Modelling long-term carbon and nitrogen dynamics in maize (*Zea mays* L.) and sugarcane (*Saccharum officinarum* L.) cropping systems in South Africa

By

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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 ____________________
(Simphiwe Khulekani Maseko)

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ABSTRACT

Maize and sugarcane production has been threatened by declining soil quality due to long-term unsustainable management practices, which have increased the reliance on inorganic fertilization. This study reports on long-term yields and soil organic matter (SOM) trends and further evaluates nitrogen (N) leaching losses from maize and sugarcane as affected by inorganic fertilization and residue management practices. The study aims to investigate the effects of long-term management practices on maize and sugarcane monocropping systems in South Africa, through the application of long-term monitoring data and mechanistic modelling. Data from the University of Pretoria’s Hillcrest Campus Experimental Farm long-term maize trial and SASRI long-term sugarcane trial, in Mt Edgecombe were used. The APSIM model was calibrated and validated using long-term yield and SOM data, and the model was further used to estimate N leaching and evaluate management scenarios that can be used for more sustainable maize and sugarcane production. Although the model could be well calibrated for simulating maize growth for 2016/2017 season, long-term yields were not always accurately estimated. The results indicated a declining trend in maize yields and SOM over the years, with greater decline in the control treatment. APSIM estimated higher drainage in the maize control but higher N leaching in the fertilized NPK treatment. A manure application scenario proved to be more sustainable for long-term maize production, although it requires a good inorganic N fertilizer management programme to minimize N leaching losses. In sugarcane, observed and simulated results indicated that fertilizer application increased yields, and mulching was the best residue management practice for reducing SOM decline. The combination of fertilization and mulching produced higher long-term sugarcane yields and retained SOM content better, but it also led to the highest NO_3-N leaching. Modelling reduced fertilizer application did not result in a significant reduction in yield, indicating that mineralized N from SOM can be able to satisfy a proportion of crop N demand, so fertilizer application recommendations should also account for mineralized N to minimize N losses. This can be the best way of improving N management in sugarcane cropping systems, thus reducing inputs, increasing profits and minimizing losses that can lead to environmental pollution. Modelling has the potential of helping us understand the complex long-term C and N dynamics in cropping systems and identification of ways to improve management practices.

CHAPTER I

INTRODUCTION

The growing world population has necessitated high yields for agronomic crops and this has led to the exploration of crop management practices that can improve crop production. The major challenge faced by humanity this century is meeting the escalating food demands without compromising the quality of the supporting ecosystem (Postel 2000). Early in the 20th century, soil fertility was better-maintained using organic amendments, but since World War II, there has been an increase in the use of synthetic agro-chemicals in crop production often to the detriment of soil quality. Fertilizers, when used well, can increase soil productivity and produce high yields, but long-term sustainability and environmental impact must also be considered. Nitrogen (N) application as inorganic fertilizer represents a significant cost in crop production. Nitrogen is needed in large amounts to enable high biomass production and optimum yields. Long-term fertilizer use, however, has led to accelerated soil degradation and even a decline in yields in some cases (Calegari et al. 2013, Barker and Pilbeam 2015). Inorganic N stimulates plant growth when added in appropriate amounts, which usually has a positive effect on yield, but can also result in soil acidification through leaching of nitrate (NO_3^-) and associated base cations, and the addition of hydrogen ions (H^+) when N is added as ammonium (NH_4^+).

The soil forms an integral part of terrestrial ecosystems and plays a key role in providing important ecosystem services such as nutrient cycling, water storage and carbon (C) sequestration, which are also important factors in crop production. This has drawn attention towards the improvement of soil quality, which has a positive impact on crop production (Duval et al. 2013). Soil quality is the ability of a soil to perform to its potential in delivering ecosystem services that sustain life (Mills and Fey 2003). Maintaining crop productivity and soil quality at desirable levels involves climatic, soil, plant and human factors, with their myriad interactions making it a very complex process (Sharma et al. 2005). Soil quality indicators can be classified as physical, chemical and biological. This may include soil organic matter (SOM) content, microbial biomass, biological activities, soil pH, cation exchange capacity, salinity, bulk density and soil aggregation (Aziz et al. 2013). These properties are used as indicators because they are quick to respond to management practices.

Soil organic matter is a key soil component in agricultural production that is influenced by long-term management practices. The incorporation of plant residues into the soil or leaving them on the surface is followed by decomposition of the residues, which is a biological process where organic molecules are physically and chemically transformed to simpler organic and inorganic molecules (Cates et al. 2016). According to Dominy et al. (2002), the key factor contributing to agriculturally induced soil degradation is the loss of SOM. The main drivers that influence SOM content include tillage practices, removal of crop residues, with other factors such as temperature, soil water content and microbial populations and their activity also contributing but to a less direct extent.

Burning of crop residues prior to harvest has been commonly practiced in sugarcane production (Vallis et al. 1996, Galdos et al. 2009). This releases greenhouse gases into the environment as well as reducing the organic residues and nutrients returned to the soil, which would otherwise have improved soil quality (Galdos et al. 2009). Singh et al (2005) noted that burning crop residues can provide some short-term N supply benefits to the next crop, but it generally has a negative impact on long-term N supply and soil quality. This is because a large amount of C and N is lost to the atmosphere during burning with only small amounts added to the soil with the ash. A beneficial practice that helps retain SOM in sugarcane is green cane harvesting and mulching (Graham et al. 2002). This practice also helps improve soil water conservation, reduces erosion, increases soil fertility, yields, and improves soil structure (Vallis et al. 1996). Adopting management practices such as conservation agriculture and manure application has been highly recommended due to their positive contributions to C sequestration, although the change in C storage capacity can be highly dependent on soil type and climate (Lal 2015). Good soil management is an important factor that determines ecosystem functioning and high agricultural productivity (Mills and Fey 2003), and a thorough understanding of soil ecosystem processes is important in improving management practices as well as soil conservation methods that will help sustain future soil productivity (Morgan et al. 2005).

1.1 Problem statement

The escalating demand for agricultural produce and diminishing arable land due to an increasing population serves as a motivation for farmers to maximise crop production per unit area available. This has led to the adoption of practices that could potentially maximise production such as inorganic fertilization and crop residue burning, but such practices can have detrimental environmental effects. Application of inorganic fertilizer, especially NPK, is vital for sustaining high maize and sugarcane yields. In the long-term, however, this may result in a wide range of soil quality impacts. Nitrogen fertilization, especially if applied at rates above crop demand, may result in soil acidification and non-point source nutrient pollution and eutrophication of water bodies, whilst too little N may result in significant yield losses. Burning crop residues can lead to SOM decline, and the consequent release of greenhouse gases may have long-term effects in terms of climate change and air pollution. This creates the need for long-term assessment of management practices, including the application of mechanistic crop modelling, to help provide information on sustainability of different management practices and where improvements can be made.

1.2 Aim

This study aims to investigate the effects of long-term management practices, including inorganic fertilization and residue burning versus mulching, on intensive monocrop maize and sugarcane production systems in South Africa, through the application of long-term monitoring data together with mechanistic modelling. This can provide information that can be applied for sustainable maize and sugarcane production. The long-term maize trial in Pretoria and sugarcane trial in Durban both started in 1939, offering a unique opportunity to carry out a comparative study on the effects the different management practices on the C and N dynamics for two different soils in different climates.

1.3 Objectives

i. To conduct a growth analysis and calculate the soil water balance for a maize crop grown at the University of Pretoria’s long-term trial to generate crop and soil data for APSIM model calibration.

ii. To utilize historical weather, soil and yield data in order to calibrate and validate the APSIM model for the long-term maize and sugarcane trials.

iii. To apply long-term data and modelling outputs to assess the impacts of full and zero NPK fertilization on maize yields and soil C and N dynamics

iv. To apply long-term data and modelling outputs to assess the impacts of burning and mulching, zero and full NPK fertilization on sugarcane yields and soil C and n dynamics.

v. To explore the potential contribution of certain management practices on improving the long-term sustainability of maize and sugarcane cropping systems in South Africa.

1.4 Hypotheses

1. The APSIM model can be effectively calibrated and validated for the University of Pretoria, Hillcrest Campus Experimental Farm long-term maize trial, and the long-term sugarcane trial (BT1) at South African Sugar Research Institute (SASRI), Mt Edgecombe.
2. Continuous crop cultivation results in reductions in SOM levels and these reductions occur faster for treatments receiving no inorganic fertilizer compared to treatments receiving NPK fertilizer.
3. Application of inorganic N fertilizer leads to higher NO_3^- leaching than in treatments receiving zero N, despite higher plant N uptake in fertilized treatments.
4. Burning and removal of sugarcane residues reduce SOM levels faster than when residues are retained on the soil surface.
5. The cultivation of sugarcane still leads to a decline in SOM levels in SASRI's BT1 trial even where residues are retained after harvest.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

The soil is the largest terrestrial carbon (C) reservoir and stores more C than the atmosphere and vegetation combined (Schlesinger and Bernhardt 2013). Soil C mostly exists in soil organic matter (SOM), which is a complex mixture of organic materials, including plant stems, leaves and roots that are at different stages of decomposition. This makes the soil an important component of the C cycle (Aziz et al. 2013). The fertility status of the soil is closely linked to SOM status, which depends on various factors including climate, biomass residue inputs and management, mineralization and immobilization of C and nitrogen (N), as well as erosion (Guimarães et al. 2013). Soil organic matter cycling consists of four fundamental processes and is mainly facilitated by the availability and activity of micro-organisms in the soil. These processes are decomposition of residues, nutrient mineralization/immobilization, transfer of organic C and nutrients from one pool to another, and the continuous release of carbon dioxide (CO_2) through chemical oxidation and microbial respiration (Brady and Weil 2000, Bationo et al. 2007).

The conversion of natural land to agriculture has had major influences on soil C (West and Post 2002, Ogle et al. 2005, Pardo et al. 2012). These changes depend on the type of native ecosystem being altered and the management practices used (Beza and Assen 2016). Continuous soil cultivation with limited SOM addition can lead to a disintegration of soil aggregates that can lead to soil erosion (Blair 2000). Soil C changes following land conversion to agriculture have been commonly evaluated by a comparison of a cultivated, and adjacent uncultivated sites (Ogle et al. 2005, Swanepoel et al. 2016). A review of SOC changes on cultivated soils in southern Africa reported a 25 – 53% SOC decline in different precipitation zones (Swanepoel et al. 2016). It has been reported that the rate of soil C losses from cultivated land are initially very high but decrease until a new equilibrium is reached with increasing duration of cultivation (Beza and Assen 2016).

2.2 Carbon dynamics in maize and sugarcane cropping systems

Soil cultivation is a commonly used tillage practice that buries crop residues, weeds and breaks soil crumbs to finer particles, allowing easy penetration of air, moisture and plant roots (Kayombo and Lal 1993). Recent studies have highlighted the importance of minimum tillage or conservation agriculture (CA) in increasing soil quality and reduce input costs (Lal 2015, Blanco-Moure et al. 2016, Swanepoel et al. 2018). According to Aziz et al. (2013), tillage has a great influence on microbial biomass at different soil depths, and there was a significant increase in SOM levels and improved soil physical properties under no-tillage when compared to conventional tillage. A medium-term (six years) CA maize monoculture trial in South Africa showed a SOC increase in treatments under reduced tillage compared to conventional tillage in clay soils (Swanepoel et al. 2018). Minimal soil disturbance led to the accumulation of crop residues near the surface which slows down the rate of organic matter decomposition and loss when compared to conventional tillage (Loke et al. 2012). Some key management practices influencing long-term SOM content in field crops are discussed below.

2.2.1 Effect of retaining crop residues on soil carbon levels

Crop residues are added to the soil as stalks, roots and leaves after senescence when they detach from the plant and fall on the soil surface. They can be incorporated into the soil during tillage potentially increasing soil C or can be lost through burning or removal from the field (Thorburn et al. 2005). Retaining residues can improve soil water conservation by reducing evaporation and erosion, improving soil structure, increasing SOM and soil fertility through improved nutrient cycling (Vallis et al. 1996). The maintenance of suitable SOM levels in the soil depends on the supply/input and mineralization residues in the soil. The removal of residues can be to the detriment of nutrient cycling and affects the sustainability of agricultural systems, making it necessary to replace the nutrients exported through this practice. Increasing organic residue inputs and minimizing soil disturbance will decrease the rate of SOM loss (Loke et al. 2012). Thorburn et al. (2012) studied changes in SOC fractions and soil fertility in response to sugarcane residue retention over time. Though the magnitude of the SOM changes were site-specific, generally there was an increase in SOC when residues were retained. The SOC increase and nutrient retention abilities of the soil was not consistent between sites, and changes between SOC between soil layers was reported to only be apparent after at least five years.

In addition to C, crop residues contain certain amounts of N as well as other nutrients. When recycled in agroecosystems, these can offer a sustainable natural alternative to providing nutrients in the form of synthetic fertilizers. Organic matter also contributes to the cation exchange capacity necessary for increased nutrient availability in the soil. According to Butterly et al. (2013), SOM increases the soils buffering capacity, which is the ability of the soil to resist changes such as in pH. Sapkota (2012) reported that the efficiency of inputs added to the soil by plants increases with an increase in the SOM content, which reduces the fertilizer requirements of crops.

Soil organic matter can improve the physical properties of the soil by enhancing aggregate stability, and increasing aeration and infiltration (reducing runoff), all of which are key in achieving good crop yields (Mills and Fey 2003). According to Van Antwerpen et al. (2001), sugarcane yield data assessment showed a positive response in dry seasons on retained residues treatments. Higher nutrient retention and reduced erosion will also lead to less non-point source pollution, reducing the off-site impacts of crop production.

2.2.2 Effect of residue burning and removal on soil carbon levels

Residue burning and removal is more commonly used practice in sugarcane than in maize production in South Africa. Sugarcane harvesting is done using either manual or mechanical harvesting. In mechanical harvesting, the harvesters are used to cut sugarcane at ground level. In South Africa, about 90% of sugarcane is harvested manually due to high costs associated with mechanical harvest and steep slopes, and burning prior to harvest becomes necessary as the leaf material slows down cane cutters (Van Antwerpen et al. 2001, MI et al. 2006). Burning crop residues leads to reduced returns of SOM to the soil, with over 70% of N and dry matter as well as low quantities of other nutrients being lost from the system under this management practice (Blair 2000, Van Antwerpen et al. 2001). Retaining crop residues and the increases soil C sequestration, thus reduces atmospheric carbon dioxide (CO_2) concentrations that are a strong driver of climate change (Thorburn et al. 2012).

2.2.3 Inorganic nitrogen fertilization

Modern agriculture is often characterized by intensive farming methods that rely on high fertilizer inputs to sustain productivity. Nutrients can be applied routinely as inorganic fertilizers containing mainly N, P and K or combinations of these nutrients in conventional crop production to maintain or improve yields. Fertilizers can be defined as natural or synthetic, organic or inorganic materials that can be added to the soil to increase the availability of elements essential for plant growth (Soil Conservation Society of America, 1982).

The main purpose of inorganic fertilization is enhancing crop production by increasing soil fertility in one of two ways, firstly through directl nutrient availability to crops, thus increasing biomass production leading to an increase in organic matter returns to the soil. This improves soil physical properties such as porosity, infiltration, and hydraulic conductivity and decreases bulk density (Haynes and Naidu 1998). Secondly, indirectly increasing soil fertility through better nutrient cycling. The fertilizers can influence the chemical composition of the soil solution, which affects nutrient cycling by controlling soil microbial population and their activities.

A plethora of studies have been done on the influence of fertilization and residue retention on different aspects of crop production and soil quality. For example, in an experiment with barley (*Hordeum vulgare* L.) in Hoosfield, England, Haynes and Naidu (1998) reported that fertilized plots had 15% higher SOM content than unfertilized treatments. A strong linear correlation between annual fertilizer applied and accumulation of SOM was also observed in the long-term continuous wheat experiment in Rothamsted, England (Edwards and Lofty 1982). Kaur et al. (2008) reported that long-term use of inorganic fertilizers can significantly affect the distribution of SOC, noting that NPK fertilizer use is beneficial in maintaining the active C and N pools in the top layers of the soil surface (0 – 15 cm depth), which helps to maintain the C associated nutrients in the rhizosphere thereby increasing nutrient availability. Nel et al. (1996) also reported a higher SOM depletion in unfertilized and imbalanced treatments (NP, NK, PK) than those fertilized with NPK after 50 years in the University of Pretoria long-term maize trial in South Africa. In the same trial, Belay et al (2002a) later reported increases in soil microbial biomass C of greater than 75% on fertilized treatments over the control (zero fertilizer).

2.3 Nitrogen dynamics in maize and sugarcane cropping systems

Nitrogen is a nutrient that is of high demand for plant growth, but it requires careful management as it is susceptible to various losses in the soil and can cause different types of air and water pollution. In soils, N can be available in four major forms, which are (i) part of organic matter (plant materials, humus etc.); (ii) part of soil organisms and microorganisms; (iii) as ammonium (NH_4^+) ions adsorbed to organic matter and clay minerals; (iv) as mineral-N in soil solution, which includes nitrate (NO_3^-), nitrite (NO_2^-) and NH_4^+ (Cameron et al. 2013). Nitrogen availability is not only determined by the soil physical and chemical environment, but is also influenced by the role of soil microbes involved in N cycling.

The availability of N in crop residues is complex as most N cycling goes through SOM. Soil cultivation can negatively influence the soil organic nitrogen availability in the soil by increasing aeration, drainage and exposing organic materials to soil micro-organisms (Swanepoel et al. 2016). This can lead to a decline of total soil N content to a new equilibrium level and an overall loss in soil fertility. For example, Du Preez et al. (2011) reported average N losses caused by cultivation in the Free State province, South Africa, to be 55% in the 0 – 15 cm layer, 17% in the 15 – 50 cm layer and 6% in the 50 – 100 cm layer, by comparing cultivated and uncultivated soils. This decline can be influenced by various factors including, for example, climate as it was reported to be quicker in dry warm areas than in cool wet areas (Dominy and Haynes 2002). The quantity and pathways in which N is lost in agricultural systems are highly variable because it is determined by the conditions of a certain period of time. Nitrogen can undergo a series of transformations in the soil, which are influenced by environmental and management practices (Figure 2.1). These transformations are discussed below.

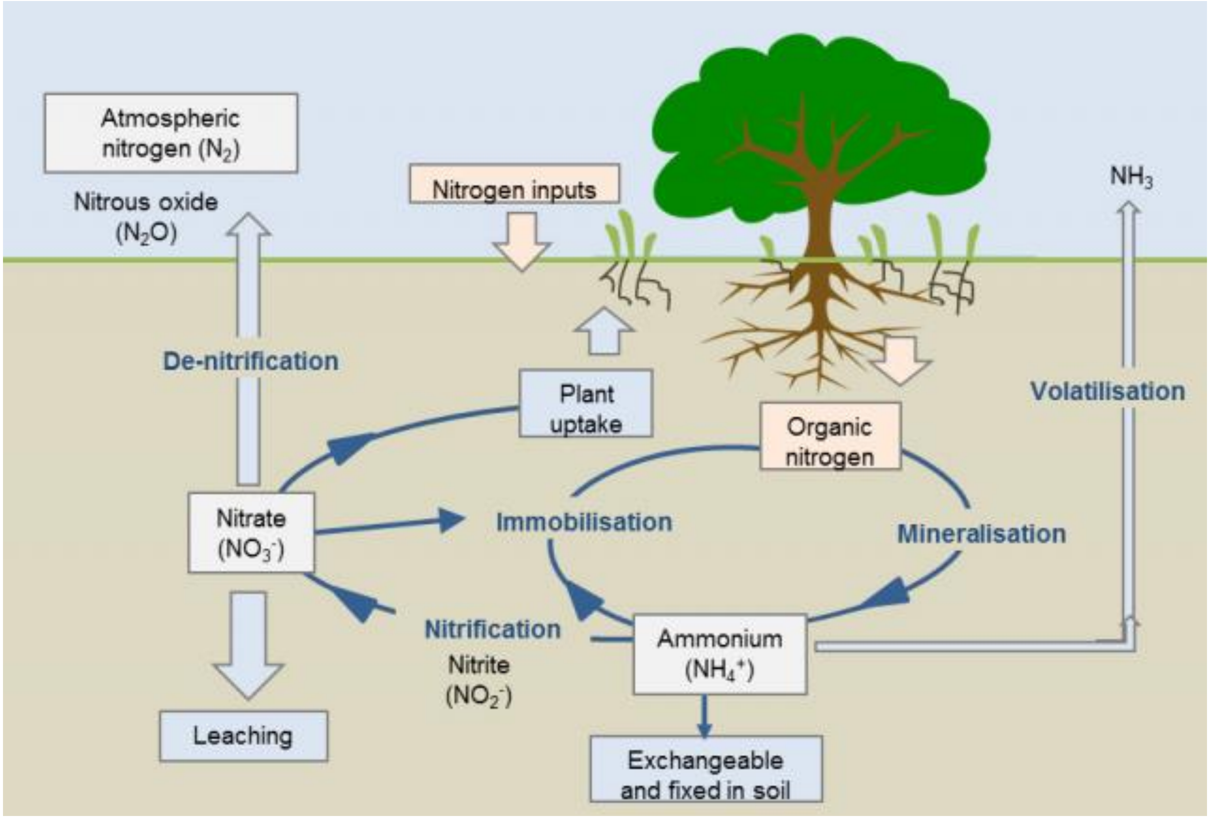


Figure 2.1 Possible nitrogen transformation pathways in cropping systems (https://www.agric.wa.gov.au/soil-carbon/immobilisation-soil-nitrogen-heavy-stubble-loads)

2.3.1 Mineralization and immobilization

Mineralization of N is the conversion of organic N to the inorganic form rendering it available for plant uptake. Organic N is converted to NH_4^+ through ammonification, and can then be converted to NO_2^- and then NO_3^- by nitrifying bacteria through nitrification. Immobilization is the conversion of N from the inorganic form (NH_4^+ and NO_3^-) to organic form making the N unavailable for plant uptake. These processes are driven by soil microbes and are influenced by factors that affect microbial activity including temperature, moisture, pH, availability of other nutrients.

Soil micro-organisms need C as a source of energy and N for the synthesis of body tissues and must obtain both C and N from organic materials or the soil (Dikgwatlhe et al. 2014). Residues with high C:N ratio (greater than 20:1) promote immobilization of N, due to high C for the micro-organisms to consume, and residues with low C:N ratio (less than 12:1) promotes net mineralization of N. High C:N ratio increases heterotrophic organisms as a result of high C to consume, but the loss of C during respiration from micro-organisms decreases the C:N ratio of residues over time, slowing down microbial activities, which then leads to N mineralization in the soil.

Maintaining a balance between mineralization and immobilization is important in crop production. Immobilization of N can prevent the loss of NO_3^- from the soil and reduce the risk of groundwater contamination. Immobilized N can be mineralized at a later stage and be available for plant uptake. Excessive immobilization can trigger N competition between plants and micro-organisms leading to N deficiency in plants, on the other hand, excessive mineralization can result in N loss from the soil (Ladha et al. 2005). Soil disturbance, such as tillage, exposes occluded SOM to microbes, oxygen (O_2) and water, which results in increased mineralization rates.

2.3.2 Denitrification and volatilization

Denitrification is a chemical reaction that converts NO_3^- to NO_2^-, and then to nitrous oxide (N_2O), nitric oxides (NO) and/or dinitrogen gas (N_2) which are lost to the atmosphere. This is common in a saturated soil as the soil micro-organisms use NO_3^- and NO_2^- as electron acceptors in the absence of oxygen (Cameron et al. 2013). This makes soil water and aeration the most important factors influencing denitrification, though it can also be influenced by soil pH as it depends on microbial activity (denitrifying bacteria). In contrast, volatilization occurs when N is lost through the conversion of NH_4^+ to ammonia gas (NH_3), which is then released to the atmosphere. This process is mostly controlled by temperature, soil pH, water status and NH_4^+ levels.

These processes can contribute to considerable N losses from the soil and can result in low nitrogen use efficiency (NUE) in cropping systems, with plants unable to take up N to full potential. Loss of N through volatilization is also undesirable due to its potential threats to the environment. Volatilized NH_3 can be returned to the surface with rainwater (wet deposition) or attached to particulate matter (dry deposition) contributing to terrestrial and aquatic acidification and eutrophication (Cameron et al. 2013). According to Sommer et al. (2004), agricultural practices contribute about 50% of volatilized NH_3. The sources of NH_3 volatilization are the application of N fertilizers such as urea, application of animal waste, and also through the mineralization of SOM and plant residues (Sommer et al. 2004).

2.3.3 Leaching losses

Leaching has been singled out as the primary loss of large amounts of N in the form of NO_3^- in cropping systems by many studies (Gheysari et al. 2009, van der Laan et al. 2010, Thorburn et al. 2011). The leaching of NO_3^- out of the root zone to groundwater is one of the major negative impacts of agriculture on the environment (Van der Laan et al. 2014). Nitrates are usually present in higher quantities than NH_4^+ in most soils and are more susceptible to leaching as they are anions and not adsorbed in soils with high cation exchange capacity, and this makes them more susceptible to leaching when carried with percolating water below the root zone. Nitrate leaching is the most likely N loss pathway of irrigated cropping systems in arid and semi-arid regions due to rainfall (Cameron et al. 2013). Nitrogen can also be lost in the form of soluble NH_4^+, especially in soils with high anion exchange capacity, which results in higher sorption of NO_3^- rather than NH_4^+.

Quantifying N and water interaction and its effect on NO_3^- leaching can be an important insight for effective N and water management. Different methods have been used to measure NO_3^- leaching, but none of the techniques have been suitable for all situations. These techniques include routine soil sampling, active and passive samplers, drainage lysimeters and field scale drainage facilities (Goulding et al. 2000). Nitrate leaching is highly related to N application and the volume of drainage water moving out of the root zone. It is especially linked to a history of applying fertilizer N in excess of crop demand. It can be promoted by periods of crop absence such as in winter if a heavy rainfall event occurs, where there are no crops planted that will take up mineralized N causing it to be lost with percolating water.

2.3.4 Crop nitrogen uptake

Crop N uptake is important in reducing N loses and helps to increase the NUE of crops. Nitrogen uptake can largely depend on crop stage, seasonal effects, soil water content and the availability and uptake of other nutrients. Nitrogen application coinciding with when the crop is most actively taking up N can maximize the efficiency of N use (Weih 2014). Increased NUE through optimal plant N uptake can play a role in preserving the environment as this can reduce the amount of N that needs to be applied and improve sustainable agricultural production. Luxury N uptake can sometimes negatively affect crop production. Increasing N application has been reported to lower NUEs as a result of luxury N uptake where biomass increase is not proportional to N uptake, lowering the biomass produced per unit N uptake (Allison and Pammenter 2002). In sugarcane, however, maturation can be delayed if there is excess N uptake and sucrose content reduced at harvest as a result (Thorburn et al. 2005). Most N is taken up in the initial stages of crop development in sugarcane than in later stages where less quantities taken up. According to Meyer et al. (2007), low NUEs in sugarcane production have been estimated to contribute to 65% loss of applied N through various pathways, and only about 35% taken up by the crops.

2.4 Modelling carbon and nitrogen dynamics in maize and sugarcane cropping systems

2.4.1 Crop modelling overview

Crop simulation models represent the product of interactions between the plants and the environment, and sometimes the reactions that occur within the plant using mathematical equations. They have been widely accepted worldwide as an important tool for agricultural research and management purposes (Singels and Bezuidenhout 2002). The interaction between the crop and its environment is often difficult to understand due to the complexity of agricultural systems, this makes crop models important tools for predicting and understanding the overall agroecosystem performance for specific processes. According to Akponikpè et al. (2010), the sustainability of agricultural production can be evaluated using outputs of crop growth models in relation to weather, soil conditions, and management practices. Agricultural models can help explore and develop sustainable land management practices in diverse agro-ecological and socio-economic conditions. Research efficiency can be increased by models through their ability to analyze system performance at different locations and for varying season lengths and unpredictable climatic conditions (Keating et al. 1999). Model development and application can be used as research tools to contribute to identifying knowledge gaps, which can help in more efficient and targeted research planning. Models can help in screening potential risk areas that may be identified for more detailed field studies to be carried out. Application of crop models is increasing worldwide in exploring options and solutions for food security, climate change adaptation and mitigation, as well as sustainable production systems (Holzworth et al. 2014).

2.4.2 APSIM model overview

Agricultural Production Systems sIMulator (APSIM) model was developed by the Agricultural Production Systems Research Unit (APSRU) in Australia. It is a modular framework made up of a set of biophysical modules which simulates physical and biological processes in farming systems, a set of management modules that allow certain management rules to be specified by the user which characterize a scenario being simulated and control the conduct of the simulation (Carberry et al. 1996). The model describes crop growth, soil water, soil N soil C and residue dynamics as a function of climate, cropping history and soil management. It allows individual modules of key components of the farming system to be plugged in and out (Keating et al. 2003, Holzworth et al. 2014). In other crop growth models, the crop takes the central position, in APSIM the soil state changes in response to climate and management, making soil take a central position.

APSIM-Maize

The maize modules in APSIM were developed through a combination of algorithms from the CERES-MAIZE modules, namely ‘CM-KEN’ (Keating et al. 1992) and ‘CM-SAT’ (Carberry and Abrecht 1991) originally developed for different maize cultivars. It simulates growth on a daily time step, as maize responds to soil water, soil N, and weather conditions (Keating et al. 2003). Maize has 11 growth stages with nine phases (time between growth stages), and the commencement of each stage is determined by thermal time (except sowing to emergence which is determined by soil moisture). For each day thermal time is calculated by phenology routines (in degree days) from interpolating hourly air temperature estimates from the daily minimum and maximum temperatures. Leaf area is estimated through consideration of canopy development, which is driven by temperature, and the final estimate leaf area index (LAI) increment also depending on water, N and C availability. Biomass accumulation is estimated from the minimum of two potential biomass increment values, one determined by light (RUE) and the other determined by soil water availability. This estimated accumulation can be adjusted to account for the effects of temperature, N, and soil moisture on canopy photosynthesis. Dry matter partitioning to different plant parts is dependant on crop stage. From emergence to flowering, C and N allocation priority is towards leaf development, and from flowering to physiological maturity priority goes to the grains (Archontoulis et al. 2014).

APSIM-Sugarcane

The APSIM-Sugarcane module also simulates the growth of sugarcane in relation to climate, soil water and soil N (Keating et al. 1999). The model uses a daily time step to estimate cane yield, sucrose yield, commercial sucrose concentration, plant biomass, water use, crop N uptake and partitioning to different plant parts (Keating et al. 1999). Dry matter accumulation is driven by RUE. Intercepted radiation is used to produce assimilates which are partitioned to different plant parts including leaf, stalk, roots, and sucrose as determined by crop stage. The leaf canopy expansion is estimated as a function of time and temperature, and its growth increases leaf area index (LAI). These processes respond to temperature, radiation, moisture and N supply in the soil (Thorburn et al. 2002). Extreme temperatures, low soil moisture or soil N can limit canopy development and photosynthesis, which reduces RUE of the crop. The sugarcane module estimates N uptake from the soil as well as crop water use, via exchanges with relevant APSIM soil modules that track the status of these variables. Other factors like aging, light competition and moisture stress can result in leaf senescence, which, together with non-millable stalk and leaf sheaths, are maintained as thrash in the model. This later detaches from the plant and become surface residue in the 'SurfaceOM' module. Specific aspects of sugarcane management such as ratooning and thrash management are simulated by the APSIM-Sugarcane module.

Soil water module

The soil module simulates the processes that take place in the soil profile, including water movement and infiltration, evaporation, runoff, drainage, temperature variations, nutrient cycling and solute movement (Keating et al. 2003, Holzworth et al. 2014). APSIM has two possible modelling approaches for the soil water balance and solute movement. These are the cascading soil water balance and Richard's equation approach (Keating et al. 2003). The cascading approach is called SOILWAT, operates on a daily time step, and water movement is characterized by movement from saturated to unsaturated soil layers. The soil is characterized in terms of soil water content at the drained upper limit (DUL), lower limit (LL-15), and saturation (SAT). Water movement can be upward or downward between layers depending on soil water potential. Distribution of soil solutes, such as N, are also carried out in SOILWAT, and its movement with water between layers is influenced by a user-specified efficiency factor. According to Probert et al. (1998), most processes in SOILWAT were adopted from the PERFECT model. This includes the ability of the module to modify surface runoff and potential soil evaporation with respect to surface residues and crop cover. Soil evaporation is described by the first stage and second stage evaporation, with small rainfall events lost through first stage evaporation, and second stage evaporation being the slower process that provides more flexibility in describing long-term soil water changes with response to soil characteristics and environmental effects. Soil water conductivity (SWCON) is specified for each layer and it determines the amount of water above DUL which drains to an adjacent soil layer in one day. This module is interfaced with the 'Residue' and crop modules to enable the simulation of soil water balance in response to changes in surface residue and crop cover.

Residue module

The Residue module deals with residue cover and tillage incorporation, as well as surface residue decomposition, and transfers of C and N from residues to the soil (Probert et al. 1998). All above-ground material is classified as residue and can be burnt or incorporated into the soil as fresh organic matter (FOM). When new residues are added, new values are calculated to describe the total available mass of residues present and C:N ratios. Residue on the soil surface has the ability to influence soil hydrological and N cycles, so it is essential that crop models accurately predict the decomposition of crop residues. The decomposition of residues is controlled by, among other factors, a crop specific decomposition rate and soil contact fraction factor of the residues. The crop-specific decomposition rate can be influenced by residue C:N ratio, temperature and soil moisture. Nitrogen concentrations in the plant material control the residue C:N ratio when they are transferred to the SurfaceOM module (Thorburn et al. 2011).

Soil nitrogen module

The soil nitrogen module (Soil-N) simulates the N supply from previous crops' residues available to a crop, which the model does by simulating the mineralization of N in the soil (Probert et al. 1998). It describes SOM dynamics in terms of soil C and N flow. Soil organic matter exists in three different pools in the soil-N module. These pools are fast decomposing (BIOM), an intermediate (HUM), and a stable pool (INERT). Fresh organic matter from roots and residues from the previous crop that has recently been incorporated by tillage forms a separate pool (FOM) (Keating et al. 2003). In APSIM, the soil N module simulates processes which include mineralization, immobilization, denitrification and urea hydrolysis. The reason for APSIM to have three different pools is that a weakness of treating all organic matter to be equally susceptible to mineralization gave unrealistic mineralization rates in CERES model, which made long-term SOM simulations inaccurate (Keating et al. 2003). The INERT pool is stable and not susceptible to decomposition and this prevents the decomposition of SOM in deeper layers in APSIM.

2.4.3 Significance of long-term trials in agricultural research

Long-term trials can play an important role in identifying economically and environmentally sustainable management practices to counter the increasing production costs and environmental concerns of current practices. Keeping these trials available and functioning effectively can serve as a scientific heritage for generations and be the basis important studies in the near future. This study indicated that modelling has the potential of helping to understand the complex C and N dynamics in agricultural systems. The long-term datasets generated from these trials can be important in developing these mathematical models which can be used to evaluate a range of management practices on yields and productive capacity of soils for South African maize and sugarcane cropping systems. It can be recommended that when testing the model performance, enough reliable measured data is available. This can be done if the historical dataset available on these experiments are of good quality, which can be highly recommended especially in the maize trial. This can include reliable and consistent data collection of yields, amount of crop residues and seasonal soil samples being taken and archived for future reference.

The relevance of these trials can sometimes come under question due to pressures of possible shortage of maintenance funds. To compensate for the costs of maintaining these trials, it is important to develop new avenues of research that will justify the continuation of these trials. The long-term sugarcane trial has been extensively studied in the past, but not the same can be said about the maize and wheat trials at the University of Pretoria. More studies should be conducted on these trials, as the value of such trials can potentially increase with time if they are serving more than one objective. These objectives can be archived if the trials are actively managed, carefully modified over time to examine factors affecting food security, by considering possible consequences without altering their initial objectives.

2.4.4 Use of APSIM model in simulating long-term carbon and nitrogen dynamics

The complex interaction of the natural environment and agricultural practices hinders the ability to predict C and N changes over a certain period. Modelling cropping systems give us the opportunity to explore the interaction between climate, soil and crop management practices and their effect on C and N dynamics in cropping systems. The APSIM model, together with other crop models, have been widely used to simulate long-term C and N dynamics. The amount of N leaching out of the root zone has been difficult to measure directly, and this problem can be solved using crop models. These models can provide insights on the causes and evaluating management practices to reduce the problem, however, these exercises have proven to require precise model parameterization and initialization information for credible predictions (Thorburn et al. 2005, Van der Laan et al. 2014). The APSIM model does provide the functionality required to estimate soil C and N changes as affected by management practices and the environment.

The APSIM model was reported to be able to reasonably simulate the soil C dynamics in cropping systems (Luo et al. 2011). The simulation of soil C, however, can come with some uncertainties that need to be addressed when interpreting results. Soil C decline is expected to be rapid after land conversion to agriculture (Ogle et al. 2005, Luo et al. 2010, Swanepoel et al. 2016), but after some time an equilibrium steady state expected to be reached. According to Luo et al (2011), in APSIM, tillage incorporates organic matter into the soil and the decomposition of soil C can be underestimated after tillage as a result of the changes on the soil environment that comes with tillage possibly accelerating decomposition. In a simulation of long-term C dynamics in wheat using APSIM, a scenario on soil C changes in the top 0.3 m of the soil profile indicated that soil C has still not reached an equilibrium after 120 years of simulation (Luo et al 2011).

A decline in SOC with time also resulted to a decline in soil N fertility in a long-term sugarcane simulation, and this decline was affected by residue management and fertilizer N application (Thorburn et al. 2002). Nitrogen fertilizer application can increase biomass production thus increasing crop residue returns in cropping systems that retain residues. These residues can act as soil N sinks through net immobilization of N during SOM decomposition, thus reducing the amount of N susceptible to leaching. The difficulties to quantify mineralization and immobilization processes in terms of the carbon-nitrogen interactions makes it difficult to simultaneously optimise the C and N dynamics in cropping systems (Luo et al. 2014). Simulations by the APSIM model indicated higher N leaching in rainfed than irrigated treatments in sugarcane as a result of low N use if rainfed crops enabling excess N to be susceptible to leaching in a high rainfall event (Thorburn et al. 2005).

CHAPTER III

MAIZE GROWTH ANALYSIS AND SOIL WATER BALANCE MONITORING FOR PARAMETERISATION OF THE APSIM MODEL

3.1 INTRODUCTION

Maize (*Zea mays L.*) is a cereal crop that is widely grown in a range of agro-ecological environments throughout the world. It is a staple food for more than 1.2 billion people in sub-Saharan Africa and Latin America. It is the most important grain crop in South Africa, produced throughout the country (Du Plessis 2003). Maize production can be negatively affected by factors such as harsh weather conditions, poor crop management, low input availability, and lack of good quality seeds. A good understanding of crop growth processes under different conditions influences farmers' decisions on the best crop management practices to be adopted. Rainfall reliability, timing, duration and intensity of drought stress can influence planting date, planting density and choice of hybrid to be planted (Seyoum et al. 2018).

Field experiments can only be used to investigate a limited number of management practices for different environments under specific climatic conditions. Crop models, however, can estimate plant growth as a function of weather, soil conditions and crop management (Holzworth et al. 2014). They use mathematical equations to estimate important plant processes such as light interception, dry matter partitioning, crop phenology, stresses and soil processes including temperature, soil water movement and evapotranspiration (ET). Crop modelling is an alternative to investigate the influence of varying management practices, weather conditions and other environmental factors on crop production. Modelling can be an important tool in helping to achieve research goals of increasing crop production and maintaining good soil quality with minimal impacts on the environmental (Archontoulis et al. 2014). By analyzing model predictions, different scenarios of crop production decisions and soil management can be compared regarding their economic and environmental benefits.

Crop models need to be calibrated for local conditions and cultivars before they can be used as valuable tools in crop production. Calibration enables the model to be more robust in its predictions and the user to gain confidence in the simulation results. This calibration process demands a lot of time, and its feasibility and precision largely depend on the available measured dataset used. Crop models with reliable soil water and soil nitrogen (N) components, can be a valuable tool in evaluating long-term water and N management (Boote et al. 1996). Models require the location and cultivar dependent parameters, as well as input data for weather and management practices that need to be supplied by the user, although in some cases default values can be used.

Crop models have been increasingly used to support research that focusses on efficient and sustainable water use in cropping systems. Agricultural systems are mostly water limited, but one of the big threats to dryland production can also be excess water in the soil (Keating et al. 2002). This excess water can be lost with salts from farming systems, with their movement polluting agricultural land and water bodies. This problem can be a result of more water use in the natural vegetation that was replaced than the current agricultural systems, thus increasing water loss in cropping systems (Walker et al. 1999).

In this chapter, the main objective was to conduct a growth analysis and calculate the soil water balance for a maize crop grown in the University of Pretoria long-term trial during the 2016–2017 season to generate parameters for APSIM model calibration.

3.2 MATERIALS AND METHODS

3.2.1 Experimental site

The trial was carried out on the field trial section of the University of Pretoria's Hillcrest Campus Experimental Farm (25.45°S, 28.16°E, 1 372 m above sea level). The soil is classified as a sandy loam of the Hutton form which belongs to the Suurberkom Family (Soil Classification Working Group, 1991). The long-term annual rainfall for Pretoria is about 670 mm, and rainfall is mostly received in summer, with about 80% falling between October and March. Average annual potential evapotranspiration is approximately 2 000 mm which gives the site an aridity index of 0.3 – 0.35 (Rethman et al. 2007).

3.2.2 Experimental design, treatments and historical management practices

The experiment was laid out according to a randomized complete block design with five factors at two levels each. From 1939 maize was grown in summer in rotation with field pea (*Pisum sativum* L.) in winter until 1989. The field pea was not fertilized, only differential water treatments were applied. Before 1983, field pea seeds were harvested and residues were incorporated into the soil. Since then up to the discontinuation of field pea rotation, the seed and residues were removed. The treatments included those that originally received supplementary irrigation (W_1), zero irrigation (W_0) relying solely on rainfall, and combinations of N, phosphorus (P), potassium (K), and manure (M), which when combined, resulted in a total of 32 treatments with four replications leading to the experiment having 128 plots (Nel et al. 1996). The original intention was to ensure a minimum of 450 mm of water (rainfall + irrigation) was received by the W_1 treatments, while the W_0 treatments would be purely rain-fed. Since 1990, however, irrigation water was not applied and all treatments were only rain-fed except W_1 treatments that received supplementary irrigation whenever there was inadequate precipitation and 80% of plant available water was depleted (Nel et al. 1996). The W_0 treatment was discontinued in 1989, so previous treatments with and without irrigation are now viewed as additional replicates of each other (Nel et al. 1996).

The historical fertilizer application for the different treatments has been changing over time in response to soil analysis results which have shown accumulation of some nutrients to high levels (Table 3.1). Fertilizers were broadcasted before planting, and additional N to NPK treatment was applied as top dressing from 1985 – 2004. Nitrogen was initially applied as ammonium sulphate ($(NH_4)_2SO_4$) and later in the form of ammonium nitrate (NH_4NO_3) (Belay 2002a), but in recent years it is applied in the form of limestone ammonium nitrate (LAN). Phosphorus has been applied in the form of superphosphate ($Ca(H_2PO_4)_2$) and potassium (K) as potassium chloride (KCl). The application of P was discontinued in 1984 as levels on some plots had built up to above 200 mg P kg^{-1} (Bray 2) (Nel et al. 1996).

Table 3.1 Nitrogen (N), phosphorus (P) and potassium (K) applied per treatment to the different treatment combinations between 1939 and 2017 (Nel et al 1996, Belay 2002b).

Season	N	P	K
		kg ha^{-1}	
1939/40 –1966/67	43	34	32
1967/68 – 1972/73	85	68	63
1973/74 –1983/84	205	100	100
1984/85	205	0	100
1985/86 – 2004/05	125 + 125*	0	80 + 100*
2005/06 – 2011/12	100 + 50*	0	80
2012/13 – 2017	100	0	80

*Applied as a split at planting and top dressing six weeks later

For this chapter, planting was done on 18 November 2016, using a plant population of five plants m^{-2} (50 000 plants ha^{-1}). Fertilization was done at sowing at a rate of 100 kg N ha^{-1} applied as ammonium nitrate on fertilized treatments and no fertilization was done on the control. Dry matter accumulation, grain yield and soil moisture content for two treatments were monitored, namely the control (zero fertilization) and NPK treatments. The gross plot size is 8.3 × 6.3 m (52.3 m^2) and the net size is 7.5 × 4.9 m (36.8 m^2).

3.2.3 Data collection

Maize dry matter accumulation was monitored by routinely taking plant growth measurements during the cropping season. Crop growth measurements included fresh mass, dry matter weight, and leaf area index (LAI). Destructive sampling was done every two weeks on each plot with four plants harvested per plot. Using the four sampled plants, a Licor Li-3001 leaf area meter was used for destructive leaf area determination. The measured leaf area was used to determine the LAI. Leaf area index was calculated using equation 3.1

Leaf area index (LAI) = $\frac{LA}{P}$ (Eq. 3.1)

Where LA is leaf area and P is ground area per plant (m^2).

Dry matter was measured after oven-drying the plant material at a temperature of 70°C until a constant mass was achieved.

Daily weather data (maximum and minimum temperature, and rainfall) for the season was obtained from an automatic weather station right next to the long-term trial. In addition to rainfall data from the weather station, rain gauges were installed on the trial to monitor rainfall and irrigation applied. Solar radiation was generated using the method of Bristow and Campbell (1984). The equation estimates solar radiation as a function of the difference between the minimum and maximum temperatures, and estimations of the sun’s position relative to the point of interest on the earth’s surface calculated by the Julian Jay (J), which represents the day of the year in the formula, latitude and elevation. Soil moisture content was monitored on a weekly basis using a neutron probe (IntroTek International, New York, USA). Access tubes were installed in six plots (three tubes for each of the two treatments), and measurements were made at 0.2 m depth increments up to a depth of 1.0 m.

Soil samples were collected from each plot for nutrient analysis in the laboratory after harvesting. Other samples from an adjacent, undisturbed site were taken for analysis to represent initial soil conditions of the trial. The samples were taken at 0 − 0.05 m, 0.05 − 0.1 m, 0.1 − 0.3 m and 0.3 − 0.6 m. Soil chemical analysis was done to determine soil pH (H_2O), P (Bray-1), exchangeable cations (NH_4OAc), and organic carbon (C) (Walkley-Black method) and were used for soil parameterization in APsoil. Soil physical properties including bulk density, field capacity, saturation and wilting point were also estimated using percent sand, silt and clay of the hutton soil on SPAW Hydrology model of Water Budgets programme. The initial N levels were taken from an undisturbed soil under *Cynodon dactylon* for the past 40 years (Nel et al. 1996).

3.2.4 Model application

Model set up

A crop specific module (APSIM Maize) (Carberry and Abrecht 1991), a soil water module (SOILWAT2) (Probert et al. 1998), soil nitrogen module (SOILN) and the residue module (RESIDUE2) (Probert et al. 1998) were all linked in APSIM. The maize cultivar DKC 7374 BR used in the trial was not available in the APSIM default cultivars. Due to thermal time to complete the different physiological stages not available for the maize cultivar DKC 7374 BR used in the trial, these were estimated through sensitivity analysis to arrive at the best match between measured and simulated dry matter accumulation of NPK treatment in 2016 – 2017 season. Crop parameters for the cultivar were obtained from one of the default varieties DKC 6018 110 in the APSIM model database, which was used as a template to calibrate the new variety DKC 7374 BR. This variety was calibrated by altering thermal time required to complete the different physiological stages on the default variety to match growth analysis of the NPK treatment (Table 3.2). The rest of the variety properties were the same as default properties of DKC 6018 110 used as a template.

Table 3.2 APSIM calibration values for cultivar DKC 7374 BR used in the long-term maize trial.

Parameter	Value	Description
head_grain_no_max	500	Total grain number
grain_gth_rate	6.5 (mg grain^{-1} day^{-1})	Grain growth rate
tt_emerg_to_endjuv	290 (°Cd)	Thermal time - Emergence to end of juvenile
est_days_endjuv_to f_ini	25	Number of days - End of juv. to floral initiation
tt_endjuv_to_init	0.0 (ºCd)	Thermal time - End of juv. to floral initiation
photoperiod_crit1	12.5 (hours)	Photoperiod factor
photoperiod_crit2	24.0 (hours)	Photoperiod factor
photoperiod_slope	10.0 (ºC/hour)	Photoperiod factor
tt_flower_to_maturity	800 (°Cd)	Thermal time - Flowering to Maturity
tt_flag_to_flower	10 (ºCd)	Thermal time - Flag leaf to Flowering
tt_flower_to_start_ grain	300 (ºCd)	Thermal time - Flower to start of grain
tt_maturity_to_ripe	1 (ºCd)	Thermal time - Maturity to ripe

A ‘Hutton soil’ already in the APSoil database was used as a template to create the soil profile used for the simulation. Initial sand (45%) silt (14 %) and clay (41%) properties (Nel et al. 1996), were used to parameterize the Hatfield experimental farm Hutton soil. Table 3.3 shows the parameterization of the soil properties lower limit water content at 15 bars matric pressure (LL15), bulk density (BD) organic carbon (OC), soil pH (H_2O) from 2017 undisturbed site soil analysis, The samples were taken from an undisturbed site adjacent to the experiment at the end of the 2016/2017 cropping season up to a depth of 0.6 m and averages based on their sampling depths. Initial ammonium nitrogen (NH_4-N) and nitrate nitrogen (NO_3-N) which were based on measurements from a previous publication of this experiment (Nel et al. 1996). APSIM uses the SCS curve number approach to estimate runoff (Probert et al. 1998), and the bare soil runoff number was set to 80 to account for the fact that runoff was very low due to the low percent slope of the topography and high infiltration rate of the sandy loam soil of the trial. The soil water conductivity (SWCON) was considered equal (0.7) for all depths. Drainage rate coefficient, as well as first and second (CONA) stage soil evaporation, were not changed

(3.5). Soil hydraulic conductivity was measured using a dual head infiltrometer (Decagon Devices, Inc. 2365 NE Hopkins Court Pullman WA 99163) in the 2016-2017 growing season and used to parameterize infiltration rate (Ks).

Table 3.3 Bulk density (BD), saturation (SAT), drained upper limit (DUL), lower limit at 15 metric bar pressure (LL15), soil pH, organic carbon (OC), ammonium-nitrogen (NH_4-N), nitrate-nitrogen (NO_3-N) for the maize trial at the University of Pretoria's Hillcrest Campus Experimental Farm.

Soil Layer (m)	OC (%)	BD (Mg m^{-3})	SAT (m^3 m^{-3})	DUL (m^3 m^{-3})	LL15 (m^3 m^{-3})	pH (H_2O)	NH_4-N (mg kg^{-1})	NO_3-N (mg kg^{-1})
0.00 – 0.15	1.60	1.48	0.43	0.24	0.16	6.0	60	80
0.15 – 0.30	0.70	1.48	0.43	0.29	0.20	6.0	60	80
0.30 – 0.60	0.50	1.46	0.43	0.33	0.23	6.0	60	80
0.60 – 0.90	0.40	1.45	0.43	0.33	0.23	6.0	60	80
0.90 – 1.20	0.40	1.46	0.43	0.33	0.23	6.0	60	80

The 2016 – 2017 season above-ground dry matter accumulation and leaf area index dataset for NPK and control treatments were used to validate the growth properties of the calibrated cultivar DKC 7374 BR. Soil water content data were used to validate the soil water properties of the parameterized Hutton soil for NPK and control treatment.

3.2.5 Testing model performance

The aim of comparing measured and simulated values statistically when testing a model is to objectively determine what proportion of treatment error, excluding experimental error, is accounted for by the model (Yang et al. 2000). Model performance was evaluated using the reliability criteria recommended by De Jager (1994). The square of the correlation coefficient (r^2) is used to evaluate the association between measured and simulated values, mean absolute error (MAE) used to determine average errors, root mean square error (RMSE) summarising overall error and Wilmot's index of agreement (D) is used to indicate the relative size of the differences. Statistical criteria for an accurate simulation are r^2 and D values above 0.80, and MAE below 20%. RMSE depends on the data and units used for analysis. High values of RMSE indicate poor model performance. Model evaluation was performed using above-ground dry matter accumulation, LAI and soil moisture content data for the control and NPK treatments for the 2016-2017 growing season. The measured and simulated data were also graphically compared.

3.3 RESULTS

Above-ground dry matter

Above-ground dry matter (ADM) was well simulated for the 2016/2017 growing season. The measured and simulated ADM was well estimated in the early stages of maize growth in both treatments, but later in the season, the simulated ADM became slightly lower than measured ADM for the control treatment (Figure 3.1). In the simulation, harvesting was initiated at 17 weeks after emergence (WAE) and the dry matter was estimated to be 9 268 kg ha^{-1} and 20 955 kg ha^{-1} for control and NPK respectively, in the field the crop was dry at 17 WAE and the last dry matter was taken for both treatments (10 852 kg ha^{-1} and 19 984 kg ha^{-1} for control and NPK, respectively).

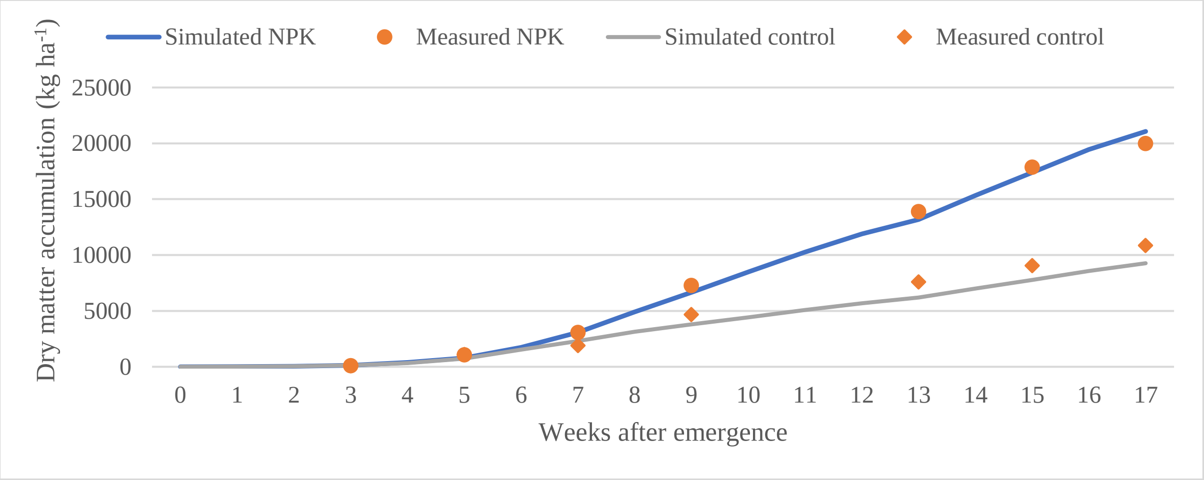


Figure 3.1 Measured and simulated aboveground dry matter accumulation comparison for the NPK and control treatments of the maize trial for the 2016/2017 growing season.

The results showed a good model performance in estimating maize ADM over the 2016/2017 growing season and complied with statistical criteria in almost all cases (Table 3.4). Dry matter accumulation comparisons in the NPK treatment showed a high correlation, low error and a good agreement between measured and simulated data, indicating a good calibration. There was high r^2, D and low MAE between measured and simulated ADM for NPK and control treatment, thus meeting the statistical criteria for a good simulation. Higher simulation precision for the NPK treatment was indicated by a lower RMSE than for the control.

Table 3.4 Statistical evaluation of measured and simulated above-ground dry matter accumulation in the NPK and control treatments.

Treatments	r^2	D	MAE (%)	RMSE (kg ha^{-1})
Control	0.99	0.98	16.8	1092.4
NPK	0.99	1.00	5.4	649.1

Leaf area index

Leaf area index increased with time up until 10 weeks after emergence where it reached its peak and started declining afterwards in both treatments (Figure 3.2). The measured and simulated LAI showed a similar trend and was estimated relatively well in the NPK treatment over the growing season. Measured LAI was slightly higher than simulated LAI for the first five weeks. The NPK treatment had a higher LAI than the control in each of the stages when it was measured but the difference was small in the first five weeks. The control had a maximum measured LAI of 2.1 m^2 m^{-2} and the NPK treatment had 3.4 m^2 m^{-2}. Comparing measured and simulated LAI showed a good prediction in the NPK treatment, but in the control, LAI was overestimated in the later growth stages.

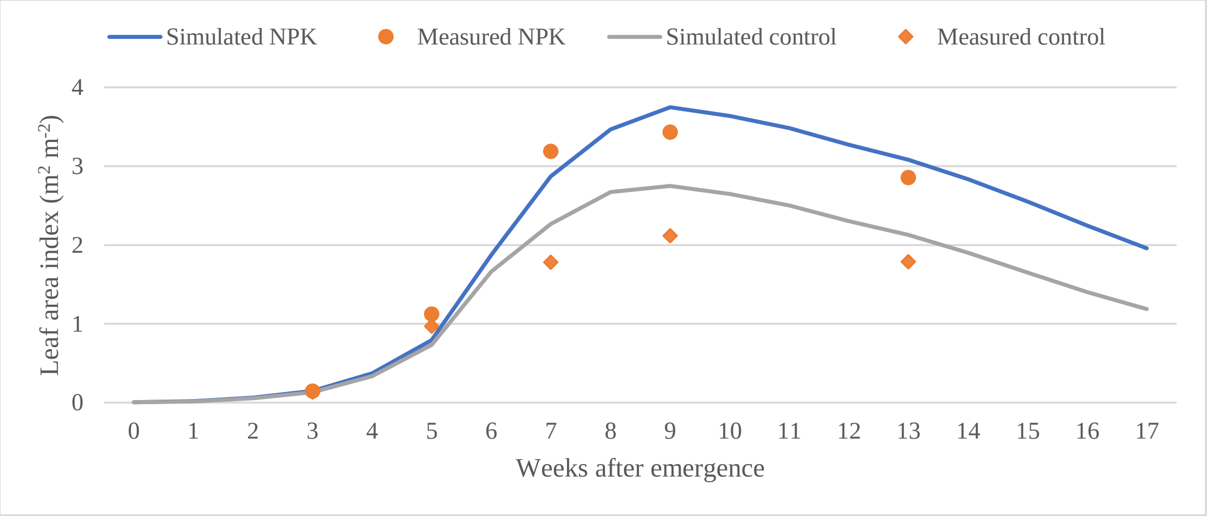


Figure 3.2 Measured and simulated leaf area index of NPK and control treatments in the 2016/2017 growing season.

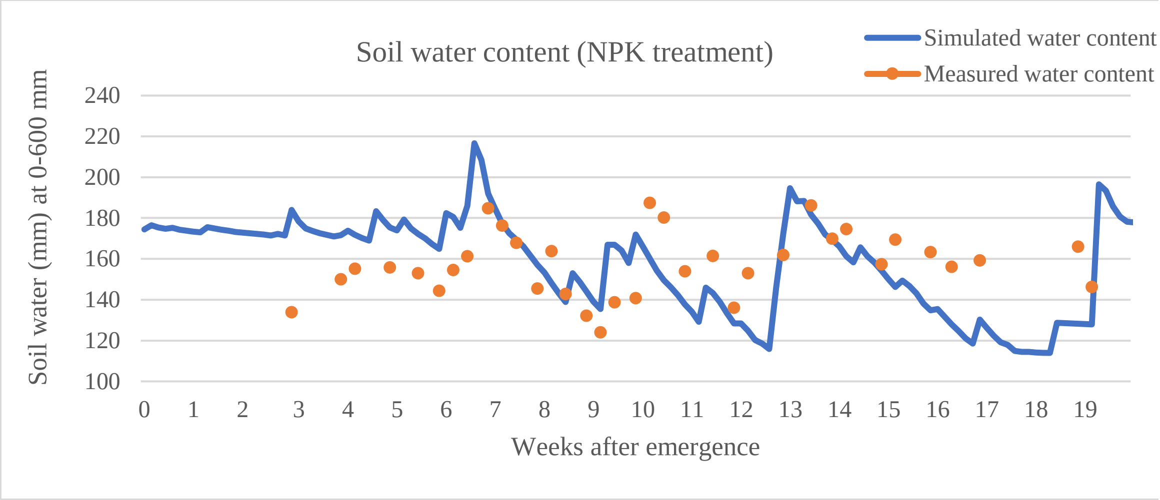
There was a high r^2 and D between measured and simulated LAI for both treatments (Table 3.5). A good model validation was indicated by a high relationship (r^2 = 0.96), agreement (D = 0.99) and low error (MAE = 11.2%) in the NPK treatment. In the control treatment, there was a high correlation ($r^2 = 0.96$), high agreement (D = 0.95) meeting the statistical criteria, except for MAE which was above 20%. This was a result of LAI being overestimated between week 7 and 14 in this treatment. In this period the death and senescence of lower leaves in the field were observed which influenced the measured LAI. The NPK treatment had lower RMSE than control indicating that it was estimated better than control, but both treatments showed low estimation error.

Table 3.5 Statistical evaluation of measured and simulated leaf area index (LAI) in control and NPK treatment.

Treatments	**r^2**	**D**	**MAE (%)**	**RMSE (m^2 m^{-2})**
Control	0.96	0.95	25.0	0.45
NPK	0.96	0.99	11.2	0.31

Soil water content

Figure 3.3 shows the soil water content comparison over the 2016/2017 growing season in the maize trial. Measured and simulated soil water content in the top 0.6 m of the soil profile was generally higher in the control than NPK treatment. The measured water content ranged from 124 mm to 184 mm in the NPK and 143 mm to 199 mm in control treatment. This may be a result of a better maize growth in the NPK treatment resulting in higher evapotranspiration than in control.



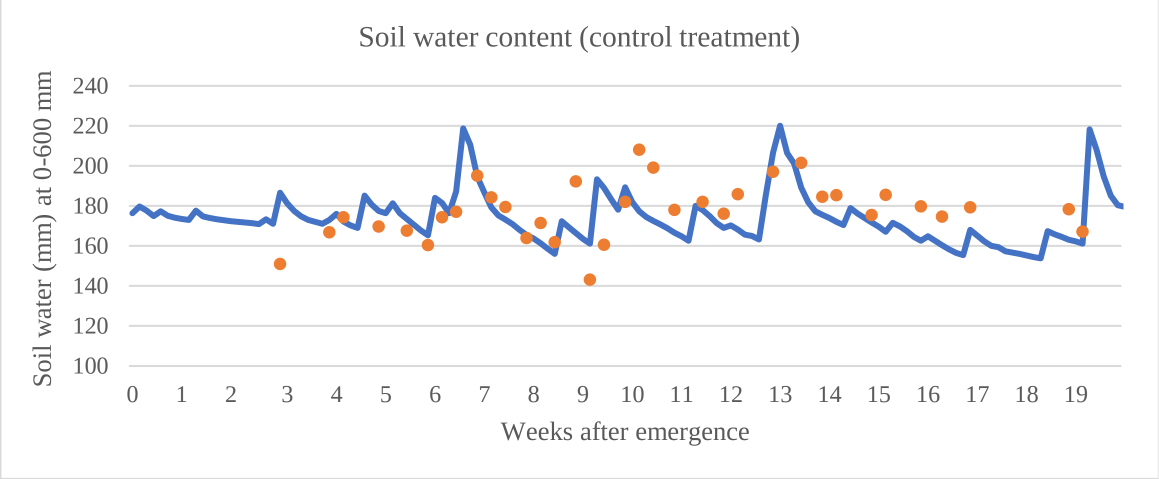


Figure 3.3. Measured and simulated soil water content (0 – 0.6 m) for the NPK and control treatments.

The statistical analysis of the control and NPK soil moisture content is summarised in Table 3.6. Comparison of measured and simulated results met the statistical criteria for both treatments with respect to MAE, and D in NPK, but r^2 was poor. The control was estimated at a much higher precision compared to the NPK treatment as indicated by lower MAE and RMSE values. The correlation between measured and simulated data was generally poor for both treatments due to inconsistent over and underestimations of soil water. Despite those imperfections, soil moisture was well simulated by the model in NPK, but fairly in the control.

Table 3.6 Statistical evaluation of measured and simulated soil water content in NPK treatment.

Treatments	**r^2**	**D**	**MAE (%)**	**RMSE (mm)**
Control	0.14	0.62	6.4	14.5
NPK	0.40	0.81	11.7	21.8

Components of the soil water balance as modeled by APSIM

Soil water balance was estimated for the treatments using simulated data (Table 3.7). Precipitation was the same for both treatments at 515 mm of rainfall. Evapotranspiration (ET) accounted for more than 50% water of the water balance in each of the treatments, with the other proportion contributing to drainage and runoff. Evapotranspiration was higher in the NPK than control treatment, whereas deep drainage contributed a higher proportion in control, which was almost three times as much as in NPK, resulting to higher change is soil water content (Δs) in NPK. Surface runoff and drainage can also be highly influenced by soil properties and the intensity of rainfall events. There was no supplementary irrigation in the trial during the 2016/2017 growing season.

Table 3.7 Estimated soil water balance components for the control and NPK treatments for 2016/2017 growing season (21 November 2016 – 28 March 2017) in the Hillcrest Campus Experimental Farm long-term maize trial (ET- evapotranspiration, Δs- change in soil water content).

Treatment	**Rain**	**Irrigation**	**Runoff (mm)**	**Drainage**	**ET**	**Δs**
Control	515	0	88	130	285	+13
NPK	515	0	86	48	325	+56

3.4 DISCUSSION

Dry matter accumulation was well simulated for the maize variety DKC 7374 BR, and it complied with the statistical criteria in most cases. The model was, therefore, able to estimate maize growth for the two treatments considered through thermal time calibration. Dry matter accumulation was similar on both treatments in the first five weeks despite the control treatment being unfertilized. This could be a result of newly mineralized N over the winter period stimulating early growth in the control, and this was also predicted by the model. In

APSIM, dry matter accumulation is estimated as a function of weather conditions, soil water and N availability. Simulated LAI agreed with measured data in the initial stages of growth but was overestimated from seven weeks after emergence to harvesting. In the model, LAI is estimated using a number of parameters including leaf number, leaf size, water stress factor, number of plants per square metre and the senescence of leaves due to age (Archontoulis et al. 2014). There was greater over-estimation in the control than NPK, which can be a result of leaf death and senescence predicted to be less or later than what was observed in the field. In reality, the low fertility status of the control treatment contributed to a large proportion of death and senescence of lower leaves than in NPK treatment. Although the model can simulate the senescence of lower leaves, it might have been underestimated resulting in a higher simulated LAI.

The crop plays a significant role in the water balance of agricultural systems, therefore, a good estimation of crop growth can be a good indication of correct water use prediction. Although the amount of moisture that can be stored in the soil or used by crops can vary with soil and crop characteristics, fertilization can promote plant growth which increases crop water use in fertilized crops. For this reason, measured and simulated soil water content was often higher in the control compared to the NPK, indicating that the model was able to get soil water relations right. Evapotranspiration was 55% and 63% of total precipitation on the control and NPK treatments, thus contributing the largest proportion of water loss. This was consistent with findings by Keating et al. (2002), who reported that ET generally makes up the largest use of precipitation in semi-arid and sub-humid environments. Crop canopy development can influence ET and overall ground cover, which can, to some extent, have an effect on infiltration and runoff as well as percolation in case of rainfall events. The lower volume of water lost through drainage and runoff in NPK treatment can be a result of NPK having a better crop canopy cover and root development than the control. Better crop development leads to higher water use, increasing the water demand, hence, leading to lower drainage.

3.5 CONCLUSION

Model calibration and testing exercises are important in evaluating and gaining confidence in the ability of a model to simulate in-field processes. It was shown that the APSIM model can be used to simulate maize dry matter accumulation, soil water content as these variables were judged to have been adequately simulated according to De Jager (1994) model reliability criteria. Now that the model has been calibrated and tested for a specific site and crop for the season, we have more confidence in its application in long-term simulations.

CHAPTER IV

LONG-TERM EFFECTS OF INORGANIC FERTILIZER APPLICATION ON MAIZE *(Zea mays L.)* YIELD, SOIL ORGANIC MATTER AND NITROGEN LEACHING

4.1 INTRODUCTION

Long-term experiments are important for understanding and evaluating the interactions between crops and the environment and have been essential in providing means of evaluating sustainable management systems in agriculture. The present knowledge of soil fertility has had a significant contribution from long-term field experiments (Körschens 2006). They are useful in developing beneficial management practices that can be able to economically produce high crop yields whilst maintaining soil quality at acceptable levels (Liu et al. 2011). Short-term studies may not reliably reveal certain soil processes, which can only be studied over a long period of time by looking at the trends. Long-term experiments are able to provide the best practical means of evaluating soil quality factors such as declining soil organic matter (SOM) levels and soil acidification on crop growth and soil properties (Poulton 1995). These experiments have been used for several objectives, including determining optimal fertilizer requirements, testing the sustainability of a particular management system over a long period and determining changes that can improve productivity, and providing long-term data that can be used in validating crop models that can be used in the further evaluation of management practices.

Inorganic fertilizers are often used as the main source of nutrients needed to produce high yields in commercial agriculture. These fertilizers, however, can influence the soil chemical characteristics, affecting nutrient cycling and potentially resulting in negative environmental impacts (Galloway et al. 2008). This has highlighted the importance of appropriate fertilizer management to maintain soil fertility and increase yields while minimizing negative impacts on the environment. There have been conflicting reports on the on the subject of long-term inorganic fertilizer usage, with some studies highlighting that it contributes to SOM loss (Belay 2002a, Nardi et al. 2004)), and others reporting beneficial effects of fertilization on SOM levels (Malhi et al. 1997, Meng et al. 2005).

Soil organic matter is often used as an indicator of soil quality and the sustainability of a cropping system due to its influence on soil physical, chemical and biological properties

(Herrick 2000, Mills and Fey 2003, Aziz et al. 2013). It can be influenced by management practices such as fertilization and tillage practices, as has been reported by various studies on long-term experiments (Dominy and Haynes 2002, Cates et al. 2016). These management practices influence SOM by controlling the overall input of soil C and the rate at which it is decomposed (Kaur et al. 2008). To sustain high yields and maintain soil quality over the long-term, a good understanding of the effects of management practices on crop production is required.

Data from a long-term experiment which started in 1939 at the University of Pretoria's Hillcrest Campus Experimental Farm (previously called the Hatfield Experimental Farm) can be valuable for studying the effects of management practices on yields and soil quality. In this chapter, the performance of the APSIM model in predicting long-term maize (*Zea mays* L.) yields and SOM changes under NPK fertilization will be investigated. The model was then applied to evaluate the potential yield and SOM benefits of including manure (which was part of the initial treatments, but discontinued in 1990) in a fertilizer programme.

4.2 MATERIALS AND METHODS

4.2.1 Trial description

The long-term maize trial is described in Section 3.2. In this section, only the part relevant to this chapter will be described. The specific treatments used for long-term simulation were the control (zero fertilization) and NPK treatment. The trial was initially established to determine fertilizer requirements of maize on the specific soil type. However, the objectives changed over the years, with more emphasis recently being placed on monitoring the performance of maize under different nutrient levels (balanced and imbalanced nutrients treatments) (Nel et al. 1996). It was envisaged that this would help in evaluating the sustainability of the different inorganic nutrient applications and gain a better understanding of how basic production processes are affected by fertilizer treatment combinations.

4.2.2 Long-term measured data

4.2.2.1. Long-term yield and SOM data

Data from the experimental plots with zero and full fertilizer treatments was acquired from the trial records and published literature (Nel et al. 1996, Belay et al 2002a). Yield data from 1990 – 2017 for both treatments was acquired, but SOM data were more challenging to find as few previous publications focused on this variable in the long-term trial. Certain publications, however, did have data for percentage soil organic carbon (SOC) or total carbon (C) content in the soil (Nel et al. 1996, Belay et al. 2002b, Bello 2008). Data for SOC in 1998, 2006, 2013 and 2017 were used to compare with model estimates. The factor of 1.724 (Stevenson and Cole 1999) was used to convert SOC to SOM. Initial SOM content in 1950, which was the start of the simulation period, was estimated using analysis from samples from an undisturbed site adjacent to the trial at the end of 2016/2017 cropping season (-25º44'53"S, 28º15'36"E).

4.2.2.2 Long-term weather data

The minimum weather input required to run APSIM includes daily solar radiation (MJ m^{-2}), daily maximum and minimum temperature (ºC) and rainfall (mm). Hatfield daily weather data from 1950 – 1983 was obtained from a database developed by a team from the school of Bio-resources Engineering and Environmental Hydrology at University of KwaZulu Natal using the South African Atlas of Climatology and Agro Hydrology (Van Heerden et al. 2009). Pretoria automatic weather station provided 1984–2000 data, while data for 2001–2017 was obtained from the database of the South African Weather Service (SAWS). Daily solar radiation was estimated using the minimum and maximum temperature, latitude and altitude (Section 3.2). The annual average ambient temperature (TAV) and annual amplitude in monthly temperature (AMP) were calculated using the long-term daily minimum and maximum temperatures using the 'tav_amp' software provided by the APSIM platform. These calculated values of TAV and AMP were inserted to the weather file automatically by the software.

4.2.3 Model application

4.2.3.1 Long-term maize simulation

The model requires inputs that describe field management, daily weather, soil profile characteristics, initial soil condition, and cultivar characteristics. The field management inputs include tillage date and type, planting date and density, irrigation, fertilizer application and residue management. The 'planting rule' was based on personal dialogue with the farm manager Mr. Burger Cillie on 11 November 2016. Tillage was done every year on 1st October to a depth of 0.3 m using a disc plough and 70% of the residues were assumed to be incorporated. The planting window period was from 1 October to 1 January every year, and sowing was done when a total of over 20 mm of rain occurred over five consecutive days. No sowing was allowed after 1 January as the growing season would then be too short for the crop to complete its life cycle. The maize variety calibrated in Section 3.2.4 was used for the simulation at a planting density of 50 000 plants ha^{-1}, although in reality a range of maize cultivars were planted over the years including Pretoria Potchefstroom Pearl (1939 – 1971), R200 (1972 – 1984), Pioneer 6431 (1985 – 2005) (Nel et al. 1996) and Pioneer Phb 32W7, which is a short season variety planted in January 2006 after crop failure of initial planting due to birds attack (Bello 2008). Fertilization was applied at sowing for the full fertilizer treatment (100 kg ha^{-1} N for the entire duration of the simulation). Soil profile characteristics, initial soil conditions, and cultivar characteristics are as described in Section 3.2. Supplementary irrigation was simulated based on rainfall, with 15 mm irrigation being applied if rainfall over the previous 15 days was less than 5 mm.

4.2.3.4 Long-term manure application scenarios

Initially, manure (M) treatments were part of the long-term maize trial but were discontinued in 1990 after 50 seasons. A scenario of manure application (1950 – 2017) was simulated to assess the long-term beneficial effects of manure application and to what extent SOM levels could have been maintained. Historical data indicated that 9 tonnes ha^{-1} manure was applied (Nel et al. 1996), hence the same amount was used in this scenarios. A manure only and NPK + manure treatments were simulated in the scenarios. An APSIM default manure was used, applied at sowing, and had C:N ratio of 12:1.

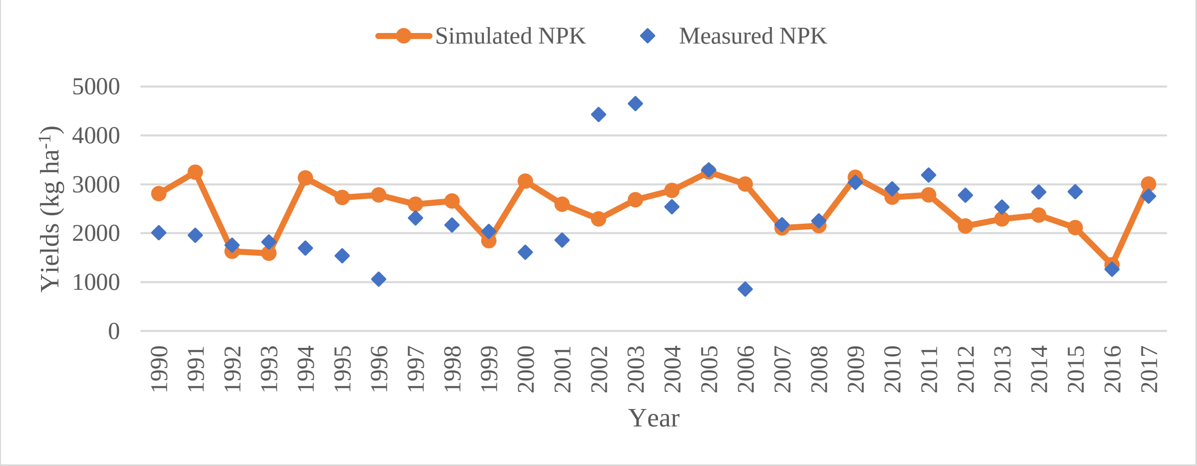
4.2.4 Testing model performance

Model evaluation was performed using long-term yields (1990 – 2017) and SOM (1950 – 2017) data control (zero fertilizer) and NPK treatments. Model performance was tested using the square of the correlation coefficient (r^2), the mean absolute error (MAE), root mean square error (RMSE) and the index of agreement (D) based on the criteria outlined in Section 3.2.5. The measured and simulated data were also graphically compared.

4.3 RESULTS

4.3.1 Long-term fertilization effects on maize yields

The measured and simulated yields of the control and NPK treatments from 1990 to 2017 are shown in Figure 4.1. Measured and simulated yields were generally higher in the fertilized treatment than the control, clearly demonstrating the importance of fertilization on increasing yields over the years. There were yield over-estimations by the model in the NPK treatment in most seasons from 1990 – 2001, and after that period the yields were well estimated. The calibrated cultivar DKC 7374 BR, which was used for the simulation, was in reality first planted during the 2011 – 2012 season and this might explain the better estimations from 2011–2017. The control yields were poorly estimated, with a high variation of simulated yields in successive season from 1990 – 2010, but it was well estimated after 2011 when DKC 7374 BR was used for measured data. In some seasons the plots had erratic yields (plots of the same treatments recording very different yields), as reported in 1993 (Belay 2002b), or the crop failure, reported in 2006 due to birds attack on initially planted crop (Bello 2008), which also contributes to inaccurately measured yields.



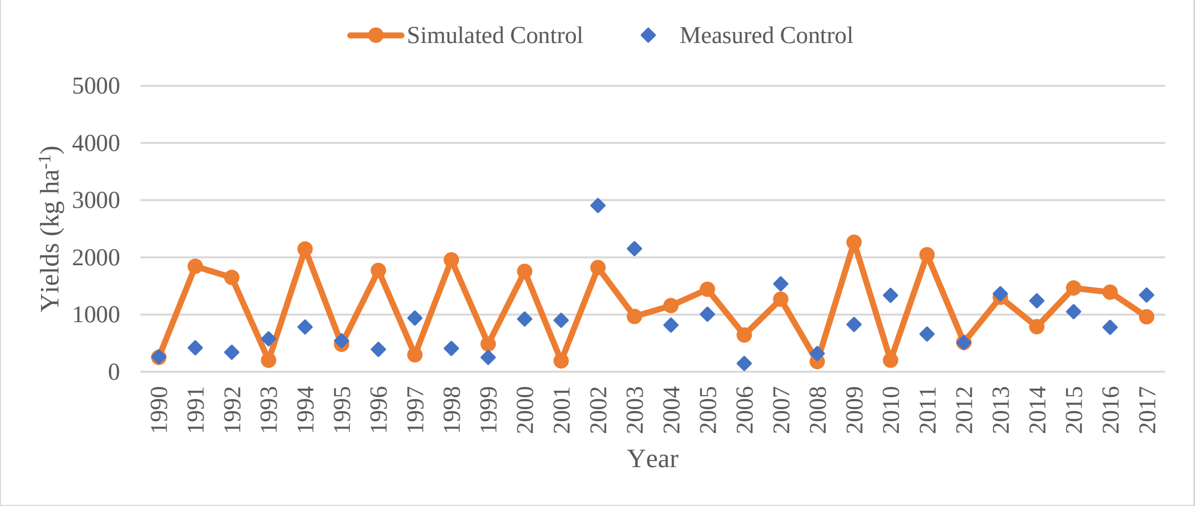


Figure 4.1 Measured and simulated maize grain yields for the NPK treatment and control treatments from 1990 to 2017.

Simulating long-term yields proved to be a difficult exercise as shown by the poor statistical analysis on both treatments (Table 4.1). There was a low correlation on both treatments indicating a poor linear relationship between measured and simulated yields. This can be a result of outliers or inconsistent overestimations and underestimations deflating the linear relationship between the measured and simulated yields. These outliers can be caused by instances of high uncontrolled yield variance in some years due to possible the difficulties of simulating real situations on long-term basis as a result of environmental influences that may not be considered in some seasons.

Table 4.1 Statistical evaluation of measured and simulated yields in the control and NPK treatments.

Treatment	**r^2**	**D**	**MAE (%)**	**RMSE (kg ha^{-1})**
NPK	0.1	0.44	30.0	991.5
Control	0.02	0.45	79.9	885.4

4.3.2 Long-term fertilization effects on soil organic matter content

Comparisons between observed and simulated SOM content of fertilized treatments are shown in Figure 4.2. Observed and simulated results showed a declining trend in SOM for both treatments, although the magnitude of SOM decline differed between the treatments. The results showed a higher long-term SOM loss in the control than NPK treatment. Similar results were reported by Luo et al. (2011), where there was a continuous C decline in fertilized wheat, though the N fertilization proved to slow down the decline. This demonstrates the beneficial effects of fertilization to SOM levels. Higher organic residue returns in fertilized plots in the trial were reported by (Belay 2002a), but it was also highlighted that the organic crop residues were mineralized at faster rates due to inorganic N applications enhancing the decomposition process. The simulated SOM (top 0.6 m) declined from 1.24 % in 1950, to 0.96 % and 0.86 % in 2017 in the NPK and control treatments, respectively. Despite thevfew measured data points, the SOM seem not to have reached the equilibrium stage after 66 years as shown by measured and simulated data.

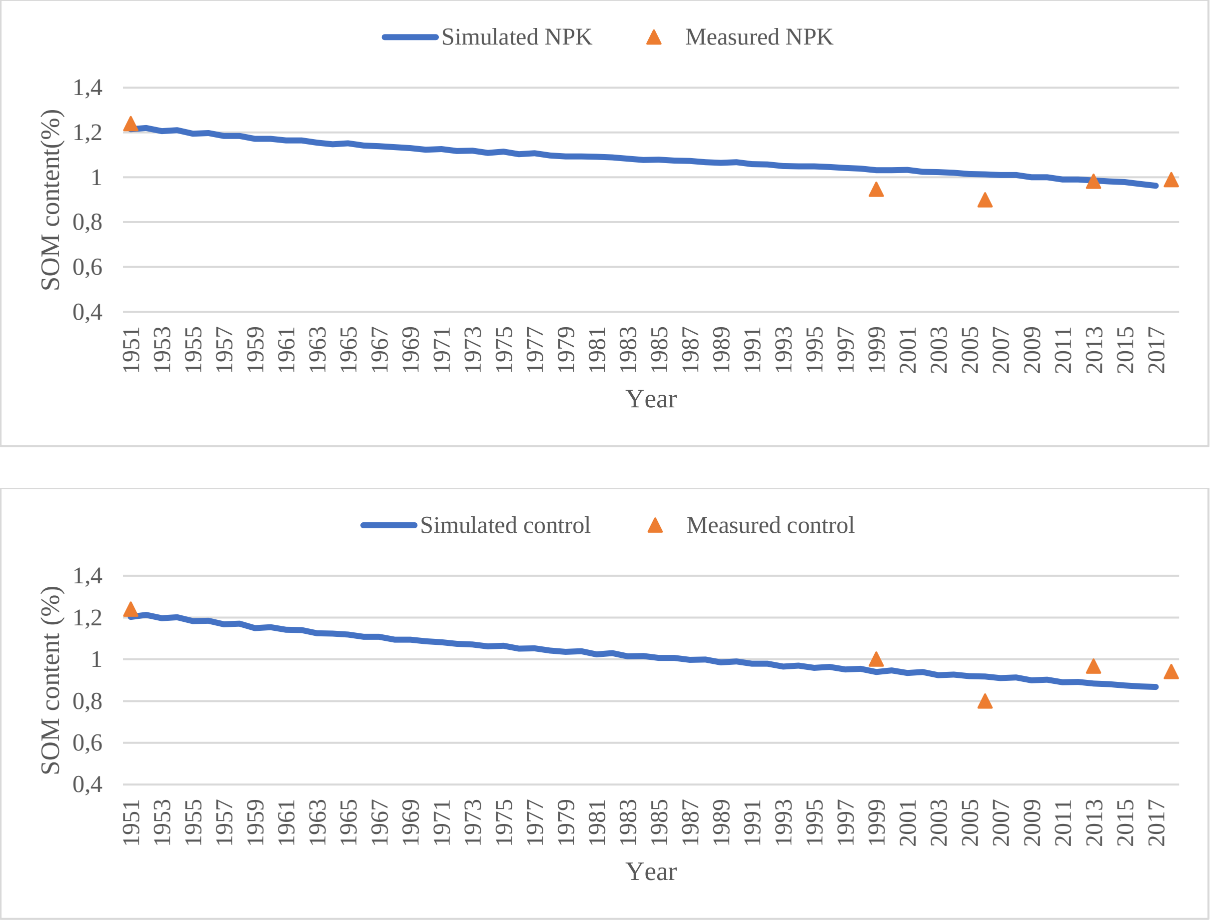


Figure 4.2 Observed and simulated soil organic matter content for the control and NPK treatments (soil sampling depths: 1950 = 0.6 m, 1999 = 0.2 m, 2006 = 0.2 m, 2013 = 0.6 m, 2017 = 0.6 m).

A statistical summary of the comparison between observed and simulated SOM is shown in Table 4.2. Despite simulated data being taken from the top 0.6 m and measured data from various soil depths, statistical criteria for a good simulation were met in terms of overall error (MAE). The r^2 did not meet the statistical criteria but were all above 0.62. The control was well estimated compared to the NPK treatment as indicated by higher r^2, D and lower MAE and RMSE.

Table 4.2 Statistical evaluation of measured and simulated soil organic matter content in the control and NPK treatments.

Treatment	**r^2**	**D**	**MAE (%)**	**RMSE (%)**
NPK	0.62	0.87	6.5	0.10
Control	0.68	0.90	5.3	0.09

4.3.3 Long-term fertilization effects on deep drainage and nitrogen leaching.

Deep drainage volumes differed between the treatments, which influenced the amount of N lost through leaching. The control had a higher volume of water lost through drainage over the simulated period of 66 years (Figure 4.3). By 2016, the control was estimated to have lost a cumulative 11 984 mm of water compared to 7 110 mm in the NPK treatment. This was a result of fertilization promoting growth and crop water use thus decreasing water loss through drainage. These results were consistent with findings by Thorburn et al. (2005) who observed that poor crop growth due to low N fertilization reduced soil water uptake, resulting to increased water loss through drainage.

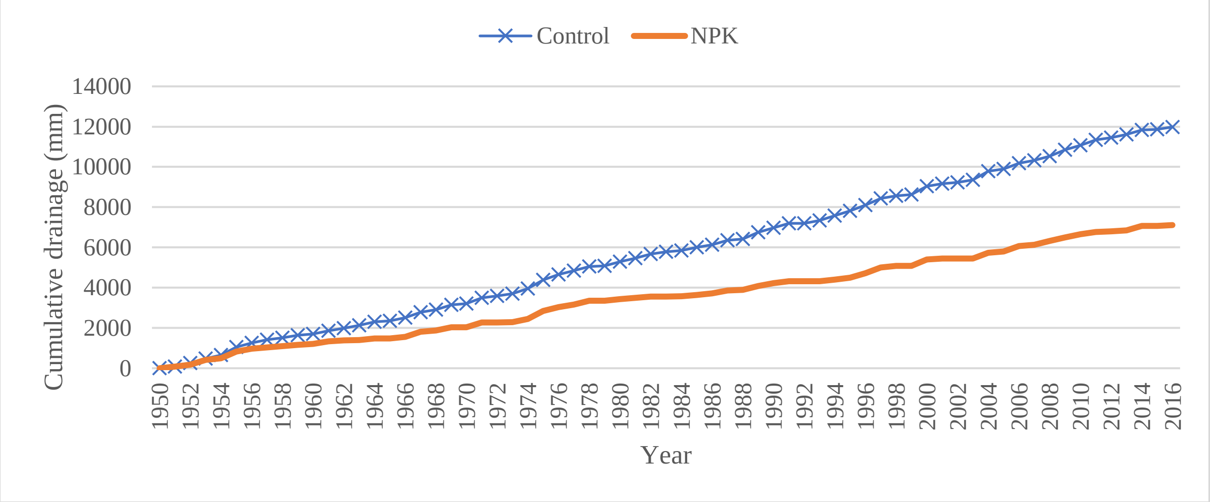


Figure 4.3 Cumulative deep drainage for the 1950 – 2016 simulation period for the control and NPK treatments.

Simulated NO_3^- leaching was highly variable between seasons and years closely linked to rainfall and was higher in the NPK treatment than the control due to the application of N fertilizer (Figure 4.4). In the 1950s, there was a relatively high loss of NO_3^- through leaching in both the control and NPK treatments, with the highest leaching simulated in 1953. The control had relatively low amounts of NO_3^- leaching, with some years with low rainfall even having no leaching estimated.

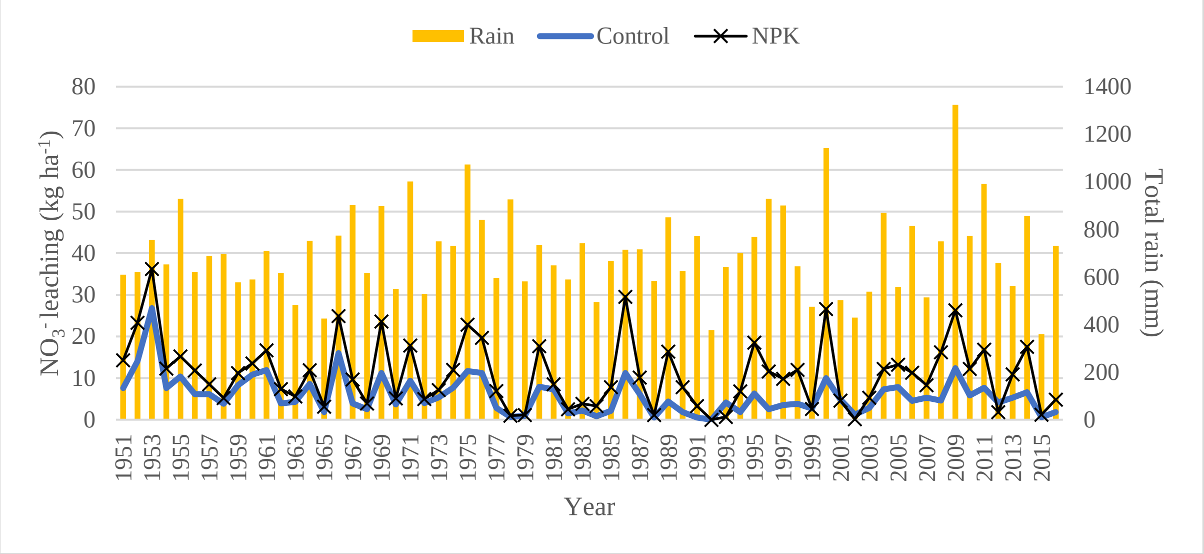


Figure 4.4 Total rainfall and estimated nitrate-nitrogen (NO_3-N) leaching per year for the control and NPK treatment.

Even when there was significant drainage in the control treatment, it did not necessarily result in high NO_3^- leaching (Figure 4.5). Since 1950, an estimated 4 022 kg ha^{-1} N was estimated to have been lost through leaching in the NPK treatment, and this estimation is over 10 times higher than in control (387 kg ha^{-1}). This NO_3^- loss, however, cannot only be attributed to fertilizer N input, as a considerable amount would have come from SOM mineralization and other possible sources such as lightning or small amounts contained in rain water. This was the source of N leached from the control treatment which eventually reached a cumulative value of 387 kg ha^{-1} N over 66 years.

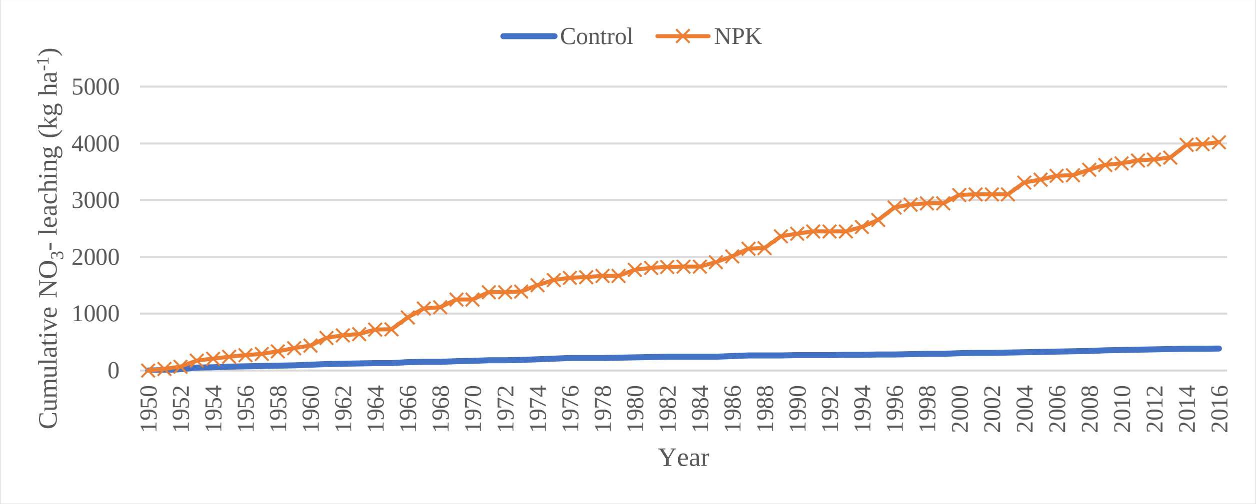
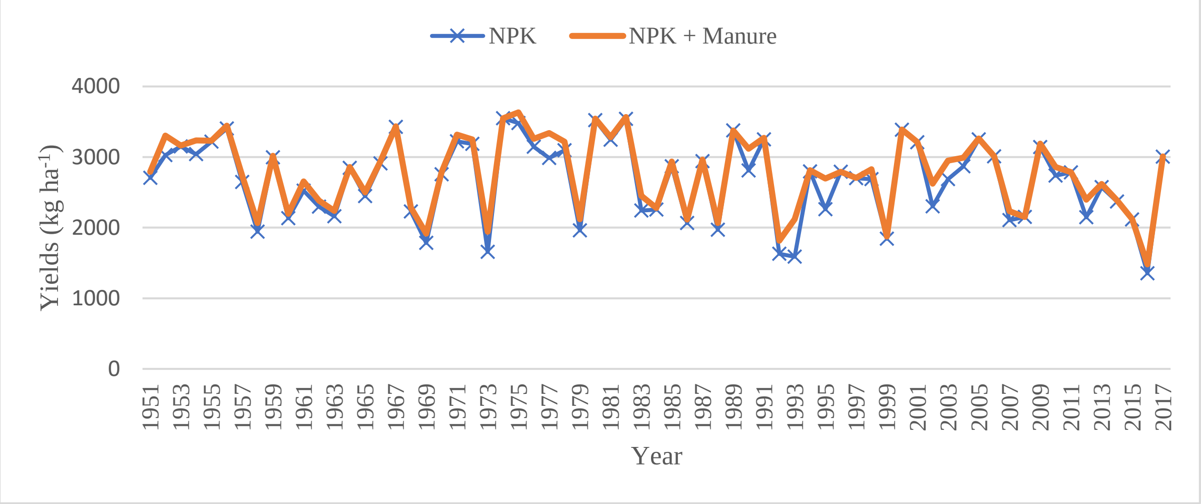


Figure 4.5 Cumulative nitrate-nitrogen (NO_3-N) leaching for the 1950 – 2016 simulation period of control and NPK treatments.

4.3.4 Manure application scenario

4.3.4.1 Simulating long-term manure application effects on yields

Manure application was estimated to be beneficial to yields as indicated by the comparisons in Figure 4.6. The yield differences were low in fertilized treatments, though NPK + manure treatment had slightly higher yields than NPK treatments with average yields of 2 778 kg ha^{-1} and 2 679 kg ha^{-1}, respectively, over 66 years, indicating low yield benefits of manure application over fertilized treatments in term of final yields in this long-term scenario. In unfertilized treatments, the final yield data of the 66-year simulation period was observed to be higher and more consistent for the manure treatment than control. The manure treatment achieved an average yield of 2 555 kg ha^{-1} compared to 1 463 kg ha^{-1} for the control, indicating significant yield benefits of manure application compared to the unfertilized control.



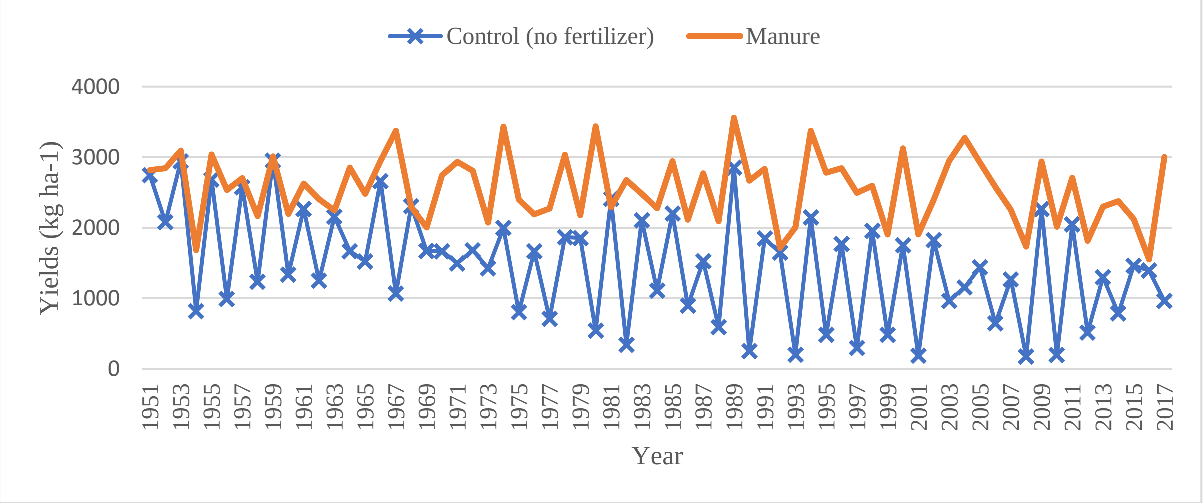


Figure 4.6 Seasonal yields over a 66 year simulation period for the NPK fertilizer, manure and control (zero fertilizer) scenarios.

4.3.4.2 Simulating long-term manure application effects on soil quality

Soil organic matter

Manure application proved to be beneficial in maintaining SOM levels (Figure 4.7). The control treatment had the highest SOM loss, from 1.24% in 1950 to 0.87% in 2017 and the NPK and manure treatment had the lowest decline having predicted to have 1.07% in 2017. The manure treatment had higher SOM than NPK treatment after 66 years, indicating that manure addition is beneficial to SOM content than fertilizer application. The addition of manure could not, however, maintain SOM at initial levels.

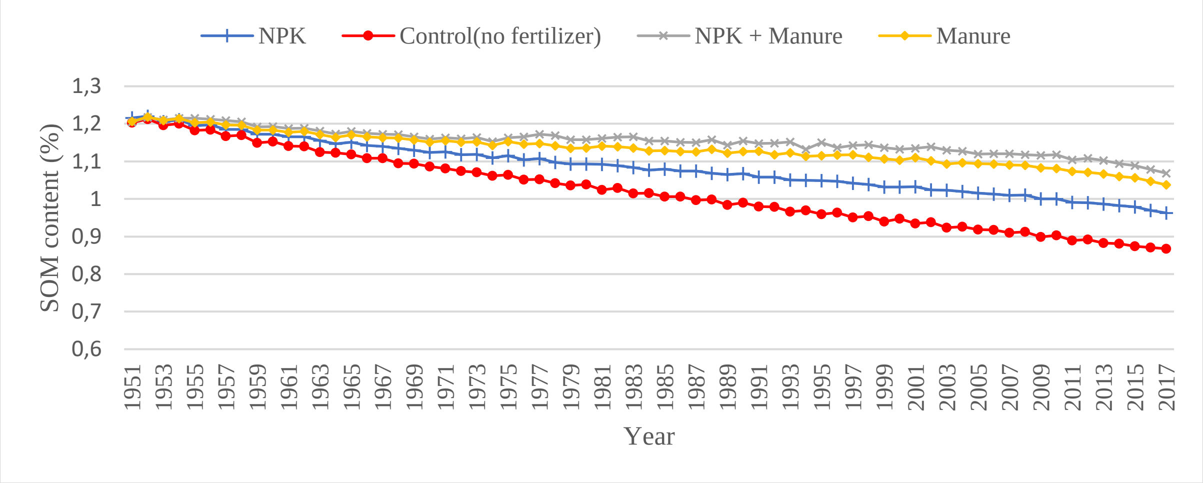


Figure 4.7 Seasonal soil organic matter content over a 66 year simulation period for the NPK fertilizer, manure and control (zero fertilizer) scenarios.

Deep drainage

The simulation showed that unfertilized treatments (control and manure) had the highest volume of water lost through drainage over the 66 years simulation period (Figure 4.8). NPK treatment was estimated to have lost a cumulative 7 110 mm and NPK + manure lost 10 498 mm. This indicates that manure application increases deep drainage. This was further shown by manure treatment estimated to have lost a higher volume of water (12 332 mm) than the control (11 984 mm). This indicates that the beneficial effects of manure application on reducing surface crusting, increasing water holding capacity hence reduced runoff thus increasing drainage.

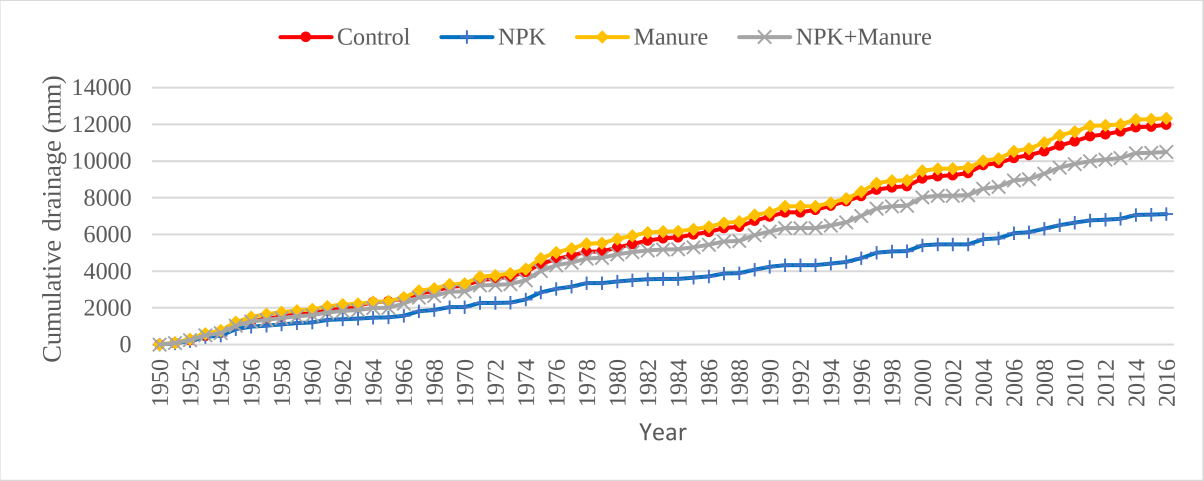


Figure 4.8 Cumulative deep drainage over a 66 year simulation period for the NPK fertilizer, manure and control (zero fertilizer) scenarios.

Nitrate Leaching

Manure application was estimated to increase NO_3^- leaching due to the additional N mineralized from the applied manure (Figure 4.9). The NPK and manure treatment was estimated to have lost 7 312 kg ha^{-1} N since 1950. This indicated that as much as manure application can be beneficial to crop production, it can also increase N leaching if N is applied at rates greater than the crop demands.

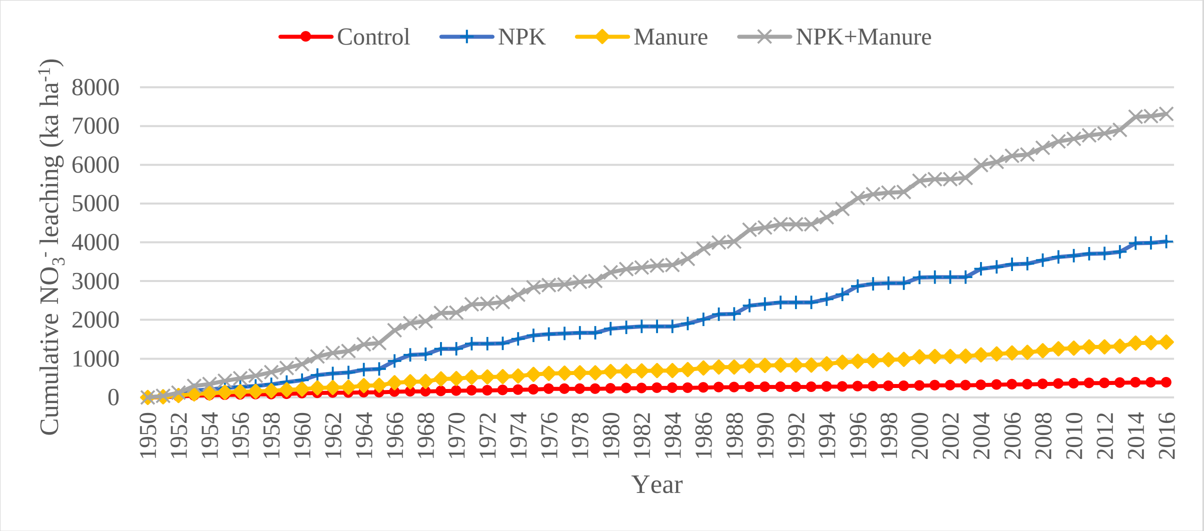


Figure 4.9 Simulated cumulative nitrate-nitrogen (NO_3-N) leaching over a 66 year simulation period for the NPK fertilizer, manure and control (zero fertilizer) scenarios.

4.4 DISCUSSION

Maize yields

Yields of maize over the long-term are not easy to simulate. This was shown by seasonal yield variations in both treatments that proved to be difficult to predict. These variations can be brought about by extreme short-term duration environmental conditions such as high temperatures and moisture stress at critical periods, hail damage, high winds and possible attacks from pests, diseases or birds on the field influencing measured yields that the model cannot consider. A similar study on long-term maize simulation also considered extreme short duration weather events not considered by the model the reason behind imprecise long-term maize simulation (Liu et al. 2010). Planting date is known to influence maize yield (Saseendran et al. 2005, Soler et al. 2007), and in this simulation, the planting dates over the years were not known but only based on a management rule that initiated planting in a pre-defined planting window (Section 4.2.3.1). In reality, planting date can also be influenced by factors other than weather, for example, the availability of planting equipment and labour. For the NPK treatment, yield overestimations between 1990 and 2001 may be a result of cultivars planted in that period not being as vigorous as calibrated DKC 7374 BR which was used for the whole simulation. Another possible reason for erroneous yield estimation for the control would be the model reporting N and moisture limited yields yet in the measured yields there is also the contribution of the other factors not considered by the model. Over the years, yield measurements were done by different people, and this could possibly be another source of error in measured yields. All these factors show that in most cases the poor statistical results can be a result of a combination of poor model performance and possible inconsistencies in measured data if secondary data is being used.

Soil organic matter

Soil organic matter content was generally well simulated by APSIM as it proved to be robust by being able to estimate similar trends with measured data. In the simulation, the slow steady decline from the start of the simulation might be an indication that the decomposition of SOM of an uncultivated site is underestimated. It has been extensively reported that soil cultivation results to SOM loss in cropping systems, with high initial SOM loss when natural vegetation is replaced with cropping systems (Dominy et al. 2002, Luo et al. 2010, Swanepoel et al. 2016). Changes in SOM content are influenced by organic inputs and the rate of decomposition, which is highly influenced by management practices. In virgin soils, SOM is normally at equilibrium, which is a level where humus is formed and decomposed at the same rate. This equilibrium is then disturbed by human activities such as cultivation, which creates favorable conditions for oxidation that results in SOM decline and the ultimate decrease in plant nutrient reserves such as N, P and S which are integral parts of organic matter. Higher SOM in NPK than in the control treatment is attributed to higher C input as a result of fertilization increasing biomass production in NPK treatment. The decline in control is a result of soil cultivation and low C inputs from residues, yet for NPK, soil cultivation and N application can lead to high mineralization of organic inputs despite high C inputs. Belay (2002a) reported a higher mineralization rate of organic inputs in NPK plots due to N fertilization enhancing the decomposition process by increasing N availability required by microbes hence increasing their activity. As yields were not always accurately simulated, it is possible that biomass was not always accurately simulated, and this might have influenced the SOM level estimations.

Nitrate leaching

Higher cumulative drainage in the control treatment did not subsequently result in higher N leaching. Nitrate leaching is highly dependent on the amount of percolating water and the NO_3^- concentrations of the water moving out of the root zone. In rainfed agricultural systems, rainfall distribution and intensity can influence the amount of water lost through drainage. This is coupled with crop water use, where better crop growth in fertilized treatments increases ET, thus reducing deep drainage. In the simulation, fertilization was done at planting and this has the potential to increase N leaching in seasons with high rainfall events early in the season. Nitrates mineralized from SOM would have increased NO_3^- concentrations in percolating water. The contribution of mineralized N from the natural breakdown of SOM to overall soil N is often not accounted for in fertilizer recommendations used by farmers for different crops, and this can have a significant contribution to excess N loss in cropping systems. Nitrate is an anion in nature and these characteristics make then not to be adsorbed in soils with a high cation exchange capacity (CEC). This makes it easy for these NO_3^- to be carried with percolating water making them more susceptible to leaching (Cameron et al. 2013). In this simulation, fertilizer application was done only at planting, therefore, a split fertilizer application at critical growth stages of high N demand can reduce NO_3^- and increase nitrogen use efficiency. Planting a cover crop in the winter fallow period that can use NO_3^- mineralized during the winter season can also reduce the loss of NO_3^- through leaching in the event of heavy rains before the maize crop is planted.

Manure application scenario

This is clearly demonstrated by the control and manure treatment, where both treatments receive equal amounts of moisture from rainfall and the yield differences can only be a result of the beneficial effects of manure application on soil properties. Manure can improve soil porosity hence increasing the water storage capacity, thus reducing potential water stress at critical crop growth stages that can negatively influence yields. This can explain the higher yield variations in the control compared to the manure treatment. In the NPK and NPK + manure treatments, the yields over the years are almost the same, with only small annual yield differences in some seasons. This can be brought about by a possible higher soil moisture content in NPK + manure treatment reducing moisture stress in seasons with poor rainfall distribution thus beneficial to the yields.

The scenario indicated that manure application can be a consistent method of slowing down long-term SOM decline. The direct C inputs by manure application as well as increased net biomass production are the reasons behind higher SOM levels in manured plots, and this was clearly shown in the control compared to manure plots. The simulated decline in SOM content across all treatments can be a result of organic C applied with manure and residue retention unable to compensate for soil C lost due to the conversion of natural soils to cultivated land or via other possible pathways over the season, but manure application proved to significantly lower the decline.

Despite the beneficial effects of manure application on yields and SOM, this practice was shown to increase deep drainage. The depth of soil water fluctuates over time, with periods of rapid increase after rainfall or irrigation followed by periods of slow decline through evapotranspiration. However, if the rate of water loss is less than the amounts added during the same period, deep drainage occurs. Manure application improves soil structure and reduce surface crusting, hence decreasing runoff, and increasing infiltration rates allowing more water storage. The high drainage estimated in manure application treatments can be a result of a lower soil water deficit in manure treatments compared to other treatments between two periods of rainfall or irrigation events. The high infiltration rates can allow more water to fill remaining water deficit to saturation and excess water lost through drainage. In the NPK and control treatments without manure application, the water deficit might be larger than manure treatments (which have a high water holding capacity) and able to accommodate more water additions through rainfall or irrigation thus reducing drainage.

Deep drainage and NO_3^- concentration in the soil solution are the main drivers of NO_3^- leaching. Manure application can bring a lot of N into the plant/soil system depending on the type of manure used. For this reason, manure + NPK treatment was estimated to have the highest NO_3^- leaching. The amount of N in the soil solution can be controlled by mineralization and immobilization of N in SOC. This makes SOC improvement important in regulating N turnover due to the beneficial effects it has on increasing N immobilization, thus reducing N losses.

4.5 CONCLUSION

The long-term sustainability of agronomic management practices can be evaluated using the APSIM model for maize. Based on the results, long-term inorganic fertilization negatively affects soil quality. Model calibration, with sufficient data set, is essential for long-term simulations to increase the precision in estimating long-term trends. Long-term yields and SOM were not easy to accurately predict, but the model was useful in giving insights and a more representative estimate of long-term yields and SOM trends. The model indicated that Inorganic fertilization affected deep drainage and overall NO_3^- leaching, highlighting the importance of carefully applying nutrients that the crops will remove to improve sustainable agricultural production. With soil water and nitrogen often being the most limiting factor in crop production, additional nutrients received from manure are beneficial to biomass production, thus contributing to increased yields. Improved soil physical, chemical and biological properties following manure application allows roots to extend deeper into the soil profile, which increases water and nutrient access, thus contributing to higher yields. Manure application can be beneficial to long-term productivity and maintenance of soil quality, but careful N management strategies are necessary to reduce N leaching. For stable and sustainable crop production, rational fertilizer and manure applications rates that will account for mineralized N has to be identified to reduce leaching.

CHAPTER V

LONG-TERM EFFECTS OF MULCHING, BURNING AND INORGANIC FERTILIZATION ON SUGARCANE (*Saccharum officinarum L.*) YIELD, SOIL ORGANIC MATTER AND NITROGEN LEACHING

5.1 INTRODUCTION

Sugarcane *(Saccharum officinarum* L.*)* is one of the most important agricultural crops in South Africa. Favorable soils and climate on the eastern parts of South Africa have seen the exclusive occurrence of sugarcane production in that region. In recent years, the South African sugar industry has been greatly concerned about decreasing sugarcane production (Jones and Singels 2015). In 2011/2012, land under sugarcane production was reportedly 378 300 ha producing 16.8 million tonnes of cane, which is an indication of the gradual decrease in production when compared to 1999/2000 when a reported 421 600 ha of land was planted to sugarcane 23 million tonnes of cane stalks (SASA 2014). This decrease can potentially harm the sugar industry through loss of revenue for commercial companies and individual farmers as well as reducing the availability of job opportunities. Sugarcane has been grown under monoculture for over a century in South Africa, Brazil, Australia, and elsewhere, as this has shown to be a viable production system for this crop (Meyer and Van Antwerpen 2001). Monoculture production has proven to contribute to yield declines in other crops due to the absence of the beneficial effects that come with crop rotations, such as pest and disease control, and maintenance of soil fertility. To address such a potential decline in production, one of the major steps can be understanding the contribution of sugarcane monoculture to soil quality decline, which in the long-term, can contribute to decreasing yields.

Inorganic fertilization has been extensively used following WorldWar II to enhance crop production by increasing soil fertility. Sugarcane can produce large quantities of biomass, often 70 – 90 t cane ha^{-1} yr^{-1} fresh weight, which usually requires significant amounts of fertilization (Shand 2007). This means that inorganic fertilization represents a significant input cost in sugarcane production. Nitrogen (N) is the nutrient that most often limits plant growth as it is required in the highest proportion by crops. Sugarcane, like most agronomic crops, has a reportedly low nitrogen use efficiency (NUE), with only an estimated 35% of applied N being taken up by the crop (Meyer et al. 2007). The other 65% remains in the soil or is lost to the environment through various pathways such as leaching, denitrification, volatilization, or runoff. This makes NUE an important aspect of production, and directly influencing the profitability and environmental sustainability of sugarcane production.

Sugarcane growers in South Africa commonly burn cane before harvest to make manual harvesting easier for the cane cutters. This residue management practice of burning rather than mulching crop residues potentially reduces the organic matter returns to the soil, which in the long-term, can reduce the favorable physical, chemical and biological properties of the soil (Van Antwerpen et al. 2001). Retaining residues can increase yields by conserving soil organic matter (SOM), reducing evaporation, and improving nutrient cycling. Pre-harvest burning is considered to be the cause of soil aggregate destabilization as a result of SOM loss leading to reduced microbial activities (Graham et al. 2002). Optimal SOM levels can be maintained by balancing residues continually added to the soil and organic matter mineralization by micro-organisms. Retaining residues after harvest has been reported to improve SOM content compared to burning, as it allows the retention of a significant amount of residues at harvest containing about 42% carbon (C) (Vallis et al. 1996, Blair 2000, Graham et al. 2002, Thorburn et al. 2012).

Complex C and N dynamics of agroecosystems, such as in sugarcane cropping systems, can often be investigated better when combining physical measurements and mechanistic crop modelling. These crop models can be used as research tools to address specific hypotheses and explain trends that occur in the crop production cycles (Boote et al. 1996), but the robustness and accuracy of these models first need to be tested.

In this chapter, the aim was to assess the long-term impacts of residue burning and mulching, with or without inorganic fertilization on sugarcane yields and soil quality by combining historical data and mechanistic modelling. Data from 1939–2016 was compared with simulated data from the APSIM model to test model performance and study the long-term trends.

5.2 MATERIALS AND METHODS

5.2.1 Experimental site

The long-term trial on which this study is based on was established in 1939 and is being maintained by the South African Sugarcane Research Institute (SASRI) in Mt Edgecombe, Durban, South Africa (29.04°S, 31.04°E, 123 m above sea level). The climate of the region is humid sub-tropical and characterized by predominantly summer rainfall with an annual average of 950 mm and an annual average temperature of 20.4 °C (Graham et al. 2002). The site is located on a south-west facing slope of 13.5% and 18.5% for the upper and lower parts of the trial site respectively. The soil on the upper slope is classified as a Mayo form and on the lower slope as a Bonheim form (Soil Classification Working Group, 1991) (Mthimkhulu et al. 2016).

5.2.2 Experimental design and treatments

The trial covers an area of approximately 7200 m^2 (90 m × 80 m) consisting of 32 plots of 175 m^2 each with sugarcane planted in rows with a spacing of 1.4 m. The experiment is a split-plot factorial design arranged in a randomized complete block with four replicates for treatments burnt and eight replicates for treatments not burnt at harvest. The main plot treatments are (1) green cane harvesting with all residues mulched over the plot area (M), (2) cane burnt prior to harvesting with cane tops (unburnt top green leaves) left scattered evenly over plot area covering two thirds of the surface area (BS), and (3) cane burnt prior to harvesting with all residues removed from the plots (BR). The split-plots consist of fertilized (F) and unfertilized (F0) treatments (Table 5.1). For this modelling study, data from 24 plots out of the 32 were selected to work with an even number of four replicates for all treatments.

Table 5.1 Different treatments in the South African Research Institute (SASRI) BT-1 long-term sugarcane trial

No	Treatment	Code
1	Mulched, fertilized	MF
2	Mulched, not fertilized	MF0
3	Burnt with tops scattered, fertilized	BSF
4	Burnt with tops scattered, not fertilized	BSF0
5	Burnt with all residues removed, fertilized	BRF
6	Burnt with all residues removed, not fertilized	BRF0

The sugarcane crop was grown for an average of eight years per cycle, which equates to a planted crop and seven ratoons. Conventional tillage was used before planting for the first 30 years, but since then minimum tillage has been used (Graham et al. 2002). Since 1939, fertilizer was applied as a 5:1:5 (46) nitrogen phosphorus and potassium (NPK) combination at 670 kg ha^{-1} on F plots, translating into a rate of 140 kg ha^{-1} N, 28 kg ha^{-1} P and 140 kg ha^{-1} K. Fertilizer was applied 40 days after harvesting the previous crop (Van Antwerpen et al. 2001).

5.2.3 Measured data

5.2.3.1 Long-term yield and soil organic matter data

Five sugarcane varieties were grown on the site from 1939 to 2017. These were Co281 (1939–1947), Co301 (1948 – 1956), NCo376 (1957 – 1990), N16 (1991–2001), N27 (2002–2013) and currently N41 (2014 – present) (Van Antwerpen et al. 2001, Mthimkhulu et al. 2018). Harvesting dates changed over the years with cane harvested every 24 months from 1930–1965, every 15 months from 1966–1986, and every 12 months from 1987 to present. Yield and SOM data for sugarcane treatments were retrieved from the SASRI trial records and published literature.

5.2.3.2 Soil data

Soil from strips between the experimental blocks have had grass growing on them for the duration of the experiment was previously sampled and considered to be a close representation of the initial soil conditions before the start of the trial (Graham et al. 2002). This site has an unusually high SOM content compared to other South African soils. The virgin soil contains 4% OC, and this makes it to fall under a small proportion of South African soils that have more than 2% OC (representing only 4% of the South African soils) (FSSA 2007). The average clay, sand, silt content of the soil were 43.4, 33.5 and 23.2% across all depths respectively (Mthimkhulu et al. 2016). Soil parameters used for modelling include drained upper limit (DUL), lower limit water content at 15 MPa (LL15), and saturation (SAT) estimated from soil texture using DSSAT software, bulk density (BD), organic C (%), and soil pH (H_2O) from measured data (Table 5.2). Soil hydraulic conductivity was measured using a dual-head infiltrometer (Decagon Devices, Inc. 2365 NE Hopkins Court Pullman WA 99163) during the 2016 – 2017 growing season to be used in the parameterization of the APSIM soil file.

Table 5.2 Bulk density (BD), saturation (SAT), drained upper limit (DUL), lower limit at 15 MPa (LL15), soil pH (H_2O), and organic carbon (OC) for the BT-1 long-term trial at SASRI, Mt Edgecombe.

Soil Layer (m)	BD ($Mg\ m^{-3}$)	SAT ($m^3\ m^{-3}$)	DUL ($m^3\ m^{-3}$)	LL15 ($m^3\ m^{-3}$)	pH (H_2O)	OC (%)
0–0.05	1.25	0.48	0.37	0.22	6.6	6.0
0.05–0.15	1.15	0.48	0.37	0.22	7.0	4.0
0.15–0.30	1.15	0.48	0.37	0.22	6.9	2.0
0.30–0.45	1.15	0.48	0.37	0.22	6.9	1.0
0.45–0.65	1.15	0.48	0.37	0.22	6.9	1.0
0.65–0.85	1.15	0.48	0.37	0.22	6.9	1.0
0.85–1.00	1.15	0.48	0.37	0.22	6.9	1.0

DUL: represents field capacity

LL15: represents permanent wilting point

5.2.3.4 Daily weather data

Daily minimum and maximum temperature, precipitation and solar radiation data were used to create a long-term weather file from 1939-2017. Mount Edgecombe weather data were obtained from the SASRI WeatherWeb database (https://sasri.sasa.org.za/weatherweb/weatherweb.ww menus.menu_frame?menuid=1). The annual average ambient temperature (TAV) and annual amplitude in monthly temperature (AMP) was calculated using the long-term daily minimum and maximum temperatures. These calculated values of TAV and AMP were inserted into the meteorological file by the tav_amp software programme (https://www.apsim.info/Products/Utilities.aspx).

5.2.3.5 APSIM model set-up

The model is influenced by soil, crop management, environmental and genetic variables (Keating et al. 1999). The APSIM sugar module (Carberry and Abrecht 1991), soil water module (SOILWAT), soil nitrogen (SOILN) and residue module (RESIDUE2) (Probert et al. 1998) were already within APSIM to simulate the scenarios described in this chapter. These are one-dimensional modules, using a daily time step and influenced by weather conditions. The APSIM sugar module used default values of radiation use efficiency (RUE) for plant and ratoon crops (1.8 and 1.65 g of above-ground dry matter production per MJ^{-1} of intercepted solar radiation, respectively) (Keating et al. 1999). Root mass is calculated as a fraction of above-ground dry matter, and this fraction varies from 0.3 at emergence to 0.2 at flowering. The model partitions 70% of above-ground dry matter production to the stalk, and sucrose mass is calculated by partitioning a constant fraction of stalk mass increments to this pool after a given threshold of stalk matter has accumulated. The leaf sink demand and a stalk growth stress factor can adjust sucrose partitioning (Singels and Bezuidenhout 2002).

5.2.4 Model application: Long-term simulations

Model calibration was done using the MF treatment (best management practice recommended by SASRI). Crop parameters for sugarcane were obtained from the APSIM sugar module. The variety used for the simulation was NCo376, a very popular variety in South Africa for about 30 years and one of the default varieties in the model. Planting was simulated on 1 November at a depth of 150 mm and there were four ratoons before another planting was done (APSIM model allows a maximum of four ratoons). Fertilizer was applied every year as ammonium nitrate at a rate of 140 kg ha^{-1} on 1 December on all fertilized treatments (no P and K added in the model). Harvesting was done as per the intervals outlined in Section 5.2.3.1. For the mulched treatments (MF, MF0), all residues were simulated to be retained after harvest, while for the BS treatments 70% of residues were retained and for the BR treatments, all residues were simulated to be removed after harvest. The leaching of NO_3-N was estimated using the model for different residue management and fertilization treatments.

5.2.5 Low fertilizer application rates scenarios

The soil fertility decline and leaching of nutrients out of the root zone can be addressed using various management practices in sugarcane production. One of these management practices can be reducing the amount of N fertilizer applied, taking advantage of potential N mineralization from residues. After calibration and testing, the model was used to simulate low fertilization rate scenarios to investigate whether long-term N benefits from mulching can substitute a certain proportion of N fertilizer application and maintain high yields on lower fertilization rates. Scenarios of 40 kg ha^{-1} and 80 kg ha^{-1} N application on mulched treatment were simulated and compared to MF treatment. The same procedures outlined in 5.2.4 were used for the simulation, with only the low fertilizer rates for these scenarios used.

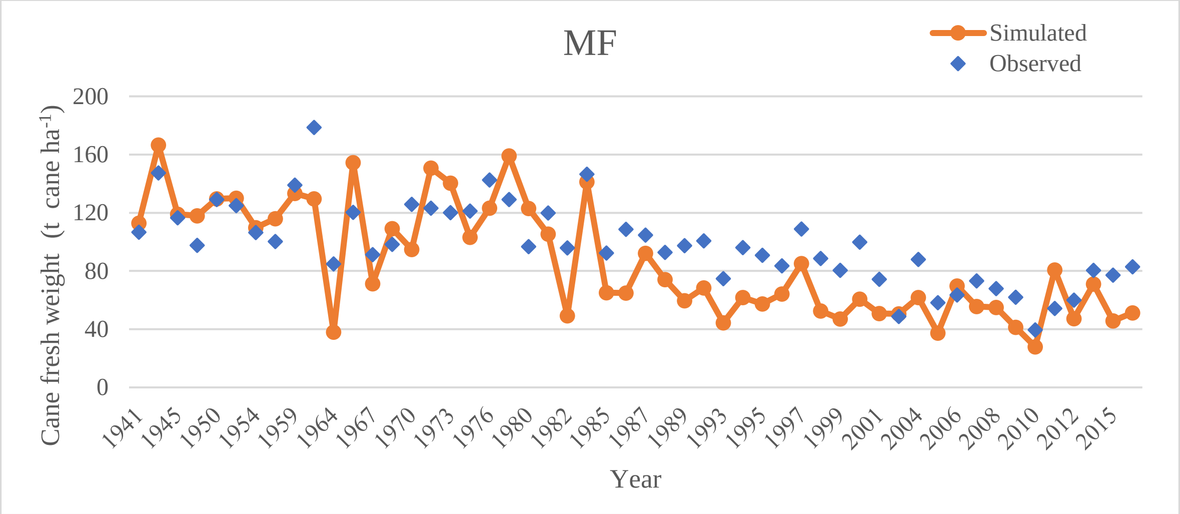
5.2.6 Testing model performance

Model evaluation was performed using long-term yields and SOM data from the MF, MF0, BSF and BSF0 plots from 1941, and from the BRF and BRF0 plots from 1980 (burning and removing cane tops started in 1980). Model performance was tested using the square of the correlation coefficient (r^2), the mean absolute error (MAE), root mean square error (RMSE), and the index of agreement (D) based on the criteria outlined in Section 3.2.5. The measured and simulated data were also graphically compared.

5.3 RESULTS

5.3.1 Influence of long-term management practices on sugarcane yields

Sugarcane management practices (fertilized and unfertilized, mulched and burnt) had significant effects on yields. Fertilized treatments generally had higher yields compared to unfertilized treatments. Mulched treatments had higher yields than burnt treatments in either of the fertilizer regimes used. Decreasing trends in yields were evident for all treatments in both the measured and modelled data (Figure 5.1), although this is more closely related to the change in crop duration over the years (cutting age was 24 months at the beginning of the trial, changed to 15 months in 1966 and 12 months in 1987). Generally, the model yield estimations were robust, but there was a poor prediction in some years, such as underestimations in 1961 and 1964. In 1963 harvesting was done and another was done in 1964, thus resulting to low yields for that year in all treatments due to one-year crop duration instead of the normal two years for that period. Fertilized treatments yields were underestimated (difference between measured and simulated yields above RMSE) in the period between 1987 and 2009 when harvesting was done every 12 months. Unlike the fertilized treatments, unfertilized treatments were mostly overestimated by the model, more so in the early stages of the trial and becoming more accurately estimated in later years. The BRF0 treatment was generally overestimated, but the trends over time were similar.


MF
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Observed
Cane fresh weight (t cane ha^{-1})
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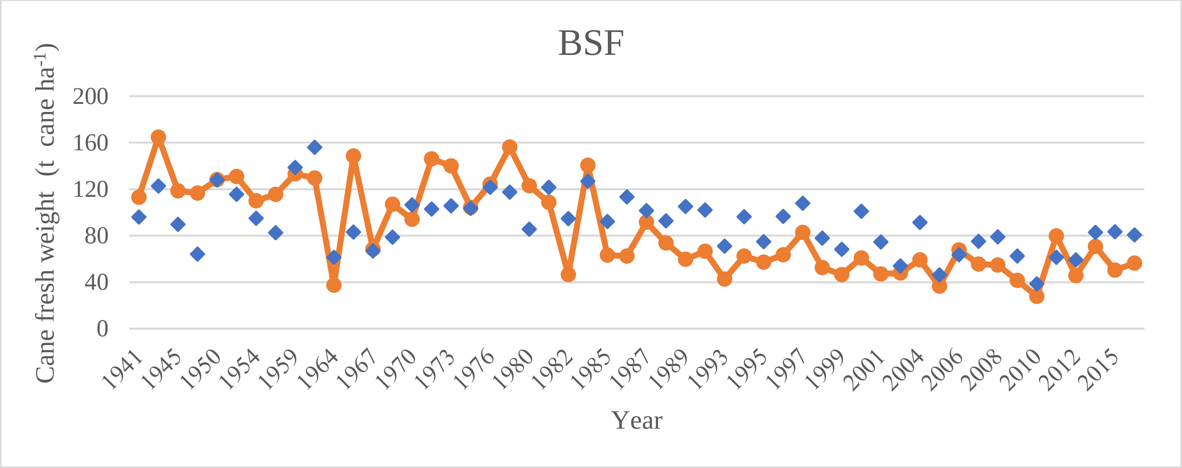
BSF
Cane fresh weight (t cane ha^{-1})
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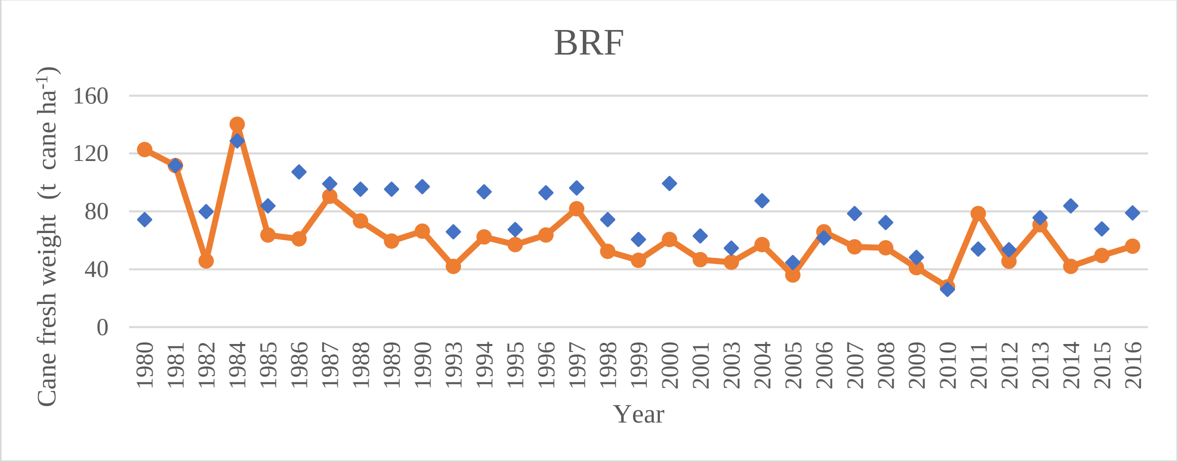
BRF
Cane fresh weight (t cane ha^{-1})
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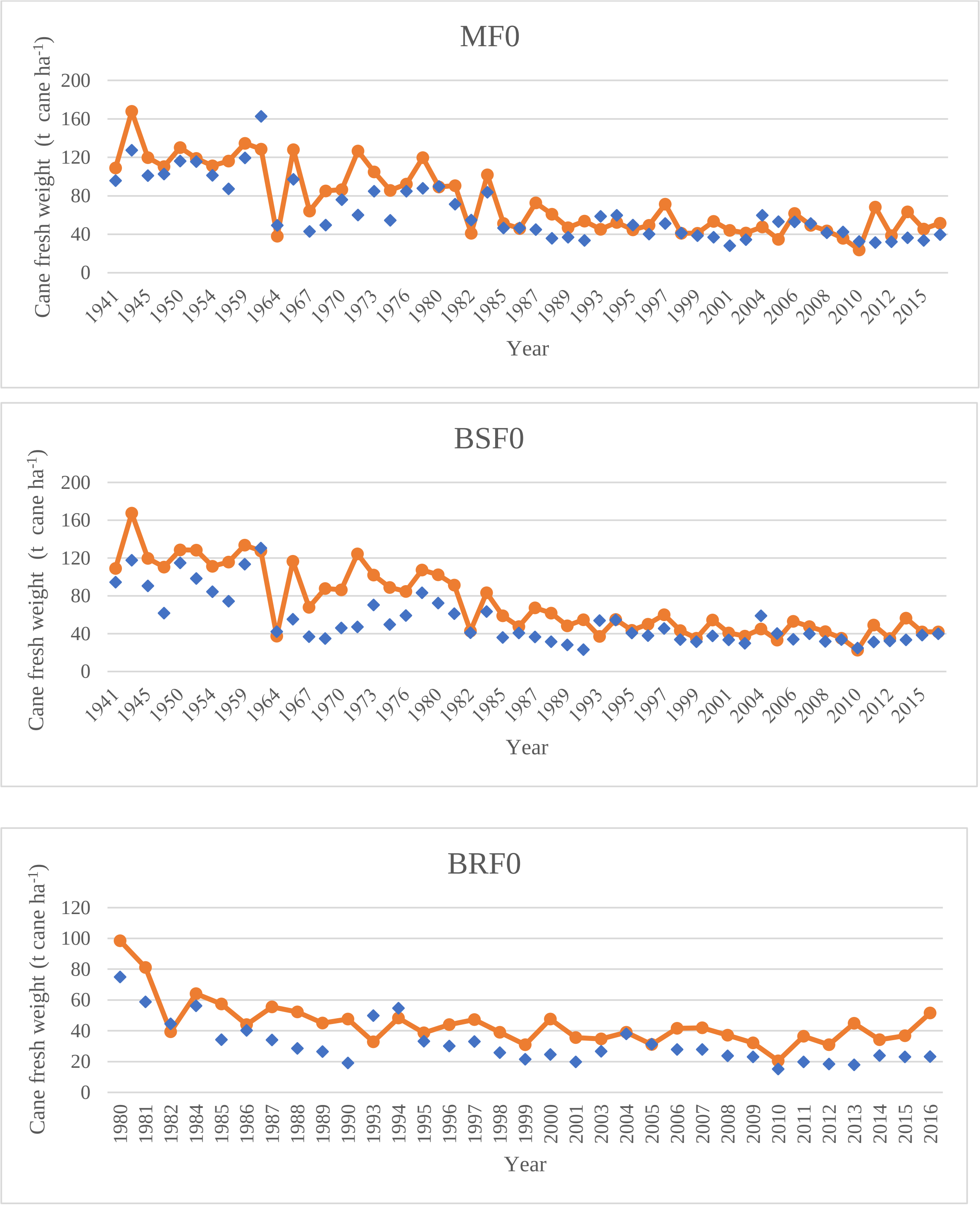


Figure 5.1. Observed and simulated cane fresh weight yields of mulched (M), burnt with cane tops scattered (BS), burnt with cane tops removed (BR), fertilized (F) and unfertilized (F0) treatments in the long-term sugar cane trial. (1941 – 2016 for M and BS, 1980 – 2016 for BR treatments)

Statistical analysis of measured and simulated yields did not indicate a good yield simulation in most cases (Table 5.3). Retaining residues after harvest proved to be beneficial to yield, as both measured and simulated data showed relatively higher yields on mulched than burnt treatments. The model was, therefore, able to simulate the relative effect of residue management and inorganic fertilization on sugarcane yields. Comparison of measured and simulated data resulted in MAE higher than the acceptable 20% in fertilized and unfertilized treatments, with only the MF0 treatment meeting the statistical criteria. The MF0 had an MAE of 18.8%, meeting the statistical criteria, and the BSF0 and BRF0 treatments had higher MAEs of 33.4% and 44.8%, respectively, indicating the least accurate simulation by the model for these two treatments. The RMSE was relatively higher in fertilized than unfertilized treatments. The D value met statistical criteria ($D > 0.8$) in the MF, MF0 and BSF0 treatments, and for all other treatments, the D value was above 0.73. The r^2 did not meet statistical criteria for any of the treatments indicating a poor correlation between measured and simulated cane yields.

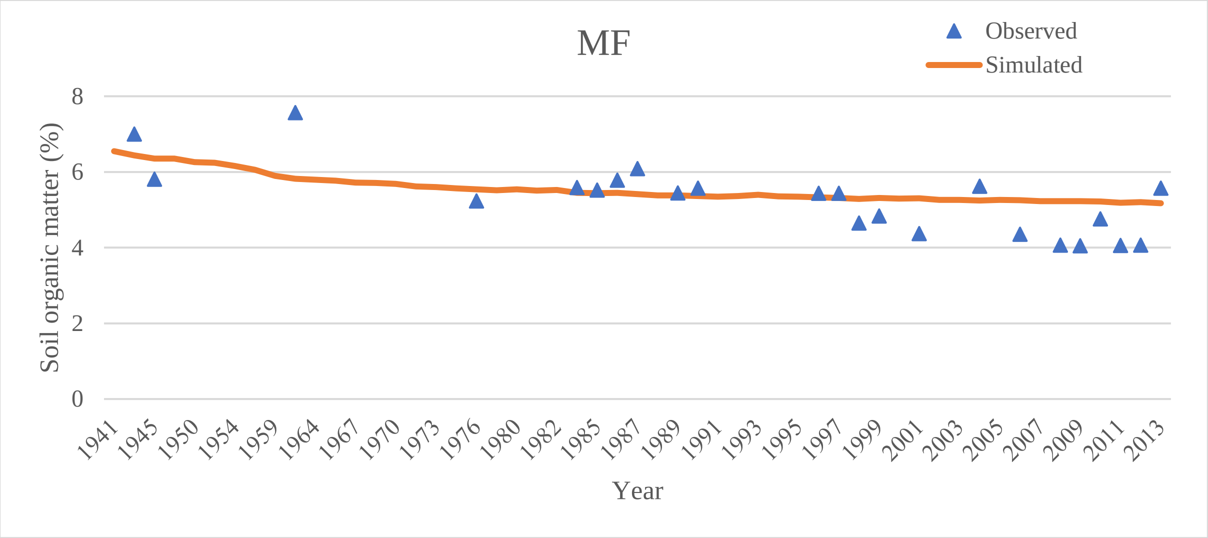
Table 5.3 Statistical evaluation of Observed and simulated cane fresh weight yields of mulched (M), burnt with cane tops scattered (BS), burnt with cane tops removed (BR), fertilized (F) and unfertilized (F0) treatments in the long-term sugar cane trial. (1941 – 2016 for M and BS, 1980 – 2016 for BR treatments)

Treatment	r^2	D	MAE (%)	RMSE (t cane ha^{-1})
MF	0.65	0.84	22.5	25.7
BSF	0.44	0.77	29.1	27.1
BRF	0.43	0.74	26.5	24.6
MF0	0.74	0.92	18.8	16.3
BSF0	0.68	0.80	33.4	26.1
BRF0	0.54	0.73	44.8	16.4

5.3.2 Simulating long-term sugarcane management practices on soil quality

5.3.2.1. Soil organic matter

Simulation of SOM dynamics over the years (1939-2013) indicated a decline in SOM content across all treatments. Comparisons between observed and simulated SOM content of fertilized treatments are shown in Figure 5.2. Observed and simulated results showed a decline in SOM for all treatments regardless of mulching or residue burning and removal after harvest. The magnitude of SOM decline, however, differed with the management practices used between the treatments. The mulched treatments (MF and MF0) had relatively higher SOM levels than burnt treatments (BSF, BRF, BSF0, BRF0) over the 73 years of simulation, which clearly indicates the beneficial effects of retaining crop residues on SOM. This was consistent with a study by Luo et al. (2011) who reported that changes in SOM were highly correlated with the amount of residues retained in agricultural practices. The MF and MF0 treatments displayed SOM declines from 7% SOM in 1939 to 5.5% and 4.4% in 2013, respectively, with the BSF and BSF0 declining from 7 % to 4.6% and 3.9% SOM respectively in 2013. The SOM content was not significantly influenced by the retention of cane tops (BS treatments) when compared with burning and removing all residues. The difference between SOM content was 0.2 % in BSF and BRF treatments, 0.1 % in BSF0 and BRF0 treatments after 73 years of simulation. Fertilized treatments generally had higher SOM levels than their unfertilized partner treatments, which indicates that fertilization can slow down the decline of SOM content. A study by Beza and Assen (2016) reported high soil C loses after land has been converted to agriculture, which was stabilized with an increased duration of agricultural activities. In this trial, the SOM seem to have reached the stabilization phase, both observed and simulated SOM are almost stable from year 2000 to 2014.


MF
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Soil organic matter (%)
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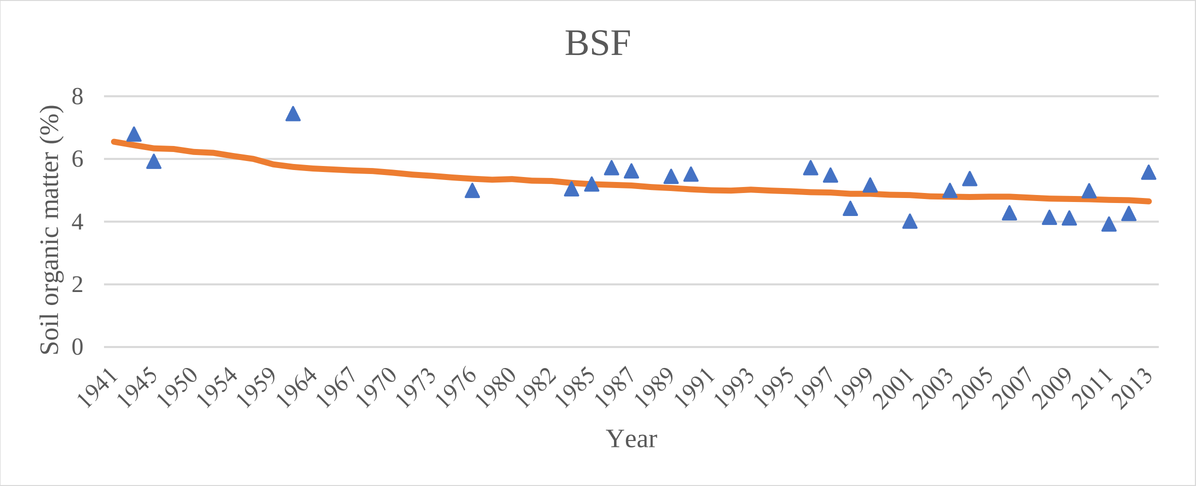
BSF
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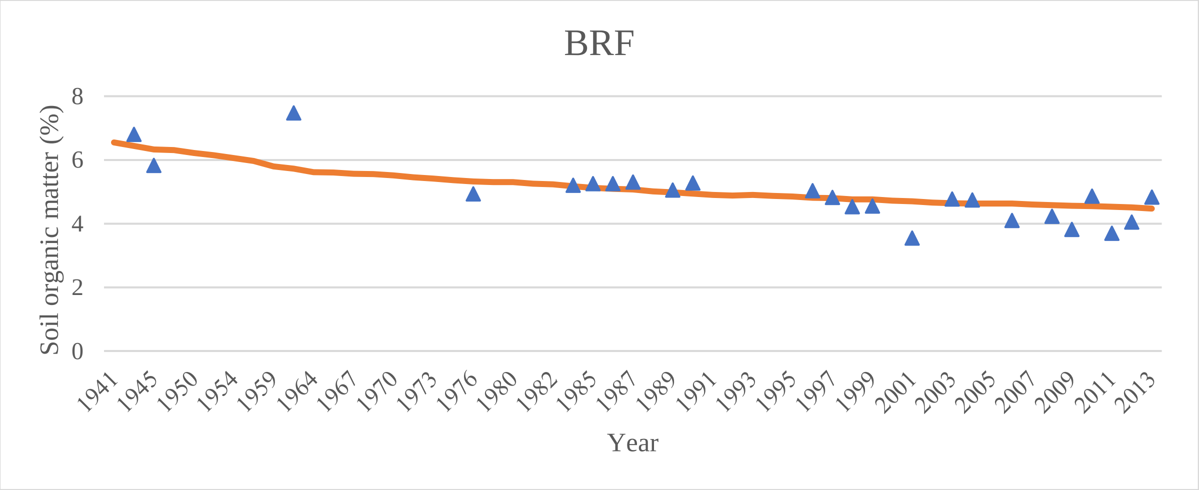
BRF
Soil organic matter (%)
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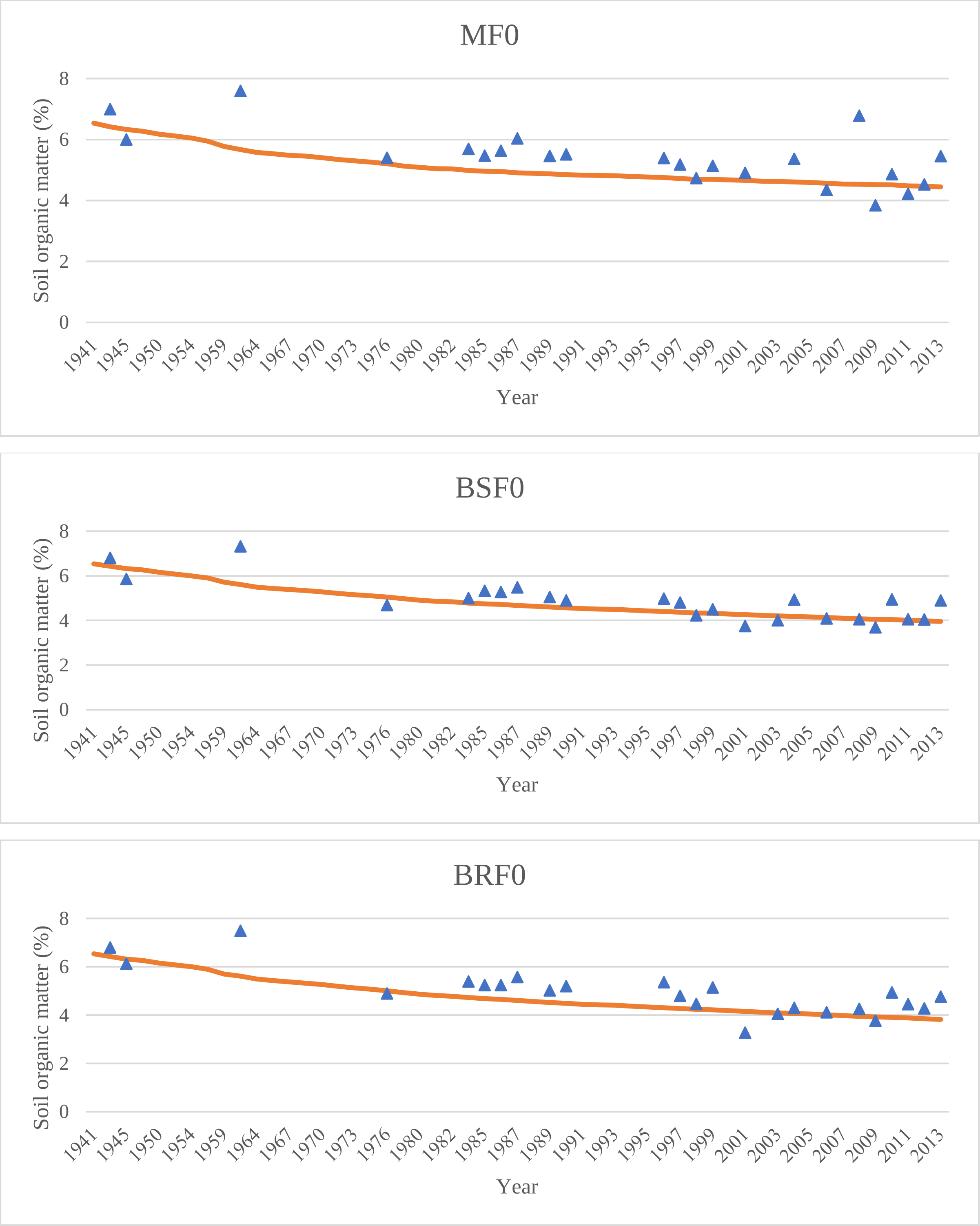


Figure 5.2. Observed and simulated soil organic matter content of the mulched (M), burnt with cane tops scattered (BS), burnt with cane tops removed (BR), fertilized (F) and unfertilized (F0) treatments in the long-term sugar cane trial (comparison done at a depth of 0.2 m).

A summary of the statistical comparison between observed and simulated SOM is shown in Table 5.4. The model did not meet the statistical criteria for r^2 and D, but was only met with

MAE across all treatments. Fertilized treatments had a higher RMSE than unfertilized treatments, indicating a higher degree of precision in unfertilized treatments. The D and r^2 values, however, did not meet the statistical criteria in any of the treatments. Despite the high error variance between the treatments (low r^2), the model performed fairly well in estimating SOM changes over the years.

Table 5.4 Statistical evaluation of Observed and simulated soil organic matter content of the mulched (M), burnt with cane tops scattered (BS), burnt with cane tops removed (BR), fertilized (F) and unfertilized (F0) treatments in the long-term sugar cane trial.

Treatment	**r^2**	**D**	**MAE (%)**	**RMSE (%)**
MF	0.22	0.57	12.4	0.86
BSF	0.14	0.56	13.1	0.94
BRF	0.29	0.63	11.2	0.81
MF0	0.29	0.67	9.8	0.73
BSF0	0.31	0.66	11.4	0.76
BRF0	0.37	0.68	10.6	0.75

5.3.2.2 Deep drainage and nitrogen leaching dynamics

The total amount of water lost through deep drainage differed between the treatments, which would have also influenced the amount of N leaching between treatments. The residue cover present in these treatments is known to influence soil water content through reducing evaporation (Vallis et al. 1996, Van Antwerpen et al. 2002). Residue burning reduced the amount of drainage as indicated but scattering of the cane tops after burning led to increased drainage compared to removal of tops (BR) (Figure 5.3). The results showed that mulched treatments are estimated to have lost the highest volume of water through drainage over 76 years (MF and MF0 lost 13 209 mm and 15 164 mm respectively) and the burnt treatments with cane tops raked off losing the smallest amounts (BRF and BRF0 lost 10 701 mm and 12 908 mm respectively). This was also reported in a similar study by Cheong and Teeluck (2016) where sugarcane grown on fields with leaf residue cover lost more water through drainage than treatments with no residue cover in a water use efficiency study in Mauritius. The overall trend in the amount of cumulative drainage based on residue management observed on both fertilized and unfertilized treatments showed the following declining order: M > BS > BR. Less drainage was simulated for the fertilized treatments when compared to their similar but unfertilized treatments. The fertilized treatments had higher yields which can result to higher water use leading to a lower proportion of water lost through drainage.

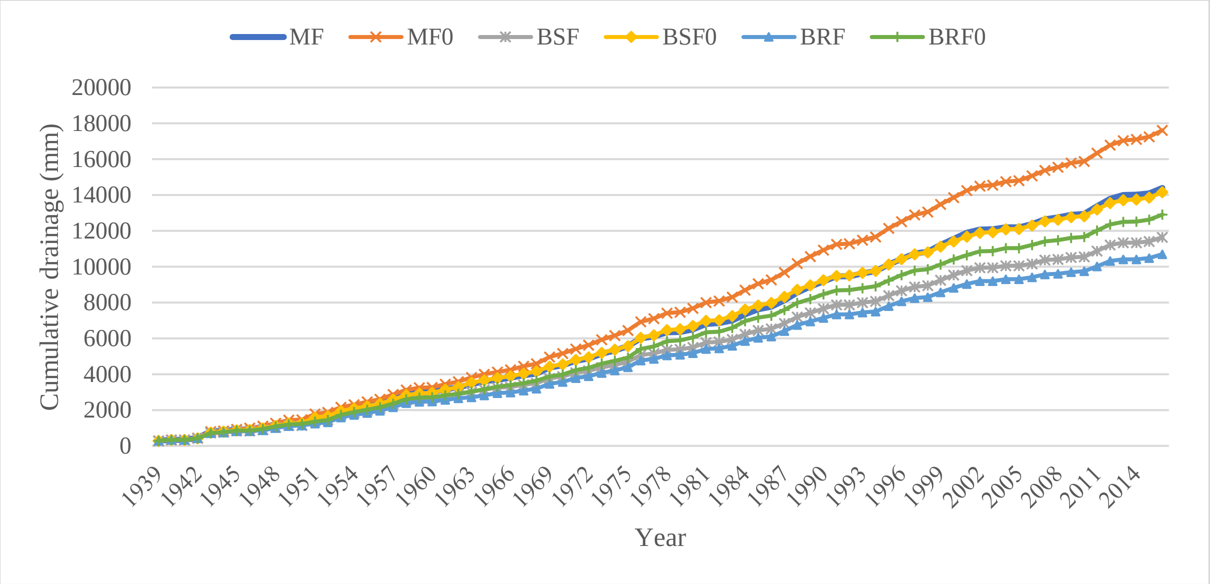


Figure 5.3 Cumulative deep drainage over the 76 year simulation period for mulched (M), burnt with cane tops scattered (BS), burnt with cane tops removed (BR), fertilized (F) and unfertilized (F0) treatments in the long-term sugar cane trial.

Annual N leaching proved to be highly variable for successive years as affected by rainfall, amount of deep drainage and fertilizer application strategy. Fertilized treatments (MF and BSF) generally had higher N leaching than unfertilized treatments. Leaching was also predicted for unfertilized treatments (MF0 and BSF0) which showed a declining trend in N leaching over the years (data not shown). In the last 20 years, NO_3-N leaching was below 20 kg N ha^{-1} per year. The differences in cumulative drainage also brought differences in cumulative leaching among the treatments. The model simulated higher N loss in fertilized treatments over the years, which could be expected as the result of seasonal inorganic N addition. At least 3 900 kg N ha^{-1} has been lost in each of the fertilized treatments since the experiment started in 1939. Residue burning reduced the amount NO_3-N leaching in the fertilized treatments (Figure 5.4) as shown by the MF having higher cumulative leaching than BRF and BSF. The MF had the highest cumulative leaching (1939-2016) estimated to have lost 4 526 kg ha^{-1} NO_3-N over the years (or about 59.6 kg NO_3-N ha^{-1} yr^{-1}). The burnt treatments (BSF and BRF) lost 3 909 kg ha^{-1} (or about 51.4 kg NO_3-N ha^{-1} yr^{-1}) and 3 914 kg ha^{-1} (or about 51.5 kg NO_3-N ha^{-1} yr^{-1}) respectively, showing an insignificant difference in NO_3-N leaching between the latter two treatments. The unfertilized treatments (MF0, BSF0, and BRF0) had relatively low leaching, that was almost identical. Unfertilized treatments showed no difference between burning or mulching treatments with regards to the amounts of N leached over the years, with about 700 kg ha^{-1} N over 76 years (or about 9.2 kg NO_3-N ha^{-1} yr^{-1}).

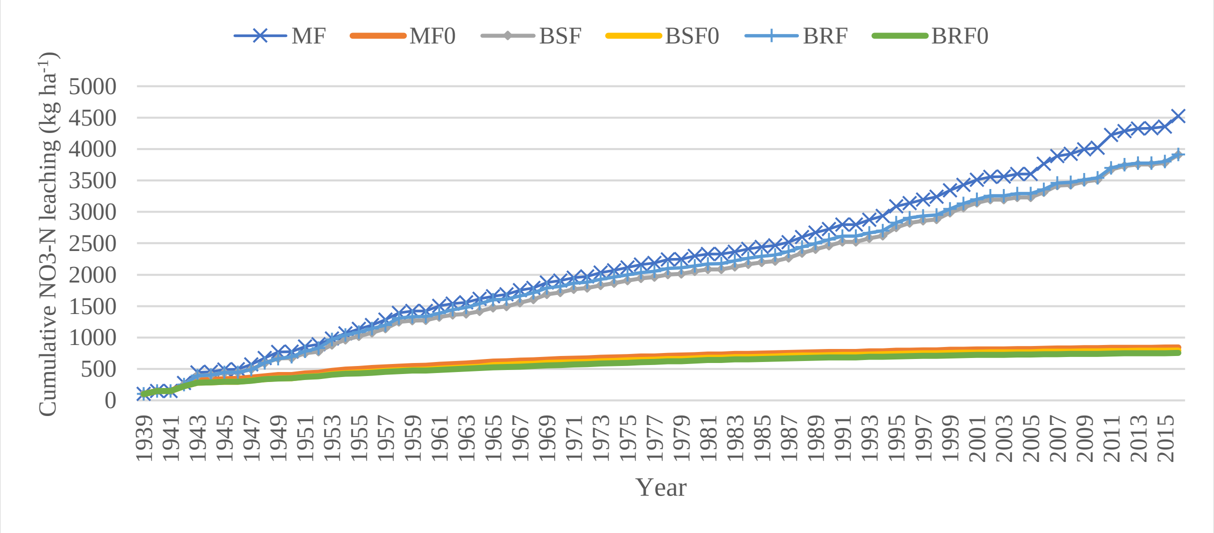


Figure 5.4 Cumulative nitrate-nitrogen (NO_3-N) leaching over a 76-year simulation of the mulched (M), burnt with cane tops scattered (BS), burnt with cane tops removed (BR), fertilized (F) and unfertilized (F0) treatments in the long-term sugar cane trial.

5.3.2.3 Fertilizer application scenario results

Sugarcane yields

Fresh cane weight yield on mulched treatments did not significantly differ with the reduction in N fertilization rate (Figure 5.5). For different fertilization rates scenarios, the model indicates that high (140 k ha^{-1} N application) fertilization on mulched treatments did not increase yields compared to lower rates (40 and 80 kg ha^{-1} N application). Yield differences can only be seen in high rainfall seasons whereby moisture was likely non-limiting (see period between 1970 and 1978 in Figure 5.5). Since the year harvesting was done every 12 months (1987 to present) the yields are almost the same across all fertilizer rates. The results indicate that under mulching there is a high possibility of over-fertilization if the benefits of NO_3-N released from the mineralization from microbial decomposition of residues is not considered in the fertilization programme.

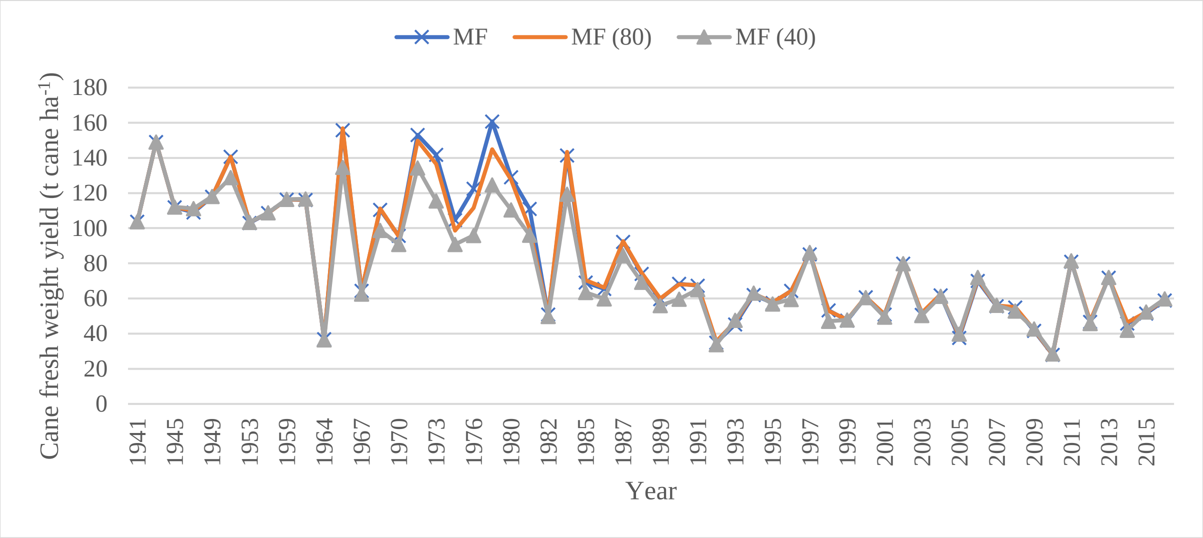


Figure 5.5 Simulated cane fresh weight of mulched and fertilized (MF) treatments on recommended rate (140 kg ha^{-1} N) used in the long-term sugarcane trial and lower rates fertilizer application scenarios (40 and 80 kg ha^{-1} N). MF: mulched and fertilized, MF (40): 40 kg ha^{-1} application rate, MF (80): 80 kg ha^{-1} application rate.

Nitrate leaching

As expected, simulated NO_3-N leaching in the mulched treatment was reduced by lower inorganic N fertilization rates (Figure 5.6). The cumulative leaching over 76 years was estimated to be reduced from 4 526 kg ha^{-1} for the 140 kg ha^{-1} fertilization rate to 1 313 kg ha^{-1} in the 40 kg ha^{-1} scenario (or about 17.3 kg NO_3-N ha^{-1} yr^{-1}), and 2 261 kg ha^{-1} in the 80 kg ha^{-1} scenario (or about 29.8 kg NO_3-N ha^{-1} yr^{-1}). This shows a 70% reduction in N leaching in the 40 kg ha^{-1} fertilizer rate with no significant effect on the cane fresh weight at harvest.

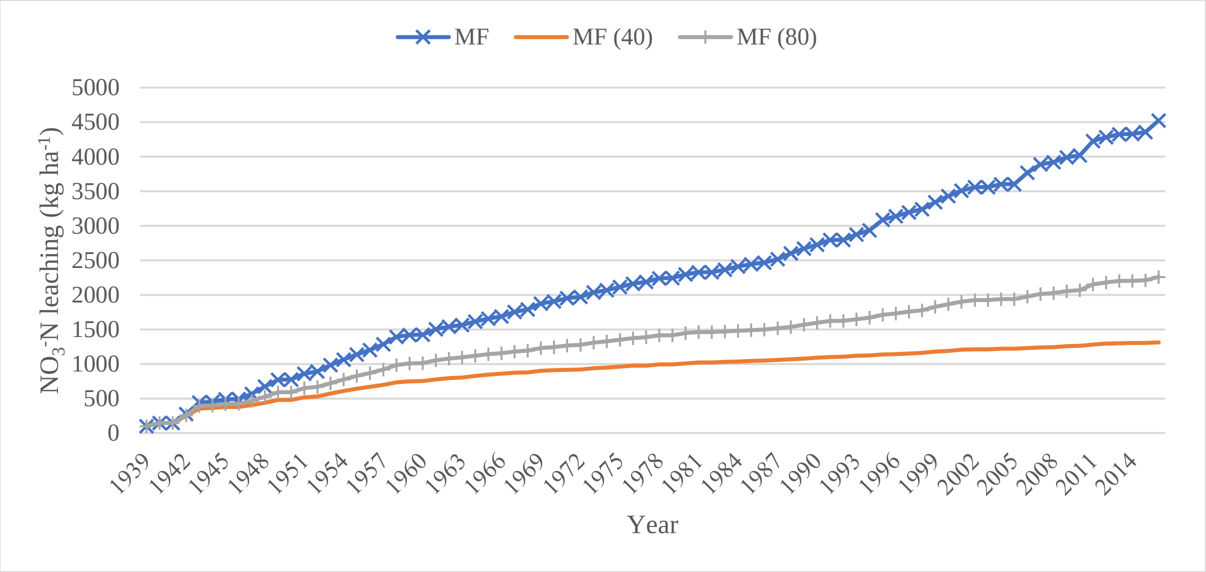


Figure 5.6 Simulated **c**umulative nitrate-nitrogen (NO_3-N) leaching of mulched and fertilized treatments on recommended rate (140 kg ha^{-1} N) used in the long-term sugarcane trial and lower rates fertilizer application scenarios (40 and 80 kg ha^{-1} N). MF: mulched and fertilized, MF (40): 40 kg ha^{-1} application rate, MF (80): 80 kg ha^{-1} application rate.

5.4 DISCUSSION

Simulating sugarcane yields

Observed and simulated results indicated that fertilizer application increased yields in sugarcane monoculture system. Non-fertilized treatments also produced relatively high yields, especially for the first two periods (1939 – 1960), and this can be attributed to the high nutrient storage capacity of the soil. Cation exchange capacity (CEC) ranged between 14.8 and 20.1 cmol$_c$ kg^{-1} in the 0 – 200 mm soil layer (Van Antwerpen and Meyer 1998). The high soil fertility resulted in measured yields of fertilized and non-fertilized treatments not being significantly different over the first 18 years (Van Antwerpen et al. 2001). Residue retention led to consistently higher yields in the mulched treatments compared to the burnt, however, Van Antwerpen et al. (2001) reported that the yields between the treatments over the years were not statistically significant. This agrees with a previous study by Vallis et al. (1996) on beneficial effects associated with residue retention, which included conserving moisture by reducing evaporation, reducing erosion, improving soil structure and increasing soil fertility when residues are decomposed, and all these factors have shown to be beneficial to long-term sugarcane yields. In some years, poor yield estimations were observed mostly in the form of overestimations by the model. This is probably a result of short-term extreme weather conditions at critical stages of the crop affecting growth, which the model cannot account for.

Temperature, water use, rainfall and incident solar radiation can be highly variable from one day, week, month and season to the next, thus causing variation in attainable yields. High temporal spatial variabilities due to short-term weather patterns and extreme events not considered by the model can be the cause of poor yield estimations in some years. In addition, poor estimations could have also been caused by other factors such as insect pest attacks, or outbreak of diseases, which have not been simulated by APSIM.

The different sugarcane varieties planted in the trial over the years can negatively influence the ability of the model to estimate yields. Changing varieties can have a significant influence on yields (Liu et al. 2010), thus affecting the long-term measured yields. The same cultivar was used throughout the simulation, therefore, yields from different varieties (measured vand simulated yields) were compared in some years. The model simulates cane growth as a function of weather, soil water and N inputs, with yields strongly influenced by radiation, temperature, crop phenology, physiology and architecture (Cheeroo-Nayamuth et al. 2000). In the model, varieties may not be properly parameterized for local conditions and can negatively affect the robustness of the model predictions.

Harvested stalks and residue burning can contribute to substantial nutrient losses from the system if they are not adequately addressed in fertilizer programmes, thus negatively influencing the yields. A decline in P and K in long-term sugarcane mono-cropping system as a result of nutrient mining was reported in a study on the same trial (Van Antwerpen et al. 2001). The N limited yields estimated by the model might be overlooking the beneficial or limiting effects of other nutrients that comes with NPK fertilizers which can lead to overestimations in unfertilized treatments (P and K limited yields) or underestimations in fertilized treatments (yields promoted by P and K additions) if the other factors are assumed to be non-limiting. Fertilizer application leads to higher biomass production and contributes to elevated SOM and lower the soil pH levels. The lowering of soil pH is mainly driven by the N-fertilizer and to a much lesser extend (not significant) by organic matter decomposition (Van Antwerpen et al. 2001). This acidification potential of inorganic fertilization can also negatively influence measured yields in fertilized treatments.

Simulating soil C dynamics

Soil cultivation has been highlighted to be the major reason of declining SOM trends in arable agriculture by burying crop residues and increasing soil microbial activities (West and Post 2002, Ogle et al. 2005). Measured and simulated results showed a decline over the years, with an initial steeper decline in the early compared to later years shown by simulated SOM content. The high SOM decline in the early years of land conversion to agriculture indicated by all management practices was a consistent observation that has also been reported in previous studies (Dominy et al. 2002, Beza and Assen 2016). After a rapid decline in the early years of cultivation, SOM is expected to reach a steady phase where the decline levels off (Swanepoel et al. 2016), but in the simulation that period has not yet been reached since all management practices are still showing a decline.

Soil organic carbon is a product of the decomposition of organic matter and accumulation of C in the soil, thus making residue management crucial in determining long-term soil C stocks in cropping systems. The higher biomass production, as a result of fertilization, increases the amount of crop residue inputs into the soil, hence, higher SOM in fertilized than unfertilized treatments. The simulation clearly indicated the benefits of mulching on maintaining high SOM content is sugarcane monoculture systems. In a study by Mthimkhulu et al. (2018) on the same trial, the residue retention benefits on SOC were only restricted to shallow depths regardless of the amount of residues retained. This was in agreement with the simulated results, as the model's robustness in estimating soil C dynamics was shown by high SOC in the top layer compared to other soil layers as a result of high residue returns and minimal soil disturbance in sugarcane cropping systems. According to Thorburn et al. (2001), sugarcane decomposition is a relatively slower process compared to other residues with similar biochemical composition. This keeps residues on the soil surface for a longer period allowing more time to be incorporated into the soil, thus contributing to soil C accumulation.

Burning the residues negatively affect soil C sequestration and the overall benefits of residue cover to soil properties that can be beneficial to the next crop. The results indicated a difference between long-term SOM content of mulched compared burnt treatments. However, despite burning residues for 73 years in BR treatments, the SOM content is still relatively high (soil organic carbon (SOC) > 3.5%, (Mthimkhulu et al. 2016) confirming that the magnitude of SOM loss with respect to management practices can be site specific. The underground roots that remain after burning in the BR treatments might still be adding considerable amounts of organic residues that slows down the decline of carbon over the years.

Simulating soil N dynamics

The simulation indicated that residue retention did not subsequently result in higher N benefits compared to burning or removal of residues in sugarcane monoculture system. Despite high residue returns and SOM content in mulched treatments, total N mineralization from residues and SOM pools was less than in burnt treatments since the trial commenced. The addition of residues increase soil microbial activities, but the high C:N ratio of the residues results to initial N immobilization, with a small amount of N mineralized (Robertson and Thorburn 2007). Since 1939, an estimated 1 778 kg ha^{-1} N and 2 028 kg ha^{-1} N has been mineralized in the MF and MF0 treatments respectively, indicating more mineralization in unfertilized than fertilized treatment under mulching. Thorburn et al. (2002) reported that many years of residue retention may be needed for soil C and N cycling to reach a new equilibrium for N immobilization to match mineralization, and further net N mineralization from residues.

Nitrate leaching showed to be highly related to N application and the volume of water moving out of the root zone through drainage. The amount of nitrates and water lost through drainage differed among treatments, indicating that soil moisture and N leaching can be greatly influenced by management practices. The high drainage on the M treatments can be attributed to the benefits of the thrash blanket to SOM returns, reduced runoff and an increase of soil water content. In the short term, a thrash blanket can reduce soil evaporation which increases soil water content in top layers. About 90% ground cover is provided by sugarcane residues of mass greater than 3 t ha^{-1} (Thorburn et al. 2001). In the long term, it can increase the soil C stocks resulting in high SOM content which improves soil structure and increase microbial activities (Graham et al. 2002). This increases water infiltration in mulched compared to burnt treatments where the soil can be prone to surface crusting and increase runoff thus reducing the amount of water getting into the soil profile which will reduce overall drainage.

Nitrate leaching was estimated to be high on fertilized compared to unfertilized treatments. In a study by (Cameron et al. 2013), it was stated that NO_3^-N leaching is highly dependent on NO_3^-N concentration in the soil solution and the amount of water lost through drainage over a certain period. This can be influenced by the ability of the soil to adsorb anions, as it can help retain NO_3^- making them available for plant uptake, enhancing soil nutrition in the process.

The addition of N fertilizers increased the amount of N in the soil solution thus increasing the NO_3^-N prone to leaching. The results showed that MF treatment had the highest annual NO_3-N leaching compared to the other treatments. Van Antwerpen et al. (2001) reported that an estimated 2 200 kg N ha^{-1} N input from mineralization in mulched and fertilized treatments, which was higher than the prediction of the current simulation (1 778 kg ha^{-1} N), with an additional 3 900 kg ha^{-1} from fertilizer application since the trial commenced. This proved that considerable amounts of NO_3^- are mineralized through the breakdown of organic residues, thus contributing to soil N and this is also the reason NO_3-N leaching also occurs in unfertilized treatments. This was also reported study by Mthimkhulu et al. (2018), where the N content of mulched treatments was reported to have increased significantly in both fertilized and unfertilized plots in the top 10 cm, indicating the benefits of retaining residues to increasing N content in both fertilized and unfertilized treatments.

Fertilization scenarios

The ability of the model to adequately simulate the long-term soil C and N dynamics of the BT 1 long-term trial allowed the application of the model to investigate a fertilizer application strategy that can minimize NO_3^- leaching. The results show that reducing the amount of fertilizer N applied can reduce NO_3^- N leaching without a significant reduction in yields on sugarcane cropping systems where all residues are retained after harvest. This has been previously reported in a study by Wiedenfeld (1995), where there was no yield response with increasing N application rates on rain-fed sugarcane production. This can be an indication of a significant contribution of potential N mineralization from SOM being able to satisfy a greater proportion of the crops N demand under mulching. Getting the same yields at different N rates indicates that increasing yields can only be achieved by exploring other factors rather than increased N application. Reducing fertilizer N can increase NUE and reduce N loss, but the high biomass production benefits that come with inorganic fertilization have to be maintained for high organic residue inputs to minimize SOM loss.

The cumulative NO_3-N loss increased with increases in fertilizer N application rate in the scenarios. This was an indication of over-fertilization regarding the fertilizer rate used in the trial. Reducing N export to the environment by accounting for mineralized N is an important management intervention required in the mulched and fertilized management practice. The balance between available N and crop N uptake is a key determinant of potential N loss from the soil system. Crop N uptake can be affected by soil characteristics, cultural practices as well as timing and method of N fertilizer application (Van der Laan et al. 2015). These results are emphasizing the importance of a better understanding of the fate of N in sugarcane production to improve fertilizer recommendations for improved NUE and reduce environmental losses. Small amounts of N mineralization can occur throughout the season, but this N may not be able to satisfy crop's demand at critical growth stages of high N demand. Timely N application to supplement mineralized N at these critical stages can be an important management intervention that can help reduce N leaching, though this will not be an easy exercise in large-scale sugarcane production.

5.5 CONCLUSION

Declining trends in long-term yields and soil quality in sugarcane monoculture systems requires new management practices to maintain high productivity without negatively affecting the quality of the soil and environment (offsite impacts). These gradual changes due to management practices are difficult to study in short-term experiments, therefore a combination of crop modelling and long-term monitoring data can be used to improve the understanding and evaluate long-term changes in yields and SOM under certain management practices as indicated by this study. Based on the results, the APSIM model was judged to adequately simulate long-term C and N dynamics in sugarcane cropping systems. The combination of mulching and fertilization was beneficial to long-term SOM content but needs N management strategies to reduce N leaching.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Overview of the study

Maintaining long-term high yields and good soil quality requires a thorough understanding of the carbon (C) and nitrogen (N) dynamics under different crop management practices. Long-term field trials offer valuable information on the sustainability of various cropping systems. The long-term maize trial in Pretoria and sugarcane trial in Mount Edgecombe offered a unique opportunity to carry out a study on the long-term effects of different management practices on C and N dynamics in South Africa. Due to the complexity of studying C and N dynamics in cropping systems, mechanistic modelling with APSIM was also employed to help understand these transformations and to evaluate different management options. The model was further used to estimate N leaching losses over the years for a comparative analysis between the different management practices. Manure application in maize and reduced N fertilizer application in sugarcane were assessed as management options that could maintain soil organic matter (SOM) or reduce leaching.

6.2 General conclusions for modelling long-term carbon and nitrogen dynamics in maize and sugarcane cropping systems

Calibrating and testing the APSIM model with growth analysis and soil water content data from the University of Pretoria, Hillcrest Campus Experimental Farm long-term maize trial in the 2016/2017 growing season was an important step to gain confidence in the model's ability to simulate aboveground growth dynamics of the newly calibrated maize cultivar. The model was able to adequately simulate aboveground dry matter (ADM), leaf area index (LAI) as well as soil water content over the season (see Chapter 3) following the modification of a few key crop parameters in APSIM. The ADM was well estimated in the early stages of maize growth in both treatments, but later in the season the simulated ADM became slightly higher than measured ADM for the control treatment. The leaf area index (LAI) was well predicted in the NPK treatment, but in the control, LAI was over-estimated during certain growth stages. Measured and simulated soil water content in the top 0.6 m of the soil profile was generally higher in the control (zero fertilizer) than NPK (full fertilizer) treatments. The results indicated that the APSIM model can be used to simulate maize dry matter accumulation and soil water content to help improve the understanding of C and N dynamics over the long-term.

Simulating annual yields accurately with the APSIM model proved to be a challenging exercise, especially for the control treatment due to a combination of various factors that may not have been represented in the model, for example, extreme (short-term) weather conditions, inconsistent planting dates, and use of various cultivars over the years (see Chapter 4). This highlights the importance identifying possible limitations of crop models and working on improving such aspects for accurate future simulations. Fertilizer application in maize had higher yields and SOM content over the 66-year long-term simulation, but the negative impacts on soil quality that comes with fertilizer application, which includes acidification due to N fertilizers and high N leaching, can negatively influence the long-term sustainably of crop production. The model estimated lower SOM in the control than NPK treatment. This agreed with measured data and gave confidence in model output by showing the potential of the model in helping to understand and identify improved the management practices in maize cropping systems. A scenario simulation indicated that manure application can be beneficial towards maintaining long-term SOM content. The application of manure can be highly recommended for sustainable maize production due to the direct C inputs and N benefits that can increase net biomass production and crop residue returns thus increasing SOM content. Modified N management strategies must be included along with manure application practices due to the potential increase in NO_3^- leaching as a result of additional N from manure. The current management practice used in the maize trial were shown to be unsustainable, indicating that measures have to be taken in maize production under monocropping system. For stable and sustainable maize production, it is recommended that further research must be done on rational fertilizer and manure applications rates that will account for mineralized N to reduce leaching.

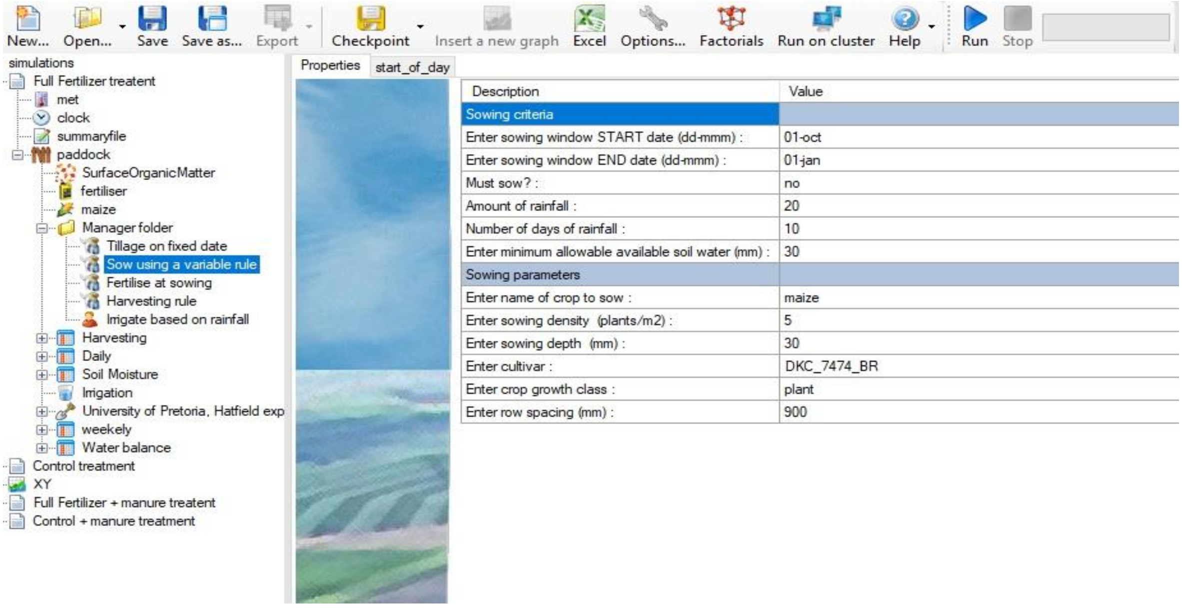
The C and N dynamics in the soil were also investigated in sugarcane production under varying residue management practices and two of fertilizer application. The APSIM model proved to be robust in simulating the long-term effects of residue retention/burning and fertilizer application on yields (fresh cane weight) and SOM (see Chapter 5). Mulching stimulated higher yields and SOM levels over 76 years compared to residue (thrash) burning in preparation for the harvesting, evident in both measured and simulated data. Nitrogen fertilizer application had a significant contribution to increase yields and SOM by increasing biomass production. Management practices were observed to have a large impact on the magnitude of SOM decline. Both measured and simulated SOM showed a declining trend over 76 years, with more SOM loss in burnt than mulched treatments. The benefits of residue retention are reported to increase soil water content due to reduced evaporation and runoff (higher water holding capacity), and led to increased N leaching. Soil water conservation is important in rain-fed agricultural systems, but the possible increase in N leaching as a result of mulching and excessive fertilization need to be addressed with improved management practices due to the economic losses and detrimental effects of N pollution to the environment.

This study further indicated that mulching and fertilization is the best management practice to maintaining high yields and minimizing SOM decline. Reducing N export to the environment by accounting for mineralized N is an important management intervention required in the mulched and fertilized management practice. This problem can only be reduced by retaining residues and using fertilizer recommendations that account for mineralized N from SOM. Reduced fertilizer application scenarios showed no significant reduction in yields on the mulched and fertilized treatment, indicating that the amount of mineralized N can be able to satisfy a significant proportion of the crop’s N requirements. This study has shown that improved management practices can improve yields and profitability while reducing the environmental degradation that comes with the commonly used management practices. The use of crop models has proven to be an important tool in the identification of these management practices by helping to understand the complex processes occurring in agroecosystems and playing out over the long-term.

APPENDIX

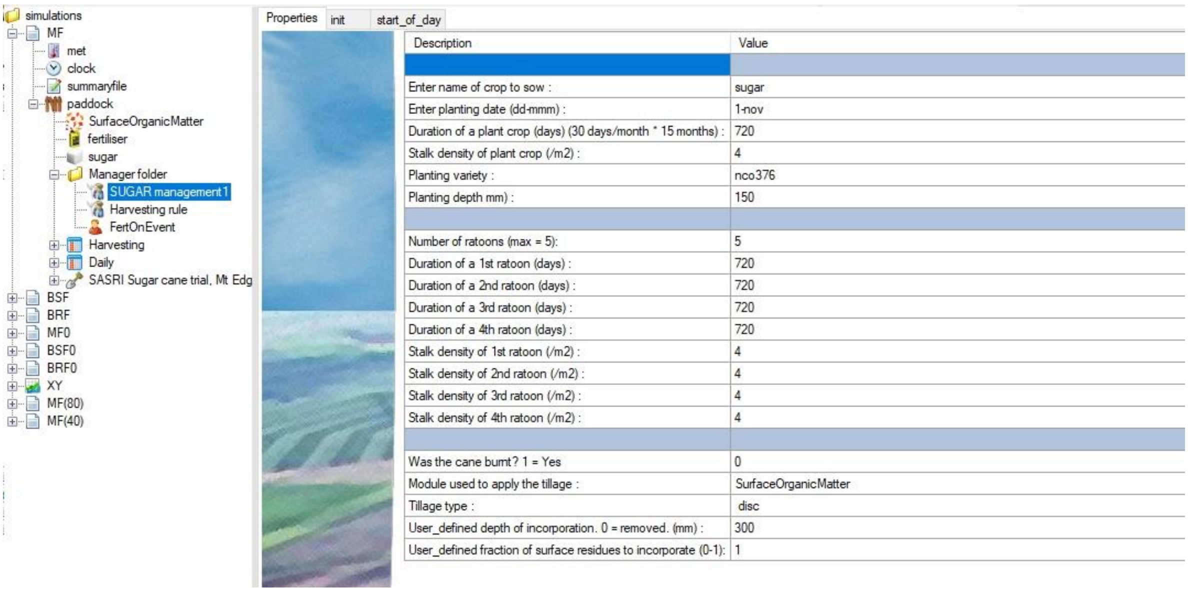
Appendix A: APSIM maize (a) and sugarcane (b) simulations interface screens showing management initialization.

(a)



Description	Value
Sowing criteria	
Enter sowing window START date (dd-mmm) :	01-oct
Enter sowing window END date (dd-mmm) :	01-jan
Must sow? :	no
Amount of rainfall :	20
Number of days of rainfall :	10
Enter minimum allowable available soil water (mm) :	30
Sowing parameters	
Enter name of crop to sow :	maize
Enter sowing density (plants/m2) :	5
Enter sowing depth (mm) :	30
Enter cultivar :	DKC_7474_BR
Enter crop growth class :	plant
Enter row spacing (mm) :	900

(b)



Description	Value
Enter name of crop to sow :	sugar
Enter planting date (dd-mmm) :	1-nov
Duration of a plant crop (days) (30 days/month * 15 months) :	720
Stalk density of plant crop (/m2) :	4
Planting variety :	nco376
Planting depth mm) :	150
Number of ratoons (max = 5):	5
Duration of a 1st ratoon (days) :	720
Duration of a 2nd ratoon (days) :	720
Duration of a 3rd ratoon (days) :	720
Duration of a 4th ratoon (days) :	720
Stalk density of 1st ratoon (/m2) :	4
Stalk density of 2nd ratoon (/m2) :	4
Stalk density of 3rd ratoon (/m2) :	4
Stalk density of 4th ratoon (/m2) :	4
Was the cane burnt? 1 = Yes	0
Module used to apply the tillage :	SurfaceOrganicMatter
Tillage type :	disc
User_defined depth of incorporation. 0 = removed. (mm) :	300
User_defined fraction of surface residues to incorporate (0-1):	1

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