SOIL CARBON AND PHOSPHORUS DYNAMICS UNDER VARIOUS WHEAT-BASED CONSERVATION AGRICULTURE OPTIONS

by

NONDUMISO ZANELE SOSIBO

A thesis submitted in fulfilment of the academic requirements for the degree of

Doctor of Philosophy in Soil Science

Discipline of Soil Science

School of Agriculture, Earth and Environmental Science

College of Agriculture, Engineering and Science

University of KwaZulu-Natal

Pietermaritzburg

South Africa

December 2020

PREFACE

The research contained in this thesis was completed by the candidate while based in the Discipline of Soil Science, School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg Campus, South Africa. The research was financially supported by the Agricultural Research Council-Professional Development Programme, the National Research Foundation, and the Winter Cereal Trust.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

[redacted]

Signed: Main Supervisor: Pardon Muchaonyerwa

Date: 03 December 2020

[redacted]

Signed: Co-Supervisor: Ernest Dube

Date: 03 December 2020

DECLARATION 1: PLAGIARISM

I, Nondumiso Zanele Sosibo declare that:

(i) the research reported in this thesis, except where otherwise indicated or acknowledged, is my original work;

(ii) this thesis has not been submitted in full or in part for any degree or examination to any other university;

(iii) this thesis does not contain other persons' data, pictures, graphs or other information unless specifically acknowledged as being sourced from other persons;

(iv) this thesis does not contain other persons' writing unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

a) their words have been re-written but the general information attributed to them has been referenced;

b) where their exact words have been used, their writing has been placed inside quotation marks, and referenced;

(v) where I have used material for which publications followed, I have indicated in detail my role in the work;

(vi) this thesis is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

(vii) this thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and the References sections.

[redacted]

Signed: Nondumiso Zanele Sosibo

Date: 03 December 2020

DECLARATION 2: LIST OF PUBLICATIONS AND PRESENTATIONS

My role in each paper and presentation is indicated. The * indicates the corresponding author.

Original research article

1. Sosibo NZ*, Dube E, Tsilo TJ and Muchaonyerwa P. Cropping sequences and important soil quality parameters of Oxidic soils under irrigated winter wheat-based conservation agriculture in Kwazulu-Natal, South Africa. (Submitted to Soil and Tillage Research).

Conference presentations

1. Sosibo NZ*, Muchaonyerwa P, Tsilo TJ. No-tillage with residue retention and conventional tillage with residue burning reduced soil carbon stocks after 37 years of wheat (*Triticum aestivum L.*) Production. The 6th International Symposium on Soil Organic Matter, Rothamstead research, Harpenden, United Kingdom 3-7th September 2017. (Oral presentation).
2. Sosibo NZ*, Kilian W, Dube E, Muchaonyerwa P, Tsilo TJ. Dryland wheat yield and soil properties after 40 years of continuous cropping under different tillage and residue management systems. Agricultural Research Council Postgraduate Conference, VOPI, Pretoria, South Africa 7-9th October 2019. (Oral presentation).

- I collected the data, analysed the results and wrote the first drafts of all the papers and presentations listed above.

[redacted]

____

Signed: Nondumiso Zanele Sosibo

Date: 03 December 2020

LIST OF ABBREVIATIONS

Al:	Aluminium
ANOVA:	Analysis of variance
ARC:	Agricultural Research Council
ARC-ISCW:	Agricultural Research Council-Institute for Soil Climate and Water
ARC-SG:	Agricultural Research Council-Small Grain
AS:	Acid saturation
BD:	Bulk density
C:	Carbon
Ca:	Calcium
CA:	Conservation agriculture
$CaCl_2$:	Calcium chloride
CEC:	Cation exchange capacity
CH_4:	Methane
CO:	Carbon monoxide
CO_2:	Carbon dioxide
CNS:	Carbon nitrogen and sulphate
CT:	Conventional tillage
Cu:	Copper
CV:	Coefficient of variation
DOC:	Dissolved organic carbon
EA:	Exchangeable acidity
Fe:	Iron
H_2O_2:	Hydrogen peroxide
HCl:	Hydrochloric acid

$HClO_4$:	Perchloric acid
HCO_3^-:	Bicarbonate
HNO_3:	Nitric acid
IUSS:	International Union of Soil Science
K:	Potassium
KCl:	Potassium chloride
KH_2PO_4:	Potassium dihydrogen phosphate
KZN:	KwaZulu-Natal
LSD:	Least significant difference
Mg:	Magnesium
Min.assoc.C:	Mineral associated carbon
Mn:	Manganese
N:	Nitrogen
N_2:	Nitrogen molecule
Na:	Sodium
$NaHCO_3$:	Sodium bicarbonate
NaOH:	Sodium hydroxide
NH_4Cl:	Ammonium chloride
NH_4OAc:	Ammonium acetate
ns:	Not significant
NT:	No tillage
OH^-:	Hydroxide
OM:	Organic matter
P:	Phosphorus
Pi:	Inorganic phosphorus

Po:	Organic phosphorus
POC:	Particulate organic carbon
Pt:	Total phosphorus
RCBD:	Randomised complete block design
SAGL:	The Southern African Grain Laboratory
SM:	Stubble mulch
SOC:	Soil organic carbon
SOM:	Soil organic matter
UKZN:	University of KwaZulu-Natal
USA:	United States of America
WRB:	World reference base for soil resources.
WSC:	Water soluble carbon
Zn:	Zinc

THESIS STRUCTURE

This thesis is made up of seven chapters, four of which have been prepared for publication. Therefore, there is a degree of unavoidable overlap. All the experimental chapters are presented in a publication format. **Chapters 1 and 2** (General Introduction and Literature Review) introduce the research problem, provide literature on soil properties, soil carbon, phosphorus pools and phosphorus sorption, and identifies opportunities for refinement of conservation agriculture systems for wheat production in South Africa, to derive maximum benefits of increased soil carbon and phosphorus availability. The Literature Review also identifies information gaps in this regard. **Chapter 3** explores soil physicochemical properties, soil carbon and phosphorus fractions under different cropping sequences of wheat after either maize or soybean in the irrigation production systems of KwaZulu-Natal. **Chapter 4** presents long-term soil quality trends under various conservation agriculture practices, in the low N-fertiliser (40 kg N ha^{-1}) input dryland wheat production systems of the semi-arid summer rainfall areas. **Chapter 5** explores long-term dryland soil carbon and phosphorus fractions as well as nutrient uptake at higher N-fertiliser (60 kg ha^{-1}) fertiliser rates. **Chapter 6** evaluates the effect of (i) tillage and wheat straw management (ii) cropping sequences and (iii) dissolved organic matter from wheat residues on phosphorus sorption. **Chapter 7** gives a general discussion, which ties up the findings of chapters 3, 4, 5 and 6 to give overall conclusions and recommendations.

ABSTRACT

Wheat farming in South Africa faces the challenge of low yields and profitability when compared to other cropping enterprises. Poor soil quality is a major cause of low yields and high cost of fertilisers is a reason for low profitability, with resulting farmer disinterest in wheat production over the years. South African wheat is produced in irrigation and dryland systems characterised by different soils, climatic conditions, as well as crop and soil management systems. This study was conducted to evaluate the effects of different conservation agriculture (CA) management practices on soil organic carbon (SOC) and phosphorus (P) fractions and their relationships on two contrasting soils under the high input irrigated (KwaZulu-Natal) and the limited input, dryland (Bethlehem) wheat production systems.

Cropping sequences of wheat with either maize or soybean did not significantly affect total nitrogen (N), soil C stocks and SOC fractions, and 94% of SOC was associated with the mineral C fraction in KwaZulu-Natal. Labile P was, however, higher in the soils where wheat was preceded by maize. At Bethlehem, particulate organic carbon fractions were significantly increased by no-tillage (NT) while mineral associated C was increased by straw burning. Overall, SOC stocks (t ha^{-1}) up to a depth of 1000 mm (1 m) and extractable P concentrations were higher under NT when straw was burnt. Other labile P fractions were increased by burning under conventional tillage (CT), but the more stable P (NaOH II Pi and residual P) fractions were higher under stubble mulch and NT. The higher concentration of SOC and its various fractions as a result of CA increased P availability. Dissolved organic C reduced P sorption in both soils with effects being more pronounced on the less acidic Acric Plinthosol of Bethlehem than the Oxidic soils of KwaZulu-Natal. These findings suggest that CA practices that support accumulation of SOC, and its fractions, reduce P sorption, improve P availability, and could enhance the sustainability of both dryland and irrigation wheat production systems.

Keywords: conservation agriculture, soil quality, carbon, phosphorus, adsorption.

ACKNOWLEDGEMENTS

I would like to thank the Almighty God, for his greatest mercy he showed me through this journey.

To my mentors: Prof Pardon Muchaonyerwa, Dr Ernest Dube and Prof Toi Tsilo; thank you for seeing a potential in me and patiently guiding me through this journey. Your advice, encouragement and support have nurtured me to be a better person; I appreciate you all.

The Agricultural Research Council provided me with an opportunity for a PhD candidature through the Professional Development Programme, the National Research Foundation and the Winter Cereal Trust provided funding for this study; and I am grateful.

I would like to thank the ARC-Small Grain for allowing me to sample from the long-term trial which was managed by different staff members of the production systems division over the years including Ms Lientjie Visser. I would also like to thank the wheat farmers in KwaZulu-Natal for allowing me to sample from their fields and for providing me with the necessary information that was required for this study.

I would like to thank Ntate Mashinini, Ntate Zwane, Matthew Coale, Small Grain colleagues, interns, and experiential training students for assistance with soil sampling. My special thanks go to Richard Taylor and Kamohelo Makuoane for liaising with wheat farmers.

I am highly indebted to Zanele Khathwayo, for sacrificing her weekends and holidays helping me with my experiments, thank you myZee. Mme Lydia Xaba, mme Anna Hescock, Alti van Deventer (ARC-Small Grain), Mom Tezi Nala and baba Joe Buthelezi (UKZN) thank you for your assistance in the laboratory. My special thanks go to Sibusiso Buthelezi, Nontokozo Mkhonza, Samkelisiwe Vilakazi, Sbonakaliso Zwane, Lwazi Mngomezulu (UKZN) and Anna Nxumalo (ARC-ISCW) for their assistance with some of my analyses, I am grateful.

My special thanks go to Thandi Gumede (UKZN), Timmy, Tebogo, Tsepiso, Elaine, Juliette, Chrissie, Dries, Ntate Phelo, Ntate Majola, Ntate Moloi, Hellen, Mme Agnes and all the ARC-Small Grain staff for their support in various parts of this study, I appreciate you all.

To my partner: Mpilo Dlamini, my friends: Lindiwe Khumalo, Thivashnie Naidoo, Nokubonga Langa and to my colleagues who became family: ausi Lisemelo, Sandi, Zaza, Thobeka, Lungi, Lavinia and Peter thank you for your undying support. You kept me going.

Finally, my most sincere gratitude goes to my family for their endless love and support. Nime njalo!

DEDICATION

This thesis is dedicated to my lovely son: ***Lwandile Mnini Fanele***, thank you for arriving at the most critical time in my life. You redefined success and happiness for me, your laughter made all my frustrations disappear. I thank God for you.

TABLE OF CONTENTS

PREFACE i
DECLARATION 1: PLAGIARISM ii
DECLARATION 2: LIST OF PUBLICATIONS AND PRESENTATIONS iii
LIST OF ABBREVIATIONS iv
THESIS STRUCTURE vii
ABSTRACT viii
ACKNOWLEDGEMENTS ix
DEDICATION xi
TABLE OF CONTENTS xii
LIST OF TABLES xvi
LIST OF FIGURES xviii
CHAPTER 1: INTRODUCTION 1
1.1 Background 1
1.2 Problem statement 4
1.3 Research questions 5
1.4 Hypotheses 5
1.5 Objectives 5
CHAPTER 2: LITERATURE REVIEW 7
2.1 Background to the study 7
2.2 The importance of long-term trials in studies of soil and crop management effects on soil quality in wheat production systems 9
2.3 Effects of tillage, residue and fertiliser management on nutrient uptake, yield, and wheat profitability 9
2.4 The effect of conservation agriculture on selected soil physical properties 10
2.5 Effects of conservation agriculture practices on selected soil properties for wheat production 11
2.5.1 Cropping sequence effects on soil quality and yield of wheat 14
2.6 The effect of CA practices on total nitrogen 15
2.7 Tillage, crop residue and fertiliser management effects on SOC 17
2.8 Fractions of soil organic carbon as affected by different conservation agriculture practices 24
2.8.1 The effects of tillage, residue management and crop rotation on SOC fractions 25
2.9 The effects of residue management and tillage on P availability 27

2.9.1 Fractions of soil phosphorus as affected by different conservation agriculture practices 32
2.9.2 The effects of soil organic carbon on phosphorus adsorption........................ 34
2.10 Potential interaction effects of soil organic carbon and phosphorus fractions in conservation agriculture systems 36
2.11 Summary and prospects 37
CHAPTER 3: SELECTED QUALITY PARAMETERS OF OXIDIC SOILS AS AFFECTED BY CROPPING SEQUENCES UNDER IRRIGATED WHEAT-BASED CONSERVATION AGRICULTURE IN KWAZULU-NATAL, SOUTH AFRICA 39
ABSTRACT... 39
3.1 INTRODUCTION 41
3.2 MATERIAL AND METHODS 44
3.2.1 Description of study sites 44
3.2.2 Soil sampling... 45
3.2.3 Physico-chemical analyses 46
3.2.4 Soil carbon fractions.. 46
3.2.5 Soil phosphorus fractions 47
3.2.6 Statistical data analyses 48
3.3 RESULTS 49
3.3.1 Differences in carbon and phosphorus fractions across cropping sequences and soil depths 49
3.3.1.1 Soil carbon stock, concentrations, and fractions 50
3.3.1.2 Bray 1 extractable and other fractions of phosphorus..................................... 51
3.3.3 Other soil chemical properties across cropping sequences and soil depths 52
3.3.4 Comparison of cropped lands with virgin soils.. 55
3.3.5 Correlation of fractions of carbon and phosphorus 56
3.4 DISCUSSION 57
3.5 CONCLUSION... 62
CHAPTER 4: SOIL QUALITY OVER 40-YEARS OF TILLAGE AND STRAW MANAGEMENT PRACTICES UNDER SEMI-ARID CONDITIONS 64
ABSTRACT... 64
4.1 INTRODUCTION 65
4.2 MATERIALS AND METHODS 67
4.2.1 Description of the Bethlehem long term trial 67
4.2.2 Soil sampling and analyses 69
4.2.3 Statistical analyses.. 69

4.3 RESULTS 70
4.3.1 Effects of tillage and straw management on selected soil properties after 40 years 70
4.3.1.1 Soil pH 70
4.3.1.2 Extractable soil phosphorus 71
4.3.1.3 Soil organic carbon and total nitrogen 72
4.4 DISCUSSION 73
4.4.1 Changes in soil pH across management systems 73
4.4.2 Changes in extractable phosphorous 73
4.4.3 Changes in soil organic carbon and total nitrogen across management systems 76
4.5 CONCLUSIONS 78
CHAPTER 5: EFFECTS OF TILLAGE AND STRAW MANAGEMENT AT HIGH NITROGEN RATE ON STOCKS AND LABILE POOLS OF SOIL CARBON AND PHOSPHORUS UNDER DRYLAND WHEAT PRODUCTION IN SEMI-ARID CONDITIONS 79
ABSTRACT 79
5.1 INTRODUCTION 80
5.2 MATERIALS AND METHODS 84
5.2.1. Description of the Bethlehem long-term trial and design 84
5.2.2. Soil Sampling and Analyses 86
5.2.2.1 Soil sampling and analysis of selected soil parameters 86
5.2.2.2 Soil carbon and phosphorus fractions 86
5.2.3. Measurement of wheat dry matter 87
5.2.4. Measurement of plant tissue nutrient composition and uptake 87
5.2.5. Data Analyses 88
5.3 RESULTS 88
5.3.1 Soil carbon stocks 88
5.3.2. Soil pH, organic C, charcoal, total N and available P 90
5.3.3. Soil carbon and phosphorus fractions 94
5.3.4. Nutrient uptake 98
5.4 DISCUSSION 98
5.5 CONCLUSION 102
CHAPTER 6: SORPTION OF PHOSPHORUS ON SOILS FROM WHEAT FIELDS AS AFFECTED BY MANAGEMENT AND DISSOLVED ORGANIC MATTER 103
ABSTRACT 103
6.1 INTRODUCTION 104
6.2 MATERIALS AND METHODS 107

6.2.1 Description of study sites and soil sampling 107
6.2.2 Phosphorus adsorption experiment 111
6.2.3 Dissolved organic carbon extraction 111
6.2.4 Sorption of phosphorus and dissolved organic carbon on soil 112
6.2.5 Statistical analyses 113
6.3 RESULTS 114
6.3.1 Sorption of phosphorus on Oxidic soils under different cropping sequences 114
6.3.2 Effects of tillage and straw management on P sorption indices in the Acric Plinthosol 116
6.3.3 The effect of DOC addition on P adsorption indices on two contrasting soils from KZN and Bethlehem 118
6.3.4 Sorption isotherms and sorption indices of DOC on two contrasting soils 120
6.4 DISCUSSION 121
6.5 CONCLUSION 125
CHAPTER 7: GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS 126
7.1 General Discussion 126
7.2 Conclusions 134
7.3 Recommendations 135
LIST OF REFERENCES 136

LIST OF TABLES

Table 2. 1: The effects of conservation agriculture (CA) on selected soil quality parameters. 13

Table 2. 2: The main effects of tillage practice and residue management practice on soil total N (%) at the Bethlehem trial. 17

Table 2. 3: The main effects of tillage and straw management practice on soil organic carbon (%). 22

Table 2. 4: The interaction effect of tillage and residue practice on soil P levels (mg kg^{-1}) based on published results from the Bethlehem trial. 31

Table 2. 5: The various fractions of phosphorus and their pertinent pools (Source: Daroub et al., 2001). 32

Table 3. 1: Climatic conditions for the KwaZulu-Natal irrigated wheat production region. 45

Table 3. 2: Significant differences per Kruskal-Wallis H test at a 95% confidence level (n=20) for C and P fractions in the soil. 49

Table 3. 3: Soil C stocks (t ha^{-1}) and fractions (g kg^{-1}) variations across soil sampling depths and cropping sequences. 51

Table 3. 4: Variations in soil P fractions (mg kg^{-1}) across cropping sequences and soil depths. 52

Table 3. 5: Significant differences per Kruskal-Wallis test at a 95% confidence level (n=20) for soil properties under irrigated wheat fields in KZN. 53

Table 3. 6: Differences in selected soil properties of wheat fields across soil depths and cropping sequences. 54

Table 3. 7: Chemical properties of virgin soils in the KwaZulu-Natal wheat production region (n= 4). 55

Table 3. 8: Spearman's rank correlation coefficients between organic carbon and phosphorus fractions in the 0-200 mm (with clear shades) and 200-400 mm (with grey shades). 57

Table 4. 1: Soil properties of the grassland next to the trial in 2018. 67

Table 4. 2: Statistical significance (p-values) of treatment combinations effects from general ANOVA. 70

Table 4. 3: The effects of tillage × straw management × depth on soil pH. 71

Table 4. 4: The effects of tillage × straw management × soil depth on extractable phosphorus. 71

Table 4. 5: The effect of tillage and straw management on soil organic carbon and total nitrogen. 72
Table 5. 1: Soil properties of the natural grassland next to the Bethlehem long-term trial in 2016...85
Table 5. 2: Tillage and straw management effects on soil carbon stocks (t ha^{-1}) at different soil depth (mm)...89
Table 5. 3: The general ANOVA of soil properties at 95% confidence level (n=18). 91
Table 5. 4: The effect of tillage and straw management on soil pH, soil organic carbon, charcoal total nitrogen and Bray 1 extractable phosphorus in the 0-50 mm layer. 91
Table 5. 5: The effect of tillage and straw management on soil pH, soil organic carbon, charcoal and total nitrogen in the 50-200 mm layer. 92
Table 5. 6: The effect of tillage and residue management on soil organic carbon and total nitrogen in the 200-400 mm layer..94
Table 5. 7: The general ANOVA of soil C and P pools at 95% confidence level (n=54) under long-term wheat monoculture in Bethlehem...95
Table 6. 1: Properties of the topsoils (0-200 mm) from KZN different cropping sequences. 109
Table 6. 2: Properties of the topsoils (0-50 mm) from different tillage and straw management practices in Bethlehem. 110
Table 6. 3: Properties of the low carbon soils from different localities (800-1000 mm depth) used in the sorption experiments...113
Table 6. 4: Spearman’s correlation matrix for P sorption indices with various nutrient availability parameters in KZN irrigated wheat fields...115
Table 6. 5: The significance of differences as per ANOVA at 95% confidence limit..........117
Table 6. 6: The interaction effect of tillage and straw management on Smax (mg kg^{-1}) in a Bethlehem Acric Plinthosol. 117
Table 6. 7: Pearson’s correlation matrix for P sorption indices with various soil parameters in a Bethlehem Acric Plinthosol. 118
Table 6. 8: The effect of adding or removing dissolved organic carbon (DOC) on Bethlehem 120
Table 6. 9: The effect of dissolved carbon and phosphorus on carbon sorption indices in two contrasting soils. 121

LIST OF FIGURES

Figure 5. 1: Temperature conditions at the Bethlehem long-term trial site. 84
Figure 5. 3: The interaction effect of tillage and wheat straw management on total carbon stocks (0-1000 mm). An error bar and different letters (a-b) in the bars represent significant differences at $p<0.05$). 89
Figure 5. 4: The interaction effect of tillage and wheat straw management on soil carbon stocks in the 50-200 mm depth. An error bar and different letters (a-b) in the bars represent significant differences at $p<0.05$). 90
Figure 5. 5: The interaction effect of tillage and straw management on soil total nitrogen concentration in the 50-200 mm depth. An error bar and different letters (a-d) in the bars represent significant differences at $p<0.05$). 93
Figure 5. 6: The interaction effect of tillage × straw management on micro POC (g kg^{-1}) in the 0-50 mm soil layer. An error bar and different letters (a-b) in the bars represent significant differences at $p<0.05$). 96
Figure 5. 7: The interaction effect of tillage × straw management on (a) $NaHCO_3$ Pi (b) NaOH I Pi and fractions (mg kg^{-1}) in the 0-50 mm soil layer. An error bar and different letters (a-b) in the bars represent significant differences at $p<0.05$). 97
Figure 6. 1: Phosphorus sorption isotherms from KZN wheat fields that had (a) soybean or (b) maize before wheat. 114
Figure 6. 2: Phosphate adsorption isotherms in different tillage and straw management treatments in soils from Bethlehem. 116
Figure 6. 3: The effect of dissolved organic carbon from wheat straw on P sorption in (a) KwaZulu-Natal and (b) Bethlehem soils with low native soil carbon.DOC 3800, DOC 20 and DOC 0 refers to the amount of DOC added in mg L^{-1}..119
Figure 6. 4: The sorption isotherms for dissolved organic carbon from wheat straw on two contrasting soils from KZN and Bethlehem. 120

CHAPTER 1: INTRODUCTION

1.1 Background

Poor soil quality is a major constraint to sustainable intensification efforts for crop production, including wheat (*Triticum aestivum* L.) in sub-Saharan Africa (Nziguheba et al., 2016). Organic matter, nutrient composition, bulk density, texture, acidity, salinity, and microbial activity, and other attributes, are among the measurable indicators of soil quality (Muñoz-Rojas, 2019). The sensitivity of some of these parameters to soil and crop management makes them essential to understand how various crop production practices affect soil quality and productivity.

Phosphorus (P), the second most important macronutrient after nitrogen, in terms of wheat nutritional requirements, is important from root growth, tiller emergence, up to seed development and maturity (Rodríguez et al., 1999). In sub-Saharan Africa, P deficiency is common due to a combination of low P reserves, high P fixation capacity of soils, and conventional crop production practices that further reduce P availability through nutrient mining (Nziguheba et al., 2016). Production systems that are characterised by intensive tillage of the soil, referred to as conventional tillage (CT) systems, generally result in a decline in soil quality, including low soil organic matter and P availability. Conservation agriculture (CA), with combinations of reduced or no-tillage, crop rotation, and permanent soil cover, is generally considered as the best approach for improving soil quality (Vanlauwe et al., 2014).

In South Africa, wheat is produced under irrigation and dryland systems under different soil types, climatic conditions, tillage practices, residue management strategies, and cropping sequences. Either conventional or conservation tillage (minimum soil disturbance) practices are used, and the wheat is rotated with legumes or non-legumes crops, or bare fallow, with crop residues, either being retained as soil cover, fed to livestock, or burned (Muirhead, 2018 personal communication[1]). Many studies that have been previously conducted to assess different management practices in South Africa concede that soil quality challenges prevail across the different wheat production systems (Du Preez et al., 2001; Kotzé and du Preez, 2007, 2008; Loke, 2012; Sosibo et al., 2017; Mtyobile et al., 2019; Dube et al., 2020).

Long-term research trials in dryland wheat production systems of the summer rainfall area in South Africa showed that no-tillage preserved significantly more soil moisture, and nutrients in the topsoil compared to conventional tillage (Du Preez et al., 2001; Kotzé and du Preez, 2007, 2008; Loke, 2012). No-tillage also improved SOC in the topsoil after 20 (Kotzé and du Preez, 2007) and 30 years (Loke et al., 2012) of the trial in Bethlehem, South Africa, but recently, SOC was improved by residue burning (Motema et al., 2020). Recent surveys across the irrigated wheat production systems of South Africa showed nearly twice as much mean SOC from conservation tillage (2.15 ± 0.10 %) wheat fields compared to conventional tillage (1.02 ± 0.05 %) fields (Sosibo et al., 2017). As such, no-tillage and permanent soil cover have been recommended to restore soil organic carbon (SOC) in the drought-prone dryland wheat production systems of the summer rainfall areas (Loke, 2017). However, soil acidity and P deficiency are more prominent problems under conservation tillage as opposed to conventional tillage, especially in the Oxidic soils of KwaZulu-Natal (KZN) (Sosibo et al., 2017). The KwaZulu-Natal region has highly weathered soils, with low pH and high concentrations of sesquioxides due to humid climate, which are a main reason for P fixation hence P deficiency. The decomposition of organic matter and mineralisation of N fertiliser under conservation tillage, further increases soil acidity.

[1] Terrie Muirhead. KwaZulu-Natal No-till farmer

Many researchers have highlighted the importance of organic matter inputs on improving SOC and P in South African crop production systems, particularly under reduced tillage. Mtyobile et al. (2019) recommended rotation with leguminous crops, against mono-cropping, for improving soil quality and crop productivity in the dryland wheat production systems. Significant effect of cover crop species, biomass yield, and fertiliser management on SOC fractions and P were reported by Dube et al. (2012) from maize-based CA systems of the Eastern Cape on a Haplic Cambisol. Co-application of manure and low doses of mineral P was shown to be a cost-effective strategy for managing P fertilisation on acidic soils. This combination enhanced P cycling through microbial biomass P and reduced P fixation in highly weathered soils (Gichangi et al., 2009). Tillage, fertiliser, and crop residue management practices that improve SOC and its pools could reduce P fixation and improve P availability in highly weathered soils through the promotion of microbial biomass P as a temporal sink. Furthermore, soil clay fractions can also interact with SOC limiting or enhancing P availability (Li et al., 2007; Muindi et al., 2015). Singh et al. (2016) showed that iron and aluminium oxides adsorbed substantial quantities of dissolved organic matter. Dissolved organic matter, in wheat-based CA systems, could compete with P for sorption sites (Guppy et al., 2005; Nziguheba et al., 2016), potentially making P more available. Strategies that improve SOC and P cycling could significantly improve wheat yields and profitability.

Some studies have quantified the benefits of CA practices such as reduced tillage, crop rotation, and crop residue cover on soil quality, including carbon and P fractions, in various CA crop production systems in South Africa (Dube et al., 2012; Sithole et al., 2016; Ncoyi et al., 2020; Motema et al., 2020). There is limited literature on the effects of different crop and soil management practices (tillage, fertiliser, crop residues, and rotations) and soil types on P and SOC fractions in wheat-based CA systems of South Africa. Effects of interactions between

SOC fractions, including water-soluble C, and P availability need to be understood, to optimise benefits of the CA through the reduction of P fertiliser application.

1.2 Problem statement

Wheat farming in South Africa faces the challenge of poor soil quality, which reduces crop yield and increases external fertiliser input requirements to achieve optimum yields. The low profitability of wheat crops compared to other cropping enterprises is accepted as one of the reasons wheat production has declined over the years in South Africa (Dube et al., 2020).

Intensive irrigation wheat production systems, such as those found in KwaZulu-Natal, South Africa, have high soil nutrient removal rates and P fertiliser requirements. The soils are highly weathered, with inherently low P, making it difficult for farmers to maintain adequate plant-available P for crop demands (Sosibo et al., 2017). A possibility of enhancing labile P fractions under conservation tillage systems could be a potential solution for reducing P fertiliser, as shown by findings from Gichangi et al. (2009) and Dube et al. (2013). Conversely, under low-fertiliser input dryland production conditions, in the semi-arid summer rainfall areas, wheat is produced on soils with plinthic horizons to benefit from the stored moisture. The dryland wheat must be rotated with a bare fallow to minimize moisture removal by a summer crop; hence monocropping is a prevalent practice in this region. Under these dry conditions, crop yields may be limited by the low soil organic matter and nutrients contents.

Conservation agriculture has been promoted to improve soil quality, organic C, and available P. Gichangi et al. (2009) showed that co-application of animal manure and mineral fertiliser resulted in increased P cycling in acidic soils, with benefits for maize productivity on acidic soils. Dube et al. (2013) and Mukumbareza et al. (2016) showed that high biomass inputs, through cover crops and retention of crop residues, increased organic matter, microbial biomass

P and available P on a moderately weathered soil. These findings suggest that both dryland and irrigated wheat-based CA systems could benefit from increased soil C stocks and labile organic matter fractions, with positive effects on P availability. However, these benefits could depend on the soil types, crop and soil management practices within the CA systems.

1.3 Research questions

(i) What are the effects of cropping sequences on SOC stocks, and fractions of SOC and P and overall quality of acidic soils under irrigated wheat-based CA system?

(ii) What are the long term effects of tillage, residue, and fertiliser management on soil quality parameters like soil C stocks, C and P fractions and nutrient uptake of low input dryland wheat under semi-arid conditions?

(iii) Does increasing SOC content, and its various fractions, reduce sorption and increase the availability of P in wheat-based CA systems on contrasting soils?

1.4 Hypotheses

(i) Wheat/maize cropping sequences improves soil quality, SOC stocks and fractions of SOC and P compared to wheat/soybean on acidic soils under irrigated wheat-based conservation agriculture.

(ii) Long-term reduced tillage, wheat straw retention and higher N fertiliser improve soil quality parameters, soil C stocks, fractions of SOC and P and nutrient uptake, of dryland wheat under semi-arid conditions.

(iii) Conservation agriculture options and labile organic carbon fractions reduce sorption and increase P availability in both moderately and highly weathered soils.

1.5 Objectives

(i) To assess the effects of cropping sequences on selected soil quality parameters and SOC stocks under irrigated wheat conservation agriculture on acidic soils.

(ii) To determine the long-term effects of tillage, residue and fertiliser management on selected soil quality parameters, including C stocks, C and P fractions, and nutrient uptake in an Acric Plinthosol soil under dryland wheat.

(iii) To determine the effects of CA options and labile organic carbon fractions on P sorption and availability in moderately and highly weathered soils.

CHAPTER 2: LITERATURE REVIEW

Soil Factors Affecting Wheat Productivity and the Contribution of Conservation Agriculture in South Africa

2.1 Background to the study

Wheat production in South Africa has since declined due to several biotic and abiotic factors such as climate change, poor soil quality, insect pests and diseases. The crop became less profitable following the deregulation of the wheat market and the discontinuation of the fixed marketing price by the Wheat Board (Shew et al., 2020) and lost most of its production area to alternative crops such as maize and soybean. The decline in land area and low profitability of wheat has contributed to about 50% drop in annual wheat production, failure to meet wheat demands and continued reliance on wheat imports since the termination of the Wheat Board in 1997, (De Wet and Liebenberg, 2018; SAGL, 2020). Nonetheless, wheat production has stabilised. This is evidenced by consistent high wheat production (≥1.8 million tons) in seven out of ten seasons from 2009/2010 to 2018/2019 (SAGL, 2020). At a farm level, wheat profitability is a function of crop yield, input cost and producer price. Farmers can improve their wheat profits through strategies that maximize their crop yields and reduce input costs. In addition to erratic climatic conditions and quelea bird damage, poor soil quality, including soil acidity and phosphorus deficiency are major challenges that reduces farmers' profits (Dube et al., 2020). Farmers incur additional liming and fertiliser input costs due to poor soil and lack of strategies for improving wheat profitability. Conservation agriculture (CA) presents an opportunity to improve poor soil quality and wheat yields under both irrigated and dryland crop production systems (Swanepoel et al., 2018).

Conservation agriculture, by definition, involves a combination of reduced soil disturbance, permanent soil cover through crop residue retention or cover crops, crop rotation with diverse species of plants and a good fertiliser management strategy (Vanlauwe et al., 2014). Although the extent of 'true' CA adoption is still low among South African wheat farmers (Sosibo et al., 2017), there is a strong tendency towards CA as evidenced by wide scale adoption of no-till practices, especially in KwaZulu-Natal. The low CA adoption rate is partly due to lack of education of farmers about CA, preference to use crop residues for livestock instead of retaining them, and higher weed pressure under no-tillage practices that requires costly herbicides (Muzangwa et al., 2017; Thierfelder et al., 2014; Giller et al., 2009). Elsewhere, soil compaction, waterlogging (in clayey soils) and nutrient immobilization were the major soil constraints to CA adoption (Rusinamhodzi et al., 2011). However, CA effects on soil properties could positively contribute to wheat productivity. As such, variations of CA that fit the farmers' soil types, properties and resources are being adopted. For example, in humid areas, wheat is rotated with summer crops e.g. maize or soybean and supplementary irrigation is often used for greater biomass and yield production. Conversely, in the semi-arid areas of South Africa, wheat is produced under dryland conditions with a fallow rotation to benefit from the soil moisture conserved in summer (Bennie and Hensley, 2001). These findings elicited a quest to review the literature on the effects of soil, crop and residue management practices on soil properties, particularly SOC and P dynamics and their relationships in wheat-based crop production systems. This review also aims to identify information gaps that will help to guide further research aimed at improving soil quality parameters SOC, pH and P under wheat production systems in South Africa. The current chapter seeks to answer the following questions using the most recently published literature;

1) What is the effect of CA and CT practices on nutrient uptake, yield, and profitability of wheat?
2) What is the effect of CA options on SOC and P fractions and overall soil quality, in wheat production systems?

3) Does the increase in SOC fractions affect the availability of P in wheat-based CA systems on South African soils?

2.2 The importance of long-term trials in studies of soil and crop management effects on soil quality in wheat production systems

Long-term trials are often reliable for investigating changes in soil quality as a result of management, but the challenge is that these experiments are not only scarce but access to them is often limited. A 40-year-old wheat production practices trial exists in Bethlehem, South Africa. This trial was originally established to determine effects of tillage, residue burning and N fertiliser levels on dryland wheat yields on an Acric Plinthosol. It will be referred to as the "Bethlehem trial" from this point onwards in this review. The long-term Bethlehem trial (40 years) is the oldest in South Africa after the world's longest (> 100 years) running experiments namely: (i) Broadbalk wheat experiment at Rothamsted Research in the United Kingdom, (ii) the Morrow Plots in Illinois, and (iii) the Old Rotation in Alabama (Hmielowski, 2017). The Bethlehem trial is important for understanding the effects of tillage, residue management and N fertiliser rate on soil quality parameters, particularly SOC and P fractions and their interactions in the soil.

2.3 Effects of tillage, residue and fertiliser management on nutrient uptake, yield, and wheat profitability

Conservation tillage is recommended as a component of CA but has several drawbacks that need to be addressed such as slow germination due to cooler and wetter conditions, slow residue decomposition, disease and weed pressure (Thierfelder et al., 2014; Giller et al., 2009; Machado et al., 2007). In a semi-arid region where wheat is rotated with fallow in summer, the higher crop yields in the conventionally tilled plots than stubble mulch and no-till resulted from improved aeration that enables quicker residue decomposition and readily available nutrients for the growing crop (Seepamore et al., 2020). Conservation agriculture with crop rotation and high inputs has a promising yield increase in the dry areas (Rusinamhodzi et al., 2011). Agenbag (2012) highlighted the importance of crop rotation to reduce pests and diseases, improve soil and crop productivity as a way to achieve high yields under CA. Elsewhere, conservational tillage significantly improved nutrient uptake in the soybean/wheat system, which ultimately translated to greater soybean yields (Aulakh et al., 2012). Singh et al. (2020) also reported that no-tillage and residue retention significantly improved N, P and K uptake by the soybean and that higher nutrient uptake and yields were recorded under conservation tillage as opposed to conventional tillage in a soybean-cotton system (Age et al., 2019). A good balance between cereals and legumes crop rotation resulted in higher crop yields under no-tillage in sandy loam soil over time (Martínez et al., 2016). Reduced tillage and partial residue retention have provided high and stable wheat yields and economic gains under contrasting climatic conditions in Bihar, India (Keil et al., 2020). These findings show that CA can improve nutrient uptake, crop yields and improve farmers' profits. Yigezu et al. (2019) showed an increase in economic gains when wheat was rotated with beans in the dry areas of Morrocco as highlighted in Table 2.1. This improvement could be a result of the positive effects of CA on soil quality. Thus, the need to identify wheat-based CA systems that improve soil quality and productivity in South Africa.

2.4 The effect of conservation agriculture on selected soil physical properties

Water availability is typically a crucial factor that affects the potential yield of dryland field crops in South Africa. Stored soil moisture is critical for the successful establishment of dryland wheat that is sown during the dry winter months in the summer rainfall area. Conservation of rainfall before planting is therefore critical for successful production of dryland wheat.

Agronomic practices such as reduced tillage and crop residue retention are known to influence soil moisture dynamics (Alvarez and Steinbach, 2009; Zhang et al., 2009; Brunel et al., 2013), but the magnitude of benefit tend to vary across localities and production systems. Hoffman (1990) investigated the influence of cultivation on soil water balance from the Bethlehem trial (previously described in section 2.2). No-tillage stored more water followed by stubble mulch plots, while ploughed plots retained the least water. Based on these findings, it can be deduced that reduced tillage practices could be used as a strategy for improving soil moisture storage and to mitigate drought of dryland wheat crops in this region. However, CA involving rotation of wheat with beans reduced the bulk density of a Nitisol in a dry sub-humid region in Ethiopia (Degu at al., 2019).

2.5 Effects of conservation agriculture practices on selected soil properties for wheat production

Soil quality parameters affect the ability of the soil to carry out ecosystem functions (Doran and Parkin, 1994) such as sustaining plant and animal productivity and enhancing water and air quality (Herrick, 2000). Measurable indicators of soil quality include soil bulk density, texture, organic matter, acidity, salinity, nutrients and microbial activity (Muñoz-Rojas, 2018). Some of these soil quality parameters are sensitive while others take longer to respond to changes in soil management and affect crop productivity as reported by some recent studies (Table 2.1). There is abundant evidence of CA benefits on soil quality and wheat yield from elsewhere, but with highly variable magnitudes of benefit. For example, CA involving rotation of wheat with beans improved the exchangeable bases, soil pH and generally improved soil fertility status of a Nitisol in a dry sub-humid region in Ethiopia (Degu at al., 2019). Crop residue retention improved the nutrient status of an infertile cambisol (Malobane et al., 2020), through improvements in plant-available nitrogen, P, and exchangeable bases (Ca, Mg and K) in a semi-arid region in South Africa. Although the effects of CA are not the same in all agroecosystems, they seem to generally improve soil properties regardless of soil types, crop type and climatic conditions. These effects are known to vary with the duration of the CA practice, soil type, crop types and climatic conditions. Hence, there are suggestions that future CA research should be conducted under varying climatic conditions, soil texture, soil heterogeneity or cropping systems diversity (Li et al., 2019; Zhang et al., 2009).

Preliminary investigations, through surveys, on wheat production systems across South Africa, showed higher soil organic carbon (SOC) accumulation and phosphorus (P) deficiency under no-till and reduced tillage when compared to conventional tillage (CT) systems (Sosibo et al., 2017). This finding could mainly be because most of the no-till was practiced in high rainfall areas that are naturally acidic, compared to other regions. In South Africa, different wheat production regions practice different sets of CA. As such the effects of CA varied significantly across production regions. KwaZulu-Natal has the highest CA adoption rate followed by the Warmer Northern region. In KwaZulu-Natal, farmers rotate wheat with either maize or soybean while the Warmer Northern farmers rotate wheat with maize, tobacco, sugar beans or soybean. In the Cooler Central and the Eastern Highveld production region, there was a low CA adoption rate as most farmers still practised conventional tillage. However, the farmers maintain permanent soil cover through intensive, all year round cropping of wheat in rotation with summer crops. Choice of summer crops include maize, oats, cotton, groundnuts, potatoes, white beans, or soybean. The KwaZulu-Natal region has lower soil pH and P availability where wheat is rotated with legumes compared to the other regions (Sosibo et al., 2017).

In the Warmer Northern regions, cropping sequences where wheat was rotated with legume crops had relatively lower soil pH, which was ascribed to the mineralization of N from the legume residues. Similarly, the Eastern Highveld region soils had a lower soil pH under legume crop rotations. The Cooler Central region had lower soil pH, but generally adequate nutrients for plant growth (Sosibo, 2016). The effects of CA practices varied across the regions and depended on tillage and crop rotation systems used.

In the semi-arid Eastern Highveld region of South Africa, farmers produce wheat mostly under no-tillage, stubble mulch and conventional tillage in rotation with a summer fallow. This system is meant to conserve enough moisture since this is a low rainfall area. The crop residues are occasionally burnt or removed to avoid build-up of soil-borne diseases. Research has shown that this practice does not build enough SOC (Loke, 2017). As such, no-tillage for improving soil moisture conservation, and crop rotation were suggested to improve SOC and possibly nutrient availability (Kotzé and du Preez, 2007, 2008; Loke et al., 2012; Loke, 2017).

Table 2. 1: The effects of conservation agriculture (CA) on selected soil quality parameters.

Reference	Soil quality parameter	Cropping sequence	Effects
Eze et al. (2020)	Hydraulic properties, SOC	Maize/cowpea/pigeon pea/velvet pea	CA improved soil hydraulic properties but SOC did not improve after 10-12 years.
Mondal et al. (2019)	Hydraulic properties, SOC level and OC stocks	Rice/wheat	CA lowered BD, increased the infiltration, SOC and OC stocks in the 0-30 cm layer.
Li et al. (2019)	Bulk density and soil pH	-	BD increased by 1.4% under no-till with residue retention while soil pH decreased under CA over time.
Rai et al. (2018)	Bulk density	-	CA reduced BD and improved porosity.
Kumar et al. (2018)	Bulk density	Rice/wheat	CA improved soil physical properties including the bulk density.

-findings are based on a systematic meta-analysis study, Rai et al. (2018), Li et al. (2019)

2.5.1 Cropping sequence effects on soil quality and yield of wheat

Planting a variety of crops is recommended as part of the conservation agriculture practice. There is abundant evidence showing the positive effects of cropping sequences on soil quality and grain yield globally. For example, Aziz et al. (2011) evaluated the crop rotation (continuous maize or maize/soybean or maize/soybean/wheat/cowpea) effects on soil quality parameters (microbial biomass C, basal respiration, total C, active C, total N, aggregate stability, POM, total porosity) on a Fluventic Hapludoll soil type in a temperate climate in Ohio, USA. After five years, maize/soybean/wheat/pea crop rotation had 23%, 16%, 7% and 15% increase in biological, chemical, physical and overall soil quality indices compared to the continuous maize or maize/soybean rotation. This was in agreement with Zuber et al. (2015) whereby 15 years of maize/soybean/ wheat crop rotation, reduced bulk density, improved K, total N and water-stable aggregates compared to maize/soybean and continuous soybean on a poorly drained Typic Endoaquoll soil in temperate Illinois, USA. Earlier on, Fuentes et al. (2009) investigated tillage, cropping sequences and crop residue retention effects on a Cumulic Phaeozem soil type in a semi-arid area in Mexico and reported similar findings. Their study reported improvements in soil quality parameters (volumetric moisture content, penetration resistance, bulk density, aggregate stability, aggregate distribution, N, SOC, pH, electrical conductivity) and grain yields on a maize/wheat rotation with residue retention after 14 years. These findings confirm the importance of cropping sequences on soil quality.

Furthermore, Naab et al. (2017) investigated the effect of continuous maize, soybean/maize and soybean/maize intercropping on soil quality parameters and grain yields on a Ferric Lixisol in Ghana. Soya/maize crop rotation and soya/maize intercropping improved SOC, N and the maize yield. The increase in maize yield was ascribed to the N benefit from soybean. These findings agreed with those by Yusuf et al. (2009), who reported that cowpea/maize and soybean/maize cropping sequences improved soil quality (water-soluble C, microbial biomass

C and N) and maize yield on the Alfisol in Nigeria. Similar findings were reported in the temperate region of India, whereby soybean/pea and soybean/rapeseed cropping sequences improved available N, microbial biomass C, dehydrogenase enzyme activity but did not affect SOC and bulk density (Das et al., 2018). A combination of conservation tillage practices with soybean-based crop rotation showed a potential to improve yields of the subsequent crops (Das et al., 2018). A legume-based crop rotation (maize/soybean/wheat) contributed significantly to the stable C fractions by improving coarse fraction associated C and mineral associated C in a well-drained Typic Argiudoll soils of Argentina (Romaniuk et al., 2018). This showed that legumes can also improve carbon sequestration and it further emphasizes the importance of legume inclusion in the crop sequence. However, some studies show the negative effects of cropping sequences on soil quality. For example, Agomoh et al. (2020) investigated the effect of wheat monoculture, wheat/soybean, and wheat/maize/soybean crop rotations and red clover cover crop on soil quality and wheat yield on a poorly drained Typic Argiaquoll in Canada. After 17 years of study, crop rotation improved wheat yields, active C and inorganic N but reduced soil respiration, potentially mineralizable N, K, water-extractable organic C and POC compared to wheat monoculture in the presence or absence of a cover crop.

There is enough evidence that a diverse cropping sequence and the inclusion of legumes in the cropping sequence has a potential to improve soil quality and grain yields of the subsequent crops regardless of the soil type or climate. The information about the effects of cropping sequences on soil quality, especially fractions of SOC and P, and wheat yield in South African soils is limited and requires further investigation.

2.6 The effect of CA practices on total nitrogen

Sampling after 13 years of various tillage (no tillage, stubble mulch, conventional tillage) and residue management (burning, not burning) practices from the Bethlehem trial, there were significant differences in total N across tillage systems at 0 - 250 mm depth (Wiltshire and du

Preez, 1993). The total soil N was in the order: no-tillage (0.11 ± 0.001%) > stubble mulch (0.09 ± 0.001%) > ploughed (0.08 ± 0.001%) plots, showing the importance of minimal soil disturbance in soil N storage. The mean N was similar in no-tillage and stubble mulch plots, whether residues were burnt/unburnt. Hence, Wiltshire and du Preez (1993) concluded that residue management would not have much effect on total N as long as conservation tillage is practised. After 20 years, Kotzé and du Preez (2007) sampled deeper and reported that residue management significantly affected only subsoil N, whereby more N was found on the unburnt residue plots (0.057 ± 0.002%) at 250-350 mm as opposed to 0.054 ± 0.002% for burnt plots (Table 2.2). Tillage system also affected total N in 0-50 mm depths significantly, whereby no-tillage (0.070 ± 0.007%) had the most total N followed by mulched (0.067 ± 0.07%) and ploughed (0.060 ± 0.07%) plots (Table 2.2). The trend was the same (no-tillage>mulched>ploughed) in the 50-100 mm depth, but the levels were lower. A higher level of total N under conservation tillage was probably because of a combination of less disturbance to soil microbes (Balota et al., 2004) and residue retention on the soil surface, which slows down decomposition.

After approximately 32 years of practice, Loke et al. (2012) also reported that there was significantly more N in the soil at 0-50 mm and 50-100 mm in unburnt treatments when compared to the burnt ones. These findings from the Bethlehem trial consistently proved that burning of residues would increase the N losses from the system and increase N fertiliser requirement for dryland wheat production. Nitrogen fertiliser costs currently contribute the most to the total variable costs of wheat production (DAFF, 2013). It would be interesting to quantify the N losses and estimate the total financial value of loss due to residue burning. Total N also decreased with higher intensity of tillage, whereby no-tillage (0.066%) had most N followed by stubble mulched (0.063%) then ploughed (0.055%) plots (Loke et al., 2012) in the top 0-50 mm depth. This trend resembled a trend reported by Kotzé and du Preez (2007) whereby no-tillage treatments maintained more N in the topsoil in all the years but had less N at lower depths, probably implicating less decomposition within the soil profile (Six et al., 2002).

Table 2. 2: The main effects of tillage practice and residue management practice on soil total N (%) at the Bethlehem trial.

		Total N (%)				
		Straw management		**Tillage practice**		
Depth (mm)	**Year**	**Unburnt**	**Burnt**	**No-tillage**	**Stubble mulch**	**Plough**
0-50	[2]2007	0.068	0.063	*0.070	*0.067	*0.060
	[3]2012	*0.063	*0.058	*0.066	*0.063	*0.055
50-100	[2]2007	0.059	0.057	*0.063	*0.057	*0.054
	[3]2012	*0.059	*0.056	0.058	0.058	0.055
100-150	[2]2007	0.058	0.056	0.057	0.057	0.055
	[3]2012	*0.057	*0.056	0.056	0.057	0.055
150-250	[2]2007	0.055	0.054	0.053	0.053	0.054
	[3]2012	0.057	0.058	0.057	0.057	0.056
250-350	[2]2007	*0.057	*0.054	0.056	0.055	0.054
	[3]2012	0.059	0.057	*0.058	*0.059	*0.055
350-450	[2]2007	0.058	0.057	0.057	0.059	0.058
	[3]2012	0.057	0.056	0.056	0.056	0.055

Source= [2]Kotzé and du Preez (2007), [3]Loke et al. (2012); *=the data was significant at $p<0.05$.

2.7 Tillage, crop residue and fertiliser management effects on SOC

Soil organic carbon is most central to the sustainable improvement of soil quality on cropped fields and plays a major role in carbon (C) cycling of the terrestrial ecosystem (Haynes, 2005). Its benefits include the provision of available nutrients, improving soil hydraulic conductivity, buffering capacity, soil tilth among others. (Brady and Weil, 2008; Krull et al., 2004). Conventional tillage (CT) breaks soil aggregates, thus exposing SOM to decomposition while zero or minimum tillage encourages the formation of micro aggregates that promote the protection of soil C (Six et al., 2000). Soil organic carbon stored in the micro aggregates is more stable than that stored in macro aggregates (Snapp and Grandy, 2011; Denef et al. 2004; Six et al., 2000). Several recent studies report the effects of tillage, residue and fertiliser management on SOC. For example, Mondal et al. (2019) reported that 1/3 of the cereal and 100% bean residues that were incorporated or left in the soil surface depending on the tillage practice improved aggregate associated SOC by 27-35% and SOC stocks by 11% in the 0-30 cm soil depth. These tillage and residue management practices ultimately improved rice-wheat productivity in the subtropical humid Indo-Gangetic plains of Bihar, India. Tillage and residue management practices in the study by Mondal et al. (2019) included a full or partial CA practice that involved directly seeded rice/wheat/ mungbean under no-tillage or puddled transplanted rice/no-till wheat/conventional tillage mungbean or unpuddled transplanted rice-potato/conventional till maize/ no tillage mungbean. Alijani et al. (2012) investigated the short-term influence of maize residue management and N fertilization on selected soil properties and winter wheat yield under two tillage practices i.e., mouldboard plough (soil disturbed up to 300 mm by harrow disking and chopped residues completely incorporated) and chisel plough (soil disturbed up to 200 mm by harrow disking and chopped residues partially incorporated). Higher SOC and wheat yields were observed with 25-50% incorporation of maize residues coupled with a higher N fertiliser application rate of 150 kg ha^{-1} to the maize under the chisel plough treatment. The higher application rate of N fertiliser reduced the C: N ratio of maize residues, thus adequate nutrients were released to support maximum wheat yields (Alijani et al., 2012). Rotating wheat with beans improved the SOC status of a Nitisol in a dry sub-humid region in Ethiopia (Degu et al., 2019). Soil organic carbon increase is one of the benefits of including legumes in the crop rotation on highly weathered oxisols (Balota et al., 2014).

Hou et al. (2012) investigated the effect of tillage and residue management on SOC and N pools in a winter wheat and summer maize double-crop system, in a semi-arid region in China.

Conventional tillage retained more SOC and N within the soil profile (0-600 mm) than no tillage, although there was higher SOC and N content in the surface soil layer (0-50 mm). This was attributed to the uniform mixing of soil in the conventional tillage system as compared to no-till, which confines crop roots near the surface where nutrients are mostly distributed. In a low organic C soil (Chromic cambisol) with a wheat/fallow production system in the semi-arid region of China, Liu et al. (2014) reported an increase in SOC stocks in the 0-60 cm and an increase in SOC fractions in the topsoil (0-50 mm) under the no-tillage plots where wheat residues were crushed and mulched in the surface after 17 years. Likewise, in the humid region of southern Brazil, 18 years of no-tillage with irrigated summer maize/ winter black oat+vetch crop rotation maintained SOC stocks similar to the native grassland and higher than conventional tillage even with equal added residues under both no-tillage and conventional tillage (Souza et al., 2014). The improvement of soil C stocks was attributed to the surface placement of crop residues in the no-tillage compared to soil tilling which mixes soil and crop residues, accelerate residue decomposition while breaking soil aggregates and exposing SOC to oxidation (Souza et al., 2014). These findings corroborated a study by Huang et al. (2010) who reported 18.1% increase of SOC under no-tillage with continuous maize compared to conventional tillage in the semi-arid region in China; as well as Six et al. (2002) earlier on, who showed through a systematic review that about 325 ± 113 kg C ha^{-1} yr^{-1} was retained under no-tillage than conventional tillage for both the temperate and tropical soils. Earlier suggestions by Dong et al. (2009) were that SOC levels in low clay soils are linearly correlated with residue addition.

In the humid region of KwaZulu-Natal, non-legume crop rotation significantly improved SOC status and more SOC was accumulated in the topsoil (0-200 mm) under conservation tillage. However, the lack of correlation between SOC and soil nutrients suggested that there were other factors e.g. soil type that influenced nutrient availability (Sosibo et al., 2017). In the Warmer Northern region of South Africa, SOC was higher from cropping sequences where wheat was rotated with legume crops. Soil organic carbon was also negatively correlated with soil pH and extractable P suggesting that SOC accumulation reduces soil pH and P availability (Brady and Weil, 2008). Strong correlations of SOC with clay content also suggested that SOC accumulation was more influenced by the soil clay fraction than the management practices (Sosibo et al. 2017). Soils of the Eastern Highveld region (South Africa) had a lower SOC content which correlated positively with clay %, CEC and exchangeable nutrients. This suggested that SOC accumulation is driven by the clay fraction. Likewise, in the Cooler Central region (South Africa), SOC was also low <1% and was not affected by tillage or soil depth. The correlation with clay content, CEC and soil nutrients suggested that clay fraction may be more influential in SOM build up in this region and good SOM management may improve nutrient availability (Sosibo, 2016). These findings partly agreed with Wiltshire and du Preez (1993) whereby, there were no significant differences in total SOC of different tillage and crop residue management treatments from the Bethlehem trial, and the average SOC content was 0.53%. Kotzé and du Preez (2007) tested SOC from the same dryland wheat trial after 20 years of practice. More SOC was present in the no-tillage (0.84 ± 0.16%) plots, followed by stubble mulched (0.72 ± 0.16%) and ploughed (0.60 ± 0.16%) plots in the top 50 mm depth. The same trend of SOC was observed in the 50-100 mm soil depth, but the levels were slightly lower (Table 2.3). Conservation tillage plots tend to have a higher accumulation of SOC due to reduced soil disturbance, surface accumulation of residues and reduced decomposition (Six et al., 2002).

Loke et al. (2012) conducted another evaluation of SOC from the Bethlehem trial and the findings were consistent with those of Kotzé and du Preez (2007). The plots with burnt straw had similar mean C (0.62%) levels as the unburnt (0.60%) plots at 0 – 100 mm depth (Table 2.3). However, after nearly 40 years of experimentation, Motema et al. (2020) reported higher total SOC upon residue burning as opposed to residue retention in the intermediate N fertiliser treatments of 40 kg N ha^{-1}. This raised several important questions around the SOC sequestration potential of treatments and prompted the need to investigate the effects of higher N fertiliser rates of 60 kg ha^{-1} from this trial. Some soil microbes such as fungi (responsible for SOC build-up) do not survive in high temperature (Boerner et al., 2005). Generally, the fire model is assumed to be as follows: combustion = water + CO_2 + ash containing minerals. Oxygen deficiencies are common during the process, thus the reaction ends up yielding CH_4 + CO + hydrocarbons + particulate OM (González-Pérez et al., 2004). The above process yields particulate organic matter and hydrocarbons which are decomposed by microorganisms which tend to be largely available after the fire (Adeniyi, 2010). Elsewhere, burns that are conducted in the spring season have been reported to consume less soil organic material (Erickson and White, 2008) because of higher fuel moisture content, thus more organic material is available after the fire.

No-tillage consistently maintained more SOC in the topsoil over years although there was a general decline in SOC in all plots across the trial (Loke et al., 2012). Based on studies conducted at the Bethlehem trial (Kotzé and du Preez, 2007; Loke et al., 2012), no-tillage (0.75 ± 0.08%) had more SOC than both stubble mulch and ploughed (0.67 ± 0.08%) plots in the top 0-50 mm soil layer (Table 2.3). However, ploughed plots had much more SOC than either no-tillage or mulched plots at all depths below 150 mm (Table 2.3). It is common for conservation and no-tillage practices to retain more SOC in the topsoil layers whereas conventional tillage harbours most of its SOC in deeper soil layers within the soil profile (Nascente et al., 2013; Kay and Vanden Bygaart, 2002; Six et al., 2000). However, the experiences from the Bethlehem trial also seem to suggest that reduced tillage may also store more C in the deeper soil layers because the C is better protected against losses. This calls for further work aimed at examining the benefits of reduced tillage on C stocks in deeper layers beyond 450 mm. Comparing 2007 and 2012 results shows that there was a general decline in SOC across all treatments in the 0 – 450 mm soil depth (Table 2.3).

According to Giller et al. (2009), the benefits of increasing SOC with long-term conservation agriculture (CA) are more of a function of increased organic matter inputs, rather than reduced tillage *per se*. Review of the Bethlehem trial results suggests that biomass input from the wheat-on-wheat rotation was not adequate for maintaining or increasing SOM levels. There is a need to look at better options for improving biomass input in this system as a means of increasing organic C build-up.

Table 2. 3: The main effects of tillage and straw management practice on soil organic carbon (%).

		Soil organic carbon (%)				
		Straw management		**Tillage practice**		
Depth (mm)	**Year**	**Unburnt**	**Burnt**	**No-tillage**	**Stubble mulch**	**Ploughed**
0-50	[2]2007	0.72	0.74	*0.84	*0.72	*0.60
	[3]2012	0.69	0.71	*0.75	*0.67	*0.67
50-100	[2]2007	0.64	0.65	*0.68	*0.65	*0.59
	[3]2012	0.62	0.63	0.64	0.60	0.65
100-150	[2]2007	0.65	0.66	0.65	0.67	0.63
	[3]2012	0.58	0.62	0.58	0.59	0.66
150-250	[2]2007	0.60	0.60	0.59	0.59	0.61
	[3]2012	0.58	0.61	*0.59	*0.57	*0.68
250-350	[2]2007	0.61	0.62	0.63	0.62	0.60
	[3]2012	0.59	0.61	0.58	0.59	0.64
350-450	[2]2007	0.57	0.58	0.57	0.56	0.58
	[3]2012	0.52	0.54	*0.51	*0.51	*0.62

Source= [2]Kotzé and du Preez (2007), [3]Loke et al. (2012); *= Data was significant at $p<0.05$.

While biomass input is a limitation to CA practice in low-fertiliser input dryland wheat production systems of the semi-arid areas, the same cannot be said for intensive irrigated wheat production systems. Excessive residue amounts under irrigation and no-tillage may hinder seed emergence due to inhibited soil warming, and these challenges may need to be solved before yield benefits of no tillage and residue retention on C sequestration are observed (Machado et al., 2007). The negative effect of no-tillage on crop yield was reported by Seepamore et al. (2020) in a semi-arid region of South Africa, whereby low wheat yields were recorded under no-tillage as opposed to stubble mulch and conventional tillage due to low soil-seed contact as well as limited SOC mineralisation.

Measurements of SOC stocks are ideal as an indicator of the net SOC or SOC sequestration in the soil (Paustian et al., 2019; Schrumpf et al., 2011). Most of the studies on SOC stocks from these long-term trials only sampled up to 650 mm and rarely explored the whole rooting depth because of difficulties experienced in soil sampling from deeper soil layers (Petrokofsky et al., 2012). The SOC stocks are generally positively affected by CA, or reduced tillage and residue retention practices (Bhattacharyya et al., 2015). Labile SOC and C stocks were increased by organic fertiliser after 26 years in the North China Plains (Li et al., 2018). While these studies only sampled up to 650 mm, there is evidence that more SOC stocks may be found in deeper soil layers (Jobbágy and Jackson, 2000; Torres-Sallan et al., 2017; Rumpel and Kögel-Knabner, 2011). This is due to high clay content in the subsoil or clay eluviation to the subsoil. Soil aggregate size, soil type, soil texture play an important role in SOC protection (Mutuo et al., 2004). Soil organic carbon storage and stability are related to soil depth, occlusion within soil aggregates and attachment to soil minerals (Schrumpf et al., 2012). Soil C stock was not adequately studied on the Bethlehem trial, and sampling was limited to the top 650 mm, while deeper layers could still have more C due to root biomass contribution (Zengqiang et al., 2016; Jobbágy and Jackson, 2000). Therefore, there is a need for further studies to investigate SOC stocks up to 1000 mm. It can be noted that a possible trade-off between SOC required for soil productivity and SOC stored for climate change mitigation exists. Farmers may need to decide whether to store enough SOC in the topsoil for their crop productivity or in the subsoil and mitigate climate change.

2.8 Fractions of soil organic carbon as affected by different conservation agriculture practices

While differences in total SOC accumulation because of different CA options have been reported (Mondal et al., 2019; Degu et al., 2019; Liu et al., 2014; Souza et al., 2014; Alijani et al., 2012; Hou et al., 2012), variations in the fractional composition of the SOC could be more important in terms of soil biological life, nutrient cycling and aggregate stability/resistance to erosion. Soil organic carbon embodies an array of soil C fractions, which are responsible for different functions in the soil. These C fractions are microbial biomass C, dissolved organic carbon (DOC), particulate organic C (Liu et al., 2014), mineral associated C, fulvic, humin, humic acid associated fractions (Guimarães et al., 2013). These fractions differ in terms of their lability; i.e. less labile, moderately labile and stable fractions (De Moraes Sá and Lal, 2009; Schrumpf et al., 2012). The labile fractions are important as a substrate for soil microbes and a source of nutrients (Snapp and Grandy, 2011). For example, water-soluble C contains root mucilages as well as extracellular polysaccharides from bacteria and fungi responsible for enmeshing soil particles together (Roldán et al., 1996). This carbon pool increases with higher biomass addition. Stable fractions are responsible for water and nutrient retention and are protected against microbial breakdown within the stable soil aggregates (Chenu and Plante, 2006). As such, they respond differently to soil management practices such as tillage, residue retention or removal or fertiliser addition. The labile fractions of organic matter are more sensitive to soil management practices (Dong et al., 2009) while the stable fractions are less likely to respond to management practices but contribute significantly to C sequestration (Powlson et al., 2012).

2.8.1 The effects of tillage, residue management and crop rotation on SOC fractions

The effects of tillage, residue management, cropping sequences and crop rotations on SOC fractions have been studied extensively under different soil types and climatic conditions. For example, a long-term conservation tillage with dryland cereal/sunflower/legume crop rotation in a semi-arid region in Spain showed a higher total SOC, active C and microbial biomass C in the top 0-50 mm depth compared to conventional tillage (Melero et al., 2009). This was corroborated by Awale et al. (2013) whereby conservation tillage (strip-till and no-tillage) with maize/soybean/sugarbeet crop rotation had 22% and 25% more particulate organic matter and 4.8% and 4.1% more active C than conventional tillage in the semi-arid South Dakota, USA. Blanco-Moure et al. (2013) reported higher particulate SOC under no-tillage with continuous cereal, cereal/legume or cereal/fallow rotation in the semi-arid and Mediterranean climate in Spain. However, mineral associated C and SOC were less sensitive to soil management compared to particulate organic C (Blanco-Moure et al., 2013). In a semi-arid region of China, Liu et al. (2014) noted a higher availability of labile organic carbon fractions in the top 100 mm of the no-tillage plots where crop residues were crushed and left on the soil surface compared to conventional tillage.

Elsewhere in Padova, Italy, straw incorporation compared to straw removal improved DOC, non-resistant C associated with clay and silt particles and ultimately SOC stocks after 30 years of conventional tillage and maize/sugarbeet/soybean or maize/potato/wheat rotation (Reiter, 2015). The N fertiliser level did not affect soil C or its fractions (Reiter, 2015). From the Bethlehem trial in South Africa, no-tillage improved SOC, fulvic and humic acids compared to stubble mulch and conventional tillage under the intermediate N (40 kg N/ha) fertiliser level but residue burning did not have a significant effect on soil C fractions studied (Motema et al., 2020). This was ascribed to minimal soil disturbance which limits SOC loss through microbial breakdown under no-tillage. There was no attempt to investigate the effect of treatments on POC and mineral associated C in the study conducted by Motema et al. (2020). These results raise a question, do the fractions change at a higher N rate, which is also practised in this trial? Soil organic carbon in the unburnt plots is probably dominated by more stable pools of carbon that do not decompose easily (González-Pérez et al., 2004) and are less sensitive to management practices. These findings are partly similar to those of Chan et al., (2002) who reported an increase in particulate organic C under a 19 yr old no-tillage with retained crop residues compared to conventional tillage with burned crop residues in the subtropical area in Australia. The particulate organic C fraction was more sensitive to tillage and soil management compared to other SOC fractions. Overall, the increase in SOC fractions was attributed to the surface placement of crop residues and limited disturbance under no-tillage suggesting that tillage and crop residue management have significant effects on soil C fractions.

De Moraes Sá and Lal (2009) also observed a strong correlation between SOC and labile C fractions (microbial biomass C, basal respiration and microbial biomass N). While the studies that determined the effects of CA on water-soluble C are scarce, WSC can be potentially sorbed on to soil colloids reducing its concentration in the soil. Schrumpf et al. (2012) confirmed the earlier findings of Kalbitz and Kaiser (2008) and Guggenberger and Kaiser (2003) for the affinity of DOC to rapidly sorb to soil minerals accumulating the stable mineral associated C. These correlations suggest that labile fractions can potentially improve nutrient availability. The sorption of DOC into the stable C fraction can result in a competition between DOC and P for sorption sites making P more available in the soil, while reduction of decomposition of the sorbed DOC minimises mineralisation of nutrients. Further studies are required to evaluate the long-term effects of cropping sequences and tillage and residue burning on SOC pools that are important in nutrient cycling, soil fertility and improved soil quality (Snapp and Grandy, 2011; De Moraes Sá and Lal, 2009; Bot and Benites, 2005).

2.9 The effects of residue management and tillage on P availability

Globally, P is the second-most limiting nutrient for crop production, including wheat, after N (Ortiz-Monasterio et al., 2002), especially under no-tillage systems (Varela et al., 2014). A decline and potential extinction of global P mineral deposits motivates a pressing need to reduce reliance on inorganic fertilisers and use of more organic fertiliser sources. Strategies that significantly improve overall soil quality and P cycling in cropping systems for the benefit of wheat crops are required. Several studies have been done previously to investigate the effects of CA, tillage, crop residue management on P availability. For example, Lupwayi et al. (2007) monitored P release during decomposition of red clover, canola, field pea and wheat crop residues under different tillage systems. The study reported that P release varied with tillage systems, and more residual P was released by clover green manure in the conventional tillage plots. No tillage resulted in the net immobilisation of total P from wheat residues. Apart from the higher C: P ratio of wheat residues, immobilisation of P from wheat residues was attributed to less residue to soil contact under no tillage. Although the rotational crops studied are somewhat different from those found in South Africa, these findings confirm that P availability varies with tillage practices and cropping sequence. Elsewhere, the significant effect of cover crop on P cycling has been well documented, with different cover crops being suggested for better P cycling (Soltangheisi et al., 2018; Calegari et al., 2013; Murungu et al., 2011).

The importance of microbial interactions in the P cycles of highly weathered subtropical soils under no tillage systems, where large amounts of residues are returned to the soil annually, was recognised (Tiecher et al., 2012), as the no-tillage system showed high soil organic P levels, soil microbial biomass P content and phosphatase enzyme activity. Similar findings were reported by Margenot et al. (2017), Tiecher et al. (2017) and Calegari et al. (2013) whereby no-tillage improved soil acidity, P and K availability as well as general soil fertility in the topsoil compared to conventional tillage. Reddy et al. (2014) reported an increase in labile P fractions and ultimately higher P availability where crop residues were retained compared to where crop residues were burnt. These reports show that minimum tillage, crop rotation and residue retention have a significant effect on P availability, but the magnitude of effects are expected to vary with different production systems and soil types.

Sosibo et al. (2017) reported variable P levels across wheat production regions of South Africa due to tillage and crop rotation practices in South Africa. The KwaZulu-Natal region had the lowest P availability under a wheat-legume crop rotation, and this was ascribed to the decomposition of N rich crop residues, hence reducing soil pH and P availability. In KwaZulu-Natal, the soils are naturally acidic due to high rainfall and extent of weathering, therefore low soil pH and fixation by aluminium and iron oxides explain low P availability. From the Bethlehem trial, Du Preez et al. (2001) noted significant effects of straw management and tillage on soil P levels. More P was available in the burned plots than unburnt plots in the whole soil profile and no-tillage contained more P as opposed to stubble mulch and ploughed plots in the topsoil (0-50 mm). In the 150-250 mm soil layer, stubble mulch contained more available P compared to no-tillage and ploughed plots that had equal P levels. Soils under conservation tillage (no-tillage or stubble mulch) are presumed to be able to provide more organic P from decomposing crop residues.

On the contrary, Kotzé and du Preez (2008) reported that residue management did not significantly affect soil P concentration, but tillage significantly affected it in almost all the sampled layers except for the 150-250 and 350-450 mm layers. In the 0-50 and 100-150 mm depths, the soil under no-tillage contained more available P, followed by stubble mulched, then ploughed plots. It is worth noting that ploughing reduced P in the upper soil layers and increased it in deeper layers. Loke (2012) noted that P was significantly affected by straw management (0-150 mm) and tillage practice (0-350 mm). More P was still measured in the burnt residue plots throughout the sampled depth, after 30 years of practice. Kotzé (2004) reported a significant interaction of straw management × tillage in the 350-450 mm layer where burned and ploughed plots had significantly more P than the no-tillage plots that were unburnt. Phosphorus decline with depth became clearer in this study as more layers were sampled (0-450 mm) compared to 0-250 mm (Du Preez et al., 2001). Also, ploughed plots contained more P in deeper layers as opposed to no-tillage and stubble mulch that contained more P in the upper soil layer. Physical mixing of soil during ploughing ensured better distribution of soil nutrients in the ploughed plots. Loke et al. (2012) also reported significant straw management × tillage interaction on P (Table 2.4). Burning residues enhanced P availability in the surface of the no-tillage plots than not burning. This was probably because burning converts organic P to orthophosphate form that is readily taken up by plants (Cade-Menun et al., 2000). Burning also increases the soil pH which favours higher P availability (Schaller et al., 2015; Cade-Menun et al., 2000). The question is, what would be the effect of burning on different P pools over time?

Du Preez et al. (2001) and Kotzé (2004) observed that P availability continued to decrease with depth regardless of treatment in the Bethlehem trial (Table 2.4). This can be expected because

P is less mobile thus will be more concentrated in the surface than in deeper soil layers (Li et al., 2019; Balemi and Negisho, 2012). This will be more pronounced in an Acric Plinthosol soil due to the increase in sesquioxides and clay content in deeper soil layers (Fey, 2010b; Sharpley, 2003). These soil properties promote P fixation thus less soil solution P availability. Similarly, Neugschwandtner et al. (2014), Calegari et al. (2013) and Franzluebbers and Hons (1996) reported more available P in the surface and a sharp decline with depth, ascribing this phenomenon to surface addition of fertilisers and crop residues. According to Calegari et al. (2013), black oat and blue lupine species should be included in a crop rotation system to promote P cycling in the highly weathered soils with high P fixation capacities under no-tillage systems.

Table 2. 4: The interaction effect of tillage and residue practice on soil P levels (mg kg^{-1}) based on published results from the Bethlehem trial.

			Tillage practice		
Soil depth (mm)	**Year**	**Straw management**	**No-tillage**	**Stubble mulch**	**Ploughed**
0-50	[1]2001	Unburnt	27.00	26.00	21.00
	[2]2004	Unburnt	33.30	36.20	22.20
	[3]2013	Unburnt	*28.61	*22.74	*19.82
	[1]2001	Burnt	31.00	30.00	24.00
	[2]2004	Burnt	43.30	36.80	26.40
	[3]2013	Burnt	*28.98	*23.13	*24.18
¶50-150	[1]2001	Unburnt	25.00	28.00	20.00
	[2]2004	Unburnt	30.85	32.10	22.75
	[3]2013	Unburnt	*28.28	*22.13	*17.74
	[1]2001	Burnt	30.00	35.00	27.00
	[2]2004	Burnt	34.65	36.65	26.60
	[3]2013	Burnt	*29.98	*22.60	*24.37
150-250	[1]2001	Unburnt	22.00	21.00	19.00
	[2]2004	Unburnt	28.60	33.20	23.40
	[3]2013	Unburnt	*20.34	*16.97	*16.31
	[1]2001	Burnt	23.00	26.00	25.00
	[2]2004	Burnt	34.70	37.70	31.60
	[3]2013	Burnt	*15.97	*18.25	*22.64
250-350	[2]2004	Unburnt	13.60	16.90	19.10
	[3]2013	Unburnt	*11.48	*11.97	*12.35
	[2]2004	Burnt	17.60	20.40	25.30
	[3]2013	Burnt	*9.96	*13.12	*17.74

Source= [1]du Preez et al. (2001), [2]Kotzé (2004), [3]Loke et al. (2013); *=the data was significant at $p<0.05$; Kotzé (2004) and Loke et al. (2013) used somehow different sampling depth intervals to du Preez et al. (2001) thus ¶; P (50-150 mm) = Average of 50-100 and 100-150.

2.9.1 Fractions of soil phosphorus as affected by different conservation agriculture practices

Phosphorus can be clustered into many pools namely: labile, moderately labile and non-labile P pools based on their susceptibility to decomposition (Agbenin and Anumonye, 2006). Phosphorus fractions and their associated pools are shown in Table 2.5. These P fractions can be further clustered into labile (resin P, $NaHCO_3$ Pi, $NaHCO_3$ Po), moderately labile (NaOH Pi, NaOH Po) and non-labile (HCl Pi and residual P) organic and inorganic P pools (Agbenin and Anumonye, 2006). The moderately labile pool is in equilibrium with labile P pool (Nziguheba et al., 1998) and it is largely affected by crop residue quality and environmental characteristics.

Table 2. 5: The various fractions of phosphorus and their pertinent pools (Source: Daroub et al., 2001).

Phosphorus fractions	Phosphorus pool
Resin P, NH_4Cl Pi, $NaHCO_3$ Pi, Po	Labile P
NaOH I Pi	Aluminium (Al) bound P
NaOH I Po	Moderately labile P
NaOH II Pi, Po	Physically protected P
HCl Pi	Calcium bound P
Residual P	Recalcitrant P

A recent study conducted using intermediate fertiliser N (40 kg ha^{-1}) treatments in the Bethlehem trial showed that labile Pi and stable Pi fractions were higher under no-tillage and stubble mulch as opposed to conventional tillage, although Po increased under conventional tillage and decreased under no-tillage and stubble mulch while residue burning increased the stable P fractions (Ncoyi et al., 2020). These findings raised the following question: “Do the soil P fractions vary with tillage and straw management at a higher N rate”? Elsewhere, Margenot et al. (2017) evaluated tillage (conventional tillage or reduce tillage) and residue (removal or retention) management effects on P availability on a highly weathered soil in Kenya. After nine years of investigation, residue management did not have any effect on P fractions and phosphatase activities in all sampled depths, but reduced tillage increased labile and total P availability in the 0-150 mm soil depth. The lack of significant effects was assumed to be the result of the low amount of residues retained and perhaps the short duration of investigation (Daroub et al., 2001). The significant correlation between labile ($NaHCO_3$Pi, Po, NaOH Pi, Po) and less labile (HCl Pi) P fractions with P adsorption maxima (Margenot et al., 2017) indicated the possible effects of these P fractions on P sorption. This study emphasized the effects of reduced tillage over conventional tillage although conventional tillage is better than other land management practices in terms of P accumulation.

Katsalirou et al. (2016) evaluated the effects of continuous conventional tillage with winter wheat and other land management systems (undisturbed land for over 50 years, heavily grazed pasture with more than 50 animals per hectare, moderately grazed pasture with 25 animals per hectare) on the P cycling dynamics in semi-arid prairie soils in Oklahoma. Thirty years of continuous winter wheat cultivation significantly reduced microbial P pool and phosphatase activities but accumulated plant-available P due to fertiliser application over the years. Grazing did not have any significant effect on P, but undisturbed land had an improved, near-natural soils P cycling ability.

Other studies highlighted the importance of tillage, residue management, fertiliser management and cropping sequences on P fractions. For example, Reddy et al. (2014) investigated the long-term effects of wheat residue management (residue surface retention under no tillage, burning or incorporation under conventional tillage), and fertiliser (farmyard manure or inorganic fertiliser) management on P fractions and adsorption behaviour of a vertisol in a soybean/wheat rotation system in a tropical sub-humid area in India. Residue incorporation/retention and manure or fertiliser improved labile ($NaHCO_3$ Pi, Po) P fractions and reduced P sorption compared to residue burning. The stable (HCl Pi, residual P) P fractions were not affected by fertiliser additions or residue management. Residue incorporation or retention encourages residue decomposition and ultimately improved P availability potentially through competition for sorption sites between phosphate ions and organic acids as well as the formation of metal ions that blocks sorption sites (Nziguheba et al., 1998). Tiecher et al. (2012) investigated soil organic P forms under different tillage (conventional tillage and no tillage) systems and winter crops (black oat, blue lupin, hairy vetch, oilseed radish, fallow, winter wheat) in a long-term experiment situated in the tropical sub-humid area in Brazil. No-tillage improved the availability of labile and moderately labile P fractions while black oats and blue lupin improved the availability of labile P fractions in the soil surface under no-tillage. These findings proved the importance of residue management, fertiliser management and cropping sequences on microbial interactions in the P cycle, especially in highly weathered subtropical soils under the no tillage systems where large amounts of residues are returned to the soil annually. Some crops e.g. blue lupin and black oat can secrete large amounts of organic acids such as citrate, malate and fumarate that can displace sorbed P from the adsorption sites to attain large cycled P. These effects are more pronounced under no-tillage (Calegari et al., 2013). This agrees with Dube et al. (2013) and Gichangi et al. (2009); that there is a possibility of reducing P fertiliser and optimising the use of labile soil organic P pool from crop residues under CA systems in future.

2.9.2 The effects of soil organic carbon on phosphorus adsorption

It is acknowledged that P availability in the soil is affected by a range of processes i.e. soil type, pH, SOM, Fe and Al, fertiliser placement (Dorneles et al., 2015; Asomaning, 2020). As such the P content measured does not necessarily reflect the amount of P available to crop. Phosphorus availability in the soil is driven by both the adsorption (physical or chemical attachment of P into soil colloids) and precipitation (formation of insoluble P complexes) processes collectively referred to as ‘sorption’, depending on the prevailing soil properties (Asomaning, 2020). These processes occur simultaneously in the soil and they are very difficult to distinguish (Von Wandruszka, 2006). Phosphorus sorption has been shown to significantly respond to farmers’ management practices such as tillage, crop rotation and residue management. For example, Gou et al. (2020) found low adsorption in the soils that rotated pea with maize and soils that had continuous taro, while P adsorption was lower under no-tillage versus conventional tillage on the Rhodic Paleudult and Hapludox (Fink et al., 2016). This was ascribed to higher SOM under no-tillage and not necessarily the mineralogy which is often the overriding factor in P sorption. These findings were complemented by Mnthambala et al. (2016), whereby no-tillage and crop rotation reduced the P adsorption capacity compared to conventional tillage. The long-term cropping sequences affect the soil physicochemical properties and ultimately P adsorptive capacities (Guo et al., 2020; Montalvo Grijalva, 2014; Noack et al., 2014; Jagadamma et al., 2012; Hunt et al., 2007). For example, Hunt et al. (2007) showed the importance of maize (*Zea mays* L.) and crimson clover (*Trifolium incarnatum* L.) residue decomposition on reducing soil P sorption and increasing its bioavailability for crop uptake while hairy vetch (*Vicia villosa* L.) favoured the formation of new sorption sites. This shows that different crops have different effects on P cycling.

The effects of soil physicochemical properties on P adsorption are well documented (Singh et al., 2017; Muindi et al., 2014; Jagadamma et al., 2012; Li et al., 2007). Soil adsorptive capacities for P were improved by residue retention as opposed to residue burning (Reddy et al., 2014) and this was explained by the decomposition of retained residues. These findings show that crop sequences, crop residue retention, fertiliser addition, and tillage practices in addition to soil types and soil physicochemical properties, have positive effects on P sorption.

2.10 Potential interaction effects of soil organic carbon and phosphorus fractions in conservation agriculture systems

Crop residues release organic acids which compete with available P for sorption sites upon decomposition (Nziguheba et al., 1998). The competition of SOM and P for adsorption sites is well documented (Yang et al., 2019; Maluf et al., 2018; Guppy et al., 2005; Kastelan-Macan and Petrovic, 1996). Some of the studies reported that SOM removal increased P availability (Shirvani et al., 2005; Debicka et al., 2016), and this may have been due to variations in the soil types studied. As much as the relationship between SOM and P has been established, some studies argue that it is only certain fractions of organic matter that significantly relate to P availability/adsorption. For example, Maluf et al. (2018) reported that adding humic acids into an oxisol reduced P adsorption and made P more available while the presence of oxalate and organic matter improved P availability (Bhatti et al. 1998). This competition between oxalate and P further confirmed the findings by Violante et al. (1991). There are also some studies suggesting that the labile and highly reactive pools of C, such as DOC, have a significant effect on P adsorption. For example, Hunt et al. (2007) showed that DOC can use various mechanisms to make P available in the solution i.e. (1) DOC competes with P for adsorption sites e.g. negatively charged DOC compounds such as malate and oxalate among others compete with P for sorption sites; (2) coats Fe and Al so that they are unable to fix P and (3) forms cation bridges to adsorb P. All these processes are expected because of the nature of the DOC (Bolan et al., 2011; Gmach et al., 2020). Based on these findings, the effects of soil management, soil properties as well as labile fractions of SOC on P adsorption are significant; suggesting that dissolved organic C can reduce P sorption. The effect of SOM on P adsorption has not been tested using the dissolved organic C from wheat residues. As such, there is a need to further investigate the relationships between labile SOM fractions (specifically dissolved organic C from wheat residues), soil physico-chemical properties and soil management practices on P availability in South African wheat production systems, considering the variation in soil types and climate.

2.11 Summary and prospects

There is a lack of consensus about the magnitude of positive benefits of CA practices (crop rotation, reduced tillage and crop residue retention) on soil quality parameters, SOC, P availability and ultimately its role on crop yield and farmers' profit improvement. Recent evidence suggests that diverse cropping sequence that consists of legumes will potentially improve soil quality and grain yields of the subsequent crops regardless of the climatic conditions or soil type. Cropping sequence effects on soil quality and wheat yield in South African soils and production systems are not well understood and require further investigation. Most of the field trials on CA were conducted over a short duration of time before conclusive results could be established due to a lack of stable/ well maintained long-term trials. Also, sampling was mostly limited to 650 mm, yet there are possibilities to study SOC up to 1000 mm at least. Agricultural researchers must invest in well maintained long-term trials. New evidence shows that labile SOC fractions may influence other nutrient gradients e.g. P availability, and such effects may be dependent on soil types, climatic conditions, texture and cropping systems. Based on a distillation of research findings produced from a 40-year-old wheat-fallow trial, it was found that no-tillage conserves more soil moisture, improves N, SOC, P cycling, and soil microbial community compared to ploughing. Burning might increase nutrient requirements in these production systems. The soil quality parameters in the Bethlehem long term trial were last studied after 32 years since trial inception, thus there is a need to understand if they are the same or higher after 40 years of the trial. Also, previous studies only focused on the 40 kg N ha^{-1} with less residue input. The results could be different or higher in the 60 kg N ha^{-1} where residue input could be higher. There is also a need to investigate the effect of SOC and its labile fractions from different tillage, residue management and cropping sequences on P sorption and availability since wheat is produced in various regions with different SOC accumulation levels. For example, could sorption of DOC from wheat straw reduce P sorption and increase availability?

CHAPTER 3: SELECTED QUALITY PARAMETERS OF OXIDIC SOILS AS AFFECTED BY CROPPING SEQUENCES UNDER IRRIGATED WHEAT-BASED CONSERVATION AGRICULTURE IN KWAZULU-NATAL, SOUTH AFRICA

ABSTRACT

Cropping sequences effects on carbon (C) sequestration, nutrient availability and overall soil quality, in wheat (*Triticum aestivum* L.)-based conservation agriculture (CA) systems are not well understood. The main objectives of this study were to determine the effects of cropping sequences and soil depth on soil C stocks, and fractions of soil organic C and P of Oxidic soils under irrigated wheat-based CA. Sampling was conducted on CA farms where wheat was rotated with either soybean (*Glycine max* L.) or maize (*Zea mays* L.) in CA systems of KwaZulu-Natal (KZN), South Africa. The soil was sampled at 200 mm increments from 0 to 1000 mm depths between July and August 2017. All the samples were analysed for organic carbon (C) particulate organic C (POC), mineral associated C, and bulk density, and total C stocks were calculated. Samples from the 0-200 and 200-400 mm depths were further analysed for total N, inorganic phosphorus (P) fractions, pH, exchangeable acidity (EA), exchangeable potassium (K), calcium (Ca) and magnesium (Mg), extractable zinc (Zn) and copper (Cu) and cation exchange capacity (CEC). Soil C stocks, organic C, and total N were not significantly different across cropping sequences, but significantly ($p<0.05$) decreased with soil sampling depth. Over 94% of total C was associated with the mineral fraction, thus protected against decomposition. Labile P ($NaHCO_3$ Pi), soil pH, CEC, and exchangeable K, Ca, and Mg concentrations were higher after maize, while NaOH I Pi, acid saturation, and Ca: Mg were lower, compared to soybean. Extractable P, $NaHCO_3$ Pi, K, and Zn concentrations were higher in the 0-200 mm depth than the 200-400 mm. Physically protected P (NaOH II Pi), residual P and Cu were not significantly different across cropping sequences and soil depths. There were significant positive correlations between Bray-1 P and POC fractions. The findings imply that cropping sequences have limited influence on C sequestration in these CA systems, but wheat crop preceded by maize could benefit from higher soil pH, K and labile P.

Keywords: crop rotation, carbon fractions, maize, nutrient availability, phosphorus fractions, soybean.

3.1 INTRODUCTION

Conservation agriculture (CA), based on a combination of the four key principles of (1) minimum tillage, (2) crop rotation, (3) permanent soil cover (Derpsch, 2005), and (4) efficient fertiliser use (Vanlauwe et al., 2014), have been shown to improve soil quality and crop profitability in many production systems (Keil et al., 2020; Yigezu et al., 2019). Minimum tillage is known to improve soil aggregate stability, soil resilience to structural degradation, and also to minimize mycorrhizal hyphae breakdown (Verhulst et al., 2010). Rotating unrelated crop species and retention of crop residues maintains nutrient availability, improves soil organic matter (SOM) quality (West and Post, 2002) and quantity, microbial biomass and biodiversity, porosity, moisture, and temperature, and protects the soil against erosion (Verhulst et al., 2010).

Sosibo et al. (2017) documented higher soil organic carbon (SOC) content, phosphorus (P) deficiency, and acidity problems in the highly weathered Oxidic soils of KwaZulu-Natal (KZN) compared to other irrigated wheat (*Triticum aestivum* L.) production regions of South Africa. The oxidic soils in South Africa include the Hutton, Clovelly and Griffin forms (Soil Classification Working Group, 1991), which are equivalent to Oxisols in the US Soil Taxonomy (Soil Survey Staff, 2010) and Ferralsols (IUSS Working Group WRB, 2015). On these soils, farmers apply large amounts of inorganic P to meet wheat requirements. The continual increase in fertiliser prices makes wheat production progressively less profitable in South Africa (De Wet and Liebenberg, 2018; Dube et al., 2020). Sosibo et al. (2017) also reported generally higher plant-available P from intensive 'wheat on maize *(Zea mays* L.)' rotations or cereal-based cropping systems across South Africa. A possible explanation was that such production lands could retain high SOC through the retention of sufficient quantities of biomass (Sosibo et al., 2017). This also suggested a need to further investigate relations between P availability, fractions of P, organic carbon, and cropping sequence in CA systems. Hence, there is a quest for focused studies on the effects of cropping sequences on the abundant C, soil acidity, and P deficiency in '*no-till*' systems of KZN. The most popular summer crops in KZN are soybean (*Glycine max* L.) and maize in the past 20 years of CA. The relationship between cropping sequences and soil quality parameters under CA on Oxidic soils of KZN is not clearly understood. This knowledge is essential for crop rotation recommendations and fertiliser management guidelines for effective CA practices.

The ability of soils to sequester C in various fractions lies mainly on biophysical (climate, soil type, vegetation) and soil management (tillage, fertiliser, and crop residue management) factors (Petrokofsky et al., 2012; Smith et al., 2012). The Paris Climate Agreement of the United Nations Climate Conference held in 2015 aimed to reduce global warming and greenhouse gases emitted to the atmosphere through its initiative of "*4 per 1000*" (Corbeels et al., 2019; Schütte et al., 2019), through storing C in the soil (Paustian et al., 2016). This initiative has encouraged the investigation of soil C stocks up to at least 1000 mm depth to probe the potential of storing C in deeper soil layers (Torres-Sallan et al., 2017). It is not clear whether differences in crop sequencing could affect soil C stocks or the C fractions that dominate at different soil layers in wheat-based CA systems. The mineral associated C is generally stabilised against microbial decomposition, increases soil aggregation, water, and nutrient retention (Chenu and Plante, 2006). On the other hand, the light OM fractions (water-soluble OM and particulate OM) are important as a substrate of soil microorganisms and as sources of nutrients (Snapp and Grandy, 2011). Several studies have looked at humin, humic and fulvic (Guimarães et al., 2013; Jamala and Oke, 2013) fractions of soil organic matter but the concept of humification is being questioned in recent literature (Lavalle et al., 2020; Lehmann and Kleber, 2015) as the extraction of these fractions uses harsh alkaline chemicals that mimic the inaccurate presentation of naturally occurring SOM fractions. As such more recently, studies focus on particulate organic C and mineral associated C (Romaniuk et al., 2018; Blanco-Moure et al., 2013) that are separated physically based on their size and density. Soil C and P fractions are pivotal in explaining soil productivity and the quality of SOM being generated by various cropping systems.

The labile, moderately labile, and non-labile fractions of P are classified based on how readily available they are to crops and microorganisms (Agbenin and Anumonye, 2006). Potential differences in C fractions in CA systems may have effects on soil P fractions. Soil organic matter inputs decrease P adsorption capacity of highly weathered soils and thus increase the availability of P to plants (Iyamuremye et al., 1996). However, P deficiency has also been reported for soils with high organic matter levels in South Africa (Sosibo et al., 2017). The increase in SOM through the retention of cereal crop residues with a high C: N ratio in conservation-farming practices has been reported to result in net immobilisation of P (Lupwayi et al., 2007). While CA has largely been successful in some areas, some reports suggest that some farmers have not realised the benefits they hoped for (Findlay, 2015; Lal, 2019). There is a need to investigate crop management systems relations with soil quality on Oxidic soils of KZN where P deficiency and soil acidity are major problems. Therefore, the main objectives of this study were to determine the effects of cropping sequences and soil depth on soil C stocks, and fractions of soil organic C and P of Oxidic soils under irrigated wheat-based CA. It was hypothesized that there would be significant differences in soil organic C and P fractions, as well as other important soil quality parameters in wheat fields, depending on the type of crop preceding the wheat as well as sampling depth.

3.2 MATERIAL AND METHODS

3.2.1 Description of study sites

The study was conducted on soils from irrigated wheat farms in the province of KwaZulu-Natal (KZN), South Africa. Specific farms were located in Bergville, Colenso, and Winterton. In this region, irrigated wheat is mostly produced at high altitude areas ranging from 959 to 1026 m.a.s.l, with highly weathered and well-drained Oxidic soils. These soils are described based on their uniform colours as a result of iron enrichment through weathering (Fey, 2010a). The soils are classified as various families of Hutton, Griffin, Clovelly, and Shortlands, among others (Soil Classification Working Group, 1991). They are deep soils characterised by orthic A, red apedal, yellow-brown apedal, or red structured B (Fey, 2010a). Internationally, these soils can be translated to Acrisols, Alisols, Ferralsols, Luvisols, Lixisols, Arenosols, Cambisols, or Nitisols (IUSS Working Group WRB, 2015). The climate (Table 3.1) is sub-humid and warm, with average temperatures ranging between 17.3 °C and 18.1 °C and an average annual rainfall of 723–843 mm with most of the rain falling in January (en.climate-data.org/ accessed on 20 February 2020). Representative farmers' fields were selected from the South African National Wheat Cultivar Evaluation Program database of the Agricultural Research Council. The farmers were contacted to request information about tillage practice and the crop produced before wheat planting, as well as permission to sample from their fields. All farms sampled practised conservation agriculture with minimum tillage, retention of residues, and had planted either soybean or maize before wheat. Twenty representative fields were systematically selected in order to have ten fields where wheat was preceded by soybean and another ten where the wheat was preceded by maize. On average, farmers apply compound fertilisers to supply about 51.5 ± 17.6 kg N ha^{-1}, 56.8 ± 11.9 kg P ha^{-1}, 71.0 ± 11.0 kg K ha^{-1} and 0.5% Zn fertiliser, as well as 2 t ha^{-1} of lime annually before wheat planting. Nitrogen (166

± 8.50 kg ha^{-1}) is later applied as topdressing during the jointing stage in the form of urea or a combination of urea and the less acidifying lime ammonium nitrate.

Table 3. 1: Climatic conditions for the KwaZulu-Natal irrigated wheat production region.

	Study locations		
Climate parameters	Bergville	Colenso	Winterton
Altitude (m.a.s.l)	1119	959	1026
Average rainfall (mm)	843	723	789
Minimum temperature (°C)	9.9	10.5	10.5
Maximum temperature (°C)	22.3	23.4	22.7
Average annual temperature (°C)	17.3	18.1	17.8

°C, degrees celcius; m.a.s.l, metres above sea level; mm, millimetres.

3.2.2 Soil sampling

The current study is a follow-up to Sosibo et al. (2017). As such, soil sampling depth was maintained (200 mm increments) for comparison purposes. Soil samples were collected following a random sampling procedure from 0-1000 mm depth in 200 mm increments using a 50 mm diameter soil core sampler. Four representative samples were randomly collected from each field and bulked to form composite samples per layer. Likewise, soils (0-200 and 200-400 mm) were also collected from virgin grasslands with similar conditions as wheat farms to determine the effects of agroecosystems when compared with natural grassland. Soil sampling was done at least two months after wheat planting between July and August 2017 during the wheat growth period. The CA farmers apply fertilisers directly to the wheat rows using no-till implements. As such, sampling was done between wheat rows to minimise the effects of the fertiliser applied at planting. Visible debris was removed from the samples before they were air-dried and milled (< 2 mm).

3.2.3 Physico-chemical analyses

The samples were analysed for soil organic C using Walkley–Black method (Combs and Nathan, 1998). Bulk density was determined using the core method for all depths. Soil C stock (t ha^{-1}) was calculated using SOC, bulk density (g cm^{-3}) and depth thickness for each sampling interval (Gattinger et al., 2012). Soil total nitrogen (N) was determined using a Leco TruMac CNS/NS analyser (TruMaC CNS/NS, USA). Bray 1 extractable P, pH (1:5 soil to 1 M KCl suspension), exchangeable acidity (1 M KCl), exchangeable Ca, Mg, and K (1 N NH_4OAc at pH 7), and 0.1 M HCl extractable zinc (Zn) and copper (Cu) were analysed for samples from the 0-200 and 200-400 mm depths using procedures of the Non-Affiliated Soil Analysis Work Committee (1990). Cation exchange capacity (CEC) was calculated from the sum of exchangeable acidity [H and Al] and basic [Ca, Mg, K, and Na] cations ($cmol_c$ kg^{-1}). Acid saturation (AS) was calculated from exchangeable acidity as a percentage of the CEC. The Ca: Mg ratio was calculated from Ca and Mg contents in $cmol_c$ kg^{-1} (Non-Affiliated Soil Analysis Work Committee, 1990).

3.2.4 Soil carbon fractions

Macro- and micro particulate organic carbon (POC) fractions were determined following the procedure by Cambardella and Elliot (1992) for soils sampled from 0-1000 mm depth. Three sets of each air-dried soil sample (50 g) were suspended in 100 ml of a 5g L^{-1} sodium hexametaphosphate solution (Calgon) in a tightly sealed bottle. The mixture was shaken on an end-to-end shaker for one hour and poured over a set of 250 and 50 µm sieves. Sieves with soil were then rinsed with distilled water until the water was clear. The soil in the sieves was then back-washed into glass beakers (50-250 and >250 µm POC) for each sample. The samples were dried at 60 °C for 24 h, weighed, milled, and analysed for two fractions, namely: POC_{50-250} (fine POC) hereafter (micro POC) and $POC_{250-2000}$ (Coarse POC) hereafter (macro POC) using the Walkley Black method. Non-particulate organic carbon (non-POC) hereafter (mineral associated C) was calculated as the difference between SOC and total POC (macro POC + micro POC) following a method by Cambardella and Elliot (1992). Water-soluble carbon (WSC) was analysed following a method by Sparling et al. (1998) whereby three sets of each air-dried soil samples (2 g) were suspended in 10 ml of distilled water in the tightly sealed test tubes and incubated at 70°C for 18 h. After incubation, the test tubes were hand-shaken, filtered and the WSC was analysed using the Walkley Black method.

3.2.5 Soil phosphorus fractions

Fractions of soil P were sequentially extracted following the Hedley et al. (1982) method, as modified by Chen et al. (2000). The procedure utilizes extracting reagents of varying ionic strengths and capable of breaking relevant bonds within the soil colloids, thus solubilise occluded or mineral bound P into the soil solution. This method determined inorganic P (Pi) from direct analysis of the extract filtered after 16 h of agitation. Some of the filtered extracts following alkaline ($NaHCO_3$ and NaOH) extractants were digested with perchloric acid (HNO_3 + $HClO_4$) to determine total P (Pt). Organic P (Po) was calculated as the difference between Pt and Pi. Three sets of 0.5 g of air-dried soil per sample were initially suspended with 30 ml of 1M NH_4Cl followed, sequentially, by 30 ml of 0.5M $NaHCO_3$, 30 ml 0.1M NaOH I, 30 ml 1M HCl and 30 ml of 0.1M NaOH II in a test tube. After all the extractions, the remaining soil was also subjected to perchloric (HNO_3 + $HClO_4$) digestion to determine residual P. After adding each extractant, the mixture was agitated for 16 h on an end to end shaker, centrifuged, filtered and the extract was analysed colourimetrically for P using the Seal AA3 HR Phosphate XY-2 auto analyser (Seal Analytical, Germany), which uses molybdenum/ascorbic acid procedure (Murphy and Riley, 1962) for the fractions NH_4Cl Pi, $NaHCO_3$ Pi, $NaHCO_3$ Pt, NaOH I Pi, NaOH I Pt, HCl Pi, NaOH II Pi, NaOH II Pt and residual P. These P fractions can be clustered into labile (NH_4Cl Pi, $NaHCO_3$ Pi, $NaHCO_3$ Po), moderately labile (NaOH Pi, NaOH Po) and non-labile (HCl Pi and residual P) pools based on their susceptibility to decomposition (Agbenin and Anumonye, 2006). Ammonium chloride extractable- P and organic P fractions were not detectable and were therefore not reported in this chapter.

3.2.6 Statistical data analyses

The virgin soils data were analysed using a two-tailed pairwise comparison t-test while the farmers' fields' data were subjected to a non-parametric Kruskal Wallis H statistical test at a 95% confidence level to evaluate the differences between previous crop (maize or soybean) and sampling depth as treatments on Genstat 18th edition. This test uses the critical Chi-square (χ^2) value based on the confidence level and the degrees of freedom (d.f) for each treatment to determine whether the medians of two or more groups are different. The null hypothesis (H_0: population medians are equal) is rejected when the H statistic value is larger than the tabled critical χ^2 probability (Chan and Walmsley, 1997) or if the χ^2 probability is >0.05. The Mann-Whitney post hoc test was used to locate the source of differences on the parameters that varied significantly with previous crop or soil depth. The range (min-max) was presented with means for all the study parameters together with H and χ^2 probability to show significant differences between treatments. The strength and direction of relationships between parameters significantly affected by treatments were tested using a two-sided correlation between Spearman's correlation *r* coefficients and 0 at the 95% confidence limit. The results were discussed in comparison to the virgin soils data (Table 3.7).

3.3 RESULTS

3.3.1 Differences in carbon and phosphorus fractions across cropping sequences and soil depths

Soil C stocks, organic C, and its fractions were not significantly affected by cropping sequence but varied significantly with depth (Table 3.2). The $NaHCO_3$ Pi and NaOH I Pi fractions varied significantly with the previous crop, while Bray 1 extractable P and $NaHCO_3$ Pi varied significantly with soil depth (Table 3.2). The NaOH II Pi and residual P fractions did not differ significantly with either previous crop or soil depth (Table 3.2).

Table 3. 2: Significant differences per Kruskal-Wallis H test at a 95% confidence level (n=20) for C and P fractions in the soil.

	Significance of χ^2 values	
	Cropping sequence	Soil depth
Organic carbon	ns	**
Carbon stock	ns	**
Macro POC	ns	**
Micro POC	ns	**
Min. assoc. C	ns	**
WSC	*	ns
Extractable phosphorus	ns	**
$NaHCO_3$ Pi	*	**
NaOH I Pi	*	ns
NaOH II Pi	ns	ns
Residual phosphorus	ns	ns

*$\chi^2 < 0.05$; ** $\chi^2 < 0.001$; C, carbon; Min. assoc. C, mineral associated carbon; ns, no significant differences; Pi, inorganic phosphorus; POC, particulate organic carbon; WSC, water-soluble carbon.

3.3.1.1 Soil carbon stock, concentrations, and fractions

Total soil C stock and organic C concentrations significantly decreased with soil depth with the 0-200 mm having higher levels, while the 400-600, 600-800 and 800-1000 cm depths did not differ (Table 3.3). The 0-200 mm depth had >20 g C kg^{-1}, while beyond 800 mm, the C content was <10 g C kg^{-1}. However, it is important to note that 74.3 (34%) and 145 t ha^{-1} (66%) of the profile soil C stock were in the 0-200 and 200-1000 mm depths, respectively. Furthermore, macro POC, micro POC, and mineral associated C concentration was higher in the 0-200 mm than in the 200-400 mm soil depth (Table 3.3). Over 94% of the total C was in mineral associated form while the difference was in POC (6%). The WSC in the 0-200 and 200-400 mm depths was significantly higher (H= 4.99; χ^2 probability =0.025) under soybean (6.59 mg kg^{-1}) than under maize (3.81 mg kg^{-1}), with no significant differences between the depths.

Table 3. 3: Soil C stocks (t ha^{-1}) and fractions (g kg^{-1}) variations across soil sampling depths and cropping sequences.

	C stock	Organic C	Macro POC	Micro POC	Min. assoc. C
Depth (mm)					
0-200	3.86-184 (74.3)a	1.50-45.9 (25.4)a	0.34-0.79 (0.70)a	0.46-0.79 (0.70)a	0-44.4 (24.0)a
200-400	3.86-96.1 (55.1)b	0.80-30.6 (16.7)b	0-0.70 (0.20)b	0.20-0.80 (0.60)b	0.4-29.8 (15.8)b
400-600	0.97-71.0 (33.9)c	0.20-19.0 (10.3)c	0-0.40 (0.10)c	0.10-0.80 (0.40)c	0-18.5 (9.80)c
600-800	4.47-101 (30.4)c	0.80-26.6 (9.40)c	0-0.40 (0.10)c	0-0.80 (0.30)c	0.3-26.4 (9.00)c
800-1000	0.72-137 (25.5)c	0.20-25.2 (6.40)c	0-0.40 (0.10)c	0-0.80 (0.30)c	0.10-24.0 (6.00)c
H value	30.29	37.48	48.47	49.30	33.78
χ^2 probability	<0.001	<0.001	<0.001	<0.001	<0.001
Cropping sequence					
Maize	0.97-114 (41.1)	0.20-43.2 (13.5)	0-0.80 (0.30)	0-0.80(0.50)	0-41.6 (12.7)
Soybean	0.72-184 (46.5)	0.20-45.9 (13.8)	0-0.80 (0.20)	0-0.80(0.50)	0-44.4 (13.1)
H value	0.15	0.02	0.03	0.10	0.03
χ^2 probability	0.69	0.88	0.88	0.75	0.87

Values in parentheses indicate the means and values outside parentheses indicate the data range; C, carbon; Min. assoc. C, mineral associated carbon; χ^2, Chi-square critical probability value; H value, Kruskal Wallis H test; POC, particulate organic carbon. Similar letters in a column indicate medians that did not differ from each other.

3.3.1.2 Bray 1 extractable and other fractions of phosphorus

As expected, the Bray 1 extractable P and $NaHCO_3$ Pi concentrations were higher in the 0-200 than 200-400 mm depth (Table 3.4). Soils previously under maize had more $NaHCO_3$ Pi, and less NaOH I Pi than after soybean (Table 3.4).

Table 3. 4: Variations in soil P fractions (mg kg^{-1}) across cropping sequences and soil depths.

	Bray 1 P	$NaHCO_3$ Pi	NaOH I Pi	NaOH II Pi	Residual P
Depth (mm)					
0-200	15.4-132	33.6-788	60.4-189	7.50-224	4.36-31.6
	(47.4)a	(213)a	(118)	(82)	(17.7)
200-400	1.40-40.2	0-191	12.4-357	6.34-390	0-42.1
	(10.8)b	(58)b	(152)	(95)	(13.4)
H value	23.97	13.14	1.057	0	2.213
χ^2 probability	<0.001	<0.001	0.304	1.00	0.137
Cropping sequence					
Maize	2.40-132	0-788	12.4-296	7.50-390	0-42.1
	(35.9)	(192)a	(113)b	(99)	(16.8)
Soybean	1.40-60.0	2.72-398	60.4-357	6.34-223	0.72-31.6
	(22.3)	(79)b	(157)a	(77)	(14.3)
H value	1.00	4.68	4.01	0.70	0.80
χ^2 probability	0.32	0.03	0.05	0.40	0.37

Values in parentheses indicate the means and values outside parentheses indicate the data range; Chi-square critical probability value; H value, Kruskal Wallis H statistic; P, phosphorus; Pi, inorganic phosphorus. Similar letters in a column indicate medians that did not differ from each other.

3.3.3 Other soil chemical properties across cropping sequences and soil depths

Cropping sequences differed significantly in terms of soil pH, AS, K, Ca, Mg, CEC, and Ca: Mg (Table 3.5). The soil previously under maize had higher soil pH and CEC, as well as exchangeable K, Ca and Mg concentrations, and lower AS and Ca: Mg than that under soybean-wheat (Table 3.6). Soil total N, exchangeable K, and Zn concentrations were higher in the 0-200 mm than in the 200-400 mm depth (Table 3.6). Extractable Cu concentration did not vary with either crop sequence or soil depth (Table 3.6).

Table 3. 5: Significant differences per Kruskal-Wallis test at a 95% confidence level (n=20) for soil properties under irrigated wheat fields in KZN.

Parameter	**$\chi2$ values for various soil properties**	
	Cropping sequence	Depth
pH (KCl)	*	ns
Acid saturation	*	ns
Total nitrogen	ns	**
Potassium	*	**
Calcium	**	ns
Magnesium	**	ns
CEC	**	ns
Ca: Mg	**	ns
Copper	ns	ns
Zinc	ns	**

*$\chi2$ probability < 0.05; ** $\chi2$ probability <0.001; ns, no significant differences; CEC, cation exchange capacity; KCl, potassium chloride.

Table 3. 6: Differences in selected soil properties of wheat fields across soil depths and cropping sequences.

	N	pH	K	Ca	Mg	CEC	Ca: Mg	AS	Cu	Zn
Depth (mm)										
0-200	0.28-1.79 (1.10)a	4.10-5.40 (4.67)	119-359 (223)a	639-2261 (1186)	123-767 (280)	4.86-18.8 (9.12)	1.63-5.78 (3.00)	0-10.6 (2.85)	1.02-2.70 (1.84)	2.29-17.9 (6.87)a
200-400	0.41-1.68 (0.70)b	4.20-5.50 (4.80)	52.6-300 (126)b	511-2315 (1143)	129-947 (334)	4.25-19.4 (9.14)	1.34-3.91 (2.47)	0-13.3 (3.54)	0.87-3.53 (1.94)	0.12-7.60 (2.13)b
H value	11.99	0.82	14.34	0.90	0.15	0.85	3.38	0.01	0.13	22.67
χ^2 probability	<0.001	0.364	<0.001	0.344	0.70	0.36	0.07	0.93	0.72	<0.001
Cropping sequence										
Maize	0.28-1.79 (0.90)	4.20-5.50 (4.88)a	80.0-359 (209)a	819-2315 (1454)a	162-947 (447)a	5.91-19.4 (11.8)a	1.34-3.23 (2.20)b	0-6.51 (1.26)a	0.87-3.53 (1.84)	0.62-7.06 (3.38)
Soybean	0.29-1.68 (0.80)	4.10-5.03 (4.59)b	52.6-288 (141)b	511-1422 (876)b	123-286 (167)b	4.25-10.0 (6.47)b	1.76-5.78 (3.27)a	0-13.3 (5.13)b	0.98-2.91 (1.94)	0.12-17.9 (5.62)
H value	0.21	5.23	5.80	14.75	24.24	19.20	15.81	7.9	0.90	2.90
χ^2 probability	0.65	0.02	0.02	<0.001	<0.001	<0.001	<0.001	0.003	0.34	0.09

Values in parentheses indicate the means and values outside parentheses indicate the data range; acid saturation (%); Ca, calcium (mg kg^{-1}); CEC, cation exchange capacity (cmolckg-1); $\chi 2$, Chi-square critical probability value; Cu (mg kg^{-1}), copper; H value, Kruskal Wallis H statistic; K, potassium (mg kg^{-1}); Mg, magnesium (mg kg^{-1}); N, total N (g kg^{-1}); Zn, zinc (mg kg^{-1}). Similar letters in a column indicate medians that did not differ from each other.

3.3.4 Comparison of cropped lands with virgin soils

Measured virgin soil properties did not differ significantly with depth; thus, all presented against the standard error of difference (Table 3.7). Virgin soils generally had a lower mean soil pH and lower concentrations of Bray 1 P, Ca, Mg, Ca: Mg, CEC and Zn and higher concentrations of AS and SOC (Table 3.7) compared to the cropped wheat fields (Tables 3.3; 3.6). The AS and SOC in the 0-200 mm depth were 7.24% and 27.3 g kg^{-1} respectively, in the virgin soils, while the wheat field had 2.85% AS (39% more) and about 13.7 g SOC kg^{-1} (50% less).

Table 3. 7: Chemical properties of virgin soils in the KwaZulu-Natal wheat production region (n= 4).

	Mean		
Soil properties	**0-200 mm**	**200-400 mm**	**SED**
pH	4.45	4.43	0.264
Acid saturation (%)	7.24	7.47	4.84
Organic carbon (g kg^{-1})	27.3	26.9	7.44
Extractable phosphorus (mg kg^{-1})	1.28	1.48	1.64
Exchangeable potassium (mg kg^{-1})	202	206	178
Exchangeable calcium (mg kg^{-1})	506	501	74.8
Exchangeable magnesium (mg kg^{-1})	187	188	33.3
Ca:Mg	1.69	1.65	0.201
CEC ($cmol_c kg^{-1}$)	4.92	4.94	0.829
Zinc (mg kg^{-1})	0.870	0.690	0.307

All studied soil parameters did not vary significantly with soil depth; SED, standard error of the difference of means.

3.3.5 Correlation of fractions of carbon and phosphorus

Soil pH was negatively correlated with acid saturation but was not significantly correlated to any fractions of C and P at the 0-200 mm depths (Table 3.8; clear shade). In the 200-400 mm depth (Table 3.8 under grey shades), AS was correlated positively with micro POC and Al bound P (NaOH I Pi), and negatively with Bray 1 extractable P and labile ($NaHCO_3$ Pi). Mineral associated C had a strong positive correlation with organic C and physically protected P (NaOH II Pi) and correlated negatively with labile P fraction ($NaHCO_3$ Pi). Bray 1 P was positively correlated with $NaHCO_3$ Pi at both the 0-200 and the 200-400 mm depths (Table 3.8) and with NaOH I Pi in the 0-200 mm depth (Table 3.8).

Macro POC negatively correlated with physically protected P (NaOH II Pi) in the 0-200 mm depth and positively correlated with micro POC and Bray 1 extractable P in both 0-200 and 200-400 mm depths (Table 3.8). Micro POC was positively correlated with Bray 1 extractable P and physically protected P in the 0-200 mm but negatively correlated with soil pH in the 200-400 mm depth. Residual P was positively correlated with Ca-bound P in the 200-400 mm and physically protected P in both 0-200 and 200-400 mm depths (Table 3.8). The labile P fraction ($NaHCO_3$ Pi) was positively correlated with NaOH I Pi in the 0-200 mm (Table 3.8) and SOC, soil pH in the 200-400 mm (Table 3.8).

Table 3. 8: Spearman's rank correlation coefficients between organic carbon and phosphorus fractions in the 0-200 mm (with clear shades) and 200-400 mm (with grey shades).

Variables	1	2	3	4	5	6	7	8	9	10	11
1 AS	-	-0.06^{ns}	0.09^{ns}	0.23^{ns}	-0.18^{ns}	0.14^{ns}	-0.07^{ns}	0.02^{ns}	-0.16^{ns}	0.22^{ns}	-0.88^{***}
2 Macro POC	0.21^{ns}	-	0.47**	-0.06^{ns}	0.44*	-0.22^{ns}	0.19^{ns}	-0.45*	0.13^{ns}	$-0,03^{ns}$	$-0,13^{ns}$
3 Micro POC	0.40^{*}	0.57^{**}	-	0.03^{ns}	0.35*	-0.05^{ns}	-0.03^{ns}	-0.34*	-0.07^{ns}	0.05^{ns}	-0.04^{ns}
4 Mineral C	-0.07^{ns}	-0.02^{ns}	0.15^{ns}	-	0.15^{ns}	0.26^{ns}	-0.24^{ns}	0.38*	0.01^{ns}	0.99^{***}	-0.16^{ns}
5 Bray 1 P	-0.34^{*}	0.46^{**}	0.26^{ns}	-0.05^{ns}	-	0.05^{ns}	0.63**	0.16^{ns}	0.44^{*}	0.18^{ns}	-0.03^{ns}
6 P residual	-0.15^{ns}	-0.01^{ns}	0.10^{ns}	-0.13^{ns}	0.26^{ns}	-	0.18^{ns}	0.57**	0.30^{ns}	0.27^{ns}	-0.20^{ns}
7 $NaHCO_3$ Pi	-0.33^{*}	0.41^{*}	0.18^{ns}	-0.33^{*}	0.72^{***}	0.25^{ns}	-	-0.06^{ns}	0.41^{*}	-0.22^{ns}	-0.22^{ns}
8 NaOH II Pi	-0.06^{ns}	-0.23^{ns}	0.04^{ns}	0.19^{ns}	0.19^{ns}	0.64^{***}	0.13^{ns}	-	-0.03^{ns}	0.38^{*}	0.10^{ns}
9 NaOH I Pi	0.33^{*}	-0.26^{ns}	-0.12^{ns}	0.08^{ns}	-0.12^{ns}	-0.28^{ns}	-0.28^{ns}	-0.13^{ns}	-	0.02^{ns}	-0.14^{ns}
10 Organic C	-0.06^{ns}	-0.01^{ns}	0.16^{ns}	1.00^{***}	-0.04^{ns}	-0.14^{ns}	-0.32^{*}	0.19^{ns}	0.08^{ns}	-	-0.16^{ns}
11 Soil pH	-0.87^{***}	-0.14^{ns}	-0.34^{*}	-0.02^{ns}	0.37^{ns}	0.19^{ns}	0.40^{*}	0.05^{ns}	-0.54^{**}	-0.03^{ns}	-

*$p<0.05$; ** $p<0.01$; ***$p<0.001$; ns, no significant differences; AS, acid saturation; C, carbon; P, Bray 1 extractable phosphorus; Pi, inorganic phosphorus; POC, particulate organic carbon.

3.4 DISCUSSION

Compared with immediately adjacent virgin soils (27.3 g SOC kg^{-1}), most of the cropped lands sampled in the current study still had lower SOC content on average (maize: 13.5 g kg^{-1}, soybean: 13.8 g kg^{-1}). This is below the minimum 20 g kg^{-1} SOC that is recommended for sustainable agricultural production (Musinguzi et al., 2013), and below this SOC content, soil deterioration may occur. It should be noted that before conversion to CA, conventional (mouldboard) tillage was used on these lands, exposing aggregate protected organic matter to rapid degradation (Beare et al., 1994; Busari et al., 2015). On the cropped lands, however, SOC levels and C stocks (e.g., 41.1 t ha^{-1} for maize; 46.5 t ha^{-1} for soybean) were similar across cropping sequences. This was not expected, as the general view is that higher biomass input following retention of maize residues contribute more C than legumes (Sosibo et al., 2017). However, the measured values were comparable to C stocks (47.1 ± 6.3 t ha^{-1}) accumulated by annual crops elsewhere (Ledo et al., 2020). The lack of differences of organic C and its stocks could be because C has since stabilized in this system, but at a lower level than the virgin soils, which are dominated by grassland. Grassland sequester more C than the cropped fields due to their high root biomass (Chen et al., 2000), in addition to rapid C mineralisation as a result of tillage. Furthermore, the short-term changes in carbon input induced by variation in crop sequencing may not make a significant impact on overall C stock. In some of these cropping systems, the cropping sequence was in the order: wheat/soybean/wheat/maize, making them similar in the long-term. Although the water-soluble C was extremely low compared to other fractions, it was higher in wheat fields preceded by soybean than maize. The WSC fraction is a sensitive fraction that can show changes in the short-term. The higher WSC under soybean is an indication that the straw from this crop is relatively more labile than maize, which supports greater decomposition and mineralisation of nutrients. This agrees with the results obtained by Zengqiang et al. (2016) who reported the little effect of maize residues on water extractable carbon and other labile organic carbon fractions. However, considering the low proportion of this fraction, its decomposition would not show a significant effect on overall SOC. Large quantities of crop residues that are retained through CA practice in these intensive, irrigated crop production systems, combined with fertiliser, explain the higher concentration of total N, SOC, macro POC, micro POC, and mineral C contents in the topsoil than in the 200-400 mm (Zengqiang et al., 2016). A decline of SOC content and its fractions with depth is due to the immobile nature of SOM (Baldock and Nelson, 2000) and the nature of CA, which minimizes soil turning such that SOM remains in the topsoil.

A higher concentration of mineral C, strongly correlated with SOC, compared to other C pools, suggests that most of the SOC may be associated with the soil mineral fraction (Table 3.8). This is in agreement with the study by Blanco-Moure et al. (2013) where mineral associated C accounted for 70-90% of the total SOC and Mikutta et al. (2006), who reported that more than 73% of their studied soils were associated with mineral associated C. This C is adsorbed to soil minerals and is physically protected within finer (<53 µm) soil aggregates (Lavalle et al., 2020; Chenu and Plante, 2006). Thus it is resistant to biological decomposition and may be a good atmospheric C reservoir (Jamala and Oke, 2013). Mineral associated C may also be associated with high clay content and high oxides (organo-mineral complexes) stabilising it from decomposition (Chang et al., 2020; Poirier et al., 2020). The soils used in the current study are highly weathered with high concentrations of oxides. These complexes may also increase P fixation through OM-Al/Fe oxide-P bridges (Fink et al., 2016), considering the positive correlation between mineral associated C and NaOH II Pi in the 0-200 mm depth (Table 3.8).

The higher Bray 1 extractable P concentration in the cropped soils compared to virgin soil (Table 3.7) could be explained by the addition of P as fertilisers for the different rotation crops, and higher pH and lower AS is associated with liming over the years. Lower P observed in the 200-400 mm could be a result of low P mobility in the no-till systems and lower pH, which resulted in greater fixation of P by Al and Fe oxyhydroxides. The soils studied had a mean pH below 5. Below pH 5, Al and Fe solubilise and could then precipitate as variscite ($Al\text{-}PO_4.2H_2O$) and strengite ($Fe\text{-}PO_4.2H_2O$) from the soil solution, and these forms of P are not available for plant uptake (Havlin et al., 2005). This view was supported by the low availability of $NaHCO_3$ and the high concentration of NaOH I Pi fraction (Al bound P fraction). The negative correlation between soil pH and Al bound P fraction, and a positive correlation with labile P fraction suggests that an increase in soil pH may favour availability of labile Pi and reduce Al-bound P fraction. The higher Bray 1 (47.4 mg kg^{-1}) extractable P and labile inorganic P ($NaHCO_3$ Pi) in the topsoil than the 200-400 mm depth was probably due to inorganic fertiliser additions and decomposing organic matter accumulated in the topsoil in the CA system with no-till (Verhulst et al., 2010). This P content was however slightly lower than the P (50 mg kg^{-1}) required for a target yield of 7 t ha^{-1} (ARC-SGI, 2015). Bray 1 extractable P measures readily available P just like $NaHCO_3$ and NaOH I Pi fractions. The results show that more P fertiliser is required for a wheat crop produced on the same soil after a summer soybean crop, than that produced after maize.

A strong correlation between Bray 1 extractable P, $NaHCO_3$, and NaOH I Pi fractions indicates that these fractions were probably all influenced more by fertiliser additions and liming, particularly in the 0-200 mm depth. The positive correlation between micro POC and Bray 1 P in the 200-400 mm depth, where there is the limited influence of P fertilisation, suggests that the labile organic C fractions increase P availability. The higher NaOH I Pi (Al bound P pool) fraction in the 200-400 mm soil depth suggests mobility of this fraction to deeper layers. The lack of significant variation in the content of stable fractions of P, i.e., sodium hydroxide II Pi (physically protected) and residual P (recalcitrant) suggests that all these fractions are less sensitive to crop sequencing effects. All the organic P pools were not detected, most likely because most of the organic P was part of the residual fraction.

Phosphorus is largely immobile in the soil; thus, it accumulates in the soil surface. Phosphorus immobility combined with surface accumulation of SOM may increase the availability of soil P in the topsoil. The positive correlation between micro POC and Bray 1 P in the 0-200 mm depth suggests that the labile organic C fractions may be an essential source of P for wheat crops in this system. This could be a result of competition for sorption sites between micro POC and Bray 1 P. This view was supported by the negative correlation between micro POC and NaOH II Pi. A positive correlation of micro POC (and NaOH II Pi) with residual P suggests that the micro POC improves the colloidal P fixation. The negative correlation between macro POC and physically protected P also suggests that the presence of labile organic C fractions may reduce P fixation in these soils. Although there were no significant differences in soil C fractions between crop sequences, it is clear that these fractions influence the availability/fixation of P.

The soil pH and Ca: Mg ratio was higher on cropped lands than natural land due to annual liming as confirmed by wheat farmers. The higher Ca: Mg ratio after soybean and in the topsoil (0-200 mm) was possibly due to annual calcitic lime application by most farmers. KwaZulu-Natal wheat farmers apply at least 2 t ha^{-1} of calcitic lime and less dolomitic lime annually to control their soil acidity challenges (Potgieter, 2017; Mostert, 2017 personal communication[2]). Calcitic lime dissolves slowly, thus remains concentrated in the topsoil for longer periods than in the subsoil. Soybean generates organic N for the growing crops from the biological nitrogen (N) fixation of molecular dinitrogen (N_2) in the atmosphere. Lower soil pH in the wheat fields preceded by soybean was also noted, owing to H^+ released during the decomposition of the N rich residues, N mineralization, and nitrification. Nitrification releases H^+ ions, which explain the higher AS after soybean. The lower AS on cropped lands than virgin land (Table 3.7) is explained by liming as a correction of soil acidity in cropped soil. The higher Zn availability in the topsoil was expected because all the compound (NPK) fertilisers that farmers apply prior planting contain at least 0.5% Zn (Sosibo et al., 2017). In addition, soil pH below 6.2 ($CaCl_2$) is expected to enhance Zn mobility and bioavailability (Martínez and Motto, 2000) therefore, pH of 4.67 was adequate for higher Zn observed. The lack of crop sequence effect on Zn and Cu suggests that a choice of rotation crops did not significantly influence the removal of these micronutrients, as reported in other studies elsewhere (Rosa et al., 2019; Duru et al., 2017; Xue

[2]J Potgieter. Bergville farmer; P Mostert. Winterton farmer

et al., 2016). Lower Zn on the natural land suggests that crop production in these Oxidic soils has improved Zn availability over time, due to fertilisation.

Wheat grows well in the pH range of 5.5-6 (Horneck et al., 2011) as such the wheat fields had lower pH for wheat growth. Farmers in KwaZulu-Natal wheat production region target a wheat yield of 7 t ha^{-1} to make a profit (Sosibo, 2016) and require at least 100 mg K kg^{-1}, >150 mg Ca kg^{-1}, and >60 mg Mg kg^{-1}, and as such, the K, Ca and Mg were generally adequate for wheat growth (Table 3.6). The lower CEC, exchangeable K, Ca, and Mg after soybean could be linked to lower soil pH, reducing negatively charged sites on soil colloids, while the higher concentrations of acidic cations result in leaching of basic actions. Nawaz et al. (2012) reported that losses of exchangeable bases increase with a decreasing soil pH.

3.5 CONCLUSION

Soil organic carbon in the wheat fields was below the minimum 20 g SOC kg^{-1} required for good soil quality and sustainable crop production. Cropping sequences did not significantly affect total C stocks, total N, SOC, and C fractions in the wheat-based CA systems on Oxidic soils of KZN. Although WSC was extremely lower than the other SOC fractions, the soils previously under soybean (6.59 mg kg^{-1}) had higher WSC than under maize (3.81 mg kg^{-1}) in the 0-200 mm depth. On average, maize had 13.5 g SOC kg^{-1}, 0.30 g kg^{-1} macro POC, 0.50 g kg^{-1} micro POC and 12.7 g kg^{-1} mineral associated C contents. Soybean had 13.8 g SOC kg^{-1}, 0.20 g kg^{-1} macro POC, 0.50 g kg^{-1} micro POC and 13.1 g kg^{-1} mineral associated C contents. Over 94% of total C is associated with the mineral fraction, with lower C in the form of POC. These lands under CA have a lower mean SOC content than uncultivated soils which had a mean 27.3 g kg^{-1} SOC content. Nonetheless, maize and soybean accumulated 41.1 t ha^{-1} and 46.5 t ha^{-1} soil C stocks, respectively.

Soil pH, $NaHCO_3$ Pi, CEC, K, Ca, and Mg are higher while AS, Ca: Mg and NaOH I Pi are lower under wheat crops preceded by maize than those preceded by soybean. Extractable P, $NaHCO_3$ Pi, total N, K, and Zn accumulate in the 0-200 mm depth than in the 200-400 mm. Physically protected P (NaOH II Pi), residual P and Cu are not significantly related to crop sequence or soil depth. Soil pH was lower than 5.5, a minimum required for wheat growth. Extractable P in wheat fields (maize: 35.9 mg kg^{-1}, soybean: 22.3 mg kg^{-1}) was lower than the P (50 mg kg^{-1}) required for a target yield (7 t ha^{-1}) while K was adequate for a target yield in this production region. The findings imply that farmers may need more lime, K and P fertiliser for wheat crops produced after soybean than those produced after maize. A strong positive correlation between labile organic C fractions and extractable P suggests that labile organic C fractions increase P availability. It is recommended that future studies evaluate soil quality parameters under different tillage systems, cropping sequences and residue management strategies.

CHAPTER 4: SOIL QUALITY OVER 40-YEARS OF TILLAGE AND STRAW MANAGEMENT PRACTICES UNDER SEMI-ARID CONDITIONS

ABSTRACT

Long term field trials are important for evaluating the environmental and economic sustainability of crop and soil management practices. The current study evaluated differences in soil organic carbon (SOC), total nitrogen (N), extractable phosphorus (P) and pH across tillage and straw management systems of dryland wheat monocrop after 40 years (1979 - 2018) of experimentation on an Acric Plinthosol (Avalon). The treatments consisted of plots under conventional (CT), stubble mulch (SM) and no-tillage (NT), combined with either straw burning (burned) or retention (not burned), for wheat fertilised at 40 kg N ha^{-1}. Straw burning significantly ($p<0.05$) increased soil pH and Bray-1 extractable P under NT, but not in other tillage systems. The Bray-1 extractable P declined down the profile, regardless of tillage or straw management. Total soil N was higher under NT than other tillage practices but did not vary with straw management, while SOC was not significantly affected by tillage or straw management. The findings imply that no-till could be beneficial to improve total N, soil pH and available P, especially when combined with straw burning, but an alternative strategy for sustainable SOC build-up in dryland wheat production on similar soil types, under the semi-arid conditions, needs to be sought.

Keywords: carbon, low-fertiliser input, nitrogen, phosphorus, straw management.

4.1 INTRODUCTION

Wheat (*Triticum aestivum* L.) is an important food crop as it contributes about 20% of the total dietary calories and proteins worldwide (Shiferaw et al., 2013). The demand for wheat is increasing in South Africa due to rapid urbanization and a growing middle-class population. However, dryland wheat production is declining because of challenges such as an increasingly variable climate and rising costs of fertiliser inputs (Dube et al., 2020). Current yields of dryland wheat average 2.7 t ha^{-1}, yet up to 11.5 t ha^{-1} is attainable with optimal management under irrigation in the country (Sosibo et al., 2017). The lower yields in a large proportion of wheat-producing regions, in South Africa, could also be attributed to poor soil quality, including soil organic carbon (SOC) levels lower than 10 mg C kg^{-1} as a result of conventional tillage, monocropping, and burning of straw (Sosibo et al., 2017). Reduced tillage and crop residue retention are sustainable farming practices that could make a significant contribution to soil quality and productivity of dryland wheat and could reduce reliance on fertiliser inputs and improve yield stability in the face of climate change.

Sosibo et al. (2017) reported that minimum soil disturbance with straw retention (conservation tillage) resulted in higher SOC and lower available P than conventional tillage (intensive turning of soil without straw retention). While modern agriculture promotes the use of rotations, like those presented in Chapter 3 for irrigated wheat, dryland wheat monocropping is common under semi-arid conditions, especially on Plinthic soils to benefit from moisture stored in the subsoil (Bennie and Hensley, 2001; Wiltshire and du Preez, 1993). Rotating wheat with a summer crop could deplete the moisture, making wheat production impossible under these conditions. No-tillage and residue retention have been proposed as management practices to improve soil quality, and wheat productivity under these conditions. A thorough understanding of the sustainability of these production practices, especially under semi-arid conditions, on soil quality and wheat crop productivity, requires long term trials. Data on long term crop management effects on soil quality in the low fertiliser-input dryland wheat systems is scant globally, as most field trials are not sustained long enough to make reliable conclusions. The experimental trial established in 1979 in Bethlehem, South Africa, is valuable in this regard. Several previous studies on the long-term dryland wheat trial in South Africa focused mainly on soil fertility parameters and grain yield.

In 1989, after 10 years of experimentation, Wiltshire and du Preez (1993) showed that soil N and C did not vary with tillage or straw management treatments although SOC in the trial was lower compared to natural pasture near the trial. In 1999, after 20 years, Du Preez et al. (2001) investigated the same treatment effects and reported that soil quality parameters had declined across all treatments. After approximately 30 years of the trial, Loke et al. (2012) reported that not burning wheat straw resulted in lower extractable P but higher total N, when compared to burning, and that no-tillage (NT) accumulated more SOC in the topsoil (0-50 mm) compared to other tillage practices while both NT and stubble mulching (SM) enhanced total N, soil pH and P availability (Loke et al., 2012). At the conclusion of this trial in 2018 after 40 years of experimentation, it was essential to investigate the differences in soil quality parameters across treatments.

The current study, therefore, determined the effects of tillage and straw management on selected soil quality parameters after 40 years, only for treatments where N fertiliser level was 40 kg ha^{-1}, to relate with findings of previous studies on soil quality parameters in the same trial. It was hypothesized that, continued wheat monocropping results in deterioration of soil quality parameters in low fertiliser input systems, but such effects may be mitigated by reduced tillage and straw retention practices.

4.2 MATERIALS AND METHODS

4.2.1 Description of the Bethlehem long term trial

The dryland wheat trial was established at the Agricultural Research Council-Small Grain (ARC-SG) farm, formerly known as Small Grain Institute (SGI), near Bethlehem in the Free State Province of South Africa (28°9′S, 28°17′E; 1,680 m.a.s.l). The area is semi-arid with a mean annual rainfall of 743 mm and average temperatures ranging from 7.1˚C to 20.3˚C (ARC-ISCW, 2013). Bethlehem is a summer rainfall region and dryland wheat is normally planted in the first week of June and harvested in the beginning of January.

The soil at the trial site was classified as a luvic Avalon soil, under the Mafikeng family (Soil Classification Working Group, 1991). It is characterized by orthic A, yellow-brown apedal B and a soft plinthic B-horizons (Fey, 2010b), and can be translated to an Acric Plinthosol (IUSS Working Group WRB, 2015). Before the commencement of the trial, the land was under conventional tillage (mouldboard plough) for at least 20 years (Du Preez et al., 2001). The soil data for a natural grassland next to the trial is presented in Table 4.1. This soil is naturally deficient in P, slightly acidic and has very low SOC (Table 4.1).

Table 4. 1: Soil properties of the grassland next to the trial in 2018.

Soil depth (mm)	Carbon ($g\ C\ kg^{-1}$)	Nitrogen ($g\ N\ kg^{-1}$)	C:N	pH	Phosphorus ($mg\ kg^{-1}$)
0-200	7.00	0.60	11.7	5.6	9.1
200-400	6.10	0.50	12.2	5.4	7.3

Carbon, soil organic carbon; Nitrogen, total nitrogen; Phosphorus, Bray-1 extractable phosphorus.

The initial objective of the trial was to determine the effects of tillage, straw burning and N fertiliser application rates on wheat grain yields on an Acric Plinthosol. At the beginning of this trial, there were two wheat straw management treatments (burned and not burned), three tillage methods (mouldboard ploughing, stubble mulch tillage, and no-tillage), two weed control methods (mechanical and chemical) and three N fertilization levels (20, 30 and 40 kg N ha^{-1}) in a factorial arrangement. The trial was a randomized complete block design on a 2-3% north-facing slope, with 36 treatments and 3 replicates. A constant amount of P (12.5 kg P $ha^{-1}y^{-1}$), but no K was added. A hard red winter wheat cultivar *Betta* was planted. In 2002, *Betta* was replaced with a new improved cultivar *Elands*. At the same time, the N fertiliser rate was also increased in synchrony with the higher nutrient requirements of newly introduced *Elands* cultivar compared to *Betta*. The original 30 and 40 kg N ha^{-1} were replaced with 40 and 60 kg N ha^{-1}, respectively. Each plot was 6 × 30 m with a separation distance of 3 m between plots. An inter-row spacing of 450 mm was used in all plots. The intra-row spacing was 30 mm to achieve a rate of 74 seeds m^2. Over the years, wheat was consistently planted every year during the last week of June. This planting date was selected to optimize wheat yield potential for this specific environment. After harvesting of grain, wheat straw was either burned or retained. In the stubble mulched treatment, a 50 mm wide chisel plough was used to till the soil without much disturbance to the surface mulch. In the ploughed treatment (conventional tillage), wheat ashes, char or unburned straw were incorporated into the soil using a two-way offset disc up to 150 mm depth. In February of each year, a mouldboard plough further incorporated wheat ashes, char or wheat straw up to 250 mm depth in the ploughed treatment. The ploughed treatment is referred to as conventional tillage in this chapter. For the ploughed and stubble mulch treatments, a tine tiller was used to control weeds in March of every year before planting. Additionally, two herbicides {glyphosate (N-phosphonomethyl glycine) or paraquat (N, N′-dimethyl-4,4′-bipyridinium dichloride)} were used to control weeds. The herbicides were alternated to avoid the development of herbicide resistance. Fertiliser application and seeding were done using a conventional wheat planter in other treatments, but a no-till planter was used under no-tillage treatment.

4.2.2 Soil sampling and analyses

For soil quality evaluation, soil samples were collected in June 2018, before wheat planting from the 0-200 and 200-400 mm depths of plots fertilized with 40 kg N ha^{-1}. The 0-200 mm depth was selected as the average of the 0-150 mm ploughing depth and the 0-250 mm depth of incorporation of straw, char, and ashes in the CT treatment. This 40 kg N ha^{-1} rate was selected to relate with previous studies on this trial (Wiltshire and du Preez, 1993; Kotzé and du Preez, 2007; Loke et al., 2012). The treatments sampled were conventional tillage (CT), stubble mulch (SM) and no-tillage (NT) systems where straw was either burned or retained and weeds were chemically controlled. Four random samples were collected from each of the plots and bulked to form a composite sample per layer. Visible debris was removed, and the samples were air-dried, milled (< 2 mm) and analysed for pH, organic C, total N, and Bray 1 extractable P as described in Section 3.2.3. The results from this study were compared to findings from previous studies in the same plots by Wiltshire and du Preez, (1993), Du Preez et al. (2001), Kotzé and du Preez (2007, 2008) and Loke et al. (2012, 2013) to infer changes in soil quality.

4.2.3 Statistical analyses

The significance of differences between treatments on soil quality parameters were analysed by a generalized ANOVA with tillage, straw management, and soil depth as factors. The analyses were done using Genstat 18^{th} edition. Means were separated using the Tukey's test at 95% confidence limit.

4.3 RESULTS

4.3.1 Effects of tillage and straw management on selected soil properties after 40 years

There were relatively narrow ranges of soil pH (4.66 - 5.56), organic C (4.20 - 8.90 g kg^{-1}) and total N (0.50 - 0.80 g kg^{-1}) but the Bray-1 extractable P ranged from 7.67 - 45.58 mg kg^{-1}. Interaction effects of tillage, straw management and soil depth were significant on soil pH and extractable P only, while total N was significantly affected by tillage (Table 4.2). Organic C was not significantly affected by tillage, straw management, or soil depth.

Table 4. 2: Statistical significance (p-values) of treatment combinations effects from general ANOVA.

Source of variation	**P-values**				
	d.f.	**pH**	**Soil organic Carbon**	**Total Nitrogen**	**Extractable Phosphorus**
Tillage	2	ns	ns	**	**
Straw management	1	*	ns	ns	*
Soil depth	1	ns	ns	ns	**
Tillage × straw management	2	*	ns	ns	*
Tillage × soil depth	2	ns	ns	ns	*
Straw management × soil depth	1	ns	ns	ns	*
Tillage × straw management × soil depth	2	*	ns	ns	*

*$p<0.05$; **$p<0.001$; ns = no significant differences at 95% confidence level (n =36).

4.3.1.1 Soil pH

Burning wheat straw significantly increased soil pH in the 0-200 mm depth under NT when compared with straw retention, but there were no differences under CT and SM, and this effect was not significant in the 200-400 mm depth (Table 4.3). For each treatment combination, soil depth did not affect pH.

Table 4. 3: The effects of tillage × straw management × depth on soil pH.

		Soil pH	
Tillage system	**Straw management**	**0-200 mm**	**200-400 mm**
No-tillage	Burned	5.39a	5.28a
	Unburned	4.78b	4.94ab
Stubble mulch	Burned	5.03ab	5.03ab
	Unburned	4.98ab	4.99ab
Conventional tillage	Burned	5.05ab	5.02ab
	Unburned	5.04ab	5.19ab

Values with different letters (a-b) represent significant differences at $p<0.05$.

4.3.1.2 Extractable soil phosphorus

At the 0-200 mm soil depth, the soil under NT with burned wheat straw had higher extractable P concentration than the soil under SM or CT treatments, irrespective of straw management (Table 4.4). Where straw was not burned, there were no significant differences between tillage systems. At 200-400 mm, there were no significant differences among all tillage × straw management combinations (Table 4.4). However, there was evidence of P stratification across all treatments, with more extractable P in the 0-200 mm depth than the 200-400 mm depth.

Table 4. 4: The effects of tillage × straw management × soil depth on extractable phosphorus.

		Extractable P (mg kg^{-1})	
Tillage system	**Straw management**	**0-200 mm**	**200-400 mm**
	Burned	38.5a	15.1cd
No-tillage	Unburned	33.1ab	13.5cd
	Burned	31.9b	12.4d
Stubble mulch	Unburned	27.5b	11.8d
	Burned	26.2b	13.9cd
Conventional tillage	Unburned	23.4bc	8.65d

Values with different letters (a-d) in columns indicate significant differences at $p<0.05$.

4.3.1.3 Soil organic carbon and total nitrogen

All interaction effects did not significantly affect SOC and total N (Table 4.4). Soil organic C and total N concentrations were also similar at the sampling depths of 0-200 and 200-400 mm (Table 4.5). Main effects of tillage were only significant for total N with higher total N under NT than other tillage practices (Table 4.5). Tillage and straw management did not affect the C: N ratio, but the treatments resulted in an average C: N ratio of 12.7 (Table 4.5).

Table 4. 5: The effect of tillage and straw management on soil organic carbon and total nitrogen.

Factor	**Soil properties**		
	Organic carbon (g C kg^{-1})	**Total nitrogen (g N kg^{-1})**	**C: N ratio**
Tillage system			
No-tillage	8.50	0.70a	12.10
Stubble mulch	7.70	0.60b	12.83
Conventional tillage	7.20	0.60b	12.00
Straw management			
Burned	7.40	0.60	12.33
Unburned	8.20	0.60	13.66
Soil depth			
0-200 mm	7.50	0.60	12.50
200-400 mm	8.00	0.60	13.30
Mean	**7.90**	**0.60**	**12.67**

Values with different letters (a-b) in a column indicate significant differences at $p<0.05$.

4.4 DISCUSSION

4.4.1 Changes in soil pH across management systems

Burning of straw is a common practice in low-input dryland wheat monocropping systems for controlling diseases such as "take all" (*Gaeumannomyces graminis* var. *tritici*). Findings of the current study suggest that burning of straw under no-till, in this production system, may increase soil pH and plant available P, meriting further attention and research. Improved soil pH under straw burning in the NT treatments may be due to liming effects of ash produced from fire (Chungu et al., 2020). Ash is alkaline in nature (Chungu et al., 2020; Molina et al., 2007) and is composed of carbonates that are hydrolysed to produce hydroxide ions (Heydari et al., 2017). These findings are comparable to Loke et al. (2013) and Du Preez et al. (2001) who also found a significantly higher soil pH in the 0-50 mm due to residue burning as well as no tillage in the 0-100 mm (Loke et al., 2013; Kotzé and du Preez, 2008) and 0-150 mm (Du Preez et al., 2001). A comparison of adjacent grassland data (Table 4.1) with soil quality over the years showed that soil pH at 0-200 mm has declined across all treatments. The initial design of the experiment used lime-ammonium nitrate, with the lime being added to neutralise acidity caused by nitrification of ammonium-N from the fertiliser. However, nitrification of ammonium-N from the decomposition of organic matter could have increased soil acidity (Wong and Swift, 2003). Wheat can tolerate soil acidity to pH 5.5 (KCl) without significantly affecting yield (Lollato et al., 2013). Based on the pH values from the current study, liming must be considered, but the no-till treatment where straw was burned will require the least amount of lime.

4.4.2 Changes in extractable phosphorous

After 40 years of wheat monocropping, the higher extractable P in the surface soil of the NT with burned straw treatments (Table 4.4) than SM and CT (irrespective of straw management) could be explained by nutrient-rich ash, higher soil pH and conversion of organic P to orthophosphate as a result of burning (Molina et al., 2007; Cade-Menun et al., 2000). These findings are comparable to the previous findings from this trial (Loke et al., 2013; Du Preez et al, 2001). Romanya et al. (1994) also reported higher Bray 1 P upon burning which was explained by the conversion of organic P from the burnt organic matter to inorganic P forms. Higher soil pH in the NT treatment with burned straw could have reduced P fixation by Fe and Al oxides that are likely to be prevalent in the soil type, on which the trial is located (Fey, 2010b) when compared to the other treatments. However, the pH in this treatment (5.39) is borderline in terms of Al being solubilised (5.3) to contribute to P fixation. Lowering soil pH in the other treatments may result in precipitation of P as plant unavailable forms with Al and Fe, resulting in lower plant-available P (Havlin et al., 2005; Poswa, 2016). Higher availability of P in the topsoil (0-20 mm) than the deeper layers is attributed to P fertiliser addition (Sharpley, 2003) and the immobile nature of this nutrient (Li et al., 2019). Phosphorus moves in the soil mainly through diffusion and because of its low diffusion coefficient, it is considered highly immobile (Balemi and Negisho, 2012). The lack of differences in tilled treatments where straw was retained (not burned) could imply that the straw generated in this system was insufficient to significantly impact P availability in the 0-200 mm layer. This is confirmed by no significant differences in SOC across all treatments (Table 4.2). Reduced tillage systems with sufficient organic matter inputs are known to have more organic P in the topsoil because of the slower decomposition of crop residues (Zibilske et al., 2002). Organic compounds from organic matter could either decompose and mineralise P, compete with P for sorption sites or coat Al/Fe oxides such that these oxides do not fix available P, all these mechanisms result in more plant-available P in the topsoils of reduced tillage systems (Havlin et al., 2005). However, this effect was not observed in the current study.

Comparison of the results after 40 years with other sampling intervals (Du Preez et al., 2001; Kotzé and du Preez, 2008; Loke et al., 2013) showed that extractable soil P concentration in the topsoil slightly declined across all treatments over 30 years. However, at the 40-year interval, the P level appeared to be higher in the topsoil of NT and SM treatments (Table 4.4). Because of the lack of soil incorporation in the reduced tillage treatments, there may be a faster build-up of P applied as fertiliser in the topsoil. It should be noted though, that plant-available P concentration in the 0-200 mm soil layer has remained within the requirements of dryland wheat for water-limited yield potential of 3.5 Mg ha^{-1} across all treatments (ARC-Small Grain, 2018). Over the 40 years, this can be credited to consistent annual P fertiliser application practices of 12.5 kg P ha^{-1}. Hence, all treatments have not yet developed a P limitation for yield. Considering that the threshold soil P for fertiliser application of wheat is 40 mg P kg^{-1} (ARC-Small Grain, 2018), the NT with burned straw (38.5 mg P kg^{-1}) would require less than the constant 12.5 kg P ha^{-1} P fertiliser, if soil test based fertiliser recommendations were used for this production system. The reduction could significantly reduce the P fertiliser costs, and possibly increase profitability, on dryland monocrop wheat farms where NT with burned straw are used under semi-arid conditions. Phosphorus fractions were not studied in this chapter but the recent findings by Ncoyi et al. (2020) indicated an increase of labile ($NaHCO_3$ Pi) and stable (HCl Pi) inorganic P fractions upon straw burning, the effects were more pronounced under no tillage compared to stubble mulch and conventional tillage practices. These findings suggest a possible buildup of labile and stable Pi fractions under NT with burned straw in the low input fertiliser system. A possible higher dry matter input from a higher N (60 kg N ha^{-1}) fertiliser addition may result in significant changes in P dynamics and higher P availability.

4.4.3 Changes in soil organic carbon and total nitrogen across management systems

Modern sustainable farming tends to encourage crop rotations and diversification and discourage monocropping and straw burning, which causes release of greenhouse gases and harm to some soil organisms and is thought to accelerate SOC losses (Lohan et al., 2018; Bhuvaneshwari et al., 2019). Several studies on wheat straw management reported positive effects of straw burning on SOC (Sidhu and Beri, 1989; Virto et al., 2007). The burning of wheat straw over 40 years did not significantly lower SOC in this study (Table 4.2). The lack of significant change could be because the SOC in the soils was low (<10 g kg^{-1}) (Table 4.5), even in the adjacent undisturbed grassland (7.0 g kg^{-1}) as shown on Table 4.1.

The lack of tillage and straw management effects on SOC (Table 4.2) may mean that the equilibrium level of SOC has been reached across all treatments (Table 4.5). Plinthic soils in the Highveld region, of South Africa, require about 34 years for SOC to reach equilibrium (Lobe et al., 2001). The SOC may have equilibrated at low levels of 7.9 g C kg^{-1} (average) in this system due to the relatively low levels of straw generated annually for SOC input as well as high oxidation rates due to lack of protection in the highly aerated loam soil. The organic C levels in the tillage and straw management treatments were generally close to the concentrations (7.0 g kg^{-1}) in the undisturbed grassland adjacent to the trial (Table 4.1). The similarity of the experimental treatments (7.2 - 8.5 g kg^{-1}) and undisturbed soils (7.0 g kg^{-1}) suggest that the C levels of the soil used could not be significantly increased by the treatments. The low dry matter added annually may have been inadequate to significantly increase the SOC status thus it remained constant. A trend analysis of SOC across the years also showed that there have been no significant changes in SOC over the years (Wiltshire and du Preez, 1993; Kotzé and du Preez, 2007; Loke et al., 2012). While SOC has not changed over the years, changes in the organic matter fractions could have significant effects on nutrient cycling in these systems. Although the SOC fractions were not studied in this chapter, the findings on the same trial showed that fulvic and humic fractions of carbon increased under conservation (no-tillage and stubble mulch) tillage practises than under conventional tillage in the 40 kg N ha^{-1} fertiliser input (Motema et al., 2020). These findings indicate a possibility of higher nutrient cycling as a result of decomposing fulvic and humic SOC fractions under no tillage and stubble mulch practices. As such, a higher nitrogen (60 kg N ha^{-1}) rate than the rate studied by Motema et al. (2020) could result in higher additions of SOC and its fractions, with major implications on nutrient cycling in these systems.

Rainfall is the main limiting factor to wheat yield, hence lower biomass input, in this system (Dube et al., 2016). Supplemental irrigation and perhaps high biomass yielding summer cover crops for rotation, in this and similar systems, may be required to improve SOC. However, another possible explanation for the lack of treatment effects could be that sampling at 0-200 mm could also have masked the small differences in SOC. Reports of significant benefits of no-till on SOC normally refer to the top 0-50 and 50-100 mm soil layers (Venzke Filho et al., 2004; Houshyar and Esmailpour, 2020). Studies that consider sampling at 0-50, 50-100 and 100-200 mm depths could show differences between the no-till and other tillage treatments. This study did not distinguish the SOC between these fine layers. However, total soil N appeared more sensitive than SOC, as the concentration was significantly increased by no-till.

Higher total N observed under NT may be due to a combination of less soil disturbance and straw retention on the soil surface. Less soil disturbance coupled with straw retention slows SOM decomposition thus reducing N loss through leaching from the system (Balota et al., 2004; Liu et al., 2006). These findings are similar to Loke et al. (2012) who reported higher N under NT due to less decomposition. The higher total soil N in NT than CT, while SOC was not affected, in the current study as well as in the previous one on the same trial (Wiltshire and du Preez, 1993) suggested that soil N may be more responsive to management changes (Hofman and Cleemput, 2004). Although total N declined in the first years of cropping, the levels appear to have reached equilibrium at a lower level (0.60 g kg^{-1}) since 20 years ago (Wiltshire and du Preez, 1993; Kotzé and du Preez, 2007; Loke et al., 2012).

4.5 CONCLUSIONS

The practice of NT increases total soil N (0.70), but not SOC when compared with CT, while straw burning does not affect both total soil N and SOC concentrations in this dryland wheat production system. No-till with burned straw increases soil pH (5.39) and Bray 1 extractable P (38.5 mg kg^{-1}), particularly in the surface layer, when compared with CT. The higher soil pH and available P in NT with burned straw imply that lower fertiliser P would be required in this treatment, and P fertiliser costs may be reduced when the fertiliser recommendations are based on soil tests. The lack of differences, between tillage and straw management treatments, indicate that an alternative strategy for building SOC on these soils is required, including higher N fertiliser rate and crop rotations with supplemental irrigation where possible.

CHAPTER 5: EFFECTS OF TILLAGE AND STRAW MANAGEMENT AT HIGH NITROGEN RATE ON STOCKS AND LABILE POOLS OF SOIL CARBON AND PHOSPHORUS UNDER DRYLAND WHEAT PRODUCTION IN SEMI-ARID CONDITIONS

ABSTRACT

This study quantified long-term effects of tillage and straw management strategies on soil carbon (C) stocks, soil organic carbon (SOC) and phosphorus (P) pools, and wheat nutrient uptake after nearly 40 years of continuous wheat mono-cropping with 60 kg ha^{-1} nitrogen fertiliser. Tillage and straw management interaction effects were significant for total soil C stocks in the 1000 mm soil depth. After nearly 40 years of wheat mono-cropping, soil C stocks were increased by either no-tillage (NT) with straw burning, conventional tillage (CT) with straw retention, or stubble mulch (SM) tillage, compared to NT with straw retention and CT with straw burning. In the pedoderm (0-50 mm), NT improved total N, particulate organic carbon (POC), available P and NaOH II Pi concentration than SM and CT systems. Soil pH, available P and $NaHCO_3$ Pi concentrations were higher, while total N concentration was lower where straw was burnt. At the 50-200 mm soil depth, total N, macro POC and residual P concentration were also higher under NT regardless of straw management strategy. Soil pH and $NaHCO_3$ Pi concentration were higher where wheat straw was burnt. Soil organic C, mineral associated C and $NaHCO_3$ Pi concentrations were increased by straw burning. No-tillage improved the uptake of N than SM and CT systems, but treatment effects on P uptake were not significant.

Keywords: carbon fractions, phosphorus fractions, plant nutrients, sustainability.

5.1 INTRODUCTION

Summer rainfall regions of South Africa are generally ill-suited for the production of dryland wheat (*Triticum aestivum* L.). An exception is the cooler Highveld areas of South Africa, where a combination of relatively colder winter temperatures, high water tables, and Plinthic soils that have high moisture-storage efficiency, have enabled the production of dryland wheat over the past decades. Average yields of this wheat produced under severely water-limited conditions are low when compared to irrigated wheat (Dube et al., 2016). To ensure that the low yields of dryland wheat are profitable, farmers in this region are encouraged to adopt a unique, but extremely efficient farming practice, which entails reduced fertiliser and pesticide inputs, reduced tillage, and at times straw burning for plant disease control. The major wheat diseases that are borne out of inoculum and controlled through straw burning in this region are: take all (*Gaeumannomyces graminis* var. tritici), karnal bunt (*Tilletia indica*) and Fusarium root rots (*Fusarium graminearum and Fusarium culmorum*).

The area planted to dryland wheat in these summer rainfall areas of South Africa was estimated at approximately 450 000 ha in 2005, contributing nearly 50% of South Africa's domestic wheat requirements (DAFF, 2012). At present, South Africa faces a wheat production crisis and increasing farmer disinterest in dryland wheat production due to rising input costs and profitability challenges (Dube et al., 2016). With low-fertiliser input wheat monocropping on Plinthic soils that are low in soil organic carbon (SOC) and cation exchange capacity (CEC), rapid nutrient depletion may be the biggest threat to sustained production. Soil acidity (including subsoil) develops on these soils under cultivation, resulting in aluminium (Al) toxicity and poor root growth. According to Fey (2010b), surface horizons of Plinthic soils degrade easily under excessive tillage because of low SOC and a lack of iron oxides. Excessive tillage increases the susceptibility of soils to wind erosion on the open plains of the highveld, resulting in the loss of particulate organic matter and other nutrient-rich sediments of the topsoil (Mahasa, 2015). Tillage intensity influences wind erosion, and the very fine sand and coarse silt fractions of soil are the most susceptible to wind erosion (Segovia et al., 2017). Intensive tillage and crop residue burning may also accelerate the loss of SOC and increase the susceptibility of soil to erosion. If nutrient losses from the soil are not abated, this could gradually increase fertilization costs for dryland wheat crops, thus reducing profitability. Suggested strategies for arresting soil degradation in the dryland wheat systems include the adoption of conservation agriculture (CA) practices such as crop residue retention and no-tillage (NT). These practices are envisaged to improve SOC, thus possibly counter long-term nutrient depletion and soil degradation effects of low-fertiliser input cereal mono-cropping.

Soil organic C occurs in various pools, based on decomposability (De Moraes Sá and Lal, 2009; Snapp and Grandy, 2011). The active pool is the most easily decomposable, and generally viewed as an important source of plant nutrients (Snapp and Grandy, 2011). The recalcitrant or passive pool contains organic C that is resistant to further biodegradation but is important in C sequestration (De Moraes Sá and Lal, 2009; Snapp and Grandy, 2011). In any given crop production system, the concentration and storage of C can be affected by management factors such as tillage intensity and frequency, crop residue management, fertiliser input and interactions of these factors (Petrokofsky et al., 2012; Smith et al., 2012). No-till has been shown to reduce losses of sequestered C from the soil (Carter, 2005; Luo et al., 2010). On the other hand, organic matter accumulates on the surface under no-till, and this may result in higher losses due to wind erosion than in ploughed systems where residues are buried.

Worldwide, concerns about the concentration of carbon dioxide in the atmosphere are increasing (Taub, 2010). Soils are recognized as the largest reservoir of C, and that increased

C sequestration in soils can help mitigate climate change (Tifafi et al., 2018). Meanwhile, little is known about the magnitude of changes in C stocks due to major crop and soil management systems in South Africa. A review of studies that evaluated effects of tillage and residue management practices on selected parameters (García-Marco et al., 2014; Gómez-Rey et al., 2014; Neugschwandtner et al., 2014; Sapkota et al., 2017), shows that limited work has been done on quantifying long-term C and soil fertility benefits of soil management systems for winter-cereal mono-crops on marginal soils in summer rainfall areas.

Phosphorus is the most important nutrient in optimizing wheat growth, grain yield and quality after N, yet most soils under wheat production in the tropics are P fixing in nature, and deficient in P (Nziguheba et al., 1998). Retention of crop residues is known to increase SOC, and potentially decrease P adsorption capacity of soils through complexation of soluble Al, among other mechanisms (Iyamuremye et al., 1996; Nziguheba et al., 1998). Organic sources are generally known to favour build-up of labile P pools at the expense of recalcitrant P when compared to inorganic P sources (Reddy et al., 2001). Retention of wheat straw may further enhance the availability of nutrients in the surface soil through reducing soil erosion. However, the magnitude of such effects is likely to be variable depending on residue type, quantity, tillage intensity, soil and climatic conditions, as well as interactions of these factors. Understanding the effects of CA options of SOC stocks and concentrations and fractions of SOC and P require long-term trials in order to get reliable results.

The only long-term experiment evaluating crop management strategies for dryland wheat production in the summer rainfall area was established in 1979 at the Small Grain Institute in South Africa. This trial was originally established to investigate effects of tillage, crop residue, fertiliser and weed management effects on yield of continuous wheat. Several studies were conducted previously on the aforementioned trial after 10 (Du Preez et al., 2001), 20 (Kotzé, 2004), 30 (Loke, 2012) and 37 (Seepamore et al., 2020; Motema et al., 2020; Ncoyi et al., 2020) years of trial inception. Based on a distillation of research findings produced since the trial inception, it was found that NT conserved more soil moisture, gradually increased soil pH (Du Preez et al., 2001), total N, and organic C (Motema et al., 2020; Loke et al., 2012), relative to conventional tillage (CT) although other studies found no significant effects of tillage or straw management on SOC (Chapter 4; Wiltshire and du Preez, 1993). The effects of the higher total soil N on wheat N uptake has not been established. Stratification of most soil nutrients was also evident, with the nutrients becoming more concentrated in the upper layers. Results in Chapter 4 indicate that SOC concentration is not affected by tillage (NT, conventional tillage-CT, stubble mulch -SM) and straw management in the dryland wheat production trial at Bethlehem, fertilised at 40 kg N ha^{-1}. The lack of effects could have been a result of low biomass production. The NT with straw burning increases soil pH and available P relative to other treatments (Chapter 4). The effects of the higher pH and available P on P uptake has not been established. All the previous studies, including Chapter 4, were based on treatments fertilised at 40 kg N ha^{-1} and none investigated the sustainability of the various production systems in terms of C stocks. A higher N fertiliser level (60 kg N ha^{-1}) could have higher dry matter addition and SOC than the 40 kg N ha^{-1}, with significant effects on fractions of SOC and P in these soils. Since there were no studies conducted in the treatments fertilised at 60 kg N ha^{-1} for the whole period of the trial, it was therefore important to determine the effects of tillage and straw management on SOC stocks, total soil N, fractions of SOC and P, uptake of N and P, at the higher N rate as the conclusion of this long-term trial after 40 years in 2019 approached. It was hypothesized that long-term reduced tillage and straw retention would significantly increase C stocks, SOC and P fractions as well as N and P uptake as a result of higher biomass addition due to higher N fertiliser rate.

5.2 MATERIALS AND METHODS

5.2.1. Description of the Bethlehem long-term trial and design

The trial has been described previously in section 4.2.1 of Chapter 4. The climatic data for the study site during the sampling period (2016 – 2017) is presented in Figures 5.1 and 5.2, categorised as annual, pre-plant season (January, February, March and April), early-mid season (May, June, July and August) and mid-late season (September, October, November and December) in relation to the dryland wheat phenology.

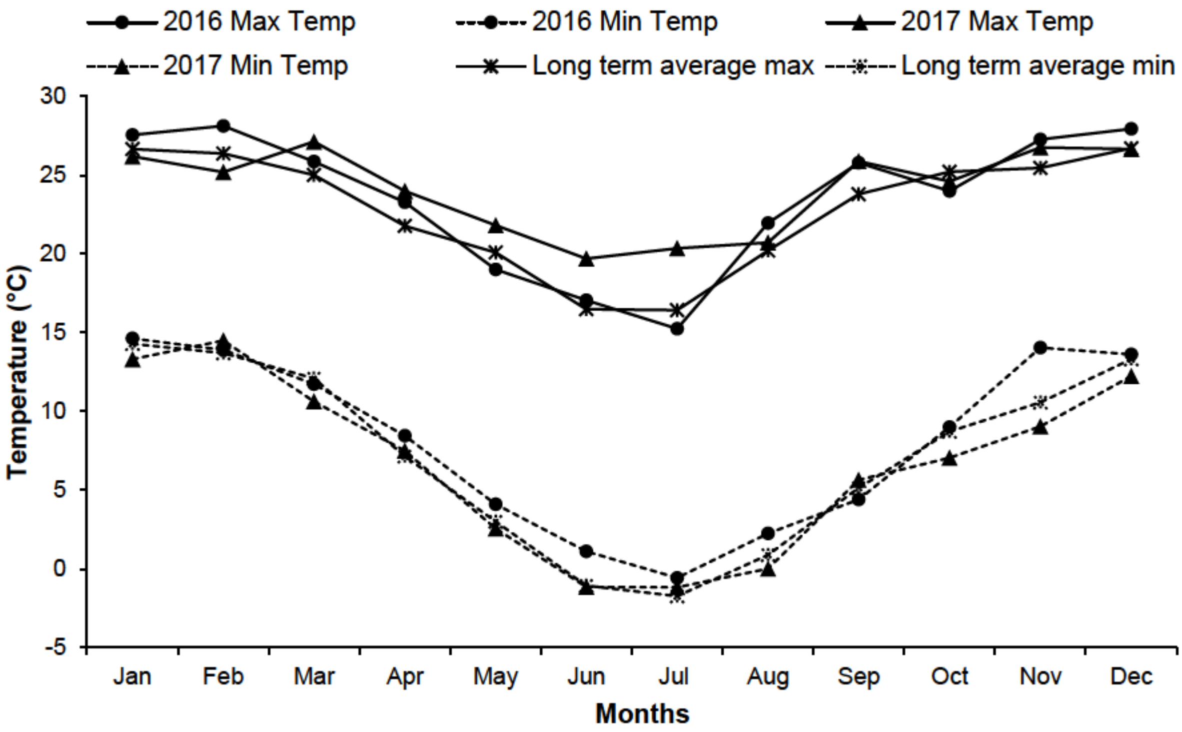

Figure 5. 1: Temperature conditions at the Bethlehem long-term trial site.

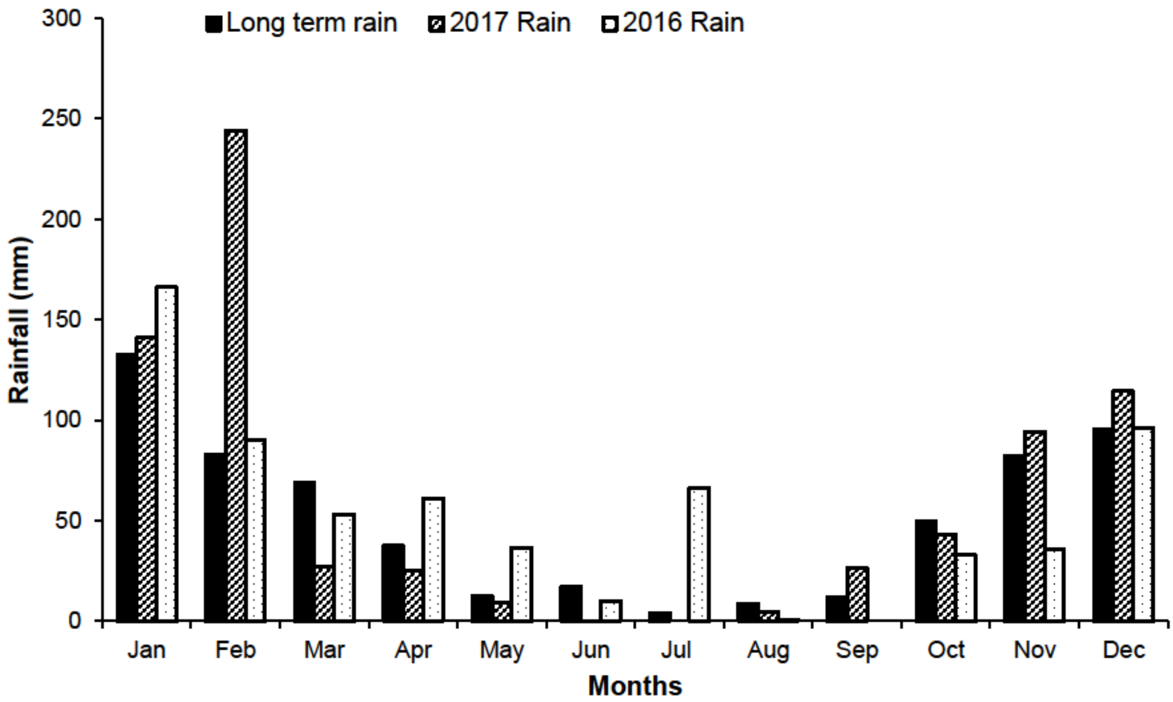

Figure 5. 2: Rainfall conditions at the Bethlehem long-term trial site.

The land surrounding the trial is a natural grassland. Analysis of the natural grassland soil next to the trial showed inherent P deficiency, slight acidity and very low SOC (Table 5.1).

Table 5. 1: Soil properties of the natural grassland next to the Bethlehem long-term trial in 2016.

Depth (mm)	pH	Organic carbon (g C kg^{-1})	Total nitrogen (g N kg^{-1})	Extractable P (mg kg^{-1})
0-50	6.00	7.80	0.80	12.1
50-200	5.97	6.60	0.50	10.1
200-400	6.10	6.20	0.60	6.90

C, soil organic carbon; N, total nitrogen; pH (water), P (Bray 1).

5.2.2. Soil Sampling and Analyses

5.2.2.1 Soil sampling and analysis of selected soil parameters

Soil samples were collected from the 0-50, 50-200, 200-400, 400-600, 600-800 and 800-1000 mm depths in the 3 tillage systems (conventional tillage (CT), stubble mulch (SM) and no-tillage (NT) and 2 straw management strategies (burnt and not burnt) in June 2016, just before wheat planting. Therefore, a total of 18 plots were sampled. Four random samples were collected from each plot using a graduated auger and bulked to form a composite sample per soil layer. After visible debris was removed, samples were air-dried, milled (< 2 mm) and analysed for pH, SOC, total N and extractable P as described in Section 4.2.2 in Chapter 4. Bulk density was calculated based on the mass and volume of undisturbed soil cores per soil layer. Soil C stocks (t ha^{-1}) were calculated for each layer using SOC, bulk density (g cm^{-3}) and depth for each sampling interval following a method by Gattinger et al. (2012) whereby Soil C stock is a product of SOC, bulk density and depth thickness. Total SOC stock in the top 1000 mm was calculated as the sum of SOC stocks of all the sampled depths. Soil samples from the 0-50, 50-200 and 200-400 mm depth were further analysed for additional soil properties as detailed in Section 3.2.4 and 3.2.5 of (Chapter 3).

5.2.2.2 Soil carbon and phosphorus fractions

The procedure used for soil carbon and phosphorus fractions has been described in Sections 3.2.4 and 3.2.5 of Chapter 3. Charcoal was analysed using a method by Kurth et al. (2006) whereby three sets of each dry soil sample (1 g) were digested with 20 ml of 30% H_2O_2 and 10 ml of 1 M HNO_3 in the Erlenmeyer flasks at 100°C for 16 h. The samples were occasionally removed from the heating plate and swirled to observe for effervescence at 30 minutes intervals. After 16 hours, the samples were filtered through Whatman number 1 filter paper, dried and finely ground with a mortar and pestle. Total C that remained after digestion (charcoal) was analysed using a Leco TruMac CNS/NS analyser (TruMaC CNS/NS, USA).

5.2.3. Measurement of wheat dry matter

Wheat plants were manually counted per plot and recorded at the flag leaf stage in November 2016 before harvest from the same plots where the soil samples were collected. At the same time, four plants were randomly cut at 2 cm above the ground level and placed into brown paper bags. The samples were weighed on a Mettler PJ 6000 balance and oven-dried at 70^{o}C to constant weight. The oven-dried weight of plants per plot and the number of plants sampled per plot were used to calculate the average weight of a plant in each plot. Total dry matter hereafter referred to as biomass, was calculated by multiplying the average weight of a plant (kg) by the total number of plants per plots and dividing by the plot area (ha).

5.2.4. Measurement of plant tissue nutrient composition and uptake

Flag leaf samples were collected from six randomly selected plants at the flag leaf stage in November 2017. The plant samples were kept in brown paper bags in a cool dry environment before they were dried and milled. This was followed by tissue analysis for total C and N using a dry combustion method (Jimenez and Ladha, 1993; Matejovic, 1995) using a CHNS-O Analyser (Thermo Scientific Flash 2000 Organic Elemental Analyser, USA). The method involved heating the plant sample in a tin foil at 950^{o}C to oxidise C and N and determine their concentrations chromatographically using calibrated thermal conductivity indicators. Total P was determined following wet digestion using perchloric and nitric acid (Zasoski and Burau, 1977) at 180^{o}C and measured with a 700 series ICP-OES. Assuming that the measured plant tissue composition from flag leaves represented the whole plant at that growth stage (Jones et al., 2011), plant nutrient uptake (kg ha^{-1}) was estimated as a product of plant biomass (kg ha^{-1}) and plant tissue nutrient content (%) divided by 100 (Sharma et al., 2012).

5.2.5. Data Analyses

To test the significance of differences between treatments, soil and plant uptake data were subjected to a general analysis of variance, with tillage and straw management as factors, using Genstat 18th edition. When the null hypothesis (H_o) was rejected at 95% confidence limit, means were separated using the Tukey test. Bulk density data were collected to calculate carbon stocks and is therefore not presented in this Chapter.

5.3 RESULTS

5.3.1 Soil carbon stocks

Straw burning increased soil C stock in the 200-400 mm depth while SM had higher C stocks than both NT and CT in the 600-800 mm depth (Table 5.2). Soil C stocks in the 0-50, 400-600 and 800-1000 mm were not significantly affected by tillage or straw management (Table 5.2). Tillage × residue management interaction and tillage as the main factors were significant for total soil C stocks in the 0-1000 mm soil depth. The interaction showed that after nearly 40 years of wheat mono-cropping, soil C stocks were higher under the following production systems: CT with straw retention, NT with straw burning, SM with straw burning, and SM with no burning, than NT with straw retention and CT with straw burning (Figure 5.3). Furthermore, an analysis of soil C stock per soil layer showed that tillage × straw management was only significant in the 50-200 mm depth, where the soil carbon stocks were higher under NT than under CT when the straw was burnt (Figure 5.4).

Table 5. 2: Tillage and straw management effects on soil carbon stocks (t ha^{-1}) at different soil depth (mm).

	0-50	200-400	400-600	600-800	800-1000
Tillage practice					
No-tillage	7.13	18.7	13.1	9.67b	9.61
Stubble mulch	8.89	24.8	18.5	26.4a	27.1
Conventional tillage	7.07	19.3	24.4	8.07b	18.3
LSD	5.67	10.8	15.8	10.2	21.1
Straw management					
Burnt	8.88	26.1a	17.4	11.4	12.6
Not burnt	6.51	15.8b	20.0	18.0	24.0
LSD	4.63	8.79	12.9	8.30	17.3

Values with different letters (a-b) in a column for each factor indicate significant differences at $p<0.05$. LSD, the least significant difference at 95% confidence limit.

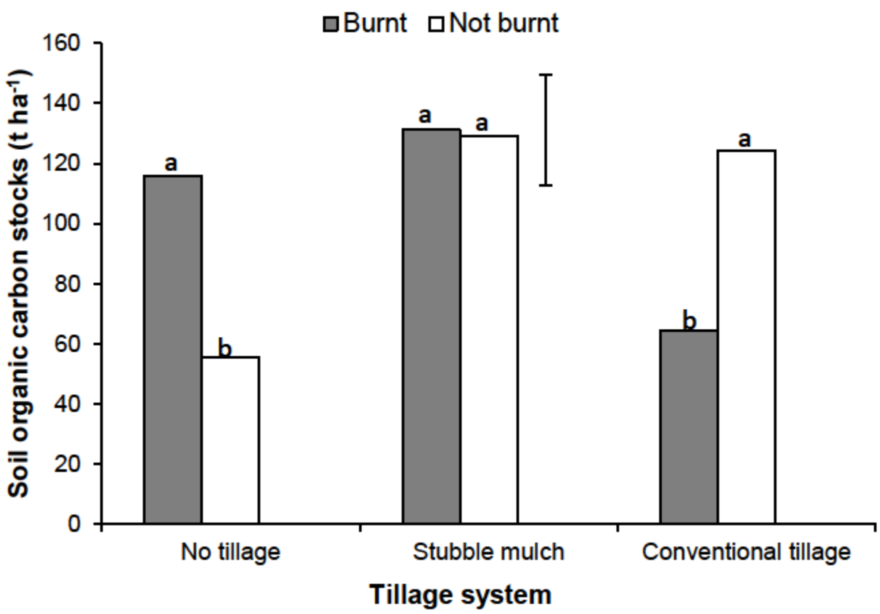

Figure 5. 3: The interaction effect of tillage and wheat straw management on total carbon stocks (0-1000 mm). An error bar and different letters (a-b) in the bars represent significant differences at $p<0.05$).

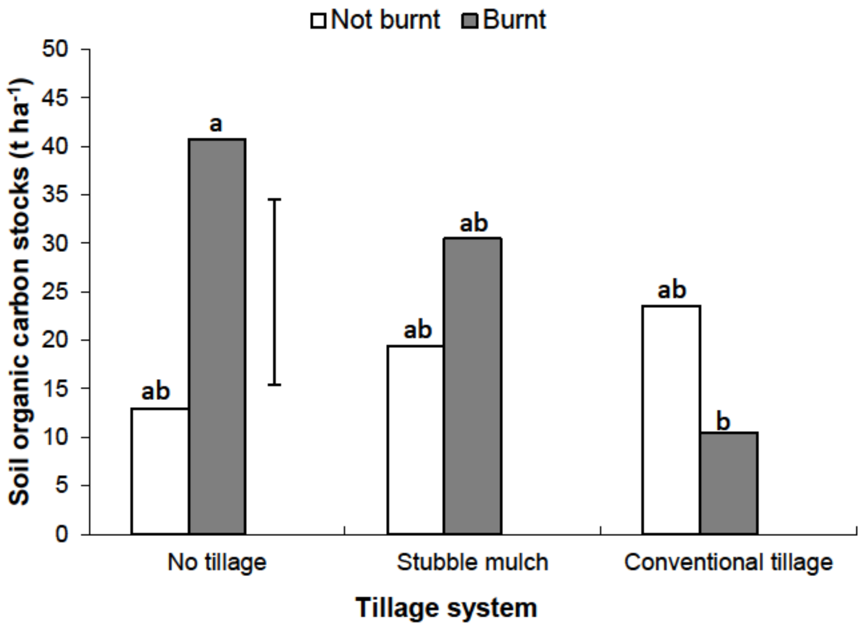

Figure 5. 4: The interaction effect of tillage and wheat straw management on soil carbon stocks in the 50-200 mm depth. An error bar and different letters (a-b) in the bars represent significant differences at $p<0.05$).

5.3.2. Soil pH, organic C, charcoal, total N and available P

In the 0-50 mm soil depth, tillage as the main factor had a significant effect on total soil N and available P (Table 5.3). Total N concentration was in the order, NT > SM > CT (Table 5.4). No-tillage had higher available P concentration than the other two tillage systems (Table 5.4) Soil pH and available P were higher, while total N concentration was lower where straws were burnt (Table 5.4). Tillage and straw management treatments did not significantly affect soil organic C and charcoal (Table 5.4). The interaction effect of tillage × straw management was not significant at the 0-50 mm ($p>0.05$) for all the studied soil properties (Table 5.3).

Table 5. 3: The general ANOVA of soil properties at 95% confidence level (n=18).

Factors	d.f.	pH	SOC	Charcoal	N	P
0-50 mm						
Tillage	2	ns	ns	ns	**	*
Burning	1	*	ns	ns	*	*
Tillage × Burning	2	ns	ns	ns	ns	ns
50-200 mm						
Tillage	2	ns	ns	ns	**	ns
Burning	1	*	ns	ns	ns	ns
Tillage × Burning	2	ns	ns	ns	*	ns
200-400				-		
Tillage	2	ns	ns	-	**	ns
Burning	1	ns	*	-	ns	ns
Tillage x Burning	2	ns	ns		ns	ns

*p<0.05; **p<0.001; ns, no significant differences; Burning represents straw management.

Table 5. 4: The effect of tillage and straw management on soil pH, soil organic carbon, charcoal total nitrogen and Bray 1 extractable phosphorus in the 0-50 mm layer.

	pH	SOC (g kg^{-1})	Charcoal (g kg^{-1})	N (g kg^{-1})	P (mg kg^{-1})
Tillage practice					
No-tillage	4.94	9.10	1.20	1.00a	40.3a
Stubble mulch	4.84	11.5	1.10	0.70b	29.9b
Conventional tillage	5.10	9.10	1.50	0.40c	23.1b
LSD	0.289	7.30	0.41	0.11	8.13
Straw management					
Burnt	5.09a	11.3	1.40	0.60b	35.4a
Not burnt	4.83b	8.40	1.10	0.80a	26.8b
LSD	0.236	5.96	0.34	0.090	6.64
CV (%)	4.50	57.5	25.5	12.1	20.3

Values with different letters (a-b) in a column for each factor indicate significant differences at p<0.05. LSD, the least significant difference at 95% confidence limit; CV, coefficient of variation.

In the 50-200 mm soil depth, soil pH varied significantly with straw management (Table 5.3). The soil pH was higher where wheat straw was burnt than not burnt (Table 5.5). Tillage or straw management treatments did not significantly affect soil organic C, charcoal (Table 5.5) or available P at the 50-200 mm soil depth (Table 5.3). The interaction effect of tillage × straw management was significant for total soil N ($p<0.05$). Total soil N was in the order: NT > SM > CT, when straw was not burnt and NT > SM = CT, when the straw was burnt (Figure 5.5).

Table 5. 5: The effect of tillage and straw management on soil pH, soil organic carbon, charcoal and total nitrogen in the 50-200 mm layer.

	pH	**SOC (g kg^{-1})**	**Charcoal (g kg^{-1})**	**Total N (g kg^{-1})**
Tillage system				
No-tillage	4.95	10.2	0.90	0.80a
Stubble mulch	4.95	10.9	1.20	0.60b
Conventional tillage	5.01	7.50	1.00	0.40c
LSD	0.214	5.98	0.67	0.09
Straw management				
Burnt	5.08a	10.9	1.00	0.50
Not burnt	4.86b	8.30	1.10	0.60
LSD	0.175	4.88	0.54	0.07
CV (%)	3.30	48.5	49.1	11.7

Values with different letters (a-b) in a column for each factor indicate significant differences at $p<0.05$. LSD, the least significant difference at 95% confidence limit; CV, coefficient of variation.

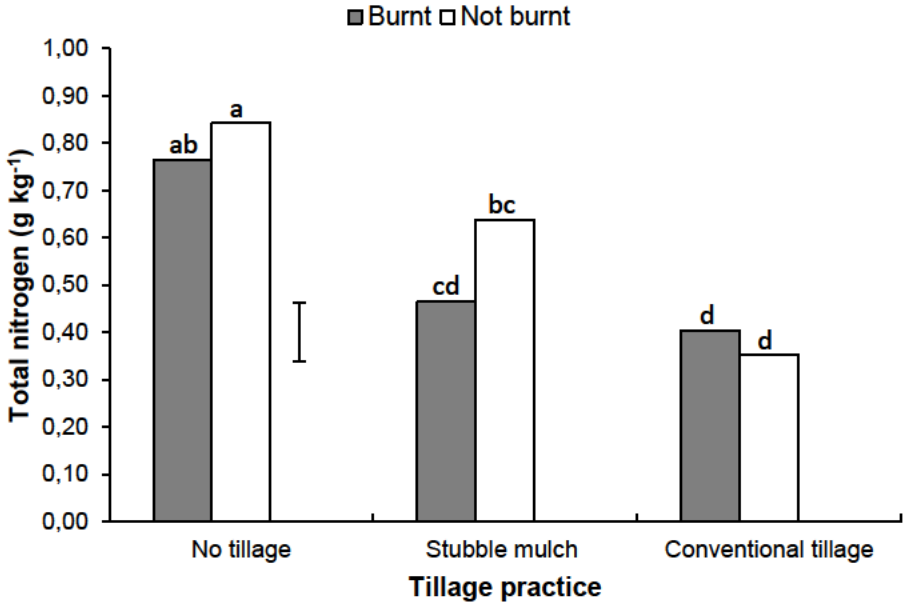

Figure 5. 5: The interaction effect of tillage and straw management on soil total nitrogen concentration in the 50-200 mm depth. An error bar and different letters (a-d) in the bars represent significant differences at p<0.05).

In the 200-400 mm soil depth, tillage as a main effect had a significant effect on total soil N. No-tillage had higher total N (Table 5.6). Soil organic C varied significantly with residue management at the 200-400 mm soil depth and was significantly higher in treatments where residues were burnt (Table 5.6). Tillage or residue management treatments did not significantly affect soil pH and available P in the 200-400 mm depth (p>0.05). The interaction effect of tillage × residue management was not significant for all soil properties in the 200-400 mm (Table 5.3).

Table 5. 6: The effect of tillage and residue management on soil organic carbon and total nitrogen in the 200-400 mm layer.

	Soil organic carbon (g C kg^{-1})	Total nitrogen (g N kg^{-1})
Tillage practice		
No-tillage	7.14	0.90a
Stubble mulch	8.88	0.50b
Conventional tillage	7.13	0.40b
LSD	3.62	0.170
Straw management		
Burnt	9.67a	0.60
Not burnt	5.76b	0.60
LSD	2.96	0.140
CV (%)	36.5	21.8

Values with different letters (a-b) in a column for each factor indicate significant differences at $p<0.05$. LSD, the least significant difference at 95% confidence limit; CV, coefficient of variation.

5.3.3. Soil carbon and phosphorus fractions

In the 0-50 mm soil depth, tillage as a main factor was significant for macro POC, micro POC, WSC, $NaHCO_3$, NaOH I Pi and NaOH II Pi fraction (Table 5.7). Straw management as the main factor was only significant for $NaHCO_3$. Tillage × straw management interaction was significant for micro POC, $NaHCO_3$ Pi and NaOH I Pi (Table 5.7). Soil organic C, mineral associated C, HCl Pi and residual P were not significantly affected by tillage and straw management (Table 5.7).

In the 50-200 mm soil depth, tillage as a main factor was only significant for macro POC, $NaHCO_3$ and residual P (Table 5.7). Only $NaHCO_3$ varied significantly with residue management (Table 5.7). Tillage × residue management interaction was not significant (Table

5.7). Soil organic carbon, micro POC, mineral C, NaOH I Pi, NaOH II Pi and HCl Pi were not significantly affected by tillage and straw management (Table 5.7).

In the 200-400 mm, tillage as a main factor was only significant for micro POC and $NaHCO_3$ Pi (Table 5.7). Only SOC and mineral associated C varied significantly with residue management. Tillage × residue management interaction was not significant (Table 5.7). Macro POC, NaOH I Pi, NaOH II Pi, HCl Pi and residual P were not significantly affected by treatments (Table 5.7).

Table 5. 7: The general ANOVA of soil C and P pools at 95% confidence level (n=54) under long-term wheat monoculture in Bethlehem.

	p values for various soil carbon and phosphorus fractions								
	0-50 mm			50-200 mm			200-400 mm		
	Tillage	**Burning**	**Tillage × burning**	**Tillage**	**Burning**	**Tillage × burning**	**Tillage**	**Burning**	**Tillage × burning**
SOC	ns	ns	ns	ns	ns	ns	ns	*	ns
Macro POC	**	ns	ns	*	ns	ns	ns	ns	ns
Micro POC	**	ns	*	ns	ns	ns	*	ns	ns
Min.assoc. C	ns	ns	ns	ns	ns	ns	ns	*	ns
WSC	*	ns	ns	ns	ns	ns	ns	ns	ns
$NaHCO_3$ Pi	**	**	*	**	*	ns	*	ns	ns
NaOH I Pi	*	ns	*	ns	ns	ns	ns	ns	ns
NaOH II Pi	*	ns	ns	ns	ns	ns	ns	ns	ns
HCl Pi	ns	ns	ns	ns	ns	ns	ns	ns	ns
Residual P	ns	ns	ns	*	ns	ns	ns	ns	ns

*p<0.05; **p<0.001; ns, no significant differences; burning, straw management; Min.assoc.C, mineral associated carbon; WSC, water soluble carbon.

In the 0-50 mm soil depth, macro POC was higher under NT (0.67 ± 0.05 g kg^{-1}) and SM (0.63 ± 0.05g kg^{-1}) than under CT (0.30 ± 0.05 g kg^{-1}). The WSC concentration in the 0-50 mm soil depth was lower in the NT (10.6 mg kg^{-1}) than CT (21.1 mg kg^{-1}), with SM having 16.8 mg kg^{-1} (similar to the other two). While NaOH II Pi was higher under SM (9.67 ± 1.28 mg kg^{-1}) compared to both NT (7.91 ± 1.28 mg kg^{-1}) and CT (8.02 ± 1.28 mg kg^{-1}).

No tillage and SM had a higher concentration of micro POC compared to CT with burnt straw in the 0-50 mm soil depth (Figure 5.6). When the straw was not burnt, the tillage did not differ in terms of micro POC (Figure 5.6).

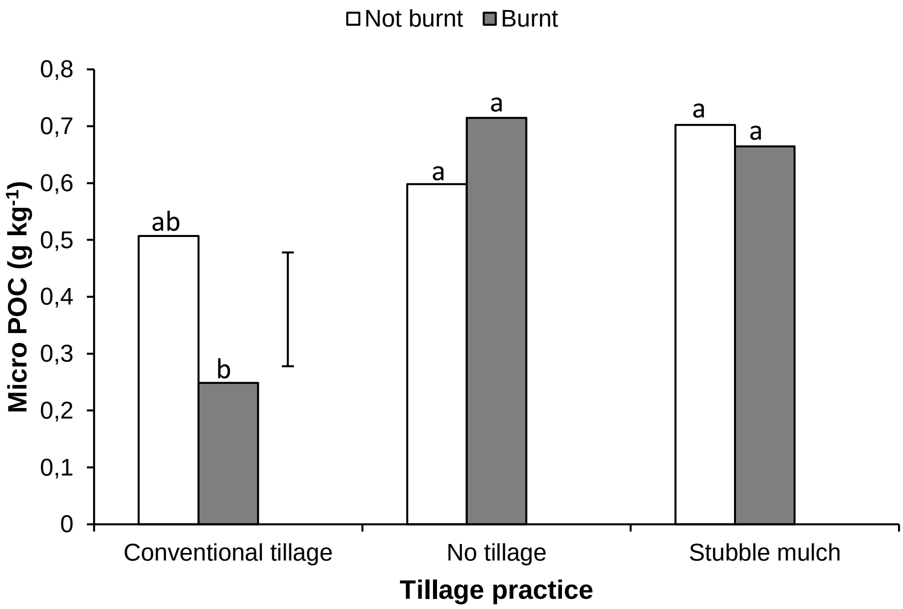

Figure 5. 6: The interaction effect of tillage × straw management on micro POC (g kg^{-1}) in the 0-50 mm soil layer. An error bar and different letters (a-b) in the bars represent significant differences at $p<0.05$).

Burning of straw under CT increased $NaHCO_3$ Pi compared to all other treatments in the 0-50 mm soil depth (Figure 5.7a). The NaOH I Pi was higher under CT compared to SM and NT, where straw was not burnt (Figure 5.7b). When straw was burnt, NaOH I Pi was similar in all the tillage treatments (Figure 5.7b).

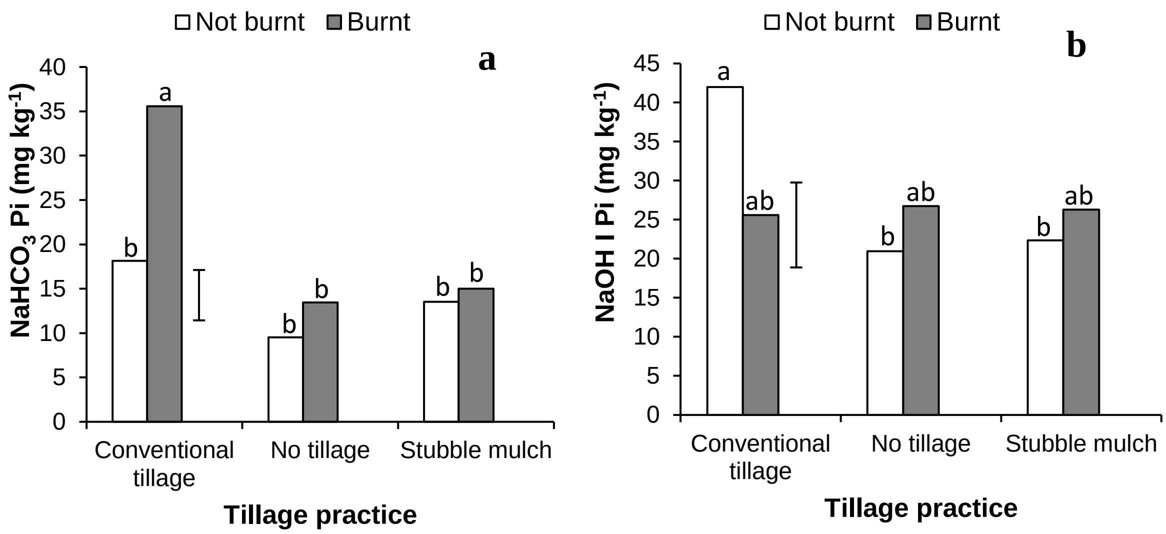

Figure 5. 7: The interaction effect of tillage × straw management on (a) $NaHCO_3$ Pi (b) NaOH I Pi and fractions (mg kg^{-1}) in the 0-50 mm soil layer. An error bar and different letters (a-b) in the bars represent significant differences at $p<0.05$).

In the 50-200 mm soil layer, macro POC concentration was higher under SM (0.33 ± 0.06 g kg^{-1}) but lower under NT (0.13 ± 0.06 g kg^{-1}). In the 200-400 mm, straw burning increased soil organic carbon (9.67 ± 1.33 g kg^{-1}) and mineral associated C (9.20 ± 1.30 g kg^{-1}) compared to not burning. Micro POC concentration was higher under stubble mulch (0.35 ± 0.04 g kg^{-1}) and the least under no tillage (0.24 ± 0.04 g kg^{-1}). While residual P was higher under NT (6.47 ± 0.414 mg kg^{-1}) compared to SM (5.26 ± 0.414 mg kg^{-1}), $NaHCO_3$ was higher under CT (25.7 ± 2.63 mg kg^{-1}) than both NT (9.20 ± 2.63 mg kg^{-1}) and SM (14.0 ± 2.63 mg kg^{-1}). Burning (19.7 ± 2.15 mg kg^{-1}) wheat straw increased $NaHCO_3$ compared to not burning (12.9 ± 2.15

mg kg^{-1}). In the 200-400 mm, $NaHCO_3$ Pi was higher under conventional tillage (15.5 ± 3.03 mg kg^{-1}) compared to no tillage (6.00 ± 3.03 mg kg^{-1}).

5.3.4. Nutrient uptake

Tillage as the main factor had a significant effect on the uptake of N ($p<0.05$). Under NT, N uptake (236 ± 22.4 kg ha^{-1}) was significantly higher than SM (173 ± 22.4 kg ha^{-1}). Phosphorus uptake was not significantly different across tillage or straw management. The interaction of tillage × straw management had no significant effect on the uptake of N and P by wheat at the critical flag leaf emergence growth stage. However,

5.4 DISCUSSION

The higher concentration of total soil N under conservation tillage practices (NT > SM> CT) could be explained by lower N removal as grain over the years. Higher total N under NT was consistent for both the 0-50 and 50-200 mm showing that amongst all the tillage practices, NT maintained a higher N reservoir. Seepamore et al. (2020) showed that irrespective of straw management and N fertiliser level, wheat yield increased with the level of soil disturbance (CT > SM > NT). The higher yields removed more N from the CT treatment. Also, straw burning under CT systems most likely resulted in gaseous losses of N oxides, upon combustion, lowering soil N as suggested by Pellegrini et al. (2018), Certini (2005) and Neary (2004). Compared to the grassland nearby, the total N in the NT treatment was higher in both the 0-50 (1.0 g kg^{-1}) and the 50-200 mm (0.8 g kg^{-1}) depths, while SM and CT had lower N at both depths, indicating the importance of NT in at least maintaining total N. Both SM and CT systems result in soil disturbance, which enhances soil aeration. The combination of these practices with burning might have led to removal and loss of N. The higher N in the NT resulted in greater N uptake by wheat than CT in the 2016 season (the only year sampled).

The higher total soil C stocks to a depth of 1000 mm under NT than CT where straw was burnt (Figure 5.3) suggests that this combination improves C sequestration. This agrees with the study by Chan et al. (2002), whereby CT and burning reduced different SOC fractions. The higher profile (0-1000 mm) SOC stock, was mainly explained by SOC stocks in the 50-200 depth, which followed the same trend (Figure 5.4), and not any other depth. The lack of tillage and straw management on SOC concentrations in the 0-50 and 50-200 may be due to low biomass input in the semi-arid conditions and high oxidation as a result of lack of protection in the loam soil. Soil organic carbon ranged from 6.6 to 7.8 g C kg^{-1} in the natural grassland (Table 5.1) next to the trial which is slightly lower than 7.5 to 11.5 g C kg^{-1} in the cultivated trial (Table 5.4; 5.5). This shows that there has been a general increase in SOC due to biomass addition from wheat over time and 11.5 ± 3.28 g C kg^{-1} have been accumulated to date. The higher C concentration (Table 5.6) and stock (Table 5.2) in the 200-400 mm depth of the burnt plots than the non-burnt plots, indicates that straw burning increases C sequestration, at deeper layers, in dryland wheat production systems under semi-arid conditions. The lack of differences on charcoal as a result of tillage or straw burning agrees with the study by Rumpel (2008) who reported no significant effects of stubble burning in the aromatic and recalcitrant black carbon after 30 years of experimentation in France. The lack of differences was attributed to (i) the nature of the input material, (ii) low intensity of fire used for straw burning and (iii) the potential loss of black carbon from the site through erosion (Rumpel et al., 2006). The Bethlehem long term trial is located in the open plains of the Eastern Highveld region which are more susceptible to wind erosion (Mahasa, 2015).

The higher soil pH and available P where straw was burnt in the NT treatment could also have increased root biomass accumulation in the NT with burnt straw, than where straw was retained. The organic matter from roots and their exudates could have been stabilised as part of mineral associated C. Straw retention in the NT could have resulted in massive losses through the wind (Mahasa, 2015).

Burning straw reduced biomass incorporated under CT, and with lower available P, root biomass production may have been limited, lowering soil C stocks and POC. Although SOC concentrations were not affected by tillage and straw management in the 0-50 and 50-100 mm depths, POC was reduced by CT especially when straw was burnt, indicating that minimising soil disturbance resulted in accumulation of the labile soil fraction, possibly explaining the results of total N which followed the same trend.

The higher macro POC and available P under NT followed by SM suggested that these parameters accumulated at the surface with less soil disturbance, while CT mixed the material added with deep soil layers (Bot and Benites, 2005). Although the WSC was extremely lower than the other SOC fractions, the lower WSC in the NT (10.6 mg kg^{-1}) than the CT (21.1 mg kg^{-1}) in the 0-50 mm depth (opposite to macro POC and available P) suggest that the more of the macro POC is broken down into simpler forms (soluble) and that there could be competitive sorption between WSC and P in these soils. Contrary to other parameters, $NaHCO_3$ P (labile) was higher under burnt CT treatments while burning wheat straw increased Al associated NaOH I Pi suggesting that straw burning increased pH and made P more available by reducing P bound to Al. This view was supported by higher soil pH where straw was burnt. The higher $NaHCO_3$ Pi in burnt CT treatment was in agreement with the findings by Romanya et al. (1994) who also reported higher labile P on the burnt treatment.

Nutritional requirements were generally adequate across all treatments except for P, when compared with known requirements of wheat (Sosibo et al., 2017). When compared with the grassland soil nearby, all the treatments at least doubled the concentration of available P (Table 5.4), in response to the annual addition of 12.5 kg P ha^{-1} $year^{-1}$. Only the NT systems had adequate levels of available P (40 mg kg^{-1}) in the surface soil (Table 5.4). This is further supported by the NaOH II Pi (physically protected P), which was higher under NT and SM. These findings are comparable to findings by Ncoyi et al. (2020) who reported 5.07 mg kg^{-1} higher labile ($NaHCO_3$ Pi) and 2.16 mg kg^{-1} stable (HCl Pi) under conservation tillage (stubble mulch and no tillage) practices. This suggests NT is a more sustainable approach for managing P depletion and reducing external fertiliser requirements in these systems. It should be noted that straw was retained and nutrient removal in grain was limited because of the relatively low yields obtained in these systems. This probably explains why most of the other nutrient levels remained adequate for the dryland after 40 years of continuous cropping, except for P.

When compared to the soil on the adjacent grassland, all tillage practices and both straw management strategies resulted in lower soil pH. This effect could have been a result of decomposition of the added organic matter and nitrification of N due to the cultivation activities, especially the CT that was practised before the establishment of the trial, about 20 years before. Burning of straw produces ash, which increased mean pH in the burnt systems at both 0-50 and 50-200 mm soil depths, making it favourable for the availability of some nutrients. Carbonates released after burning increases soil pH (Heydari et al., 2017; Molina et al., 2007; Certini, 2005). During this process, organic P is converted to inorganic P making it more available in the burnt treatments (Romanya et al., 1994). Higher P in the surface soil under NT and SM could be explained by the accumulation of straw under these systems. Burning of straw increases soil pH, compared to straw retention, making it favourable for the availability of some nutrients.

5.5 CONCLUSION

The findings of this work showed that no-tillage improved the uptake of N than either SM or CT systems. Tillage and straw management did not affect SOC and charcoal concentration in the top 200 mm of the soil, while NT with straw burning increased labile soil C fractions, total N and Bray 1 extractable P, under dryland wheat-based CA, where N fertiliser is applied at 60 kg ha^{-1}. The NT increased available P and decreased WSC in the 0-50 mm depth. No tillage with straw burning increased SOC stocks (up to 116 t ha^{-1}) in the 0-1000 mm depth, while other combination showed lower stocks. Under these conditions, labile P fraction ($NaHCO_3$ Pi) was higher under CT with a burnt straw while NaOH I Pi was higher when the straw was not burnt. While straw burning reduced concentrations of total soil N, it increased soil pH and P availability, as well as C sequestration. It is recommended that future studies consider understanding the effects of different SOC and P fractions on P sorption/desorption and availability in wheat fields.

CHAPTER 6: SORPTION OF PHOSPHORUS ON SOILS FROM WHEAT FIELDS AS AFFECTED BY MANAGEMENT AND DISSOLVED ORGANIC MATTER

ABSTRACT

Conservation agriculture (CA) practices are known to affect soil phosphorus (P) and organic matter (SOM) fractions. However, effects of different CA options and the presence of dissolved organic carbon (DOC) on P sorption and availability in contrasting soils are not clearly understood. This study was conducted to understand the effects of crop rotation, tillage, residue management, different forms of aluminium (Al) and iron (Fe), and presence of DOC on P adsorption on two contrasting soils. Phosphorus sorption isotherms for Oxidic and Acric Plinthosol soil types of two distinct wheat (*Triticum aestivum* L.)-based production systems of South Africa were studied. The Oxidic soil samples were from KwaZulu-Natal's (KZN) irrigated production systems under minimum-till and various cropping sequences, whereas the Acric Plinthosol soil samples were from a long term, low fertiliser input dryland wheat trial in Bethlehem which had various tillage and straw management treatments. Another set of sorption experiments was conducted to determine the effects of DOC on P sorption using soils with low native C from KZN and Bethlehem. Four P levels (0, 5, 10, and 15 ppm) and three DOC (0, 20 and 3800 mg L^{-1}) levels were used. Phosphorus sorption maxima were similar for the acidic Oxidic soils across cropping sequences where wheat was preceded by either soybean (*Glycine max* L.) or maize (*Zea mays* L.). Under no-tillage (NT) on an Acric Plinthosol, wheat straw retention lowered P sorption than when burned. Addition of DOC reduced sorption and increased available P, with greater effects on the less acidic soil. The affinity for P adsorption was related to acid saturation, oxalate Al, dithionite Al and macro particulate carbon in the highly weathered Oxidic soils, whereas it was related to oxalate Al, aluminium bound inorganic P (NaOH I Pi) and residual P on an Acric Plinthosol soils.

Keywords: Adsorption, conservation agriculture, dissolved organic carbon, sorption maxima, straw burning.

6.1 INTRODUCTION

Wheat (*Triticum aestivum* L.) farmers apply large amounts of inorganic phosphorus (P) fertiliser to meet crop requirements on the P deficient soils of South Africa. With global P resources declining and the inorganic P fertiliser prices increasing (De Wet and Liebenberg, 2018), scientists are on a quest for sustainable ways of managing P on deficient soils. Conservation agriculture (CA) practices that include minimum tillage, crop residue retention, crop rotation, fertilisation and lime application may have positive effects on soil organic matter (SOM) pools and P availability. Zibilske et al. (2002) noted an increase in P availability owing to higher soil organic carbon (SOC) in the topsoil. In agreement, Hou et al. (2014) reported an increase in organic P upon SOC accumulation, suggesting that some SOC fractions positively influenced P availability. Results from Chapter 5 on work from low fertiliser input dryland wheat production systems of South Africa showed that long-term no-tillage (NT) increased particulate organic carbon (POC), available P pools and residual P fraction, while wheat straw burning increased soil organic carbon (SOC), mineral-associated C, and plant available P pools in the topsoil. Results from Chapter 3, from fertiliser intensive, irrigated systems, showed that soils from maize/wheat crop rotations had significantly higher C fractions and plant-available P in the topsoil, than those from soybean-wheat rotations. It is essential to understand whether these effects on SOM fractions, as a result of soil management practices, reduce sorption and increase the availability of P in agricultural soils.

Water-soluble carbon (WSC) is part of the labile organic matter fraction that is obtained through <0.45µm filters, it is characterised by its finer diameter, high reactivity, high mobility and bioavailability and faster turnover time (Chantigny et al., 2008; Bolan et al., 2011), and plays an important role in soil aggregation and provision of soil nutrients (Gmach et al., 2020). Preliminary experiments (Chapters 3 and 5) showed low measurable WSC in the soils that differed in the extent of weathering, with relatively lower WSC in soils from KwaZulu-Natal than Bethlehem, in South Africa. The extremely low WSC than the other fractions was possibly because the WSC released from the straw could have been rapidly decomposed or sorbed by soil minerals and stabilised, increasing the mineral associated C (Kaiser and Zech 1998; Kalbitz et al., 2000). The lower WSC in KZN (23% clay) than Bethlehem (16% clay) soils, could be explained by the higher clay content which could have sorbed this SOC fraction. Sorption of WSC contributes significantly to SOC stabilisation (Kaiser and Guggenberger, 2000) and the lower WSC in NT, where available P was higher than CT suggest that WSC may reduce fixation of P in soils. Dissolved organic carbon (WSC) is believed to reduce P sorption and make P available in the soil solution through multiple mechanisms. The mechanisms include (1) competing for adsorption sites with P; in this process, P is outcompeted by negatively charged dissolved organic compounds such as malate and oxalate among others for sorption sites thus it remains available in the soil solution; (2) coating of Fe and Al so that they do not fix P and (3) formation of cation bridges to adsorb P (Hunt et al., 2007). Sosibo et al. (2017) reported that intensive no-till wheat-based systems, where wheat is rotated with summer crops and crop residues are retained resulted in increased P availability. This view was supported by the results of Chapter 3, especially where wheat was preceded by maize. The maize/wheat cropping sequence showed lower WSC than where wheat was preceded by soybean, and this suggested that there was a close relationship between WSC and P availability, either through competitive sorption or through the decomposition of the WSC mineralising P. Minimum tillage and residue retention could release WSC into the surface soils, which may have significant effects of increasing P availability in no-till systems. Dube et al. (2014) reported that high biomass input from cover crops increased available P in a maize-based CA system, which was explained by the potential release of organic acids (e.g., malate and oxalate) competing with P for sorption sites, as well as increased microbial biomass P. There is a need to understand the effects of the presence of dissolved organic carbon (DOC) from crop residues, representing WSC, on P sorption on contrasting soils and production systems. Sorption refers to the physical or chemical removal of soil nutrients e.g. P from the soil solution, including the formation of insoluble complexes (precipitation) and attachment to the soil colloids (adsorption) depending on the prevailing soil physico-chemical conditions (Li et al., 2007; Moazed et al., 2010; Muindi et al., 2015).

Many studies on DOC dynamics have been conducted on shallow temperate, forest and peatland soils (Gmach et al., 2020). The findings from these studies suggest that DOC can be quickly sorbed onto Al and Fe oxides upon its release into soil solution (Kaiser and Zech, 1998) and may inhibit P sorption to metal oxides (Hunt et al., 2007; Gmach et al., 2020). The information about DOC dynamics in deep highly weathered soils under agriculture is scarce (Gmach et al., 2020). Most soils on which wheat is produced in South Africa are moderate to highly weathered, some with deep profiles (Sosibo et al., 2017). The current study differs from previous studies that focused on understanding the factors governing the persistence of DOC as an ecosystem property (Kalbitz et al., 2005; Kaiser and Kalbitz, 2012), without understanding the competitive sorption with P. The co-sorption of organic matter is necessary to understand the effects DOC on P sorption (Singh et al., 2016). Hence, the current study aims to establish the relationship between labile C pool and P sorption in the South African moderate to highly weathered wheat production soils.

This study hoped to answer these questions: (1) Does the type of CA practice significantly influence P sorption energy and capacity? (2) Do P sorption indices relate to soil acidity, Fe, Al, P and C fractions? (3) Do the wheat production soils have a high affinity for sorption of DOC, which may significantly stabilise as part of mineral associated C (native carbon) of the soil? (4) Does the sorption of DOC reduce adsorption of P, making P more available in the soil solution? Understanding the DOC sorption and P availability will be a significant contribution to the management of P, especially in the fields under conservation agriculture. Farmers will also benefit from knowing the importance of CA in improving P availability. We hypothesize that (1) soil management in different CA options significantly affects P sorption capacity, (2) the sorption capacity of soils on wheat fields can be explained by soil acidity, Fe, Al, P and C fractions; (3) The soils on wheat fields have a high affinity for DOC, which is sorbed to become mineral associated C; (4) Sorption of DOC on soil particles reduces fixation of P and increases its availability.

6.2 MATERIALS AND METHODS

6.2.1 Description of study sites and soil sampling

The study was conducted on soils from two major wheat production regions of South Africa, namely KwaZulu-Natal (KZN) and Eastern Highveld. The KZN wheat fields and Bethlehem trial in the Eastern Highveld have been previously described in Chapter 3 (section 3.2.1) and 4 (section 4.2.1) respectively.

The soils were characterised for soil properties as described in Section 3.2.3, 3.2.4 and 3.2.5 of Chapter 3 including extractable iron (Fe) in 0.1 M HCl (1990), amorphous Fe and Al in oxalic acid pH (3.0) adjusted 0.2 M ammonium oxalate method (Warren, 1994) and crystalline Fe and Al using dithionite citrate bicarbonate method (Mehra and Jackson, 1960). In this chapter, these Fe and Al forms are referred to as extractable Fe, Oxalate (Fe, Al) and dithionite (Fe and Al) respectively. Clay content was determined using the bouyoucos hydrometer method (Bouyoucos, 1962). The average characteristics of the soils are presented in Table 6.1 for the Oxidic (KwaZulu-Natal) and Table 6.2 for the Acric Plinthosol (Bethlehem) soils. The soil properties varied significantly between the two soil types with the Oxidic soils having a higher clay % and soil organic carbon than the Acric Plinthosol (Table 6.1, 6.2).

Table 6. 1: Properties of the topsoils (0-200 mm) from KZN different cropping sequences.

Soil parameters	Soybean/Wheat	Maize/Wheat
Soil pH	4.63 ± 0.11	4.70 ± 0.13
Acid saturation	3.84 ± 1.38	1.87 ± 0.66
Soil organic carbon	**25.4 ± 3.91**	**25.5 ± 4.19**
Macro POC	0.68 ± 0.05	0.77 ± 0.01
Micro POC	0.74 ± 0.03	0.75 ± 0.03
Mineral associated carbon	24.0 ± 3.92	24.0 ± 4.18
Bray 1 P	36.5 ± 5.01	58.3 ± 12.0
$NaHCO_3$ Pi	122 ± 34.4	305 ± 80.2
NaOH II Pi	77.8 ± 20.7	86.0 ± 19.1
NaOH I Pi	119 ± 13.0	118 ± 14.9
Residual P	16.9 ± 3.24	18.5 ± 2.80
Dithionite extractable aluminium	196 ± 13.6	165 ± 8.25
Oxalate extractable aluminium	227 ± 25.0	218 ± 25.0
Extractable iron	52.9 ± 12.7	39.9 ± 9.48
Dithionite extractable iron	259 ± 37.8	245 ± 37.3
Oxalate extractable iron	579 ± 47.7	623 ± 74.2
Exchangeable calcium	970 ± 89.0	1403 ± 148
Clay	**21.4 ± 2.54**	**23.6 ± 2.07**
Cation exchange capacity	6.98 ± 0.54	11.3 ± 1.20

The means are presented with the standard error of means. Acid saturation (%); aluminium (mg kg^{-1}); Bray 1 P, extractable phosphorus (mg kg^{-1}); exchangeable calcium (mg kg^{-1}); cation exchange capacity ($cmol_c kg^{-1}$); Clay (%); iron (mg kg^{-1}); mineral associated carbon (g kg^{-1}); $NaHCO_3$ Pi, sodium bicarbonate inorganic phosphorus (mg kg^{-1}); NaOH Pi, Sodium hydroxide inorganic P (mg kg^{-1}); pH (KCl); POC, particulate organic carbon (g kg^{-1}); residual P (mg kg^{-1}); Soil organic carbon (g kg^{-1}).

Table 6. 2: Properties of the topsoils (0-50 mm) from different tillage and straw management practices in Bethlehem.

	Not burnt			Burnt		
Soil parameters	NT	SM	CT	NT	SM	CT
Soil pH	4.70 ± 0.12	4.70 ± 0.066	5.09 ± 0.24	5.18 ± 0.20	4.97 ± 0.11	5.12 ± 0.05
Acid saturation	3.61 ± 2.23	2.93 ± 1.80	1.38 ± 1.68	0	0	0
Soil organic carbon	**9.12 ± 0.25**	**8.77 ± 1.37**	**7.42 ± 2.30**	**9.00 ± 1.83**	**14.2 ± 7.17**	**10.7 ± 0.48**
Macro POC	0.66 ± 0.13	0.63 ± 0.02	0.29 ± 0.03	0.67 ± 0.04	0.62 ± 0.06	0.30 ± 0.04
Micro POC	0.60 ± 0.10	0.70 ± 0.04	0.51 ± 0.06	0.72 ± 0.06	0.67 ± 0.04	0.25 ± 0.13
Min.assoc. C	7.86 ± 0.37	7.44 ± 1.37	6.62 ± 2.33	7.62 ± 1.91	13.0 ± 7.07	10.2 ± 0.48
Bray 1 P	34.6 ± 6.50	27.1 ± 5.53	18.7 ± 0.73	45.9 ± 4.88	32.7 ± 2.53	27.5 ± 2.37
$NaHCO_3$ Pi	9.51 ± 0.96	13.5 ± 2.09	18.1 ± 1.97	13.5 ± 2.49	15.0 ± 2.39	35.6 ± 6.28
NaOH II Pi	7.91 ± 0.52	9.41 ± 1.08	7.76 ± 0.27	7.91 ± 1.05	9.94 ± 0.46	8.29 ± 0.57
NaOH I Pi	21.0 ± 4.07	22.4 ± 0.26	42.0 ± 3.64	26.8 ± 0.74	26.3 ± 7.14	25.6 ± 4.24
Residual P	7.64 ± 0.89	5.23 ± 0.26	9.08 ± 2.98	5.64 ± 0.37	5.43 ± 0.53	5.49 ± 0.29
Dithionite Al	123 ± 9.17	110 ± 21.4	131 ± 30.3	98.3 ± 55.3	88.4 ± 30.0	184 ± 1.14
Oxalate Al	232 ± 15.9	203 ± 29.9	140 ± 16.0	162 ± 13.2	138 ± 11.1	156 ± 10.7
Extractable iron	20.5 ± 3.02	17.8 ± 0.26	21.1 ± 0.76	21.8 ± 1.53	17.7 ± 1.25	20.3 ± 0.74
Dithionite Fe	184 ± 17.9	155 ± 0.16	102 ± 0.08	156 ± 0.33	120 ± 21.7	102 ± 0.25
Oxalate Al	294 ± 64.5	369 ± 77.6	215 ± 26.3	280 ± 22.2	236 ± 17.7	249 ± 17.7
Ca	579 ± 60.9	696 ± 67.8	793 ± 72.3	719 ± 80.1	598 ± 78.4	761 ± 51.7
Clay	**16.3 ± 0.82**	**15.3 ± 0.82**	**16.0 ± 0.01**	**15.3 ± 1.08**	**15.3 ± 1.63**	**16.7 ± 0.82**
CEC	5.10 ± 0.26	5.66 ± 0.30	5.75 ± 0.27	6.33 ± 0.81	5.18 ± 0.54	5.58 ± 0.40

The means are presented with the standard error of means.Acid saturation (%); Al, aluminium (mg kg^{-1}); Bray 1 P, extractable phosphorus (mg kg^{-1}); Ca, exchangeable calcium (mg kg^{-1}); CEC, cation exchange capacity ($cmol_c kg^{-1}$); CT, conventional tillage; Clay (%); Fe, iron (mg kg^{-1}); Min.assoc. C, mineral associated carbon (g kg^{-1}); $NaHCO_3$ Pi, sodium bicarbonate inorganic phosphorus (mg kg^{-1}); NaOH Pi, Sodium hydroxide inorganic P (mg kg^{-1}); NT, no tillage; pH (KCl); POC, particulate organic carbon (g kg^{-1}); residual P (mg kg^{-1}); Soil organic carbon (g kg^{-1}); SM, stubble mulch.

6.2.2 Phosphorus adsorption experiment

Samples (3 g) of the Ferralsols (0-200 mm) from KZN wheat fields, and the Plinthosol soil groups (0-50 mm) from the Bethlehem long-term trial (Chapter 3 and chapter 5), were weighed into 50 mL centrifuge tubes in triplicates. The sampled depths were selected because of their significant response to soil management practices in the respective production regions. Four P levels (0, 10, 30, 40 ppm for Oxidic soils; 0, 5, 10, 15 ppm for an Acric Plinthosol) as KH_2PO_4 were prepared in 0.01 M $CaCl_2$. Different P concentrations were used because the soils studied were at different stages of weathering and it is presumed the P fixing capacity would vary. The P solutions (30 mL) were added into the centrifuge tubes with the soil samples. Three drops of toluene were added to inhibit microbial activity and the tubes were sealed and shaken on an end to end shaker at 100 oscillations per minute at 25 ± 1℃ for 24 h. Blank samples without soil were included to account for possible P adsorption onto centrifuge tubes. The suspensions were then centrifuged on a BECKMAN COULTER Avanti J-26 XPI to obtain clear extracts. Phosphorus from the extracts was determined as described in Section 3.2.3 of Chapter 3. Phosphorus sorbed was calculated as the difference between the amount of P added and P remaining in solution after 24 h.

6.2.3 Dissolved organic carbon extraction

The DOC used in this study was extracted from wheat straw that was collected at wheat harvest from the long-term trial in Bethlehem. The straw was oven-dried at 105°C for 24 h in forced circulation oven type (model- Labcon FSOE-HD). It was then chopped with a pair of scissors and finely milled with a hammer mill (lab World Scientec - serial number 308). The ground straw (556 g) was weighed into a 5L bottle, and 2.5 L of Milli-Q water (18 MΩ.cm) was added and the mixture was shaken on an end-to-end shaker at 100 oscillations min^{-1} for 1 h. The straw suspension was left to settle in the fridge set at 4°C for 4 d, followed by centrifugation at 4000 r.p.m for 20 min using a BECKMAN COULTER Avanti J-26 XPI centrifuge. The extract was filtered through Kartell Art. 442 Imbuto Büchner Ø filter 110 mm at room temperature within 2 h. The extract was analysed for SOC using Walkley Black method (Combs and Nathan 1998) and pH. Calcium, magnesium, sodium, potassium and sulphur (mg L^{-1}) were measured using the Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) (Perkin Elmer 5300V, USA). The wheat straw extract had a pH of 4.32, 3800 mg C L^{-1}, 662 mg Ca L^{-1}, 180 mg K L^{-1}, 415 mg Mg L^{-1}, 32.3 mg Na L^{-1} and 3089 mg S L^{-1}.

6.2.4 Sorption of phosphorus and dissolved organic carbon on soil

Two soils with low C were sampled from the 800-1000 mm depth from KZN and Bethlehem wheat fields. The properties of the selected soils are shown in Table 6.3. Four P (0, 5, 10 and 15 ppm) levels were prepared in 0, 20 mg L^{-1} and 3800 mg L^{-1} DOC respectively. Four P levels with or without DOC were added into the weighed 3 g of soil in triplicates. Blank samples without soil were included to account for possible P adsorption onto centrifuge tubes. The samples were shaken for 24 h in the cold-room set at 4°C. After shaking, the samples were centrifuged and filtered to obtain clear extracts. Phosphorus in the extract was determined colorimetrically in the Seal AA3 HR Phosphate XY-2 auto analyser (Seal Analytical, Germany) within 2 h off the cold-room. The amount of P adsorbed was calculated as the difference between P added and P that remained in the solution after 24 h. This experiment was repeated with four DOC (0, 240, 479 and 957mg C L^{-1}) in 18 MΩ.cm Milli-Q water and no P added. Dissolved C was analysed using Walkley Black method (Combs and Nathan 1998), to determine sorption of DOC. The amount of C adsorbed was calculated as the difference between C added and C that remained in the solution after 24 h.

Table 6. 3: Properties of the low carbon soils from different localities (800-1000 mm depth) used in the sorption experiments.

		Soil properties					
Location	**Soil type**	C	Clay	pH	P	CEC	Ca
Bethlehem	Acric Plinthosol	5.65	30.0	5.42	3.83	8.69	955
KwaZulu-Natal	Ferralsols	4.69	40.0	4.50	0.00	4.22	385

C, soil organic carbon (g kg^{-1}); pH (KCl); P, extractable phosphorus (mg kg^{-1}); CEC, cation exchange capacity ($cmol_c kg^{-1}$); Ca, exchangeable calcium (mg kg^{-1}); Clay (%).

The sorption data were fitted to the Langmuir sorption isotherms, and maximum sorption (Smax) and the parameter associated with bonding energy (b) were obtained by fitting the sorption data were fitted into the linearized Langmuir equation (Gichangi et al. 2008) below.

$$\frac{C}{S} = \frac{1}{Smax \times b} + \frac{C}{Smax}$$

Whereby C (mg L^{-1}) refers to P remaining after 24 h equilibrium, S is P sorbed in mg kg^{-1}, b is an affinity constant or a constant related to P bonding energy (L mg^{-1}) and Smax refers to P adsorption maximum (mg kg^{-1}). The ratio of C/S versus C (Olsen and Watanabe 1957) were plotted and the reciprocal of the slope of the linear regression from the regression equation is Smax.

6.2.5 Statistical analyses

The significance of differences between crop rotation systems from KZN data were analysed using the Kruskal-Wallis non-parametric test and the differences were based on the Kruskal-Wallis H test and Chi-square probability (P). Tillage and wheat straw management effects on sorption parameters (Smax and b), Fe and Al in Bethlehem, were tested using a two-way ANOVA on Genstat 14th edition. The means for ANOVA were separated using Tukey's test at a 95% confidence interval. The sorption indices (Smax and b) were correlated with Fe, Al fractions and other soil properties (soil pH, AS, exchangeable Ca, C and phosphorus fractions) characterised in preliminary studies for Bethlehem and KZN using Spearman's correlations for KZN (Oxidic soils) and Pearson's correlations for Bethlehem (Acric Plinthosol). Data from the sorption of P and DOC were fitted to the Langmuir equations and Smax and b-value calculated.

6.3 RESULTS

6.3.1 Sorption of phosphorus on Oxidic soils under different cropping sequences

The average sorption isotherms followed a typical Langmuir isotherm under both cropping sequences (Figure 6.1). The sorption indices Smax {H(10)=0.463, p=0.492} and b {H(10)=3.29, p=0.070} did not vary significantly with cropping sequence. The Smax was 455 ± 59.5 mg kg^{-1} for both maize-wheat and soybean-wheat crop rotations while the b value ranged between 0.431 ± 0.68 L mg^{-1} (maize) to 0.917 ± 0.68 L mg^{-1} (soybean).

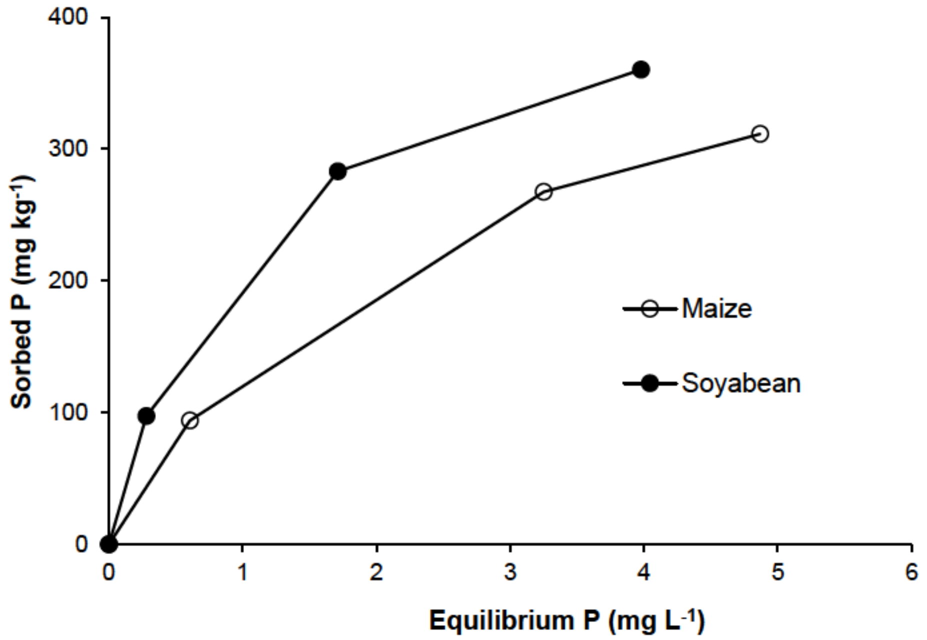

Figure 6. 1: Phosphorus sorption isotherms from KZN wheat fields that had (a) soybean or (b) maize before wheat.

The P sorption maximum was positively correlated with macro POC (r = 0.48) (Table 6.4) while the "b" value was correlated positively with oxalate-extractable aluminium (r = 0.51) and dithionite-extractable aluminium (r = 0.38) and negatively with macro POC (r = -0.38), Bray 1 extractable P (r = -0.36), and $NaHCO_3$ Pi (r = -0.38).

Table 6. 4: Spearman's correlation matrix for P sorption indices with various nutrient availability parameters in KZN irrigated wheat fields.

Variables	Smax	b
1 Soil pH	-0.08ns	-0.05ns
2 Acid saturation	0.06ns	0.09ns
3 Organic carbon	-0.13ns	0.13ns
4 Macro POC	**0.48***	**-0.38***
5 Micro POC	0.01ns	0.20ns
6 Mineral associated carbon	-0.14ns	0.14ns
7 Bray 1 P	0.33ns	**-0.36***
8 $NaHCO_3$ Pi	0.09ns	**-0.38***
9 NaOH II Pi	0.13ns	-0.19ns
10 NaOH I Pi	-0.10ns	0.17ns
11 Residual P	-0.05ns	0.15ns
12 Aluminium dithionite	-0.05ns	**0.38*****
13 Aluminium oxalate	-0.18ns	**0.51***
14 Extractable iron	-0.07ns	-0.14ns
15 Iron dithionite	0.01ns	0.13ns
16 Iron oxalate	0.10ns	0.17ns
17 Exchangeable calcium	0.10ns	-0.21ns

*p<0.05; ** p<0.01; ***p<0.001; **b**, a constant related to phosphate adsorption binding energy required; ns, no significant differences; Pi, inorganic phosphorus; POC, particulate organic carbon; $NaHCO_3$ Pi, sodium bicarbonate inorganic phosphorus; NaOH Pi, Sodium hydroxide inorganic P; **Smax**, a parameter that reflects the size of phosphate adsorption sites available.

6.3.2 Effects of tillage and straw management on P sorption indices in the Acric Plinthosol

The sorption followed a typical Langmuir isotherm for all the tillage and straw management practices (Figure 6.2) although Smax varied significantly between tillage and wheat straw management practices (Table 6.5). Under NT, straw burning increased Smax as opposed to not burning (Tables 6.5 and 6.6). This is further illustrated in Figure 6.2 whereby NT with no burning wheat straw significantly reduced the P sorption maxima as opposed to when straw was burned (Figure 6.2). The coefficient of bonding energy (b) was not significantly affected by treatments (Table 6.5).

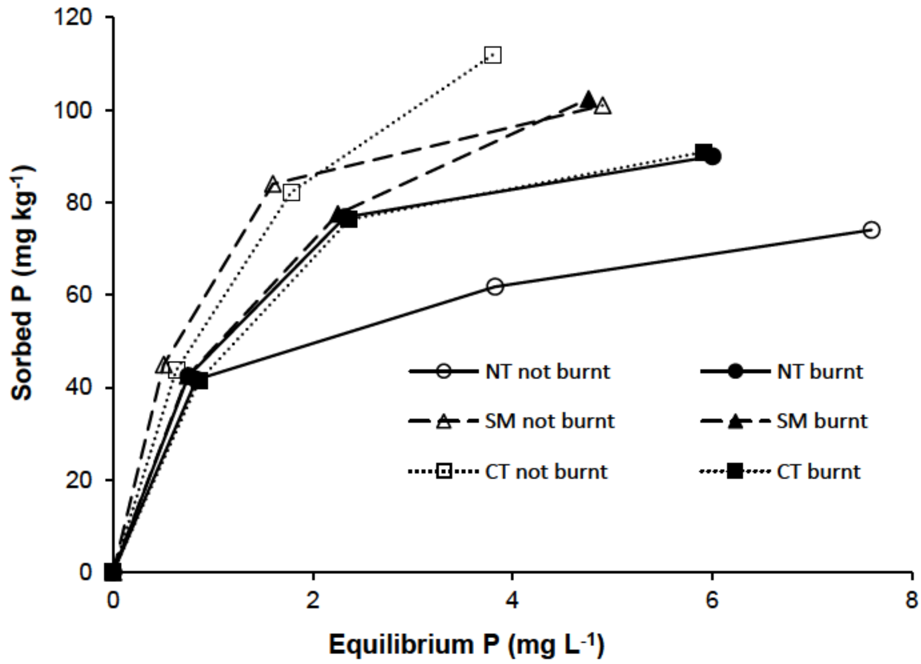

Figure 6. 2: Phosphate adsorption isotherms in different tillage and straw management treatments in soils from Bethlehem.

Table 6. 5: The significance of differences as per ANOVA at 95% confidence limit.

Factors	Smax	b
Tillage	*	ns
Straw management	*	ns
Tillage x straw management	*	ns

Smax, maximum sorption reflects the size of phosphate adsorption sites available; **b**, a constant related to binding energy; R^2, coefficient of determination; **ns**, no significance differences; *$p<0.05$; **$p<0.001$.

Table 6. 6: The interaction effect of tillage and straw management on Smax (mg kg^{-1}) in a Bethlehem Acric Plinthosol.

Tillage	Burnt	Not burnt
Conventional tillage	113a	100ab
Stubble mulch	113a	117a
No tillage	107a	64.3b
SED	10.3	
CV (%)	12.3	

Values with different letters (a-b) in a column indicate significant differences at $p<0.05$; SED, standard error of difference; CV, coefficient of variation.

The sorption maxima was negatively correlated to oxalate Al (r=-0.55) while the "b value" was positively correlated to NaOH I Pi (r=0.62) and residual Pi (r=0.87) (Table 6.7).

Table 6. 7: Pearson's correlation matrix for P sorption indices with various soil parameters in a Bethlehem Acric Plinthosol.

Variables	Smax	b
1 Soil pH	0.30ns	0.22ns
2 Acid saturation	-0.35ns	-0.15ns
3 Organic carbon	0.00ns	-0.28ns
4 Macro POC	-0.11ns	-0.38ns
5 Micro POC	-0.09ns	-0.07ns
6 Mineral associated C	0.01ns	-0.25ns
7 Bray 1 P	0.01ns	-0.37ns
8 $NaHCO_3$ Pi	0.39ns	0.03ns
9 NaOH II Pi	0.04ns	-0.16ns
10 NaOH I Pi	0.07ns	**0.62****
11 Residual P	-0.26ns	**0.87*****
12 Aluminium dithionite	-0.06ns	0.04ns
13 Aluminium Oxalate	**-0.55***	-0.21ns
14 Extractable iron	-0.44ns	0.22ns
15 Iron dithionite	-0.43ns	-0.25ns
16 Iron oxalate	-0.01ns	-0.26ns
17 Exchangeable calcium	0.36ns	0.39ns

*p<0.05; ** p<0.01; ***p<0.001; **b**, a constant related to phosphate adsorption binding energy required; ns, no significant differences; Pi, inorganic phosphorus; POC, particulate organic carbon; $NaHCO_3$ Pi, sodium bicarbonate inorganic phosphorus; NaOH Pi, Sodium hydroxide inorganic P; **Smax**, a parameter that reflects the size of phosphate adsorption sites available.

6.3.3 The effect of DOC addition on P adsorption indices on two contrasting soils from KZN and Bethlehem

Addition of DOC had a significant effect on the shape of the adsorption isotherms for both soils. Adding P together with DOC in these soils reduced P adsorption as more P remained in the soil solution (Figure 6.3). The sorption of P on both soils followed the high affinity (H-type) isotherm when no DOC or when 20 mg DOC L^{-1} was added (Figure 6.3a, b). When a higher concentration of DOC (3800 mg C L^{-1}) was added, P sorption followed a typical Langmuir isotherm for both soils (Figure 6.3). Addition of DOC reduced both P sorption indices on both soils types although this was more pronounced on Bethlehem soil (Table 6.8). The Smax followed the trend no DOC > DOC 20 > DOC 3800 for both soils and the trend was similar for b values in KZN soil (Table 6.8).

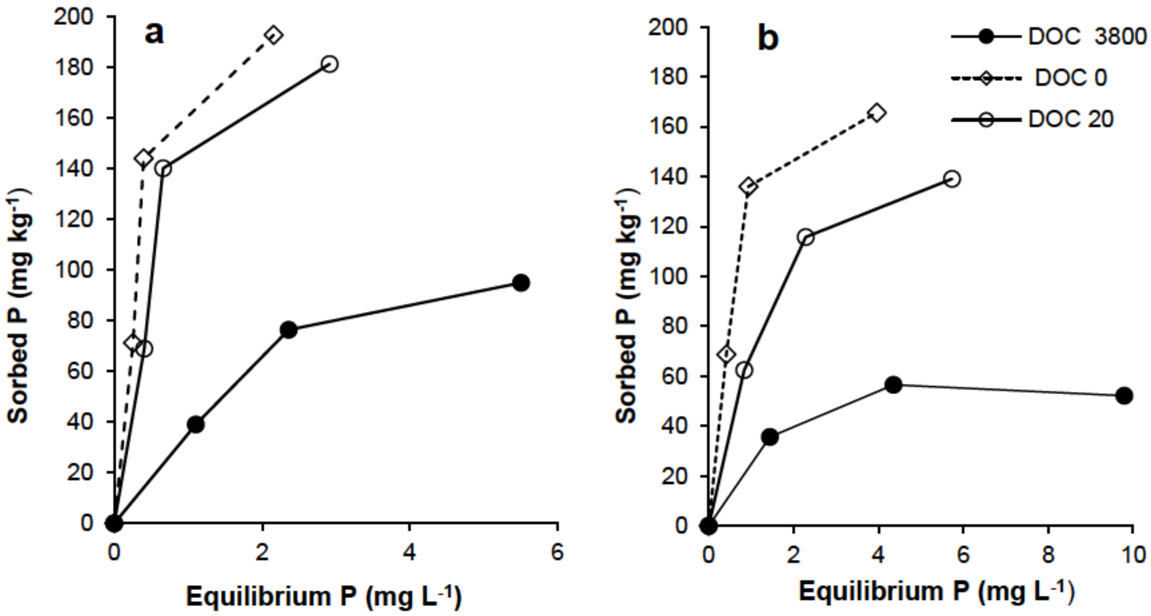

Figure 6. 3: The effect of dissolved organic carbon from wheat straw on P sorption in (a) KwaZulu-Natal and (b) Bethlehem soils with low native soil carbon.DOC 3800, DOC 20 and DOC 0 refers to the amount of DOC added in mg L^{-1}.

Table 6. 8: The effect of adding or removing dissolved organic carbon (DOC) on Bethlehem and Kwazulu-Natal low carbon soils.

	KwaZulu-Natal			Bethlehem		
	DOC 0	DOC 20	DOC 3800	DOC 0	DOC 20	DOC 3800
Smax	227	196	141	169	145	55.6
b	2.44	2.13	0.399	2.68	1.33	2.17
R^2	0.972	0.956	0.960	0.971	0.926	0.988

DOC (mg L^{-1}); **Smax,** a parameter that reflects the size of phosphate adsorption sites available; **b,** a constant related to phosphate adsorption binding energy required; DOC 3800, DOC 20 and DOC 0 refer to the amount of DOC added in mg L^{-1}.

6.3.4 Sorption isotherms and sorption indices of DOC on two contrasting soils

The sorption of DOC on the Acric Plinthosol (Bethlehem soil) followed a high affinity (H-type) isotherm while on the soil from KZN it followed a typical L type isotherm (Figure 6.4). The sorption maxima were 2299 mg kg^{-1} for KZN soil and 4367 mg kg^{-1} for Bethlehem soil (Table 6.8) and the bonding energy coefficient (b) was slightly higher for KZN compared to Bethlehem (Table 6.9).

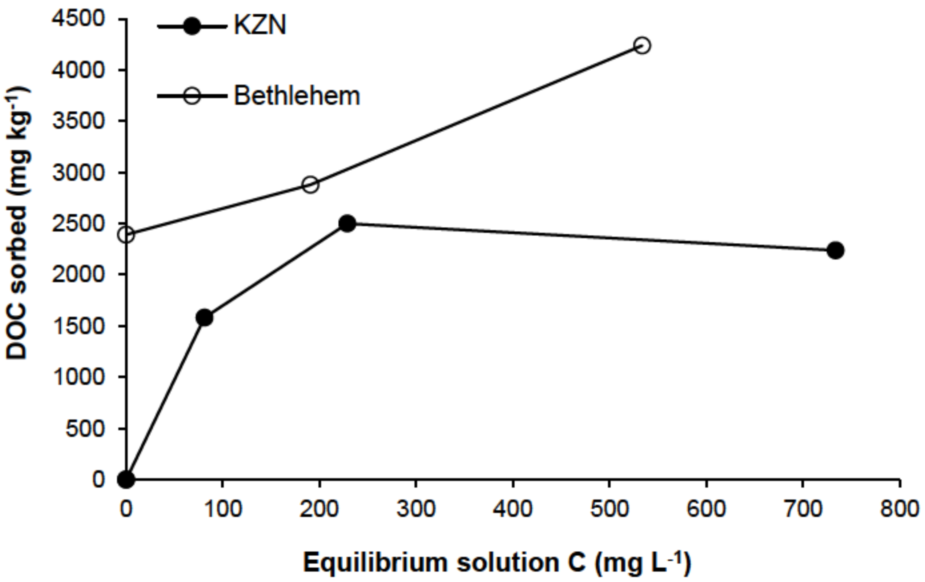

Figure 6. 4: The sorption isotherms for dissolved organic carbon from wheat straw on two contrasting soils from KZN and Bethlehem.

Table 6. 9: The effect of dissolved carbon and phosphorus on carbon sorption indices in two contrasting soils.

Soil type	Smax	b	R^2
KwaZulu-Natal	2299	0.0798	0.993
Bethlehem	4367	0.0259	0.963

Smax, a parameter that reflects the size of phosphate adsorption sites available; **b**, a constant related to phosphate adsorption binding energy required; **P**, phosphorus; $\mathbf{R^2}$, coefficient of determination.

6.4 DISCUSSION

The higher sorption indices shown by the Ferralsol (KZN) than the relatively younger Acric Plinthosol soil (Bethlehem) was explained by the higher P fixing capacity of Oxidic soil. The higher P fixation can be explained by the greater composition of iron (Fe) and aluminium (Al) fractions due to a more advanced stage of weathering. This view was supported by the positive correlation of bonding energy ('b' value) with both oxalate-extractable and dithionite extractable Al. This finding was in agreement with the studies that reported a higher sorption index in Oxidic soils (Fink et al., 2016; Mnthambala et al., 2016) due to higher clay, hematite and goethite contents. The higher Smax values in the current study are comparable to Mnthambala et al. (2016). These soils are well-known for their P deficiency challenges due to their high P fixing nature as a result of the high Fe and Al oxides. In these soils, P adsorption occurs mainly through the formation of less reversible inner-sphere complexes with strong adsorptive forces (Thomas Sims and Pierzynski, 2005). However, this can be improved through good soil management practice (Fink et al., 2016).

The lack of a significant relationship of P sorption with cropping sequence in Oxidic soils was contrary to other studies where crop rotation was found to have a significant effect on P adsorption capacity (Gou et al., 2020; Mnthambala et al., 2016; Montalvo Grijalva, 2014). These soils have a high affinity for P, such that at low solution P concentration, most of the P is removed from the solution. This phenomenon would have been expected in the soil under soybean-wheat rotation due to the higher acid saturation, which results in P fixation and precipitation with solution Fe and Al. The lack of differences in sorption parameters suggests that the high affinity of these soils for P overrides the crop rotation effects, which could have short term effects on other soil parameters. In the long-term, the rotations would be similar as (i) soybean-wheat-maize or (ii) maize-wheat-soybean, although the crop sequences are different.

A positive correlation of sorption maxima (Smax) with macro POC suggest that SOC may improve the P adsorption sites through the formation of Fe/Al-SOC-P multicomplexes (Hunt et al., 2007) hence increasing P availability (Table 6.4). The low pH of these soils could have resulted in a net positive charge of the surfaces of the organic matter, increasing P fixation (Bhatti et al., 1998). The positive correlation of the b index with aluminium oxalate and aluminium dithionite suggest that the affinity for P adsorption was encouraged by these parameters. However, the negative correlation of b sorption index with macro POM, Bray 1 extractable P and $NaHCO_3$ Pi suggest that more macro POC in these fields may reduce the bond energy between soil colloids (including Al and Fe oxides with SOM) and P. The weaker bond energy suggests that the sorbed P may desorb, making P available during the season. The finding affirms the positive effect of SOC on reducing P adsorption as reported elsewhere (Muindi et al., 2015; Moazed et al., 2010; Li et al., 2007). When compared with soils from KZN (Smax = 455 mg kg^{-1}) the soils from Bethlehem has lower sorption capacity (64 -117 mg kg^{-1}) irrespective of treatments. This difference in P sorption capacity was explained by differences in the extent of weathering, resulting in lower pH, high oxalate extractable Fe and Al, and dithionite extractable Fe and Al, in the soil from KZN than the one from Bethlehem.

Acric Plinthosols have a high affinity for P, such that at low solution concentration most of the P was removed from the solution (Figure 6.2). This was shown by the typical Langmuir sorption isotherm whereby the slope steadily fell as P concentration increased because vacant P sorption sites became limited (Ayawei et al., 2017; Giles et al., 1974). The higher P sorption maxima recorded under NT with burning of straw, as opposed to not burning, may be due to a higher soil pH as a result of burning, resulting in the possibility of Ca-phosphate precipitation. These findings imply that NT dryland systems of Bethlehem may require less external P fertiliser input, if the wheat straw is not burned, than when burned. Alternatively, NT with straw retention could encourage the growth of mycorrhizal fungal hyphae network. The mycorrhizae hyphae network and its interaction with rhizosphere microorganisms that release organic acids and phosphatase enzymes that solubilise P and enhance its uptake (Roy-Bolduc and Hijri, 2011), even though the available concentration is lower than when straw is burnt. The higher sorption and higher Bray 1 extractable P (Table 6.2) under no tillage where residues are burnt agrees with the findings by Romanya et al. (1994) who reported higher sorption and higher extractable P upon burning. The increase of P was explained by the conversion of organic P from the burnt organic matter into inorganic P forms while the increase in P sorption was mostly linked to (i) release of hydroxyl Al from organic matter and (ii) opening of new sorption sites during SOM loss due to combustion and most of the sorbed P was loosely bound. A negative correlation between the sorption maxima and oxalate Al (r=-0.55), was not expected but suggests that lower amorphous Al oxide content results in increasing Smax, possibly through higher availability of Ca, to result in Ca-P precipitation. On the other hand, the positive correlation between the b value, NaOH I Pi (r=0.62) and residual Pi (Table 6.7) suggests that the higher concentration of these P pools may contribute to a greater affinity for P sorption in these soils. The mechanism involved is not clear.

A significant reduction of P sorption maxima with an increase in DOC (Table 6.8) suggested that there was a competition for sorption sites, resulting in more P in the soil solution. These low C soils which also happen to have low P (Table 6.2) have unsaturated binding sites, which explains the higher Smax on low C soils before DOC was added. The presence of DOC, just like any organic anion, reduces P sorption by adsorbing onto soil minerals, saturating binding sites (He et al., 1999; Bolan et al., 2011) thus making P available. This view was supported by the high affinity of the soils for DOC (Figure 6.4), which showed that at low concentration, all DOC is sorbed on soil particles. The addition of both P and DOC further reduces Smax as P gets outcompeted by DOC for adsorption sites resulting in more P in soil solution (Guppy et al., 2005). In agreement to these findings, the addition of fulvic acid (Kastelan-Macan and Petrovic, 1996) and humic acids (Maluf et al., 2018; Yang et al., 2019) was found to outcompete P for sorption sites, reduce P sorption, thus enhancing P availability in the soil. The greater reduction in sorption maxima for Bethlehem compared to KZN soils (Figure 6.3 and Table 6.8) is likely to be related to its higher affinity for C (Figure 6.4 and Table 6.8). This suggests that DOC produced from crop residues, under CA, rapidly gets adsorbed to soil particles, lowering the concentration of DOC in solution while increasing mineral associated C. The competitive sorption of SOC (mainly DOC) and P, makes P more available, where CA is practised with retention of crop residues. As such, CA farmers in low-input wheat production systems would require less external P fertiliser input than non-CA farmers. The findings of this study contradicted those of Debicka et al. (2016), who reported an increase in available P upon SOM removal. The contradictions could be due to the differences in studied soil types. The current study was conducted in relatively clayey soils compared to the sandy soils studied by Debicka et al. (2016). In clayey soils, SOM addition may improve P availability in the soil solution by lowering P adsorption maximum and P buffering capacity (Shirvani et al., 2005) while in sandy soils, SOM binds P preventing it from leaching, especially if the pH is low.

The higher sorption maximum for DOC and the H-type isotherm (high affinity) on Bethlehem soil, as opposed to the soil from KZN, could be due to the physicochemical properties of these soils such as pH, clay content and Fe oxides (Jagadamma et al., 2012). Singh et al. (2017) reported that soil clay fraction and its various properties such as clay mineralogy, sesquioxides, specific surface area, surface charge, surface functional groups may influence the soils ability to adsorb DOC. The high affinity of the soils for DOC could also explain the low composition of water-soluble C, which was in low concentration in preliminary studies (Chapter 3 and Chapter 5). These findings indicate a high potential for C stabilisation in these soils (Kalbitz et al., 2005; Singh et al., 2016), which increase P availability.

6.5 CONCLUSION

The effect of CA practices on P sorption capacity varies significantly on the contrasting soil types studied. Highly weathered soils from different cropping sequences involving wheat, maize and soybean under minimum-till and irrigation in KZN, had a similar effect on P sorption maxima (455 ± 59.5 mg kg^{-1}) and constant related to the binding energy. The moderately weathered soils under NT with straw retention (64.3 ± 10.3 mg kg^{-1}) reduced Smax when compared with straw burning (107 ± 10.3 mg kg^{-1}). Acid saturation, Al oxalate, Al dithionite and macro POC may influence the affinity of P adsorption in KZN Oxidic soils, while in Bethlehem Acric Plinthosol, P adsorption may be related to oxalate Al, NaOH I Pi and residual Pi. The soils have a strong affinity for DOC, which reduces sorption and increases the availability of solution P, with greater effects in moderately weathered than highly weathered soils. These findings imply that increase in DOC from crop straw in CA systems with crop rotation, wheat straw retention and NT reduce P fixation which could reduce external P fertiliser input requirements.

CHAPTER 7: GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

7.1 General Discussion

Poor soil quality has contributed to the decline in wheat productivity in recent years and increasing fertiliser prices lower profitability, and interest in wheat production in South Africa (Dube et al., 2020). Low organic matter, high acidity and low available P are the major soil factors limiting wheat production in South Africa (Sosibo et al., 2017; Dube et al., 2020). Feasible options of conservation agriculture (CA), in various wheat production regions, could improve soil organic matter (SOM), nutrient availability and crop productivity. For example, irrigated wheat is produced in rotation with summer maize or soybean, and crop residues are retained, on well-drained highly weathered Oxidic soils under humid climatic conditions of the KwaZulu-Natal (KZN) region. In dryland production regions, under semi-arid conditions, wheat is produced using no-tillage, minimum tillage or conventional tillage on relatively young Acric Plinthosol, to benefit from the stored soil moisture in the plinthic horizons, and the residues are either burnt or retained. Some of these CA options could significantly improve wheat yields and profitability through an increase in SOM, phosphorus (P) fractions, and their potential interaction effects on P availability. This study was conducted to understand the effects of CA management options for irrigated and dryland wheat production systems on carbon and phosphorus dynamics and quality of contrasting soils from two wheat production regions of South Africa.

This study's findings showed that total nitrogen (N), soil organic carbon (SOC), and SOC stocks did not vary across the cropping sequences in KZN. Although the SOC concentration in the 0-200 mm depth has slightly declined from its natural state, the irrigation, higher fertiliser application, intensive wheat/soybean/maize rotation, and the higher average clay content of the soil have maintained high SOC stocks. These findings suggest that soil C sequestration in this area may not be dependent on the cropping sequence but other factors such as climatic conditions (high rainfall and cool temperatures), clay rich soil types and high residue input (Dong et al., 2009) which result in high natural organic matter through high biomass additions, root activity and SOC protection within fine clay particles (Mutuo et al., 2004). In a humid environment such as KZN, seasonal cropping sequences effects are not sensitive enough to cause significant changes in SOM, but soybean resulted in higher water-soluble C than maize, although the concentrations were extremely low. The average concentration of SOC in KZN topsoil was 25.4 g kg^{-1} versus 27.3 g kg^{-1} in the natural grassland. This was much higher than the average SOC of the natural grassland (7.00 g kg^{-1}) and average under no-tillage with residue retention (6.40 g C kg^{-1}) in the semi-arid Bethlehem. The lower SOC in Bethlehem could be because of lower rainfall, low clay content and higher temperatures, resulting in lower organic matter input, and rapid decomposition in the soil with lower clay content (16%).

The findings from the Bethlehem trial show that N fertiliser at both low (40 kg N ha^{-1}) and high (60 kg N ha^{-1}) application rates did not improve SOC on most treatments, while only residue burning increased SOC only at 60 kg N ha^{-1}. The lack of significant effects of no-tillage and straw retention on the Bethlehem trial could be due to low moisture conditions (semi-arid), which results in low biomass production when compared to KZN, humid region (Lal, 2007). However, when compared with the adjacent natural grassland, the NT treatment had relatively higher SOC concentrations in the 0-50 and 50-200 mm depths, showing the positive effects of NT even under conditions of relatively low organic matter inputs. Total SOC stock was higher under NT when residues were burnt, and under stubble mulch, in the treatments fertilised at 60 kg N ha^{-1}. This effect was also significant in the 50-200 due to possibly higher biomass production at the 60 kg N ha^{-1} treatment. It should be noted that in both KZN (high rainfall,

high input system) and Bethlehem (low rainfall, low input system), more than 66% of total C stocks were found in soil layers deeper than 0-200 mm. These findings confirmed the need to study deeper layers to at least 1000 mm for SOC stocks, in relation to SOC sequestration for climate change mitigation, as more stocks are found below the usually studied 0-200 mm layer (Jobbágy and Jackson, 2000; Torres-Sallan et al., 2017; Rumpel and Kögel-Knabner, 2011).
No-tillage increased the total N than other tillage practices irrespective of residue management, possibly due to limited soil disturbance, which slows decomposition thus reducing N loss through leaching from the system (Balota et al., 2004; Liu et al., 2006) while burning of residues reduced total N. These findings agree with previous studies in this trial (Kotze´and du Preez, 2007; Loke et al., 2012) and suggest that this parameter is more sensitive to soil disturbance (Hofman and Cleemput, 2004) than SOC. The lower total N upon burning may suggest that N loss may have occurred through volatilization during the combustion process (Pellegrini et al., 2018; Certini, 2005; Neary, 2004). Nitrogen mineralisation and nitrification could also have occurred, resulting in leaching losses. However, the contribution to N availability in these soils could depend on the organic matter fractions, than overall SOC concentration. The labile fractions are ready substrates for microorganisms (Snapp and Grandy, 2011), and their decomposition and mineralisation of elements could increase available soil nutrients, including N and P. Regardless of the cropping sequences effects, there is a possibility that major variations can occur in SOM fractions and the resultant nutrient availability.

While macro- and micro-POC fractions were not affected by cropping sequences in the soils from KZN, these fractions were increased by NT in the soils from Bethlehem, which suggested a higher sensitivity of particulate organic matter to soil management. Similar findings were reported by Liu et al. (2014), Blanco-Moure et al. (2013) and Six et al. (2000) whereby NT improved POC fractions. Mineral associated C was increased by burning wheat straw, which agreed with the results on SOC and SOC stocks that indicated that burning favours C stabilisation in a more aromatic and less decomposable form. The mineral associated C was more dominant than particulate organic C for both soils from humid KZN and semi-arid Bethlehem, for all the treatment combinations. For example, although C fractions were not affected by cropping sequences in KZN, 94% of the total C stock was associated with mineral C fraction. This agreed with Blanco-Moure et al. (2013) and Mikutta et al. (2006) who reported that mineral associated C accounted for about 70-90% and 73%, respectively, of the total SOC. This suggests that most of the SOC is protected against decomposition in both these production systems as it is associated with mineral C fraction (Chang et al., 2020; Poirier et al., 2020; Chenu and Plante, 2006). The extremely higher mineral associated C in the KZN soil (24 g kg^{-1}) than the 9 mg kg^{-1} at Bethlehem, is due to differences in SOC contents, which is related to climatic conditions and biomass addition, together with the higher clay content (23%) in soil from KZN. It should be noted that water-soluble C was extremely low in both production systems, possibly because it may have been adsorbed into soil colloids contributing to the large mineral C fraction in Bethlehem and KZN. This view was supported by the high affinity of both soils for DOC (Figure 6.4) in Chapter 6. Soil clay particles have a high specific surface area and CEC that enable it to retain dissolved organic C (Bolan et al., 2011; Singh et al., 2017). Although WSC was extremely lower than the other SOC fractions, it was lower in soils previously under maize than soybean in KZN, and in NT with straw burning than the other treatments, at Bethlehem, showing that this fraction is the most dynamic in these CA systems. Higher WSC in a CA system could increase dynamics of nutrient cycling through its rapid decomposition and also potential sorption of soil particles.

Sorption of WSC may reduce this fraction's contribution to nutrient cycling but contribute towards C storage in these soils. The physical occlusion of adsorbed dissolved SOC within stable soil micro aggregates protects it from microbial attack making it more stable (Kalbitz et al., 2005; Kaiser and Guggenberger, 2000; Kaiser and Zech, 1998), which explains the >94% of SOC being mineral associated. One nutrient that may be affected is P, which is deficient in these wheat production regions of South Africa (Sosibo et al., 2017). In Bethlehem production systems, Bray 1 extractable P was higher under NT and where straw was burnt at 40 kg N ha^{-1} (Chapter 4) and was also higher under NT where straw was burnt at 60 kg N ha^{-1} (Chapter 5) which is the same treatment that had lower WSC, in the surface layers. This could be due to less disturbance of soil (no-till) and conversion of organic P to orthophosphates as a result of burning to form the nutrient-rich alkaline ash, which also raised soil pH (Cade-Menun et al., 2000). However, these findings were not comparable to KZN where Bray 1 extractable P was not affected by the cropping sequences. However, the Bray 1 extractable P was higher in the topsoil than deeper layers, both for KZN and Bethlehem soils, and is explained by low mobility of P to deeper layers (Li et al., 2019; Balemi and Negisho, 2012) under no-till. The average extractable P in KZN was 47.4 mg kg^{-1} compared to 38.5 mg kg^{-1} in Bethlehem under no-till with burnt straw. The difference in P concentration could be due to higher P (>50 kg P ha^{-1}) application coupled with lime, higher biomass addition and SOC in KZN while lower P (12.5 kg ha^{-1}) is applied in Bethlehem. The high concentration of Bray-1 extractable P under no-tillage in Bethlehem could be explained by the higher macro and micro POC fractions in the same depth (0-50 mm). The particulate organic C fraction form part of the light SOM fractions that are important as the source of soil nutrients (Snapp and Grandy, 2011). Likewise, more Bray-1 extractable P was related to higher SOC fractions in the topsoil.

The labile ($NaHCO_3$ Pi) fraction was consistently higher under conventional tillage with the burning of residues while Al-bound (NaOH I Pi) fraction was higher for conventional tillage with residue retention compared to other tillage and residue management practices in the top

0-400 mm in the treatments with 60 kg N ha^{-1} at Bethlehem (Chapter 5). The higher bicarbonate- extractable inorganic P in CT where the residues were burnt could be due to 1) the release of nutrients from the nutrient-rich ash and 2) the breakdown of phospholipids, nucleic acids and phosphoprotein into the soil solution facilitated by CT (Kovar and Pierzynski, 2009). Residue burning could have increased the soil pH making it unfavourable for Al-bound P (NaOH I Pi). These findings are similar to Ncoyi et al. (2020), who found more $NaHCO_3$ Po under CT as opposed to conservational (NT and SM) tillage practices in the 40 kg N ha^{-1} plots in the same trial. As such, soil pH may be important in explaining P availability in these soils. No-tillage and residue retention resulted in lower values of bicarbonate P (9.51 mg kg^{-1}) and sodium hydroxide P (20.96 mg kg^{-1}) compared to KZN soils, which had 213 mg $NaHCO_3$ Pi kg^{-1} and 118 mg NaOH I Pi kg^{-1} in the topsoil. In KZN, soils on fields that had soybean preceding wheat had lower labile ($NaHCO_3$ Pi) and higher Al-bound P (NaOH I Pi) fraction and WSC, than for maize. The lower pH due to decomposition of organic matter (including WSC) and nitrification in the soybean/wheat systems could have resulted in less available P and more Al-bound P after soybean than maize implying that farmers may need to apply more lime and P fertiliser after soybean. While the higher WSC could have limited P sorption in the soil under soybean, the effects of higher acidity could have been more dominant on P fixation. A strong correlation between Bray 1 extractable P, $NaHCO_3$ and NaOH I Pi in KZN indicated that all these fractions are mostly influenced by liming and fertiliser additions while the positive correlation between micro POC and Bray 1 extractable P suggested that labile SOC fraction can improve P availability. The results showed that different P fractions respond differently to soil management practices and under different production conditions. The physically protected (NaOH II Pi) and residual (recalcitrant) P fraction were higher under conservation tillage practices than CT at Bethlehem but were not affected by cropping sequences in KZN soils. These findings suggest that residue burning under both conventional ($NaHCO_3$-Pi) and no-till

(Bray 1 P) results in more readily available P in the soil, and where residues are retained under no-till soybean results in lower available P than maize as crops preceding wheat.

The decomposition of soybean residues (lower C/N) and nitrification of N lowers the soil pH and increases levels of soluble Al and Fe, resulting in higher Al bound Pi fraction and a lower labile P fraction. The finding that soil pH was positively correlated with labile P fraction and negatively correlated with Al bound P fraction, supported the importance of soil pH on P availability and fixation (Asomaning, 2020). In addition to the importance of soil pH, the positive correlation between micro POC and Bray 1 P in the 0-200 mm depth suggests that the labile organic C fractions may be essential either as a source of P or in limiting P sorption and increasing its availability for wheat (Hunt et al., 2007; Guppy et al., 2005). The water-soluble C may occupy P sorption sites; making P added more available. The P sorption isotherms supported the view that SOC fractions affect the availability of P in both Bethlehem and KZN soils.

In Bethlehem, straw retention under NT had a low sorption maximum, while cropping sequences yet again did not influence P adsorption in KZN. Sorption maxima (Smax) was positively correlated with macro POC in the acidic soils of KZN suggesting that SOC may improve the P adsorption sites hence the P availability (He et al., 1999). However, macro POC, Bray 1 extractable P and $NaHCO_3$ negatively correlated with the b (phosphate adsorption binding energy constant) sorption index suggesting that the higher SOC concentration in these fields may reduce the bond energy between soil colloids (including Al and Fe oxides with SOM) and P. The weaker bond energy suggests that the sorbed P may desorb, making P available during the crop growing season. It should be noted that both soils followed a typical Langmuir sorption isotherm, showing that the soils have an affinity for P. The P adsorption affinity was related to acid saturation, oxalate Al, dithionite Al, and macro particulate C in the highly weathered KZN Oxidic soils and oxalate Al, aluminium-bound inorganic P (NaOH I Pi) and residual P on an Acric Plinthosol. The relationship with oxalate Al, confirms that the amorphous fraction of Al oxides is important for the fixation of P (Jiang et al., 2015; Arai and Livi, 2013). However, in highly weathered soils of KZN, the high acidity and crystalline fractions (dithionite Al) also contribute due to their abundance in these soils (Asomaning, 2020; Borggaard et al., 1990).

The positive relationship of P affinity with NaOH I Pi and residual P in the Bethlehem soil indicates that the P is fixed into these forms, with some of the NaOH I Pi possibly being released during the growing season (Zhang et al., 2002; Chen et al., 2000). On the other hand, the positive correlation of P affinity and micro-POC suggest that this organic matter fraction may contribute to P retention in the young soils from Bethlehem, but it is not clear whether this P would be released during the season. However, the presence of DOC significantly reduced P adsorption in both soils from KZN and Bethlehem, with greater effect in the less acidic Bethlehem soil, possibly because the soils naturally have less SOC compared to KZN soils. Sorption of DOC in the soil colloids may have made more nutrients available in addition to P. Based on these findings, soil type and other soil properties such as soil acidity, amorphous and crystalline forms of Al and Fe as well as SOM fractions may be the overriding factors to P availability. The CA systems could release dissolved organic matter, which can be rapidly adsorbed to the soil colloidal surfaces and reduce P fixation, making it more available. Also, the decomposition of other labile organic matter will increase microbial activity and can release P through mineralisation, while some P is immobilised into microbial cells, which limits P fixation (Hou et al., 2014; Balota et al., 2003). Gichangi et al. (2009) and Dube et al. (2013) reported that practices that favour higher SOM can make P more available. The different CA systems for wheat in South Africa could increase SOC fractions, affect pH, and increase concentrations of labile P fractions and ultimately improve wheat yields in both Bethlehem and KZN production systems. The KZN farmers may benefit from higher soil pH, K, and P availability for the wheat that is produced on the same soil immediately after maize.

7.2 Conclusions

Conservation agriculture options used in the wheat production regions differ on the effects on soil quality parameters that affect crop productivity. It can be concluded that SOC content is not affected by annual wheat/soybean or wheat/maize rotations used in KZN. Where NT is practised under irrigation, with straw retention, both rotations result in carbon concentration that is only slightly lower than that of the virgin soil. In these production systems, where no-till is practised, in combination with irrigation, and crop residues are retained under humid conditions, cropping sequences do not affect total N and stocks and concentrations of SOC fractions, but up to 94% of SOC is associated with the mineral fraction. However, where wheat is preceded by maize, soil pH, K, Ca, Mg, and labile P are higher, and WSC is lower than where soybean precedes wheat.

In dryland production conditions like those of the Bethlehem area, the tillage practices (no tillage and stubble mulch), compared with the conventional tillage, and straw burning, relative to retention, do not increase SOC, irrespective of N fertiliser rate, although the 60 kg N/ha rate had relatively higher SOC concentrations. However, macro and micro POC are increased and WSC is reduced by no-tillage. Mineral associated C is increased when the straw is burnt, while SOC stocks are increased by no-tillage when the straw is burnt. It can be concluded that under dryland wheat production, NT with straw burning increases soil pH, Bray 1 extractable P and total N but the effects are affected by the N fertiliser rate. The NT increased available P and total N, burning increased available P and pH (NT only) at 40 kg N ha^{-1}, while at 60 kg N ha^{-}

[1], available P was increased by burning only under NT, while NT and burning, as main factors, increased total N, and pH was increased by burning in all tillage treatments. The $NaHCO_3$ Pi P fraction is significantly increased by burning under conventional tillage, but the less labile residual P fraction is higher under NT.

The higher SOC fractions in CA systems, increase P availability through competitive sorption particularly with WSC, and also possibly due to more rapid decomposition of the labile SOC fraction, with greater effects on the less acidic Acric Plinthosols than the highly weathered soils. Overall, it can be concluded that wheat-based CA options that increase SOC fractions, especially WSC, will increase P availability, and reduce the P fertiliser needed for the subsequent crop.

7.3 Recommendations

The KZN wheat farmers should maintain their no-till, irrigation, crop rotation strategies, and residue retention as they result in higher SOC levels and more P available. Farmers may need to apply lime, K and P fertiliser for wheat crops, based on soil tests to benefit from the better fertility after maize than after soybean. Under dryland production conditions, like those in Bethlehem, no-tillage can be recommended to improve micro and macro POC, which are important fractions for nutrient cycling, while straw burning under no-tillage will increase soil pH, labile P fractions and total SOC stocks. However, increases in biomass input and crop rotation will likely increase SOC, P availability and ultimately produce higher wheat yields. Dryland wheat farmers should consider supplementary irrigation to make crop rotation possible, in order to increase biomass input, irrespective of N fertiliser rate.

LIST OF REFERENCES

Adeniyi, A.S., 2010. Effects of slash and burning on soil microbial diversity and abundance in the tropical rainforest ecosystem, Ondo State, Nigeria. *African Journal of Plant Science, 4*(9), pp.322-329.

Agbenin, J.O. and Anumonye, M., 2006. Distribution and sorption of phosphate in a savanna soil under improved pastures in northern Nigeria. *Communications in Soil Science and Plant Analysis*, *37*(3-4), pp.493-511.

Age, A.B., Kadu, P.R., Gabhane, V.V., Jadhao, S.D., Mali, D.V. and Zodge, S.D., 2019. Effect of various conservation practices on yield and nutrient uptake by soybean under soybean–cotton rotation in Vertisol. *Journal of Pharmacognosy and Phytochemistry*, *8*(3), pp.3272-3277.

Agenbag, G.A., 2012. Growth, yield and grain protein content of wheat (*Triticum aestivum* L.) in response to nitrogen fertiliser rates, crop rotation and soil tillage. *South African Journal of Plant and Soil*, *29*(2), pp.73-79.

Agomoh, I.V., Drury, C.F., Phillips, L.A., Reynolds, W.D. and Yang, X., 2020. Increasing crop diversity in wheat rotations increases yields but decreases soil health. *Soil Science Society of America Journal*, *84*(1), pp.170-181.

Alijani, K., Bahrani, M.J. and Kazemeini, S.A., 2012. Short-term responses of soil and wheat yield to tillage, corn residue management and nitrogen fertilization. *Soil and Tillage Research*, *124*, pp.78-82.

Alvarez, R. and Steinbach, H.S., 2009. A review of the effects of tillage systems on some soil physical properties, water content, nitrate availability and crops yield in the Argentine Pampas. *Soil and Tillage Research*, *104*(1), pp.1-15.

Arai, Y. and Livi, K.J., 2013. Underassessed phosphorus fixation mechanisms in soil sand fraction. *Geoderma*, *192*, pp.422-429.

ARC-ISCW., 2013. *Agro-climatology database. Agricultural Research Council-Institute for Climate Soil and Water*. Pretoria, South Africa.

ARC-SGI., 2015. *Production of the small grains in the summer rainfall area*. Bethlehem, South Africa.

ARC-Small Grain., 2018. *Wheat production guidelines for the production of small grains in the summer rainfall region*. Bethlehem, South Africa.

Asomaning, S.K., 2020. Processes and Factors Affecting Phosphorus Sorption in Soils. In *Sorption in 2020s*. IntechOpen.

Aulakh, M.S., Manchanda, J.S., Garg, A.K., Kumar, S., Dercon, G. and Nguyen, M.L., 2012. Crop production and nutrient use efficiency of conservation agriculture for soybean–wheat rotation in the Indo-Gangetic Plains of Northwestern India. *Soil and Tillage Research*, *120,* pp.50-60.

Awale, R., Chatterjee, A. and Franzen, D., 2013. Tillage and N-fertilizer influences on selected organic carbon fractions in a North Dakota silty clay soil. *Soil and Tillage Research*, *134*, pp.213-222.

Ayawei, N., Ebelegi, A.N. and Wankasi, D., 2017. Modelling and interpretation of adsorption isotherms. *Journal of Chemistry*, pp.1-11.

Aziz, I., Ashraf, M., Mahmood, T. and Islam, K.R., 2011. Crop rotation impact on soil quality. *Pakistan Journal of Botany*, *43*(2), pp.949-960.

Baldock, J. and Nelson, P.N., 2000. Soil organic matter. *Handbook of Soil Science.* CRC Press, Boca Raton, FL. USA, pp. B25-B84.

Balemi, T. and Negisho, K., 2012. Management of soil phosphorus and plant adaptation mechanisms to phosphorus stress for sustainable crop production: a review. *Journal of Soil Science and Plant Nutrition*, *12*(3), pp.547-562.

Balota, E.L., Calegari, A., Nakatani, A.S. and Coyne, M.S., 2014. Benefits of winter cover crops and no-tillage for microbial parameters in a Brazilian Oxisol: A long-term study. *Agriculture, Ecosystems and Environment*, *197*, pp.31-40.

Balota, E.L., Colozzi-Filho, A., Andrade, D.S. and Dick, R.P., 2003. Microbial biomass in soils under different tillage and crop rotation systems. *Biology and Fertility of Soils*, *38*(1), pp.15-20.

Balota, E.L., Kanashiro, M., Colozzi Filho, A., Andrade, D.S. and Dick, R.P., 2004. Soil enzyme activities under long-term tillage and crop rotation systems in subtropical agro-ecosystems. *Brazilian Journal of Microbiology*, *35*(4), pp.300-306.

Beare, M.H., Hendrix, P.F., Cabrera, M.L. and Coleman, D.C., 1994. Aggregate-protected and unprotected organic matter pools in conventional-and no-tillage soils. *Soil Science Society of America Journal*, *58*(3), pp.787-795.

Bennie, A.T.P. and Hensley, M., 2001. Maximizing precipitation utilization in dryland agriculture in South Africa—a review. *Journal of Hydrology*, *241*(1-2), pp.124-139.

Bhattacharyya, R., Das, T.K., Sudhishri, S., Dudwal, B., Sharma, A.R., Bhatia, A. and Singh, G., 2015. Conservation agriculture effects on soil organic carbon accumulation and crop productivity under a rice-wheat cropping system in the western Indo-Gangetic Plains. *European Journal of Agronomy*, *70*, pp.11-21.

Bhatti, J.S., Comerford, N.B. and Johnston, C.T., 1998. Influence of oxalate and soil organic matter on sorption and desorption of phosphate onto a spodic horizon. *Soil Science Society of America Journal*, *62*(4), pp.1089-1095.

Bhuvaneshwari, S., Hettiarachchi, H. and Meegoda, J.N., 2019. Crop residue burning in India: Policy challenges and potential solutions. *International Journal of Environmental Research and Public Health*, *16*(5), pp.1-19.

Blanco-Moure, N., Gracia, R., Bielsa, A.C. and López, M.V., 2013. Long-term no-tillage effects on particulate and mineral-associated soil organic matter under rainfed Mediterranean conditions. *Soil Use and Management*, *29*(2), pp.250-259.

Boerner, R.E.J., Brinkman, J.A. and Smith, A., 2005. Seasonal variations in enzyme activity and organic carbon in soil of a burned and unburned hardwood forest. *Soil Biology and Biochemistry*, *37*(8), pp.1419-1426.

Bolan, N.S., Adriano, D.C., Kunhikrishnan, A., James, T., McDowell, R. and Senesi, N., 2011. Dissolved organic matter: biogeochemistry, dynamics, and environmental significance in soils. *Advances in Agronomy*, *110*(1-75), pp.1-75.

Borggaard, O.K., Jdrgensen, S.S., Moberg, J.P. and Raben-Lange, B., 1990. Influence of organic matter on phosphate adsorption by aluminium and iron oxides in sandy soils. *Journal of Soil Science*, *41*(3), pp.443-449.

Bot, A. and Benites, J., 2005. *The importance of soil organic matter: Key to drought-resistant soil and sustained food production* (No. 80). Food and Agriculture Org.

Bouyoucos, G.J., 1962. Hydrometer method improved for making particle size analyses of soils 1. *Agronomy Journal*, *54*(5), pp.464-465.

Brady, N.C., Weil, R.R. and Weil, R.R., 2008. *The nature and properties of soils* (Vol. 13, pp. 662-710). Upper Saddle River, NJ: Prentice-Hall.

Brunel, N., Seguel, O. and Acevedo, E., 2013. Conservation tillage and water availability for wheat in the dryland of central Chile. *Journal of Soil Science and Plant Nutrition*, *13*(3), pp.622-637.

Busari, M.A., Kukal, S.S., Kaur, A., Bhatt, R. and Dulazi, A.A., 2015. Conservation tillage impacts on soil, crop and the environment. *International Soil and Water Conservation Research*, *3*(2), pp.119-129.

Cade-Menun, B.J., Berch, S.M., Preston, C.M. and Lavkulich, L.M., 2000. Phosphorus forms and related soil chemistry of Podzolic soils on northern Vancouver Island. II. The effects of clear-cutting and burning. *Canadian Journal of Forest Research*, *30*(11), pp.1726-1741.

Calegari, A., Tiecher, T., Hargrove, W.L., Ralisch, R., Tessier, D., de Tourdonnet, S., de Fátima Guimarães, M. and Dos Santos, D.R., 2013. Long-term effect of different soil management systems and winter crops on soil acidity and vertical distribution of nutrients in a Brazilian Oxisol. *Soil and Tillage Research*, *133*, pp.32-39.

Cambardella, C.A. and Elliott, E.T., 1992. Particulate soil organic-matter changes across a grassland cultivation sequence. *Soil Science Society of America Journal*, *56*(3), pp.777-783.

Carter, M.R., 2005. Long-term tillage effects on cool-season soybean in rotation with barley, soil properties and carbon and nitrogen storage for fine sandy loams in the humid climate of Atlantic Canada. *Soil and Tillage Research*, *81*(1), pp.109-120.

Certini, G., 2005. Effects of fire on properties of forest soils: a review. *Oecologia*, *143*(1), pp.1-10.

Chan, K.Y., Heenan, D.P. and Oates, A., 2002. Soil carbon fractions and relationship to soil quality under different tillage and stubble management. *Soil and Tillage Research*, *63*(3-4), pp.133-139.

Chan, Y. and Walmsley, R.P., 1997. Learning and understanding the Kruskal-Wallis one-way analysis-of-variance-by-ranks test for differences among three or more independent groups. *Physical Therapy*, *77*(12), pp.1755-1761.

Chang, Z., Tian, L., Li, F., Wu, M., Steinberg, C.E., Pan, B. and Xing, B., 2020. Organo-mineral complexes protect condensed organic matter as revealed by benzene-polycarboxylic acids. *Environmental Pollution, 260*, p.113977.

Chantigny, M.H., Angers, D.A., Kaiser, K. and Kalbitz, K., 2008. Extraction and characterization of dissolved organic matter. *Soil sampling and methods of analysis*, *2,* pp.617-635.

Chen, C.R., Condron, L.M., Davis, M.R. and Sherlock, R.R., 2000. Effects of afforestation on phosphorus dynamics and biological properties in a New Zealand grassland soil. *Plant and Soil*, *220*(1-2), pp.151-163.

Chenu, C. and Plante, A.F., 2006. Clay‐sized organo‐mineral complexes in a cultivation chronosequence: revisiting the concept of the 'primary organo‐mineral complex'. *European Journal of Soil Science, 57*(4), pp.596-607.

Chungu, D., Ng'andwe, P., Mubanga, H. and Chileshe, F., 2020. Fire alters the availability of soil nutrients and accelerates growth of Eucalyptus Grandis in Zambia. *Journal of Forestry Research*, *31*(5), pp.1637-1645.

Combs, S.M. and Nathan, M.V., 1998. Soil organic matter. *Recommended chemical soil test procedures for the north-central region. North Central Regional Research 221*, pp.53-58.

Corbeels, M., Cardinael, R., Naudin, K., Guibert, H. and Torquebiau, E., 2019. The 4 per 1000 goal and soil carbon storage under agroforestry and conservation agriculture systems in sub-Saharan Africa. *Soil and Tillage Research*, *188*, pp.16-26.

DAFF., 2012. *Abstract of Agricultural Statistics*. Department of agriculture, forestry and fisheries. Pretoria, South Africa.

DAFF., 2013. *Wheat Value Chain Profile*. Department of Agriculture Forestry and Fisheries. Pretoria, South Africa.

Daroub, S.H., Ellis, B.G. and Robertson, G.P., 2001. Effect of cropping and low-chemical input systems on soil phosphorus fractions. *Soil Science*, *166*(4), pp.281-291.

Das, A., Lyngdoh, D., Ghosh, P.K., Lal, R., Layek, J. and Idapuganti, R.G., 2018. Tillage and cropping sequence effect on physico-chemical and biological properties of soil in Eastern Himalayas, India. *Soil and Tillage Research*, *180*, pp.182-193.

De Moraes Sa, J.C. and Lal, R., 2009. Stratification ratio of soil organic matter pools as an indicator of carbon sequestration in a tillage chronosequence on a Brazilian Oxisol. *Soil and Tillage Research*, *103*(1), pp.46-56.

De Wet, F. and Liebenberg, I., 2018. Food security, wheat production and policy in South Africa: Reflections on food sustainability and challenges for a market economy. *TD: The Journal for Transdisciplinary Research in Southern Africa*, *14*(1), pp.1-11.

Debicka, M., Kocowicz, A., Weber, J. and Jamroz, E., 2016. Organic matter effects on phosphorus sorption in sandy soils. *Archives of Agronomy and Soil Science*, *62*(6), pp.840-855.

Degu, M., Melese, A. and Tena, W., 2019. Effects of Soil Conservation Practice and Crop Rotation on Selected Soil Physicochemical Properties: The Case of Dembecha District, Northwestern Ethiopia. *Applied and Environmental Soil Science*, pp.1-14.

Denef, K., Six, J., Merckx, R. and Paustian, K., 2004. Carbon sequestration in micro aggregates of no-tillage soils with different clay mineralogy. *Soil Science Society of America Journal*, *68*(6), pp.1935-1944.

Derpsch, R., 2005. The extent of conservation agriculture adoption worldwide: implications and impact. In *Proceedings on CD, III World Congress on Conservation Agriculture, Nairobi, Kenya* (pp. 3-7).

Dong, W., Hu, C., Chen, S. and Zhang, Y., 2009. Tillage and residue management effects on soil carbon and CO_2 emission in a wheat–corn double-cropping system. *Nutrient Cycling in Agroecosystems*, *83*(1), pp.27-37.

Doran, J.W. and Parkin, T.B., 1994. Defining and Assessing Soil Quality Defining Soil Quality for A Sustainable Environment ed JW Doran. *DC Coleman, DF Bezdicek and BA Stewart (USA: SSSA Special Publication Number 35)*.

Dorneles, E.P., Lisboa, B.B., Abichequer, A.D., Bissani, C.A., Meurer, E.J. and Vargas, L.K., 2015. Tillage, fertilization systems and chemical attributes of a Paleudult. *Scientia Agricola*, *72*(2), pp.175-186.

Du Preez, C.C., Steyn, J.T. and Kotze, E., 2001. Long-term effects of wheat residue management on some fertility indicators of a semi-arid Plinthosol. *Soil and Tillage Research*, *63*(1-2), pp.25-33.

Dube, E., Chiduza, C. and Muchaonyerwa, P., 2012. Conservation agriculture effects on soil organic matter on a Haplic Cambisol after four years of maize–oat and maize–grazing vetch rotations in South Africa. *Soil and Tillage Research*, *123,* pp.21-28.

Dube, E., Chiduza, C. and Muchaonyerwa, P., 2013. Conservation agriculture effects on plant nutrients and maize grain yield after four years of maize–winter cover crop rotations. *South African Journal of Plant and Soil*, *30*(4), pp.227-232.

Dube, E., Chiduza, C. and Muchaonyerwa, P., 2014. High biomass yielding winter cover crops can improve phosphorus availability in soil. *South African Journal of Science, 110*(3-4), pp.01-04.

Dube, E., Mare-Patose, R., Kilian, W., Barnard, A. and Tsilo, T.J., 2016. Identifying high-yielding dryland wheat cultivars for the summer rainfall area of South Africa. *South African Journal of Plant and Soil*, *33*(1), pp.77-81.

Dube, E., Tsilo, T.J., Sosibo, N.Z. and Fanadzo, M., 2020. Irrigation wheat production constraints and opportunities in South Africa. *South African Journal of Science*, *116*(1-2), pp.1-6.

Duru, C.E., Duru, I.A., Ibe, F.C. and Enedoh, M.C., 2017. Profiling of Zn^{2+} ion sorption in modelled aqueous solutions by different parts of maize biomass. *IOSR Journal of Applied Chemistry*, *10*(3), pp.70-75.

Erickson, H.E. and White, R., 2008. Soils under fire: soils research and the Joint Fire Science Program (Vol. 759). US Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Eze, S., Dougill, A.J., Banwart, S.A., Hermans, T.D., Ligowe, I.S. and Thierfelder, C., 2020. Impacts of conservation agriculture on soil structure and hydraulic properties of Malawian agricultural systems. *Soil and Tillage Research*, *201*, p.104639.

Fey, M.V., 2010a. A short guide to the soils of South Africa, their distribution and correlation with World Reference Base soil groups. In *Proceedings* (Vol. 19, pp. 32-35).

Fey, M.V., 2010b. *Soils of South Africa*. Cambridge University Press.

Findlay, R., 2015. No-till in SA - Why conservation agriculture must be promoted in SA. *Farmers Weekly*.

Fink, J.R., Inda, A.V., Bavaresco, J., Barrón, V., Torrent, J. and Bayer, C., 2016. Phosphorus adsorption and desorption in undisturbed samples from subtropical soils under conventional tillage or no-tillage. *Journal of Plant Nutrition and Soil Science*, *179*(2), pp.198-205.

Franzluebbers, A.J. and Hons, F.M., 1996. Soil-profile distribution of primary and secondary plant-available nutrients under conventional and no tillage. *Soil and Tillage Research*, *39*(3-4), pp.229-239.

Fuentes, M., Govaerts, B., De León, F., Hidalgo, C., Dendooven, L., Sayre, K.D. and Etchevers, J., 2009. Fourteen years of applying zero and conventional tillage, crop rotation and residue management systems and its effect on physical and chemical soil quality. *European Journal of Agronomy*, *30*(3), pp.228-237.

Gattinger, A., Muller, A., Haeni, M., Skinner, C., Fliessbach, A., Buchmann, N., Mäder, P., Stolze, M., Smith, P., Scialabba, N.E.H. and Niggli, U., 2012. Enhanced top soil carbon stocks under organic farming. *Proceedings of the National Academy of Sciences*, *109*(44), pp.18226-18231.

García-Marco, S., Gómez-Rey, M.X. and González-Prieto, S.J., 2014. Availability and uptake of trace elements in a forage rotation under conservation and plough tillage. *Soil and Tillage Research*, *137*, pp.33-42.

Gichangi, E.M., Mnkeni, P.N. and Brookes, P.C., 2009. Effects of goat manure and inorganic phosphate addition on soil inorganic and microbial biomass phosphorus fractions under laboratory incubation conditions. *Soil Science and Plant Nutrition*, *55*(6), pp.764-771.

Gichangi, E.M., Mnkeni, P.N.S. and Muchaonyerwa, P., 2008. Phosphate sorption characteristics and external P requirements of selected South African soils. *Journal of Agriculture and Rural Development in the Tropics and Subtropics (JARTS)*, *109*(2), pp.139-149.

Giles, C.H., Smith, D. and Huitson, A., 1974. A general treatment and classification of the solute adsorption isotherm. I. Theoretical. *Journal of Colloid and Interface Science*, *47*(3), pp.755-765.

Giller, K.E., Witter, E., Corbeels, M. and Tittonell, P., 2009. Conservation agriculture and smallholder farming in Africa: the heretics' view. *Field Crops Research*, *114*(1), pp.23-34.

Gmach, M.R., Cherubin, M.R., Kaiser, K. and Cerri, C.E.P., 2020. Processes that influence dissolved organic matter in the soil: a review. *Scientia Agricola*, *77*(3), pp.1-10.

Gómez-Rey, M.X., García-Marco, S. and González-Prieto, S.J., 2014. Soil P and cation availability and crop uptake in a forage rotation under conventional and reduced tillage. *Soil Use and Management*, *30*(4), pp.445-453.

González-Pérez, J.A., González-Vila, F.J., Almendros, G. and Knicker, H., 2004. The effect of fire on soil organic matter—a review. *Environment International*, *30*(6), pp.855-870.

Gou, X., Cai, Y., Wang, C., Li, B., Zhang, Y., Tang, X., Shen, J. and Cai, Z., 2020. Effects of different long-term cropping systems on phosphorus adsorption and desorption characteristics in red soils. *Journal of Soils and Sediments*, *20*(3), pp.1371-1382.

Guggenberger, G. and Kaiser, K., 2003. Dissolved organic matter in soil: challenging the paradigm of sorptive preservation. *Geoderma*, *113*(3-4), pp.293-310.

Guimarães, D.V., Gonzaga, M.I.S., da Silva, T.O., da Silva, T.L., da Silva Dias, N. and Matias, M.I.S., 2013. Soil organic matter pools and carbon fractions in soil under different land uses. *Soil and Tillage Research*, *126*, pp.177-182.

Guppy, C.N., Menzies, N.W., Moody, P.W. and Blamey, F.P.C., 2005. Competitive sorption reactions between phosphorus and organic matter in soil: a review. *Soil Research*, *43*(2), pp.189-202.

Havlin, J.L., Beaton, J.D., Tisdale, S.L. and Nelson, W.L., 2005. *Soil fertility and fertilizers: an introduction to nutrient management*. Prentice-Hall. New Jersey.

Haynes, R.J., 2005. Labile organic matter fractions as central components of the quality of agricultural soils: an overview. *Advances in Agronomy*, *85*, pp.221-268.

He, J.Z., De Cristofaro, A. and Violante, A., 1999. Comparison of adsorption of phosphate, tartrate, and oxalate on hydroxy aluminum montmorillonite complexes. *Clays and Clay Minerals*, *47*(2), pp.226-233.

Hedley, M.J., Stewart, J.W.B. and Chauhan, B., 1982. Changes in inorganic and organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations. *Soil Science Society of America Journal*, *46*(5), pp.970-976.

Herrick, J.E., 2000. Soil quality: an indicator of sustainable land management? *Applied Soil Ecology*, *15*(1), pp.75-83.

Heydari, M., Rostamy, A., Najafi, F. and Dey, D.C., 2017. Effect of fire severity on physical and biochemical soil properties in Zagros oak (Quercus brant ii Lindl.) forests in Iran. *Journal of Forestry Research*, *28*(1), pp.95-104.

Hmielowski, T., 2017. The value of long-term data in agricultural systems. *CSA News*, *62*(1), pp.4-7.

Hoffman, J.E., 1990. *Die invloed van grondbewerkingspraktyke op die waterbalans van ‘n Avalongrondonderkoringte Bethlehem (*MSc verhandeling, Universiteit van die Vrystaat).

Hofman, G. and Cleemput, O., 2004. Soil and Plant Nitrogen. *International Fertiliser Industry Association* (49): Paris, France.

Horneck, D.A., Sullivan, D.M., Owen, J.S. and Hart, J.M., 2011. *Soil test interpretation guide*. Corvallis, OR: Oregon State University Extension Service.

Hou, E., Chen, C., Wen, D. and Liu, X., 2014. Relationships of phosphorus fractions to organic carbon content in surface soils in mature subtropical forests, Dinghushan, China. *Soil Research*, *52*(1), pp.55-63.

Hou, R., Ouyang, Z., Li, Y., Tyler, D.D., Li, F. and Wilson, G.V., 2012. Effects of tillage and residue management on soil organic carbon and total nitrogen in the North China Plain. *Soil Science Society of America Journal*, *76*(1), pp.230-240.

Houshyar, E. and Esmailpour, M., 2020. The impacts of tillage, fertilizer and residue management on the soil properties and wheat production in a semi-arid region of Iran. *Journal of the Saudi Society of Agricultural Sciences*, *19*(3), pp.225-232.

Https://en.climate-data.org/Accessed on 20 February 2020

Https://sagl.co.za/wheat/reports/Accessed on 12 November 2020

Huang, S., Yan-Ni, S.U.N., Wen-Yi, R.U.I., Wu-Ren, L.I.U. and Zhang, W.J., 2010. The long-term effect of no-tillage on soil organic carbon fractions in a continuous maize cropping system of Northeast China. *Pedosphere*, *20*(3), pp.285-292.

Hunt, J.F., Ohno, T., He, Z., Honeycutt, C.W. and Dail, D.B., 2007. Inhibition of phosphorus sorption to goethite, gibbsite, and kaolin by fresh and decomposed organic matter. *Biology and Fertility of Soils*, *44*(2), pp.277-288.

IUSS Working Group WRB., 2015. The world reference base for soil resources 2014, update 2015: International soil classification system for naming soils and creating legends for soil maps. *World Soil Resources Reports No. 106*, p.192.

Iyamuremye, F., Dick, R.P. and Baham, J., 1996. Organic amendments and phosphorus dynamics: I. Phosphorus chemistry and sorption. *Soil Science, 161*(7), pp.426-435.

Jagadamma, S., Mayes, M.A., Phillips, J.R., 2012. Compound-specific Sorption of Dissolved Organic Carbon on Soil Minerals Selective Sorption of Dissolved Organic Carbon Compounds by Temperate Soils. *PLoS One, 7*(11), pp.1-9.

Jamala, G.Y. and Oke, D.O., 2013. Humic substances and mineral-associated soil organic carbon as influenced by land use in southeastern Adamawa state, Nigeria. *Journal of Environmental Science, Toxicology and Food Technology*, *6*(5), pp.59-70.

Jiang, X., Bol, R., Willbold, S., Vereecken, H. and Klumpp, E., 2015. Speciation and distribution of P associated with Fe and Al oxides in aggregate-sized fraction of an arable soil. *Biogeosciences*, *12*(21), pp.6443-6452.

Jimenez, R.R. and Ladha, J.K., 1993. Automated elemental analysis: A rapid and reliable but expensive measurement of total carbon and nitrogen in plant and soil samples. *Communications in Soil Science and Plant Analysis*, *24*(15-16), pp.1897-1924.

Jobbágy, E.G. and Jackson, R.B., 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications*, *10*(2), pp.423-436.

Jones, C., Olson-Rutz, K. and Dinkins, C.P., 2011. *Nutrient uptake timing by crops*. Montana, USA: Montana State University.

Kaiser, K. and Guggenberger, G., 2000. The role of DOM sorption to mineral surfaces in the preservation of organic matter in soils. *Organic Geochemistry*, *31*(7-8), pp.711-725.

Kaiser, K. and Kalbitz, K., 2012. Cycling downwards–dissolved organic matter in soils. *Soil Biology and Biochemistry*, *52*, pp.29-32.

Kaiser, K. and Zech, W., 1998. Rates of dissolved organic matter release and sorption in forest soils. *Soil Science*, *163*(9), pp.714-725.

Kalbitz, K. and Kaiser, K., 2008. Contribution of dissolved organic matter to carbon storage in forest mineral soils. *Journal of Plant Nutrition and Soil Science*, *171*(1), pp.52-60.

Kalbitz, K., Schwesig, D., Rethemeyer, J. and Matzner, E., 2005. Stabilization of dissolved organic matter by sorption to the mineral soil. *Soil Biology and Biochemistry*, *37*(7), pp.1319-1331.

Kalbitz, K., Solinger, S., Park, J.H., Michalzik, B. and Matzner, E., 2000. Controls on the dynamics of dissolved organic matter in soils: a review. *Soil Science*, *165*(4), pp.277-304.

Kastelan-Macan, M. and Petrovic, M., 1996. The role of fulvic acids in phosphorus sorption and release from mineral particles. *Water Science and Technology*, *34*(7-8), pp.259-265.

Katsalirou, E., Deng, S., Gerakis, A. and Nofziger, D.L., 2016. Long-term management effects on soil P, microbial biomass P, and phosphatase activities in prairie soils. *European Journal of Soil Biology*, *76*, pp.61-69.

Kay, B.D. and Vanden Bygaart, A.J., 2002. Conservation tillage and depth stratification of porosity and soil organic matter. *Soil and Tillage Research*, *66*(2), pp.107-118.

Keil, A., Mitra, A., McDonald, A. and Malik, R.K., 2020. Zero-tillage wheat provides stable yield and economic benefits under diverse growing season climates in the Eastern Indo-Gangetic Plains. *International Journal of Agricultural Sustainability*, pp.1-27.

Kotzé, E. and du Preez, C.C., 2007. Influence of long-term wheat residue management on organic matter in an Avalon soil. *South African Journal of Plant and Soil*, *24*(2), pp.114-119.

Kotzé, E. and du Preez, C.C., 2008. Influence of long-term wheat residue management on acidity and some macronutrients in an Avalon soil. *South African Journal of Plant and Soil*, *25*(1), pp.14-21.

Kotzé, E., 2004. *Influence of long-term wheat residue management on some fertility indicators of an Avalon soil at Bethlehem* (Doctoral dissertation, University of the Free State).

Kovar, J.L. and Pierzynski, G.M., 2009. Methods of phosphorus analysis for soils, sediments, residuals, and waters second edition. *Southern cooperative series bulletin*, *408*.

Krull, E.S., Skjemstad, J.O. and Baldock, J.A., 2004. *Functions of soil organic matter and the effect on soil properties* (p. 129). Canberra, Australia: Cooperative Research Centre for Greenhouse Accounting.

Kumar, V., Kumar, M., Singh, S.K. and Jat, R.K., 2018. Impact of conservation agriculture on soil physical properties in the rice-wheat system of eastern Indo-Gangetic plains. *Journal of Animal and Plant Sciences*, *25*(5), pp. 1432-1440.

Kurth, V.J., MacKenzie, M.D. and DeLuca, T.H., 2006. Estimating charcoal content in forest mineral soils. *Geoderma*, *137*(1-2), pp.135-139.

Lal, R., 2007. Carbon management in agricultural soils. *Mitigation and Adaptation Strategies for Global Change*, *12*(2), pp.303-322.

Lal, R., 2019. Promoting "4 Per Thousand" and "Adapting African Agriculture" by south-south cooperation: Conservation agriculture and sustainable intensification. *Soil and Tillage Research*, *188*, pp.27-34.

Lavallee, J.M., Soong, J.L. and Cotrufo, M.F., 2020. Conceptualizing soil organic matter into particulate and mineral-associated forms to address global change in the 21st century. *Global Change Biology*, *26*(1), pp.261-273.

Ledo, A., Smith, P., Zerihun, A., Whitaker, J., Vicente-Vicente, J.L., Qin, Z., McNamara, N.P., Zinn, Y.L., Llorente, M., Liebig, M. and Kuhnert, M., 2020. Changes in soil organic carbon under perennial crops. *Global Change Biology*, 26, pp.4158–4168.

Lehmann, J. and Kleber, M., 2015. The contentious nature of soil organic matter. *Nature*, *528*(7580), pp.60-68.

Li, F.Y., Liang, X.Q., Liu, Z.W. and Tian, G.M., 2019. No-till with straw return retains soil total P while reducing loss potential of soil colloidal P in rice-fallow systems. *Agriculture, Ecosystems and Environment*, *286*, p.106653.

Li, J., Wen, Y., Li, X., Li, Y., Yang, X., Lin, Z., Song, Z., Cooper, J.M. and Zhao, B., 2018. Soil labile organic carbon fractions and soil organic carbon stocks as affected by long-term organic and mineral fertilization regimes in the North China Plain. *Soil and Tillage Research*, *175*, pp.281-290.

Li, M., Hou, Y.L. and Zhu, B., 2007. Phosphorus sorption–desorption by purple soils of China in relation to their properties. *Soil Research*, *45*(3), pp.182-189.

Li, Y., Li, Z., Cui, S., Jagadamma, S. and Zhang, Q., 2019. Residue retention and minimum tillage improve the physical environment of the soil in croplands: A global meta-analysis. *Soil and Tillage Research*, *194*, p.104292.

Liu, E., Teclemariam, S.G., Yan, C., Yu, J., Gu, R., Liu, S., He, W. and Liu, Q., 2014. Long-term effects of no-tillage management practice on soil organic carbon and its fractions in northern China. *Geoderma*, *213*, pp.379-384.

Liu, X., Herbert, S.J., Hashemi, A.M., Zhang, X. and Ding, G., 2006. Effects of agricultural management on soil organic matter and carbon transformation-a review. *Plant Soil and Environment*, *52*(12), p.531.

Lobe, I., Amelung, W. and du Preez, C.C., 2001. Losses of carbon and nitrogen with prolonged arable cropping from sandy soils of the South African Highveld. *European Journal of Soil Science*, *52*(1), pp.93-101.

Lohan, S.K., Jat, H.S., Yadav, A.K., Sidhu, H.S., Jat, M.L., Choudhary, M., Peter, J.K. and Sharma, P.C., 2018. Burning issues of paddy residue management in north-west states of India. *Renewable and Sustainable Energy Reviews*, *81*, pp.693-706.

Loke, P.F., 2012. *Long-term effects of residue management on soil fertility indicators, nutrient uptake and wheat grain yield* (Masters dissertation, University of the Free State).

Loke, P.F., 2017. *Response of soil carbon fractions to land-use systems under arid to semi-arid climates in South Africa* (Doctoral thesis, University of the Free State).

Loke, P.F., Kotzé, E. and du Preez, C.C., 2012. Changes in soil organic matter indices following 32 years of different wheat production management practices in semi-arid South Africa. *Nutrient Cycling in Agroecosystems*, *94*(1), pp.97-109.

Loke, P.F., Kotzé, E. and du Preez, C.C., 2013. Impact of long-term wheat production management practices on soil acidity, phosphorus and some micronutrients in a semi-arid Plinthosol. *Soil Research*, *51*(5), pp.415-426.

Lollato, R.P., Edwards, J.T. and Zhang, H., 2013. Effect of alternative soil acidity amelioration strategies on soil pH distribution and wheat agronomic response. *Soil Science Society of America Journal*, *77*(5), pp.1831-1841.

Luo, Z., Wang, E. and Sun, O.J., 2010. Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. *Agriculture, ecosystems and environment*, *139*(1-2), pp.224-231.

Lupwayi, N.Z., Clayton, G.W., O'Donovan, J.T., Harker, K.N., Turkington, T.K. and Soon, Y.K., 2007. Phosphorus release during decomposition of crop residues under conventional and zero tillage. *Soil and Tillage Research*, *95*(1-2), pp.231-239.

Machado, S., Petrie, S., Rhinhart, K. and Qu, A., 2007. Long-term continuous cropping in the Pacific Northwest: Tillage and fertilizer effects on winter wheat, spring wheat, and spring barley production. *Soil and Tillage Research*, *94*(2), pp.473-481.

Mahasa, P.S., 2015. *Wind erosion and soil susceptibility in the free State Province, South Africa* (Doctoral dissertation, University of the Free State).

Malobane, M.E., Nciizah, A.D., Mudau, F.N. and Wakindiki, I.I., 2020. Tillage, Crop Rotation and Crop Residue Management Effects on Nutrient Availability in a Sweet Sorghum-Based Cropping System in Marginal Soils of South Africa. *Agronomy*, *10*(6), pp. 1-13.

Maluf, H.J.G.M., Silva, C.A., Curi, N., Norton, L.D. and Rosa, S.D., 2018. Adsorption and availability of phosphorus in response to humic acid rates in soils limed with $CaCO_3$ or $MgCO_3$. *Ciência e Agrotecnologia*, *42*(1), pp.7-20.

Margenot, A.J., Paul, B.K., Sommer, R.R., Pulleman, M.M., Parikh, S.J., Jackson, L.E. and Fonte, S.J., 2017. Can conservation agriculture improve phosphorus (P) availability in weathered soils? Effects of tillage and residue management on soil P status after 9 years in a Kenyan Oxisol. *Soil and Tillage Research*, *166*, pp.157-166.

Martínez, I., Chervet, A., Weisskopf, P., Sturny, W.G., Etana, A., Stettler, M., Forkman, J. and Keller, T., 2016. Two decades of no-till in the Oberacker long-term field experiment: Part I. Crop yield, soil organic carbon and nutrient distribution in the soil profile. *Soil and Tillage Research*, *163*, pp.141-151.

Martínez, C.E. and Motto, H.L., 2000. Solubility of lead, zinc and copper added to mineral soils. *Environmental Pollution*, *107*(1), pp.153-158.

Matejovic, I., 1995. Total nitrogen in plant material determined by means of dry combustion: A possible alternative to determination by Kjeldahl digestion. *Communications in Soil Science and Plant Analysis*, *26*(13-14), pp.2217-2229.

Mehra, O.P. and Jackson, M.L., 1960. Iron oxide removal from soils and clays by a dithionite-citrate system buffered with sodium bicarbonate. 317-327 p. In *7th National Conference on Clays and Clays Minerals, Washington. Committee on Clay Minerals of the National Academy of Sciences-National Research Council, Washington, USA.*

Melero, S., López-Garrido, R., Murillo, J.M. and Moreno, F., 2009. Conservation tillage: Short-and long-term effects on soil carbon fractions and enzymatic activities under Mediterranean conditions. *Soil and Tillage Research*, *104*(2), pp.292-298.

Mikutta, R., Kleber, M., Torn, M.S. and Jahn, R., 2006. Stabilization of soil organic matter: association with minerals or chemical recalcitrance?. *Biogeochemistry*, *77*(1), pp.25-56.

Mnthambala, F., Maida, J.H., Lowole, M.W. and Kabambe, V.H., 2016. Soil management effects on phosphorus sorption and external P requirement in oxisols of Malawi. *Journal of Soil Science and Environmental Management*, *7*(8), pp.106-114.

Moazed, H., Hoseini, Y., Naseri, A.A. and Abbasi, F., 2010. Determining phosphorus adsorption isotherm in soil and its relation to soil characteristics. *Journal of Food, Agriculture and Environment*, *8*(2), pp.1153-1157.

Molina, M., Fuentes, R., Calderón, R., Escudey, M., Avendaño, K., Gutiérrez, M. and Chang, A.C., 2007. Impact of forest fire ash on surface charge characteristics of Andisols. *Soil Science*, *172*(10), pp.820-834.

Mondal, S., Poonia, S.P., Mishra, J.S., Bhatt, B.P., Karnena, K.R., Saurabh, K., Kumar, R. and Chakraborty, D., 2019. Short-term (5 years) impact of conservation agriculture on soil physical properties and organic carbon in a rice–wheat rotation in the Indo-Gangetic plains of Bihar. *European Journal of Soil Science*, pp.1-14.

Montalvo Grijalva, D.F., 2014. *Improving phosphorus availability in Andisols and Oxisols* (Doctoral dissertation, University of Adelaide).

Motema, T., Kotzé, E., Loke, P.F. and du Preez, C.C., 2020. Response of soil organic matter indices and fractions after 37 years of wheat production management practices in semi-arid South Africa. *South African Journal of Plant and Soil*, *37*(2), pp.136-143.

Mtyobile, M., Muzangwa, L. and Mnkeni, P.N.S., 2019. Tillage and Crop Rotation Effects on Selected Soil Chemical Properties and Wheat Yield in a Sandy Loam Oakleaf Soil in the Eastern Cape, South Africa. *International Journal of Agriculture and Biology*, *21*, pp.367-374.

Muindi, E.M., Mrema, J.P., Semu, E., Mtakwa, P.W., Gachene, C.K. and Njogu, M.K., 2015. Phosphorus adsorption and its relation with soil properties in acid soils of Western Kenya. *International Journal of Plant and Soil Science*, *4*(3), pp. 203-211.

Mukumbareza, C., Muchaonyerwa, P. and Chiduza, C., 2016. Bicultures of oat (Avena sativa L.) and grazing vetch (Vicia dasycarpa L.) cover crops increase contents of carbon pools and activities of selected enzymes in a loam soil under warm temperate conditions. *Soil Science and Plant Nutrition*, *62*(5-6), pp.447-455.

Muñoz-Rojas, M., 2018. Soil quality indicators: critical tools in ecosystem restoration. *Current Opinion in Environmental Science and Health, 5*, pp.47-52.

Murphy, J.A.M.E.S. and Riley, J.P., 1962. A modified single solution method for the determination of phosphate in natural waters. *Analytica Chimica Acta*, *27*, pp.31-36.

Murungu, F.S., Chiduza, C., Muchaonyerwa, P. and Mnkeni, P.N.S., 2011. Decomposition, nitrogen and phosphorus mineralization from winter-grown cover crop residues and suitability for a smallholder farming system in South Africa. *Nutrient Cycling in Agroecosystems*, *89*(1), pp.115-123.

Musinguzi, P., Tenywa, J.S., Ebanyat, P., Tenywa, M.M., Mubiru, D.N., Basamba, T.A. and Leip, A., 2013. Soil organic carbon thresholds and nitrogen management in tropical agroecosystems: concepts and prospects. *Journal of Sustainable Development*, *6*(12), pp.31-43.

Mutuo, P.K., 2004. *Potential of improved tropical legume fallows and zero tillage practices for soil organic carbon sequestration* (Doctoral dissertation, University of London).

Muzangwa, L., Mnkeni, P.N.S. and Chiduza, C., 2017. Assessment of conservation agriculture practices by smallholder farmers in the Eastern Cape province of South Africa. *Agronomy*, *7*(3), p.46.

Naab, J.B., Mahama, G.Y., Yahaya, I. and Prasad, P.V.V., 2017. Conservation agriculture improves soil quality, crop yield, and incomes of smallholder farmers in North-Western Ghana. *Frontiers in Plant Science*, *8*, p.996.

Nascente, A.S., Li, Y.C. and Crusciol, C.A.C., 2013. Cover crops and no-till effects on physical fractions of soil organic matter. *Soil and Tillage Research*, *130*, pp.52-57.

Nawaz, R., Parkpian, P., Garivait, H., Anurakpongsatorn, P., DeLaune, R.D. and Jugsujinda, A., 2012. Impacts of acid rain on base cations, aluminum, and acidity development in highly weathered soils of Thailand. *Communications in Soil Science and Plant Analysis*, *43*(10), pp.1382-1400.

Ncoyi, K., du Preez, C.C. and Kotzé, E., 2020. Comparison of soil phosphorus fractions after 37 years of wheat production under different management practices in a semi-arid climate. *South African Journal of Plant and Soil*, *37*(3), pp.184-193.

Neary, D.G., 2004. An overview of fire effects on soils. *Southwest Hydrology*, *3*(5), pp.18-19.

Neugschwandtner, R.W., Liebhard, P., Kaul, H.P. and Wagentristl, H., 2014. Soil chemical properties as affected by tillage and crop rotation in a long-term field experiment. *Plant, Soil and Environment*, *60*(2), pp.57-62.

Noack, S.R., McBeath, T.M., McLaughlin, M.J., Smernik, R.J. and Armstrong, R.D., 2014. Management of crop residues affects the transfer of phosphorus to plant and soil pools: Results from a dual-labelling experiment. *Soil Biology and Biochemistry*, *71*, pp.31-39.

Non-Affiliated Soil Analysis Work Committee., 1990. *Handbook of standard soil testing methods for advisory purposes*. Soil Science Society of South Africa, Pretoria, 160(2020).

Nziguheba, G., Palm, C.A., Buresh, R.J. and Smithson, P.C., 1998. Soil phosphorus fractions and adsorption as affected by organic and inorganic sources. *Plant and Soil*, *198*(2), pp.159-168.

Nziguheba, G., Zingore, S., Kihara, J., Merckx, R., Njoroge, S., Otinga, A., Vandamme, E. and Vanlauwe, B., 2016. Phosphorus in smallholder farming systems of sub-Saharan Africa: implications for agricultural intensification. *Nutrient Cycling in Agroecosystems*, *104*(3), pp.321-340.

Olsen, S.R. and Watanabe, F.S., 1957. A method to determine a phosphorus adsorption maximum of soils as measured by the Langmuir isotherm. *Soil Science Society of America Journal*, *21*(2), pp.144-149.

Ortiz-Monasterio, J.I., Pena, R.J., Pfeiffer, W.H. and Hede, A.H., 2002, June. Phosphorus use efficiency, grain yield, and quality of triticale and durum wheat under irrigated conditions. In *Proceedings of the 5th International Triticale Symposium June* (pp. 1-6).

Paustian, K., Collier, S., Baldock, J., Burgess, R., Creque, J., DeLonge, M., Dungait, J., Ellert, B., Frank, S., Goddard, T. and Govaerts, B., 2019. Quantifying carbon for agricultural soil management: from the current status toward a global soil information system. *Carbon Management*, *10*(6), pp.567-587.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.P. and Smith, P., 2016. Climate-smart soils. *Nature*, *532*(7597), pp.49-57.

Pellegrini, A.F., Ahlström, A., Hobbie, S.E., Reich, P.B., Nieradzik, L.P., Staver, A.C., Scharenbroch, B.C., Jumpponen, A., Anderegg, W.R., Randerson, J.T. and Jackson, R.B., 2018. Fire frequency drives decadal changes in soil carbon and nitrogen and ecosystem productivity. *Nature*, *553*(7687), pp.194-198.

Petrokofsky, G., Kanamaru, H., Achard, F., Goetz, S.J., Joosten, H., Holmgren, P., Lehtonen, A., Menton, M.C., Pullin, A.S. and Wattenbach, M., 2012. Comparison of methods for measuring and assessing carbon stocks and carbon stock changes in terrestrial carbon pools. How do the accuracy and precision of current methods compare? A systematic review protocol. *Environmental Evidence*, *1*(1), pp.1-21.

Poirier, V., Basile-Doelsch, I., Balesdent, J., Borschneck, D., Whalen, J.K. and Angers, D.A., 2020. Organo-mineral interactions are more important for organic matter retention in the subsoil than topsoil. *Soil Systems*, *4*(1), pp.1-17.

Poswa, L.Z., 2016. *Factors affecting phosphorus requirements for the soils of South African Sugar Industry* (Masters dissertation, University of KwaZulu-Natal).

Powlson, D.S., Bhogal, A., Chambers, B.J., Coleman, K., Macdonald, A.J., Goulding, K.W.T. and Whitmore, A.P., 2012. The potential to increase soil carbon stocks through reduced tillage or organic material additions in England and Wales: a case study. *Agriculture, Ecosystems and Environment*, *146*(1), pp.23-33.

Rai, V., Pramanik, P., Aggarwal, P., Krishnan, P. and Bhattacharyya, R., 2018. Effect of conservation agriculture on soil physical health. *International Journal of Current Microbiol Applied Sciences*, *7*(2), pp.373-389.

Reddy, D.D., Kushwaha, S., Srivastava, S. and Khamparia, R.S., 2014. Long-term wheat residue management and supplementary nutrient input effects on phosphorus fractions and adsorption behavior in a vertisol. *Communications in Soil Science and Plant Analysis, 45*(4), pp.541-554.

Reddy, D.D., Rao, A.S. and Singh, M., 2001. Crop residue addition effects on myriad forms and sorption of phosphorus in a Vertisol. *Bioresource Technology*, *80*(2), pp.93-99.

Reiter, L., 2015. *Effect of crop residue incorporation on soil organic carbon dynamics* (Masters dissertation, Swedish University of Agricultural Sciences).

Rodríguez, D., Andrade, F.H. and Goudriaan, J., 1999. Effects of phosphorus nutrition on tiller emergence in wheat. *Plant and Soil*, *209*(2), pp.283-295.

Roldán, A., Albaladejo, J. and Thornes, J.B., 1996. Aggregate stability changes in a semiarid soil after treatment with different organic amendments. *Arid Land Research and Management*, *10*(2), pp.139-148.

Romaniuk, R., Beltrán, M., Brutti, L., Costantini, A., Bacigaluppo, S., Sainz-Rozas, H. and Salvagiotti, F., 2018. Soil organic carbon, macro-and micronutrient changes in soil fractions with different lability in response to crop intensification. *Soil and Tillage Research*, *181*, pp.136-143.

Romanya, J., Khanna, P.K. and Raison, R.J., 1994. Effects of slash burning on soil phosphorus fractions and sorption and desorption of phosphorus. *Forest Ecology and Management*, *65*(2-3), pp.89-103.

Rosa, A.T., Diaz, D.R., Hansel, F.D., Sebastian, J.S.V. and Adee, E.A., 2019. Genotypic variation on root growth and nutrient uptake in corn and soybean. *Agrosystems, Geosciences and Environment*, *2*(1), pp.1-12.

Roy-Bolduc, A. and Hijri, M., 2011. The use of mycorrhizae to enhance phosphorus uptake: a way out the phosphorus crisis. *Journal of Biofertilizers and Biopesticides*, *2*(104), pp.1-5.

Rumpel, C. and Kögel-Knabner, I., 2011. Deep soil organic matter—a key but poorly understood component of terrestrial C cycle. *Plant and Soil*, *338*(1-2), pp.143-158.

Rumpel, C., 2008. Does the burning of harvesting residues increase soil carbon storage? *Journal of Soil Science and Plant Nutrition*, *8*(2), pp.44-51.

Rumpel, C., Alexis, M., Chabbi, A., Chaplot, V., Rasse, D.P., Valentin, C. and Mariotti, A., 2006. Black carbon contribution to soil organic matter composition in tropical sloping land under slash and burn agriculture. *Geoderma*, *130*(1-2), pp.35-46.

Rusinamhodzi, L., Corbeels, M., Van Wijk, M.T., Rufino, M.C., Nyamangara, J. and Giller, K.E., 2011. A meta-analysis of long-term effects of conservation agriculture on maize grain yield under rain-fed conditions. *Agronomy for Sustainable Development*, *31*(4), pp.657-673.

Sapkota, T.B., Jat, R.K., Singh, R.G., Jat, M.L., Stirling, C.M., Jat, M.K., Bijarniya, D., Kumar, M., Saharawat, Y.S. and Gupta, R.K., 2017. Soil organic carbon changes after seven years of conservation agriculture in a rice–wheat system of the eastern Indo-Gangetic Plains. *Soil Use and Management*, *33*(1), pp.81-89.

Schaller, J., Tischer, A., Struyf, E., Bremer, M., Belmonte, D.U. and Potthast, K., 2015. Fire enhances phosphorus availability in topsoils depending on binding properties. *Ecology*, *96*(6), pp.1598-1606.

Schrumpf, M., Kaiser, K., Guggenberger, G., Persson, T., Kögel-Knabner, I. and Schulze, E.D., 2012. Storage and stability of organic carbon in soils as related to depth, occlusion within aggregates, and attachment to minerals. *Biogeosciences*, *10,* pp.1675-1691.

Schrumpf, M., Schulze, E.D., Kaiser, K. and Schumacher, J., 2011. How accurately can soil organic carbon stocks and stock changes be quantified by soil inventories? *Biogeosciences*, *8*(5), pp.1193-1212.

Schütte, S., Schulze, R. and Paterson, G., 2019. *Identification and mapping of soils rich in organic carbon in South Africa as a climate change mitigation option*. Department of Environmental Affairs, Pretoria, South Africa.

Seepamore, M.K., du Preez, C.C. and Ceronio, G.M., 2020. Impact of long-term production management practices on wheat grain yield and quality components under a semi-arid climate. *South African Journal of Plant and Soil*, *37*(3), pp.194-201.

Segovia, C., Gómez, J.D., Gallardo, P., Lozano, F.J. and Asensio, C., 2017. Soil nutrients losses by wind erosion in a citrus crop at southeast Spain. *Eurasian Soil Science*, *50*(6), pp.756-763.

Sharma, N.K., Singh, R.J. and Kumar, K., 2012. Dry matter accumulation and nutrient uptake by wheat (*Triticum aestivum* L.) under poplar (*Populus deltoides*) based agroforestry system. *ISRN Agronomy*, pp.1-7.

Sharpley, A.N., 2003. Soil mixing to decrease surface stratification of phosphorus in manured soils. *Journal of Environmental Quality*, *32*(4), pp.1375-1384.

Shew, A.M., Tack, J.B., Nalley, L.L. and Chaminuka, P., 2020. Yield reduction under climate warming varies among wheat cultivars in South Africa. *Nature Communications*, *11*(1), pp.1-9.

Shiferaw, B., Smale, M., Braun, H.J., Duveiller, E., Reynolds, M. and Muricho, G., 2013. Crops that feed the world 10. Past successes and future challenges to the role played by wheat in global food security. *Food Security*, *5*(3), pp.291-317.

Shirvani, M., Shariatmadari, H. and Kalbasi, M., 2005. Phosphorus buffering capacity indices as related to soil properties and plant uptake. *Journal of Plant Nutrition*, *28*(3), pp.537-550.

Sidhu, B.S. and Beri, V., 1989. Effect of crop residue management on the yields of different crops and soil properties. *Biological Wastes*, *27*(1), pp.15-27.

Singh, D., Lenka, S., Lenka, N.K., Trivedi, S.K., Bhattacharjya, S., Sahoo, S., Saha, J.K. and Patra, A.K., 2020. Effect of Reversal of Conservation Tillage on Soil Nutrient Availability and Crop Nutrient Uptake in Soybean in the Vertisols of Central India. *Sustainability*, *12*(16), p.6608.

Singh, M., Sarkar, B., Biswas, B., Churchman, J. and Bolan, N.S., 2016. Adsorption-desorption behavior of dissolved organic carbon by soil clay fractions of varying mineralogy. *Geoderma*, *280*, pp.47-56.

Singh, M., Sarkar, B., Hussain, S., Ok, Y.S., Bolan, N.S. and Churchman, G.J., 2017. Influence of physico-chemical properties of soil clay fractions on the retention of dissolved organic carbon. *Environmental Geochemistry and Health*, *39*(6), pp.1335-1350.

Sithole, N.J., Magwaza, L.S. and Mafongoya, P.L., 2016. Conservation agriculture and its impact on soil quality and maize yield: A South African perspective. *Soil and Tillage Research*, *162*, pp.55-67.

Six, J., Feller, C., Denef, K., Ogle, S., de Moraes Sa, J.C. and Albrecht, A., 2002. Soil organic matter, biota and aggregation in temperate and tropical soils-Effects of no-tillage. *Agronomie 22*(7-8), pp.755-775.

Six, J.A.E.T., Elliott, E.T. and Paustian, K., 2000. Soil macroaggregate turnover and micro aggregate formation: a mechanism for C sequestration under no-tillage agriculture. *Soil Biology and Biochemistry*, *32*(14), pp.2099-2103.

Smith, P., Davies, C.A., Ogle, S., Zanchi, G., Bellarby, J., Bird, N., Boddey, R.M., McNamara, N.P., Powlson, D., Cowie, A. and van Noordwijk, M., 2012. Towards an integrated global framework to assess the impacts of land use and management change on soil carbon: current capability and future vision. *Global Change Biology, 18*(7), pp.2089-2101.

Snapp, S.S and Grandy, A.S., 2011. *Advanced soil organic matter management*. Michigan State University Extension Bulletin. E3137. East Lansing, MI: Michigan State University, USA.

Soil Classification Working Group., 1991. Soil classification: a taxonomic system for South Africa. *Memoirs on the agricultural natural resources of South Africa*, *15*, pp.1-262.

Soil Survey Staff., 2010. Keys to Soil Taxonomy. 11th edition. Natural Resources Conservation Service, United States Department of Agriculture, Washington, DC.

Soltangheisi, A., Rodrigues, M., Coelho, M.J.A., Gasperini, A.M., Sartor, L.R. and Pavinato, P.S., 2018. Changes in soil phosphorus lability promoted by phosphate sources and cover crops. *Soil and Tillage Research*, *179*, pp.20-28.

Sosibo, N.Z., 2016. *Soil fertility constraints of irrigated wheat production in South Africa* (Masters dissertation, University of KwaZulu-Natal).

Sosibo, N.Z., Muchaonyerwa, P., Visser, L., Barnard, A., Dube, E. and Tsilo, T.J., 2017. Soil fertility constraints and yield gaps of irrigation wheat in South Africa. *South African Journal of Science*, *113*(1-2), pp.1-9.

Souza, E.D., Costa, S.E.V.G.A., Anghinoni, I., Carneiro, M.A.C., Martins, A.P. and Bayer, C., 2014. Soil quality indicators in a Rhodic Paleudult under long term tillage systems. *Soil and Tillage Research*, *139*, pp.28-36.

Sparling, G., Vojvodić-Vuković, M. and Schipper, L.A., 1998. Hot-water-soluble C as a simple measure of labile soil organic matter: the relationship with microbial biomass C. *Soil Biology and Biochemistry*, *30*(10-11), pp.1469-1472.

Swanepoel, C.M., Swanepoel, L.H. and Smith, H.J., 2018. A review of conservation agriculture research in South Africa. *South African Journal of Plant and Soil*, *35*(4), pp.297-306.

Taub, D.R., 2010. Effects of Rising Carbon Dioxide Levels and Plants Effects of Rising Atmospheric Concentrations of Carbon Dioxide on Plants. *Nature Education Knowledge*, 3, pp. 21-23.

Thierfelder, C., Rusinamhodzi, L., Ngwira, A.R., Mupangwa, W., Nyagumbo, I., Kassie, G.T. and Cairns, J.E., 2014. Conservation agriculture in Southern Africa: Advances in knowledge. *Renewable Agriculture and Food Systems*, *30*(4), pp. 328-348.

Thomas Sims, J. and Pierzynski, G.M., 2005. Chemistry of phosphorus in soils. *Chemical processes in soils*, *8*, pp.151-192.

Tiecher, T., Calegari, A., Caner, L. and dos Santos Rheinheimer, D., 2017. Soil fertility and nutrient budget after 23-years of different soil tillage systems and winter cover crops in a subtropical Oxisol. *Geoderma*, *308*, pp.78-85.

Tiecher, T., dos Santos, D.R. and Calegari, A., 2012. Soil organic phosphorus forms under different soil management systems and winter crops, in a long term experiment. *Soil and Tillage Research*, *124*, pp.57-67.

Tifafi, M., Guenet, B. and Hatté, C., 2018. Large differences in global and regional total soil carbon stock estimates based on SoilGrids, HWSD, and NCSCD: Intercomparison and evaluation based on field data from USA, England, Wales, and France. *Global Biogeochemical Cycles*, *32*(1), pp.42-56.

Torres-Sallan, G., Schulte, R.P., Lanigan, G.J., Byrne, K.A., Reidy, B., Simó, I., Six, J. and Creamer, R.E., 2017. Clay illuviation provides a long-term sink for C sequestration in subsoils. *Scientific Reports*, *7*(1), pp.1-7.

Vanlauwe, B., Wendt, J., Giller, K.E., Corbeels, M., Gerard, B. and Nolte, C., 2014. A fourth principle is required to define conservation agriculture in sub-Saharan Africa: the appropriate use of fertilizer to enhance crop productivity. *Field Crops Research*, *155*, pp.10-13.

Varela, M.F., Scianca, C.M., Taboada, M.A. and Rubio, G., 2014. Cover crop effects on soybean residue decomposition and P release in no-tillage systems of Argentina. *Soil and Tillage Research*, *143*, pp.59-66.

Venzke Filho, S.D.P., Feigl, B.J., Piccolo, M.D.C., Fante Jr, L., Siqueira Neto, M. and Cerri, C.C., 2004. Root systems and soil microbial biomass under no-tillage system. *Scientia Agricola*, *61*(5), pp.529-537.

Verhulst, N., Govaerts, B., Verachtert, E., Castellanos-Navarrete, A., Mezzalama, M., Wall, P., Deckers, J. and Sayre, K.D., 2010. Conservation agriculture, improving soil quality for sustainable production systems. *Advances in Soil Science: Food Security and Soil Quality*, *1799267585*, pp.137-208.

Violante, A., Colombo, C. and Buondonno, A., 1991. Competitive adsorption of phosphate and oxalate by aluminum oxides. *Soil Science Society of America Journal*, *55*(1), pp.65-70.

Virto, I., Imaz, M.J., Enrique, A., Hoogmoed, W. and Bescansa, P., 2007. Burning crop residues under no-till in semi-arid land, Northern Spain—effects on soil organic matter, aggregation, and earthworm populations. *Soil Research*, *45*(6), pp.414-421.

Von Wandruszka, R., 2006. Phosphorus retention in calcareous soils and the effect of organic matter on its mobility. *Geochemical Transactions*, *7*(1), pp.1-8.

Warren, G.P., 1994. Influence of soil properties on the response to phosphorus in some tropical soils: I. Initial response to fertilizer. *European Journal of Soil Science*, *45*(3), pp.337-344.

West, T.O. and Post, W.M., 2002. Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. *Soil Science Society of America Journal*, *66*(6), pp.1930-1946.

Wiltshire, G.H. and du Preez, C.C., 1993. Long-term effects of conservation practices on the nitrogen fertility of a soil cropped annually to wheat. *South African Journal of Plant and Soil*, *10*(2), pp.70-76.

Wong, M.T.F. and Swift, R.S., 2003. Role of organic matter in alleviating soil acidity. *Handbook of soil acidity. Marcel Dekker, New York*, pp.337-358.

Xue, Y., Xia, H., Christie, P., Zhang, Z., Li, L. and Tang, C., 2016. Crop acquisition of phosphorus, iron and zinc from the soil in cereal/legume intercropping systems: a critical review. *Annals of Botany*, *117*(3), pp.363-377.

Yang, X., Chen, X. and Yang, X., 2019. Effect of organic matter on phosphorus adsorption and desorption in a black soil from Northeast China. *Soil and Tillage Research*, *187,* pp.85-91.

Yigezu, Y.A., El-Shater, T., Boughlala, M., Bishaw, Z., Niane, A.A., Maalouf, F., Degu, W.T., Wery, J., Boutfiras, M. and Aw-Hassan, A., 2019. Legume-based rotations have clear economic advantages over cereal monocropping in dry areas. *Agronomy for Sustainable Development*, *39*(58), pp. 1-14.

Yusuf, A.A., Abaidoo, R.C., Iwuafor, E.N.O., Olufajo, O.O. and Sanginga, N., 2009. Rotation effects of grain legumes and fallow on maize yield, microbial biomass and chemical properties of an Alfisol in the Nigerian savanna. *Agriculture, Ecosystems and Environment*, *129*(1-3), pp.325-331.

Zasoski, R.J. and Burau, R.G., 1977. A rapid nitric-perchloric acid digestion method for multi-element tissue analysis. *Communications in Soil Science and Plant Analysis, 8*(5), pp.425-436.

Zengqiang, L.I., Bingzi, Z.H.A.O. and Zhang, J., 2016. Effects of maize residue quality and soil water content on soil labile organic carbon fractions and microbial properties. *Pedosphere*, *26*(6), pp.829-838.

Zhang, S., Lövdahl, L., Grip, H., Tong, Y., Yang, X. and Wang, Q., 2009. Effects of mulching and catch cropping on soil temperature, soil moisture and wheat yield on the Loess Plateau of China. *Soil and Tillage Research*, *102*(1), pp.78-86.

Zhang, M.K., He, Z.L., Calvert, D.V., Stoffella, P.J., Li, Y.C. and Lamb, E.M., 2002. Release potential of phosphorus in Florida sandy soils in relation to phosphorus fractions and adsorption capacity. *Journal of Environmental Science and Health, Part A, 37*(5), pp.793-809.

Zhang, X., Li, H., He, J., Wang, Q. and Golabi, M.H., 2009. Influence of conservation tillage practices on soil properties and crop yields for maize and wheat cultivation in Beijing, China. *Soil Research*, *47*(4), pp.362-371.

Zibilske, L.M., Bradford, J.M. and Smart, J.R., 2002. Conservation tillage induced changes in organic carbon, total nitrogen and available phosphorus in a semi-arid alkaline subtropical soil. *Soil and Tillage Research*, *66*(2), pp.153-163.

Zuber, S.M., Behnke, G.D., Nafziger, E.D. and Villamil, M.B., 2015. Crop rotation and tillage effects on soil physical and chemical properties in Illinois. *Agronomy Journal*, *107*(3), pp.971-978.