Edition
GenStat Procedure Library Release PL25.1

```
   1  SET [WORKINGDIRECTORY='C:/Users/DubeE/Documents']
   2  "Data taken from file: 'E:/Mt Edg/Mt Edg.Yield.xlsx'"
   3  DELETE [REDEFINE=yes] _stitle_: TEXT _stitle_
   4  READ [PRINT=*; SETNVALUES=yes] _stitle_
   8  PRINT [IPRINT=*] _stitle_; JUST=left
```

Data imported from Excel file: E:\Mt Edg\Mt Edg.Yield.xlsx
on: 8-Dec-2014 10:28:41
taken from sheet "GENDAT", cells A2:C25

```
   9  DELETE [REDEFINE=yes] Treatment,Rep,Yield
  10  UNITS [NVALUES=*]
  11  FACTOR [MODIFY=no; NVALUES=24; LEVELS=6; LABELS=!t('N-Mng','N-
splt','N0',\
  12  'N150','N250','N75'); REFERENCE=1] Treatment
  13  READ Treatment; FREPRESENTATION=ordinal
```

Identifier	Values	Missing	Levels
Treatment	24	0	6

```
  15  FACTOR [MODIFY=no; NVALUES=24; LEVELS=4; LABELS=*; REFERENCE=1] Rep
  16  READ Rep; FREPRESENTATION=ordinal
```

Identifier	Values	Missing	Levels
Rep	24	0	4

```
  18  VARIATE [NVALUES=24] Yield
  19  READ Yield
```

Identifier	Minimum	Mean	Maximum	Values	Missing
Yield	66.38	97.75	121.2	24	0

```
  26
  27  %PostMessage 1129; 0; 100001 "Sheet Update Completed"
  28  "General Analysis of Variance"
  29  BLOCK Rep
  30  TREATMENTS Treatment
  31  COVARIATE "No Covariate"
  32  ANOVA [PRINT=aovtable,information,means,%cv; FACT=32; CONTRASTS=7;
PCONTRASTS=7; FPROB=yes;\
  33  PSE=diff,lsd; LSDLEVEL=5] Yield
```

Analysis of variance

Variate: Yield

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Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	2340.4	780.1	6.12	
Rep.*Units* stratum					
Treatment	5	666.4	133.3	1.05	0.427
Residual	15	1911.0	127.4		
Total	23	4917.9			

Message: the following units have large residuals.

Rep 3 *units* 1	-18.6	s.e.	8.9
Rep 4 *units* 1	20.1	s.e.	8.9

Tables of means

Variate: Yield

Grand mean 97.8

Treatment	N-Mng	N-splt	N0	N150	N250	N75
	99.7	93.1	100.5	106.5	90.3	96.4

Standard errors of differences of means

Table	Treatment
rep.	4
d.f.	15
s.e.d.	7.98

Least significant differences of means (5% level)

Table	Treatment
rep.	4
d.f.	15
l.s.d.	17.01

Stratum standard errors and coefficients of variation

Variate: Yield

Stratum	d.f.	s.e.	cv%
Rep	3	11.40	11.7
Rep.*Units*	15	11.29	11.5

```
  34         APLOT     [RMETHOD=simple]     fitted,normal,halfnormal,histogram
  35                    AGRAPH          [METHOD=means;          PSE=differences]
```


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Appendix C. Statistical evaluation output for aboveground N mass data for Mount Edgecombe trial

Analysis of variance

Variate: Biomass

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
Replicate stratum	3		15568.1	5189.4	10.68	
Replicate.*Units* stratum						
Treatment	5		4526.2	905.2	1.86	0.188
Residual	10	(5)	4857.9	485.8		
Total	18	(5)	20023.2			

Message: the following units have large residuals.

Replicate 2 *units* 3 31.5 s.e. 14.2

Tables of means

Variate: Biomass

Grand mean 184.2

Treatment	N-75	N-Mang	N-Split	N0	N150	N250
	160.7	187.5	203.7	179.8	177.9	195.5

Standard errors of differences of means

Table	Treatment
rep.	4
d.f.	10
s.e.d.	15.59

(Not adjusted for missing values)

Least significant differences of means (5% level)

Table	Treatment
rep.	4
d.f.	10
l.s.d.	34.73

(Not adjusted for missing values)

Stratum standard errors and coefficients of variation

Variate: Biomass

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Stratum	d.f.	s.e.	cv%
Replicate	3	29.41	16.0
Replicate.*Units*	10	22.04	12.0

Missing values

Variate: Biomass

Unit	estimate
3	209.9
4	144.4
5	148.8
18	220.8
21	175.6

Max. no. iterations 6

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