Agro-ecological and Conservation Agriculture principles to assist large-scale dryland sugarcane farmers in the KwaZulu-Natal Midlands South region to improve soil quality

by

William Adriaan Gibson

Thesis presented in partial fulfilment of the requirements for the degree of Master of Philosophy in Sustainable Development in the Faculty of Economic and Management Sciences at Stellenbosch University

Supervisor: Dr Gareth Haysom

March 2016

Declaration

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

Date: March 2016

Abstract

Average sugarcane yields over the past four decades in some regions of the South African sugarcane industry have reached a plateau or are declining. One of the reasons for sugarcane yield decline is soil degradation. The aim of this research was to ascertain if Agro-ecological and Conservation Agriculture principles could assist large-scale dryland sugarcane farmers to improve soil quality. The research questions were designed to determine the perspectives of researchers and the targeted group of sugarcane farmers' on soil quality and how they engaged with the topic. A further objective was to ascertain what sugarcane farming practices were recommended and implemented to improve soil quality and whether they conformed to Agro-ecological or Conservation Agriculture practices. A third objective was to investigate whether Agro-ecological and Conservation Agriculture practices could contribute towards the development of a management system to help sugarcane farmers improve soil quality.

An extensive literature review was undertaken. The main topics researched were soil degradation, soil quality, sugarcane yield decline, Agro-ecology and Conservation Agriculture. Four case studies were conducted in the Midlands South sugarcane region. Four preselected large-scale dryland sugarcane farmers were interviewed on-farm using a semi-structured interviewer administered questionnaire. These sugarcane farmers had already implemented various sugarcane farming practices to improve soil quality. The questionnaire was designed to capture the farmers' practices, perspectives and soil quality improvement needs.

All the interviewed farmers wished to improve their soil quality. They requested more information on the topics of soil degradation, soil quality improvement practices and requested practical soil health monitoring tests. The farmers mainly implemented farming practices that practically fitted their farm system and did not require large capital outlays.

Whilst a large volume of research has been conducted on sugarcane soil quality, no literature was found directly associating Agro-ecological or Conservation Agriculture farming systems with sugarcane soil management in South Africa. Many potential sugarcane farming practices that improve soil quality were documented. Those practices that conformed to Agro-ecological and / or Conservation Agriculture principles were identified.

A key principle of Agro-ecology is that ecological relationships and beneficial interactions must be promoted within the farming system. A key principle of Conservation Agriculture is that it will only work optimally if all the technical aspects are implemented simultaneously. The proposal is made to adopt site specific farming practices that have multiple soil quality benefits and are synergistic or complementary to existing practices.

Three key aspects of Agro-ecology and Conservation Agriculture that may improve sugarcane soil quality were identified from the research. Soil organic matter should be conserved and enhanced, biodiversity should be promoted and ecosystems should be protected and enhanced. It is proposed that when farmers decide which soil quality improvement farming practices to implement they should consider the impact these will have on the above three factors.

A sustainable soil quality management system, based on Agro-ecological and Conservation principles to improve sugarcane soil properties is proposed. Practical research will need to be conducted to test this hypothesis.

Opsomming

Die gemiddelde suikerrietopbrengs het oor die afgelope vier dekades in sekere streke van Suid-Afrika ‘n plato bereik of selfs afgeneem. Een van die redes vir hierdie afname in suikerrietopbrengs kan grondagteruitgang wees. Die doel van hierdie navorsing is om te bepaal of Agro-ekologiese en Bewaringslandboubeginsels grootskaalse droëland suikerrietboere kan help om grondkwaliteit te verbeter. Die navorsingsvrae is ontwerp om te bepaal wat die perspektief van navorsers en spesifiek geteikende suikerrietboere rakende grondkwaliteit is en hoe hulle grondkwaliteit benader. ‘n Verdere doelwit was om te bepaal watter boerderypraktyke vir suikerrietboere aanbeveel is en wel toegepas word om grondkwaliteit te verbeter en of hierdie aanbevelings wel aan Agro-ekologiese en Bewaringslandboubeginsels voldoen. ‘n Derde doelwit was om ondersoek in te stel of Agro-ekologiese en Bewaringslandboupraktyke ‘n bydrae kan maak tot die ontwikkeling van ‘n bestuurstelsel om suikerrietboere te help om grondkwaliteit te verbeter.

‘n Uitgebreide literatuurstudie is onderneem. Die hoofonderwerpe wat nagevors is was grondagteruitgang, grondkwaliteit, afname in suikerrietopbrengs, agro-ekologie en bewaringslandbou. Vier gevalle studies is in die Midelland-Suid suikerrietgebied onderneem. Daar is onderhoude met vier voorafgekose grootskaalse droëland suikerrietboere op die plaas gevoer, waartydens ‘n semi-gestruktureerde vraelys deur die onderhoudvoerder gebruik is. Hierdie suikerrietboere het alreeds verskeie boerderypraktyke begin toepas om grondkwaliteit te verbeter. Die vraelys is so ontwerp dat dit die boer se praktyke, perspektief en behoefte om grondkwaliteit te verbeter, vasvang.

Al die boere waarmee daar onderhoude gevoer was, het die behoefte om grondkwaliteit te verbeter. Die boere soek meer inligting rakende grondagteruitgang, grondkwaliteitverbeteringspraktyke asook ‘n praktiese toets om grondgesondheid te monitor. Die boere het hoofsaaklik boerderypraktyke ge-implementeer wat binne hulle boerderystelsel inpas en wat nie groot kapitale uitleg benodig nie.

‘n Groot hoeveelheid navorsing is al op grondkwaliteit by suikerriet gedoen maar geen literatuur is gevind wat Agro-ekologiese en Bewaringslandbouboerderystelsels en suikerrietgrondbestuur in Suid-Afrika in verband met mekaar bring nie. Daar is wel ‘n groot hoeveelheid potensiële boerderypraktyke oor die verbetering van grondkwaliteit gedokumenteer. Praktyke wat aan Agro-ekologiese en / of Bewaringslandboubeginsels voldoen, is ge-identifiseer.

‘n Sleutelbeginsel van Agro-ekologie is dat die ekologiese verwantskap en voordelige interaksie binne die boerderystelsel bevorder moet word. ‘n Sleutelbeginsel van Bewaringslandbou is dat dit slegs optimaal sal funksioneer indien alle tegniese aspekte gelyktydig ge-implementeer word. Die voorstel word gemaak dat plekspesifieke boerderypraktyke wat veelvoudige grondkwaliteit voordele het en waar daar sinergisme bestaan met, of komplimentêr is tot huidige praktyke, aangeneem moet word.

Daar is drie sleutelaspekte van Agro-ekologie en Bewaringslandbou met hierdie navorsing ge-identifiseer wat moontlik grondkwaliteit onder suikerrietverbouing kan verbeter. Grondorganiese-materiaal behoort bewaar en verbeter te word, biodiversiteit behoort bevorder te word en ekosisteme behoort bewaar en verbeter te word. Dit word voorgestel dat wanneer boere besluit om grondkwaliteitboerderypraktyke te implementeer, die invloed van hierdie praktyke op die drie bogenoemde faktore oorweeg moet word.

‘n Volhoubare grondkwaliteitbestuurstelsel wat op Agro-ekologiese en Bewaringslandboubeginsels gebasseer is word voorgestel om grondeienskappe te verbeter. Praktykgerigte navorsing sal gedoen moet word om hierdie hipotese te toets.

Acknowledgements

Firstly I wish to thank the farmers who participated in the case studies. I really appreciated the time and knowledge that was willingly shared with me.

Secondly I express my sincere gratitude to my supervisor Dr Gareth Haysom for the patience, encouragement, dedication and flexibility he showed in assisting me to complete this thesis.

I also thank Mrs Beatrix Steenkamp from the Sustainability Institute for the patience she has shown with me, whilst I tried to juggle many responsibilities and still meet deadlines.

I thank Dr Johan van Biljon for agreeing to translate the abstract on short notice. I also thank Omnia originally and now Kynoch for accommodating me in completing this thesis.

Finally and most importantly I thank my family for allowing me the space and time to focus on the thesis. Your support and understanding is acknowledged and appreciated.

This thesis is dedicated to my sons Daniel and Adam.

Sow and reap your crops for six years, but let the land rest and lie fallow during the seventh year, and let the poor among the people harvest any volunteer crop that may come up; leave the rest for the animals to enjoy.
Exodus 23: 10 – 11

But the good soil represents honest, good-hearted people. They listen to God's words and cling to them and steadily spread them to others who also soon believe.
Luke 8: 15

The Living Bible

.

Table of Contents

List of Figures and Tables

List of Acronyms and Abbreviations

ATTRA	National Sustainable Agriculture Information Service
BT1	SASRI long-term sugarcane burn / trash trial
CANESIM	SASRI crop simulation model
CMS	Condensed Molasses Solids
FAO	Food and Agriculture Organization of the United Nations
FAS	Fertiliser Advisory Service
GM	Genetically modified
IAASTD	International Assessment of Agricultural Knowledge. Science and Technology for Development
SASRI	South African Sugarcane Research Institute
SASA	South African Sugar Association
SASIAA	South African Sugar Industry Agronomists Association
SASTA	South African Sugar Technologists Association
SSSA	Soil Science Society of America
SUSFARMS®	Sustainable Sugarcane Farm Management System
UNEP	United Nations Environment Programme
WCED	World Commission on Environment and Development
WESSA	Wildlife and Environment Society of South Africa
WWF-SA	Worldwide Fund for Nature – South Africa
ZAE	Sugarcane Agro-ecological Zoning

Chapter 1: Introduction

1.1 Background and motivation

Since 1971, average sugarcane yields in South Africa have been declining or reached a plateau in some regions (Meyer & van Antwerpen, 2001). This is despite on-going advances in agronomy and the breeding of new high potential varieties (Meyer, van Antwerpen, & Meyer, 1996). One of the reasons for sugarcane yield decline is soil degradation (South African Sugarcane Research Institute, 2000; Garside, 1997). .

Having worked in the sugar industry for over twenty years I have noticed that sugarcane farmers have become increasingly aware of yield decline and soil degradation, especially as the financial returns from sugarcane have been low for a number of years (South African Cane Growers Association, 2008). Declining sugarcane crop yields will impact on-farm profitability.

Over the years I became increasingly interested in sustainable agriculture and the contribution it could make towards improving soil quality in the sugar industry. In 2008 and 2009 I studied part-time for a BPhil Honours in Sustainable Development Planning and Management, based at the Sustainability Institute, at the University of Stellenbosch, specialising in Sustainable Agriculture.

Whilst writing the assignments for some of the courses, I found myself increasingly drawn to focus on soil degradation and soil quality within the sugarcane industry. I was linking many of the systems and technologies that we were learning about, to managing soil and crops in the sugarcane industry. This MPhil thesis is an extension of this work and an opportunity to bring many of the sustainable development and sustainable agriculture principles together in one study.

The World Commission on Environment and Development (WCED) stated in their report titled, Our Common Future, that sustainable development is, *"... development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* (World Commission on Environment and Development, 1987: 43). This definition has a strong social and environmental focus.

The South African government has a broader view on sustainable development. It incorporates aspects of ecology, economy and governance:

> *We must acknowledge and emphasize that there are non-negotiable ecological thresholds; that we need to maintain our stock of natural capital over time; and that we must employ the precautionary principle in this approach. We must accept that social, economic and ecosystem factors are embedded within each other, and are underpinned by our systems of governance* (Republic of South Africa. Department: Environmental Affairs and Tourism, 2007:21).

The concept of sustainable agriculture is a fairly recent response to a decline in quality of the natural resource base resulting from some harmful modern conventional agriculture farming practices

(McIsaac & Edwards, 1994 in Altieri, 1999). Agricultural production is no longer seen as a technical function, but as a far more complex function, characterised by economic, cultural, social and political dimensions (Altieri, 1999). *S*ustainable Agriculture is a whole system approach and concentrates on long-term solutions to problems. Complex economic, social and environmental sustainability objectives constantly overlap. Managing the three objectives of the triple bottom line simultaneously, requires clear goal setting, effective decision making and careful monitoring of progress towards the goals and the health of the system (Sullivan, 2003).

This study focuses on large-scale[1], commercial sugarcane farmers. The growers interviewed for the case studies all farm in the Eston / Richmond area of the southern Midlands of KwaZulu-Natal. In this region sugarcane is produced under dryland conditions and in two year cycles.

The main topic that this research builds on is whether or not principles from Agro-ecology and Conservation Agriculture can assist dryland sugarcane farmers to improve soil quality. A literature review was completed and four farmers were interviewed to ascertain their opinions on soil quality and to identify the interventions they were using to improve soil quality.

The first person narrative is occasionally used to convey my thoughts and experience to the reader. This is an accepted writing technique at the Sustainability Institute. It is also intended to contribute towards the flow of the thesis.

1.2 Research problem statement and research objectives

The research problem was to investigate if Agro-ecology and / or Conservation Agriculture principles could assist to improve soil quality in the South African dryland sugarcane industry

This research investigated whether soil quality was a problem in the South African dryland sugarcane farming sector. The causes of soil degradation were investigated as well as the remedial actions that were proposed by research literature and implemented by the case studies that were conducted.

Agro-ecology and Conservation Agriculture were studied to determine the contribution that these two farming systems could make towards improving sugarcane soil quality. The intention was also to investigate if themes emerged from the study that could contribute towards the development of a management system to improve soil quality in the dryland sugarcane industry. It is hoped that this system will assist sugarcane farmers when deciding which farming practices or combinations of farming practices they should implement to improve soil quality.

1.3 Research questions

The research questions are:

I. Is soil degradation a problem in the South African dryland sugarcane industry?

[1] A farmer who harvests more than 5000 tons of sugarcane per annum.

II. Do local researchers and large-scale dryland sugarcane farmers in the KwaZulu-Natal region identify soil quality as a factor they should focus resources on?

If they do:

III. From what perspective do researchers and the targeted group of farmers approach the issue of soil quality?

IV. What sugarcane farming practices are currently recommended and implemented to improve soil quality?

V. Which soil quality improvement practices conform to Agro-ecological or Conservation Agriculture principles and are they currently recognised as practices from these paradigms?

VI. Can principles from Agro-ecology or Conservation Agriculture contribute towards the development of a management system for the sustainable exploitation of soil, in the South African dryland sugarcane industry?

VII. What common themes emerge from the study which may contribute towards the development of this soil quality management system?

1.4 Value and relevance of this study

This study aims to investigate whether Agro-ecological and Conservation Agriculture farming principles can contribute towards improving soil quality on large-scale South African dryland sugarcane farms. As stated previously, sugarcane margins have been squeezed for many years in the sugarcane industry. Sugarcane farming revenue has not kept pace with rising farming input costs (Thomson, 2010). Many sugarcane farmers face a debt squeeze. Costs can only be reduced to a point, before one receives diminishing returns for one's investment. Besides costs, the focus should also be on the top-line. Sugarcane yield and quality need to be increased, but with a proposed caveat. This must be achieved whilst not compromising soil quality.

Increasing sugarcane yields will also assist to ensure that enough sugarcane is produced to supply the requirements of the extensive sugar mill infrastructure in South Africa. According to the South African Sugar Association website (South African Sugar Association, 2015) over the period, 2001/02 to 2012/13, total area under sugarcane in South Africa decreased from 431 771 hectares to 379 870 hectares. Area harvested for milling decreased from 325 704 hectares in 2001/02 season to 257 095 hectares in the 2012/13 season. If average sugarcane yields decrease, and sugarcane supply area continues to dwindle, more marginal areas and virgin land may be planted to sugarcane in the future. This would have negative environmental consequences. If sugar mills cannot source sufficient sugarcane in the long-run to remain economically viable, then some may close. This will have negative economic and social ramifications in the region. It is proposed that a concerted effort needs to be made to ensure that soil degradation does not play a major role in terms of reducing sugarcane yield.

This study proposes an alternative to the research paradigm that reacts to sugarcane yields declining by focusing on researching farming practices that will improve soil quality. This thinking reacts to the symptom (yield decline) and then tries to address the causes (soil degradation). Perhaps soil quality could be approached from a different perspective? Instead of initially focusing on yield decline and then specific farming practices to increase sugarcane yields, the main focus could be to ensure that sugarcane farmed soils are managed holistically in such a manner that soil quality is not an over-riding factor in limiting long-term sugarcane yields? If soils are healthy and other farming inputs are supplied optimally, then sustainably good sugarcane yields may be produced over the long-term? In other words soil productivity is decoupled from soil deterioration (Follett, 2001). Or put another way, economic growth is decoupled from resource consumption. If one approaches soil quality from this perspective, then investment into the environment, and in particular the soil environment, takes precedence in the decision-making process. This approach is one that conforms to a sustainable development paradigm. A cost-benefit analysis would need to be conducted to determine which soil quality improvement practices would be economically sustainable in the long run.

There needs to be an awareness of how some common sugarcane farming practices are affecting the long-term ability of soils to remain productive. These farming practices are discussed in section 2.8. This is a serious issue, as history tells us that many past, successful societies damaged their environment to the point where it could no longer support their populations. Some examples are the Old Kingdom of Egypt (1950 BC), the Sumerians (1800 BC), the Maya (600 AD) and the Polynesians (1600 AD) of Easter Island (Clayton & Radcliffe, 1996).

These societies failed to respond timeously to changes in their environmental resources. A sustainable balance was not strived for. History tells us that the causes of the decline developed slowly, society reacted too late, and social disintegration occurred fairly quickly (Clayton & Radcliffe, 1996). We do not want a similar situation to occur with our soils in the sugarcane industry.

Soil is a non-renewable resource (Food and Agriculture Organization of the United Nations, 2015) and a national asset. It should not be allowed to degrade. Plant breeders and plant genetic modification may be able to produce plants that can overcome degraded soils to a point. I believe a safer option will be to conserve the soil resource, rather than relying on developing technologies that can overcome the degraded resource?

The first genetically modified (GM) commercial sugarcane crop was planted in Indonesia in 2013 (Richardson, 2014). This sugarcane variety was developed for drought resistance.

The commercial release of GM sugarcane has been slow. An article published in The Link in May 2011, stated that the hold-up in biotechnology delivering to the sugarcane industry was as a result of:

- Negative consumer perceptions and market resistance to sugar derived from GM sugarcane.
- Issues around ownership of intellectual property. These are usually owned by large multi-national agricultural companies. Licences are also very expensive.
- Due to sugarcane being vegetatively propagated, this presents many challenges in terms of licensing costs and royalty payments to the owners of GM technologies

(Watt & Snyman, 2011).

A report titled: *GM sugarcane, A long way from commercialisation*, published by the African Centre for Biosafety, declared that there was no immediate or medium term prospect of commercial GM sugarcane cultivation in South Africa (African Centre for Biosafety, 2010). GM sugarcane however remains on the agenda in the South African sugarcane industry.

Historically GM crops have not been developed specifically to increase crop yields. The two main commercialised GM crop traits are herbicide resistant crops and Bt gene crops that contain a bacteria that is used as a biological pesticide.

Influencing yield with GM manipulation is far more complex than the manipulation of one or two genes. Many genes would need to be manipulated, whilst the plants new trait would need to be stable under varying field conditions. This is a highly complex process and there is a high risk of trait instability (Roberts, 2008).

Will there be a time where plant breeders can no longer overcome the limitations of degraded soils – what then? Would a better long-term solution possibly be to breed improved varieties, whilst also conserving the medium that they grow in? The latter could be a win-win sustainable solution.

Questions should be asked about the role of some technologies in agriculture. Some Green Revolution[2] farming technologies have improved crop yields, but at the expense of the environment (Bot & Benites, 2005). Farmers may end up on a never ending technological treadmill (Cochrane, 1958). The question should be asked - can this be sustained in the long-term?

Another reason for this study having value and being relevant is that certain gaps were identified in the literature. No local literature proposing Agro-ecological or Conservation Agriculture principles as possible solutions to improving soil quality in the South African sugarcane industry could be found. No research was found documenting South African sugarcane farmers' perspectives on the topic of soil quality.

It is hoped that this study will benefit all sugarcane farmers; dryland and irrigated; large-scale and small-scale. It will hopefully also add value to sugarcane researchers and policy-makers in the country. It is also hoped that this study will stimulate discussion about soil quality and soil degradation in the sugarcane industry, and that the proposals may be considered for implementation or further research.

This study aims to provide sugarcane farmers with information that will assist them to manage soil quality whilst remaining within a sustainable agriculture paradigm. Sugarcane farmer's long-term survival depends on productive soils.

[2] The process of agricultural intensification, post World War Two, to increase agricultural production.

1.5 Introduction to research design and methodology

The purpose of this study is to make a contribution towards dealing with a practical on-farm challenge – improving soil quality on large-scale dryland sugarcane farms. The study is largely exploratory in nature. One of the objectives is to contribute towards theory building by proposing an alternative hypothesis for improving soil quality on sugarcane farms.

An extensive literature review was conducted. The literature review was used to frame the case studies which took the form of face-to-face interviews with four farmers using a semi-structured questionnaire.

Both primary and secondary sources of data were used in this study. Primary sources included farm visits and a semi-structured questionnaire. Secondary sources included previous research, media products, industry specific reports and historical data and information. My personal experience within the sugarcane industry was drawn upon and this knowledge has been integrated into the study.

The main literature that was studied related to soil degradation, soil quality, sugarcane yield decline, Agro-ecology and Conservation Agriculture. Information on sugarcane yield decline and soil quality was mainly sourced from local South African sources - mainly the South African Sugarcane Research Institute (SASRI). Information on Agro-ecology was mainly sourced from international literature as there was a dearth of local literature on this subject.

Four case studies were conducted in the Midlands South sugarcane growing region. Four large-scale farmers were selected. The participant selection process is explained in section 3.5.2. They were interviewed using a semi-structured interviewer administrated questionnaire. The questionnaire was compiled after completion of the literature review. The questionnaire was designed to document the farmers' personal information and their farming practices, perspectives and needs related to soil quality.

The case studies were used to augment the literature review, gauge farmer perceptions, and determine their farming practices. The case studies specifically helped to answer research questions I, II, III, IV and VII. The Midlands South region was chosen for the case studies because I know this region well, having lived and worked in this region for many years. This region has many progressive farmers who have implemented many different environmentally sustainable sugarcane farming practices. It was anticipated that willing candidates would be found in this region, who matched the criteria I was looking for. Participant selection criteria are covered in section 3.5.2.

Research design and methodology is covered in more detail in Chapter Three.

1.6 Key concepts

The terms below are important to clarify as they are central to the study and some of the terms have ambiguous meanings. These definitions clarify what is meant by each of the concepts in the context of this thesis. Most of these key concepts are elaborated on in more detail in the literature review.

- ***Green Revolution:*** The process of agricultural intensification, post-World War Two, to increase agricultural production. This process entailed the increased use of synthetic chemical inputs, predominantly herbicides, pesticides and fertilisers. It also entails the use of high yielding crop varieties, increased mechanisation and increased irrigation (Magdoff, 2007a).

- ***Agro-ecology:*** Agro-ecology states that new methods of farming are required. These methods must produce food whilst taking the environment, particularly ecosystems into account. Agro-ecology is based on the application of ecological science (Altieri, 1995). It believes in a whole system approach to agriculture. Ecological relationships must be promoted in the design and management of sustainable agro-ecosystems (Principles of Agro-ecology, 2010). Beneficial biological interactions must be promoted between the components of the agro-ecosystem (Wijeratna, 2012). Unnecessary use of external inputs must be avoided (Pretty, 2011). The use of practices that adversely impact on human health and the environment must be minimised (Pretty, 2011). Agro-ecology is highly knowledge intensive and context specific. Agro-ecology seeks to secure food self-sufficiency, whilst preserving the natural resource base and ensuring economic viability and social equity (Altieri & Nicholls, 2005).

- ***Conservation Agriculture:*** Conservation Agriculture aims to maintain a balance between agricultural production and conserving agricultural resources (Donaldson, 2003). The soil resource is conserved by enhancing natural biological processes below and above the ground surface (Gowing & Palmer, 2007; Hobbs, Sayre & Gupta, 2008). Specific farming practices are recommended as Conservation Agriculture farming practices. These practices must all be implemented together for the farmer to qualify as a Conservation Agriculture farmer.

- ***Sugarcane yield decline:*** A decrease in the productivity of land, excluding the effects of changes in harvest age and climate (Jones, Sithole, Ferrer & Singels, 2012).

- ***Soil degradation:*** This is caused by detrimental human activities. These activities lead to a decrease in soil quality (Heap & Kent, 2000).

- ***Soil health:*** This is not a clearly defined concept. In the literature it is often used synonymously with soil quality. The definition used in this study is the state of a soil at a particular *time*. It can be evaluated by comparing the present state of the soil with a set of baseline values or indicators (South African Sugarcane Research Institute, 2004; van Antwerpen, Berry, van Antwerpen, Sewpersad & Cadet, 2009).

- ***Soil quality:*** This refers to the *sustained* capacity of a soil to accept, store and recycle nutrients and water, within ecosystem boundaries, climatic conditions and land use boundaries, in order to sustain biological productivity, maintain environmental quality, maintain economic yields, and promote animal, human and plant health (Bell & Raczkowaki, 2008; Gruver & Weil, 2007; Haynes, 1997; van Antwerpen 2005).

1.7 Assumptions and limitations of this research

This research is based on the following assumptions:

- Farmers are adapting some of their farming practices to improve soil quality.
- Improved soil quality should increase sugarcane yields over time.

The research has the following limitations:

- Although every attempt has been made to uncover all sugarcane farming practices that are linked to improved soil quality, there may be some practices that are not mentioned in this study.
- Soil is not a homogenous entity – it is a complex ecosystem. What works in one place, may not work in another due to different soil types. Farm micro-climate also varies and will have an impact on the success or otherwise of some of the recommended practices.
- One of the objectives of this research is to ascertain if principles from Agro-ecology and Conservation Agriculture can assist to develop a management system for the sustainable exploitation of sugarcane farmed soils. Clayton and Radcliffe (1996) state that it is very difficult to model complex dynamic systems. Soil systems fall into this category. With soils however there is a pattern of connectedness between the elements. This allows us to influence the behaviour of the system within limits.
- Agro-ecology and Conservation Agriculture are the two farming systems that have been chosen for this study. Other farming systems could also contribute towards a sustainable soil quality management system.
- Four large-scale farmers in one district of the dryland sugarcane farming area in South Africa were interviewed. Other sugarcane districts are faced with different climatic and soil conditions. Irrigated sugarcane farming also poses different challenges to dryland farming. The proposed farming practices would need to be tested in-field in many different locations to test if universal or region specific improvements in soil quality can be achieved. This will be future work for agricultural scientists to complete.
- Sugarcane farmers who continue farming conventionally using Green Revolution technologies and who are not concerned about soil quality were not included in the case studies. The focus of this study was not on this group of farmers. Farmers who met specific criteria regarding farming practices aligned to improving soil quality were identified and interviewed. These criteria are laid out in section 3.5.2 of the thesis covering participant selection for the case studies.
- Proposed soil quality improvement technologies would need to be subjected to a cost-benefit analysis. Besides being beneficial to the soil environment, they also need to be economically viable in the long-term.

- Some of the proposed practices may take a couple of seasons before they start showing improvements in soil quality.
- Every sugarcane farm is different with amongst other things different management philosophies, machinery, topography, climate and financial resources. What works and is practical to implement on one farm may not work on another.
- The South African sugar industry does not currently have a routine practical soil health test where recommended interventions to improve soil quality can be made, based on the tested health of the soil. Soil health indicators were not covered in this study.

1.8 Outline of chapters

There are five chapters in this thesis. This section provides a brief overview of each chapter in order to clarify the overall structure of the thesis.

1. Chapter One states the background and motivation behind the study. It provides the reader with an understanding of the context in which this study is undertaken. The research problem, research objectives and research questions are stated. The value and relevance of the study is discussed. There is a brief introduction to the research design and methodology used in this study. Key concepts are defined. The assumptions made in conducting this research are specified and some limitations of this research are also expressed.

2. Chapter Two reviews literature that is relevant to this study. As this study is fairly broad many topics were researched. The chapter begins with background information on the soil system and quantity of productive soil in South Africa. This leads onto the concepts of soil degradation and soil quality. Sugarcane yield decline is covered. Soil chemical, physical and biological properties as indicators of soil quality are stated. This moves onto specifying what constitutes a healthy soil. The effects of common sugarcane agricultural practices on soil quality and sugarcane yield are covered. This leads onto farming practices that may improve soil quality**.**

   Different farming systems are discussed. Agro-ecological and Conservation Agriculture farming systems are explained in detail, in particular the principles and aims of each system and how they apply to the management of sugarcane soils. This chapter ends with examples of existing local and international sugarcane industry sustainable agriculture initiatives that can be linked to Agro-ecology or Conservation Agriculture.

3. Chapter Three provides details on the research design and methodology that was used in this study. It describes how the research was conducted and the motivation for choosing the research tools. The main research tools were a broad literature review and a semi-structured interviewer administered questionnaire.

4. Chapter Four presents the results of the case studies. The farmer's practices and perspectives on soil quality are covered. This includes long-term sugarcane yields on their farms, how they perceive soil quality, where they source information on the topic from, soil health indicators they use and their views on what causes soil degradation on their farms.

   The farming practices they have implemented in the past and those practices that they won't consider implementing to improve soil quality are presented. The reasons why they have chosen certain farming practices and the main barriers of adoption hindering the implementation of other farming practices are covered. Lastly the outside support that farmers require when making decisions on which soil quality interventions to use on their farms is specified.

5. Chapter Five concludes the thesis. The major research findings are stated, evaluated and interpreted. The research questions posed in Chapter One are answered. Conclusions are drawn on the findings and recommendations for future practice and further study are proposed.

Chapter 2: Literature review

2.1 Introduction

The review begins with a brief introduction to soil and the soil system. Soil degradation and soil quality are discussed. This information contributes towards answering research questions I and II from a research perspective. This leads onto the detrimental effects that common sugarcane farming practices may have on soil quality and farming practices that can be adopted to improve soil quality. This assists to answer research question IV.

Sugarcane yield decline and possible causes of yield decline are discussed. Different farming systems are discussed. This then leads into a detailed overview of Agro-ecological and Conservation Agriculture farming systems. This information assists to answer research question V. The literature review concludes with brief overviews of some relevant international and local sugarcane industry sustainable agriculture initiatives. The entire literature review contributes towards answering research questions III, VI and VII.

2.2 Soil system

The soil system is central to the thesis topic. It is important to provide a background on soil as farming practices affect the soil system. Soil is the thin porous surface layer of the terrestrial parts of the earth's crust. It forms gradually over a very long period of geological time when new soil formation exceeds the rate of soil erosion. Soil is formed from parent material that comes from one or more of the following: underlying rock, wind or river depositions, or volcanic ash (Science Learning Hub, 2013).

Soil formation is influenced by parent material, climate, soil texture, topography, vegetation and time. These factors also influence soil microbes (Granatstein & Bezdicek, 1992). Soil provides a favourable medium in which water and nutrients are stored. Where climate permits plant roots grow into the soil. These roots take up plant nutrients and water which are supplied by the soil. Plants in turn protect the soil from erosion. Human activity however disrupts this relationship (Brown, 2008).

Soil is the foundation of civilisation, as it provides the medium in which we grow our food. The well-being of soil is essential for food production (Doran & Safley, 1997). During the twentieth century soil erosion started exceeding new soil formation over large areas (Brown, 2008). Brown (2008) estimated that up to a third of world cropland is losing topsoil faster than the rate at which new soil is forming. Furthermore, agriculture is tasked with simultaneously conserving and developing soils for future generations, whilst feeding an ever increasing world population (Doran & Safley, 1997).

In 1862, Friedrich Albert Fallou wrote:

> *There is nothing in the whole of nature which is more important than or deserves as much attention as the soil. Truly it is the soil which makes the world a friendlier environment for mankind. It is the soil which nourishes and provides for the whole of nature; the whole of creation depends upon the soil which is the ultimate foundation of our existence***.**
>
> (in Lampkin, 1999).

Soil is composed of a mixture of different sized mineral particles. These are derived from rock fragments and are classified as either gravel, sand, silt or clay particles. Soil is also composed of organic matter, water, air spaces, soluble and adsorbed nutrients. Soil is a living entity as it contains an ecosystem of many different species of living organisms, including earthworms, fungi, bacteria, protozoa, algae, arthropods and small animals (South African Sugar Association, 2002; Manson, Miles, Roberts, & Katušić, 2004; Lampkin, 1999).

The connection between the above components determines a soils physical, chemical and biological composition. All three of these soil properties must be preserved as they determine the productive capacity of the soil, which has a direct impact on the root environment and crop growth (Pierret, Moran & Doussan, 2005)**.** Pierret, Moran and Doussan (2005) articulate that one must have good knowledge about soil chemical, physical and biological processes if you wish to design and farm with a sustainable cropping system.

Farming practices have an impact on a soils physical, chemical and biological make up. Structural modifications are made to the soil which can have traumatic effects on it (Pierret, Moran & Doussan, 2005). Farmers need to understand the impact that different farming practices will have on their soils.

On a volume basis 30 to 60 percent of soil consists of solid material (Manson *et al*, 2004).This mainly consists of inorganic rock fragments. Less than 10 percent of the soil usually consists of organic matter (Manson *et al*, 2004). The remainder of the soil volume is the spaces between the solid particles. These are called pores. The smaller pores are usually filled with water and the larger ones contain air. Water and air are both necessary for plant growth.

The soil structure depends on the way the soil particles are arranged (Lampkin, 1999). The pore space is influenced by the size of the soil particles that make up the soil. This has a direct impact on water storage, water movement and soil aeration **(**Manson *et al*, 2004**).** The clay portion of the soil particles is critical for plant nutrition. They have an impact on soil pore size and therefore water storage and water movement. Plant nutrients also bond to clay particles thereby reducing leaching[3] losses of nutrients (Manson *et al*, 2004).

Soil structure provides the habitat, and essential resources for soil organisms. Soil biological activity, in turn preserves soil structure and soil fertility (Pierret, Doussan, Capowiez, Bastardie & Pagès, 2007; T.

[3] The process whereby water soluble substances are washed out of the soil profile.

van Antwerpen, 2006). The biological community of organisms living in soil is referred to as the soil food web (T. van Antwerpen, 2006). It is a complex living ecosystem. The whole is greater than the sum of its parts. If parts are destroyed or removed then the entire web is affected (T. van Antwerpen, 2006).

Farming practices such as crop rotation[4], type of crop, tillage, irrigation, fumigation and fertilisation all have an impact on soil microbes. Practices such as using cover crops and composts usually enhance the soil microbial status (Granatstein & Bezdicek, 1992). Crawford, Harris, Ritz and Young (2005) state that soil microbes self-organise in response to prevailing conditions. This may be one of the reasons why soils are fairly resilient and can adapt to disruptions from various farming methods. However when the disturbance is of a nature that soil microbial self-organisation cannot occur, then soils start to lose productive capacity (Crawford *et al*, 2005).

The soil food web sustains the important carbon cycle. Soil organisms consume organic matter that enters the soil system when plants or animals die. They convert this into nutrients and energy that plants can use. A healthy food web assists the soil to hold nutrients until the plant needs them. Soil organic matter is the driver that determines soil microbial diversity and biomass. Soil organic matter is also the glue that creates a healthy soil structure (T. van Antwerpen, 2006). It helps to prevent soil compaction[5] and promote water infiltration.

The soil food web also helps to suppress disease forming organisms and produces certain plant growth promoting hormones (Soil foodweb Inc, 2009). It helps to purify air and water and break down soil pollutants (T. van Antwerpen, 2006).

The opaque nature of soil and the very small size of many soil organisms, which can only be observed through a microscope, make it very difficult to directly observe and fully understand the nature of soil food webs. Much remains unknown about the stability of soil food webs and how they change over time. This knowledge is critical in understanding how they affect soil fertility (Wardle, 2002).

Soil is a complex system. It is also a valuable non-renewable resource that needs to be conserved and managed in a sustainable manner. This is particularly critical for a country like South Africa which has limited high potential agricultural soils (Laker, 2000).

2.3 Quantity of productive soil in South Africa

Laker (2000) reported that South Africa mainly has very shallow soils. A combination of hard rock parent material and relatively low rainfall over most parts of the country has limited soil formation. Large areas of the country have sandy soils with low agricultural potential. In many parts of the country where annual rainfall levels are suitable for crop production, poor quality soils prohibit this.

According to Laker (2000) only 13 percent of South Africa's land is suitable as arable land. Most of this land is however marginal for crop production. Only 3 percent of South Africa's surface is

[4] The growing of different crops in succession. To avoid exhausting the soil and control, weeds, pests and diseases.
[5] Soil particles are pressed together reducing the pore space between them.

considered to be high potential arable land. As South Africans this arable land must be conserved so that furture generations can benefit from it as well.

Laker (2000) also notes that most South African soils are extremely vulnerable to degradation and have low resilience. It is very difficult to rehabilitate these soils. It is critical to get land use planning right and prevent our soils from degrading.

2.4 Soil degradation

Soil degradation is caused by detrimental human activities. These activities such as deforestation, overgrazing and inappropriate farming practices, lead to a reduction in soil quality (Heap & Kent, 2000). Natural capital becomes degraded. Compared to a healthy soil, degraded soils produce less relative to the quantity of inputs used on them (United Nations Environmental Programme, 2009). Agricultural yields cannot be optimised if soils are degraded (Lal, 2006).

Due to mismanagement one-third of the world's agricultural land is either moderately or severely degraded (International Assessment of Agricultural Knowledge, Science and Technology for Development, 2009). This figure is growing by 0.2 percent per annum (United Nations Environmental Programme, 2009).

Lal (2006) specifies that soil degradation is mainly caused by the loss of topsoil from water and wind erosion, acidification[6], salination[7], nutrient depletion, and deteriorating soil structure which leads to soil compaction and crusting.

Rehabilitating soils goes beyond applying fertiliser to replace nutrients. It involves:

- Improving soil structure (Scherr, 2000; Lal, 2010)
- Enhancing soil water holding capacity (Scherr, 2000 ; Lal, 2010)
- Improving water infiltration (Lal, 2010)
- Reducing erosion by controlling the flow of water across fields (Scherr, 2000; Lal, 2010)
- Increasing soil organic matter content (Scherr, 2000; Lal, 2010)
- Restoring soil flora and fauna (Scherr, 2000)
- Buffering soil acidity (Scherr, 2000 ; Lal, 2010)
- Establishing vegetative cover (Scherr, 2000).

2.5 Soil quality

Bell and Raczkowski (2008) assert that soil quality is a prime indicator for determining management factors that contribute to soil degradation. The terms soil health and soil quality are frequently used synonymously in the literature to describe the fitness of soil to perform certain important functions

[6] A low soil pH. Amongst other things, is detrimental to root growth.
[7] Build-up of salts in soils – eventually to toxic levels for plants.

(Doran, Liebig & Santana, 1998; Gruver & Weil, 2007). As discussed in Chapter one there are some subtle differences in the meaning of these two terms.

Soil health refers to the state of a soil at a particular time. It can be influenced by dynamic properties that can change rapidly in a short space of time, such as the number and diversity of soil organisms. Soil health is concerned with the capacity of a soil to function as a living system (van Antwerpen, 2005). It looks at aspects such as soil self-regulation and distress symptoms (Gruver & Weil, 2007). It can be evaluated by comparing the present state of the soil with a set of baseline values or indicators (South African Sugarcane Research Institute, 2004). Van Antwerpen *et al* (2009) express that soil health refers to the condition of the soil at the time of sampling.

Soil quality in contrast refers to a wider and longer time scale. Soil quality can be defined as the sustained capacity of a soil to accept, store and recycle nutrients and water, within ecosystem boundaries, climatic conditions and land use boundaries, in order to:

- Sustain biological productivity
- Maintain environmental quality
- Maintain economic yields
- Promote animal, human and plant health.

(Van Antwerpen, 2005; van Antwerpen *et al*, 2009; Haynes, 1997; Bell & Raczkowaki, 2008; Gruver & Weil, 2007).

Soil quality is related to the concept of agricultural sustainability and is concerned with the capacity of a soil to function effectively in the present and also in the future (Bell & Raczkowaki, 2008). It attempts to understand the effect that management practices and climatic conditions have on soil characteristics and function over an extended period of time (Bell & Raczkowaki, 2008).

Gruver and Weil (2007) argue that soil quality is a utilitarian term. It describes the link between soil chemical, physical and biological properties and the services that the soil provides. These soil properties include inherent static properties such as soil mineralogy, texture and landscape position; and management sensitive dynamic properties such as biological activity, organic matter and aggregate stability.

The Soil Sustainability Interest Group (South African Sugarcane Research Institute, 2004) articulates that although the terms soil quality and soil health may be used interchangeably, scientists tend to favour the term soil quality, whilst farmers tend to favour the term soil health. Scientists tend to focus on analytical / quantitative properties of soil, whilst farmers tend to focus on descriptive / qualitative properties of soil. Farmer's qualitative properties may require a value judgement of the soil properties. Farmer knowledge however is a valuable resource that can contribute towards scientific investigations of soil quality (Gruver & Weil, 2007).

Acton and Gregorich (1995) suggest that when assessing soils both quality and the health of soils must be considered when determining their agricultural sustainability. For the purposes of this thesis the term soil quality will be used, as the focus is on the sustained capacity of sugarcane soils to remain productive.

2.6 Soil chemical, physical and biological properties as indicators of soil quality

As expressed in the previous section soil chemical, physical and biological parameters must be considered when studying soil quality (van Antwerpen, 2005). Soil physical, chemical and biological components must be considered as a holistic whole rather than a sum of separate parts (Sturz & Christie, 2003).

There is a strong link between sustainable land use management and healthy soil properties (van Antwerpen *et al*, 2009). Poor soil management can lead to damaging changes in soil chemical, physical and biological processes. This will impact negatively on the agricultural productivity of soils which can cause crop yield losses (van Antwerpen *et al*, 2009; Bell & Raczkowski, 2008). Soil properties that are sensitive to changes in land use may be indicators of soil quality (van Antwerpen *et al*, 2009).

Soil organic matter is an essential element for maintaining the chemical, physical and biological status of soils and providing resistance to soil degradation (van Antwerpen, 2005; Dominy, Haynes & van Antwerpen, 2001). Soil organic matter is a key characteristic of soil quality (Doran & Parkin, 1994; Dick & Gregorich, 2004). According to Haynes (1997) management of soil organic matter is at the very heart of sustainable agriculture. It plays a central role in the enhancement of soil health. Numerous soil chemical, physical and biological properties are influenced by soil organic matter (Dick & Gregorich, 2004; Miles, Meyer & van Antwerpen, 2008).

The term soil organic matter describes the organic components in the soil. These include tissues from dead plants and animals, the products produced as these decompose and the soil microbial biomass. The term soil organic carbon refers specifically to the carbon component in the soil organic matter.

Soil organic carbon includes an active (labile) and an inactive (non-labile) carbon pool. The active carbon pool constitutes a very small fraction of total soil carbon but is more sensitive than inactive carbon to management and land use changes (van Antwerpen, 2005). Soil microbial biomass is closely associated with soil carbon (van Antwerpen, 2005). Active soil carbon also influences soil aggregate stability[8], water infiltration rate, cation exchange capacity (CEC)[9] and nitrogen mineralisation[10] (van Antwerpen, 2005). Soil organic carbon also promotes water retention and reduces soil erosion (South African Sugarcane Research Institute, 2000).

[8] The ability of soil aggregates to resist disintegration when disruptive forces such as tillage, water or wind erosion are applied.
[9] The capacity of a soil to adsorb or exchange cations.
[10] The conversion of organic nitrogen to plant available inorganic nitrogen.

2.6.1 Soil chemical properties

Soil chemical properties include the nutrients in the soil and the ability of the soil to supply nutrients to the plant.

Soil pH[11] and acid saturation[12] are indicators of soil acidity (van Antwerpen, 2005). Soil acidity has an impact on nutrient availability and microbial communities (van Antwerpen *et al*, 2009). Soil macro and micronutrients and soil cation exchange capacity are important soil chemical properties. Soil organic matter assists soil to hold onto cations[13] and prevents them from leaching (Haynes, 1997).

Soil organic matter buffers soil against large changes in soil pH. It also helps the soil to bind toxic metals such as lead and chromium which may be added to the soil in waste materials (Haynes, 1997). Soil organic matter content is also directly related to the adsorption of certain herbicides by the soil.

Soil organic matter is a primary source of plant available nutrients for plant growth via mineralisation (Haynes, 1997). Haynes (1997) avers that soil organic matter can supply up to 95 percent of soil nitrogen and sulphur and about 50 percent of soil phosphorous. The mineralisation process is a biological one. It is mediated by soil bacteria and fungi.

Soil chemical properties that are related to soil fertility are fairly easy to measure with soil testing (Haynes & Hamilton, 1999).

2.6.2 Soil physical properties

Soil physical properties refer to the arrangement of the soil particles and also cover the movement of water and air in the soil.

Soil depth is a good indicator of potential soil productivity. Root depth is restricted in shallow soils. Nutrient and water reserves are also restricted in shallow soils. Water drainage may be inadequate, which can result in increased soil erosion (van Antwerpen, 2005). Available plant water capacity is a soil quality indicator (van Antwerpen *et al*, 2009).

Although soil texture doesn't directly impact on soil quality it is an important basic soil property. There is a good relationship between soil texture and some parameters that affect soil health. These are aeration, porosity, nutrient and water retention (van Antwerpen, 2005).

Soil bulk density[14] is a reflection of historical management practices. It has an impact on soil physical, chemical and biological properties (van Antwerpen, 2005). Soil compaction happens when soil particles are forced closer together due to external forces. This causes less space between the soil particles for aeration, root development and water storage.

---

[11] A measure of soil acidity or alkalinity. It is based on the activity of the hydrogen ion in a water or salt solution.
[12] A measure of aluminium toxicity. It is expressed as a percentage of total cations.
[13] A positively charged ion.
[14] A soils mass, per unit value of the soil.

Soil aggregate stability is one of the most sensitive measurements of soil quality (van Antwerpen, 2005). A well-structured soil has pores that vary in size with varying functions. The soil structure should be stable (Haynes, 1997). A soils capacity to maintain its structure is assessed by measuring its aggregate stability.

Soil organic matter also has a profound effect on the structure of soil (Haynes, 1997). Changes in the quantity of soil organic matter depends on five factors namely landscape, climate, soil texture, soil inputs and disturbance. Some of these factors can be managed others cannot. Loss of soil organic matter from soils leads to them becoming more compact, harder and cloddy (Haynes, 1997).

High soil organic matter content tends to favourably affect soil aeration, permeability and water holding capacity (Haynes, 1997). It binds soil particles into structural units or aggregates. These assist the soil to maintain an open loose granular state. Water infiltration into the soil improves and the large pores allow better gas exchange between the soil and the atmosphere (Haynes, 1997). Earthworms are the main natural agents that make large pores in soils. Soil compaction however damages large pores (Haynes, 1997).

Soil aggregate stability can be lost and soil structure can breakdown in certain situations, even when soil organic matter content is high. A common example is soil salinity[15] which disperses soil particles and leads to a breakdown in soil structure (Haynes, 1997).

A breakdown of soil surface aggregates can lead to surface crusting[16]. This impedes water infiltration which results in surface water ponding or water run-off and soil erosion. Soil water levels will decrease. Surface crusting is mainly caused by high intensity irrigation or rainfall striking a bare soil surface. A surface crust, up to 10 mm thick forms on the soil surface.

Soil physical properties are usually not very well documented as they often need to be measured in field conditions and they can change markedly during the season such as after cultivation (Haynes & Hamilton, 1999).

2.6.3 Soil biological properties

These properties refer to the living components within the soil. Soil biological processes are important for the healthy ecological function of soil (Dominy, Haynes & van Antwerpen, 2001). Soil microbes degrade organic residue, transform organic matter, mineralise organic nutrients and stabilise soil aggregates (Dominy, Haynes & van Antwerpen, 2001).

Soil organic matter is a food source for soil microbes. Soil enzymatic activity is highly correlated to soil organic matter. It is a good soil health indicator (van Antwerpen, 2005). Two factors that influence the ability of soil microbes to decompose organic substances are soil respiration activity[17] and

[15] Soils with excess salt content.
[16] Relatively thin compacted layer on the soil surface.
[17] The production of carbon dioxide when soil organisms and plant roots respire.

dehydrogenase[18] activity (van Antwerpen, 2005). Soil organic matter is a source of energy for bacteria, fungi and earthworms (South African Sugarcane Research Institute, 2000). Soil microbes play a vital role in soil fertility.

Nematode community composition may also be a good indicator of soil quality as they have an influence on nitrogen cycling and decomposition (van Antwerpen, 2005). The microbial biomass and bacteria to fungi ratio are also soil quality indicators (van Antwerpen *et al*, 2009).

According to van Antwerpen (2005) the following factors influence soil microbial numbers: soil organic carbon; soil type; geographic region; soil temperature; season stage; soil water content and certain nutrients.

More is known about soil chemical and physical properties than about soil biological properties (Haynes & Hamilton, 1999). There is increasing evidence that measuring the size and activity of the soil biological community may provide an early indicator of soil degradation (Haynes & Hamilton, 1999). More research is needed on biological indicators of soil quality (Haynes & Hamilton, 1999).

2.7 Healthy soil

A healthy soil has healthy chemical, physical and biological properties. It must be able to meet a range of ecosystem functions, which are appropriate to its environment. A healthy soil has the ability to sustain plant and animal productivity and diversity, maintain or enhance air and water quality, and support human habitation and health. Soil is much more than a growing medium; it is a living and complex dynamic system. Healthy soil can reach its full potential and resists degradation. Healthy soil provides a full range of functions especially nutrient, carbon and water cycling, and can maintain this capacity into the future.

A soil is healthy if it has a variety of different organisms living in it. A healthy soil provides water and nutrients to the crop. Roots are healthy and are allowed to grow well (Anon, 2006**).** A healthy soil produces healthy crops with minimal external inputs and few ecological effects (Altieri & Nicols, 2005). Healthy soils are more resilient than degraded soils (Rosenberg, 2006; Scialabba & Muller-Lindenlauf, 2010). Soils that are healthy produce higher yields (Lal, 2006).

2.8 The effect of common sugarcane agricultural practices on soil quality

2.8.1 Introduction

This section discusses the harmful effect that certain sugarcane farming practices have on soil quality. Section 2.9 discusses farming practices that may improve soil quality.

Sugarcane production has been shown to reduce soil quality throughout the world (Haynes & Hamilton, 1999). Soil surveys in the South African sugar industry have shown a steady deterioration of soil chemical, physical and biological properties (van Antwerpen, Haynes, Meyer, Qongqo, Dominy &

[18] Is a class of enzymes that are used by microorganisms in the soil, to break down organic matter.

Hlanze, 2003b). Soil productivity is largely determined by the soil environment provided for root growth (Gruhn, Goletti & Yudelman, 2000). The sugarcane industry has been aware of and struggled with poor or restricted sugarcane root growth for many decades (Garside, 1997). Egan, Hurney, Ryan and Mathews (1984) call this poor root syndrome.

Soil quality has an impact on agricultural productivity (Gruhn, Goletti & Yudelman, 2000). Some common agricultural practices and factors that cause soil degradation are covered below.

2.8.2 Monocropping

Meyer and van Antwerpen (2001) argue that there is good reason to believe that the declining productive capacity of sugarcane soils is largely due to the effects of long-term monocropping[19]. Sugarcane has been grown as a monoculture crop in South Africa for well over a century. Sugarcane produces a high quantity of biomass and therefore places high demands on soil resources (van der Laan & Miles, 2010).

Long-term monocropped soils have low levels of microbial biomass and biological diversity (Haynes & Hamilton, 1999). They lose some of their natural suppressiveness, and detrimental soil organisms increase in numbers (Meyer & van Antwerpen, 2001). Monoculture farming leads to an increase in pest and disease problems (Cadet & Spaull, 2001).

2.8.3 Soil organic matter

The soil organic matter content of most South African soils varies between 0.1 to 9 percent. The vast majority of South African soils however have low organic matter contents. About 58 percent of soils have less than 0.5 percent organic carbon content. Only 4 percent of South African soils contain more than 2 percent organic carbon (Du Preez, van Huyssteen & Mnkeni, 2011).

A conversion factor of 1.72 is commonly used to convert organic carbon to organic matter. This factor however varies depending on the type of organic matter, soil type and soil depth (Soil quality, 2015). Using the conversion factor stated above 0.5 percent organic carbon is equivalent to 0.875 percent organic matter content. The two percent organic carbon content stated in the paragraph above equates to 3.44 percent organic matter content.

The two main factors that account for variations in organic matter content are soil texture and soil management practices (Miles, Meyer & van Antwerpen, 2008). Sugarcane production where the crop is burnt prior to harvest significantly reduces soil organic matter content as compared to virgin land (South African Sugarcane Research Institute, 2000; Haynes & Hamilton, 1999; Dominy, Haynes & van Antwerpen, 2001). This is due to a reduced return of organic material to the soil. Sugarcane plants are widely spaced in rows, so there is less root and top material produced per unit of ground than under pasture (Haynes, 1997) or natural vegetation (Dominy, Haynes & van Antwerpen, 2001).

[19] The long-term use of land to grow only one type of crop.

The sugarcane harvesting process also removes most of the above ground material. Soil tillage at planting leads to decomposition of soil organic matter. It leads to accelerated oxidation of organic matter (Miles, Meyer & van Antwerpen, 2008). The increased soil aeration stimulates decomposition processes and microbial activity. Soil cultivation also breaks up soil aggregates and exposes the previously protected organic matter to microbial breakdown (Haynes & Hamilton, 1999). According to Dominy, Haynes and van Antwerpen (2001) burning sugarcane before harvesting leads to detrimental effects on soil chemical, physical and biological properties due to soil organic matter loss.

Lower soil organic matter levels reduce soil microbial biomass and respiratory rates particularly in the topsoil (South African Sugarcane Research Institute, 2000; Haynes, 1997; Dominy, Haynes & van Antwerpen, 2001). Earthworm numbers and aggregate stability decline. As soil organic matter content declines there is a corresponding decline in soil physical properties and soil biological activity (Haynes, 1997). So soils with low aggregate stability are difficult to manage and maintain in a productive state because of low organic matter content and low biological activity. They are also very prone to soil capping or crusting due to the aggregates on the soil surface breaking down (Haynes, 1997). Maintenance and improvement of soil organic matter is therefore an important objective for sustainable agricultural systems (Dominy, Haynes & van Antwerpen, 2001).

The South African sugar industry does not have ready access to large quantities of off-farm organic matter material. Sugarcane growers must use what is available to them. The only widespread, consistent and local sources of organic matter are on-farm sugarcane trash[20] and off-farm filterpress[21] from the sugar mills (van Antwerpen, Thorburn, Horan, Meyer, & Bezuidenhout, 2002). Sugarcane trash is a free source of organic matter. It is available to all sugarcane growers but the majority of farmers choose to burn their fields before harvesting. Filterpress is a limited resource in the sugarcane industry and is expensive to transport long distances.

Maintaining or building up soil organic matter levels are crucial to sustaining soil quality.

2.8.4 Burning at harvest

The vast majority of harvested sugarcane in South Africa is burnt before harvest. The main reason for this is that burning removes the dead leaves from the sugarcane stalk. This improves cane cutter productivity and increases transport payloads. Certain areas of the industry are also not suited to green cane harvesting[22] as this practice may reduce sugarcane yields. According to Donaldson, Redshaw, Rhodes and van Antwerpen (2008) these are areas where soils are continuously wet such as valley bottoms and areas that are prone to frosting or where soil temperatures in winter are less than two degrees celcius. Exceptionally wet seasons before the crop has reached the full canopy growth stage may also reduce sugarcane yields where the previous crop was harvested green.

[20] When sugarcane is not burnt at harvesting, the leaves and tops are left as a mulch on the soil surface.
[21] A by-product of the sugarcane milling process (also known as filter-cake).
[22] Harvesting unburnt sugarcane.

The burning of sugarcane at harvest leaves only the unburnt green leaves on the soil surface. If these are not spread then the soil surface is left largely bare. Besides the soil surface drying out quicker certain soils are prone to soil crusting. These are soils derived from Middle Ecca, Dwyka and Beaufort sediments. The soils include Westleigh, Kroonstad, Longlands, Valsrivier and Katspruit soil forms (Meyer, Dewey & Wood, 1988). Raindrops physically disaggregate soil particles on impact. This compact's the soil surface layer which limits water penetration into the soil (South African Sugarcane Research Institute, 2010b). Soil crusting is a precursor to soil erosion.

Burning the crop before harvesting substantially reduces the contribution the crop can make towards organic matter content of the soil. Annual sugarcane trash yields in excess of twenty ton per hectare can be produced by some commercial South African sugarcane varieties under irrigation (Donaldson, Redshaw, Rhodes & van Antwerpen, 2008).

Green cane harvested sugarcane recycles large quantities of nutrients back into the soil. However these may not be available to the following crop in the short term. If sugarcane is burnt then most of the nitrogen is lost and up to seventy five percent of the other nutrients are also lost (Donaldson, Redshaw, Rhodes & van Antwerpen, 2008).

2.8.5 Soil compaction and crusting

In-field vehicle movement especially during wet conditions can lead to soil compaction, particularly in the sugarcane interrow spaces where traffic tends to travel (Haynes & Hamilton, 1999). Soil compaction reduces nitrogen availability and soil hydraulic conductivity[23]. Pore volume is reduced and soil strength is increased. Water infiltration and root density are reduced. Tillage energy requirements increase. Soil microbial activity and organic carbon levels also decrease. All these factors lead to reduced cane growth and yield (van Antwerpen, 2005).

Soil compaction can be a particular problem under minimum tillage[24] systems as the soil is not generally loosened by tillage between crops. By alleviating soil compaction soil water intake may increase, water runoff will decrease and soil erosion will decrease. The growth, depth and coverage of roots will also be greater. Sugarcane yields may increase as a consequence of more developed root systems.

2.8.6 Soil acidity

The conversion of virgin land to sugarcane production invariably leads to soil acidification especially in high rainfall areas (Haynes & Hamilton, 1999). Soil acidification results in toxic levels of exchangeable aluminium in the soil. This reduces sugarcane growth as roots become stunted. Water uptake and plant nutrient uptakes are reduced (South African Sugarcane Research Institute, 2010b).

Human induced soil acidification is a major problem in the South African sugarcane industry. Harmful farming practices such as applying excessive rates of nitrogenous fertiliser, incorrect timing of nitrogen

[23] The ease with which a fluid can move through pore spaces or fractures in the soil.
[24] Using the minimum amount of soil tillage to establish the crop. Does not generally entail deep ploughing.

applications and crop removal of nutrients from fields (nutrient mining) have led to an accelerated trend in soil acidification (lower soil pH) since the 1980's (Schumann, 1998). Soil acidification is caused by the oxidation of ammoniacal fertilisers to nitric acid, organic matter mineralisation and the leaching of basic cations from soils (South African Sugarcane Research Institute, 2010b; Haynes & Hamilton, 1999). At harvesting cations present in the crop are removed from the soil. Lower soil pH leads to decreased soil microbial activity and decreasing availability of certain crop nutrients.

2.8.7 Soil fertility

Soil fertility plays an important role in soil quality. The FAO defines soil fertility as the capacity of a soil to supply all essential plant nutrients and soil water in adequate quantities and proportions for plant growth and reproduction. There must also be an absence of toxic substances which may inhibit plant growth (Bot & Benites, 2005).

Sugarcane removes large quantities of nutrients, particularly potassium. Exchangeable soil potassium levels often decline over time. Exchangeable calcium and magnesium levels will also decrease as soils acidify (Haynes & Hamilton, 1999). Soils should be managed in such a way that they provide adequate nutrition to the crop so that sustainable yield targets can be met.

Soil fertility status also impacts on the chemical quality of the sugarcane juice. This is one of the important parameters on which a sugarcane farmer is paid. Excessive potassium fertilisation can result in luxury uptake of the nutrient which impacts negatively on sugarcane juice quality.

Van der Laan and Miles (2010) conducted a study on soil fertility trends within the South African sugarcane industry. They accessed data from SASRI's Fertiliser Advisory Service (FAS) database. They analysed data from 1998 to 2009.

Leaf analysis data indicated that nitrogen deficiency was widespread throughout the industry. Thirty six percent of leaf samples were deficient in nitrogen.

Whilst soil phosphorous levels were generally adequate there were some soils with excessively high levels. This raises concerns about the potential for surface and ground water pollution. Soil potassium reserves were generally low in many regions. Sulphur deficiencies were widespread and zinc deficiencies were also fairly common in certain regions (van der Laan & Miles, 2010).

The dryland sugarcane regions often had low soil pH (acid soils). As stated previously these soils are also often associated with calcium and magnesium deficiencies. Soil acidity restricts the root development of plants.

2.8.8 Soil salinity and soil sodicity

Soil salinity can develop from high water tables where insufficient subsurface drains are installed. This usually occurs in relatively low rainfall areas where excess irrigation is applied. Saline ground water rises into the root zone of the crop through capillary movement (South African Sugarcane Research

Institute, 1997; Haynes & Hamilton, 1999). Salinity can also result from poor quality irrigation water (South African Sugarcane Research Institute, 1997). Excess salts hinder plant root uptake of water which affects plant growth.

Many saline soils are also sodic[25]. These soils disperse with water and are very difficult to manage (Haynes & Hamilton, 1999). Excess sodium alters the soil structure. Surface crusting can occur and soil hydraulic conductivity is reduced. Water infiltration is reduced.

2.8.9 Soil erosion

Soils can erode if farmers don't have good water carrying structures on their farms. Bare soil surfaces should be kept to a minimum. Soil erosion affects soil fertility as topsoil contains plant nutrients. There are also environmental consequences to losing soil from erosion.

2.8.10 Studies on farming practices and soil quality

Van Antwerpen and Meyer (1996); Qongqo and van Antwerpen (2000) and Dominy, Haynes and van Antwerpen (2001) all conducted sugarcane soil quality trials in South Africa. Qongqo and van Antwerpen (2000) trial was similar to the one conducted in Australia by Haynes and Hamilton (1999).

Van Antwerpen and Meyer (1996) conducted a paired study of sugarcane lands in Northern KwaZulu-Natal to quantify the physical and chemical condition of these soils. The study showed that soil chemical properties were more affected by sugarcane cultivation (farm management practices) than physical (inherent) soil properties. The most prominent soil chemical property contributing to soil degradation was increased soil acidity in the dryland areas and increased sodicity and salinity in irrigated areas. The common thread linking the results from dryland and irrigated areas was the reduced organic matter content of the cultivated sites relative to the virgin sites.

Qongqo and van Antwerpen (2000) undertook a paired site survey of 65 old and new sites from the South Coast and Midlands regions of the KwaZulu-Natal sugar industry. This study showed that cropped land was more degraded than uncropped land. It contained less organic matter and microbial biomass than uncropped land. In the rainfed areas, soils were more acidic, cation exchange capacity decreased, amounts of plant available macro and micronutrients were reduced and there was a tendency towards greater surface crusting and soil compaction. Sugarcane cultivation affected soil chemical properties more than soil physical properties.

As previously stated, little is known about soil biological changes that occur under sugarcane cultivation. Australian research of paired old and new land sites showed that soil microbial biomass is significantly less in old sugarcane lands (Haynes & Hamilton, 1999). Sugarcane establishment leads to a rapid loss of soil microbial biomass. Australian research has also shown that a trash blanket increases the size of the earthworm community and markedly increases the soil microbial biomass in the soil surface (Haynes & Hamilton, 1999).

---

[25] Soils with a disproportionately high concentration of sodium.

SASRI trials (Meyer & van Antwerpen, 2001) have shown that sugarcane cultivation changes soil properties which in turn influence the microbial diversity of soil micro-flora. Detrimental root pathogens then build up in the soil. The following management practices have an adverse effect on soil microbial communities: some fertilisers, low organic carbon levels, soil acidity, soil tillage, continuous burning of sugarcane land's and soil imbalances created from monocropping.

Dominy, Haynes and van Antwerpen (2001) investigated the long-term effects of sugarcane production on a Hutton soil in the Midlands South region. Organic carbon content declined exponentially with increasing years under sugarcane production. Sugarcane under continuous production for more than 30 years resulted in a substantial decline in organic matter in the surface 10 cm, compared to natural veld. The soil organic matter reduction led to an accompanying decline in soil microbial biomass, basal respiration and aggregate stability.

Soil surveys conducted in the South African sugar industry have shown a steady deterioration of soil chemical, physical and biological properties, as the period under sugarcane cultivation has increased (van Antwerpen *et al*, 2003b).

2.8.11 Conclusion

Many of the current sugarcane farming practices are inherently detrimental to soil quality. Sustainable sugarcane production systems must be implemented on farms. These systems should improve soil quality or at the very least maintain it, whilst improving sugar yields. This will help to ensure the sustainable future of the sugarcane industry (Haynes & Hamilton, 1999).

2.9 Farming practices that may improve soil quality

2.9.1 Introduction

This section covers various sugarcane farming practices that can be adopted to overcome some of the soil quality challenges stated in the previous section.

2.9.2 Overcome monocropping

The adverse effects of sugarcane monocropping can be reduced by implementing certain practices which include minimum tillage, green manuring[26], strip cropping[27], green cane harvesting, spreading crop residues[28] and nutrient recycling by fertilising with products like filterpress and animal manures (Haynes &Hamilton, 1999). Ley crops[29] can also be planted (Meyer & van Antwerpen, 2001).

Whilst none of the above practices are standard practice in the South African sugar industry, many farmers do implement one or more of them. There is an increasing trend in the adoption of some of these practices.

[26] A secondary crop that is grown to break the repetitive cycle of planting the same crop year after year.
[27] Growing different crops in alternate strip's following the contour of the land, to minimise soil erosion.
[28] At harvesting, the top leaves of the sugarcane are cut off and left in the field. These are then spread more evenly on the soil to provide better soil cover.
[29] Land normally planted to grain or cash crops is planted to pasture for a number of seasons.

Other factors that must be taken into account, to counteract the negative consequences of monocropping include sugarcane variety selection, fertiliser rates, timing and placement, season of harvest, irrigation scheduling[30] and regular lime and gypsum applications to counteract soil acidification (Haynes & Hamilton, 1999).

Trials conducted in Swaziland with sunn hemp green manure confirmed large yield responses to green manuring - 10 to 54 percent in the plant crop. Bare fallowing[31] responses were in the range of 11 to 29 percent (Nixon, 1992). Small responses were recorded in subsequent ratoon crops.

In the early days of sugarcane production, pre 1960's, bare fallowing or green manure break crops were common in the sugar industry. Demand for sugar production increased from the 1960's so farmers began using their land more intensively, leaving little scope for fallows (Schumann, Meyer, & van Antwerpen, 2000).

Standard practice in the sugar industry is to replant about 10 percent of the fields per annum (Smit & Campbell, 2010). A cover crop should be used to protect and revitalise the soil during the period between final harvest and replant. The terms cover crop and green manures are often used interchangeably (South African Sugarcane Research Institute, 2010a).

Crop rotation is a method that can reduce pest and diseases, control weeds, improve yields and improve nitrogen nutrition and soil quality (van Antwerpen, 2002). If a commercial break crop is planted and harvested, besides breaking the monocropping cycle and improving soil quality, it can offset the costs of plough out, grass eradication, and if a legume is used supply nitrogen to the plant sugarcane crop (Smit & Campbell, 2010).

Sugarcane yields following a break crop increase plant crop yields and can also improve successive ratoon yields. These increased sugarcane yields are due to a combination of factors. One of these is the make-up of soil biota. Break crops have a positive effect on beneficial micro-organisms, which indicates that the soil is healthier (van Antwerpen, 2002).

Trials conducted by Parsons (2000) from 1996 to 2000 showed that planting sugarcane interrows with certain food or cash crops led to significantly improved land productivity and profits. Under dryland conditions a single line of green maize, cabbages, sweet potatoes or soybeans, planted in the centre of the sugarcane interrow, within one week of planting sugarcane in spring, could dramatically improvee the speed at which a farmer saw a return on his investment.

Parsons (2000) found that intercrops[32] must mature within three to five months, before the sugarcane reaches canopy. The intercrop must be fertilised separately according to its nutrient requirements. The sugarcane must also be fertilised at normal standard rates. The sugarcane should be planted in rows with a minimum width of 1.2 metres. There must be no long-term residual sugarcane herbicides

[30] Determining and implementing the optimum frequency and duration of irrigation.
[31] Lands are not planted during a growing season. They are allowed to "rest".

[32] Growing two or more different crops in close proximity.

present in the soil. These must not have been applied over the preceding 15 months. Weed control during the first three to five months after planting must be done by hand or use herbicides that are tolerated by both crops.

The intercrop is most productive in plant cane because the competitive effect of the plant crop is lower than the ratoon crop. In ratoon cane, only maize is able to outgrow the sugarcane crop.

There will be competition for moisture between the sugarcane crop and the intercrop. Sugarcane tonnage will decrease. However, the value of the cane lost is small in comparison to the much higher value of the intercrop produced (Parsons, 2000).

Intercrops serve the function of live mulch, counteract some of the effects of sugarcane monoculture and legume crops will provide nitrogen to the sugarcane crop. They have soil quality benefits. Water infiltration rates also improve (Lal & Singh, 2003). The intercrop will produce more surface stubble to decompose to soil mulch.

Green manuring is an ecological practice that has the potential to ameliorate the negative effects of sugarcane monocropping which leads to soil degradation and yield decline. Using green manures as cover or break crops has shown to improve soil chemical, physical and biological properties of soil for many different agricultural crops (Schumann, Meyer, & van Antwerpen, 2000). Green manure crops will promote soil sustainability. There has been renewed interest in green manuring in conjunction with the incidence of yield decline (Schumann, Meyer, & van Antwerpen, 2000).

Green manuring is the practice of growing selected crops during fallow periods and incorporating the undecomposed plant material or plant residues into the soil or leaving them on the surface, in order to increase the soil organic matter content of the soil (Schumann, Meyer & van Antwerpen, 2000). It is a natural way of adding organic matter to the soil thereby improving soil quality. The green manure crops do not necessarily have to be leguminous crops. Green manures are usually hardy crops that don't require intensive management, or much fertiliser. Fertilising green manure crops will improve their yields and much of the phosphorous and potassium will be available to the subsequent sugarcane crop (South African Sugarcane Research Institute, 2010a).

Green manures are usually planted after the final sugarcane crop has been killed. Many green manures are less acid tolerant than sugarcane, so liming operations should be carried out before planting them. Some green manures are suitable for summer crops, and others are suitable for winter crops. Green manures are allowed to grow for 3-9 months depending on the crop and season. Two successive green manure crops are sometimes planted before replanting sugarcane.

Green manure crops are usually broadcast and incorporated with a light disc harrow. Minimum tillage should be practiced on the following slopes: erodible soils – slopes > 10 percent; moderately erodible soils – slopes > 13 percent; resistant soils – slopes > 16 percent. On slopes that are steeper than those listed above, green manures should be drilled in or planted by hand (South African Sugarcane Research Institute, 2010a).

Green manure residues do not need to be incorporated into the soil. The residue can be left on the surface following mowing or spraying before flowering (South African Sugarcane Research Institute, 2010a). This minimises soil disturbance, helping to maintain soil structure and reduce organic matter depletion as well as reducing mechanical inputs (South African Sugarcane Research Institute, 2010a). Incorporation of legume crops can lead to a flush of nitrogen being released. This may be leached out of the soil profile before the plant cane's roots can access it. This can lead to soil acidification. Leaving the material on the soil surface allows for slower release of nitrogen (South African Sugarcane Research Institute, 2010a).

Sugarcane monoculture farming systems allow farmers to tailor their production methods to one crop but can result in reduced soil quality and crop yields, despite the use of fertilisers (Schumann, 2000). Green manures can be used to ameliorate some of the negative impacts of sugarcane monoculture systems and improve soil quality. Green manures can also break pest and disease cycles that are hosted in sugarcane soils from one crop to the next (South African Sugarcane Research Institute, 2010a). Green manures also improve weed control, can control nematodes and offer protection against soil erosion. Legumes supply nitrogen to the crop and increase microbial populations (South African Sugarcane Research Institute, 2010a). Green manures can also be used to attract beneficial insect predators and provide forage for livestock (South African Sugarcane Research Institute, 2010a).

Oats, sunn hemp and forage sorghum can decrease plant pathogenic nematode populations. Velvet beans increase numbers of the nematode *Helicotylenchus*, which mitigates damage from other harmful nematode species (South African Sugarcane Research Institute, 2010a). Forage peanuts and sunn hemp increase free living nematode populations (Berry & Wiseman, 2003). Green manuring is a worthwhile integrated pest management[33] option to consider for nematode control.

Green manures improve soil physical properties, in particular air-filled porosity, which improves rooting of subsequent sugarcane crops and allows for higher water infiltration rates (Schumann, Meyer, & van Antwerpen, 2000). Yield responses from green manures are generally more significant on poorer soils (Schumann, Meyer & van Antwerpen, 2000). The greatest benefit will be in the rainfed areas on grey sandy soils. Increases in nitrogen and organic matter will be most beneficial on these soils (South African Sugarcane Research Institute, 2010a). Most soils however will benefit from a break in the sugarcane monocrop.

Early trials by SASRI showed that sugarcane yield improved by 5 to 20 percent after a bare fallow and by 10 to 40 percent after a green manure crop, compared to continuous sugarcane cultivation (South African Sugarcane Research Institute, 2010a). Small responses were seen in subsequent ratoon crops. Australian research has shown that sugarcane yields subsequent to green manures generally improve in the plant and one or two ratoon crops (South African Sugarcane Research Institute, 2010a). Generally, legume green manures were superior to non-legume crops (South African Sugarcane Research Institute, 2010a).

[33] A strategy that focuses on the long-term control of pests through a combination of environmentally friendly techniques.

SASRI studies have shown that various green manures increase the availability of phosphorous, potassium, calcium and magnesium compared to continuous sugarcane production (South African Sugarcane Research Institute, 2010a).

2.9.3 Organic material

The addition of organic material such as that coming from green manures and crop residues will have beneficial effects on soil quality and rejuvenate soil (Haynes, 1997; Dominy, Haynes & van Antwerpen, 2001). A fundamental principle of Conservation Agriculture is that the soil surface should be covered at all times. As stated in the previous section green manures can be left as mulch on the soil surface. Green manures recycle nutrients and increase microbial activity. Green organic material can also be incorporated into the soil with vertical mulching[34] (Meyer & van Antwerpen, 2001).

Sugarcane farmers in South Africa have applied the following organic amendments to improve soil quality: flyash[35], filterpress, sugarcane trash, pine bark, poultry and cattle manures, composts and incorporation of green manures (van Antwerpen, Haynes, Meyer & Hlanze, 2003a). The amendment application rates should be determined from soil and product analysis and then be balanced with mineral fertiliser applications. A survey conducted in 2001 determined that filterpress and green manures had the greatest impact on improving soil biological properties (van Antwerpen *et al*, 2003a).

Filterpress is an underutilised resource in the sugar industry mainly because it is a bulky product that is expensive to transport. Its main benefit has traditionally been regarded as a source of phosphorous on high phosphate fixing soils (Moberly & Meyer, 1978). Filterpress is also an effective soil conditioner on hard setting duplex[36] soils. The organic matter in filterpress also improves the soil water infiltration rate, improves moisture holding capacity, increases cation exchange capacity and releases nitrogen (Meyer, van Antwerpen & Meyer, 1996).

2.9.4 Green cane harvesting

Burning sugarcane at harvest remains the main method of preparing land for harvesting in South Africa. Burnt cane is easier to harvest, has lower harvesting and transport costs and reduces the quantity of extraneous matter that is sent to the sugar mill. Burning sugarcane is however detrimental to soil quality.

Under dryland conditions, green cane harvesting has the following advantages compared to burning at harvest: higher moisture retention, better weed control, increased soil organic matter, increased soil microbial activity, improved soil structure, less soil capping, alleviates soil compaction, increased nutrient availability from the trash and less soil erosion (Tucker, 2000; van Antwerpen, Meyer & Thompson, 2006). Soil chemical, physical and biological properties are improved.

[34] Drilling organic material into the soil.
[35] A fine residue generated from combustion in sugar mills.
[36] Soils with contrasting texture between soil horizons.

The long-term average sugarcane yield response of green cane harvesting over burnt cane for the BT1 trial at SASRI was 9 tons per hectare per annum (van Antwerpen, Meyer & Thompson, 2006). This figure is commonly used in the South African sugarcane industry to represent the yield response from trashing sugarcane instead of burning it at harvest. This would be a significant yield response as the average South African sugarcane yield was 64.81 ton per hectare over the period 2001/2002 to 2013/2014 seasons (see Table 1). This figure was calculated using data from the annual average yield figures on the SASA website (South African Sugar Association, 2015).

Yield responses from other trashing trials conducted by SASRI have ranged from negative 23 to positive 25 tons sugarcane per hectare (van Antwerpen, Meyer & Thompson, 2006).

Table 1: Average yield per hectare of harvested sugarcane in South Africa (2001/02 to 2013/14 seasons)

Season	Yield per hectare of harvested cane
2001/02	64.96
2002/03	71.64
2003/04	62.64
2004/05	60.42
2005/06	66.02
2006/07	66.36
2007/08	64.17
2008/09	67.00
2009/10	67.07
2010/11	59.08
2011/12	62.06
2012/13	63.60
2013/14	67.52
Average	**64.81**

Source: Adapted from South African Sugar Association (2015)

The best responses to green cane harvesting are associated with less than long-term mean rainfall years (van Antwerpen, Meyer & Thompson, 2006). This is particularly significant as most sugarcane in South Africa is produced under rainfed conditions with rainfall from 800 mm to 1200 mm per annum. South Africa is the driest sugarcane industry in the world (van Antwerpen, Meyer & Thompson, 2006). Thompson (1965) found that trashing can potentially conserve 90 mm of water per annum. This will have a positive impact on sugarcane yield particularly in dry years.

Soil organic matter loss is less pronounced where cane is harvested green and the trash is retained on the soil surface (Haynes & Hamilton, 1999). According to Haynes (1997) green cane harvesting, where crop residues are conserved provides the best strategy to maintain soil organic matter content. (Haynes,

1997) This is also the most practical way of maintaining or increasing soil organic matter (Graham, Haynes & Meyer, 1999).

Green cane harvesting is a good long-term strategy to use for reducing soil degradation and improving soil quality. Burning sugarcane at harvest is one of the main reasons for the loss of organic matter from soils in the South African monocultural system of sugarcane production (van Antwerpen *et al*, 2002). This farming practice contributes to soil degradation.

Simulated results from a cropping systems model showed that green cane harvesting can maintain the active fraction of organic matter in topsoil (van Antwerpen, 2002). The model showed that yield responses for three rainfall scenarios namely dry, normal and wet, showed that overall yield responses were largest for dry periods and smallest for wet periods. The highest mean yield responses were 23 percent (van Antwerpen, 2002). Mean yield responses for the rainfall sites in the normal rainfall period ranged from 6 to 10 percent. The trend of improved yields from green cane harvesting was generally not affected by soil type. Red earth soil was the only soil that deviated from the trend (van Antwerpen *et al*, 2002).

Further data from the long-term trash trial site BT1 at SASRI showed that after 59 years of green cane harvesting with trash retention, soil organic matter increased significantly in the top 10 cm of the soil, compared to the burning at harvest sites (Miles, Meyer & van Antwerpen, 2008)**.** Soil microbial activity was higher and there was more diversity of soil micro flaura where sugarcane was harvested green. This will improve soil suppressiveness to root pathogens (Meyer & van Antwerpen, 2001).

Surface soil crusts will not form under sugarcane trash blankets. The soil cover intercepts and breaks the direct impact of water before it crashes into the soil surface. The trash blanket will also reduce surface water runoff. More water should penetrate the soil and water use efficiency should improve (Tucker, 2000).

Platford (1982) found that the average results from five trials conducted over a five year period with a rainfall simulator that trash saved 89 percent of the soil and 58 percent of the water, when compared to losses from plots that were burnt and the remaining cane tops were spread. Green cane harvesting combined with minimum tillage and strip cropping will reduce soil loss considerably (Meyer, Rein, Turner & Mathias, 2011). Spreading the sugarcane tops from burnt harvested sugarcane will provide more soil quality benefits than leaving the cane tops in windrows after harvesting (Moberly & McIntyre, 1983).

Crop residues cycle nutrients back to the soil. The accumulation of soil organic matter from a trash blanket leads to an increase in the size of the pool of readily mineralisable soil nitrogen in the top 30 cm of soil. Available phosphorous and exchangeable and non-exchangeable potassium will also increase with trash retention (Graham, Haynes & Meyer, 2000). Once sugarcane lands have been trashed for a couple of seasons it is likely that standard recommended fertiliser rates can be reduced (Graham, Haynes & Meyer, 2000). This must be confirmed with regular soil and leaf samples.

Studies done by the University of KwaZulu-Natal confirmed that the higher productivity of sugarcane following green cane harvesting was not only due to moisture conservation, but also due to higher soil microbial activity, higher soil organic matter turnover and greater storage and release of nutrients (Graham, Haynes & Meyer, 1999).

Some of the limiting factors for green cane harvesting are that it reduces cane cutter productivity and is therefore more expensive than burning where hand harvesting is practiced. Burning costs are however avoided. Very small areas of sugarcane in South Africa are currently cut mechanically. A survey by Anon (2005) found that 90 percent of all sugarcane fields were burnt at harvest in South Africa. Cane cutters are usually reluctant to cut green cane and additional wage incentives are often needed to encourage them to cut green cane. Cane cutters are also in short supply in South Africa. Green cane harvesting requires more cutters per hectare than burnt sugarcane. Haulage payloads are also reduced.

As stated in section 2.8.4 some sugarcane growing areas are not suited to green cane harvesting. Cooler climatic conditions in the higher lying areas of the KwaZulu-Natal Midlands may hinder the ratooning of sugarcane (Graham, Haynes & Meyer, 1999**).** Where sugarcane is trashed, there is a more serious hazard from runaway fires during warm dry conditions due to the dry material on the soil surface (Tucker, 2000).

There needs to be continued focus placed on soil quality, soil fertility and the long-term sustainability benefits of green cane harvesting. This will hopefully encourage larger scale adoption of this practice (Graham, Haynes & Meyer, 1999).

2.9.5 Soil fertility

Conserving and increasing soil organic matter levels will assist to improve soil fertility. This can be done by planting intercrops, green manures, using organic fertilisers like compost or manure and recycling nutrients by applying mill residues such as filterpress back onto sugarcane lands.

Maintaining or increasing soil organic matter content also provides greater storage and release of nutrients (Haynes, 1997). Van Antwerpen and Meyer (1998) report that shifting from the practice of burning sugarcane to green cane harvesting and retaining the trash, can lead to a significant increase in soil organic matter levels. Soil erosion will also be greatly reduced (Haynes & Hamilton, 1999).

The application of lime and inorganic fertilisers will increase soil carbon contents if they are accompanied by increased biomass production (Miles, Meyer & van Antwerpen, 2008). Data from the BT1 trial shows that fertilised treatments had higher organic matter and microbial biomass levels than unfertilised treatments. This is a reflection of higher yields and higher organic matter returns from the fertilised plots. Soil microbial activity decreased with fertiliser applications which was probably due to fertiliser nitrogen induced soil acidification. Regular lime applications can largely counteract the soil acidification effects on soil microbes (Graham, Haynes & Meyer, 1999).

Soil fertility must be monitored by taking regular soil and leaf samples. Recommended rates of plant nutrients must be applied at the optimum time in the correct manner. Nitrogen is one of the most influential nutrients for sugarcane growth. Nitrogen use efficiency is however very low with about 40 percent or less of the applied nitrogen sometimes ending up in the plant (Meyer, 2006). Best management practices must be followed. This includes using the right nitrogen source for the soil type, correct placement of the fertiliser and correct timing given the soil type and crop cycle (Meyer, 2006).

Farmers have the option of using new generation nitrogen products that limit potential volatilisation[37], denitrification[38] or leaching losses of nitrogen. These products assist to optimise nitrogen use efficiency and reduce harmful effects of nitrogen losses into the environment.

2.9.6 Lime and gypsum applications

Corrective applications of gypsum and lime must be applied to alleviate soil acidity problems. Human induced acidification can be reduced by using the correct type of nitrogen fertiliser based on soil and climatic conditions. The nitrogen fertiliser must also be applied using the best method, at the correct time and at the optimal rate.

Corrective liming and gypsum applications will also promote the availability of some plant nutrients. Root growth and beneficial biological soil processes will be promoted and the acidifying effects of nitrogen applications will be countered. Recycling nutrients by green cane harvesting and leaving the trash on the soil surface will also assist to reverse the nutrient mining cycle.

2.9.7 Ameliorate saline and sodic soils

Saline soils contain very high levels of calcium, magnesium and potassium. The high salt content induces water stress which can lead to the death of the sugarcane plant (South African Sugarcane Research Institute, 1997). Regular soil, leaf and water analysis needs to be conducted so that saline conditions can be identified early and dealt with.

The amelioration of soil salinity and soil sodicity is largely achieved by managing soil water. Irrigation scheduling is essential. Drainage must be installed in areas with salinity issues so that excess water can be drained and excess salts leached out of the soil system. Irrigation water quality must be known and water pollution must be avoided.

Where sodic soils become impermeable gypsum can be applied to the soil so that exchangeable sodium is replaced with calcium and then leached out of the soil with irrigation (Haynes & Hamilton, 1999). Reclaiming soils that are saline or sodic is an expensive exercise. In some cases abandoning the land and letting it go back to nature may be the best long-term solution.

2.9.8 Minimum tillage

Mechanical tillage systems in conventional agriculture aim to incorporate crop residues, alleviate soil compaction, control weeds and prepare a fine seedbed. This however has detrimental effects on soil

[37] Loss of ammonia nitrogen to the atmosphere.
[38] The loss of soil nitrate nitrogen to the atmosphere.

due to loss of soil organic matter, less soil biota, reduced rainfall infiltration, soil capping, soil compaction, increased soil erosion and possible suboptimum plant root functioning (Gowing & Palmer, 2007). Platford (1987) stated that 85 to 90 percent of soil loss from sugarcane fields happens at the time of replanting. Replanting is a critical time to carefully consider management options in sugarcane.

Minimum tillage will assist to preserve soil organic matter (Dominy, Haynes & van Antwerpen, 2001). It may also build up soil organic matter if the soils were previously intensively tilled (Miles, Meyer & van Antwerpen, 2008). Minimum tillage is also cheaper than conventional tillage and reduces soil erosion (South African Sugarcane Research Institute, 1998). Minimum tillage allows fields to act as sinks for carbon dioxide.

SASRI has conducted many trials on minimum tillage in sugarcane, starting in the 1970's (R. van Antwerpen, 2006). Other benefits from minimum tillage are less fossil fuel use, weeds are suppressed and mulch provides a food source for soil organisms and enhances their biodiversity. Water infiltration rates are improved resulting in increased quantities of plant available water. The soil will have a larger volume of pore spaces and soil bulk density will be reduced. Nutrient availability will improve as nutrients are recycled. Root development and yields will improve particularly on poorer soils.

The disadvantages of tilled soil are that freshly tilled soil is vulnerable to soil erosion, the rate of organic matter loss is increased and all organisms living in the soil are disturbed. The soil structure also breaks down. Plant residue movement in the soil can spread pathogens.

In a minimum tillage system the previous crop would usually be eradicated with herbicides. The dead crop provides soil cover. An environmentally friendly herbicide should be used. Herbicides are however only effective in spring or summer when sugarcane is growing vigorously. Mechanical methods of crop eradication are most effective during winter when crop growth is negligible. Manual crop eradication methods can be used at any time of the year but will be more effective during the dry winter months. This may be environmentally friendly but is costly and relatively slow (South African Sugarcane Research Institute, 1998).

It is not necessary to prepare a fine tilth to plant sugarcane. This is only necessary in close proximity to the planting setts (South African Sugarcane Research Institute, 1998). This can be achieved with minimum soil disturbance by planting with a fairly simple minimum till machine.

SASRI recommends minimum tillage as a highly recommended practice (South African Sugarcane Research Institute, 1998). However it is not suitable where lime needs to be incorporated or where serious soil compaction issues exist. As previously stated SASRI recommends that minimum tillage should definitely be practiced on erodible soils with slopes greater than 11percent, on moderately erodible soils with slopes greater than 13 percent, and on resistant soils with slopes greater than 16 percent (South African Sugarcane Research Institute, 2010a).

Minimum tillage is relatively environmentally friendly and also the most cost effective method of planting sugarcane (South African Sugarcane Research Institute, 1998). The cost of sugarcane minimum tillage can be as low as 25 percent of the cost of conventional tillage. Minimum tillage planters can reduce planting man days per hectare from between 18 to 25, to about 8 man days per hectare (Tweddle, 2012).

2.9.9 Soil conservation

Soil erosion on farms whether caused by water or wind can be dramatically reduced by implementing a land use plan and constructing suitable water carrying structures such as contours and waterways. Sugarcane rows must be aligned at right angles to the slope. Soil disturbance should be kept to a minimum by practicing zero tillage (Dominy, Haynes & van Antwerpen, 2001) or minimum tillage.

As previously stated harvesting sugarcane green instead of burning it will ensure there is adequate soil cover to reduce soil erosion. Harvesting operations should be planned so that panels of cane are harvested down a slope, instead of harvesting an entire slope at a time with no crop on it to capture and slow down water runoff. Reducing soil erosion will conserve natural capital which will promote sustainable sugarcane yields.

2.9.10 Control in-field traffic

Farmers should attempt to keep traffic out of sugarcane fields when soil moisture is close to field capacity. This will help to reduce soil compaction problems. Traffic on the sugarcane row itself should be limited to the bare minimum. Strategies to ameliorate soil compaction include cross ripping the soil before planting and planting specific green manure crops with root systems that can loosen soils.

In-field equipment should be kept to a minimum and high flotation tyres should be used. The same tracks should be used repeatedly to contain soil compaction (South African Sugarcane Research Institute, 2007). A controlled traffic[39] system can be implemented in the fields. Where feasible, labour should be used for in-field operations instead of machinery. Fields with susceptible soils should be harvested during the dry season. Row spacing and vehicle tyre width must be designed to avoid plant stool[40] damage.

2.9.11 Nematodes

Where detrimental nematodes limit sugarcane growth, particularly on poor sandy soils, other methods besides the use of nematicides are available to control them. These include planting tolerant varieties, increasing the soil organic matter content or using specific green manures that have nematicidal properties. Some green manure crops may promote plant beneficial nematodes (Berry & Rhodes, 2006). Examples of green manures that have nematicidal properties and those that promote beneficial nematodes were given in section 2.9.2.

[39] Confining all in-field machinery to permanent traffic lanes
[40] The roots and short shoots that remain after harvesting. The next crop grows from this.

2.9.12 Conclusion

Many different farming practices can be adopted by sugarcane farmers to improve their soil quality. Farmers may face constraints in terms of adopting some of the proposed practices. They must decide which of the above practices will not only have the greatest impact but can also be implemented relatively easily and cost effectively.

2.10 Sugarcane yield decline

2.10.1 Introduction

This chapter to date has focused on issues relating to the soil resource itself. Soil is the medium in which the sugarcane plant grows. The soil and the way in which it is managed will have a major impact on sugarcane yield.

There is increasing evidence of a levelling off trend or decline in sucrose yield per hectare in many sugarcane producing countries worldwide (Sumner, 2011). South Africa has experienced a long-term yield plateau in yield production since 1971 (Meyer & van Antwerpen, 2001). Declining sugarcane yields have also been recorded in Australia, United States of America, Barbados, Colombia and Hawaii sugarcane industries (Haynes & Hamilton, 1999).

Evidence of yield decline was noted in the United States as early as 1959. After ten years of research on many aspects of yield decline, researchers in the United States conceded, in 1969, that they were a long way from solving or completely understanding this complex problem (Schumann, Meyer & van Antwerpen, 2000). Research still continues on this subject.

In South Africa, poor sugarcane growth and low yields occur on about 60 percent of the area under sugarcane (Meyer, van Antwerpen & Meyer, 1996). Factors influencing sugarcane yield decline are often unclear and difficult to unravel (Ramburan, Wetttergreen, Berry & Shongwe, 2012).

2.10.2 Definition

Sugarcane monoculture farming is generally accepted as a viable practice. However the shortcomings of this farming system are becoming more apparent (Meyer & van Antwerpen, 2001). Sugarcane yield decline is widely defined as the reduction in productive capacity of soils under long-term sugarcane monoculture farming systems (Garside, 1997). This definition focuses on soil quality issues.

Jones *et al* (2012) offer a broader definition. They state that sugarcane yield decline is the decrease in productivity of land excluding the effects of changes in harvest age and climate. Climatic variability and harvest age effects can be excluded by using the Canesim[41] crop model (Bezuidenhout & Singels, 2007).

[41] A sugarcane crop simulation model based on water, temperature and radiation.

2.10.3 Studies

In South Africa, pre 2003, studies on the relationship between soil degradation and sugarcane yield decline were studied relatively one-dimensionally (South African Sugarcane Research Institute, 2004). Topics studied included (South African Sugarcane Research Institute, 2004):

- Acidification (Schroeder, Robinson, Turner & Wallace, 1994)
- Soil compaction (Swinford & Boevey, 1984)
- Soil erosion (Platford, 1979 and 1982)
- Water intake rate decline (Meyer, Dewey & Wood, 1988)
- Irrigation water quality (Culverwell & Swinford, 1985)
- Soil salinization (Johnson, 1978)
- Soil surface crusting (Dewey & Meyer, 1989)
- Soil organic matter (van Antwerpen *et al*, 1996).

The Australian sugar industry identified that sugarcane yield decline is a complex issue that was associated with many factors being out of balance in sugarcane farming systems. They adopted a multi-disciplinary scientific approach towards studying this problem by forming the Sugar Yield Decline Joint Venture in 1993. The Soil Sustainability Interest Group was formed in South Africa in 1998 by a small group of farmers, researchers, extensionists and trade representatives. It also adopted a multi-disciplinary approach to studying sugarcane yield decline (South African Sugarcane Research Institute, 2004).

Jones *et al* (2012) conducted a study using the Canesim crop model to quantify the rate of change in the productivity of sugarcane land attributable to factors other than climate variability and harvest age in the KwaZulu-Natal South Coast region. During the period 1980 to 2009, average actual yields per hectare decreased by 5.5 percent. Simulated yields over the same period, excluding the effects of reduced harvest age and climate showed a statistically significant higher yield decline of close to 11 percent per hectare. The effects of improved technology and better varieties were not considered in this study. These factors should have increased yields. The study concluded that yield decline contributed to reduced sugarcane production on the South Coast.

Yield decline is evident despite the improvement in yield potential from new varieties (Meyer, van Antwerpen & Meyer, 1996). Plant breeders have succeeded in partially compensating for yield decline. In Australia yield decline is occurring despite data suggesting that plant breeding programmes are increasing productivity by about 1 percent per annum (Australian Centre for International Agricultural Research, 2015).

Ramburan *et al* (2012) conducted four sugarcane trials in South Africa and Swaziland to examine the contributions of variety, growing environment (climate and soil) and management to sugarcane yield decline. They determined that the growing environment had an overriding effect on yield decline. This was followed by management practices. The effect of variety was of secondary importance. The implication of this study was that sugarcane farmers should place more emphasis on altering the growing environment through better management, than focusing their efforts on choosing a perceived superior variety.

Singels, Donaldson and Smit (2005) conducted a study on BT1 at SASRI to determine if climate change was impacting on sugarcane yields. Actual yield data was compared to simulated data over the time period 1954 to 2004. The burnt, with tops spread and fertilised treatment plots were used. The authors found an 8 percent increase in yield over the past 50 years due to climate change. Temperatures increased by 0.75 degrees Celsius over the period.

If it was not for improved varieties and warmer temperatures, sugarcane yields would have been even lower than current levels.

2.10.4 Causes

As articulated previously, sugarcane yield decline occurs because of a reduction in the productive capacity of the soil due to a decline in soil quality (Meyer & van Antwerpen, 2001). Plant root development is affected which influences the general well-being of the sugarcane plant.

Most research on this topic has focused on the effects of long-term sugarcane production on soil quality (Haynes & Hamilton, 1999). As stated in the previous section the following aspects linking sugarcane yield decline to soil degradation have mostly been studied in isolation in South Africa - soil acidification, soil compaction, soil erosion, soil water infiltration rate, irrigation water quality, salinization, surface crusting and soil organic matter (South African Sugarcane Research Institute , 2004). Other factors that have played a role in sugarcane yield decline include excessive tillage, burning at harvest, soil structure breakdown and insufficient plant available nutrients (Meyer, van Antwerpen & Meyer, 1996; Haynes & Hamilton, 1999).

Varietal differences and stool damage may play a role in yield decline (Kingston, Donzelli, Meyer, Richard, Seeruttun, Torres & van Antwerpen, 2005). Long-term monocropped soils lose productivity. Inappropriate use of herbicides may also play a role in sugarcane yield decline (Sumner, 2011).

Sumner (2011) argues that for yield decline to occur a combination of, or a few factors are all that is necessary to precipitate decline. The combination can be different at different locations but the end result will be the same - a loss of yield. Site specific solutions are required (Jones, *et al*, 2012).

In Australia it was found that whilst root pathogens played a significant role in yield decline, other soil chemical, physical and biological factors played a role as well (Garside, 1997). Garside, Magarey and Braunack (2000) determined that the factors that caused yield decline varied in response to soil and the environment. Garside, Magarey and Braunack (2000) stated that the magnitude of yield decline syndrome depends on the farming system, potential of the area and management. In high potential areas soil quality issues may be masked with high inputs. They suggested that more attention needed to be placed on improving soil quality in marginal growing areas in particular (Garside, Magarey & Braunack, 2000).

2.10.5 Conclusion

Sustainable sugarcane production systems are needed to ensure the long-term viability of the sugar industry. These must maintain or improve soil quality and sugar yields (Meyer & van Antwerpen, 2001; Haynes & Hamilton, 1999).

Relying on plant breeding programmes to continuously breed more hardy plants to overcome poor management and deteriorating growing conditions is not a long-term sustainable agriculture solution. An alternative practical, cost effective and long-term solution may be to deal with the root cause of the problem by identifying the most limiting growth factors and correcting them.

Garside, Magarey and Braunack (2000) articulated that the magnitude of yield decline syndrome is heavily influenced by management and the farming system that is implemented. Ramburan *et al* (2012) determined that the focus of farmers should be on implementing practices that will alter the growing environment, rather than focus on quick fix solutions such as choosing varieties that are perceived to be better. If farming practices improve, soil quality improves and sugarcane varieties improve – then the farmer should be well along the path towards a sustainable long-term solution.

Maximum sustainable crop yields should be strived for. This is defined as: "*The maximum crop yield that can be sustained for a specific soil type and climate without undue harm to the environment."* (Gregorich, Turchenek, Carter & Angers, 2001: 221). This can be interpreted to be the highest yield that can be taken from soil, under prevailing ecological and environmental conditions, without reducing the base of soil natural capital and compromising future yields. This crop yield must also not harm the long-term economic status of the farm or the needs of present and future generations who rely on the farm for sustainable livelihoods.

2.11 Different farming systems

Farmers have many options in terms of the farming practices they implement. Their philosophy around sustainability and how they view their soil resource will play a role in their decision making process.

2.11.1 Green Revolution and conventional agriculture

Huang, Pray and Rozelle (2002) assert that the Green Revolution has highlighted the importance of using technology to boost food production. These authors believe that genetic engineering and increased research funding, together with other technologies, will result in continued agricultural productivity in future decades.

The Green Revolution has increased agricultural productivity dramatically over the past forty odd years. However this has been achieved by using more resources and more virgin land was converted to agricultural land (Pretty, Guijt, Scoones & Thompson, 1995). Current Green Revolution technologies include synthetic nitrogen use, pesticide and herbicide use, increased irrigation, GM seed, high yielding crop varieties, mechanisation, large specialised farms and monocropping.

The link between ecology and farming becomes broken. Ecological principles of farming take a back seat in farm decision making. Whilst these farming systems can be very productive, natural resources may become polluted, damaged and depleted (Lampkin, 1999).

The productivity gains can also come at a high social cost which is not sustainable. Many of the technologies are expensive to implement, so household debt increases and inequalities among farmers increase (de Schutter, 2009). When agricultural systems are at or above sustainable production levels, the benefit of yield increases from further inputs may be outweighed by the increased marginal costs of those inputs. Monocropping also reduces the biodiversity of plant genetic resources and reduces access to a range of nutritious food (Bot & Benites, 2005).

According to Altieri and Nicholls (2005) monocultures can lead to a reduction in soil fertility, soil erosion, pest and disease outbreaks, resistance to pesticides and herbicides, diversity of soil biota is reduced and natural control systems are destroyed. Monocultures break synergistic linkages between crop enterprises and soils, and crops and animals. Nutrient, water, energy and waste cycles become more open rather than closed. Monocultures concentrate resources for crop pests and reduce resources for natural predators so pest outbreaks become more likely.

As stated previously sugarcane is traditionally grown as a monocrop. Sugarcane monoculture has been practiced in South Africa for over 100 years. This has lowered the productive capacity of sugarcane soils. Soil quality will diminish if crop rotation is not practiced in sugarcane fields. The vigour and yield of the crop will decrease (South African Sugarcane Research Institute, 2004).

To overcome crop growth limiting factors chemical technologies are intensified, particularly in marginal growing areas. Crop symptoms are often treated instead of dealing with the underlying problems. The assumption is that these interventions can continue indefinitely. The farmer ends up on a technological treadmill. The question must be asked if this is a sustainable long-term solution.

Plant breeders are relied on heavily to continuously breed new improved cultivars that can overcome monocultural challenges. Monocultures often need to be subsidised with increasing usage of agricultural chemicals. Growth in crop yields per hectare is closely linked to the increased unsustainable use of agro-chemicals. The efficiency of many of these chemicals unfortunately decreases with time and may lead to yield plateau or decline (Altieri & Nicholls, 2005). Agro-ecologists believe that this is due to unsustainable practices steadily eroding the productive base of agriculture. The concept of Agro-ecology is explained in detail, in section 2.12.

2.11.2 Sustainable agriculture and the need for change

The concept of sustainable agriculture has emerged fairly recently in response to modern agriculture reducing the quality of the natural resource base (McIsaac & Edwards, 1994 in Altieri, 1999). Sustainable Agriculture aims to simultaneously meet economic, social and environmental objectives (Sullivan, 2003). It is a whole system approach to agriculture (Sullivan, 2003). Complex economic, social and environmental sustainability objectives constantly overlap. Managing the three objectives of the triple bottom line simultaneously requires clear goal setting, effective decision making and careful monitoring of progress towards the goals and the health of the system (Sullivan, 2003).

Sustainable agriculture aims to manage complex interactions between soil, water, animals, plants, climate and people. All these factors should be integrated into a production system that is appropriate for the environment, people and economic conditions where the farm is located (Sullivan, 2003). It aims to maintain agricultural productivity in the long-term (Altieri & Nicholls, 2005) so that the needs of future generations are also met.

Sustainable soil management is an important component of sustainable agriculture. Soil supports all terrestrial life but is one of the most complicated biomaterials on earth. The opaque nature of soil makes it very difficult to observe and study. However new techniques and insights into the chemical, physical and biological processes of soil are leading to new approaches to sustainably manage earth's most important resource (Young & Crawford, 2004).

Farming alters the biological and physical composition of ecosystems. Farming practices should limit the impact on ecosystem resources such as soil. Ecosystem services provide value to the farmer (Donaldson, 2003). According to Crawford *et al* (2005) soil provides the following ecosystem services - provision of fresh water, flood prevention, climate regulation, and it allows grasses, shrubs, plants and trees to grow.

A combination of pressures is threatening world social and ecological systems. Conventional high input farming agricultural practices place ever increasing demands on soils. Technological and scientific developments allow us to extract more and more out of our soils. The rapidly growing world population, urbanisation, income growth, stagnant crop yields and biofuel demand are placing more and more demands on our soils to produce food (Pretty, 2011).

Swilling and Annecke (2012) stated that a number of diverse indicators are pointing towards an unprecedented poly-crisis on planet earth. They identify multiple mutually reinforcing sub-crisis that point towards the end of the unsustainable, oil based post-World War Two developmental cycle. These sub-crisis indicators include global warming, ecosystem degradation, food insecurity, peak oil, urbanisation and growing slums and inequality. These indicators are interrelated and manifest themselves in all aspects of life, including agriculture.

These factors combined with the effects of climate change, biodiversity losses, soil and water degradation, water shortages, energy scarcity and pest and disease problems, make a bold statement that agricultural systems need to change (Pretty, 2011). The United Nations Environment Programme (2009) warns that agricultural yields may be 5 to 25 percent short of demand by 2050.

A just transition is required. This must reconcile the sustainable use of natural resources with a commitment to sufficiency (Swilling & Annecke, 2012). Soil productivity must be decoupled from soil degradation (Follett, 2001). Swilling and Annecke (2012) include a transition towards Agro-ecological farming systems as one of the five key transitions that are compatible with a more sustainable long-term world development cycle.

Crawford *et al* (2005) stated that no theory existed on the sustainable exploitation of soil. Sturz and Christie (2003) declared that the processes involved in soil fertility, soil resilience, soil stability and enhanced crop production were not all fully understood. We do not know how we are affecting the long-term productive capacity of our soils. This is a very serious issue. As stated previously history tells us that past successful societies damaged their environment to the point where it could no longer support the population. These societies did not respond adequately to changes in their resources. The decline developed slowly, society reacted too late and social disintegration occurred relatively quickly (Clayton & Radcliffe, 1996). Society needs to understand the pressures we place on our soils so that it can be managed in a manner that allows us to feed the ever growing population over the long-term.

Many authors have commented on what is required from agricultural systems to meet the challenges we face moving forward. Various technologies are proposed. Some of these opinions are stated below.

Tilman, Cassman, Matson and Naylor (2002) argue that agriculturalists as the managers of agricultural lands will shape perhaps irreversibly the earth's surface over the next couple of decades. New agricultural technologies are required to ensure the sustainability of agriculture and ecosystem services. This is critical to improve yields without compromising environmental integrity.

The World Business Council for Sustainable Development (2008) believes that the main challenge for the agricultural sector is to produce enough to meet demand, whilst simultaneously conserving biodiversity, managing natural resources and improving human well-being. The IAASTD (International Assessment of Agricultural Knowledge, Science and Technology for Development, 2009) report states that the main challenge for agricultural knowledge, science and technology, is to increase agricultural productivity in a sustainable manner.

According to Altieri and Nicholls (2005) as recently as five decades ago sustainable farming methods were largely used. Crop yields were modest but stable. There was a strong link between agriculture and ecology and environmental degradation was seldom evident. As agricultural modernization progressed and new technologies were adopted the link between ecology and farming was broken. These new intensive farming systems were very productive but came at a cost to the environment and soils (Lampkin, 1999). Altieri and Nicholls (2005) go on to declare that doing away with crop rotation and diversification leads to a breakdown in key self-regulating soil mechanisms. Monocultures then become highly vulnerable agro-ecosystems that are dependent on high chemical inputs.

Current levels of agricultural productivity using conventional farming methods can often only be sustained with ever increasing levels of inputs. This is not a sustainable long-term solution. Where dominant technology degrades the soil and generates pest and weed problems, effectively destroying the basis for future production, it becomes increasingly difficult and costly to sustain yields (Rosset, Collins & Lappe, 2000).

Tilman *et al* (2002) state that conventional farming systems have incurred costs related to loss of ecosystem services, environmental degradation, biodiversity loss, emergence of pathogens and the long-term stability of agricultural production.

Gowing and Palmer (2007) argue that a second transformation of agriculture is required. It should be doubly green in that it should boost output whilst protecting the environment. Agro-ecological farming methods can develop models of agricultural development that are highly productive and can meet the multiple challenges faced by the world agricultural system (De Schutter, 2009). According to Altieri and Nicholls (2005) diversified agro-ecosystems that use low-input technologies and ecologically sensitive farming systems can produce sustained yields. The successful transition in Cuban agriculture post 1989 is a prime example of this (Rosset, Collins & Lappe, 2000).

Heap and Kent (2000) declare that ecosystems must be protected. They state that both past and future agricultural intensification has and will continue to have detrimental impacts on non-agricultural terrestrial and aquatic ecosystems. The International Assessment of Agricultural Knowledge, Science and Technology for Development (2009) report articulates that agricultural systems are needed which enhance sustainability and maintain productivity whilst protecting the natural resource base and ecological functions of agricultural systems.

Doran, Kirschenmann and Frederick (2007) present that agricultural food production and distribution systems must rely less on non-renewable resources and more on renewable resources. Future global food needs must be met from present readily available water, soil, land and fertility. This must not compromise the capacity of future generations to meet their food, resource and environmental needs.

There is an urgent need for sustainable and efficient agricultural practices to emerge. An agricultural system is required that relies more on ecology, biology and sociology, than primarily on the chemical and physical management approaches of the past. The agricultural system must move towards climate-resilient ecological agriculture (Wijeratna, 2012). Doran, Kirschenmann and Frederick (2007) believe that the solution lies in an agricultural system that is a hybridized one, lying somewhere between intensive input conventional agriculture and organic agriculture approaches.

2.12 Agro-ecological farming system

2.12.1 Principles of Agro-ecology

Proponents of Agro-ecology believe that new methods of farming are required. These methods must produce food whilst taking the environment and more particularly ecosystems into account. Agro-ecology is based on the application of ecological science (Altieri, 1995) and believes in a whole system approach to agriculture. Ecological relationships must be promoted in the design and management of sustainable agro-ecosystems (Principles of Agro-ecology, 2010). Beneficial biological interactions must be promoted between the components of the agro-ecosystem (Wijeratna, 2012). Unnecessary use of external inputs must be avoided and the use of practices that adversely impact on human health and the environment must be minimised (Pretty, 2011).

Agro-ecology is highly knowledge intensive and farm context specific. It seeks to secure food self-sufficiency whilst preserving the natural resource base, and ensuring economic viability and social equity (Altieri & Nicholls, 2005).

Agro-ecology is not associated with any one particular method of farming. There is no recipe for success as the practices recommended must be site specific. It is a multidisciplinary practice that seeks to understand the agro-ecosystem. The focus is on productivity, stability, sustainability and equitability (Conway, 1985). These four factors are inter-connected. Agro-ecology looks at interactions between humans, plants and the environment within the specific agricultural system (Dalgaard, Hutchings & Porter, 2003).

Magdoff (2007 b) declares that the following characteristics of natural ecosystems must be built into agricultural production systems: efficient energy flows, biological diversity, self-sufficiency, self-regulation and resiliency. Ecologically based agriculture must rely on local resources as much as possible and focus on building and maintaining healthy soils.

Agro-ecology is based on the following ecological principles:

- Use renewable resources
- Minimise use of toxic products
- Conserve soil, water, energy, genetic and capital resources
- Manage ecological relationships
- Adjust to local environments
- Promote diversity of landscapes, biota and economics
- Empower people
- Manage whole systems
- Maximise long-term benefits
- Value human, cultural, environmental, animal and plant health

(Principles of Agro-ecology, 2010).

Altieri (1999) adds further principles on which agro-ecological systems should be based. Implement biomass recycling such as retaining crop residues and applying manures. Balance nutrient flows and create favourable soil conditions for plant growth by enhancing organic matter and soil biotic activity. Optimise available solar radiation, air and water by managing the microclimate, water harvesting and using soil cover. Maximise species and plant diversity to build up system resilience. Monocultures must therefore be avoided. Encourage beneficial biological interactions and synergies so that natural ecological processes can enhance rather than undermine agricultural production.

Agroecology attempts to identify the ecological principles that are necessary to develop sustainable agricultural production systems (Norberg-Hodge, Goering & Page, 2001). Ecological technologies that are environmentally sensitive and can achieve permanent improvements in production must be adopted (Pretty *et al*, 1995). Agro-ecology is not a menu of technologies. Ad hoc adoption or removal of specific agricultural practices will not necessarily lead to a more self-sufficient sustainable agriculture. Practices must be adopted based on a deep understanding of the nature of agro-ecosystems and how they function (Altieri, 2002). The effects on rural communities, economic constraints and cultural factors must also be taken into account when determining which farming practices to use.

Kate (2008) states that Agro-ecological practices help to maintain soil fertility and improve soil quality. These practices also assist soils to sequester carbon. Improved soil fertility and increased soil organic matter content will help soils to maintain productivity during extreme climatic conditions which may be experienced more and more as climate change manifests itself.

2.12.2 Agro-ecology technologies

Specific Agro-ecological technologies are recommended as alternatives to conventional agriculture. These technologies improve the natural capital stocks in agro-ecosystems. Integrated nutrient management promotes a reduction in the use of agrochemicals by using manures, organic wastes, legumes and reducing soil erosion (Altieri & Nicholls, 2005; Pretty, 2006; Magdoff, 2007 b). Livestock enterprises can be integrated with crops to provide manure and utilise forages produced (Altieri & Nicholls, 2005; Pretty, 2006). Crop rotation should be adopted to interrupt disease, weed and insect cycle's (Altieri & Nicholls, 2005; Magdoff, 2007 b). Integrated Pest Management must be used for pest control. Agro-chemicals are allowed but must only be used as a last resort (Pretty, 2006). Plant cover crops or implement an intercropping system (Altieri & Nicholls, 2005; Magdoff, 2007b). Conservation tillage is recommended to conserve soil and moisture (Pretty, 2006; Magdoff, 2007b). Reduce soil compaction (Magdoff, 2007b). Agroforestry incorporates multifunctional trees into the agricultural system. Aquaculture incorporates aquatic resources and increases farm protein production. Water harvesting should be practiced.

These diversified farming technologies aim to recycle nutrients, add organic matter to soils, close energy flows, conserve water and soil and balance pest and natural enemy populations. The improved biodiversity and increased interactions between the various components will provide ecological services to the farm (Altieri & Nicholls, 2005). Agro-ecology also contributes to a range of public goods such as carbon sequestration, clean water, groundwater recharge, flood protection and landscape beauty (Pretty, 2011).

Chemical fertilisers can be used in this approach. However, Altieri (2002) states that there is a burden of proof that the fertiliser will add to economic and environmental net benefits over the long-term. These benefits must not be able to be attained from any other less costly means. The permitted use of chemical fertilisers and agro-chemicals is a key area where Agro-ecology differs from some other sustainable farming systems such as certified organic agriculture.

2.12.3 Biodiversity

Sugarcane farming impacts on the environment and on ecosystems. It reduces the biodiversity of the land and its surroundings. Diverse ecosystems can handle environmental stress better, and so are more productive. The more species an ecosystem contains the more stable it is likely to be. Technologies need to be adopted that will increase the biodiversity of sugarcane soils and their surrounding areas. This should include the biodiversity of micro-organisms in the soil.

2.12.4 Application to sugarcane soil management

Having reviewed the literature I believe that the following Agro-ecological practices have particular relevance to sustainable sugarcane management: nutrient cycling, reduction or elimination of certain agrochemical inputs, managing soil organic matter, minimising soil erosion, enhancing soil biotic activity (promote diversity), minimise loss of solar radiation and water, enhance beneficial biological interactions, maximise long-term benefits, use renewable resources, allelopathy[42], integrated pest management and the conservation of natural ecosystem areas on farms. Approaching soil quality issues from an Agro-ecological perspective may assist farmers to decide which farming technologies and practices they should adopt.

2.13 Conservation Agriculture[43] farming system

2.13.1 Aims and technologies

Donaldson (2003) explains that Conservation Agriculture aims to maintain a balance between agricultural production and conserving natural agricultural resources. The soil resource is conserved by enhancing natural biological processes below and above the soil surface (Gowing & Palmer, 2007; Hobbs, Sayre & Gupta, 2008). Land is managed so that there is:

- Minimal mechanical soil disturbance
- Soil is permanently covered with organic material
- Crop residues are retained
- Diversified crop rotations are planted.

Specific Conservation Agriculture technologies are adopted to achieve these principles (Gowing & Palmer, 2007; Hobbs, Sayre & Gupta, 2008). Conservation Agriculture will only work optimally if all the different technical aspects are considered simultaneously in an integrated way (Food and Agriculture Organization of the United Nations, 2010).

---

[42] The chemical inhibition of a plant or organism by another, due to the release of substances acting as growth inhibitors.

[43] To qualify as a Conservation Agriculture farming system - all the key practices must be implemented.

Minimum tillage in sugarcane was covered in detail in section 2.9.8. Crop rotation including cover crops, intercrops and green manures were covered in section 2.9.2. Green cane harvesting and the retention of sugarcane trash on the soil surface were covered in detail in section 2.9.4. Soil can be covered with either dead mulch or a growing crop (Gowing & Palmer, 2007). This protects the soil physically from rain, sun and wind. It also provides a favourable habitat for soil biota.

Conservation Agriculture encourages natural soil processes. The soil is not tilled mechanically but is tilled biologically. A healthy soil ecosystem is promoted. The aim is to produce sustainable good yields, reduce soil erosion and lower costs of production (Gowing & Palmer, 2007). Farmers should be encouraged to adopt Conservation Agriculture principles so that natural resources can be conserved.

Conservation Agriculture can be termed a sustainable agriculture production system. It conserves and enhances natural resources without sacrificing agricultural yields (Food and Agriculture Organization of the United Nations, 2010). Soil chemical, physical and biological properties are improved (Hobbs, Sayre & Gupta, 2008). Conservation Agriculture combines profitable agricultural production with environmental conservation and sustainability. The technology has worked in a variety of agro-ecological zones and farming systems (Food and Agriculture Organization of the United Nations, 2010).

Conservation Agriculture farming practices conform to many Agro-ecological principles. They conserve soil, water, energy and capital resources; they manage ecological relationships; and diversity of landscapes and biota is promoted. There are long-term benefits, environmental impacts are reduced and sustainability is improved.

2.13.2 Transition to Conservation Agriculture

The transition from conventional farming to Conservation Agriculture takes time. A conversion period is required. It takes time for the soil to adjust to minimum tillage and it takes time to build up organic matter levels in the topsoil and mulch on the soil surface. Soil life needs to return to the soil. Naturally occurring processes must to be restored (Food and Agriculture Organization of the United Nations, 2010).

The transition to Conservation Agriculture requires a mind shift from the farmer. Expertise needs to be sought so that costly mistakes are kept to a minimum. The conversion process will entail financial implications. Severely degraded soil may take time before it is rehabilitated to a point where agricultural yields are equal to or more than previous conventional agriculture yields. New equipment also needs to be purchased, in particular crop planters. A small portion of the farm should be concentrated on first so that expertise and experience can be gained (Food and Agriculture Organization of the United Nations, 2010).

Before starting with Conservation Agriculture certain soil physical and chemical properties need to be corrected. These include drainage, compaction, soil pH, phosphorous and potassium levels. This may require sub-soiling[44], soil levelling, green manures, lime and gypsum applications and corrections of nutrient deficiencies (Food and Agriculture Organization of the United Nations, 2010).

2.13.3 Food security

Gowing and Palmer (2007) declare that Conservation Agriculture can assist the world to meet the Millennium Development Goal food security target. This may be possible if Conservation Agriculture techniques are used in conjunction with responsible levels of external inputs, in particular fertiliser and herbicides.

Gowing and Palmer (2007) also assert that Sub-Saharan Africa must improve rainfed agricultural systems if hunger and poverty issues are going to be adequately addressed. This agricultural productivity transformation must not have adverse effects on environmental goods and services. The authors believe that Conservation Agriculture is the desired approach that can deliver sustainable agricultural development in Sub-Saharan Africa.

Conservation Agriculture promotes soil ecosystem health whereas conventional land husbandry practices may promote land degradation. A conversion to Conservation Agriculture comes with the responsibility of sustainably producing as much as, or more per unit area than with conventional farming methods.

2.14 Some sugarcane industry sustainable agriculture initiatives

The section documents various sugarcane sustainable agriculture initiatives. A study conducted by Ferrer and Nieuwoudt (1997) is included as it is the only South African on-farm study that could be sourced on soil, where the farmers' perspectives were recorded as part of this study. SUSFARMS® and the Standards and Guidelines for Conservation and Environmental Management in the South African Sugar Industry manual are included as South African sugar industry initiatives. Literature from the Sugarcane Yield Decline Joint Venture is often referenced in this thesis. This initiative was a multi-disciplinary research project completed in the Australian sugarcane industry. The Sugarcane Agro-ecological Zoning exercise completed in Brazil is an example of Agro-ecological zoning principles being used to ensure that the future expansion of their sugar industry is sustainable.

2.14.1 Study on soil conservation efforts in field panels

Ferrer and Nieuwoudt (1997) conducted a study on KwaZulu-Natal commercial sugarcane farmers, studying factors that affect their decisions with respect to soil conservation in their field panels of sugarcane. The study wanted to establish if farmers were complying with the Conservation of Natural Resources Act of 1983 or not. Multiple regressions were used to compile models that represented panel soil conservation adoption and conservation effort.

The results showed that farmers concentrated more soil conservation effort on the relatively steeper field panels, which is to be expected. The study also found that the use of farmer extension support

[44] Ripping the layer of soil below the topsoil layer.

services and education are positively related to soil conservation adoption and effort. Soil conservation decisions were found to be constrained by management time, financial resources and the technical ability of the farmers.

This study did not focus specifically on soil degradation or soil quality. It was included as an example of soil related research conducted with sugarcane farmers.

2.14.2 Standards and Guidelines for Conservation and Environmental Management in the South African Sugar Industry

A manual called Standards and Guidelines for Conservation and Environmental Management in the South African Sugar Industry, was published by the South African Sugar Association in 2002. The manual was prepared to inform sugarcane farmers of standards and guidelines covering relevant environmental issues and management practices that farmers should adopt to conserve their farms. It contains voluntary standards that assist farmers in the self-regulation process.

Land Use Plans are covered in depth and farm audit guidelines are included in the manual. There is a section on soil conservation and a section on the key factors that farmers should understand if they wish to avoid soil degradation and ensure their farm's long-term sustainability. Guidelines are given on burning and green cane harvesting, land preparation, planting, application of agro-chemicals and crop nutrition. Guidelines are also provided on irrigation, soil sodicity and salinity, water quality and drainage. Soil identification, erodibility, compaction and moisture content are covered. Soil physical and chemical properties and their limitations are stated. The manual also briefly covers nutrient levels for sugarcane and toxic levels of heavy metals. It is recommended that all of the above management practice guidelines must be adhered to by sugarcane farmers in order to prevent soil degradation.

2.14.3 SUSFARMS®

SUSFARMS® is an example of a sustainable agriculture initiative that was initiated by local sugarcane farmers. SUSFARMS® stands for Sustainable Sugarcane Farm Management System. It is a management tool to assist sugarcane farmers in South Africa to manage their farms in an economically, socially and environmentally sustainable manner. It states better management practices or higher level practices that farmers should adhere to. These guidelines can be used for sustainability auditing of the farm.

The system was initially developed in 2008 by Midlands North region sugarcane farmers represented by Noodsberg Canegrowers and SASRI staff. The project was mainly funded by the WWF with significant contributions made by WWF-SA / WESSA Mondi Wetlands Project, SASRI and Noodsberg Canegrowers. This initial version developed the system and contained detailed information on each of the auditable measures or verifiers as they are called (South African Sugarcane Research Institute, 2008).

A second edition was published in 2012 by SASRI. The contributors were various SASRI staff, South African Canegrowers and Edward Nathan Sonnenbergs.

SUSFARMS® assesses sustainability by determining if farmers adopt better management practices within economic, social and environmental principles. These principles are underpinned by specific criteria, indicators and verifiers that can be audited to show whether better management practices and legal requirements have been complied with. The following indicators refer to soil management: land use plan, ecosystems, environment conservation, soil conservation, water use, irrigation and drainage, and agro-chemical usage.

SUSFARMS® integrates the farm management system with the local resource base and existing environmental and socio-economic conditions. The desired end result is long-term economic, social, agronomic and ecological sustainability of the production system. Negative impacts on the environment are reduced, whilst ensuring economic sustainability and social upliftment through implementation of the better management practices (South African Sugarcane Research Institute, 2012).

2.14.4 Sugarcane Yield Decline Joint Venture

Some of the research outcomes from this venture were previously referenced particularly in section 2.10.4 of this thesis. This venture was a multi-disciplinary, multi organisational research project focusing on sugarcane yield decline within the Australian sugarcane industry. This was in response to their industry reaching a productivity plateau in the early 1970's and increasing pressure from environmental lobbies. Previous industry research focused mainly on single discipline research focused on various production factors. Few answers were forthcoming as to the reasons for the productivity plateau.

A research and development approach was applied to sugarcane yield decline. Research outputs were geared to integrate them into a farming system. The project conducted research over two phases. Phase one was from 1993 to 1999. Phase two started in July 1999 and finished in June 2006. The research leader was Dr A. Garside. Phase two built on the solid research base and research outcomes from phase one.

According to the final report of the Sugarcane Yield Decline Joint Venture (Garside & Bell, 2006) the research confirmed that yield decline is a complex issue. It is associated with many factors being out of balance in the way that sugarcane is traditionally grown. The research found that changes to the Australian sugarcane cropping system had a lot to do with yield decline. These changes included expansion into poorer quality soils, removal of enforced fallowing restrictions, excessive cultivation (recreational tillage as they call it), mechanical harvesting with heavy machinery, removal of organo-chlorine pesticides, and increased usage of nitrogen fertiliser to overcome soil limitations.

Soil chemical, physical and biological properties on paired sites were studied. They concluded that long-term sugarcane soils are degraded and that yield decline is a consequence of degraded soils. Soil quality must be improved to manage yield decline. Sugarcane yield decline is largely manifested through very poor root systems.

The research showed that all sugarcane growing areas in Australia experience yield decline. The ultimate effect on productivity is however associated with the prevailing growing conditions. In some areas high inputs of nitrogen and water could overcome poor soil conditions and still produce reasonable crops. This comes at a cost and may degrade soils further in the long-term.

One of the most important research outcomes was confirmation of the importance of soil organic matter in the farm system. Sugarcane trash is the main source of organic matter on sugarcane farms. This highlighted the contribution that sugarcane trash conservation and green manure residues can make to improving soil chemical, physical and biological properties.

It was found that monoculture itself was not the major cause of yield decline. The way in which it is practiced is a large part of the problem. Excessive tillage, uncontrolled traffic and field removal of organic material are possibly as important contributing factors as the lack of crop rotation.

Phase one showed that there was large yield responses (20 to 30 percent) to breaking the sugarcane monoculture cycle. These responses extended into the subsequent ratoon crops. The research found that this was mainly due to the establishment of a healthy root system in the planted crop.

Assessments of measurable soil biota determined that they returned to pre-break crop levels within twelve months of re-planting the sugarcane. Unfortunately the diagnostic tools are not available to comprehensively quantify soil microbial activity which makes it difficult to measure all biological factors. This particular research outcome therefore has some limitations.

It was determined that it would be beneficial to change the traditional row spacing from 1.5m to 1.85m. This will reduce soil compaction and allow a controlled traffic system to be implemented in the fields. It was concluded that due to the environmental plasticity of sugarcane maximum yields could still be produced with wider row spacing as long as soil health was not a limiting growth factor.

The research also demonstrated that a well-managed legume green manure crop is a very important component of any sustainable sugarcane cropping system. This farming practice helps to improve soil health and fix atmospheric nitrogen. This nitrogen is also better utilised by the crop if the legume residue is retained on the soil surface and not incorporated. This facilitates the implementation of a minimum / zero till farming system.

Garside and Bell (2006) stated that the main legacy of this project has been the development of a new practical sugarcane farming system to improve soil quality. It is being adopted in all sugarcane farming regions of Australia. This cropping system is based on minimum / zero tillage, legume green manure crops, controlled traffic, green cane harvesting and sugarcane trash retention. The researchers believe this farming system will take the Australian sugarcane industry into the future. It will improve profitability, be sustainable and is environmentally responsible.

2.14.5 Sugarcane Agro-ecological Zoning (ZAE Cana) in Brazil

Brazil wished to expand their area under sugarcane. The federal government undertook a sugarcane Agro-ecological zoning exercise to ensure that the growth in the industry was sustainable and that natural capital would be preserved as best as possible (Unica, 2012). The programme was called Sugarcane Agro-ecological Zoning (ZAE Cana). Specific regions in Brazil were studied taking their climate and soils into account. Environmental, economic and social aspects were taken into account to ensure the sustainable expansion of sugarcane production.

The federal government compiled rules and regulations for the expansion and for the extension of credit for the sector. Their catch phrase was to expand production, preserve life and ensure a future.

The following guidelines were set to guide the expansion. Areas where native vegetation was dominant were excluded. Some regions were excluded totally such as the Amazon and Pantanal biomes and the Upper Paraguay River Basin. Production areas had to be mainly rainfed. Slope had to be less than 12 percent to allow for mechanical harvesting. This avoids burning sugarcane and carbon dioxide emissions. There had to be no risk to food production or food security. Priority should be given to planting sugarcane on areas already used for pastures or on degraded land.

The environmental, economic, social, climate and soil restriction set by ZAE Cana meant that 7.5 percent of the Brazilian territory was suitable for sugarcane production. This was 64.7 million hectares. 19.2 million hectares of this was classed as being of high suitability for sugarcane production. The area under sugarcane production in Brazil during the 2008 / 2009 season was 7.8 million hectares. The area planned for sugarcane expansion by 2017 was 6.7 million hectares (Unica, 2012). As a comparison, South Africa only had 379 870 hectares under sugarcane in the 2012 / 2013 season (South African Sugar Association, 2015).

The federal government has also regulated burning of sugarcane in existing production areas of Brazil. There is a transition period until 2017 when areas that can be mechanically harvested can no longer be burnt. This measure will reduce greenhouse gas emissions by six million tons of carbon dioxide using 2008 as the reference year.

Besides being an Agro-ecological zoning exercise, this is also an example of the state playing a role in regulating practice. The state has taken the lead in protecting and conserving the commons.

2.15 Summary

Chapter Two begins with a broad overview of soil and the soil system. Soil forms gradually over a long period of time. Soil is the foundation of civilization as we grow our food in it. Soil must be conserved for present and future generations. South Africa is not blessed with large areas of high potential arable land. Many of our soils also have low resilience and are very vulnerable to degradation. Degraded soils are difficult to rehabilitate. Farmers are the key custodians of land.

Soil physical, chemical and biological properties must be preserved as they determine the productive capacity of soil. The three soil properties should be considered as a holistic whole rather than as a sum of separate parts. Soil is a complex living entity with its own ecosystem. Sugarcane farming practices have impacted negatively on all three of the soil properties. This has reduced soil quality. Sugarcane farming practices that promote rather than degrade soil quality should be adopted. There is a strong link between sustainable land management and healthy soil properties. A healthy soil resists degradation, can reach its full potential and maintain its capacity into the future.

Soil organic matter is an essential component for enhancing all the properties of soils. Management of soil organic matter lies at the heart of sustainable agriculture. Soil organic matter provides resistance to soil degradation. South African soils generally contain low quantities of soil organic matter.

A healthy soil can meet a range of ecosystem functions. A healthy soil maintains animal and plant productivity and diversity. Roots are healthy and crops grow with minimal external inputs. Healthy soils are more resilient and produce higher yields than degraded soils. Soil productivity is largely determined by the environment that is provided for root growth.

Sugarcane yield decline is a complex issue. A combination of a few factors may be all that is needed for yield decline to occur. Site specific solutions are required. Factors influencing sugarcane yield decline are often unclear and difficult to unravel. Sugarcane farmers should implement farming practices that will improve soil quality.

The farming system that farmers subscribe to will play a role in determining the farming practices and management philosophies they adopt. Agriculture needs a second transformation that takes the triple bottom line sustainability objectives into account. Soil productivity must be decoupled from soil and environmental degradation (Follett, 2001). Sustainable sugarcane production systems are needed that improve both soil quality and sugarcane yields in the long-term

Sustainable agriculture is a whole system approach that concentrates on long-term solutions to problems. The objectives of the triple bottom line are managed simultaneously. The aim is to meet the needs of present and future generations.

Agro-ecology farming systems take the environment and ecosystems into account. Agro-ecology is context specific and seeks food self-sufficiency whilst preserving the natural resource base. It is a multi-disciplinary whole system practice. Agro-ecological practices help to build up soil fertility and improve soil quality.

Conservation Agriculture aims to maintain a balance between agricultural production and conserving natural agricultural resources. Specific technologies are recommended to achieve this goal. Conservation Agriculture encourages natural soil processes and a healthy soil ecosystem. The aim is to produce good sustainable yields, reduce soil erosion and lower the costs of production. Soil properties are improved.

Approaching soil quality issues from an Agro-ecological or Conservation Agriculture farming system perspective may help farmers when they need to decide which sustainable farming practices and technologies to adopt.

Various sustainable agriculture initiatives have been commissioned by a diverse set of sugarcane stakeholders. They all have one common objective - to produce sugarcane in a sustainable manner. This highlights an emerging trend of more focus being placed on sustainability issues in the sugarcane industry.

Chapter Three covers the research design and methodology that was used in this study.

Chapter 3: Research design and methodology

3.1 Introduction

This chapter outlines the research process that was undertaken during the study. It covers the rationale behind the process followed to answer the research questions stated in Chapter One. The ethical implications of the research are discussed. An extensive literature review was conducted and four case studies were completed. This chapter explains how the literature was searched and the role it played in meeting the research objectives. Participant selection, structure of the questionnaire, the on-farm interviews and the data capture process for the case studies are also discussed.

3.2 Research design

The research was designed to answer the research questions that were posed in Chapter One. The questions are:

I. Is there a problem with soil degradation in the South African dryland sugarcane industry?

II. Has soil quality been identified by local researchers and large-scale sugarcane farmers as an issue they should focus resources on?

If it is:

III. From what perspective is the issue of soil quality approached by researchers and the targeted group of sugarcane farmers?

IV. What sugarcane farming practices are recommended and implemented to improve soil quality?

V. Which of these soil quality improvement practices conform to Agro-ecological or Conservation Agriculture principles and are they currently recognised as practices from these paradigms?

VI. Can any principles from Agro-ecology or Conservation Agriculture, contribute towards developing a management system on the sustainable exploitation of soil, in the South African dryland sugarcane industry?

VII. Are there any common themes that emerge from this study that may contribute towards the development of this soil quality management system?

Two main research design types were used to achieve the research objectives. Firstly a broad literature review of grey and academic literature was conducted to source pertinent information on soil management in sugarcane agriculture, soil degradation, soil quality, Agro-ecology and Conservation Agriculture. Care was taken to ensure that the literature was reliable, suitable and adequate (Kathari, 2004).

No literature was found linking Agro-ecological or Conservation Agriculture principles to improving the soil quality of South African sugarcane soils. Information on local sugarcane farmers perspectives on how they relate to soil quality on their own farms could not be sourced either. The lack of published literature on these topics confirmed that original research would be conducted on these topics.

Secondly four case studies were completed. These were based on a sample of dryland commercial sugarcane farmers from the Midlands South region of KwaZulu-Natal who met certain selection criteria. These farmers were concerned about soil quality and were proactive about managing this resource. The case studies were used to capture farmer practices, perspectives and needs on soil quality. They also built on the information gained from the literature study.

A semi-structured interviewer administered questionnaire research methology was used for the farmer case studies. This design strategy can provide reliable comparable qualitative data (Cohen & Crabtree, 2008). The questionnaire was compiled after completing the literature review. This allowed me to develop an understanding of the topic so that relevant and meaningful questions could be asked (Cohen & Crabtree, 2008).

3.3 Ethical implications of the research process

Ethical clearance for this proposed research project was requested from Stellenbosch University on the 21/05/2011. Ethical clearance was requested as information would be gathered from farmers. Ethical clearance was granted.

No field trials were to be conducted and there was no risk of any environmental degradation occurring from this research. The commitment was given to ensure the farmers right to privacy, confidentiality of personal information and to minimize any risks they could be exposed to during the research process. This process was complied with. The farmers were informed that the information that was garnered from them during the interview process could be used in this thesis. None of them objected to any of the gathered information being published.

However on completion of the study, although participant anonymity was not originally requested by me or stipulated by the University, I decided that some of the information may be construed as sensitive and private. I decided to remove the farmer’s names and farm names from the questionnaires and to rather refer to them as Farmers 1, 2, 3 and 4.

Sections 3.4 and 3.5 describe the research methodology used for the literature review and case studies in more detail.

3.4 Literature review

3.4.1 Introduction

This chapter defines a literature review as it was used in this study. The role of the literature review in meeting the research objectives and the manner in which it was searched and how the literature was selected are also covered.

It is essential that a review project begins with a review of a whole range of existing literature produced on a subject (Mouton, 2009). It should be directly related to the research questions that one wants to answer (Taylor & Proctor, 2008). Bak (2004) explains that a literature review should show that one is capable of searching for relevant material, summarising it, arranging it in various themes, putting it in context and relating it to one's own work. The literature is therefore used to inform the issues being addressed.

According to Mouton (2009) a review of the existing body of scholarship is important for many reasons:

- It ensures that one does not duplicate a previous study.
- It is used to discover what the most up-to-date and authoritative theories about a subject are.
- To find out what are the most accepted and mainstream empirical findings in the field of study.
- Identify the tools used to prove the reliability and validity of the subject.
- Ascertain what are the most widely accepted definitions of key concepts generally used in the subject.
- Save time and avoid unnecessary repetition and duplication of previous results.
- It supplies clues and provides suggestions about what avenues to investigate further.

Taylor and Proctor (2008) add that the literature review should also identify what is not known. Furthermore it should also identify areas of controversy in the literature.

3.4.2 Searching the literature

A number of different channels were used to search for literature relevant to this study. Informal channels included resources and knowledge that have been accumulated during my career to date. This also included information gained during local and overseas study tours, conferences and meetings.

In 2009 SASTA supplied all the delegates that attended their annual congress with a compact disc. This contained the proceedings from the 85th Annual Congress of the South African Sugar Technologists' Association. It also included all the historical proceedings dating back to 1923. The following key words were searched: Agro-ecology, Conservation Agriculture, soil health, soil degradation, sugarcane yield decline, soil sustainability and triple bottom line. Literature was found on all the topics, except for Agro-ecology and Conservation Agriculture. The proceedings of subsequent annual congresses up to and including the 2015 congress were also searched. These proceedings were available to congress delegates at http://www.sasta2015.co.za/user. Once again a key word search for Agro-ecology and Conservation Agriculture yielded no results. SASTA is the premier South African institution where sugarcane technologists present their research findings on an annual basis

SASRI produced a compact disc titled Info Pack 2010. This contains copies of historical SASRI publications, The Link and Ingede newsletters, annual SASRI Progress Reports, Information Sheets, various posters, several booklets and manuals. This literature was also searched using key words. Once again no results were found for searches on Agro-ecology or Conservation Agriculture. The same result was obtained from a search of the latest January 2015 Info Pack (2015) compact disc. No SASRI published research could be found on any aspects relating to Agro-ecology or Conservation Agriculture. SASRI is the premier sugarcane research institute in South Africa. The Info Pack compact disc was used extensively to source literature on other topics for this thesis.

Formal research channels include primary sources such as my own personal library and ancestry literature sourced from the course notes, printed course packs and compact discs received for assignments written for some of the modules completed during the BPhil(Honours) in Sustainable Development Planning and Management degree, specialising in Sustainable Agriculture.

Literature was mainly sourced from the following modules: Sustainable Development, Biodiversity and Sustainable Agriculture, Systems and Technologies for Sustainable Agriculture, Complexity Theory and Systems Thinking, Policy and Legal Framework for Rural Development in the Agricultural Sector and Managing Sustainable Agriculture Enterprises. Literature was also sourced from one of the modules completed during my studies towards the MPhil in Sustainable Development Planning and Management degree, namely the Food Security and Globalised Agriculture module.

The H.H. Dodds library at SASRI was visited on 26 January 2010. The library has a comprehensive collection of published literature on sugarcane. This includes books, journals, farmer information sheets and sugarcane industry publications such as newsletters and magazines. Local and international literature on sugarcane farming is also available in the library.

Their large collection of past theses on sugarcane written at various universities in South Africa produced no literature linking Conservation Agriculture or Agro-ecology practices to improving soil quality in the South African sugarcane farming sector. The librarian also conducted a search for other literature including journal articles, research reports, books, pamphlets, reports and compact discs that contained the key words sugarcane soil degradation, Agro-ecology, and Conservation Agriculture. Although there are many published books or articles on conservation farming and soil conservation, there was no literature on overcoming soil degradation in the South African sugarcane farming sector by implementing Agro-ecological or Conservation Agriculture farming principles.

The librarian conducted a Cab-direct[45] search for any journals, workshop and congress proceedings or symposia which contained the key words sugarcane soil degradation, Agro-ecology and Conservation

[45]Provides an extensive source of references in the applied life sciences discipline

Agriculture. Six hundred and ninety nine citations were found. I went through the list of all the citations, looked at the title of the document and highlighted the publications that I thought might contain the information I was looking for. If the title was unclear but appeared relevant, the abstract was read to confirm relevance or not.

A large volume of literature was found focusing on alternative tillage systems, soil and water conservation production systems, conservation tillage, environmental conservation, sustainable sugarcane production, soil degradation, soil health, restoration of soils, sugarcane yield decline, best management practices on farms, soil organic carbon, trash farming systems, recycling of nutrients, soil cover, soil biodiversity, soil microbial activity, soil compaction, intercropping, fallowing, break crops, crop rotation, green manures, organic or inorganic fertilisers, linkages between crops and livestock, management of plant parasitic nematodes[46], and liming to manage acid soils[47]. No literature was found that directly linked Agro-ecological or Conservation Agriculture principles to overcome sugarcane soil degradation in South Africa.

Google Scholar (2010) was also used to search the following key phrases, Agro-ecology, Conservation Agriculture, South Africa and sugarcane. No literature linking these subjects was found. Following the searches it was concluded that a gap in the academic literature was found.

3.4.3 Role of the literature review in meeting research objectives

The literature review was a study on its own as well as the first formal phase of this research project. The goal was to identify and source relevant literature that would contribute towards meeting the research objectives. One of the specific research goals was to investigate how other researchers had historically studied the topic of soil quality. A further goal was to collate the information into a coherent argument. The aim was to learn from the literature but also to identify possible gaps in it so as to contribute further to the existing body of literature on the subject. The literature review also assisted to refine the research questions. Another important goal was to source information to assist in compiling the case study questionnaire.

The literature review contributed towards the achievement of the seven research questions as follows:

RESEARCH QUESTION I:

Is soil degradation a problem in the South African dryland sugarcane industry?

Existing research on soil degradation in the South African dryland sugarcane industry was studied. The literature confirmed that soil degradation was indeed a problem in this farming sector. Specific farming practices degrade soil chemical, physical or biological properties. Identifying that soil degradation is a problem confirmed that the literature search could continue to source information that would contribute towards answering the other research questions.

[46] Small worms that live in soil and are harmful to plant roots.
[47] Soils that have a low pH. This can be detrimental to certain crops.

RESEARCH QUESTION II:

Do local researchers and large-scale dryland sugarcane farmers in the KwaZulu-Natal region identify soil quality as a factor they should focus resources on?

An abundance of literature was found on research that had been conducted on soil quality in the dryland sugarcane farming sector. No research was found specifically documenting farmers' perspectives on soil quality. The main local research has historically been conducted by SASRI.

As this research question was also confirmed to be relevant to the study the next five questions were also pertinent.

RESEARCH QUESTION III:

From what perspective do researchers and the targeted group of farmers approach the issue of soil quality?

The literature review assessed the perspective from which researcher's approached the issue of soil quality. Most of the local South African research has focussed on identifying which sugarcane farming practices could contribute to soil degradation and yield decline. Alternative practices that should improve soil quality were then researched. These farming practices were largely studied in isolation. In 1998 the Soil Sustainability Programme was launched to adopt a multi-disciplinary approach to studying the link between soil degradation and sugarcane yield decline.

No literature on commercial farmer's perspectives towards the issue of soil quality was found. Four farmer's perspectives were captured in case studies as part of this project.

RESEARCH QUESTION IV:

What sugarcane farming practices are currently recommended and implemented to improve soil quality?

The literature review provided an extensive list of farming practices that were recommended to improve soil quality. These were discussed in section 2.9. No research could be found specifically documenting all the farming practices that are adopted to improve soil quality by commercial dryland sugarcane farmers in South Africa.

RESEARCH QUESTION V:

Which soil quality improvement practices conform to Agro-ecological or Conservation Agriculture principles and are they currently recognised as practices from these paradigms?

No literature was sourced linking Agro-ecological or Conservation Agriculture principles directly to sugarcane soil quality improvement practices in the South African dryland sugarcane region. All the soil quality improvement farming practices that were identified in the study were confirmed by me to conform to one or more of the key Agro-ecological or Conservation Agriculture principles. This is discussed in section 3.5.3.

RESEARCH QUESTION VI:

Can principles from Agro-ecology or Conservation Agriculture contribute towards the development of a management system for the sustainable exploitation of soil, in the South African dryland sugarcane industry?

The literature review highlighted that principles from Agro-ecology and Conservation Agriculture can make an alternative and meaningful contribution towards the development of a system on the sustainable exploitation of soil in the dryland commercial sugarcane farming region. This is discussed in Chapter Five.

RESEARCH QUESTION VII:

What common themes emerge from the study which may contribute towards the development of this soil quality management system?

The literature review highlighted themes that emerged from the literature on the topic of sustainable soil management in the South African dryland commercial sugarcane region. Two important themes that contributed towards the proposed soil quality management system are firstly that combinations of farming practices may be more beneficial to improve soil quality than ad hoc implementation of individual farming practices. This factor was also highlighted by the findings of the Australian Sugarcane Yield Decline Joint Venture (Garside & Bell, 2006). Secondly factors that are key elements to soil quality improvement farming practices include soil organic matter, biodiversity and the conservation of ecosystems. These themes are discussed in Chapter Five.

This concludes the description of the literature review. The next sub-section describes the methodology used for the case studies.

3.5 Case studies

3.5.1 Introduction

The case studies consisted of semi-structured interviewer administered questionnaires that were conducted with four dryland commercial sugarcane farmers in the Midlands South region of KwaZulu-Natal. These case studies were used to augment the literature review, gauge farmer perceptions and determine their farming practices.

3.5.2 Participant selection

Four large-scale dryland commercial sugarcane farmers in the Midlands South region of KwaZulu-Natal were interviewed.

Following the literature study four soil quality improvement sugarcane farming practices were identified that were closely aligned to Agro-ecological and Conservation Agriculture principles and were also already being used in the Midlands South area. These were minimum tillage, introducing the animal factor back on the land, organic fertiliser amendments and green manuring. The two main sources of organic fertiliser amendments in the Midlands South area are filterpress and chicken litter.

A list of possible farmers who are known early adopters and market leaders in terms of implementing farming practices to improve soil quality, particularly those from the four identified criteria, was compiled. This is a purposive sampling technique used to identify key research candidates. Some of the farmers did not return phone calls whilst others were away on holiday over the interview period. Whilst discussing the case study with the farmers, they also suggested other candidates. This is referred to as a chain referral or snowball sampling technique (Biernacki & Waldorf, 1981). All the farmers selected as case study candidates implemented more than one of the four identified farming practices. The four selected farmers are named Farmers 1, 2, 3 and 4 respectively (Table 2).

Planting green manure crops on sugarcane re-plant lands has become a widely adopted farming practice. The local seed supplier was contacted to identify the farmers that were the most progressive in terms of the green manure programmes on their farms. Two farmers were identified and one was interviewed. He is recorded as Farmer 2. He used chicken litter as his main crop nutrient source. He also grazed cattle on some of his green manure lands.

Farmer 1 also planted green manures, used chicken litter as his main crop nutrient source and grazed cattle on some of his green manure lands. Whilst he followed many farming practices recommended by SASRI he was also willing to look beyond SASRI for technical farming advice. At the time of the interview he was completing the Master's degree in Sustainable Agriculture at the University of the Free State.

Farmer 3 planted green manures, was using filterpress on a fairly large-scale, used minimum tillage on his slopes and was also experimenting with integrating livestock onto his sugarcane lands. He was also a successful young farmer whose farming operation had been increasing in size.

Farmer 4 was selected because he planted green manures, used chicken litter, implemented minimum tillage and was incorporating beef farming into his sugarcane enterprise albeit on a relatively small scale. He was also closely aligned to SASRI and followed their recommended farming practices closely.

Table 2: Area farmed by each interviewee

Interviewee identification number	Farm	Farm size (hectares)	Area under cane (hectares)
1	Home farm	854	500
2	Home farm	928	350
3	Home farm	440	350
	Second farm	200	190
	Leased farm	900	300
	Total	1540	840
4	Home farm	324	242
	Second farm	442	210
	Third farm	244	121
	Part owned, part leased	1500	600
	Total	2510	1173

For the interviews each farmer was phoned and asked if he would be willing to participate in the case study. The farmers were interviewed on their respective farms. Whilst they all farmed in the Midlands South region the farms were well spread out throughout this region and included different soil types and rainfall patterns. This served to broaden the potential application of the case studies findings to other farms in the region.

3.5.3 Structure of the questionnaire

The questionnaire contained closed-ended and open-ended questions. The inclusion of open-ended questions provided the opportunity to identify new ways of understanding the research topic (Cohen & Crabtree, 2008). The farmers had the freedom to express their views on certain topics in their own words. This allowed me to gain more insight and understanding about their attitudes and feelings. The open-ended questions were left until the end of the questionnaire when the farmers were more relaxed with the interview process.

Care was taken to construct the questionnaire thematically in a manner whereby there was a logical flow to the questions (Kothari, 2004). Care was also taken to phrase each question in a clear manner so as to eliminate any misunderstanding (Cohen, Manion & Morrison, 2007). As the interviews were conducted face-to-face the farmers were given the opportunity to clarify any misunderstandings before answering each question.

The questionnaire was an empirical study. According to The South African Pocket Oxford Dictionary (1994: 301) empirical means *"based on observation, experience, or experiment, not on theory".* Mouton (2009) explains that a case study captures either numerical data or text to provide in-depth qualitative information on a small number of subjects. A limitation of this research approach is that the results would not be generalized. I accepted this and did not see it as a limitation in this study. My intention was to gain an understanding of an emerging trend within the sugar industry and to provide a platform for possible future in-depth research on the subject, rather than attempting to prove the extent to which the trend occurred.

The questionnaire was structured in a manner that would assist me to gauge farmers thoughts and needs on soil quality, determine the farming practices they had implemented to improve soil quality and understand why they had changed farming practices. This information was used in answering all seven research questions.

The literature review assisted to compile the questions in the farmer questionnaire. The full questionnaire template is recorded in Appendices A to G. Completed questionnaires including individual participants responses are located in Appendices H (Farmer 1), I (Farmer 2), J (Farmer 3) and K (Farmer 4). All four farmers were asked identical questions.

The first section of the questionnaire can be viewed in Appendix A. It captured personal information on the farmer, details of the farm, and data on average long-term rainfall and dominant soil types. The following information was requested: long-term average sugarcane yields, farmer perceptions on soil quality and whether farmers required more information on soil quality or not.

Appendix B asked questions on: farmer social networks and learning structures, how they monitored soil quality and how much they knew about the concepts of Agro-ecology and Conservation Agriculture.

Appendix C asked the farmers to rank at least five main causes of soil degradation on their farm. The standard list that was provided included various farming practices and factors associated with soil chemical, physical and biological properties.

The listed farming practices that may cause soil degradation included: monocropping, excessive tillage, burning at harvest, insufficient water drainage, herbicide applications, inorganic fertiliser applications, high yielding varieties and no livestock on the land. Soil chemical properties that may cause soil degradation included: soil acidity, loss of organic carbon, soil salinity and sodicity, insufficient plant available nutrients and soil nutrient imbalance. Soil physical properties that may cause soil degradation included: soil compaction, soil crusting, soil structure breakdown, soil erosion, low soil water infiltration and low soil water holding capacity. Soil biological properties that may cause soil degradation included: low microbial biomass, low microbial diversity, lack of earthworms and presence of plant parasitic nematodes.

Requesting the interviewed farmmers to list the main causes of soil degradation in order of importance allowed me to combine the results and rank the main causes of soil degradation on their farms. It also provided an indication whether farmers were more concerned about soil degradation factors associated with farming practices or with factors associated with soil chemical, physical or biological properties.

The next section, Appendix D listed potential farming practices that could be adopted to improve soil quality. These were grouped under two headings: those that conformed to both Agro-ecological and Conservation Agriculture practices and those that conformed only to Agro-ecological practices (Table 3). Agro-ecology and Conservation Agriculture were covered in detail in sections 2.12 and 2.13 respectively in the literature review.

Table 3: Farming practices to improve soil quality that conform to Conservation Agriculture and / or Agro-ecological principles

<u>Conservation Agriculture and Agro-ecological practices</u>
Green cane harvesting
Green manure plant fields - break crop.
Green manure. Single crop.
Green manure. Double crop.
Green manure. Leave mulch on soil surface.
Green manure. Use legumes.
Green manure. For allelopathy.
Green manure. Promote microbial life.
Green manure. Reduce weed pressures.
Ley crop
Intercrop
Crop rotation
Controlled traffic
Minimum tillage
Control nematodes - plant green manures with nematicidal properties
Integrated Pest Management
<u>Agro-ecological practices</u>
Spread burnt cane residues after harvest.
Green manure. Disced or ploughed in.
Green manure. Bale / remove the crop for livestock.
Green manure. Graze livestock on the crop.
Bare fallow before re-planting
Lime and / or gypsum applications
Vertical Mulching
Apply animal manures
Apply plant compost
Nutrient recycling
Livestock integration
Strip harvesting
Implement Land Use Plan
Ripping compacted plant lands
Control nematodes - nematicide as last resort
Control nematodes - tolerant varieties
Control nematodes - increase soil organic matter
Precision Agriculture - grid sampling, soil corrections.
Manage nitrogen rates and application timing
Optimum fertiliser rates, placement and timing.

The farming practices listed in Table 3 were identified from the literature review and also from my own experience. The listed farming practices all conformed to one or more of the key Agro-ecological principles (Altieri, 1999):

1. Recycle or re-use all available biomass to replenish or restore soil nutrients.
2. Grow plants by building-up the soils particularly focusing on soil organic matter and soil biotic activity.
3. Minimise loss of growth potential both above and below ground.
4. Build resilience into the system by maximising species and plant diversity.
5. Enhance beneficial biological interactions and synergies so that natural biological processes enhance agricultural production.
6. Ecosystems must be taken into account.

The farming practices relating to Conservation Agriculture included those that conformed to the key Conservation Agriculture principles. These are:

1. Continuous minimum mechanical soil disturbance.
2. Soil covered permanently with organic material.
3. Diversified crop rotations.

These Conservation Agriculture principles also conform to Agro-ecological principles. The farming practices that conform to both farming systems are listed under the heading: *Conservation Agriculture and Agro-ecological practices.* Those farming practices that don't conform specifically to Conservation Agriculture practices are listed under the heading: *Agro-ecological practices.* These farming practices should all be considered within the context of the specific farming operation. Grouping the farming practices into those that either conformed to Conservation Agriculture and / or Agro-ecological principles was done by me. This was based on the respective principles stated above.

The farmers were asked which of the above Conservation Agriculture and / or Agro-ecological farming practices they were currently using to improve soil quality, which of these practices they used in the past and why they discontinued using them. This section of the questionnaire also highlighted some limitations that farmers experienced with certain of the farming practices.

The next questions may be viewed in Appendix E. The farmers were presented with the same list as above, of Conservation Agriculture and / or Agro-ecological farming practices that they could use to improve soil quality. The farmers were asked to state the farming practices they were considering implementing in order to improve soil quality and what constraints were holding them back.

Appendix F contains the same list of Conservation Agriculture and / or Agro-ecological farming practices as listed in Appendix D and E. The farmers were asked which of the listed farming practices they would not implement. They were also asked to state the reasons why they would not implement them.

Appendix G contains the last page of the farmer questionnaire. The farmers were asked what the main barriers of adoption were that hindered them from implementing more practices to improve soil quality. The remaining questions were open-ended ones to ascertain what prompted farmers to initially implement soil quality improvement practices, why they chose the particular practices they adopted, which practices they believed improved soil quality the most and which practices they believed were most in need of further research and development.

The next question was designed to ascertain if farmers would be more inclined to adopt a range of complementary farming practices if they were promoted under an Agro-ecological and Conservation Agriculture farming package, rather than adopting soil quality practices on an ad hoc individual basis. The farmers were then asked if they would consider adopting a complementary package of soil quality best practices if they were recommended for specific soil types and regional climatic conditions.

The penultimate question asked farmers if they would be willing to pay a soil quality consultant to advise them on the best site-specific practices to improve soil quality on their farms. The last question asked the farmers if they believed a soil health specific test would be beneficial to them in managing the soils on their farms. The last two questions were included as I wanted to gauge to what extent farmers may or may not require expert advice on improving their soil quality

3.5.4 The interview process

The interviews were prearranged telephonically to fit a date and time that suited the farmer. All four interviews were conducted on the farmers' home farms. I knew the interviewees' farms fairly well so there was no need to travel out to the fields. Farmer 2 did take me to to some of his lands to further discuss his green manure programme.

The interviews were conducted face-to-face with the farmers. The data collection method was a semi-structured interviewer administered questionnaire. I asked the questions and filled in the farmer responses on their respective questionnaire sheets. This interview method has a number of benefits over self-administered questionnaires. Brace (2008) states that these include being able to clarify the meaning of questions, correct any misunderstandings and explore deeper into responses to open-ended questions. I could also explain certain concepts that the farmer may have been unfamiliar with such as the difference between soil health and soil quality.

The interview times ranged from one and a half hours to two hours. Additional discussions took place at all the interviews, over and above filling in the questionnaires. All four interviews were conducted during October 2012. It was easy for me to gain rapport with the farmers as I have known them for many years. All four of them engaged very willingly and openly in the interview process.

3.5.5 Data capture and analysis

A standardised template (Appendices A to G) was used to capture the questionnaire responses of each interviewee. This written data was then captured into a digital format using the same template.

The first sixteen questions pertained to the farmer's personal information and basic farm information. Thereafter all the questions, bar the last nine, were closed-ended questions. The respondents were limited to a short list of answers from which they had to choose an answer to the question. This made it easier to collate and interpret the data. The farmers were also given an opportunity to provide reasons for their answers to the closed-ended questions that are on Appendices D, E and F.

The last nine questions in Appendix G are open-ended questions. This allowed the farmer to provide a personalised answer to the questions. They could include their own knowledge and feelings.

Two questions gave the farmers the option of ranking their responses from 1 to 5, with 1 being the main cause and 5 being the minor cause. These questions pertained to how the farmer monitored soil quality (in Appendix B) and what they believed were the main causes of soil degradation on their farms (in Appendix C). The ranking allowed me to gauge the significance of each stated factor.

The questions in Appendix D asked the farmers what farming practices they were currently using to improve soil quality and what farming practices they had used in the past but had discontinued using. The farmers were asked to provide reasons why these practices were discontinued. This provided information on the journey that the farmers had travelled in attempting to improve soil quality on their farms.

The case studies were also used to compile proposals for possible future implementation and to provide guidelines for future research. These are discussed in Chapter Five.

3.6 Summary

This chapter states the research design and methodology that was used in this study. The research was designed to source pertinent information that would answer the seven research questions.

Two main research design types were used. An extensive literature review was conducted followed by four case studies of selected sugarcane farmers. This was conducted using a semi-structured interviewer administered questionnaire.

A comprehensive study of various forms of literature was undertaken to source pertinent information to answer the research questions. The literature review contributed information towards answering all seven of the research questions. Common themes were identified and gaps in the literature were highlighted. This information had particular relevance to answering research questions VI and VII.

Four large-scale commercial dryland sugarcane farmers were interviewed on their farms. They were purposefully selected on the basis of specific criteria. They all implemented various farming practices to improve soil quality. The interviewees' perspectives and practices were captured using a semi-structured interviewer administered questionnaire. The questionnaire was compiled after completion of the literature review.

Chapter Four documents the research findings from the case studies.

Chapter 4: Research findings from the case studies

4.1 Introduction

The purpose of the study was to determine if Agro-ecological and Conservation Agriculture principles could contribute towards sugarcane farmers improving soil quality. The study focus area was the KwaZulu-Natal Midlands South sugarcane growing region.

The literature review broadly covered topics relating to soil quality, Agro-ecology and Conservation Agriculture. Findings from the literature review contributed towards compiling the case study questionnaire. The interviewees' farmed in the KwaZulu-Natal Midlands South region.

4.2 Principal data

The four farmer interview sheet write-ups are in appendices H, I, J and K. The four farmers were all males. Table 4 contains data pertaining to farmer age, time period farmed, longest time period one of the farms had been owned by the family, total area under sugarcane and average home farm rainfall per annum. The specific questions that were asked on these topics are in Appendix A.

Table 4: Interviewee age, time period farming and basic farm data (October 2012)

Farmer identification	Age (years)	Time period personally farmed (years)	Time period family farmed one of the farms (years)	Total area under sugarcane (hectares)	Average rainfall on home farm (mm)
1	47	16	55	500	750
2	59	32	57	350	820
3	35	8	50	840	750
4	46	22	142	1173	840
Average	**46**	**19**	**76**	**715**	**790**

As of October 2012 when the interviews were conducted the farmer's average age was 46 years. The average time period that they had personally managed or owned sugarcane farms was 19 years. One of the farms had belonged to the same family for 142 years. The average time frame that the four farmer's extended families had been on their home farms was 76 years. These farmers were experienced and they were all multigenerational farmers. All four of these farmers had a solid knowledge base to draw from in terms of the institutional memory available to them. The farms were well established.

Average rainfall on the home farms was 790 mm per annum. In section 2.9.4, van Antwerpen, Meyer, and Thompson (2006) noted that the average rainfall in South Africa's dryland sugarcane was in the region of 800 to 1200 mm per annum, making it the driest sugarcane region in the world. These farms are positioned at the lower end of this scale. These farmers need to implement farming practices that optimise the benefit of the limited annual rainfall they receive. The dominant soil types ranged from sandy to humic to heavy clay soils. These soils are typical of large areas of the KwaZulu-Natal dryland sugarcane region.

All four farmers had tertiary qualifications - three of them in agriculture and one in commerce. The farmer with a commerce degree was in the process of completing a Masters in Sustainable Agriculture degree. Two of the farmers had post-graduate degrees. All the farms they managed or owned were either in the Eston or Richmond magisterial areas of the Midlands South sugarcane farming region.

The area farmed to sugarcane ranged from 350 hectares by Farmer 2 to 1173 hectares by Farmer 4 (Table 4). Sugarcane is cut on roughly a 24 month harvesting cycle in the Midlands South area. The farmers therefore harvest roughly half their area under sugarcane on an annual basis. The interviewed farmers were all classified as large-scale sugarcane farmers. (See footnote 2 for the definition of a large-scale sugarcane farmer).

The farmers were asked how much they knew about Agro-ecology. The five reply options were: expert, a lot, reasonable amount, little and nothing. One farmer stated that he was an expert whilst two farmers stated that they knew a lot. The remaining farmer said that he knew a reasonable amount about the subject. The farmers were also asked how much they knew about Conservation Agriculture. Three of the farmers replied that they knew a lot. One farmer replied that he knew a little about the subject.

4.3 Farmer perceptions on long-term sugarcane yields

The interviewed farmers were asked to assess how their long-term average sugarcane yields had changed. They were given three answer choices – increased, static or decreased. The question purposefully did not include the time period over which the assessment needed to be made. As the farmers had farmed for different time periods and some of the farms had been farmed by their forefathers they were asked to specify which time period they were referring to. Each farmer had his own methodology of assessing his farms long-term yields.

Farmer 1 who had been farming for 16 years stated that his farm yields had decreased in the preceding 5 years due to a severe hailstorm and erratic rainfall but they had been static for 35 years prior to that. Farmer 2 who had been farming for 32 years stated that his farms average yields had decreased over the 57 years that their family had been farming there. Farmer 3 who had been farming for 8 years stated that his average yields had remained static over this 8 year time period. Farmer 4 who had been farming for 22 years stated that his average yields had increased over the past 10 years. These were all subjective statements made by the farmers but provided an indication as to the sugarcane yield trend on their farms.

Historically the optimal harvest age for sugarcane in the coastal and midlands regions has been around 18 to 24 months. Infestations of *Eldana saccharina Walker*[48] stem borer on the coast has forced those sugarcane farmers to reduce harvest age to twelve months thereby reducing potential crop yields (Ramburan, 2015). The Midlands region has not experienced major problems with the *Eldana saccharina Walker* borer so average harvesting age has remained relatively constant over the past decades. This has made long-term yield comparisons easier to make in the Midlands region than on the Coastal belt.

Only one of the interviewed farmers stated that his long-term sugarcane yields had declined. This was Farmer 2 who viewed this phenomenon over a very long time period – 57 years. This finding is not seen as a limitation to this study. The focus of the study is on improving soil quality. All four of the interviewees' already implemented many farming practices to improve soil quality.

4.4 Farmer interaction with soil health and soil quality

4.4.1 Farmer perceptions on soil quality

Five questions were asked to gauge the interviewed farmers' perceptions on soil quality. They were asked if they regarded soil quality to be an important criterion that needed to be managed on their farms. Whilst only one of the farmers stated that his average yields had decreased in the long-term, all four farmers strongly agreed that soil quality was an important aspect that needed attention on their farms. These farmers felt a sense of responsibility towards maintaining the productive capacity of their agricultural soils. The farmers understood the consequences of soil degradation. They were proactive about conserving their main natural resource.

All four farmers declared that they wanted their soil quality to improve over time and they all stated they would like to adopt more soil quality improvement practices. These farmers understood the importance of soil quality.

Three of the farmers articulated that they would like more information on the causes of soil degradation. All four farmers stated that they would like more information on specific farming practices to improve soil quality. These farmers had a desire to implement best soil quality farming practices on their farms.

4.4.2 Farmer social networks and learning structure

These questions were designed to ascertain where the farmers were sourcing information on soil quality from. Farmers 2, 3 and 4 stated SASRI and their local SASRI extension officer. Farmer 1 sourced most of his information from textbooks and the publication ACRES USA.

[48] A major stem borer pest in the South African sugar industry. Where infestations are high, the sugarcane needs to be harvested on a shorter cutting cycle, to limit crop damage. Due to cooler climatic temperatures in the Midlands, this borer has not historically been a major pest in the area.

All four farmers were members of their local farmers association. Three of the farmers were members of a local study group. Farmer 4 was also a member of the South African Sugar Technologists Association (SASTA) and the South African Sugar Industry Agronomists Association (SASIAA). All four farmers engaged with other farmers on the topic of soil quality either often or occasionally. Three of the farmers had attended farmer's days or short courses where the subject of soil quality had been covered. All four of these farmers were proactive about sourcing information on soil quality.

4.4.3 Broad soil health indicators farmer's use

The interviewed farmers were asked to state the indicators they used to monitor soil health on their farms. The two main indicators used were monitoring long-term crop yields and studying soil sample results to monitor trends in soil fertility. Other indicators included field observations / walking in the lands, pest and disease pressure trends, sugarcane quality and the number of ratoon crops that a field grew.

4.5 Farmer perceptions on the main causes of soil degradation

The interviewed farmers were provided with a list of factors that could cause soil degradation. These factors were grouped together under four headings: those that are farming practices, and those that relate to soil chemical, physical or biological properties (Table 5).

Table 5: Farmer responses on main causes of soil degradation

Possible causes of soil degradation on farms	**Farmer number**
Farming practices	
Monocropping	**2, 3, 4**
Excessive tillage	**2, 3, 4**
Burning at harvest (no surface crop residue)	**2**
Insufficient water drainage	**-**
Herbicide applications	**-**
Inorganic fertiliser applications	**1, 2, 3**
High yielding varieties	**-**
No livestock factor on land	**-**
Soil chemical properties	
Soil acidity	**2**
Loss of organic carbon	**3**
Soil salinity / sodicity	**-**
Insufficient plant available nutrients	**-**
Soil nutrient imbalance	**1, 2, 3, 4**
Soil physical properties	
Soil compaction	**1, 3**
Soil crusting	**-**
Soil structure breakdown	**-**
Soil erosion	**4**
Low soil water infiltration	**-**
Low soil water holding capacity	**-**
Soil biological properties	
Low microbial biomass	**1**
Low microbial diversity	**1**
Lack of earthworms	**-**
Parasitic nematodes	**-**

Table 5 shows that the farmers mainly highlighted factors related to farming practices as being the main causes of soil degradation on their farms. The group with the second highest chosen factors was soil chemical properties followed by soil physical properties. Farmer 1 was the only farmer who highlighted any factors from the soil biological properties list.

The only factor that was mentioned by all four farmers as contributing to soil degradation on their farms was soil nutrient imbalance which is a soil chemical property. Three farming practices were stated by three farmers each. These were monocropping, excessive tillage and inorganic fertiliser applications.

4.6 Farming practices to improve soil quality

4.6.1 Farming practices that conform to Agro-ecological and Conservation Agriculture methods

Farming practices that could be implemented to improve soil quality were grouped under two headings: those that conformed to both Agro-ecological and Conservation Agriculture practices and those that conformed only to Agro-ecological practices (Table 3). This was discussed in section 3.5.3. All the farming practices should be considered within the context of the specific farming operation.

4.6.2 Farming practices used to improve soil quality

The questionnaire listed thirty six soil quality improvement farming practices that conformed to Conservation Agriculture and / or Agro-ecological principles The interviewed farmers were asked to state the farming practices they had implemented (Table 6).

Table 6: Farming practices that were being used to improve soil quality

Soil quality farming practices	**Farmer number**
Conservation Agriculture and Agro-ecological practices	
Green cane harvesting	
Green manure plant fields - break crop.	**1, 2, 3, 4**
Green manure. Single crop.	**1, 2, 3**
Green manure. Double crop.	**1, 4**
Green manure. Leave mulch on soil surface.	**2, 3, 4**
Green manure. Use legumes.	**2, 3, 4**
Green manure. For allelopathy.	**2, 3, 4**
Green manure. Promote microbial life.	**4**
Green manure. Reduce weed pressures.	**1**
Ley crop	**-**
Intercrop	**-**
Crop rotation	**1, 3**
Controlled traffic	**-**
Minimum tillage	**3, 4**
Control nematodes - plant green manures with nematicidal properties	**2, 3**
Integrated Pest Management	**2, 3, 4**
Agro-ecological practices	
Spread burnt cane residues after harvest.	**2, 3, 4**
Green manure. Disced or ploughed in.	**1, 3**
Green manure. Bale / remove the crop for livestock.	**2**
Green manure. Graze livestock on the crop.	**1, 2, 4**
Bare fallow before re-planting	**-**
Lime and / or gypsum applications	**1, 2, 3, 4**
Vertical Mulching	**-**
Apply animal manures	**1, 2, 4**
Apply plant compost	**-**
Nutrient recycling	**1, 2, 3**
Livestock integration	**3**
Strip harvesting	**2, 3, 4**
Implement Land Use Plan	**1, 2, 3, 4**
Ripping compacted plant lands	**1, 2, 3**
Control nematodes - nematicide as last resort	**2**
Control nematodes - tolerant varieties	**2**
Control nematodes - increase soil organic matter	**1, 2, 3, 4**
Precision Agriculture - grid sampling, soil corrections.	**-**
Manage nitrogen rates and application timing	**2, 3, 4**
Optimum fertiliser rates, placement and timing.	**2, 3, 4**

Twenty eight of the listed farming practices were already being used by one or more of the interviewed farmers. Only eight of the listed farming practices had not been implemented by any of the farmers. These were green cane harvesting, planting ley crops or intercrops, controlled traffic, vertical mulching, plant compost applications, precision agriculture and bare fallow before re-planting. Bare fallow was not practiced but all these farmers used a superior practice namely green manure break crops.

Four of the farming practices were implemented by all four of the farmers in the case studies. These were:

- Planting green manure crops as break crops before re-planting a field to sugarcane.
- Applying lime and or gypsum when needed.
- Implementing a Land Use Plan on the farm.
- Controlling plant parasitic nematodes by increasing soil organic matter content.

The farmers were asked which soil quality practices they believed had improved the health of their soil the most. Farmer 1 stated that it was using chicken litter as his fertiliser source but he was concerned about nutrient imbalances from using this product. Chicken litter usually supplies excess phosphate and insufficient quantities of potassium to sugarcane.

Farmer 2 also expressed that chicken litter was the farming practice that had contributed most to improving his soil quality. He also acknowledged lime application as playing a significant role in improving his soil quality.

Farmer 3 believed that implementing green manuring had improved his soil quality the most. Farmer 4 stated that using inorganic fertiliser and applying it exactly as recommended by SASRI had improved his soil quality the most.

The farmers were also asked which soil quality practice had the second best result on their farms. Farmers 1, 2 and 4 responded that it was green manuring. Farmer 2 elaborated further by stating that it was specifically due to ridging and planting into the green manure crop residue on the soil surface. Farmer 3, who had mentioned green manuring as his premier soil quality improvement practice stated that filterpress application at a rate of eighty ton per hectare on plant fields had given him the second best result in terms of improving soil quality on his farm.

4.6.3 Soil quality farming practices considering implementing

The interviewed farmers were considering implementing more farming practices to improve soil quality on their farms. The practices they were considering together with the constraints that were holding them back are listed in Table 7. The individual responses from the four interviewed farmers are combined in the table below and the same methodology is followed in tables 8 and 9.

Table 7: Soil quality farming practices considering implementing

Farming practices considering to improve soil quality	Interviewed farmers constraints
Green cane harvesting	Lack a practical solution to implement (machinery and sugar mill set-up)
Green manure double crop	Cost vs benefit analysis. Less area under cane. Would disrupt strip harvesting cycle.
Legume green manure	Already had excess nitrogen from chicken litter
Graze livestock on green manure crop	Management of the cattle
Green manure for allelopathy	Not sure of the benefit
Crop rotation	Would use if a viable crop was found to rotate economically with sugarcane. No irrigation
Controlled traffic	Machinery wheel width would need to change
Integrated pest management	Had not got there yet
Apply plant composts	Shortage of plant material
Nutrient recycling	Considering using filterpress if available
Livestock integration	Labour and fencing constraints. Would consider if green cane harvest. Management of the cattle
Ripping compacted plant lands	Cost vs benefit analysis
Minimum tillage	Soil fertility needed be corrected first
Precision agriculture	Cost vs benefit analysis

There are constraints to changing farming practices. Farming systems need to be changed when practices change. However it was evident these farmers were engaging with the topic of improving soil quality. The farmers had some very real practical hurdles that needed to be overcome before implementing many of the soil quality improvement farming practices stated above. There was also some doubt as to the costs incurred versus the actual benefits that some of the practices would deliver.

4.6.4 Soil quality farming practices discontinued

The interviewed farmers had discontinued using some of the farming practices they had tried in an attempt to improve soil quality. These are listed in Table 8, together with reasons why they were discontinued.

Table 8: Soil quality farming practices discontinued

Farming practices discontinued	Reason discontinued
Controlled traffic	Caused more soil damage
Baling green manure or removing the crop for livestock	Was not worth the hassle and was removing organic matter - so lost the benefit
Nutrient recycling	Used vinasse but was too much effort for debatable results
Control nematodes with nematicide as last resort	Products were too risky to use
Precision agriculture	Was not sure of the benefits. Practical implementation was difficult
Leave green manure mulch on the soil surface	Preferred to use mechanical tillage as a good seedbed was more important, and wanted to move potassium down the soil profile
Minimum tillage	Wanted a good seedbed

There were a number of reasons why farmers initially implemented certain soil quality improvement farming practices but later discontinued using them. There were unintended consequences to some of the practices. Practical implementation was difficult in some instances and it was debatable whether the benefits were worth the extra effort in other cases. In the case of using certain nematicides - there was a realisation of the risks associated with using these products. In some instances other farm goals trumped the possible soil quality improvement farming practices.

4.6.5 Soil quality farming practices would not implement

The individual interviewed farmers would not consider implementing some of the suggested farming practices. These are listed in Table 9, together with the reasons why they would not implement them.

Table 9: Soil quality farming practices would not implement

Farming practices would not implement	Reason why
Ley crop	Did not make economic sense
Bare fallow	Green manure crops assisted to eradicate the previous crop of sugarcane. Possibility of soil erosion
Vertical mulching	Operation was too slow and labour intensive. High cost of fuel
Strip harvesting	Wouldn't fit the farm system - not interested
Intercrop	Not practical to implement
Green cane harvesting	Unproductive use of labour. Too much trash on Midlands cane for manual harvest of green cane
Bale / remove green manure crop for livestock feed	Removed nutrients from the fields
Controlled traffic	Caused more problems
Lime and or gypsum applications for sub-soil acidity	Was not economical

These farming practices would not be implemented by some of the farmers mainly because of economic or practical implementation challenges. Some of the practices had other unwanted consequences.

4.6.6 What prompted the farmers to initially adopt soil quality improvement practices?

The interviewed farmers had a diverse number of reasons for making the decision to adopt soil quality improvement practices. These included reading the magazine ACRES USA. One of the farmers noticed that virgin sugarcane lands were more productive than old established lands. Another farmer wanted to increase his sugarcane yields and the number of ratoons he got from the crop. One of them was farming with poor low potential soils and wanted to improve the soils and promote sustainability

Three of the four reasons were in response to observations that farmers had made on their own farms. They were not in response to outside influences. The farmers had noticed particular problems which required specific soil quality improvement practices to rectify them.

4.6.7 Why did farmers choose the particular soil quality practices they adopted?

This question was asked to try and understand why the interviewed farmers chose the particular soil quality practices from the extensive choices available to them. Their reasons included deciding from own research and from courses they had attended. The chosen practices generally practically fitted in with existing farm equipment and labour set-up. The farmers looked for synergies and linkages so that the farm system benefitted as a whole. The farmers also stated that the chosen practices were not highly specialised, were easy to implement and were eco-friendly.

4.6.8 Main barriers of adoption hindering implementation of soil quality farming practices

The two main constraints that the interviewed farmers identified as restricting them from adopting more soil quality farming practices were economic and management time constraints. Insufficient knowledge was the third most important limiting constraint. Two further constraints were shortage of manpower or equipment and a lack of practical field trial results to validate some practices.

4.7 Soil quality support for farmers

This section was designed to gain insight into what support was required by the interviewed sugarcane farmers to assist them in managing soil quality on their farms.

4.7.1 Soil quality practices in most need of research and development

The interviewed farmers stated that the following areas should be focussed on in terms of research and development:

- Soil nutrient balancing.
- Soil biological life.
- Strategies to stimulate soil microbial activity.
- Optimum time period green manures should be grown for.
- Economic responses to green manuring in terms of long-term sugarcane yield gain versus short-term yield loss.
- Organic fertilisers in terms of nutrient content, nutrient availability and their impact on the *Eldana saccharina Walker stem* borer.
- Supply of silicon to sugarcane plants.

The research and development requirements were mainly related to aspects concerning soil fertility, green manuring and soil biological life.

4.7.2 Adoption of a package of specific soil quality farming practices

The interviewees' were asked if they would be more inclined to adopt a range of soil quality practices if they were promoted under an Agro-ecological or Conservation Agriculture system package, rather than them being promoted on an ad hoc basis of individual practices. Two farmers answered yes and two farmers answered no.

This was an interesting finding. Farmers 2 and 4 both replied no to the above question. Farmer 2 generally followed SASRI recommendations and felt that SUSFARMS® was a recognised sugarcane industry developed initiative that could provide similar soil quality benefits to Agro-ecology and

Conservation Agriculture practices. Farmer 4 was very closely aligned to SASRI and usually took his lead from them in terms of implementing various farming practices on his farm.

Farmers 1 and 3 both replied yes. Farmer 1 was the one who was studying Sustainable Agriculture at the University of the Free State. He was willing to look beyond the sugarcane industry for methods to improve his soil quality. Farmer 3 was the youngest of the four farmers and was willing to consider all options to improve his soil quality.

The interviewees' were also asked if they believed that more farmers would adopt a range of soil quality practices if they were promoted as a package of best practices recommended for the dominant soil type and climate of a particular region. Farmer 1 answered yes. Farmer 3 answered yes but that it would still be difficult to evaluate the different practices and know their exact benefits. Farmer 4 said no and Farmer 2 said no as he believed that SUSFARMS® would accommodate industry wide and farm level recommendations.

4.7.3 Soil quality specialist advisors and soil health tests

The interviewed farmers were asked if they would be willing to pay a soil quality consultant to evaluate their farms and advise them on the best site specific practices to improve soil quality on their farms. One farmer replied absolutely yes, two farmers replied yes. The remaining farmer said that he would rather source information from SASRI and his local extension officer.

The farmers were asked if they believed a soil health specific test would be beneficial to managing soils on their farms. All four farmers answered yes with one farmer stating that it would need to be correctly calibrated.

4.8 Summary

The interviewees' had all been farming for many years. They were all second generation or more farmers. They understood their farms and the unique challenges their farming systems faced. They all had some understanding of Agro-ecology and Conservation Agriculture. All four of the farmers believed that soil quality was an important factor to manage on their farms and they all wanted to improve it further. They all actively searched for information on soil quality. This was despite only one of the farmers stating that his yields had declined over the long-term.

The farmers had their own on-farm indicators they used for monitoring soil health. All of the stated indicators were tangible practical indicators that relied on secondary sources of information such as long-term yield and soil fertility trends. No monitoring practices were stated that had the primary function of monitoring soil health. The farmers mainly highlighted specific farming practices as being the main causes of soil degradation on their farms.

All the interviewed farmers implemented farming practices which they hoped would improve their soil quality. Much thought and effort went into deciding which practices to adopt. These practices needed to practically fit into the farming system, enhance it and preferably did not require large capital investments. The farming system as a whole needed to benefit. Green manuring was stated as the farming practice that had contributed the most to improving their soil quality.

The interviewed farmers were considering implementing some soil quality improvement farming practices. They had also tried but discontinued using certain practices. There were also some farming practices that they would not consider implementing for various reasons. The main implementation constraints were either practical or economic in nature. Management time was also identified as a constraint. The farmers mainly identified issues relating to soil fertility, green manuring and soil biological life as areas that needed more research and development.

The results were mixed in response to the question if the farmers would adopt more soil quality practices if they were promoted under a package of Agro-ecological or Conservation Agriculture ideological practices rather than implementing them on an ad hoc basis. SUSFARMS® assists farmers in deciding which practices to adopt. The results were also mixed in response to the question whether there would be higher adoption of soil quality farming practices if a package of best practices were recommended rather than ad hoc stand-alone practices.

Three of the farmers would be willing to pay a soil quality consultant to present them with farm specific soil quality practices they could implement on their farms. The other farmer would use SUSFARMS®. All four of the farmers believed a practical soil health test would be beneficial to managing soil quality on their farms.

4.9 Role of the case studies in meeting research objectives

The case study questionnaire was compiled after the literature review process. The case study built on the knowledge that was gained from the literature review.

All four of the farmers that participated in the case study were very willing to share information. I believe they provided honest responses to the questions posed in the semi-structured questionnaire. I was pleasantly surprised to discover that only one of the farmers believed that his crop yields had decreased in the long-term. It was gratifying that all four of the farmers were actively engaging with and implementing farming practices to improve their soil quality. They all stated they required more information on soil quality so they could make sound informed decisions on sustainably managing their farming enterprises.

The case studies contributed towards the achievement of the seven research questions as follows:

RESEARCH QUESTION I:

Is soil degradation a problem in the South African dryland sugarcane industry?

This question referred to a broad South African context. The literature review confirmed that soil degradation is a problem in the South African dryland sugarcane industry. The case studies focussed specifically on the KwaZulu-Natal Midlands region. All the interviewed farmers identified the main farming practices that caused soil degradation on their farms (Table 5) and agreed that they wanted to improve their soil quality.

RESEARCH QUESTION II:

Do local researchers and large-scale dryland sugarcane farmers in the KwaZulu-Natal region identify soil quality as a factor they should focus resources on?

The literature review did not uncover any research done on whether KwaZulu-Natal farmers identified soil quality as a factor they should focus resources on. The case studies confirmed that the interviewed farmers in the KwaZulu-Natal Midlands South did believe that soil quality was an important factor they should focus resources on. Soil quality was stated to be an important criterion to manage on their farms. All the interviewed farmers wanted to adopt more soil quality improvement practices and they all requested more information on soil quality.

The farmers all actively sought information on soil quality from various sources. The farmers knew the main factors that caused soil degradation on their farms (Table 5). They had all adopted specific farming practices to improve soil quality (Table 6) and were considering adopting more farming practices to improve it (Table 7). The farmers' spent time and allocated resources to improve soil quality. There was some soil quality farming practices they had discontinued (Table 8) and others that they would not implement (Table 9).

Three of the interviewed farmers stated they would be willing to pay a soil quality consultant to advise them on the best practices for their farms. The other farmer preferred to use existing resources from SASRI for this advice. All four farmers were willing to invest resources in conducting on-farm soil health specific tests.

RESEARCH QUESTION III:

From what perspective do researchers and the targeted group of farmers approach the issue of soil quality?

No literature was found on how farmers approach the issue of soil quality. As stated previously the case studies interviewees' took soil quality seriously and they all wanted to improve it, despite only one of the farmers experiencing long-term yield decline. They were proactive about improving their soil quality.They all used indicators to monitor soil health with the two main ones being monitoring long-term sugarcane yield trends and analysing soil sample results.

The farmers made observations on their farms and were aware of the main causes of soil degradation. They changed their farming practices in response to these observations. One of the farmers actively used SUSFARMS® as his tool for improving soil quality. The farmers approached the topic from a broad perspective. They assessed the implications and consequences of the various farming practices on their farming system as a whole and then made decisions accordingly.These farmers understood the importance of conserving and enhancing their most valuable resource. They actively strived to ensure that their soils remained productive in the long-term.

RESEARCH QUESTION IV:

What sugarcane farming practices are currently recommended and implemented to improve soil quality?

The interviewed farmers specified which soil quality improvement practices they were using at the time (Table 6). The practices that were implemented by all four farmers were green manuring, applying lime and gypsum, implementing a farm Land Use Plan and increasing soil organic matter content.

RESEARCH QUESTION V:

Which soil quality improvement practices conform to Agro-ecological or Conservation Agriculture principles and are they currently recognised as practices from these paradigms?

The interviewees' all stated that they knew about Agro-ecological and Conservation Agriculture farming methods. During the farm visits none of the farmers formally stated that any of the farming practices they implemented conformed to Agro-ecological or Conservation Agriculture practices.

RESEARCH QUESTION VI:

Can principles from Agro-ecology or Conservation Agriculture contribute towards the development of a management system for the sustainable exploitation of soil, in the South African dryland sugarcane industry?

Both the literature review and the case studies contributed towards the development of a sustainable soil management system. The management system is proposed in section 5.5.

RESEARCH QUESTION VII:

What common themes emerge from the study which may contribute towards the development of this soil quality management system?

Common themes did emerge from the literature review and from the case studies. This information did contribute towards the development of the proposed soil management system. The themes are discussed in Chapter 5.

The case studies mainly contributed towards answering research questions I, II, III and IV. They also contributed towards answering questions VI and VII.

Chapter 5: Discussion and conclusions

5.1 Introduction

Chapter Five concludes the thesis. The major findings are evaluated and interpreted. The research questions posed in section 1.3 are answered. Conclusions are drawn from the research and findings that can contribute to future practice are stated. Lastly recommendations are made for possible future practice and study.

The purpose of this study was to contribute towards addressing a practical on-farm challenge sugarcane farmers' face - to improve their soil quality. The aim was to investigate if Agro-ecology and Conservation Agriculture principles could contribute towards improving the soil quality of dryland sugarcane farmers in the KwaZulu-Natal Midlands South region.

5.2 Summary

The main objective of this study was to ascertain if Agro-ecology and Conservation Agriculture could contribute towards improving soil quality in the South African dryland sugarcane industry. The main topics built on are soil quality in the sugarcane industry, Agro-ecology and Conservation Agriculture.

The literature review revealed that no literature, specifically stating Agro-ecological or Conservation Agriculture interventions existed on soil quality in the South African sugarcane industry. Information on local sugarcane farmers' perceptions, practices and needs related to soil quality on their own farms could not be sourced either.

The literature review findings are summarised below.

The soil stores nutrients and water. Plant roots grow in soil and supply these elements to the plant. Plants then produce food and protect the soil from erosion. Humans disrupt this relationship (Brown, 2008). Soils must also be conserved for future generations, whilst producing more food for ever-growing populations (Doran & Safley, 1997).

Soil chemical, physical and biological properties must all be preserved. They determine the root environment and the productive capacity of the soil**.** Farming practices have an impact on soil properties as traumatic modifications can be made to it (Pierret, Moran & Doussan, 2005). There must be an understanding of the consequences of the various available farm practices on soil properties. Good knowledge of the effects of farming practices on all soil properties are required if farmers wish to farm with a sustainable sugarcane cropping system. Unfortunately much more is known about soil chemical and physical properties than about soil biological properties.

Human activities reduce soil quality which can lead to degraded soils (Heap & Kent, 2000). Degraded soils produce less than healthy soils (United Nations Environmental Programme, 2009; Lal, 2006; van Antwerpen *et al*, 2009; Bell & Raczkowski, 2008). Degraded soils are difficult to rehabilitate (Laker, 2000). Most South African soils have low resilience and are vulnerable to degradation (Laker, 2000).

Sugarcane yield decline occurs because soils become degraded under long-term sugarcane productive systems (Garside, 1997; Haynes & Hamilton, 1999; van Antwerpen *et al*, 2003b). Soil chemical, physical and biological properties deteriorate (van Antwerpen *et al*, 2003b). The soil loses its resilience due to its inability to self-regulate. Plant roots and plant growth become compromised. Poor or restricted sugarcane root growth has been a problem in the sugarcane industry for many decades (Garside, 1997). Sugarcane yield decline is a complex issue as many factors become out of balance (Garside, 1997). Site specific solutions are required to rehabilitate the soil properties (Jones, *et al*, 2012).

In 1993 the Sugar Yield Decline Joint Venture was formed in Australia. This venture was based on a multi-disciplinary scientific approach to studying sugarcane yield. The Soil Sustainability Interest Group was formed in 1998 in South Africa. It also subscribed to a multi-disciplinary scientific approach to studying the problem of sugarcane yield decline. Before the formation of this group South African studies on the relationship between soil degradation and sugarcane yield decline were examined mainly from a single discipline approach (South African Sugarcane Research Institute, 2004). Van Antwerpen (2005) stated that any study on soil quality must consider all three soil chemical, physical, and biological properties. The soil properties must be considered holistically rather than as a sum of separate parts (Sturz & Christie, 2003).

Soils are complex living ecosystems. Healthy soils have healthy properties; they resist degradation and reach their full long-term potential. Healthy soils produce healthy crops with minimal external inputs (Altieri & Nicols, 2005). Soil properties influence the soil environment, which in turn influences plant root growth. Plant roots determine the soil productivity (Gruhn, Goletti & Yudelman, 2000).

A healthy soil provides a range of ecosystem functions to the environment. Healthy soil sustains a diverse community of soil life – the soil food web. It also sustains a diverse range of plants and animals and plays a vital role in soil quality. A soil’s organic matter content influences soil microbial diversity and biomass. The soil food web in turn sustains the carbon cycle.

Healthy soil is resilient and resists degradation. It produces food with minimal negative ecological effects. Unfortunately many conventional farming practices reduce soil quality. There needs to be a move towards more sustainable farming practices. Soil quality is related to sustainability as it attempts to understand the effect that management practices have on soil properties which in turn affect its capacity to function effectively in the present and in the future (Bell & Raczkowaki, 2008; Gruver & Weil, 2007; Gruhn, Goletti & Yudelman , 2000).

Whilst the Green Revolution has been successful at increasing agricultural productivity this has been achieved by using more resources and more virgin land has been converted to agricultural land (Pretty *et al*, 1995). There have also been negative consequences to some of the technologies. The link between ecology and farming becomes broken. Natural resources become polluted, damaged or depleted. Monocropping farming systems reduce biodiversity (Pretty *et al*, 1995).

Agriculture needs a second revolution. The transition should be towards a sustainable whole system long-term approach to Agriculture (Wijeratna, 2012; Altieri & Nicholls, 2005; Sullivan, 2003; Doran, Kirschenmann & Frederick , 2007; Gowing & Palmer, 2007; Heap & Kent, 2000; International Assessment of Agricultural Knowledge, Science and Technology for Development, 2009; Tilman *et al*, 2002; Young & Crawford, 2004; World Business Council for Sustainable Development, 2008). Complex economic, social and environmental sustainability objectives constantly overlap. Agricultural production must be more than just a technical function.

Crawford *et al* (2005) stated that there was no theory on the sustainable exploitation of soil. Sturz and Christie (2003) also stated that all the processes involved in soil fertility, soil resilience, soil stability and enhanced crop production were not fully understood. Society does not know how we are affecting the long-term productive capacity of our soils. If this is unknown then there cannot be a guarantee that soils will be able to feed the ever growing population over the long-term. Soil productivity must be decoupled from soil degradation (Follett, 2001). A paradigm on the sustainable exploitation of sugarcane soil should be developed. This is vitally important so that agricultural productivity can be increased in a sustainable manner.

The transition should be towards Agro-ecological farming systems (Wijeratna, 2012; Altieri, 1995, 2002; Altieri & Nicholls, 2005; Conway, 1985; Dalgaard, Hutchings, & Porter, 2003; De Schutter, 2009; Heap & Kent, 2000; International Assessment of Agricultural Knowledge, Science and Technology for Development, 2009; Kate, 2008; Magdoff, 2007b; Pretty, 2011; Pretty *et al*, 1995; Swilling & Annecke, 2012). Hobbs, Sayre and Gupta (2008); Gowing and Palmer, 2007; and the Food and Agriculture Organisation of the United Nations (2010) promote Conservation Agriculture as a sustainable agriculture production system.

This thesis proposes that farmers assess their farm context from an Agro-ecological and Conservation Agriculture perspective. Sugarcane farmers have many farming practices available to them to improve their soil quality. These farming practices all conform to Conservation Agriculture and / or Agro-ecological principles although they are not recognised as belonging to these farming systems (Table 3).

The literature review highlighted that one of the key principles of Agro-ecology is that ecological relationships must be promoted in the design and management of sustainable farming systems (Principles of Agro-ecology, 2010). Beneficial biological interactions are promoted in the agro-ecosystem (Wijeratna, 2012). Agro-ecology further prescribes that ad hoc adoption or removal of specific agricultural practices will not lead to a more sustainable agricultural system. The adoption of practices must rather be based on a deep understanding of agro-ecosystems and how they function (Altieri, 2002).

The impacts that individual farming practices have on soil should be identified and assessed for their suitability within the specific farming system. Some practices have an impact on all three soil properties at once. Using a legume green manure is an example of a practice that should have a positive impact on soil chemical, physical and biological properties. Leaving the green manure on the surface instead of ploughing it in will further enhance soil properties. Using a variety of plant species may enhance the benefits further. While one farming practice can have multiple soil quality benefits, combining the practice with other beneficial sustainable farming practices may provide synergistic benefits.

The literature review highlighted that one of the key principles of Conservation Agriculture is that this farming system will only work optimally if all the different technical aspects are considered simultaneously in an integrated manner (Food and Agriculture Organization of the United Nations, 2010). Combinations of farming practices are recommended. This ties in with the findings of the Sugarcane Yield Decline Venture as their research proposed a new sugarcane farming system to improve soil quality based on a combination of practices namely minimum / zero tillage, legume green manure crops, controlled traffic, green cane harvesting and sugarcane trash retention (Garside & Bell, 2006).

Mutually beneficial farming practices should be adopted to improve soil quality. If individual farming practices are implemented, they should be carefully considered to assess if they fit into the farm system and whether they provide the desired benefits to soil quality. Jones, *et al* (2012) stated these practices should be site specific and fit in with the context of the farm.

5.3 Main findings and discussion

This study has enabled me to identify three main factors related to Agro-ecology and Conservation Agriculture that are central to both farming systems in terms of soil quality management. Taking cognisance of these factors may assist dryland sugarcane farmers to decide which individual or combinations of soil quality improvement farming practices to adopt. These highlighted factors are: enhancing or conserving soil organic matter; promoting biodiversity above and below the soil; and protecting or enhancing the ecosystem. These factors are discussed below.

1. Soil organic matter plays a critical central role in ensuring healthy soil chemical, physical and biological properties (Dick & Gregorich, 2004; Dominy, Haynes & van Antwerpen, 2001; Miles, Meyer & van Antwerpen, 2008). It is a key component of soil quality (Dick & Gregorich, 2004; Doran & Parkin, 1994) and is therefore plays a critical role in assisting soil to resist soil degradation (van Antwerpen, 2005; Dominy, Haynes & van Antwerpen, 2001). The maintenance and increase of soil organic matter plays a central role in sustainable agriculture farming systems (Dominy, Haynes & van Antwerpen, 2001; Haynes 1997).

   As soil organic matter content declines there is a corresponding decline in soil physical properties and soil biological activity (Haynes, 1997). This makes it difficult to manage and maintain the soil in a productive state. Soil aggregate stability also declines making the soil less resilient. Water infiltration reduces due to soil capping (Haynes, 1997). High soil organic matter content usually improves soil water infiltration and water holding capacity (Haynes, 1997).

There is a mutually beneficial relationship between soil microbes and soil organic matter. Soil microbes mineralise plant available nutrients from the soil organic matter to supply the plant with nutrients (Haynes, 1997). As soil organic matter content declines, soil microbial biomass declines (Dominy, Haynes & van Antwerpen, 2001; Haynes, 1997; South African Sugarcane Research Institute, 2010b; van Antwerpen, 2005).

A key Agro-ecological goal is to improve and preserve the natural capital stocks in agro-ecosystems (Altieri and Nicholls, 2005; Magdoff, 2007 b; Pretty, 2006). Technologies that add organic matter to soils are recommended (Altieri and Nicholls, 2005). Implementing biomass recycling through retaining crop residues and applying manures are Agro-ecological practices (Altieri, 1999). These practices enhance soil organic matter.

Conservation Agriculture aims to conserve and enhance natural agricultural resources (Donaldson, 2003; Food and Agriculture Organization of the United Nations, 2010). Soil organic matter is a natural farm resource. Conservation Agriculture also aims to enhance natural biological processes below and above the soil surface (Gowing & Palmer, 2007; Hobbs, Sayre & Gupta, 2008). Soil organic matter is fundamental to this process. The Conservation Agriculture key technologies of minimal mechanical soil disturbance, covering the soil with organic material and retaining crop residues, will conserve and enhance soil organic matter.

One of the key research outcomes from the Sugarcane Yield Decline Joint Venture was confirmation of the importance of soil organic matter in the farm system (Garside & Bell; 2006). Excessive tillage and field removal of organic material were found to be contributing factors to sugarcane yield decline (Garside & Bell, 2006).

Van Antwerpen and Meyer (1996) also confirmed the role that soil organic matter plays in soil degradation and yield decline. Only one of the interviewed farmers (Farmer 3) identified loss of soil organic matter as a contributing factor to soil degradation on his farm. However all four farmers interviewed had implemented farming practices to increase their soil organic matter levels.

2. Biodiversity should be improved above and in the soil. Sugarcane farming is low in biodiversity as it is traditionally grown as a monocrop. Some areas have farmed sugarcane as a monocrop for over a century. A healthy soil will sustain plant and animal diversity. The more species an ecosystem contains the more stable it should be.

   A soil is healthy if it has a diversity of organisms living in it. Long-term sugarcane monocropping leads to low levels of microbial biomass and biological diversity (Haynes & Hamilton, 1999). Detrimental soil organisms increase in the soil (Meyer & van Antwerpen, 2001). Farming practices must be adopted that will increase biodiversity above and within the soil. This includes micro-organisms within the soil (Granatstein & Bezdicek, 1992).

Soil microbes self-organise in response to prevailing conditions (Crawford *et al*, 2005). This is one of the reasons why soils are resilient and can adapt to disruptions from various farming methods. However when the disturbance is such that soil microbial self-organisation cannot occur, then soils degrade (Crawford *et al*, 2005).

A key Agro-ecological principle is that species and plant diversity must be maximised to build up resilience in the system (Altieri, 2002). Biological diversity, self-sufficiency, self-regulation and resiliency must be built into the agricultural system (Magdoff, 2007b). Agro-ecology also affirms that by improving biodiversity, there will be increased interactions between the various components of the system which will supply ecological services to the farm (Altieri & Nicholls, 2005). These diverse ecosystems will be more productive as they can handle environmental stress better.

Specific Agro-ecological technologies are recommended to improve the natural capital stocks in Agro-ecosystems. Some of the practices that would improve biodiversity include: integrated nutrient management (Altieri & Nicholls, 2005; Pretty, 2006; Magdoff, 2007b); the integration of livestock with crops (Altieri & Nicholls, 2005; Pretty, 2006); crop rotation (Altieri & Nicholls, 2005; Magdoff, 2007 b); use of Integrated Pest Management; planting of cover crops; or implementation of an intercropping system (Altieri & Nicholls, 2005; Magdoff, 2007b). The improved biodiversity and increased interactions between the various components will provide ecological services to the farm (Altieri & Nicholls, 2005).

The key Conservation Agriculture land management principles namely minimum soil disturbance, retaining of crop residues, permanent soil cover and planting diversified crop rotations, will all enhance biodiversity (Gowing & Palmer, 2007; Hobbs, Sayre & Gupta 2008).

Some of the key soil quality improvement proposals from the Sugarcane Yield Decline Joint Venture (Garside & Bell, 2006) were the inclusion of legume green manure crops, green cane harvesting and sugarcane trash retention farming practices in the sugarcane farming system. All three of these practices will improve biodiversity on the farm.

According to (Altieri & Nicholls, 2005) diversified Agro-ecosystems that use ecologically sensitive farming systems can produce sustained yields.

3. The ecosystem which includes the soil ecosystem should be protected and enhanced. Soil contains an ecosystem of many different species of living organisms. A healthy soil sustains a diverse community of soil life called the soil food web. Soil organic matter content influences the microbial diversity and biomass of the soil food web. The soil food web in turn sustains the carbon cycle. The soil food web must be enhanced and protected. Soil biological processes

are therefore important for the healthy ecological function of soil (Dominy, Haynes & van Antwerpen, 2001).

Farming alters the biological and physical composition of ecosystems. Farming practices should be used that have minimal impact on the soil ecosystem. Soil erosion should be kept to a minimum and the ecosystem should be undisturbed by practicing minimum tillage (Dominy, Haynes & van Antwerpen, 2001).

Agro-ecology believes that food production must take ecosystems into account (Altieri, 1995). It takes a whole system approach to agriculture. One of the key Agro-ecological principles is that ecological relationships including biological interactions must be promoted in the design and management of sustainable agricultural production systems (Wijeratna, 2012; Altieri, 1999; Principles of Agro-ecology, 2010). Natural ecological processes must enhance rather than undermine production (Altieri, 2002). The interactions between humans, plants and the environment within the specific agricultural system must be considered (Dalgaard, Hutchings & Porter, 2003). The soil environment must be protected.

Conservation Agriculture aims to maintain a balance between agricultural production and protecting the soil ecosystem (Donaldson, 2003). Soil is conserved by enhancing natural biological processes below and above the soil surface (Gowing & Palmer, 2007; Hobbs, Sayre & Gupta, 2008). A healthy soil ecosystem is promoted.

Key Conservation Agriculture practices that protect or enhance the ecosystem are: minimal mechanical soil disturbance; covering the soil permanently with organic material; and retaining crop residues. Some farming practices that would fulfil these goals are: minimum tillage;, green manuring and green cane harvesting. These farming practices are the same ones that were promoted by the Sugarcane Yield Decline Joint Venture (Garside & Bell, 2006). They also meet all three of the proposed main Agro-ecological and Conservation Agriculture factors - they enhance soil organic matter, preserve or improve biodiversity, and protect or enhance the ecosystem. Excessive tillage was stated by three of the interviewed farmers as being one of the main causes of soil degradation on their farms.

As a guideline when farmers need to decide which soil quality improvement practices they should implement, they can ask themselves the following questions: Will it conserve and enhance soil organic matter? Will it improve biodiversity inside and on top of the soil? Will it enhance and protect the ecosystem? The implemented farming practices should build resilience and self-regulation into the farm system.

Farming practices that achieve these goals are listed in Table 10. I determined whether the individual farming practices would enhance soil organic matter and biodiversity and protect the ecosystem. This was based on the Agro-ecological and Conservation Agriculture principles determined from the literature review. These practices depend on the farm context, should be site specific (Jones, *et al*, 2012) and should optimise farm resources.

Table 10: Agro-ecological and Conservation Agriculture farming practices that should protect the ecosystem and enhance soil organic matter and biodiversity

Conservation Agriculture and Agro-ecological practices	Soil organic matter	Biodiversity	Ecosystem
Green cane harvesting.	X	X	X
Green manure plant fields - break crop.	X	X	X
Green manure. Single crop.	X	X	X
Green manure. Double crop.	X	X	X
Green manure. Leave mulch on soil surface.	X	X	X
Green manure. Use legumes.	X	X	X
Green manure. For allelopathy.	X	X	X
Green manure. To promote microbial life.	X	X	X
Green manure. To reduce weed pressures.	X	X	X
Ley crop.	X	X	X
Intercrop.	X	X	X
Crop rotation.		X	X
Controlled traffic.	X	X	X
Minimum tillage.	X	X	X
Control nematodes - plant green manures with nematicidal properties.	X	X	X
Integrated Pest Management.		X	X
Agro-ecological practices			
Spread burnt cane residues after harvest.	X	X	X
Green manure. Disced or ploughed in.	X	X	
Green manure. Bale / remove the crop for livestock.		X	X
Green manure. Graze livestock on the crop.	X	X	X
Bare fallow before re-planting.		X	X
Lime and / or gypsum applications.		X	X
Vertical Mulching.	X	X	X
Apply animal manures.	X	X	X
Apply plant compost.	X	X	X
Nutrient recycling.	X	X	X
Livestock integration on lands.		X	X
Strip harvesting.			X
Implement Land Use Plan.	X	X	X
Ripping compacted plant lands.		X	X
Control nematodes - nematicide as last resort.			X
Control nematodes – plant tolerant varieties.		X	X
Control nematodes – by increasing soil organic matter	X	X	X
Precision Agriculture - grid sampling, soil corrections.		X	X
Manage nitrogen rates and application timing.			X
Optimum fertiliser rates, placement and timing.			X

Based on my analysis the farming practices that achieve all three goals in context are: green manuring; ley crops; intercropping; controlled traffic; minimum tillage; spread burnt cane residues after harvest; vertical mulching; applying animal manure or plant compost; nutrient recycling; increasing soil organic matter; and implementing a land use plan.

These farming practices conserve or enhance soil organic matter, introduce or protect biodiversity in the farming system, and protect or enhance the physical environment. They should provide multiple benefits to the soil system. Those practices that only benefit one or two of the suggested criteria may benefit from additional practices that fulfil the outstanding criteria.

As previously stated all four of the key principles of Conservation Agriculture should be implemented together as a combination for this technology to work. These principles are: minimal mechanical soil disturbance; soil covered permanently with organic matter; crop residues retained; and diversified crop rotations. All four of these farming practices comply with all three of the proposed important criteria farmers can use as a guideline in deciding which practices to implement. They all: conserve and enhance soil organic matter; improve biodiversity; and protect the ecosystem. These farming practices provide multiple benefits to the farms soils. On-farm trials would need to be conducted with various combinations of farming practices to determine if mutually enhancing synergies exist between them or to identify possible unintended consequences from certain combinations.

Farming practices that are adopted should improve soil properties which in turn should improve soil quality. Poor and restricted root growth has been a long standing problem in the sugarcane industry (Garside, 1997). This was identified as one of the main reasons for sugarcane yield decline (Garside, 1997). A healthy soil environment should nurture a healthy root structure. Improved root health, spread and depth should lead to optimum above ground sugarcane production. Agro-ecological and Conservation Agriculture principles should assist to create an environment for healthy root systems to develop.

The sugarcane farming practices should allow for good water infiltration into the soil profile so that it can be taken up by the roots and used for crop growth, rather than flowing off the soil, being lost as a natural resource and eroding the natural capital of the farm. Soil compaction and crusting must be reduced and soils need cover to slow water down and promote infiltration. Soil cover is a key Agro-ecological and Conservation Agriculture principle.

Soils should also be managed in such a manner that they can hold optimum quantities of water. Soil organic matter and soil biological activity preserve soil structure, which influences soil water holding capacity. Water harvesting is one of the key Agro-ecological principles (Altieri, 2000). A healthy root structure together with the optimisation of plant available water should enhance sugarcane production.

Besides striving for soil quality, healthy roots, good water infiltration and water holding capacity, soil erosion must be kept to an absolute minimum on farms. Soil is a non-renewable resource as new soil formation is a very slow process. Once it has washed off the farm it is lost forever as a medium in which to grow crops. Farmers have a responsibility towards future generations to conserve this valuable resource. Bare soil surfaces must be avoided and farms must have good water carrying structures so as to minimise soil erosion. The key Conservation Agriculture principles of minimal soil disturbance and permanent crop cover will reduce soil erosion.

If the soil and roots are healthy, available water is optimised and the soil resource is conserved, then significant progress should have been made towards farming with a sustainable sugarcane management system. Agro-ecological and Conservation Agriculture farming practices are available to enhance all these processes. The farmer can control these factors and they should be focussed on - instead of relying on GM technology or sugarcane plant breeders to overcome degraded soils and sugarcane yield decline. Ramburan *et al*, (2012) reinforced this by finding that the growing environment had an overriding effect on yield decline. This was followed by management practices. The effect of variety was of secondary importance.

Sustainable agriculture sugarcane farming practices need to be adopted to improve soil quality and sugarcane yields in the long-term. The triple bottom line must also be accounted for. This is necessary to ensure the sustainable future of the South African sugarcane industry. New techniques need to be adopted to sustainably manage soil (Young & Crawford, 2004). All three soil properties need to be improved. There is a strong link between soil health and sustainable land use.

Agro-ecology and Conservation Agriculture are both sustainable agriculture farming systems. They take the triple bottom line into account and promote healthy soil properties. A soil quality management system is proposed in section 5.5. It is hoped that this system will allow for the sustainable exploitation of soil while maintaining a sustainable sugarcane yield

It is proposed the goal should be to achieve maximum sustainable sugarcane yields (Gregorich, Turchenek, Carter & Angers, 2001). The soil should be managed in such a manner that it is preserved over the long-term. The farmer then accepts the highest yield achievable under prevailing ecological and environmental conditions. Conserving the soil takes precedence in the farm decision making process. Adopting sugarcane farming practices to improve soil quality that conform to Agro-ecological and Conservation Agriculture principles should assist the farmer in achieving this goal. The goal of maximum sustainable crop yields must also not harm the economic or social sustainability of the farm.

Although some of the farmers in the case studies had not experienced yield decline they were all concerned about soil quality. They are custodians of soil and it is in their own interests to conserve and improve their most valuable asset. The interviewed farmers knew that some farming practices were degrading their soils. They were all actively searching for information to assist them in improving their soils quality.

All the interviewed farmers had adopted specific farming practices they hoped would improve their soil properties. They generally adopted those practices that: practically fitted in with the existing farm system and enhanced it; were fairly easy to implement; were eco-friendly; and cost effective. The farmers understood their own unique farm systems. The main constraints to the adoption of more soil quality farming practices were: economic and management constraints; shortage of farm machinery or labour; lack of knowledge about certain practices; and a dearth of trial data to support some practices. Green manuring was stated as the farming practice that had contributed most to improving their soil quality. The Sugarcane Yield Decline Joint Venture also highlighted green manuring as a key sugarcane farming practice that would improve soil quality in Australia (Garside & Bell, 2006).

The interviewed farmers had mixed responses as to whether they would adopt more soil quality practices if they were promoted under a package of Agro-ecological or Conservation Agriculture based best practices, rather than as single practices on an ad hoc basis. This concept possibly needs further explaining so farmers can assess the benefit or otherwise of this approach. The farmers had the option of using SUSFARMS® for this purpose.

The interviewed farmers mainly required more research and development on issues relating to soil fertility, green manuring and soil biological life. The majority of the farmers agreed they would be willing to pay a soil quality consultant to evaluate their farms and advise them on the best farming practices to improve soil quality on their farms. They required practical site specific on-farm solutions.

Each interviewed farmer had his own method of monitoring his soil's health. They used their own limited, practical, secondary indicators of soil health on their farms. The farmers all agreed that a practical, calibrated, specific soil health test would help them manage their soils in a more sustainable manner.

5.4 Answers to research questions

The extensive literature review sourced information relative to the topic and identified gaps in the literature. It also provided information to compile the research questionnaire and contributed towards answering all seven of the research questions. The case studies contributed towards answering the research questions, particularly questions I, II, III, IV and VII.

RESEARCH QUESTION I

Is soil degradation a problem in the South African dryland sugarcane industry?

The literature review confirmed that soil degradation is a problem in the South African dryland sugarcane industry. There was an abundance of research found on the topic. Certain farming practices degrade soil properties.

All the case studies interviewees' were concerned about soil quality and were actively implementing farming practices to improve their soil quality. The farming practices or soil chemical, physical or biological properties that caused soil degradation on their farms were documented (Table 5).

RESEARCH QUESTION II

Do local researchers and large-scale dryland sugarcane farmers in the KwaZulu-Natal region identify soil quality as a factor they should focus resources on?

There was also an abundance of local research literature on soil quality in the South African sugarcane industry. This has mainly been conducted by researchers from SASRI. No literature was found researching if KwaZulu-Natal dryland sugarcane farmers viewed soil quality as a problem and whether they were actively trying to address the problem.

The case studies confirmed the interviewees' believed soil quality was an important factor to manage, despite only one of the farmers experiencing long-term yield decline. They knew the main factors that caused soil degradation on their farms (Table 5). They all adopted specific farming practices to improve their soil quality (Table 6) and wanted to implement further farming practices to do the same (Table 7). There was also soil quality farming practices they had discontinued (Table 8) and practices they would not implement for a variety of reasons. Three of the interviewees' responded that they would like access to more information on the causes of soil degradation. They all stated that they required more information on specific farming practices to improve soil quality. These farmers had a desire to implement best soil quality farming practices on their farms and a requirement for more information on the subject.

Three of the interviewees' were willing to pay a soil quality consultant to assess their farms and advise them on the best soil quality improvement practices to implement. All four interviewees' indicated they would use an on-farm soil health specific test if one was available.

RESEARCH QUESTION III

From what perspective do researchers and the targeted group of farmers approach the issue of soil quality?

Based on the literature reviewed, most research on soil quality had been conducted in response to declining sugarcane yields in the sugarcane industry. Soil degradation was identified as one of the main reasons for yield decline. Research was conducted on identifying reasons for soils degrading and on farming practices that could improve soil quality. Research was also focused on breeding improved sugarcane varieties and GM technology.

My assessment is that the trigger research focus is an economic one – yield / economic decline. The initial reaction is to the symptom (yield decline). Efforts are then made to address the primary cause (soil degradation). Soil quality could perhaps be approached from a different perspective. Instead of initially focusing on yield decline and then identifying farming practices that improve soil quality, the focus could move to ensuring soils are managed holistically in a manner that ensures soil quality does not become an over-riding factor in limiting sugarcane yields now or in the future. If soils are healthy and other farming inputs are supplied optimally then sustainably good sugarcane yields should be produced in the long-term. The trigger focus then is an environmental one - environmental preservation. This approach conforms to a sustainable development paradigm.

Historically most research on soil degradation and soil quality was conducted from a single-discipline approach. Soil is a complex system. The Sugarcane Yield Decline Joint Venture also stated that sugarcane yield decline is a complex issue (Garside & Bell, 2006). It is associated with many factors being out of balance in the farming system. Complex systems cannot be understood by studying them with a single-discipline approach. In 1998 the Soil Sustainability Programme was formed at SASRI. This adopted a multi-disciplinary approach to studying the link between soil degradation and sugarcane yield decline. The Australians preceded this by launching the multi-disciplinary Sugarcane Yield Decline Joint Venture research project in 1993.

One of the principles of Agro-ecology is that the ad hoc adoption or removal of specific agricultural practices will not necessarily lead to a more self-sufficient sustainable agriculture. Farming practices should rather be adopted based on a deep understanding of the value of Agro-ecosystems and how they function (Altieri, 2002). The implementation of Conservation Agriculture will only work optimally if all the different technical aspects are considered simultaneously, in an integrated way (Food and Agriculture Organization of the United Nations, 2010). Farmers need an understanding of the multiple benefits or synergies that a farming practice can provide to their soils.

Soil quality must be studied from a multi-disciplinary perspective. No literature was found on how farmers approach the issue of soil quality.

The case studies interviewees' in the Midlands South region did not approach soil quality from the traditional economic response to yield decline approach. Only one of the interviewees had suffered from long-term yield decline, yet all of the farmers were concerned about soil quality. They were proactive as they were aware that certain farming practices could lead to long-term soil degradation and hence economic decline. Their main focus was to increase crop yields by ensuring that poor soil quality was not an over-riding limiting factor in sugarcane production. My assessment of this is that their trigger focus was an environmental one – soil preservation and enhancement. By preserving their soils and implementing practices that made economic sense they hoped to produce sustainably good sugarcane yields.

The farmers observed their farms and made changes to their farming practices in response to these observations. They assessed the implications and consequences of the various farming practices on their farming system as a whole and made decisions accordingly.

RESEARCH QUESTION IV

What sugarcane farming practices are currently recommended and implemented to improve soil quality?

The literature review provided an extensive list of sugarcane farming practices that can be used to improve soil quality (section 2.9). All the recommended farming practices are implemented on some scale in the South African sugarcane industry. Some practices like planting ley crops, intercrops and vertical mulching are used on a very small scale. No local literature was found listing all possible farming practices that could be implemented or those that had already been implemented by South African sugarcane farmers.

The case study interviewees' stated which soil quality improvement practices they had already implemented on their farms (Table 6). Practices that were implemented by all of them included: green manuring; lime and gypsum applications; implementation of a farm Land Use Plan; and practices to increase soil organic matter content.

RESEARCH QUESTION V

Which soil quality improvement practices conform to Agro-ecological or Conservation Agriculture principles and are they currently recognised as practices from these paradigms?

No literature was found linking sugarcane soil quality improvement farming practices to Agro-ecology or Conservation Agriculture in South Africa. Soil quality improvement practices that conformed to these farming systems were identified by me based on their alignment with principles from these two farming systems.This was discussed in section 3.5.3. The farming practices are listed in Table 3.

All the farming practices used by the interviewed farmers to improve soil quality conformed to Agro-ecological principles. The farmers were aware of the concept of Agro-ecology even though it was not publicised in the South African sugarcane industry.

All the case study interviewees' knew about Conservation Agriculture albeit with varying degrees of expertise. Some of the soil quality improvement farming practices they used conformed to Conservation Agriculture minimum tillage, crop rotation and soil cover principles. These practices are not formally recognised as Conservation Agriculture practices in the sugarcane industry. Farming practices linked to the core principles of Conservation Agriculture are not formally recommended as a package in the sugarcane industry either.

Whilst the interviewees' knew about Agro-ecology and Conservation Agriculture none of them directly linked soil quality improvement practices to these farming systems during the visits to their farms.

RESEARCH QUESTION VI

Can principles from Agro-ecology or Conservation Agriculture contribute towards the development of a management system for the sustainable exploitation of soil, in the South African dryland sugarcane industry?

The research highlighted principles from Agro-ecology and Conservation Agriculture that contributed towards a system on the sustainable exploitation of soil in this agricultural sector. This system is proposed in section 5.5.

Agro-ecological principles that contributed towards the proposed management system are now covered. Agro-ecological principles state that ecosystems should be considered when producing food. The natural resource base, in this case soil, must be conserved. Ecological relationships and beneficial biological interactions and synergies must be promoted when managing sugarcane soils so natural ecological processes can enhance rather than undermine sugarcane production.

Agro-ecology interventions must be context,and site specific. They must also be economically viable. There is no single recipe for success. A multidisciplinary approach should be adopted when designing Agro-ecological farming systems. Interactions between humans, plants and the environment must be considered in the agricultural system. Productivity and sustainability are important Agro-ecological principles. Local resources should be used as much as possible. Soil quality improvement must be a focus area. Renewable resources should be used whenever possible. The unnecessary use of external inputs should be avoided. Diversity of biota, landscapes and economics must be promoted. Species and plant diversity should be maximised to build up the system's resilience (avoid monocultures).

Whole systems must be managed. Long-term benefits should be maximised. Biomass re-cycling such as crop residues and manures should be used. Soil organic matter and biotic activity must be enhanced to provide favourable soil conditions for plant growth. Soil erosion must be minimised.

Four important characteristics of ecosystems must be built into sugarcane systems: biological diversity, self-suffficiency, self-regulation and resiliency. Agricultural practices must be adopted based on an understanding of the nature of agricultural ecosystems and how they function.

Implementing farming practices that conform to Agro-ecological principles should improve soil quality and enhance the sustainability of the sugarcane farming enterprise. Biodiversity of the farming operation should improve and soils should become more resilient to harsh climatic conditions. Farmers should take the above stated principles into account when deciding which soil quality practices to implement and when completing any cost-benefit analyses on new farming practices.

Conservation Agriculture principles which contributed towards the system included that a balance should be strived for between agricultural production and conserving agricultural resources. Natural biological processes should be enhanced above and below the soil surface. All of the Conservation Agriculture farming practices must be implemented simultaneously in an integrated way for Conservation Agriculture to work optimally. Natural soil processes should be encouraged. A healthy soil ecosystem must be promoted. Conservation Agriculture aims to produce sustainable good yields, reduce soil erosion and lower the costs of production.

Both Agro-ecological and Conservation Agriculture farming systems focus on conserving the environment and improving sustainability. Agro-ecology and Conservation Agriculture both contributed towards the development of a proposed system on the sustainable exploitation of soil in the South African sugarcane industry.

RESEARCH QUESTION VII

What common themes emerge from the study which may contribute towards the development of this soil quality management system?

The literature review highlighted themes that emerged from the literature on the topic of sustainable soil management in the South African dryland commercial sugarcane region. This was also confirmed by insights from the case studies.

A central theme is that some sugarcane farming practices impact negatively on soil physical, chemical and biological properties. Many South African soils have low resilience and are very vulnerable to degradation. Once they are degraded it is very difficult to rehabilitate them. Degraded soils lose their ability to self-regulate after interventions and become less resilient. Soil must be managed in a manner that ensures they are resilient and can self-regulate in response to disturbances. Agro-ecological and Conservation Agriculture practices can provide these benefits to soils.

A healthy soil will allow healthy sugarcane roots to grow. The main contributing factor to sugarcane yield decline is poor root health. Soil properties must be improved to improve the health of the sugarcane root structure. Agro-ecological and Conservation Agriculture practices will improve the soil root environment.

Soil erosion must be avoided at all costs as soil is a non-renewable resource. Farming practices that allow good water infiltration into soils must be adopted. Soils must be managed so they retain optimum quantities of water and supply this to the extensive healthy sugarcane root system. If all of the above factors are in place, then soil quality should not be a limiting factor in determining good sugarcane yields. The soil should be able to produce sustainably for future generations. Agro-ecological and Conservation Agriculture practices can promote this process.

Agro-ecological and Conservation Agriculture practices take a whole system approach to managing soils and recommend site specific solutions in the context of the situation. Agro-ecological and Conservation Agriculture farming principles need to be promoted so local researchers and farmers are aware of the benefits these practices provide in improving soil quality in the South African dryland sugarcane industry.

As discussed in section 5.3 soil organic matter, biodiversity and ecosystems are central themes to both Agro-ecological and Conservation Agriculture. Farming practices that conserve or enhance soil organic matter, conserve or improve biodiversity above and in the soil and protect or enhance the ecosystem should be adopted.

Soil organic matter in particular is a critical element for healthy soil physical, chemical and biological properties. Biological properties of soil are often ignored or discounted. A healthy soil requires a healthy soil food web. Soil organic matter sustains the soil food web.

Farming practices to improve soil quality must take the triple bottom line into account. All three soil properties should be enhanced. Practical farm solutions are required that fit the farm system and optimise farm resources. Farmers have a need for more information on soil degradation and soil quality management practices. There is a desire for practical on-farm solutions. Farmer-centric solutions are required.

The soil resource as the primary cause of sugarcane yield decline should be focused on. A sustainable soil management system is required. If soil quality improves then sugarcane yields should improve on a sustainable basis. Maximum sustainable yield should be strived for without compromising the economic and social sustainability status of of the farm. Agro-ecology and Conservation Agriculture can contribute towards increasing sugarcane yields while not compromising soil quality.

A multi-disciplinary approach should be adopted when researching soil quality. Some farming practices will provide more soil chemical, physical, biological benefits than others. More research needs to be conducted on mutually beneficial combinations of farming practices to improve soil quality and ensure sustainable livelihoods in the South African dryland sugarcane farming sector.

Improving soil quality is a long-term commitment, with long-term benefits. While it is understood that complex dynamic systems cannot be modelled, a system based on Agro-ecological or Conservation Agriculture principles that will provide guidelines to the farmer so that site specific farming practices can be adopted is proposed in section 5.5.

5.5 Conclusions

Soil quality in the South African dryland sugarcane industry needs to improve. It is recognised that while it is impossible to compile a one-theory-fits-all model for sustainably managing soils, a system that may assist sugarcane farmers in deciding which soil quality improvement farming practices to adopt is proposed. Soil quality is a vital issue to address as society does not know how it is affecting the long-term productive capacity of our soils. The farm context would need to be evaluated before proposing site-specific solutions.

The management system I propose for the South African dryland sugarcane industry is illustrated in Figure 1. It is based on Agro-ecological and Conservation Agriculture principles.

Figure 1: Proposed sustainable sugarcane soil quality management system

Current conventional farming practices

↓

Soil degradation

↓

Sugarcane yield decline

↓

Assess the farm context from an Agro-ecological and Conservation Agriculture perspective

↓

Determine what impact various practices have on soil organic matter, biodiversity and the ecosystem

↓

Recommend farming practices that are synergistic, provide multiple benefits or provide the required benefit

↓

Whole system approach should improve soil physical, chemical and biological properties

↓

Improved soil quality with resilience and self-regulation

↓

Healthy extensive root system

↓

Healthy resilient crop

↓

Maximum sustainable yield

↓

Sustainable sugarcane production system

↓

Sustainable livelihoods

↓

Sustainable food production

Some sugarcane farming practices degrade soil and as a consequence yields decline. Individual farm systems should be assessed to determine what impact they have on soil quality. This assessment should be undertaken from an Agro-ecological and Conservation Agriculture perspective. Particular attention should be focused on the impact the farm practices have on soil organic matter, biodiversity and the ecosystem. Agro-ecological or Conservation Agriculture soil quality improvement practices must be proposed. They should be synergistic; provide multiple benefits or provide the specific benefit the farm system requires.

This whole system approach should improve soil physical, chemical and biological properties. Soil quality should improve. The soils should become more resilient and able to self-regulate. Sugarcane root systems should be healthier and more extensive. It is hoped that the sugarcane crop will be healthier and more resilient.

Maximum sustainable yields should be achieved. This sugarcane production system should be sustainable. The farm must also be economically and socially sustainable. Sustainable livelihoods should be attained. This should lead to sustainable food production which will contribute towards sustainable habitation on planet Earth. It is a sustainable development solution. This proposed paradigm requires skills and knowledge to be implemented successfully.

The study proposes that Agro-ecology and Conservation Agriculture principles can assist large-scale dryland sugarcane farmers in the KwaZulu-Natal Midlands South region, to improve soil quality. Research and practical validation would need to be conducted to validate this hypothesis.

This study aimed to provide an alternative sugarcane soil management system to farmers. The proposed system (see Figure 1) provides farmers with guidelines that may assist them to decide which soil quality improvement farming practices to implement from the long list of available choices.

The research questions were all successfully answered. Soil degradation was identified as a problem in the South African dryland sugarcane industry. Researchers and large-scale sugarcane farmers in the KwaZulu-Natal region identify soil quality as a factor they should focus resources on. The perspective from which farmers and sugarcane farmers approach the issue of soil quality was determined. The sugarcane farming practices recommended and implemented to improve soil quality were identified. The soil quality improvement practices that conform to Agro-ecological and Conservation Agriculture methods were identified - although they were not recognised as practices from these farming systems. Agro-ecological and Conservation Agriculture principles contributed to compiling a management system on the sustainable exploitation of soil in the South African dryland sugarcane industry. Common themes were identified from the study. These contributed towards the development of the system.

This proposal contributes towards existing literature on sustainable soil management in the sugarcane farming sector. Agro-ecological and Conservation Agriculture principles may assist large-scale dryland sugarcane farmers in the KwaZulu-Natal Midlands South region to improve their soil quality.

5.6 Recommendations for future practice

Degraded soils contribute towards sugarcane yield decline. This problem is formally called Sugarcane Yield Decline Syndrome. The focus is placed on the symptom of the problem – yield decline. This may detract from focusing attention on the primary cause of the problem. The problem should possibly be called Sugarcane Soil Decline Syndrome. Attention should then be focused on diagnosing why soils become degraded and how to improve soil quality. When soil quality improves and sugarcane roots improve, then sugarcane yields should improve. Yield decline should be decoupled from soil quality.

Agro-ecology and Conservation Agriculture both place the focus on the soil resource. It is hoped that through publicising these practices in the South African dryland sugarcane industry, more focus will be placed on managing this natural resource.

By focusing on Agro-ecological and Conservation Agriculture principles it is hoped more farming practices will be implemented to improve soil quality. Farmers should be able to better assess the shortcomings in their farming system and be in a better position to decide which soil quality improvement practices to adopt. Soil organic matter, biodiversity and ecosystems should play a central role in this decision making process. All soil quality farming practices should benefit from one or preferably more of these factors. Combinations of practices that provide synergistic benefits, such as those proposed in the Australian sugarcane industry by (Garside & Bell, 2006) should be implemented.

This proposed farming system will require specialist skills to implement. Site specific solutions need to be proposed. A further contribution to practice is that the case study interviewees' practices and perspectives can add value to future research on sugarcane soil quality. Farmers have an understanding of the on-farm challenges they face. They are in-touch with their farming environment.

5.7 Recommendations for further study

A multi-disciplinary approach should be adopted when researching soil quality.

The interviewed farmers specifically stated that they required more information on some subjects. These were: soil nutrient balancing; soil biological life; strategies to stimulate soil microbial activity; optimum growth time period for specific green manures; economic responses to green manuring; and the supply of silicon to sugarcane plants. They also requested information specifically related to organic fertilisers in terms of nutrient content, nutrient availability and their impact on the *Eldana saccharina Walker* borer.

More research needs to be conducted on soil biological properties and the impact they have on soil quality. By approaching soil quality from an Agro-ecological or Conservation Agriculture perspective it is hoped more attention will be focused on the environment and soil biological properties.

The interviewed farmers believed they had insufficient knowledge on best practices they should adopt to improve soil quality. Proposed practices should be practical and must consider the constraints farmers face. The farmers requested more information on the financial consequences of some of the practices. They require this information to conduct cost-benefit analyses on their farms, particularly with practices requiring additional capital investments. While it is accepted that all the benefits cannot be directly accounted for financially, research needs to be conducted to provide knowledge on benefits that can be evaluated.

More research needs to be conducted on synergistic, complementary combinations of farming practices and whether these will provide greater soil quality improvements than ad hoc implementation of individual practices.The benefits of each possible farming practice needs to be highlighted. Long-term trials need to be implemented. Some practices will require a conversion time period for the soil to adjust and for the ecosystem to recover.

Farmers requested more practical soil health indicators they can use on-farm. Practical biological on-farm soil health indicators are required. None of the interviewed farmers stated that they used any biological soil property indicators. A practical calibrated laboratory soil health test needs to be developed together with suggested remedial on-farm practices to improve soil quality.

This study was exploratory in nature. The intention was to identify and propose relevant practices and trends. The proposed practices need to be substantiated with field trials. These will be invaluable in terms of building on the knowledge of strategies to improve soil quality in the sugarcane industry.

References

Acton, D.F. & Gregorich, L.J. 1995. *The health of our soils: toward sustainable agriculture in Canada.* Canada: Centre for Land and Biological Resources Research.

African Centre for Biosafety. 2010. *Gm sugarcane: A long way from commercialisation.* ACB Briefing Paper No 15, April 2010. South Africa: Melville.

Altieri, M.A. 1995. *Agroecology: The science of sustainable agriculture.* Boulder: Westview Press.

Altieri, M.A. 1999. *Agroecology: principles and strategies for designing sustainable farming systems. Agroecology in Action.* Berkeley: University of California.

Altieri, M.A. 2000. *Modern agriculture: ecological impacts and the possibilities for truly sustainable farming. Agroecology in Action.* Berkeley: University of California.

Altieri, M.A. 2002. Agriculture, Ecosystems & Environment Agroecology: the science of natural resource management for poor farmers in marginal environments. *Agriculture, Ecosystems & Environment,* 93(1-3) : 1-24.

Altieri, M.A. & Nicholls, C. 2005. *Agroecology and the search for a truly sustainable agriculture.* Mexico: United Nations Environment Programme.

Anon. 2005. *Labour utilisation and cost survey 2004/2005.* Confidential Report G/324/2005. South African Cane Growers' Association. Mount Edgecombe: SASA

Anon. 2006. *Sustaining soil health.* South African Sugarcane Research Institute, The Link, Vol.15, No.3, 10-11.

Australian Centre for International Agricultural Research. 2015. *Crop yields and global food security.* [Online]. Available: http://aciar.gov.au[1]/files/mn-158/s7_6-sugarcane-sugar-beet.html. [2015, 30 March].

Bak, N. 2004. *Completing your thesis: a practical guide.* Pretoria: Van Schaik.

Bell, M.C. & Raczkowaki, C.W. 2008. Soil property indices for assessing short-term changes in soil quality. *Renewable Agriculture and Food Systems*, 23, Special Issue 01 : 70-79.

Berry, S.D. & Rhodes, R. 2006. Green manure crops: Agronomic characteristics and effects on nematodes. *Proceedings of the South African Sugar Technologists' Association*, 80 : 269.

Berry, S.D. & Wiseman, E.J. 2003. The effect of green manure crops on plant parasitic nematodes in the South African sugar industry. *Proceedings of the South African Sugar Technologists' Association*, 77 : 114-116.

Bezuidenhout, C.N. & Singels, A. 2007. Operational forecasting of South African sugarcane production: Part 1–System description. *Agricultural Systems*, 92(1.3) : 23-38.

Biernacki, P. & Waldorf, D. 1981. Snowball sampling: Problems and techniques of chain referral sampling. *Sociological Methods & Research*, 10(2) : 141-163.

Bot, A. & Benites, J. 2005. *The importance of soil organic matter. Key to drought-resistant soil and sustained food production. FAO Soils Bulletin 80*. Rome: Food and Agriculture Organization of the United Nations.

Brace, I. 2008. *Questionnaire design: How to plan, Structure and Write Survey Material for Effective Market Research.* Kogan: Page.

Brown, L.R. 2008. *Plan B 3.0: Mobilizing to Save Civilization.* Earth policy institute. New York: Norton & Company.

Cadet, P. & Spaull, V.W. 2001. Annual and long term benefits of nematode control on yield in sugarcane. *Proceedings of the South African Sugar Technologists' Association*, 75 : 115.

Clayton, A.M.H. & Radcliffe, N.J. 1996. *Sustainability: a systems approach.* London: Earthscan publications.

Cochrane, W.W. 1958. *Farm prices: myth and reality*. Minneapolis: University of Minnesota Press Editions.

Cohen, D. & Crabtree, B. 2008. *Qualitative Research Guidelines Project.* [Online]. Available: http://www.qualres.org/HomeSemi-3629.html. [2015, 28 October].

Cohen, L. Manion, L. & Morrison. K. 2007. *Research Methods in Education.* 6th edition. London: Routledge.

Conway, G.R. 1985. Agroecosystem analysis. *Agricultural Administration,* 20 : 31-55.

Crawford, J.W., Harris, J.A., Ritz, K. & Young, I.M. 2005. Towards an evolutionary ecology of life in the soil. *Trends in Ecology & Evolution,* 20(2) : 81-87.

Culverwell, T.J. & Swinford, J.M. 1985. Attempts at improving irrigation water quality in northern Zululand. *Proceedings of the South African Sugar Technologists' Association*, 60 : 168-171.

Dalgaard, T., Hutchings, N. & Porter, J. 2003. Agroecology, scaling and interdisciplinarity. *Agriculture Ecosystems and Environment,* 100 : 39-51.

de Schutter, O. 2009. The right to food : fighting for adequate food in a global crisis. *Harvard International Review,* XXXI(2) : 1-6.

Dewey, F.J. & Meyer, J.H. 1989. The use of phosphogypsum as an ameliorant for poorly structured crust forming soils. *Proceedings of the South African Sugar Technologists' Association* 63 : 153-158.

Dick, W.A. & Gregorich, E.G. 2004. Developing and maintaining soil organic matter levels. In Schjønning, P., Elmholt, S. & Christensen, B. T. (eds.). *Managing Soil Quality: Challenges in Modern Agriculture.* Wallingford: CABI Publishing. 103-120.

Dominy, C.S., Haynes, R.J. & van Antwerpen, R. 2001. Long-term effects of sugarcane production on soil quality in the South Coast and the Midland areas of KwaZulu Natal. *Proceedings of the South African Sugar Technologists' Association*, 75 : 222-227.

Donaldson, J. 2003. Issues affecting the value of ecosystem services in agricultural systems and implications for conservation farming. *Proceedings of the VIIth International Rangelands Congress,* July 26 – August 1, Durban, South Africa. 1499-1502.

Donaldson, R.A., Redshaw. K.A., Rhodes, R. & van Antwerpen, R. 2008. Season effects on productivity of some commercial South African sugarcane cultivars, II: trash production. *Proceedings of the South African Sugar Technologists' Association*, 81 : 528-538.

Doran, J.W., Kirschenmann, F. & Frederick, M. 2007. Editorial : Balancing food, environmental and resource needs. *Renewable Agriculture and Food Systems,* 22(2) : 77-79.

Doran, J.W., Liebig, M.A. & Santana, D.P. 1998. Soil health and global sustainability. *16th World Congress of Soil Science Proceedings*. Montpellier, France. Paper no 1923.

Doran, J.W. & Parkin, T.B. 1994. *Defining soil quality for a sustainable environment.* SSSA special publication 35, SSA. Madison, Wisconsin. 3-21.

Doran, J.W. & Safley, M. 1997. Defining and assessing soil health and sustainable productivity. In Pankhurst, C., Doube, B.M. & Gupta, V.V.S.R. (eds.). *Biological indicators of soil health.* Oxon : CAB International.1-28.

Du Preez, C.C., van Huyssteen, C.W. & Mnkeni, P.N.S. 2011. Land use and soil organic matter in South Africa 2: A review on the influence of arable crop production. *South African Journal of Science*, 107 : 5–6.

Egan, B.T., Hurney, A.P., Ryan, C.C. & Mathews, A.A. 1984. A review of the northern poor root syndrome of sugarcane in North Queensland. *Proceedings of the Australian Society of Sugar Cane Technologists,* 6 : 123-127.

Ferrer, S. R. D. & Nieuwoudt, W.L. 1997. Factors affecting soil conservation decisions of KwaZulu-Natal commercial sugar cane farmers. *Agrekon, Agricultural Economics Research, Policy and Practice in Southern Africa.* 36 (4) : 453-461.

Follett, R.F. 2001. Soil management concepts and carbon sequestration in cropland soils. *Soil & Tillage Research*, 61 : 77-92.

Food and Agriculture Organization of the United Nations. 2010. *What is Conservation Agriculture?* [Online]. Available: http://www.fao.org/ag/AGS/AGSE/agse_e/1ero/INT1.htM. [2010, 29 January].

Food and Agriculture Organization of the United Nations. 2015. *Soil is a non-renewable resource.* [Online]. Available: http://www.fao.org/soils-2015/news/news-detail/en/c/275770/ [2016, 3 February].

Garside, A.L. 1997. Yield decline research in the Australian sugar industry. *Proceedings of the South African Sugar Technologists' Association*, 71 : 3-8.

Garside, A.L. & Bell, M.J. 2006. Final Report SRDC Project YDV002. Sugar Yield Decline Joint Venture Phase 2 (July 1999–June 2006). *SRDC Final Report SD06011.* Brisbane: BSES Limited.

Garside, A., Magarey, R. & Braunack, M. 2000. Soil health. In Hogarth M and Allsopp P (eds.) *Manual of Canegrowing.* Brisbane : Bureau of Sugar Experiment Stations. 141-151.

Google Scholar. 2010. *Google Scholar Citations.* [Online]. Available: https://scholar.google.co.za/ . [2010, 12 July].

Gowing, J.W. & Palmer, M. 2007. Sustainable agricultural development in sub-Saharan Africa: the case for a paradigm shift in land husbandry. *Soil Use and Management*, 24 : 92-99.

Graham, M.H., Haynes, R.J. & Meyer, J.H. 1999. Greencane harvesting promotes accumulation of soil organic matter and an improvement in soil health. *Proceedings of the South African Sugar Technologists' Association*, 73 : 53-57.

Graham, M.H., Haynes, R.J. & Meyer, J.H. 2000. Changes in soil fertility induced by trash retention and fertiliser applications on the long-term trash management trial at Mount Edgecombe. *Proceedings of the South African Sugar Technologists' Association*, 74 : 109-112.

Granatstein, D. & Bezdicek, D.F. 1992. The need for a soil quality index : Local & regional perspectives. *American Journal of Alternative Agriculture*, 7 : 12-16.

Gregorich, E.G., Turchenek, L.W., Carter, M.R. & Angers D.A. (eds.). 2001. *Soil and Environmental Science Dictionary.* Washington DC: CRC Press.

Gruhn, P., Goletti, F. & Yudelman, M. 2000. *Integrated nutrient management, soil fertility, and sustainable agriculture: current issues and future challenges.* International Food Policy Research Institute, Washington DC USA, Food, agriculture, and the Environment Discussion Paper 32.

Gruver, J.B. & Weil, R.R. 2007. Farmer perceptions of soil quality and their relationship to management-sensitive soil parameters. *Renewable Agriculture and Food Systems*, 22(04) : 271-281.

Haynes, R.J. 1997. The concept of soil quality and its applicability to sugarcane production. *Proceedings of the South African Sugar Technologists' Association*, 71 : 9-14.

Haynes, R.J. & Hamilton, C.S. 1999. Effects of sugarcane production on soil quality: a synthesis of world literature. *Proceedings of the South African Sugar Technologists' Association,* 73 : 46-52.

Heap, B. & Kent, J. 2000. *Towards Sustainable Consumption.* London and Oxford: The Royal Society.

Hobbs, P., Sayre, K. & Gupta, R. 2008. The role of conservation agriculture in sustainable agriculture. *Philosophical Transactions B*. [Online]. The Royal Society Publisher. Available: http://rstb.royalsocietypublishing.org/content/363/1491/543. [2013, 20 March].

Huang, J., Pray, C. & Rozelle, S. 2002. Enhancing the crops to feed the poor. *Nature,* 418 : 678-684.

International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD). 2009. *Agriculture at a Crossroads : Global Report.* Washington, DC: Island Press.

Johnson, M.A. 1978. Sodicity and salinity problems in the South African Sugar Industry. Unpublished MSc Agric. Thesis. Pietermaritzburg: University of Natal.

Jones, M.R., Sithole, P., Ferrer, S.R.D. & Singels, A. 2012. Quantifying cane yield and production trends in the South African sugarcane industry : results for the south coast region. *Proceedings of the South African Sugar Technologists' Association*, 85 : 197-200.

Kate, T. 2008. From industrial agriculture to agro-ecological farming – a South African perspective. Unpublished discussion paper prepared for submission to Development Southern Africa.

Kingston, G., Donzelli, J. L., Meyer, J. H., Richard, E.P., Seeruttun, S., Torres, J. & van Antwerpen, R. 2005. Impact of the green cane harvest and production system on the agronomy of sugar cane. *Proceedings of the International Society of Sugar Cane Technologists*, 25(1) : 521-531.

Kothari, C.R. 2004. *Research Methodology (Methods and Techniques).* 2nd revised edition. New Delhi: New Age International (P) Ltd.

Laker, M.C. 2000. Chapter 14: Soil resources: distribution, utilization and degradation. In Fox, R. & Rowntree, K. (eds.). *The Geography of South Africa in a Changing World*. Cape Town: Oxford University Press.

Lal, R. 2006. Managing soils for feeding a global population of 10 billion. *Journal of the Science of Food and Agriculture,* 86 : 2273-2284.

Lal, R. 2010. Managing soils for a warming earth in a food-insecure and energy-starved world. *Journal of Plant Nutrition and Soil Science,* 173 : 4-15.

Lal, M. & Singh, A.K. 2003. Cane productivity and soil health in relation to intercropped forages and nitrogen nutrition in winter initiated ratoons. *International Society of Sugar Cane Technologists Agronomy Workshop.* 21 – 25 July 2003. MSIRI, Mauritius.

Lampkin, N. 1999. *Organic Farming.* Tonbridge: Farming Press.

Magdoff, F. 2007a. Balancing food, environmental and resource needs. *Renewable Agriculture and Food Systems,* 22(2) : 77-79.

Magdoff, F. 2007b. Ecological agriculture : Principles, practices, and constraints. *Renewable Agriculture and Food Systems,* 22(2) : 109-117.

Manson, A.D., Miles, N., Roberts, V.G. & Katušić, V. 2004. *Soil fertility course notes*. Directorate Research, Analytical Services and Training. KwaZulu-Natal Department of Agriculture, Cedara.

Meyer, J.H. 2006. *Making the most of your N fertilizers.* South African Sugarcane Research Institute, The Link, Vol.15, No.2, 8 - 9.

Meyer, J.H., Dewey, F.J. & Wood, R.A. 1988. Improving the quality of soils derived from Middle Ecca, Dwyka and Beaufort sediments. *Proceedings of the South African Sugar Technologists' Association*, 62 : 215-220.

Meyer, J.H., Rein, P., Turner, P. & Mathias, K. 2011. *Good management practices manual for the cane sugar industry*. Produced for the International Finance Corporation (IFC) PGBI House. Johannesburg, South Africa.

Meyer, J.H., van Antwerpen, R. & Meyer, E. 1996. A review of soil degradation and management research under intensive sugarcane cropping. *Proceedings of the International Society of Sugarcane Technology*, 70 : 22-28.

Meyer, J.H. & Van Antwerpen, R. 2001. Soil degradation as a factor in yield decline in the South African sugar Industry. *Proceedings of the International Society of Sugarcane Technology*, 24 : 8-15.

Miles, N., Meyer, J.H. & van Antwerpen, R. 2008. Soil organic matter data : what do they mean? *Proceedings of the South African Sugar Technologists' Association*, 81 : 324-332.

Moberly, P.K. & McIntyre, R.K. 1983. Some post harvest management practices on ratoon cane in the rain fed areas of the Natal sugarbelt. *Proceedings of the International Society of Sugar Cane Technologists*, 18 : 344-356.

Moberly, P.K. & Meyer, J.H. 1978. Filtercake – a field and glasshouse evaluation. *Proceedings of the South African Sugar Technologists' Association*, 52 : 131-135.

Mouton, J. 2009. *How to succeed in your master's & doctoral studies.* Pretoria: Van Schaik Publishers.

Nixon, D. 1992. The impact of fallowing and green manuring on soil physical properties and the productivity of sugarcane in Swaziland. Unpublished PhD thesis. University of Reading: Soil Science Department.

Norberg-Hodge, H., Goering, P. & Page, J. 2001. *From the ground up: rethinking industrial agriculture.* London: Zed Books.

Parsons, M. 2000. *Increase your profits by intercropping.* South African Sugarcane Research Institute, The Link, Vol.9, No.2, 1.

Pierret, A., Doussan, C., Capowiez, Y., Bastardie, F. & Pagès, L. 2007. Root Functional Architecture: A Framework for Modeling the Interplay between Roots and Soil. *Vadose Zone Journal*, 6(2) : 269:281.

Pierret, A., Moran, C.J. & Doussan, C. 2005. Conventional detection methodology is limiting our ability to understand the roles and functions of fine roots. *New Phytologist*, 166 : 967-980.

Platford, G.G. 1979. Research into soil and water losses from sugarcane fields. *Proceedings of the South African Sugar Technologists' Association*, 53 : 152-156.

Platford, G.G. 1982. The determination of soil erodibility factors using a rainfall simulator. *Proceedings of the South African Sugar Technologists' Association*, 56 : 130-133.

Platford, G.G. 1987. A new approach to designing the widths of panels in sugarcane fields. *Proceedings of the South African Sugar Technologists' Association*, 61 : 150-155.

Pretty, J. 2006. *Regenerating Agriculture.* London: Earthscan.

Pretty, J. 2011. Interdisciplinary progress in approaches to address social-ecological and ecocultural systems. *Environmental Conservation*, 38(02) : 127-139.

Pretty, J., Guijt, I., Scoones, I. & Thompson, J. 1995. *Regenerating Agriculture: The Agroecology of Low-External Input and Community-Based Development,* in Kirkby, J., et al., Sustainable Development, The Earthscan Reader. London: Earthscan.

Principles of Agro-ecology. 2010. [Online]. Available: http://www.agroecology.org/Principles.html. [2010, 17 January].

Qongqo, L.L. & van Antwerpen, R. 2000. Effects of long term sugar cane production on physical and chemical properties of soils in KwaZulu-Natal. *Proceedings of the South African Sugar Technologists' Association,* 74 : 114-121.

Ramburan, S. 2015. Optimum harvest age in rainfed regions: Interactions between variety, age and Eldana Saccharina (Lepidoptera: Pyralidae) damage. *Proceedings of the South African Sugar Technologists' Association,* 88 : 417-420.

Ramburan, S., Wetttergreen, T., Berry, S.D. & Shongwe, B. 2012. Effects of variety, environment and management on sugarcane ratoon yield decline. *Proceedings of the South African Sugar Technologists' Association,* 85 : 180-192.

Republic of South Africa. Department: Environmental Affairs and Tourism. 2007. *People-Planet-Prosperity: A National Framework for Sustainable Development in South Africa.* Pretoria: Government printer.

Richardson, B.J. 2014. *Genetically modified sugarcane approved in Indonesia.* [Online]. Available: http://ethicalsugar.org/2014/02/14/genetically-modified-sugarcane-approved-in-indonesia/ [2016, 6 February].

Roberts, P. 2008. *The end of food.* London: Bloomsbury.

Rosenberg, A. 2006. *Global health in crisis : the answer lies in the soil.* Place of publication unknown : Lindros.

Rosset, P., Collins, J. & Lappe, F.M. 2000. Lessons from the green revolution. *Tikkun,*15(2) : 52-56.

Scherr, S.J. 2000. A downward spiral? Research evidence on the relationships between poverty and natural resource degradation. *Food Policy,* 25(4) : 479-498.

Schroeder, B.L., Robinson, J.R., Turner, P.E.T. & Wallace, J. 1994. Soil acidification occurrence and effects in the SA sugar industry. *Proceedings of the South African Sugar Technologists' Association*, 68 : 70-74.

Schumann, A.W. 1998. *Soil acidification causes and management?* South African Sugarcane Research Institute, The Link, Vol.7, No.4, 9.

Schumann, A.W. 2000. Prospects for improving nitrogen use efficiency with a new soil test and ammonia volatilization model. *Proceedings of the South African Sugar Technologists' Association*,74 : 70-78.

Schumann, R.A., Meyer, J.H. & van Antwerpen, R. 2000. A review of green manuring practices in sugarcane production. *Proceedings of the South African Sugar Technologists' Association*, 74 : 93-100.

Scialabba, N.E. & Muller-Lindenlauf, M. 2010. Organic agriculture and climate change. *Renewable Agriculture and Food Systems,* 25(2) : 158-169.

Science Learning Hub. 2013. *Soil formation.* [Online]. Available: http://sciencelearn.org.nz/Contexts/Soil-Farming-and-Science/Science-Ideas-and-Concepts/Soil-formation [2015, 14 September].

Singels, A., Donaldson, R.A. & Smit, M.A. 2005. Improving biomass production and partitioning in sugarcane : Theory and practice. *Field Crops Research*, 92(2.3) : 291-303.

Smit, M. & Campbell, P. 2010. *Let a break crop pay for plough-out & cynodon cleanup*. South African Sugarcane Research Institute, The Link, Vol.19, No.1, 2.

Soil foodweb Inc. 2009. *Benefits of a healthy food web*. [Online]. Available: http://www.soilfoodweb.com/03_about_us/approach_pgs/im. [2009, 29 May].

Soil quality. 2015. *Fact sheets - total organic carbon*. [Online]. Available: http://www.soilquality.org.au/factsheets/organic-carbon [2015, 13 October].

South African Cane Growers' Association. 2008. *Report to the Board of Directors 2007/08*. Mount Edgecombe: SASA.

South African Sugar Association. 2002. *Manual of Standards and Guidelines for Conservation & Environmental Management in the South African Sugar Industry.* Mount Edgecombe: SASRI.

South African Sugar Association. 2015. *Facts and figures.* [Online]. Available: http://www.sasa.org.za/Libraries/facts_figures_2014-2015/Total_Cane-Sugar_Production.sflb.ashx. [2015, 15 September].

South African Sugarcane Research Institute. November 1997. *: Soil salinity / sodicity in the sugar industry*. Information Sheet 5.8. Mount Edgecombe: SASRI.

South African Sugarcane Research Institute. April 1998. *Minimum tillage.* Information Sheet 4.10. Mount Edgecombe: SASRI.

South African Sugarcane Research Institute. April 2000. *Soil quality and degradation.* Information Sheet 14.1. Mount Edgecombe: SASRI.

South African Sugarcane Research Institute. 2004. *Soil Sustainability Interest Group.* Mount Edgecombe: SASRI.

South African Sugarcane Research Institute. October 2007. *Soil compaction management.* Information Sheet 14.4. Mount Edgecombe: SASRI.

South African Sugarcane Research Institute. 2008. SUSFARMS® *Sustainable Sugarcane Farm Management System*. Version 1. Mount Edgecombe: SASRI.

South African Sugarcane Research Institute. October 2010a. *Green manuring.* Information Sheet 14.2 Mount Edgecombe: SASRI.

South African Sugarcane Research Institute. December 2010b. *The pros and cons of trashing or burning at harvest*. Information Sheet 4.7. Mount Edgecombe: SASRI.

South African Sugarcane Research Institute. 2012. SUSFARMS® *Sustainable Sugarcane Farm Management System*. Version 2. Mount Edgecombe: SASRI.

Sturz, A.V. & Christie, B.R. 2003. Beneficial microbial allelopathies in the root zone: the management of soil quality and plant disease with rhizobacteria. *Soil and Tillage Research*, Elsevier, 72(2) : 107-123.

Sullivan, P. 2003. *Applying the Principles of Sustainable Farming.* [Online]. ATTRA : National sustainable agriculture information service. Available: https://attra.ncat.org/attra-pub/viewhtml.php?id=295. [2013, 13 March].

Sumner, M, E. 2011. Out of sight out of mind : subsurface factors in sugarcane yield decline. *Proceedings of the South African Sugar Technologists' Association*, 84 : 1-27.

Swilling, M. & Annecke, E. 2012. *Just transitions : explorations of sustainability in an unfair world.* Cape Town: UCT Press.

Swinford, J.M. & Boevey, T.M.C. 1984. The effects of soil compaction due to infield transport on ratoon cane yields and soil physical characteristics. *Proceedings of the South African Sugar Technologists' Association*, 58 : 198-203.

Taylor, D. & Proctor, M. 2008. *The literature review: a few tips on conducting it.* [Online]. University of Toronto. Available: http://www.utoronto.ca/writing/litrev.html. [2009, 15 April].

The South African Pocket Oxford Dictionary. 1994. 2nd South African edition. Cape Town: Oxford University Press.

Thompson, G.D. 1965. Mulching in sugarcane. Unpublished PhD thesis. Pietermaritzburg: University of Natal.

Thomson, D.N. 2010. Enhancing small-scale grower sustainability through institutional change. *Proceedings of the South African Sugar Technologists' Association*, 83 : 122-135.

Tilman, D., Cassman, K.G., Matson, P.A. & Naylor, R. 2002. Agricultural sustainability and intensive production practices. *Nature International Journal of Science*, 418 : 671-677.

Tucker, T. 2000. *Should'nt we be trashing more, like we used to?* South African Sugarcane Research Institute, The Link, Vol.9, No.2, 6-7.

Tweddle, P. 2012. *Minimum tillage mechanical planters.* South African Sugarcane Research Institute, The Link, Vol.21, No.3, 12-13.

Unica. 2012. *Sugarcane Agroecological Zoning* [Online]. Available: http://www.unica.com.br/downloads/sugarcane-agroecological-zoning.pdf. [2012, 12 July].

United Nations Environmental Programme (UNEP). 2009. *The environmental food crisis - The environment's role in averting future food crises.* Norway: Birkeland Trykkeri AS.

van Antwerpen, R. 2002. *Crop rotation. A way to manage yield decline.* South African Sugarcane Research Institute, The Link, Vol.11, No.2, 1.

van Antwerpen, R, 2005. A review of soil health indicators for laboratory use in the South African sugar industry. *Proceedings of the South African Sugar Technologists' Association*, 79 : 179-191.

van Antwerpen, R. 2006. *Is minimum tillage still relevant?* South African Sugarcane Research Institute, The Link, Vol.15, No.3, 4–5.

van Antwerpen, R., Berry, S.D., van Antwerpen, T., Sewpersad & Cadet, P. 2009. Indicators of Soil Health for use in the South African sugar industry. *Proceedings of the South African Sugar Technologists' Association*, 82 : 551-563.

van Antwerpen, R., Haynes, R.J., Meyer, J.H. & Hlanze, D. 2003a. Assessing organic amendments used by sugarcane growers for improving soil chemical and biological properties. *Proceedings of the South African Sugar Technologists' Association*, 77 : 293-304.

van Antwerpen, R., Haynes, R.J., Meyer, J.H., Qongqo, L.L., Dominy, C.S. & Hlanze, D. 2003b. The effect of management on soil organic matter and other soil properties in the South African sugar industry. *Proceedings of the Soil Science Society of South Africa. 24th congress, Stellenbosch.*

van Antwerpen, R. & Meyer, J.H. 1996. Soil degradation under sugar cane cultivation in northern KwaZulu-Natal. *Proceedings of the South African Sugar Technologists' Association,* 70 : 29-33.

van Antwerpen, R. & Meyer, J.H. 1998. Soil degradation II: Effects of trash and inorganic fertiliser application on soil strength. *Proceedings of the South African Sugar Technologists' Association*, 72 : 152-158.

van Antwerpen, R., Meyer, J.H. & Thompson, G. 2006. The impact of trashing on yield response in the South African sugar industry: A summary of results from several BT trials. *Proceedings of the South African Sugar Technologists' Association*, 80 : 130-135.

van Antwerpen, R., Thorburn, P.J., Horan.H., Meyer, J.H. & Bezuidenhout, C.N. 2002. The impact of trashing on soil carbon and nitrogen : implications for sugarcane production in South Africa. *Proceedings of the South African Sugar Technologists' Association*, 76 : 269-279.

van Antwerpen, T. 2006. *Spotlight on the soil food web*. South African Sugarcane Research Institute, The Link, Vol.15, No.2, 4-5.

van Der Laan, M. & Miles, N. 2010. Nutrition of the South African sugar crop: current status and long-term trends. *Proceedings of the South African Sugar Technologists' Association*, 83 : 195-204.

Wardle, D.A. 2002. *Communities and Ecosystems: Linking the Aboveground and Belowground Components.* Princeton: Princeton University Press.

Watt, D. & Snyman, S. 2011. *Sugarcane Biotechnology: Where are we?* South African Sugarcane Research Institute, The Link, Vol.20, No.2, 1-2.

Wijeratna, A. 2012. *Fed up. Now's the time to invest in agroecology*. Actionaid. [Online]. Available: http://www.actionaid.org/sites/files/actionaid/fed_up_-_nows_the_time_to_invest_in_agroecology.pdf. [2015, 1 September].

World Business Council for Sustainable Development. 2008. *Agricultural ecosystems facts and trends.* Switzerland: Atar roto presse SA.

World Commission on Environment and Development (WCED). 1987. *Our Common Future.* Oxford: Oxford University Press.

Young, M. & Crawford, J.W. 2004. Interactions and Self-Organization in the Soil-Microbe Complex. *Science*, 304(5677) : 1634-1637.

Appendices

Appendix A: Farmer questionnaire - page 1

Name	
Age	
Gender	
Tertiary education	

	Farm 1	**Farm 2**	**Farm 3**	**Farm 4**
Farm name				
Geographical location				
How long has family been on the farm?				
How long have you farmed the farm as owner manager?				
How long have you farmed the farm as farm manager?				

	Area (ha)	**Area (ha)**	**Area (ha)**	**Area (ha)**
Total farm size				
ha under sugarcane production				
ha under other agricultural production				
ha under conservation				
ha under pasture				

Average long-term rainfall mm	
Dominant soil type	

Over time, my long-term average sugarcane yields have	Increased	Static	Decreased	Time period

Soil quality is an important criteria to manage on my farm	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
I would like my soil quality to improve with time.	Yes	No	Undecided		
I would like to adopt more soil quality improvement principles.	Yes	No	Undecided		

I require more information on the causes of soil quality deterioration	Yes	No	Undecided
I require more information on practices to improve soil quality	Yes	No	Undecided

Appendix B: Farmer questionnaire - page 2

Social networks and learning structure

Where did you source most of your information from on strategies to improve soil quality ?	SASRI extension officer	Textbo oks	Internet	SAS RI	Other
Do you belong to a farmer's association?	Yes	No			
Do you belong to a study group ?	Yes	No			
Do you belong to other sugarcane farming learning organisations ?	Yes	No			
How often do you speak to other farmers about soil quality ?	Often	Someti mes	Never		
Have you attended farmers days or short courses on soil quality ?	Yes	No	If yes, where?		

How do you monitor soil quality ? Rate 1-5.	**1 = main, 5 = minor**
Sugarcane crop yield / ha	
Soil samples	
Pests and disease	
Field observation / walking in the lands	
Other indicators	
Other indicators	
Other indicators	
Other indicators	

How much do you know about Conservation Agriculture?	Expert	A lot	Reason able	Littl e	Nothi ng
How much do you know about Agro-ecology?	Expert	A lot	Reason able	Littl e	Nothi ng

Appendix C: Farmer questionnaire - page 3

Please rate what you believe to be the main causes of soil degradation on your farm (rank at least 5 causes).	**Main cause = 1** **5th worst = 5**
Farming practices Monocropping Excessive tillage Burning at harvest Insufficient water drainage Herbicide applications Inorganic fertiliser applications High yielding varieties No livestock factor on land	
Soil chemical properties Soil acidity Loss of organic carbon Soil salinity / sodicity Insufficient plant available nutrients Soil nutrient imbalance	
Soil physical properties Soil compaction Soil crusting Soil structure breakdown Soil erosion Low soil water infiltration Low soil water holding capacity	
Soil biological properties Low microbial biomass Low microbial diversity Lack of earthworms Parasitic nematodes	
Other	

Appendix D: Farmer questionnaire - page 4

What farming practices do you implement or have implemented in the past, to improve soil quality?	**Cur rentl y**	**Pas t**	**Why discontin ued ?**
<u>Conservation Agriculture and Agro-ecological practices</u>			
Green cane harvesting			
Green manure plant fields - break crop.			
Green manure. Single crop.			
Green manure. Double crop.			
Green manure. Leave mulch on soil surface.			
Green manure. Use legumes.			
Green manure. For allelopathy.			
Green manure. Promote microbial life.			
Green manure. Reduce weed pressures.			
Ley crop			
Intercrop			
Crop rotation			
Controlled traffic			
Minimum tillage			
Control nematodes - plant green manures with nematicidal properties			
Integrated Pest Management			
<u>Agro-ecological practices</u>			
Spread burnt cane residues after harvest.			
Green manure. Disced or ploughed in.			
Green manure. Bale / remove the crop for livestock.			
Green manure. Graze livestock on the crop.			
Bare fallow before re-planting			
Lime and / or gypsum applications			
Vertical Mulching			
Apply animal manures - which one?			
Apply plant compost			
Nutrient recycling - filterpress, flyash, CMS ?			
Livestock integration			
Strip harvesting			
Implement Land Use Plan			
Ripping compacted plant lands			
Control nematodes - nematicide as last resort			
Control nematodes - tolerant varieties			
Control nematodes - increase soil organic matter			
Precision Agriculture - grid sampling, soil corrections, and managing soil according to its potential			
Manage nitrogen rates and application timing			
Optimum fertiliser rates, placement and timing.			

Appendix E: Farmer questionnaire – page 5

What farming practices are you considering implementing to improve soil quality?	**Practices under considerati on?**	**What constraints are holding you back?**
<u>Conservation Agriculture and Agro-ecological practices</u>		
Green cane harvesting		
Green manure plant fields - break crop.		
Green manure. Single crop.		
Green manure. Double crop.		
Green manure. Leave mulch on soil surface.		
Green manure. Use legumes.		
Green manure. For allelopathy.		
Green manure. Promote microbial life.		
Green manure. Reduce weed pressures.		
Ley crop		
Intercrop		
Crop rotation		
Controlled traffic		
Minimum tillage		
Control nematodes - plant green manures with nematicidal properties		
Integrated Pest Management		
<u>Agro-ecological practices</u>		
Spread burnt cane residues after harvest.		
Green manure. Disced or ploughed in.		
Green manure. Bale / remove the crop for livestock.		
Green manure. Graze livestock on the crop.		
Bare fallow before re-planting		
Lime and / or gypsum applications		
Vertical Mulching		
Apply animal manures - which one?		
Apply plant compost		
Nutrient recycling - filterpress, flyash, CMS ?		
Livestock integration		
Strip harvesting		
Implement Land Use Plan		
Ripping compacted plant lands		
Control nematodes - nematicide as last resort		
Control nematodes - tolerant varieties		
Control nematodes - increase soil organic matter		
Precision Agriculture - grid sampling, soil corrections, and managing soil according to it's potential		
Manage nitrogen rates and application timing		
Optimum fertiliser rates, placement and timing.		

Appendix F: Farmer questionnaire - page 6

What farming practices will you not implement to improve soil quality ?	**Practices will not implement ?**	**Reasons why ?**
<u>Conservation Agriculture and Agro-ecological practices</u>		
Green cane harvesting		
Green manure plant fields - break crop.		
Green manure. Single crop.		
Green manure. Double crop.		
Green manure. Leave mulch on soil surface.		
Green manure. Use legumes.		
Green manure. For allelopathy.		
Green manure. Promote microbial life.		
Green manure. Reduce weed pressures.		
Ley crop		
Intercrop		
Crop rotation		
Controlled traffic		
Minimum tillage		
Control nematodes - plant green manures with nematicidal properties		
Integrated Pest Management		
<u>Agro-ecological practices</u>		
Spread burnt cane residues after harvest.		
Green manure. Disced or ploughed in.		
Green manure. Bale / remove the crop for livestock.		
Green manure. Graze livestock on the crop.		
Bare fallow before re-planting		
Lime and / or gypsum applications		
Vertical Mulching		
Apply animal manures - which one?		
Apply plant compost		
Nutrient recycling - filterpress, flyash, CMS ?		
Livestock integration		
Strip harvesting		
Implement Land Use Plan		
Ripping compacted plant lands		
Control nematodes - nematicide as last resort		
Control nematodes - tolerant varieties		
Control nematodes - increase soil organic matter		
Precision Agriculture - grid sampling, soil corrections, and managing soil according to its potential		
Manage nitrogen rates and application timing		
Optimum fertiliser rates, placement and timing.		

Appendix G: Farmer questionnaire - page 7

What are the main barriers of adoption, stopping you from implementing more practices to improve soil quality?	**Main barriers of adoption?**
Economic / financial Management time constraints Don't believe benefits will outweigh costs Insufficient knowledge Shortage of manpower or equipment Other Practical field trials	

What prompted you to initially implement soil quality improvement practices?	

Why did you choose the particular soil quality practices you have adopted?	

Which soil quality practice that you have adopted, do you believe has improved soil quality the most?	

Which soil quality practice that you have adopted, do you believe has had the second best result in improving soil quality?	

In your opinion, which soil quality practice is in most need of urgent research and development?	

Do you believe more farmers will adopt a range of soil quality practices, if they are promoted under a Conservation Agriculture, or Agro-ecology farming system package, rather than ad-hoc adoption of individual farming practices ?	

Do you believe more farmers will adopt a range of soil quality practices, if a package of best practices are recommended, based on the dominant soil and climate of a particular region ?	

Would you be willing to pay a soil quality consultant, to advise you on the best, site-specific practices, to improve soil quality on your farm ?	

Do you believe a soil health specific test, would be beneficial to you, to manage soils on your farm?	

Appendix H: Farmer 1 interview write-up

Name	1
Age	47
Gender	Male
Tertiary education	B Comm(Honours). [Masters in Sustainable Agriculture - Incomplete].

	Farm 1	**Farm 2**	**Farm 3**	**Farm 4**
Farm name	Home Farm			
Geographical location	Eston			
How long has family been on the farm?	55 years			
How long have you farmed the farm as owner manager?	5 years			
How long have you farmed the farm as farm manager?	16 years			

	Area (ha)	**Area (ha)**	**Area (ha)**	**Area (ha)**
Total farm size	854 ha			
ha under sugarcane production	500 ha			
ha under other agricultural production	300 ha			
ha under conservation	3 ha			
ha under pasture				

Average long-term rainfall mm	750 mm			
Dominant soil type	Lower Ecca			

Over time, my long-term average sugarcane yields have	Increased	Static **X**	Decreased	Time period **35 years**
Over time, my long-term average sugarcane yields have	Increased	Static	Decreased **X**	Time period **5 years (erratic rainfall, hail)**

Soil quality is an important criteria to manage on your farm	Strongly agree **X**	Agree	Neutral	Disagree	Strongly disagree
I would like my soil quality to improve with time.	Yes **X**	No	Undecided		
I would like to adopt more soil quality improvement principles.	Yes **X**	No	Undecided		

I require more information on the causes of soil quality deterioration	Yes **X**	No	Undecided
I require more information on practices to improve soil quality	Yes **X**	No	Undecided

Social networks and learning structure

Where did you source most of your information from on strategies to improve soil quality?	SASRI extension officer	Textbooks **X**	Internet	SASRI	Acres USA **X**
Do you belong to a farmer's association?	Yes **X**	No			
Do you belong to a study group ?	Yes	No **X**			
Do you belong to other sugarcane farming learning organisations?	Yes	No **X**	If yes, what ?		
How often do you speak to other farmers about soil quality?	Often	Sometimes **X**	Never		
Have you attended farmers' days or short courses on soil quality?	Yes **X**	No	If yes, where ? **SASRI, NTS courses, Biological Farming.**		

How do you monitor soil quality? Rate 1-5.	**1 = main, 5 = minor**
Sugarcane crop yield / ha	**1**
Soil samples - **SASRI & Brookside laboratory (Albrecht System)**	**2**
Pests and disease	
Field observation / walking in the lands	
Other indicators	
Other indicators	
Other indicators	
Other indicators	

How much do you know about Conservation Agriculture?	Expert	A lot **X**	Reasonable	Little	Nothing
How much do you know about Agro-ecology?	Expert	A lot **X**	Reasonable	Little	Nothing

Please rate what you believe to be the main causes of soil degradation on your farm (rank at least 5 causes).	**Main cause = 1 5th worst = 5**
Farming practices	
Monocropping	
Excessive tillage	
Burning at harvest	
Insufficient water drainage	
Herbicide applications	
Inorganic fertiliser applications	**5**
High yielding varieties	
No livestock factor on land	
Soil chemical properties	
Soil acidity	
Loss of organic carbon	
Soil salinity / sodicity	
Insufficient plant available nutrients	
Soil nutrient imbalance	**1**
Soil physical properties	
Soil compaction	**2**
Soil crusting	
Soil structure breakdown	
Soil erosion	
Low soil water infiltration	
Low soil water holding capacity	
Soil biological properties	
Low microbial biomass	**3**
Low microbial diversity	**4**
Lack of earthworms	
Parasitic nematodes	
Other	

What farming practices do you implement, and have implemented in the past, to improve soil quality ?	Currently	Past	Why discontinued ?
<u>**Conservation Agriculture and Agro-ecological practices**</u>			
Green cane harvesting			
Green manure plant fields - break crop.	X		
Green manure. Single crop.	X		
Green manure. Double crop.	X		
Green manure. Leave mulch on soil surface.		X	Good seedbed more important. Move K down the profile.
Green manure. Use legumes.			
Green manure. For allelopathy.			
Green manure. Promote microbial life.			
Green manure. Reduce weed pressures.	X		
Ley crop			
Intercrop			
Crop rotation - **occasionally maize**	X		
Controlled traffic			
Minimum tillage		X	Require a good seedbed.
Control nematodes - plant green manures with nematicidal properties			
Integrated Pest Management			
<u>**Agro-ecological practices**</u>			
Spread burnt cane residues after harvest.			
Green manure. Disced or ploughed in.	X		
Green manure. Bale / remove the crop for livestock.			
Green manure. Graze livestock on the crop.	X		
Bare fallow before re-planting.			
Lime and / or gypsum applications	X		
Vertical Mulching			
Apply animal manures - which one? **Chicken litter.**	X		
Apply plant compost			
Nutrient recycling - product? **Vinasse.**	X		
Livestock integration			
Strip harvesting			
Implement Land Use Plan	X		
Ripping compacted plant lands	X		
Control nematodes - nematicide as last resort			
Control nematodes - tolerant varieties			
Control nematodes - increase soil organic matter	X		
Precision Agriculture - grid sampling, soil corrections, and managing soil according to its potential			
Manage nitrogen rates and application timing			
Optimum fertiliser rates, placement and timing			
Vermi-compost		X	

What farming practices are you considering to implement to improve soil quality?	**Practices under consideration?**	**What constraints are holding you back ?**
<u>Conservation Agriculture and Agro-ecological practices</u>		
Green cane harvesting	X	Lack of practical solution. Need whole stick green cane harvester.
Green manure plant fields - break crop.		
Green manure. Single crop.		
Green manure. Double crop.	X	Not sure of economics.
Green manure. Leave mulch on soil surface.		
Green manure. Use legumes.	X	Already excess nitrogen from chicken litter.
Green manure. For allelopathy.	X	Not sure of benefit.
Green manure. Promote microbial life.		
Green manure. Reduce weed pressures.		
Ley crop		
Intercrop		
Crop rotation	X	If viable crop found to economically rotate with sugarcane.
Controlled traffic	X	Tramlines planted - machinery not set up yet.
Minimum tillage		
Control nematodes - plant green manures with nematicidal properties		
Integrated Pest Management	X	Not got there yet.
<u>Agro-ecological practices</u>		
Spread burnt cane residues after harvest.		
Green manure. Disced or ploughed in.		
Green manure. Bale / remove the crop for livestock.		
Green manure. Graze livestock on the crop.		
Bare fallow before re-planting.		
Lime and / or gypsum applications		
Vertical Mulching		
Apply animal manures - which one?		
Apply plant compost	X	Shortage of plant material. Haven't investigated seriously.
Nutrient recycling - product?	X	Use filterpress in the future.
Livestock integration	X	Labour and fencing constraints. Will consider if green cane harvest.
Strip harvesting		
Implement Land Use Plan		
Ripping compacted plant lands		
Control nematodes - nematicide as last resort		
Control nematodes - tolerant varieties		
Control nematodes - increase soil organic matter		
Precision Agriculture - grid sampling, soil corrections, and managing soil according to its potential		
Manage nitrogen rates and application timing		
Optimum fertiliser rates, placement and timing		

Other - Green manure. Specific crops to solubilise P & K nutrients.	X	

What farming practices will you not implement to improve soil quality?	**Practices will not implement ?**	**Reasons why?**
<u>Conservation Agriculture and Agro-ecological practices</u>		
Green cane harvesting		
Green manure plant fields - break crop.		
Green manure. Single crop.		
Green manure. Double crop.		
Green manure. Leave mulch on soil surface.		
Green manure. Use legumes.		
Green manure. For allelopathy.		
Green manure. Promote microbial life.		
Green manure. Reduce weed pressures.		
Ley crop	**X**	Economics not right.
Intercrop		
Crop rotation		
Controlled traffic		
Minimum tillage		
Control nematodes - plant green manures with nematicidal properties		
Integrated Pest Management		
<u>Agro-ecological practices</u>		
Spread burnt cane residues after harvest.		
Green manure. Disced or ploughed in.		
Green manure. Bale / remove the crop for livestock.		
Green manure. Graze livestock on the crop.		
Bare fallow before re-planting.	**X**	Green manure assists in killing previous crop of sugarcane.
Lime and / or gypsum applications		
Vertical Mulching	**X**	Too slow / labour committed elsewhere.
Apply animal manures - which one?		
Apply plant compost		
Nutrient recycling - product?		
Livestock integration		
Strip harvesting	**X**	Not interested.
Implement Land Use Plan		
Ripping compacted plant lands		
Control nematodes - nematicide as last resort	**X**	No nematode problems.
Control nematodes - tolerant varieties		
Control nematodes - increase soil organic matter		
Precision Agriculture - grid sampling, soil corrections, and managing soil according to it's potential		
Manage nitrogen rates and application timing		
Optimum fertiliser rates, placement and timing		

Other		

What are the main barriers of adoption, stopping you from implementing more practices to improve soil quality?	**Main barriers of adoption?**
Economic / financial	**1**
Management time constraints	**2**
Don't believe benefits will outweigh costs	
Insufficient knowledge	**3**
Shortage of manpower or equipment	**4**
Other	
Practical field trials	

What prompted you to initially implement soil quality improvement practices?	Reading the magazine Acres USA.
Why did you choose the particular soil quality practices you have adopted?	Own research and courses attended.
Which soil health practice that you have adopted, do you believe has improved soil quality the most?	Chicken litter - but concerned about nutrient imbalances.
Which soil quality practice that you have adopted, do you believe has had the second best result in improving soil quality?	Green manuring.
In your opinion, which soil quality practice is in most need of urgent research and development?	Soil nutrient balancing and soil biological life.
Do you believe more farmers will adopt a range of soil quality practices, if they are promoted under a Conservation Agriculture, or Agro-ecology farming system package, rather than ad-hoc adoption of individual farming practices?	Yes.
Do you believe more farmers will adopt a range of soil quality practices, if a package of best practices are recommended, based on the dominant soil and climate of a particular region?	Yes.

Would you be willing to pay a soil quality consultant, to advise you on the best, site-specific practices, to improve soil quality on your farm?	Absolutely yes.

Do you believe a soil health specific test, would be beneficial to you, to manage soils on your farm?	Yes.

Appendix I: Farmer 2 interview write-up

Name	2
Age	59
Gender	Male
Tertiary education	Diploma in Agriculture

	Farm 1	Farm 2	Farm 3	Farm 4
Farm name	Home farm			
Geographical location	Richmond			
How long has family been on the farm?	57 years			
How long have you farmed the farm as owner manager?	32 years			
How long have you farmed the farm as farm manager?				

	Area (ha)	Area (ha)	Area (ha)	Area (ha)
Total farm size	928			
ha under sugarcane production	350			
ha under other agricultural production - timber	400			
ha under conservation	120			
ha under pasture	40			

Average long-term rainfall mm	820 mm			
Dominant soil type	TMS derived			

Over time, my long-term average sugarcane yields have	Increased	Static	Decreased **X**	Time period **57 years**

Soil quality is an important criteria to manage on your farm	Strongly agree **X**	Agree	Neutral	Disagree	Strongly disagree
I would like my soil quality to improve with time.	Yes **X**	No	Undecided		
I would like to adopt more soil quality improvement principles.	Yes **X**	No	Undecided		

I require more information on the causes of soil quality deterioration	Yes	No	Not really **X**
I require more information on practices to improve soil quality	Yes **X**	No	Undecided

Social networks and learning structure

Where did you source most of your information from on strategies to improve soil quality?	SASRI extension officer **X**	Textbooks	Internet	SASRI **X**	Other
Do you belong to a farmer's association?	Yes **X**	No			
Do you belong to a study group?	Yes **X**	No			
Do you belong to other sugarcane farming learning organisations ?	Yes	No **X**	If yes, what?		
How often do you speak to other farmers about soil quality ?	Often **X**	Sometimes	Never		
Have you attended farmers' days or short courses on soil quality?	Yes **X**	No	If yes, where? **SASRI**		

How do you monitor soil quality ?	**Monitoring tools**
Sugarcane crop yield / ha	
Soil samples	**X**
Pests and disease	
Field observation / walking in the lands	**X**
Other indicators	
Other indicators	
Other indicators	
Other indicators	

How much do you know about Conservation Agriculture?	Expert	A lot **X**	Reasonable	Little	Nothing
How much do you know about Agro-ecology?	Expert	A lot **X**	Reasonable	Little	Nothing

What you believe to be the main causes of soil degradation on your farm ?	Causes
<u>Farming practices</u>	
Monocropping	X
Excessive tillage	X
Burning at harvest	
Insufficient water drainage	
Herbicide applications	
Inorganic fertiliser applications	X
High yielding varieties	
No livestock factor on land	
<u>Soil chemical properties</u>	
Soil acidity	X
Loss of organic carbon	
Soil salinity / sodicity	
Insufficient plant available nutrients	
Soil nutrient imbalance	X
<u>Soil physical properties</u>	
Soil compaction	
Soil crusting	
Soil structure breakdown	
Soil erosion	
Low soil water infiltration	
Low soil water holding capacity	
<u>Soil biological properties</u>	
Low microbial biomass	
Low microbial diversity	
Lack of earthworms	
Parasitic nematodes	
Other - **hot vs cold sugarcane burns**	
Other - **lack of surface crop residue**	X

What farming practices do you implement, and have implemented in the past, to improve soil quality ?	**Currently**	**Past**	**Why discontinued?**
Conservation Agriculture and Agro-ecological practices			
Green cane harvesting			
Green manure plant fields - break crop. **Doing for 4 years.**	**X**		
Green manure. Single crop. **Winter - Morgan Oats & Black Oats.**	**X**		
Green manure. Double crop.			
Green manure. Mulch on surface.	**X**		
Green manure. Use legumes.	**X**		
Green manure. For allelopathy.	**X**		
Green manure. Promote microbial life.			
Green manure. Reduce weed pressures.			
Ley crop			
Intercrop			
Crop rotation			
Controlled traffic			
Minimum tillage			
Control nematodes - plant green manures with nematicidal properties	**X**		
Integrated Pest Management	**X**		
Agro-ecological practices			
Spread burnt cane residues after harvest.	**X**		
Green manure. Disced or ploughed in.			
Green manure. Bale / remove the crop for livestock.	**X**		
Green manure. Graze livestock on the crop.	**X**		
Bare fallow before re-planting			
Lime and / or gypsum applications	**X**		
Vertical Mulching			
Apply animal manures - which ones? **Broiler litter.**	**X**		
Apply plant compost			
Nutrient recycling - filterpress, flyash, CMS?	**X**		
Livestock integration			
Strip harvesting	**X**		
Implement Land Use Plan	**X**		
Ripping compacted plant lands	**X**		
Control nematodes - nematicide as last resort	**X**		
Control nematodes - tolerant varieties	**X**		
Control nematodes - increase soil organic matter	**X**		
Precision Agriculture - grid sampling, soil corrections, and managing soil according to its potential			
Manage nitrogen rates and application timing	**X**		
Optimum fertiliser rates, placement and timing	**X**		
Other			

What farming practices are you considering to implement to improve soil quality ?	Practices under considerati on?	What constraints are holding you back?
<u>Conservation Agriculture and Agro-ecological practices</u>		
Green cane harvesting	X	Green cane harvesting machinery. Sugar mill cannot handle billet cane.
Green manure plant fields - break crop.		
Green manure. Single crop.		
Green manure. Double crop.	X	Less area under cane. Disrupt cutting cycle-strip harvesting. Cost vs benefit?
Green manure. Leave mulch on soil surface.		
Green manure. Use legumes.		
Green manure. For allelopathy.		
Green manure. Promote microbial life.		
Green manure. Reduce weed pressures.		
Ley crop		
Intercrop		
Crop rotation		
Controlled traffic		
Minimum tillage		
Control nematodes - plant green manures with nematicidal properties		
Integrated Pest Management		
<u>Agro-ecological practices</u>		
Spread burnt cane residues after harvest.		
Green manure. Disced or ploughed in.		
Green manure. Bale / remove the crop for livestock.		
Green manure. Graze livestock on the crop.		
Bare fallow before re-planting		
Lime and / or gypsum applications		
Vertical Mulching		
Apply animal manures - which ones?		
Apply plant composts		
Nutrient recycling - filterpress, flyash, CMS?		
Livestock integration		
Strip harvesting		
Implement Land Use Plan		
Ripping compacted plant lands		
Control nematodes - nematicide as last resort		
Control nematodes - tolerant varieties		
Control nematodes - increase soil organic matter		
Precision Agriculture - grid sampling, soil corrections, and managing soil according to its potential		
Manage nitrogen rates and application timing		
Optimum fertiliser rates, placement and timing		
Other		

What farming practices will you not implement to improve soil quality?	Practices will not implement?	Reasons why?
Conservation Agriculture and Agro-ecological practices		
Green cane harvesting		
Green manure plant fields - break crop.		
Green manure. Single crop.		
Green manure. Double crop.		
Green manure. Leave mulch on soil surface.		
Green manure. Use legumes.		
Green manure. For allelopathy.		
Green manure. Promote microbial life.		
Green manure. Reduce weed pressures.		
Ley crop		
Intercrop	**X**	Not practical.
Crop rotation		
Controlled traffic		
Minimum tillage		
Control nematodes - plant green manures with nematicidal properties		
Integrated Pest Management		
Agro-ecological practices		
Spread burnt cane residues after harvest.		
Green manure. Disced or ploughed in.		
Green manure. Bale / remove the crop for livestock.		
Green manure. Graze livestock on the crop.		
Bare fallow before re-planting		
Lime and / or gypsum applications		
Vertical Mulching		
Apply animal manures - which ones?		
Apply plant composts		
Nutrient recycling - filterpress, flyash, CMS?		
Livestock integration		
Strip harvesting		
Implement Land Use Plan		
Ripping compacted plant lands		
Control nematodes - nematicide as last resort		
Control nematodes - tolerant varieties		
Control nematodes - increase soil organic matter		
Precision Agriculture - grid sampling, soil corrections, and managing soil according to its potential		
Manage nitrogen rates and application timing		
Optimum fertiliser rates, placement and timing		
Other		

What are the main barriers of adoption, stopping you from implementing more practices to improve soil quality ?	**Main barriers of adoption ?**
Economic / financial	X
Management time constraints	X
Don't believe benefits will outweigh costs	
Insufficient knowledge	
Shortage of manpower or equipment	
Other	
Practical field trials	X

What prompted you to initially implement soil quality improvement practices?	New virgin sugarcane lands are more productive than old established lands. Why?

Why did you choose the particular soil quality practices you have adopted?	Use existing farm equipment and labour. Not highly specialised - are easy to implement. Practically fit into the existing farm system.

Which soil quality practice that you have adopted, do you believe has improved soil quality the most?	Inorganic fertiliser (broiler litter) and lime.

Which soil quality practice that you have adopted, do you believe has had the second best result in improving soil quality?	Green manures. Ridging and planting into the green manure crop / residue.

In your opinion, which soil quality practice is in most need of urgent research and development?	Optimum time period that green manure crop/s should be grown for . Long-term sugarcane yield gain vs yield loss, following green manuring.

Do you believe more farmers will adopt a range of soil quality practices, if they are promoted under a Conservation Agriculture, or Agro-ecology farming system package, rather than ad-hoc adoption of individual farming practices?	SASRI'S SUSFARMS initiative should achieve this goal. It takes a holistic approach, and the triple bottom line into account.

Do you believe more farmers will adopt a range of soil quality practices, if a package of best practices are recommended, based on the dominant soil and climate of a particular region?	The SUSFARMS initiative will accommodate industry wide, and farm level recommendations.

Would you be willing to pay a soil quality consultant, to advise you on the best, site-specific practices, to improve soil health on your farm?	Will source information from the SASRI Extension Officer, and from SASRI.

Do you believe a soil health specific test, would be beneficial to you, to manage soils on your farm?	Yes, if it is correctly calibrated.

Appendix J: Farmer 3 interview write-up

Name	3
Age	35
Gender	Male
Tertiary education	Higher Diploma in Agriculture

	Farm 1	**Farm 2**	**Farm 3**	**Farm 4**
Farm name	Second farm	Home farm	Leased farm	
Geographical location	Eston	Eston	Richmond	
How long has family been on the farm?	50 years	8 years	8 year lease	
How long have you farmed the farm as owner manager?		8 years		
How long have you farmed the farm as farm manager?	5 years		8 years	

	Area (ha)	**Area (ha)**	**Area (ha)**	**Area (ha)**
Total farm size	200	440	900	
ha under sugarcane production	190	350	300	
ha under other agricultural production				
ha under conservation				
ha under pasture				

Average long-term rainfall mm	750 mm	750 mm	800 mm	
Dominant soil type	Dwyka	Dwyka	Humic	

Over time, my long-term average sugarcane yields have	Increased	Static **X**	Decreased	Time period **8 years**

Soil quality is an important criteria to manage on your farm	Strongly agree **X**	Agree	Neutral	Disagree	Strongly disagree
I would like my soil quality to improve with time.	Yes **X**	No	Undecided		
I would like to adopt more soil quality improvement principles.	Yes **X**	No	Undecided		

I require more information on the causes of soil quality deterioration	Yes **X**	No	Undecided
I require more information on practices to improve soil quality	Yes **X**	No	Undecided

Social networks and learning structure

Where did you source most of your information from on strategies to improve soil quality?	SASRI extension officer **X**	Textbooks	Internet	SASRI **X**	Other
Do you belong to a farmer's association?	Yes **X**	No			
Do you belong to a study group?	Yes **X**	No			
Do you belong to other sugarcane farming learning organisations?	Yes	No **X**	If yes, what?		
How often do you speak to other farmers' about soil quality?	Often **X**	Sometimes	Never		
Have you attended farmers days or short courses on soil quality?	Yes	No **X**	If yes, where?		

How do you monitor soil quality? Rate 1-5.	**1 = main, 5 = minor**
Sugarcane crop yield / ha	**1**
Soil samples	**2**
Pests and disease	**3**
Field observation / walking in the lands	
Other indicators - **sugarcane quality**	**4**
Other indicators - **number of ratoons**	**5**
Other indicators	
Other indicators	

How much do you know about Conservation Agriculture?	Expert	A lot	Reasonable **X**	Little	Nothing
How much do you know about Agro-ecology?	Expert	A lot	Reasonable	Little **X**	Nothing

Please rate what you believe to be the main causes of soil degradation on your farm (rank at least 5 causes).	**Main cause = 1 7 th worst = 7**
<u>Farming practices</u>	
Monocropping	**1**
Excessive tillage	**3**
Burning at harvest	
Insufficient water drainage	
Herbicide applications	**6**
Inorganic fertiliser applications	**5**
High yielding varieties	
No livestock factor on land	
<u>Soil chemical properties</u>	
Soil acidity	
Loss of organic carbon	**7**
Soil salinity / sodicity	
Insufficient plant available nutrients	
Soil nutrient imbalance	**4**
<u>Soil physical properties</u>	
Soil compaction	**2**
Soil crusting	
Soil structure breakdown	
Soil erosion	
Low soil water infiltration	
Low soil water holding capacity	
<u>Soil biological properties</u>	
Low microbial biomass	
Low microbial diversity	
Lack of earthworms	
Parasitic nematodes	
Other	

What farming practices do you implement, and have implemented in the past, to improve soil quality?	Currently	Past	Why discontinued ?
<u>Conservation Agriculture and Agro-ecological practices</u>			
Green cane harvesting			
Green manure plant fields - break crop.	X		
Green manure. Single crop.	X		
Green manure. Double crop.			
Green manure. Mulch on surface. **Sandy soils - minimum till.**	X		
Green manure. Use legumes.	X		
Green manure. For allelopathy.	X		
Green manure. Promote microbial life.			
Green manure. Reduce weed pressures.			
Ley crop			
Intercrop			
Crop rotation - **occasionally maize.**	X		
Controlled traffic			
Minimum tillage - **on slopes**	X		
Control nematodes - plant green manures with nematicidal properties	X		
Integrated Pest Management	X		
<u>Agro-ecological practices</u>			
Spread burnt cane residues after harvest.	X		
Green manure. Disced or ploughed in. **Heavier soils.**	X		
Green manure. Bale / remove the crop for livestock.		X	Lose the benefit.
Green manure. Graze livestock on the crop.			
Bare fallow before re-planting			
Lime and / or gypsum applications	X		
Vertical Mulching			
Apply animal manures - which one?			
Apply plant compost			
Nutrient recycling - **5 years CMS, 2 years filterpress**	X		
Livestock integration	X		
Strip harvesting	X		
Implement Land Use Plan	X		
Ripping compacted plant lands	X		
Control nematodes - nematicide as last resort			
Control nematodes - tolerant varieties			
Control nematodes - increase soil organic matter	X		
Precision Agriculture - grid sampling, soil corrections, and managing soil according to its potential		X	Cost. Not sure of benefits. Practical implementation.
Manage nitrogen rates and application timing	X		
Optimum fertiliser rates, placement and timing	X		
Other			

What farming practices are you considering implementing to improve soil quality?	Practices under consideration?	What constraints are holding you back?
<u>Conservation Agriculture and Agro-ecological practices</u>		
Green cane harvesting		
Green manure plant fields - break crop.		
Green manure. Single crop.		
Green manure. Double crop.	X	Will do. Summer - Mix Cowpeas / Sunnhemp / Sorghum. Winter - Oats.
Green manure. Leave mulch on soil surface.		
Green manure. Use legumes.		
Green manure. For allelopathy.		
Green manure. Promote microbial life.		
Green manure. Reduce weed pressures.		
Ley crop		
Intercrop		
Crop rotation	X	Irrigation.
Controlled traffic		
Minimum tillage	X	Soils must be corrected first.
Control nematodes - plant green manures with nematicidal properties		
Integrated Pest Management		
<u>Agro-ecological practices</u>		
Spread burnt cane residues after harvest.		
Green manure. Disced or ploughed in.		
Green manure. Bale / remove the crop for livestock.		
Green manure. Graze livestock on the crop.	X	Management of the cattle.
Bare fallow		
Lime and / or gypsum applications		
Vertical Mulching		
Apply animal manures - which ones ?		
Apply plant composts		
Nutrient recycling - filterpress, flyash, CMS?		
Livestock integration	X	Management of cattle
Strip harvesting		
Implement Land Use Plan		
Ripping compacted plant lands		
Control nematodes - nematicide as last resort		
Control nematodes - tolerant varieties		
Control nematodes - increase soil organic matter		
Precision Agriculture - grid sampling, soil corrections, and managing soil according to its potential	X	Cost
Manage nitrogen rates and application timing		
Optimum fertiliser rates, placement and timing		
Other		

What farming practices will you not implement to improve soil quality?	**Practices will not implement?**	**Reasons why?**
<u>Conservation Agriculture and Agro-ecological practices</u>		
Green cane harvesting	**X**	Labour unproductive.Too much trash on Midlands cane for manual harvest.
Green manure plant fields - break crop.		
Green manure. Single crop.		
Green manure. Double crop.		
Green manure. Leave mulch on soil surface.		
Green manure. Use legumes.		
Green manure. For allelopathy.		
Green manure. Promote microbial life.		
Green manure. Reduce weed pressures.		
Ley crop		
Intercrop	**X**	Not practical.
Crop rotation		
Controlled traffic		
Minimum tillage		
Control nematodes - plant green manures with nematicidal properties		
Integrated Pest Management		
<u>Agro-ecological practices</u>		
Spread burnt cane residues after harvest.		
Green manure. Disced or ploughed in.		
Green manure. Bale / remove the crop for livestock.	**X**	Nutrient loss.
Green manure. Graze livestock on the crop.		
Bare fallow	**X**	Soil erosion.
Lime and / or gypsum applications		
Vertical Mulching	**X**	Cost of fuel.
Apply animal manures - which ones?		
Apply plant composts		
Nutrient recycling - filterpress, flyash, CMS?		
Livestock integration		
Strip harvesting		
Implement Land Use Plan		
Ripping compacted plant lands		
Control nematodes - nematicide as last resort	**X**	No nematode problem.
Control nematodes - tolerant varieties		
Control nematodes - increase soil organic matter		
Precision Agriculture - grid sampling, soil corrections, and managing soil according to its potential		
Manage nitrogen rates and application timing		
Optimum fertiliser rates, placement and timing		
Other		

What are the main barriers of adoption, stopping you from implementing more practices to improve soil quality?	**Main barriers of adoption ?**
Economic / financial	
Management time constraints	**X**
Don't believe benefits will outweigh costs	
Insufficient knowledge	**X**
Shortage of manpower or equipment	
Other	
Practical field trials	

What prompted you to initially implement soil quality improvement practices?	Need to increase yields & ratoon length.

Why did you choose the particular soil quality practices you have adopted?	Are the most practical ones.

Which soil quality practice that you have adopted, do you believe has improved soil quality the most?	Green manuring.

Which soil quality practice that you have adopted, do you believe has had the second best result in improving soil quality?	Filterpress application. Applied at 80 ton/ha on plant lands only.

In your opinion, which soil quality practice is in most need of urgent research and development?	Organic products - nutrient content, nutrient availability, impact on *eldana* stem borer. Silicon availabilit y.

Do you believe more farmers will adopt a range of soil quality practices, if they are promoted under a Conservation Agriculture, or Agro-ecology farming system package, rather than ad-hoc adoption of individual farming practices?	Yes.

Do you believe more farmers will adopt a range of soil quality practices, if a package of best practices are recommended, based on the dominant soil and climate of a particular region?	Yes. Difficult to evaluate the different practices, and know their exact benefits.

Would you be willing to pay a soil quality consultant, to advise you on the best, site-specific practices, to improve soil health on your farm?	Yes.

Do you believe a soil health specific test, would be beneficial to you, to manage soils on your farm?	Yes.

Appendix K: Farmer 4 interview write-up

Name	4
Age	46
Gender	Male
Tertiary education	MBA; B.Ag Man.

	Farm 1	Farm 2	Farm 3	Farm 4
Farm name	Second farm	Home farm	Third farm	Part owned & leased
Geographical location	Eston	Eston	Eston	Eston
How long has family been on the farm?	100 years	20 years	10 years	142 years
How long have you farmed the farm as owner manager?	22 years	20 years	10 years	6 months
How long have you farmed the farm as farm manager?				

	Area (ha)	Area (ha)	Area (ha)	Area (ha)
Total farm size	442	324	244	1500
ha under sugarcane production	210	242	121	600
ha under other agricultural production - timber	20		20	50
ha under conservation - 350 ha game fenced in total.				
ha under pasture	20		20	25

Average long-term rainfall mm	840 mm
Dominant soil type	Cartref

Over time, my long-term average sugarcane yields have	Increased **X**	Static	Decreased	Time period 10 years

Soil quality is an important criteria to manage on your farm	Strongly agree **X**	Agree	Neutral	Disagree	Strongly disagree
I would like my soil quality to improve with time.	Yes **X**	No	Undecided		
I would like to adopt more soil quality improvement principles.	Yes **X**	No	Undecided		

I require more information on the causes of soil quality deterioration	Yes **X**	No	Undecided
I require more information on practices to improve soil quality	Yes **X**	No	Undecided

Social networks and learning structure

Where did you source most of your information from on strategies to improve soil quality?	SASRI extension officer **X**	Textbooks	Internet	SASRI **X**	Other
Do you belong to a farmer's association?	Yes **X**	No			
Do you belong to a study group?	Yes **X**	No			
Do you belong to other sugarcane farming learning organisations?	Yes **X**	No	**SASTA; S A Sugar Industry Agronomists Association**		
How often do you speak to other farmers' about soil quality?	Often **X**	Sometimes	Never		
Have you attended farmers days or short courses on soil quality?	Yes **X**	No	If yes, where? **SASRI**		

How do you monitor soil quality ? Rate 1-5.	**1 = main, 5 = minor**
Sugarcane crop yield / ha	**1**
Soil samples	**2**
Pests and disease	
Field observation / walking in the lands	
Other indicators	
Other indicators	
Other indicators	
Other indicators	

How much do you know about Conservation Agriculture?	Expert **X**	A lot	Reasonable	Little	Nothing
How much do you know about Agro-ecology?	Expert	A lot **X**	Reasonable	Little	Nothing

Please rate what you believe to be the main causes of soil degradation on your farm (rank at least 5 causes).	**Main cause = 1 5th worst = 5**
<u>Farming practices</u>	
Monocropping	**1**
Excessive tillage	**5**
Burning at harvest	
Insufficient water drainage	
Herbicide applications	
Inorganic fertiliser applications	
High yielding varieties	
No livestock factor on land	
<u>Soil chemical properties</u>	
Soil acidity	
Loss of organic carbon	
Soil salinity / sodicity	
Insufficient plant available nutrients	**3**
Soil nutrient imbalance	**3**
<u>Soil physical properties</u>	
Soil compaction	
Soil crusting	
Soil structure breakdown	
Soil erosion	**2**
Low soil water infiltration	
Low soil water holding capacity	
<u>Soil biological properties</u>	
Low microbial biomass	
Low microbial diversity	
Lack of earthworms	
Parasitic nematodes	
Other	

What farming practices do you implement, and have implemented in the past, to improve soil quality?	**Currently**	**Past**	**Why discontinued ?**
<u>Conservation Agriculture and Agro-ecological practices</u>			
Green cane harvesting			
Green manure plant fields - break crop.	**X**		
Green manure. Single crop.			
Green manure. Double crop.	**X**		
Green manure. Mulch on surface.	**X**		
Green manure. Use legumes.	**X**		
Green manure. For allelopathy.	**X**		
Green manure. Promote microbial life.	**X**		
Green manure. Reduce weed pressures.			
Ley crop			
Intercrop			
Crop rotation			
Controlled traffic		**X**	Causes more soil damage.
Minimum tillage	**X**		
Control nematodes - plant green manures with nematicidal properties			
Integrated Pest Management	**X**		
<u>Agro-ecological practices</u>			
Spread burnt cane residues after harvest.	**X**		
Green manure. Disced or ploughed in.			
Green manure. Bale / remove the crop for livestock.		**X**	Bale oats -not worth the hassle. Removing organic matter.
Green manure. Graze livestock on the crop.	**X**		
Bare fallow before re-planting.			
Lime and / or gypsum applications - **for calcium, magnesium & sulphur**	**X**		
Vertical Mulching			
Apply animal manures - **Chicken Litter on plant & balance on weak ratoon lands**	**X**		
Apply plant compost			
Nutrient recycling - filterpress, flyash, CMS ?		**X**	Vinasse. Too much effort for debatable results.
Livestock integration	**X**		
Strip harvesting	**X**		
Implement Land Use Plan	**X**		
Ripping compacted plant lands			
Control nematodes - nematicide as last resort		**X**	Products are too risky to use.
Control nematodes - tolerant varieties			
Control nematodes - increase soil organic matter	**X**		
Precision Agriculture - grid sampling, soil corrections, and managing soil according to its potential			
Manage nitrogen rates and application timing	**X**		
Optimum fertiliser rates, placement and timing. **SASRI exact.**	**X**		
Other			

What farming practices are you considering implementing **to improve soil quality ?**	**Practices under considerat ion?**	**What constraints are holding you back?**
<u>Conservation Agriculture and Agro-ecological practices</u>		
Green cane harvesting		
Green manure plant fields - break crop.		
Green manure. Single crop.		
Green manure. Double crop.		
Green manure. Mulch on surface.		
Green manure. Use legumes.		
Green manure. For allelopathy.		
Green manure. Promote microbial life.		
Green manure. Reduce weed pressures.		
Ley crop		
Intercrop		
Crop rotation		
Controlled traffic		
Minimum tillage		
Control nematodes - plant green manures with nematicidal properties		
Integrated Pest Management		
<u>Agro-ecological practices</u>		
Spread burnt cane residues after harvest.		
Green manure. Disced or ploughed in.		
Green manure. Bale / remove the crop for livestock.		
Green manure. Graze livestock on the crop.		
Bare fallow before re-planting.		
Lime and / or gypsum applications.		
Vertical Mulching		
Apply animal manures.		
Apply plant compost		
Nutrient recycling - filterpress, flyash, CMS ?		
Livestock integration		
Strip harvesting		
Implement Land Use Plan		
Ripping compacted plant lands	**X**	Depends on the economics.
Control nematodes - nematicide as last resort		
Control nematodes - tolerant varieties		
Control nematodes - increase soil organic matter		
Precision Agriculture - grid sampling, soil corrections, and managing soil according to its potential		
Manage nitrogen rates and application timing		
Optimum fertiliser rates, placement and timing		
Other - **would use an eco-friendly nematicide**	**X**	Availabili ty.

What farming practices will you not implement to improve soil quality?	Practices will not implement ?	Reasons why?
<u>Conservation Agriculture and Agro-ecological practices</u>		
Green cane harvesting		
Green manure plant fields - break crop.		
Green manure. Single crop.		
Green manure. Double crop.		
Green manure. Mulch on surface.		
Green manure. Use legumes.		
Green manure. For allelopathy.		
Green manure. Promote microbial life.		
Green manure. Reduce weed pressures.		
Ley crop		
Intercrop		
Crop rotation		
Controlled traffic	x	Causes more problems.
Minimum tillage		
Control nematodes - plant green manures with nematicidal properties		
Integrated Pest Management		
<u>Agro-ecological practices</u>		
Spread burnt cane residues after harvest.		
Green manure. Disced or ploughed in.		
Green manure. Bale / remove the crop for livestock.		
Green manure. Graze livestock on the crop.		
Bare fallow before re-planting.		
Lime and / or gypsum applications.	X	Will not apply for subsoil acidity - not economical.
Vertical Mulching		
Apply animal manures.		
Apply plant compost		
Nutrient recycling - filterpress, flyash, CMS?		
Livestock integration		
Strip harvesting		
Implement Land Use Plan		
Ripping compacted plant lands		
Control nematodes - nematicide as last resort		
Control nematodes - tolerant varieties		
Control nematodes - increase soil organic matter		
Precision Agriculture - grid sampling, soil corrections, and managing soil according to its potential		
Manage nitrogen rates and application timing		
Optimum fertiliser rates, placement and timing.		
Other		

What are the main barriers of adoption, stopping you from implementing more practices to improve soil quality?	Main barriers of adoption ?
Economic / financial	X
Management time constraints	
Don't believe benefits will outweigh costs	
Insufficient knowledge	
Shortage of manpower or equipment	
Other	
Practical field trials	

What prompted you to initially implement soil quality improvement practices?	Farming with poor, low potential soils. To improve soils and promote sustainability.

Why did you choose the particular soil quality practices you have adopted?	They benefit the farm system as a whole. No extra machinery or manpower needed. Tie in with the cattle. Are eco-friendly.

Which soil quality practice that you have adopted, do you believe has improved soil quality the most?	Applying crop nutrient recommendations, with inorganic fertiliser, exactly as SASRI recommends.

Which soil quality practice that you have adopted, do you believe has had the second best result in improving soil quality ?	Green manures.

In your opinion, which soil quality practice is in most need of urgent research and development ?	Strategies to stimulate soil microbial activity.

Do you believe more farmers will adopt a range of soil quality practices, if they are promoted under a Conservation Agriculture, or Agro-ecology farming system package, rather than ad-hoc adoption of individual farming practices?	No.

Do you believe more farmers will adopt a range of soil quality practices, if a package of best practices are recommended, based on the dominant soil and climate of a particular region?	No.

Would you be willing to pay a soil quality consultant, to advise you on the best, site-specific practices, to improve soil health on your farm?	Yes.

Do you believe a soil health specific test, would be beneficial to you, to manage soils on your farm?	Yes.