

Effects of soil fertility management practices on selected soil physical properties, water use efficiency and crop productivity in Murewa smallholder farming area

By

Nothando Dunjana



**A thesis submitted in partial fulfilment of the requirements for the degree of
Master of Philosophy**

**Department of Soil Science and Agricultural Engineering
Faculty of Agriculture
University of Zimbabwe**

August 2011

Abstract

Several studies have been conducted to restore the fertility of degraded soils in sub-Saharan Africa using combinations of inorganic and organic fertilizers. The studies mainly concentrated on nutrient uptake and balances in the soil. This study was carried out to determine the effects of cattle manure and inorganic fertilizer application (fertility treatment) on soil organic carbon (SOC), bulk density, aggregate stability, aggregate protected carbon, steady state infiltration rates, porosity, unsaturated hydraulic conductivity, moisture retention characteristics, crop water productivity (CWP) and grain yields of two contrasting soils in Murewa smallholder farming area, Zimbabwe. Four long-term (6 years) and short-term (2 years) fields, sandy homefield and outfield and clayey homefield and outfield were used to take into consideration the spatial variability in soil fertility induced by farmer management practices (field-type treatment). The fields were conventionally tilled (ox-drawn mould-board ploughed annually) and maize monocrop was grown in the long-term fields under the following soil fertility amendments, control (no fertility amelioration), 5, 15 and 25 t ha⁻¹ manure + 100 kg ha⁻¹ N applied annually. Soybean-maize rotation was practiced in the short-term fields under the treatments 100 kg ha⁻¹ N (maize)/ 40 kg ha⁻¹ N (soybean), 30 kg ha⁻¹ P, 29 kg ha⁻¹ K, 20 kg ha⁻¹ Ca, 10 kg ha⁻¹ Mg, 5 kg ha⁻¹ Zn and 5 kg ha⁻¹ Mn in combination with cattle manure at 5, 10, 15 and 20 t ha⁻¹. Cattle manure application resulted in significant increases in SOC, macro-aggregation index (I_{ma}), aggregate protected carbon (APC), steady state infiltration rates (I_R), total effective porosity, unsaturated hydraulic conductivity (K_o) at 5 cm tension. Soil organic carbon ranged between 0.5-3.2 % on clay soils, in contrast to sandy soil's SOC which was between 0.3-2.4 % under combined cattle manure and inorganic fertilizer application. Mean pore sizes that were significantly improved by cattle manure application were 0.58 mm in 25 t ha⁻¹ manure while control was 0.43 mm. Moisture retention at 5 and 10 kPa was improved (p<0.05) by cattle manure application. Soil organic carbon was significantly (p<0.05) and positively correlated with macro-aggregation indices, aggregate protected carbon, steady state infiltration rates, total effective porosity, hydraulic conductivity and grain yield (r>0.6). Multiple regression analysis revealed that SOC, macro-aggregation indices, aggregate protected carbon, steady state infiltration rates accounted for some of the variability in grain yield in the long-term clay fields (p<0.001, r²=95.3). However, only SOC could account for the yield variability on sandy soils (p<0.05, r²=0.89). Generally, grain yield increased in the order control < 5 < 15 ≈ 25 t ha⁻¹ cattle manure application rates on both soil types. On the short term fields, crop yields were significantly lower in control and highest in 20 t ha⁻¹ cattle manure treatment while the intermediate treatments did not significantly differ. AquaCrop model satisfactorily simulated actual crop transpiration with higher CWP observed in 25 t ha⁻¹ cattle manure treatments relative to control. Combined cattle manure and inorganic fertilizer application significantly improved clay soils' physical and bio-chemical environment which ultimately improved crop yields. Cattle manure rates at 5 t ha⁻¹ yr⁻¹ improved crop yields on sandy soils and 15 t ha⁻¹ was required for physical properties' improvement and yield on clay soil. In addition, soil fertility gradients were revealed to be a short-term phenomenon, whereby they disappeared after 6 years on clay soils after equal application of soil fertility amendments while sandy soil's physical properties did not respond to cattle manure application.

Dedication

This work is dedicated to my late father, Stanley Dunjana whose vision, support and love was ever so inspirational, thank you for believing in your girls Father!

Acknowledgements

My sincere gratitude goes to my supervisors, Mr Phillip Nyamugafata, Prof. J Nyamangara and Dr. S Zingore for their invaluable support during this research, thank you for being there and so understanding especially when the going was tough for me. I would also like to thank my family, mom, Bongie, Ponsie and Vu, you guys have always been a pillar of strength. Special mention also goes to my friends, Grace, Blessing, mkwasha Chris, Tongai and Armwell, without you guys life (academic and social) at UZ would never have been half as interesting as it was! I would also like to acknowledge the guidance of Dr. M Wuta who was such a good mentor to me, thank you so much. I am also grateful for the support of the Department of Soil Science technical staff for their assistance during laboratory analyses.

My appreciation goes to TSBF-CIAT who provided the financial support for this research. My gratitude also goes to the CIAT staff, Harare office for the support during field work and writing up.

Contents

List of Tables	x
List of figures.....	xi
List of Symbols	xii
List of Acronyms	xiii
Chapter 1	1
Introduction.....	1
1.1 Introduction and Problem Statement	1
1.2 Hypotheses.....	4
1.3 Overall objective	5
1.3.1 Specific Objectives	5
1.4 Thesis structure	6
Chapter 2	7
Literature review	7
2.1 Soil organic matter, organic resources and effects on soil physical properties	7
2.2 Soil fertility studies	9
2.3 Aggregate stability and formation dynamics	10
2.4 Infiltration rates and soil porosity	11
2.5 Soil water studies	13
2.5.1 Water use efficiency (WUE).....	13
2.5.2 The Concept of Crop Water Productivity	14
2.5.3 Simple Soil Water Balance Methods	15
2.5.4 Soil Water Based Models.....	16
2.5.4.1 The Parch-Thirst Model.....	16
2.5.4.2 The BUDGET Model.....	16

2.5.4.3 AquaCrop Model	17
2.5.5 Advantages of using AquaCrop	18
2.6. Key Components of AquaCrop Model	18
2.6.1 The atmosphere module	18
2.6.2 The crop module	19
2.6.1.3 The soil module.....	20
2.6.1.4 The Management module	20
2.7 Studies on physical properties and crop productivity	21
Chapter 3.....	22
General Materials and Methods	22
3.1 Site description.....	22
3.2 Selection and characteristics of experimental sites.....	23
3.2.1 Experiment 1: Long term soil fertility experiments in Murewa	24
3.2.2 Experiment 2: Short term soil fertility experiments in Murewa	26
3.3 General Management of the Experimental Fields	27
3.4 Soil sampling for field characterisation	28
3.4.1 Soil pH	28
3.4.2 Soil texture	28
3.4.3 Soil organic carbon	29
3.4.4 Total N and P determination	29
3.4.5 Cation exchange capacity determination	30
Chapter 4.....	31
Effects of Soil Fertility Management Practices on Selected Soil Physical Properties of Two Contrasting Soils in Murewa Smallholder Farming Area.....	31
4.1 Introduction.....	31

4.2 Materials and Methods.....	32
4.2.1. Soil sampling, pre-treatment and storage.....	32
4.2.1 Soil Organic Carbon	33
4.2.2 Water stable macro-aggregation and macro-aggregate protected carbon determination	33
4.2.3 Bulk density	35
4.2.4 Statistical Analyses	35
4.3 Results.....	36
4.3.1 Soil Organic Carbon	36
4.3.2 Bulk density	38
4.3.3 Water stable macro-aggregation	38
4.3.4 Macro-aggregate Protected Carbon	40
4.3.5 Regression relationships between soil organic carbon, aggregate stability and aggregate protected carbon	41
4.4 Discussion.....	43
4.4.1 Soil organic carbon	43
4.4.2 Bulk density	44
4.4.3 Water stable macro-aggregation	44
4.4.4 Macro-aggregate protected carbon	46
4.4.5 Regression relationships between soil organic carbon, aggregate stability and aggregate protected carbon	47
4.5 Conclusion	47
Chapter 5.....	49
Soil hydraulic properties as influenced by soil fertility management on two contrasting soils in Murewa	49

5.1 Introduction.....	49
5.2 Materials and Methods.....	51
5.2.1 Infiltration Rates measurement.....	51
5.2.2 Porosity measurement.....	52
5.2.3 Unsaturated hydraulic conductivity using a tension infiltrometer.....	54
5.2.3 Soil moisture retention determination.....	56
5.2.4 Statistical analysis.....	57
5.3 Results.....	58
5.3.1 Steady state infiltration rates.....	58
5.3.2 Total effective porosity and pore density.....	59
5.3.3 Unsaturated hydraulic conductivity, macroscopic capillary length and mean pore sizes.....	61
5.3.4 Moisture retention characteristics.....	63
5.4 Discussion.....	65
5.4.1 Steady state infiltration rates.....	65
5.4.2 Pore density and total porosity.....	65
5.4.3 Unsaturated hydraulic conductivity, macroscopic capillary length and mean pore sizes.....	66
5.4.5 Moisture retention characteristics.....	67
5.5 Conclusion.....	69
Chapter 6.....	70
Investigating the effects of soil fertility management practices and selected soil physical properties on crop yields and crop water productivity through modelling.....	70
6.1 Introduction.....	70
6.2 Materials and Methods.....	72

6.2.1 Grain yield	73
6.2.2 Crop water productivity modelling using AquaCrop.....	73
6.2.2.1 Estimating Evapotranspiration (ET)	73
6.2.2.2 Soil parameters used to simulate evaporation.....	74
6.2.2.3 Crop parameters used to simulate transpiration.....	75
6.2.2.4 The management module	75
6.2.3 Validation of AquaCrop Model	76
6.2.4 Calculation of crop water productivity	77
6.2.5 Principal components analysis theory.....	77
6.2.5.1 Multiple regression modelling	78
6.3 Results.....	79
6.3.1 Rainfall data	79
6.3.2 Observed Grain Yields.....	79
6.3.2.1 Grain yield on the long-term fields.....	79
6.3.2.2 Grain yield on the short-term fields	81
6.4.1 Crop parameters used in the model to simulate transpiration.....	83
6.4.2 Soil parameters used to simulate evaporation.....	84
6.6 Crop water productivity	86
6.7 Multiple regression modelling	87
6.7.1 Multiple regression modelling on the long-term clay fields.....	87
6.7.2 Multiple regression modelling on the long-term sandy fields	88
6.7.3 Multiple regression modelling on the short-term clay fields	89
6.8 Discussion.....	90
6.8.1 Grain yields.....	90
6.8.2 Crop water productivity	91

6.8.3 Multiple regression analysis	93
6.9 Conclusion	95
Chapter 7	96
General discussion, conclusions and recommendations	96
7.1 Discussion and conclusions	96
7.1.1 Cattle manure application and the soil physical environment	96
7.1.3 Use of modelling in soil water studies	98
7.1.4 Regression modelling of soil physical that most significantly affected crop yields...	99
7.2 Recommendations	100
7.3 Areas of Further Research	100

List of Tables

Table 3.1 Treatments for the long term experiment	25
Table 3.2 Selected soil properties for the long terms fields in Murewa in 2002 when the experiment was started.....	25
Table 3.3 Selected soil properties for the fields used for short term experiments in Murewa established in 2007.....	27
Table 3.4 Characteristics of the cattle manure used over the two seasons	28
Table 5.1 Steady state infiltration rates using the Kostiakov-type model	58
Table 5.2a Pore density and total effective porosity on long-term clay fields	60
Table 5.2b Pore density and total effective porosity on short-term clay fields	60
Table 5.2c Pore density and total effective porosity on long-term sandy fields.....	60
Table 5.3a Unsaturated hydraulic conductivity (K_o) , macroscopic capillary length and mean pore sizes on the clay long term fields.....	61
Table 5.3b Unsaturated hydraulic conductivity (K_o) , macroscopic capillary length and mean pore sizes on the clay short-term fields.....	62
Table 5.3c Unsaturated hydraulic conductivity (K_o) , macroscopic capillary length and mean pore sizes on the sandy long-term fields.....	62
Table 6.1 Observed maize grain yield for two seasons on the long-term fields.....	80
Table 6.2 Soybean and maize grain yields on the short-term fields during the two seasons.....	82
Table 6.3 Crop parameters used to simulate crop transpiration on both clay and sandy soils.	83
Table 6.4 Initial soil parameters used to simulate crop transpiration on clay soils.	84
Table 6.5 Initial soil parameters used to simulate crop transpiration on sandy soils.....	84
Table 6.6 Pearson's correlation coefficients and p values for soil properties and maize grain yield on the long-term clay field.....	87
Table 6.7 Principal components for the clay long-term field	88

List of figures

Figure 3.1: Map showing Ward 28 (Study area) in Murewa District, Zimbabwe	23
Figure 4.1: Soil organic carbon levels in the plough layer in clay and sandy soils	37
Figure 4.2 :Macro aggregation indices on clay and sandy soils.	39
Figure 4.3: Macro-aggregate protected carbon on clay fields	40
Figure 4.4: Regression relationships between soil organic carbon, aggregate stability and aggregate protected carbon on long-term and short-term clay fields	42
Figure 5.1: Photo showing infiltration measurements using a double ring infiltrometer and a tension infiltrometer	52
Figure 5.2: Photo showing preparation of a sand and measurement of unsaturated hydraulic conductivity	54
Figure 5.3. Moisture retention characteristics on clay and sandy soils	64
Figure 6.1: Rainfall distribution in Murewa , 2007-08 and 2008-09 seasons	79
Figure 6.2: Validation of Aquacrop.	85
Figure 6.3: Crop water productivity using actual transpiration on clay and sandy soils.	86

List of Symbols

K_o	Unsaturated hydraulic conductivity
K_{sat}	Saturated hydraulic conductivity
S_o	Sorptivity
θ_o	Volumetric moisture content at measurement potential
θ_n	Volumetric moisture content at initial potential
θ_g	Gravimetric moisture content
θ_v	Volumetric moisture content
λ_c	Macroscopic capillary length
λ_m	Microscopic capillary radii
K_c	Crop coefficient
ET_{max}	Maximum evapotranspiration
ET_o	Reference evapotranspiration
ρ_b	bulk density of soil
ρ_w	density of water

List of Acronyms

AN	Ammonium Nitrate
APC	Aggregate protected carbon
AWC	Available water capacity
BD	Bulk density
CRBD	Completely randomized block design
CWP	Crop water productivity
EF	Model efficiency
ERD	Effective rooting depth
FA	Factor analysis
FC	Field capacity
GDP	Gross Domestic Product
HF	Homefield
I.R	Steady state infiltration rates
Ima	Macro-aggregation index
MWD	Mean weight diameter
N	Nitrogen
ND	Normalized deviation
OF	Outfield
P	Phosphorus
PCA	Principal component analysis
PWP	Permanent wilting point
SOC	Soil organic carbon
SOM	Soil organic matter
SSA	Sub-Saharan Africa
WAE	Weeks after crop emergence
WSA	Water stable aggregates
WUE	Water use efficiency

Chapter 1

Introduction

1.1 Introduction and Problem Statement

Agriculture accounts for about 30 % of sub-Saharan Africa's GDP, 95 % of which is practised by resource poor smallholder farmers (Gronewald, 2009). The problem of inherent low soil fertility, low use of mineral fertilizers which are scarce and exorbitantly priced and poor agronomic practices have led to rapid decline in soil fertility (Stoorvogel *et al.*, 1993, Stoorvogel and Smaling, 1998). Household food security has therefore been on the decline and it is further exacerbated by reliance on poor and erratic rainfall. Droughts are one of the risks affecting agricultural productivity (Haile, 2005) and of increasing concern are the effects of climate change on the livelihoods of the smallholder farmers.

Rainfall in Zimbabwe is unimodal (October-May) and its distribution varies temporally and spatially. This led to classification of Zimbabwe into five agro-ecological regions (natural regions) mainly differentiated by mean annual rainfall received. Agro-ecological regions I and II receive the highest rainfall between 750-1200 mm, region III is moderate between 650-800 mm while regions IV and V receive between 450-650 mm per annum (Vincent and Thomas, 1960). Although mixed crop and livestock farming is the common farming system in Zimbabwe, crop production changes from intensive to extensive as rainfall decreases. Variations in rainfall also influences the type of crops grown in an area. For example, pearl millet (*Pennisetum glaucum* L.) constitutes about 80 % of cereals grown in the drier parts of the country (Ncube *et al.*, 2009) which is in contrast with production in the high rainfall regions where maize (*Zea mays* L.) is the major cereal crop for food security (Zingore *et al.*, 2007).

The majority of Zimbabwe's smallholder farming area soils are coarse grained granitic sands with very low soil organic matter, often below 0.3 % (Campbell *et al.*, 1994). These soils are inherently infertile (Grant, 1981), have high infiltration rates, low available water capacity (Vogel, 1992, Nyamangara *et al.*, 2001) and acidity is a major problem arising from poor buffering capacity. Pockets of relatively fertile dolerite derived red clay soils (Nyamapfene, 1991) are also found in some areas, for example in Murewa these soils constitute less than 1 % of the area (Zingore *et al.*, 2007). Therefore the contribution of the more fertile soils to improved crop production is minimal. Coupled with poor agronomic practices and poor rainfall, cultivation on marginal soils has culminated in frequent crop failure and endemic food insecurity in Zimbabwe (Ncube *et al.*, 2009).

On the other hand, farming systems in sub-Saharan Africa (SSA) have been shown to exhibit a high degree of heterogeneity determined by a complex set of socio-economic and bio-physical factors (Zingore *et al.*, 2007). Smallholder farms consist of multiple plots managed differently in terms of allocation of crops, organic and mineral fertilizers and labour resources, and this has led to creation of soil fertility gradients within and across farms. In Zimbabwe existence of soil fertility gradients across farms has been extensively documented (Chikuvire, 2000; Mapfumo and Giller, 2001; Zingore *et al.*, 2007). Similar findings have also been reported by Prudencio (1993) in Burkina Fasso, Woomer *et al.*, (1998) in Uganda, Dembele *et al.*, (2000) in central Mali, and Tittonell *et al.*, (2005) in Kenya. In most cases, both organic and mineral fertilizer resources are preferentially allocated to the part of the farm used for growing the main food security crop, often close to the homestead (homefield), whilst plots further away (outfields) are neglected. This trend is driven by many factors, such as lack of adequate inputs to apply evenly across farms, shortage of labour and concentrating

on fields that are more secure against grazing by livestock (Carter and Murwira, 1995; Chikuvire, 2000). Such management decisions culminate in creation of gradients of decreasing soil fertility with increasing distance from homestead potentially leading to greater deterioration of soil physical and chemical properties on the outfields compared to the homefields thereby presenting challenges for efficient use of nutrient resources.

Combined with mineral fertilizers or applied on its own, cattle manure plays an important role in maintenance of soil fertility and development of fertility gradients. Though low rates of 1 -3 t ha⁻¹ (Ncube *et al.*, 2009; Materechera, 2010) have been characteristically regarded as typical of smallholder farming systems, rates as high as 80 t ha⁻¹ have also been reported as arising from concentration on the preferred fields (Mugwira and Murwira, 1998). However, the quality of cattle manure from most of these smallholder farms is low, with high C:N ratios due to low quality grazing for cattle, and poor handling and storage which result in high sand content (Mugwira and Murwira, 1998). On the other hand, it has been noted that low quality organic resources are good precursors to soil organic matter (SOM) build up because of their low turn-over rates (Palm *et al.*, 1997), and hence are likely to have strong effects on SOM content (Mtambanegwe and Mapfumo, 2005).

The importance of organic matter in improving soil physical properties and processes has widely been documented (Franzluebbers, 2002; Celik *et al.*, 2004; Hati *et al.*, 2007; Chakraborty *et al.*, 2010). Soil physical properties including aggregate stability, bulk density and soil hydraulic properties have been reported as positively varying with SOC (Rose, 1991; Schjønning *et al.*, 1994; Hati *et al.*, 2006) while on the other hand cases of no relation have also been reported in other studies (Mulla *et al.*, 1992). Variability of response of SOC and soil physical properties though not always clearly defined (Darwish *et al.*, 1995) can be

attributed to various factors such as the texture of the soil. Improvement of physical properties by organic matter positively affects the germination of seeds, growth and development of plant roots and shoots (Van Noordwijk *et al.*, 1993). In turn enhanced root proliferation has a positive influence on aggregate formation further improving the soil's structure (Tisdall, 1994).

Adoption of integrated soil fertility management strategies offers opportunities to restore depleted soil fertility (Zingore *et al.*, 2008). Although several studies have assessed the impact of farmer-induced soil spatial variability on nutrient uptake and consequently plant growth (Murage *et al.*, 2000; Mapfumo and Giller, 2001 and Zingore *et al.*, 2008) there have not been any studies that assessed the effect of the spatial variability on soil physical properties and plant growth in Zimbabwe. This study therefore aims to assess the implications of soil fertility management practices on soil physical fertility, and the interacting effects of soil physical factors and hydraulic properties on water use efficiency (WUE) and crop productivity.

1.2 Hypotheses

1. Different cattle manure rates combined with inorganic fertilizer lead to varying SOC, bulk density, aggregate stability and aggregate protected carbon levels within a field type in the long-term (6 years) and not short-term (2 years).
2. Soil hydraulic conductivity, steady state infiltration rate and porosity improve with increasing manure application rates over time and there are no differences between homefields and outfields in the long-term.

3. There are no differences in crop yields from homefields and outfields receiving the same cattle manure rates and inorganic fertilizers in the long term.
4. Manure application at $25 \text{ t ha}^{-1} \text{ yr}^{-1}$ results in increased crop water use efficiency or water productivity over no manure application on both homefields and outfields.
5. Soil organic carbon, macro-aggregation indices, aggregate protected carbon, bulk density, steady state infiltration rates, total effective porosity and unsaturated hydraulic conductivity can be used to predict crop yields on short-term and long-term fields.

1.3 Overall objective

To determine the effects of manure and mineral fertilizer application rates on soil physical properties, water use efficiency, and to quantify the extent to which soil physical constraints limit crop productivity under variable soil fertility conditions.

1.3.1 Specific Objectives

1. To determine the effects of combined cattle manure and inorganic fertilizer application rates on soil organic carbon, bulk density, aggregate stability and aggregate protected carbon on differently managed fields (homefields and outfields) in the short and long term.
2. To determine the effects of combined cattle manure and inorganic fertilizer application rates on soil hydraulic properties (hydraulic conductivity, steady state infiltration rate) and porosity on differently managed fields (homefields and outfields) in the short and long term.
3. To determine the effects of combined cattle manure and inorganic fertilizer application rates on crop yields.

4. To determine the effects of combined cattle manure and inorganic fertilizer application on crop water use efficiency/ water productivity on homefields and outfields in the long term through the use of a water balance model.
5. To select measured soil physical and hydraulic properties that have the most significant effect on crop yields under combined cattle manure and inorganic fertilizer application.

1.4 Thesis structure

This thesis consists of seven chapters. The first chapter is an introduction which gives a general overview of the soil fertility management practices in smallholder farming areas and the challenges they pose on soil physical fertility and ultimately overall crop productivity. It also gives the rationale, hypotheses and objectives of the study. An overview of the general literature on soil physical properties and soil water studies is given in Chapter 2. Chapter 3 gives the general methodology: description of the study sites, experimental setup and general management of the experimental fields. Specific field and laboratory methods are detailed in their relevant result chapters. Chapter 4 addresses objective 1 and gives the findings on the effects of the soil fertility management practices on soil physical properties in the short- and long-term. An assessment of the effects of soil fertility management practices on soil hydraulic properties (objective 2) is given in Chapter 5. Chapter 6 presents results on the effects of combined cattle manure and inorganic fertilizers on maize yields (objective 3) and the resulting crop water productivities using a water balance model (objective 4). Results from the regression analysis to select soil physical and hydraulic parameters most significantly affecting crop yields are also presented in Chapter 6. Chapter 7 gives the general discussion, recommendations and conclusion synthesized from the result chapters.

Chapter 2

Literature review

2.1 Soil organic matter, organic resources and effects on soil physical properties

The preservation of soil organic matter (SOM) is a key factor in land use systems since SOM is widely recognized as a key component in nutrient cycling (Bossuyt *et al.*, 2005). With rising atmospheric CO₂ and global warming, retention of organic C in soil is becoming more important (Schlesinger, 1997). SOM is one of the most important indicators of soil quality as it has the greatest influence on soil chemical, physical and biological properties (Larson and Pierce, 1994). It has an influence on soil physical properties as it improves soil aggregation (Hati *et al.*, 2007). Maintenance of good soil physical properties therefore depends strongly on good management of SOM.

Animal manure is an important nutrient resource in the mixed crop-livestock farming systems that are characteristic of Southern Africa. It has been shown in several studies that animal manure increases crop yields considerably (Probert *et al.*, 1995; Murwira *et al.*, 1995). Other benefits of manure include increase in soil pH, water holding capacity, hydraulic conductivity (Wilcocks and Cornish, 1988; Nyamangara *et al.*, 2001), infiltration rates and decreased bulk density (Alegre and Rao, 1996). These effects can persist for several years following manure application (Gilley and Risse, 2000; Wortmann and Walters, 2006). Mbagwu and Bazzoffi (1989) reported that organic carbon could account for about 70-90% of the variability of soil aggregates of a clay loam soil while Hudson (1994) reported that soils high in SOM have greater available water holding capacity than soils of similar texture with less SOM.

The availability of and access to manure in smallholder farming areas is closely related to cattle ownership (Mugwira and Murwira, 1997). Several recommendations on manure application rates have been made in Zimbabwe, Alvord recommended addition of 37 t ha⁻¹ to the maize crop in a 4-year crop rotation (Mugwira and Shumba, 1986) while Avila (1987) recommended 12 t ha⁻¹ for a significant effect on maize yield. Despite these recommendations average cattle manure application rates have remained low between 1 to 5 t ha⁻¹ yr⁻¹ (Ncube *et al.*, 2009). The average number of livestock heads owned by the medium resourced farming group in the wetter part of Zimbabwe was reported to be 2 to 9 in Murewa (Zingore *et al.*, 2007) while for the same resource group in the drier parts of Tsholotsho it was reported to be at least 2 livestock heads (Ncube *et al.*, 2009). Based on the assumption that average manure production per livestock unit is equivalent to 1.5 t yr⁻¹ (Rodel *et al.*, 1980) farmers in drier parts of the country have access to at least 3 t yr⁻¹ while those in wetter areas have between 3 to 13.5 t yr⁻¹ with some of the manure not directly usable as the dung is deposited in the grazing areas (Mugwira and Murwira, 1997). It is therefore imperative to devise ways of efficiently using the limited manure resources for significant improvements to be realised in crop productivity.

There are several other organic resources for improving soil fertility besides cattle manure. These include agroforestry technologies, such as improved fallows with fast growing leguminous trees and cover crops. They function by fixing nitrogen from the atmosphere to the soil, biomass transfer from nutrient mobilizing plants such as *Tithonia diversifolia* (Jama and Pizarro, 2008), compost and crop residues. Leguminous tree technologies help improve soil fertility, increase yields, control weeds and provide fodder and firewood (Chikowo, 2004; Nyamadzawo, 2004). In the same way as with manure, the use of agroforestry and

other organic fertilizers would still require the use of mineral fertilizers especially P and N (Jama and Pizarro, 2008).

2.2 Soil fertility studies

Manure is often applied to specific crops or preferentially to fields closer to the homestead (HFs), while fields further away from the homestead (OFs) often receive no organic amendments and little mineral fertilizer (Mapfumo and Giller, 2001). This preferential allocation of manure to HFs is driven by lack of adequate inputs and labour to apply evenly across the farms and security of HFs against grazing by livestock. Consequently, continuous concentration of nutrient resources in the smaller areas around the homestead at the expense of nutrient depletion in larger fields further away culminates in strong gradients of decreasing soil fertility with increasing distance from the homestead (Prudencio, 1993; Tittonell *et al.*, 2005). Mapfumo and Giller (2001) and Zingore *et al.* (2007) reported existence of soil fertility gradients across smallholder farms in Zimbabwe. Soil fertility gradients were also reported in other parts of Africa (Prudencio, 1993; Woomer *et al.*, 1998 and Tittonell *et al.*, 2005) leading to the classification of fields as either HFs (fields closest to homesteads and typically more fertile) or OFs (fields further away and less fertile), although cases of higher fertility in OFs compared to HFs have also been reported (Haileslassie *et al.*, 2007).

The fertility variability between fields is large enough to strongly affect crop response to applied nutrients (Mtambanengwe and Mapfumo, 2005; Zingore *et al.*, 2008). Several studies have assessed the impact of farmer-induced soil spatial variability on nutrient uptake and consequent plant growth (Prudencio, 1993; Zingore *et al.*, 2008), but there have been few studies that have assessed the effect of the spatial variability on soil physical properties and plant growth. Therefore, this study seeks to complement these studies through investigating

the effects of combined manure and inorganic fertilizer application on soil physical and hydraulic properties of HFs and OFs.

2.3 Aggregate stability and formation dynamics

The breakdown of soil aggregates and attendant poor soil structural conditions often restrict crop root growth and consequently limit their ability to explore the soil profile for water and nutrients (Haynes and Naidoo, 1998). Furthermore, a degraded soil structure is often poorly perforated such that infiltration is inhibited while surface runoff and nutrient loss is frequently high. This leads to poor crop growth due to restricted root penetration, nutrient deficiencies and water stress.

Aggregation determines organic C stabilization and it is imperative to understand the mechanisms of carbon protection within the aggregates as well as aggregate formation dynamics. An aggregation hierarchy concept proposed by Tisdall and Oades (1982) forms the most significant advancement in the understanding of aggregate-SOM interactions (Six *et al.*, 2004). Tisdall and Oades (1982) explicitly described micro-aggregates as being first formed free and then serving as building blocks for the formation of macro-aggregates. Oades (1984) postulated that the plant roots and hyphae act as temporary binding agents holding together the macro-aggregates and later form the nucleus of micro-aggregation formation within the macro-aggregates. Six *et al.*, (2004) reported that a hierarchal order of aggregates exists in the soil where SOM is the major binding agent. Micro-aggregates are formed within macro-aggregates and that SOM is predominantly stabilized in stable micro-aggregates and therefore, changes in the rate of macro-aggregation turn-over influence SOM stabilization across soil types and disturbance regimes. Thus, SOM can be improved through management

strategies that minimize aggregate breakdown and through the addition of organic residues that act as binding agents in the aggregate formation process.

Aggregate stability is an important parameter used to quantify or predict changes in soil properties with respect to soil and water erosion (Zhang and Horn, 2001). The susceptibility of soil to erosion is linked to aggregate stability which basically characterizes resistance to soil breakdown (Barthes *et al.*, 1999). Aggregate breakdown leads to superficial crusting, reduced infiltration, increased run-off and soil erosion (Levy and Miller, 1997).

Many different methods exist for measuring aggregate stability. The most commonly used include Yoder (1936), Kemper and Rosenau (1986) and Le Bissonnais (1996). Using different methods helps to give information about the stability of aggregates to different forces and the breakdown mechanisms, which is an indicator of the soil's susceptibility to erosion (Barthes and Roose, 1996).

2.4 Infiltration rates and soil porosity

The quantity, size, shape and continuity of soil pores are used to characterize soil structure. Soil pores influence the ability of soils to support plant, animal and microbial life. Soil pores retain water, allow drainage, allow entry of oxygen and removal of carbon dioxide. Soils pores are also indirectly responsible for modifying the mechanical properties of soils so that cultivation can be carried out successfully (Scott, 2000).

Luxmoore (1981) arbitrarily classified pore sizes into three groups. He defined macropores as those greater than 1000 μm and also as those that empty at tension greater than 15 cm of water. Macropores allow rapid drainage of water after heavy rainfall or irrigation. The size and distribution of macropores usually bear no relation to the particle size distribution and the

related micropore distribution (Scott, 2000). Mesopores were defined as ranging between 10-1000 μm . Luxmoore (1981) further defined micropores as those less than 10 μm which hold water tightly, some of which is available for plant use. In contrast to macropores, micropores closely correspond to the solid phase of the soil. They dominate total porosity of most fine-textured soils (Scott, 2000). Therefore, a good soil should have many mean pore sized pores which also allow infiltration and water retention.

Several models have been used to estimate infiltration, among them the Kostiakov model (Kostiakov, 1932), the Horton-type equation (Morin and Benjamin, 1977) to give approximate descriptions of one-dimensional water infiltration. Infiltration rates and hydraulic conductivities have been measured using double ring infiltrometers (Bouwer, 1986), single rings, tension infiltrometers (White and Sully, 1987) and rainfall simulators (Nyamadzawo, 2004). According to Bouwer (1986), single rings overestimate infiltration rates due to lateral divergence resulting from capillarity of unsaturated flow of ponded water in the ring while the use of double rings has been recommended as they create a buffer zone (Swartenrubler and Olson, 1961) and so reduce lateral flow of water. On the other hand, rainfall simulators have the advantage of simulating actual rainfall events although their major disadvantages are that they are expensive and tend to result in overestimation of soil and nutrient losses (Wauchope and Burgon, 1993) due to use of small plots (i.e. 1 m^2). Tension infiltrometers, on the other hand, allow for rapid measurement of hydraulic conductivity (K_o), sorptivity (S_o), macroscopic capillary length and mean pore sizes and have been used by many researchers including Moore *et al.*, (1986) and Wilson and Luxmoore (1988). Tension infiltrometers have been used to overcome the limitations of the double rings (White *et al.*, 1992) as they allow conductance of water through selected pores at a given tension while with double rings all pores conduct water (saturated water flow).

2.5 Soil water studies

Cropping in Zimbabwe is largely rain-fed and efficient utilization of rainfall is important to improve yields (Nyagumbo, 2002). Utilization of rainfall to improve availability to crops can be achieved through cultural practices that minimize runoff, increase infiltration, reduce surface evaporation and enhance availability of soil water to crops. This section explores issues that influence soil water balances and soil water productivity.

2.5.1 Water use efficiency (WUE)

Efficient and sustainable agriculture depends on proper management of water and plant nutrients (Hatfield *et al.*, 2001). Different definitions of WUE have been used in research depending on the objective. From an agronomic point of view WUE can refer to yield (biological, photosynthetic or economic) per unit of water used, while to an agricultural engineer it refers to the ratio of water stored in the root zone to that delivered for irrigation (Kijne *et al.*, 2002).

Increasing water storage within the soil profile is necessary to increase plant available water (Hatfield *et al.*, 2001). This can be achieved by tillage which roughens the soil surface and breaks apart any soil crust thus increasing infiltration as well as reducing soil water evaporation. Maintenance of crop canopy cover also plays a role in water conservation by reducing erosion and protecting soil surface from aggregate breakdown and compaction by raindrop impact (Bennie and Woyessa, 2004). The effect of tillage on water infiltration is considered positive although some results by Burns *et al.*, (1971) and Papendick *et al.*, (1973)

suggested that excessive tillage may reduce infiltration because of its negative effect on hydraulic conductivity.

Soil management practices that increase soil water holding capacity improve the ability of roots to extract more water from the soil profile, therefore they have potentially positive impacts on WUE. Organic matter content of the soil has been shown to play a central role in water availability and Hudson (1994) showed that over a wide range of soils there is an increase in water availability with increase in SOM.

2.5.2 The Concept of Crop Water Productivity

The concept of crop water productivity (CWP) has been developed in the search for measures to improve WUE in an environment of increasing water scarcity (Magodo, 2007). In physical terms CWP refers to the ratio of the product, which is usually the weight biomass of harvestable component (fresh or dry) to that amount of water depleted or applied (Kijne *et al.*, 2002). Assessment of how agricultural water is converted to beneficial output is important particularly in SSA where water availability is a major constraint to rain fed crop production.

Numerous studies have been conducted on the various aspects of crop yield to water relations (de Wit, 1958; Doreenbos and Pruit, 1977; Zhang *et al.*, 2003). In these studies, choice of the numerators have ranged from value or amount of grain yield to above ground or total biomass yield and the denominator ranging from value or amount of water input to water consumed (Kijne *et al.*, 2003). Since crop productivity is governed by transpiration it is sensible to express CWP in terms of cumulative transpiration (Hillel, 1982) or cumulative evapotranspiration. Most studies have used actual evapotranspiration (Zwart and Bastiaansen,

2004) because transpiration is difficult to measure at field scale (Kijne *et al.*, 2002) and also because transpiration and evapotranspiration are strongly correlated particularly after complete canopy formation. According to Igbadun *et al.*, (2006), CWP varied between 0.4-0.7 kg m⁻³ grain yield in terms of seasonal evapotranspiration for three maize cultivars under irrigated conditions in Tanzania and around the world maize (grain yield) CWP has been reported to range between 0.3-2.7 kg m⁻³ (Bastiaanssen. *et al.*, 2003).

2.5.3 Simple Soil Water Balance Methods

Soil water balance refers to the various pathways through which water is gained or lost from the soil profile. According to Raes (2002), the root zone is regarded as a single reservoir with incoming and outgoing fluxes and therefore water fluctuates over time. Rainfall, irrigation, and capillary rise add to the root zone while evaporation, crop transpiration, surface runoff and deep percolation losses remove water from the root zone. Marshall (1959) suggested a water balance equation:

$$ET = P - D - R \pm \Delta S \quad (2.1)$$

Where ET= evapotranspiration, P = precipitation, D = deep percolation, R = runoff and ΔS = changes in soil water content.

In situations where runoff can be assumed to be negligible, equation 2.1 reduces to equation 2.2

$$ET = P - D \pm \Delta S \quad (2.2)$$

And where both runoff and drainage are assumed to be negligible it further reduces to equation 2.3

$$ET = P \pm \Delta S \quad (2.3)$$

2.5.4 Soil Water Based Models

The reliable simulation of soil evaporation, transpiration, root water uptake and soil water content is without doubt one of the most crucial points in any water balance model under cropped conditions. Given the problems associated with measuring the various components of the field water balance, simulation modeling offers an opportunity to better understand water balance processes that are otherwise difficult to measure (Cassa *et al.*, 2000). Most models, however, suffer from limitations to their applicability due to variation in soil characteristics, spatial and temporal climatic conditions and unavailability of data to input into the models. It is therefore important to calibrate and validate models before they can be used.

2.5.4.1 The Parch-Thirst Model

The Parched-Thirst model (Young and Gowing, 1996) uses equation 2.2 and has been used by van der Meer *et al.*, (1998) to estimate crop transpiration, soil evaporation and drainage. Assuming drainage to be occurring only when outgoing flux exceeded maximum evapotranspiration (ET_{max}) and potential evaporation from a bare soil or sparse canopy estimated from a pan-factor of 0.7, the method yielded weekly estimates of evaporation and drainage successfully which are considered too crude to adequately describe the rapid water dynamics and furthermore it overestimates evapotranspiration (Nyagumbo, 2002).

2.5.4.2 The BUDGET Model

The BUDGET model is a water balance model that determines water storage and salt content in the profile by keeping track of the incoming and outgoing water fluxes within the root zone boundaries on a daily basis (Wiyo, 1999). It consists of several sub-models, which describe

the various processes of one dimensional vertical water movement and soil water uptake in a free draining soil (Raes, 2002).

However, its major limitation is that capillary rise is ignored and it is not suitable for swelling or cracking soils because these do not wet from surface down. The BUDGET model was satisfactorily used by Magodo (2007) to analyse water productivity of 3 maize cultivars at the Agriculture Research Trust (ART) farm in Zimbabwe.

2.5.4.3 AquaCrop Model

AquaCrop is FAO's crop water productivity model resulting from the revision of FAO irrigation and drainage (Doorenbos and Kassam, 1979). The model estimates the effect of water deficiency on crop yield by computing daily soil water balance. The effects of soil water and atmospheric stress on yield are evaluated and expressed as percentage yield. Yield is calculated on the basis of water stress that occurs during each critical stage of development using K_y factor (Doorenbos and Kassam, 1979).

$$1-(Y_a/Y_m)= K_y(1-ET_a/ET_c) \quad (2.4)$$

Where Y_a = actual crop yield

Y_m = maximum expected or potential yield

ET_c = crop evapotranspiration under standard conditions

K_y = yield response factor

ET_a = crop evapotranspiration as adjusted to actual conditions under which it occurs

2.5.5 Advantages of using AquaCrop

AquaCrop was chosen to simulate actual crop transpiration in this study because it requires a significantly smaller number of parameters, for example only 5 weather parameters, which are daily maximum and minimum air temperature, daily rainfall, daily evaporative demand of the atmosphere (ET_o) and the mean carbon dioxide concentration in the atmosphere are required for the atmosphere module. This requisite climatic data for the study sites was easily available. Further, AquaCrop has the advantage of including some management aspects such as fertilizer, irrigation which affect soil water balance, crop development and final yield (Steduto *et al.*, 2008).

2.6. Key Components of AquaCrop Model

2.6.1 The atmosphere module

Five weather input parameters are required to run AquaCrop. These include daily maximum and minimum air temperature, daily rainfall, daily evaporative demand of the atmosphere (ET_o) and the mean carbon dioxide concentration in the atmosphere. The first four are derived from typical meteorological stations, but CO_2 concentration uses the Mauna Loa Observatory record in Hawaii (Steduto *et al.*, 2008). The ET_o is calculated using procedures described in the FAO Paper No.56 (Allen *et al.*, 1998). Also included in the model is a software program (Raes *et al.*, 2008) for ET_o calculation based on the FAO Penman-Monteith equation.

2.6.2 The crop module

In AquaCrop, the crop system has 5 major components and associated dynamic responses namely, phenology, aerial canopy, rooting depth, biomass production and harvestable yield. Different responses occur during water stress through major feedbacks: reduction of canopy expansion (typically during initial growth), closure of stomata (typically during completed growth) and acceleration of senescence. The canopy represents the source for actual transpiration that gets translated with a proportional amount of biomass produced through the water productivity equation:

$$B = WP \cdot \Sigma Ta \quad (2.5)$$

Where B is biomass (kg/m^2), Ta is the crop transpiration (mm) and WP is water productivity parameter ($\text{kg biomass/m}^2/\text{mm}$ of cumulated water transpired over the period in which the biomass is produced) (Steduto *et al.*, 2008). The harvestable portion of such biomass (yield) is then determined via the HI equation:

$$Y = B \cdot HI \quad (2.6)$$

Where, Y is the final yield, B is biomass and HI is the harvest index.

In AquaCrop biomass production is decoupled from canopy expansion and root deepening and so AquaCrop avoids dealing with the complexity and uncertainties associated with the partitioning process which remains among the least understood and most difficult to model (Steduto *et al.*, 2008).

The root system is simulated through its effective rooting depth (ERD) and its water extraction pattern. The ERD is defined as the soil depth where most of the root water uptake is taking place and 90-95 % of the water uptake is considered to be taken up within the ERD in AquaCrop (Steduto *et al.*, 2008).

2.6.1.3 The soil module

The soil component of AquaCrop is configured as a dispersed system of variable depth allowing up to five layers of different texture composition along the profile. For each texture class, the model associates a few hydraulic characteristic and it estimates them for the texture entered by the user through pedotransfer functions (Steduto *et al.*, 2008). Alternatively, the user can input specific values for the textural classes and also specific hydraulic characteristics including drainage coefficient (τ), hydraulic conductivity at saturation (K_{sat}), volumetric water content at saturation, field capacity and permanent wilting point. It further performs a water balance that includes the processes of run-off (through curve number), infiltration, redistribution or internal drainage, deep percolation, capillary rise, uptake, evaporation and transpiration (Raes *et al.*, 2008).

2.6.1.4 The Management module

The management component is divided into two categories, the field and water management. Field management in AquaCrop considers options related to the fertility level or regime to be adopted during crop simulation, and to field surface practices, for example mulching, soil bunds etc. Three fertility levels are considered, non-limiting, medium and poor fertility. These levels influence WP, the canopy growth cover (CGC), maximum canopy cover (CCx) and the rate of decline in green canopy during senescence. Water management considers options related to rainfed agriculture or irrigation type which can be user defined (Steduto *et al.*, 2008).

2.7 Studies on physical properties and crop productivity

Several studies have been carried out, and they basically addressed issues of soil fertility management practices on the soil physical environment. Wilcocks and Cornish (1988), Nyamangara *et al.*, (2001) reported improvement on soil pH, water holding capacity, hydraulic conductivity with manure addition. Increased infiltration rates, improved aggregation, soil porosity and decreasing bulk density with long term continuous manure application have been reported in literature (Rose, 1991; Hati *et al.*, 2007). However, in as much as a lot has been done in studying the physical environment, little has been done in terms of relating the effects of physical properties to crop productivity. Multiple regression can be used to quantify the extent to which several independent variables influence one dependent variable (Mead and Curnow, 1986). Therefore use of this approach offers opportunities to analyse effects of soil physical properties on crop productivity.

Chapter 3

General Materials and Methods

3.1 Site description

The study was conducted in the Darare and Manjonjo villages (Ward 28) of Murewa (17°39 S and 31°47 E) smallholder farming area which lies 80 km east of Harare (Figure 3.1). Murewa is located in agro-ecological zone II (Natural region II) with a subtropical climate and receives between 750-1000 mm rainfall annually in a unimodal pattern (October- April). However, the amount received varies between years and also within the season, spatial and temporal variations are not an uncommon feature. The area is characterized by mainly two soil types, namely the dominant lxisols (Nyamapfene, 1991) which are derived from granitic rocks and are inherently infertile, and luvisols derived from dolerite. Nyamapfene (1991) described the luvisols as the best agricultural soils in Zimbabwe.

The farming system consists of mixed crop-livestock production and there is close interaction between the crops and livestock. Livestock provide draft power to enable timely cropping and manure for soil fertility improvement while crop residues provide feed for livestock which is key during the dry season when natural grazing is scarce and of low quality. Maize (*Zea mays* L.) is grown as the staple crop and is allocated the main farming area. Other crops including groundnut (*Arachis hypogaea* L.), sweet potato (*Ipomaea batatas* L.), sunflower (*Helianthus annus* L.) are grown either in rotation with maize or as intercrops. Cattle constitute the main livestock although some farmers may also possess goats and donkeys.

Weed control is largely achieved through ploughing of fields during land preparation and also through hand weeding after crop emergence. Conventional mould-board ploughing is the main tillage practice, ox-drawn ploughs are used to plough to 10-20 cm depth before planting and in some cases as cultivators with their mouldboards removed for weed control and to create ridges for moisture conservation.

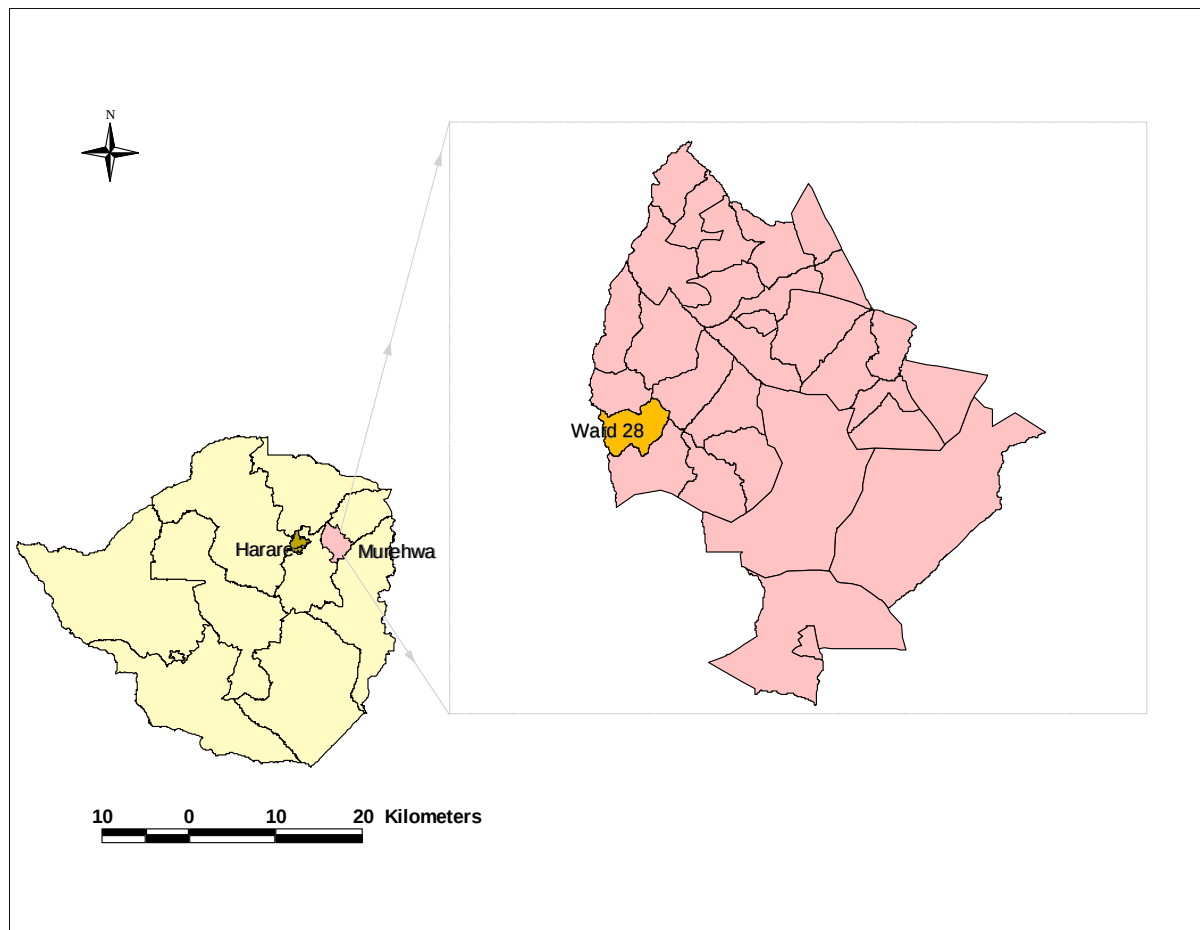


Figure 3.1: Map showing Ward 28 (Study area) in Murewa District, Zimbabwe

3.2 Selection and characteristics of experimental sites

Selection of sites was based on initial work of Zingore (2006) that established the existence of large variability of soil fertility between different fields on the same farm, and on different farms. Farmers were involved in the demarcation of fields into different plot types in accordance to what they (farmers) considered as their best, average and worst plots which

was achieved by classifying the different plots in terms of (i) distance from homestead, (ii) perception of soil fertility status and yield potential and (iii) resource allocation trends.

The main experiment (experiment 1) was established on two such farms, one on the sandy and the other on the clay soils representative of the dominant soil types in the area. On each of these two farms, a field closest to the homestead (< 50 m) and another at some distance (100-500 m) were selected to provide fields representative of typical homefields and outfields in the area. In the current study, fields which were subjected to similar management (Table 3.1) for 6 consecutive years were regarded as long-term experiments and used in determination of the effects of soil fertility management practices on soil physical properties including SOC, bulk density, aggregate stability, aggregate protected carbon and soil hydraulic properties in the long-term. Another experiment (experiment 2) consisting of four fields representing homefields and outfields on the two soil types was established in 2007. This experiment was used to determine the effects of fertility management on soil physical and hydraulic properties in the short-term (2 years). However, for the short term experiment, the sandy fields did not exhibit clear cut differences of homefields and outfields as the farmer had already established his crop on what he considered his best plot. Therefore, he offered the use of what he considered 'average' fertility plot to represent the homefield although chemical indices such as SOC, N and pH measured showed that the two plots were actually both outfields.

3.2.1 Experiment 1: Long term soil fertility experiments in Murewa

The experiment is an on-going fertility experiment that was established in 2002 by Zingore (2006) on two farms of contrasting soil types, one on the sandy and the other on the clay soils representative of the dominant soil types in the area. Fields representative of homefields and

outfields were used. Initial soil characterization was done on these fields (Table 3.2). Field layout followed a completely randomized block design (CRBD) with three replications and the plots measuring 6 X 4.5 m² were subjected to 9 treatments shown in Table 3.1. The objective was to investigate maize crop response to N, Ca, Zn and P from mineral fertilizer and cattle manure after 3 years of consecutive annual application. This study was anchored on this on-going experiment to determine the effects of soil amendments with cattle manure (control, 100 kg ha⁻¹ N + 5, 15 and 25 t ha⁻¹ manure) on soil physical and hydraulic properties of HFs and OFs after 5 and 6 years of similar management.

Table 3. 1 Treatments for the long term experiment

Treatment	Manure and mineral fertiliser application rates
1	Control (no amendment added)
2	100 kg N ha ⁻¹
3	100 kg N ha ⁻¹ + 30 kg P ha ⁻¹ (i.e. 15 tons manure ha ⁻¹)
4	100 kg N ha ⁻¹ + 10 kg P ha ⁻¹ (i.e. 5 tons manure ha ⁻¹)
5	100 kg N ha ⁻¹ + 10 kg P ha ⁻¹ (SSP) + 20 kg Ca ha ⁻¹ + 5 kg Zn ha ⁻¹ + 10 kg Mn ha ⁻¹
6	100 kg N ha ⁻¹ + 30 kg P ha ⁻¹ (SSP) + 20 kg Ca ha ⁻¹ + 5 kg Zn ha ⁻¹ + 10 kg Mn ha ⁻¹
7	100 kg N ha ⁻¹ + 50 kg P ha ⁻¹ (SSP) + 20 kg Ca ha ⁻¹ + 5 kg Zn ha ⁻¹ + 10 kg Mn ha ⁻¹
8	100 kg N ha ⁻¹ + 50 kg P ha ⁻¹ (i.e. 25 tons manure ha ⁻¹)
9	100 kg N ha ⁻¹ + 500 kg lime ha ⁻¹

Table 3. 2 Selected soil properties for the long terms fields in Murewa in 2002 when the experiment was started. Soil sampled from 0-20 cm depth.

	Sand %	Silt %	Clay %	C %	N %
Sandy homefield	85	2	13	0.5	0.04
Sandy outfield	88	4	8	0.3	0.03
Clayey homefield	46	15	39	1.4	0.08
Clayey outfield	42	14	44	0.7	0.05

Source- Zingore (2006)

3.2.2 Experiment 2: Short term fertility experiments in Murewa

Experiment 2 was established in November 2007. The objective was to determine the effects of cattle manure and inorganic fertilizer application on the physical and hydraulic properties of HFs and OFs after 2 years. In this study's context, 2 years was regarded as short-term. It consisted of four fields, 2 HFs and 2 OFs on two soil types. Prior to planting, soil samples were randomly collected from the new fields (0-15 cm) for characterization of parameters that included texture, pH, OC, total N, available P (Olsen), cation exchange capacity using standard methods (Anderson *et al.*, 1993). Soil characterisation data is shown in Table 3.3.

The experimental design followed a completely randomised block design (CRBD), replicated three times on plots measuring 5 x 4.5 m². The two main factors were manure application rate (fertility treatment) and field type. Manure was applied at 5, 10, 15 and 20 t ha⁻¹yr⁻¹ + N, P, K, Ca, Mg, and Zn & B at rates 100, 30, 29, 20, 10, and 5 kg ha⁻¹ B respectively. The manure rates were intentionally selected to differ from the 6 year experiment manure rates to achieve uniform increments which were both below and above the recommended 10 to 12 t ha⁻¹ in Zimbabwe (Mugwira and Shumba, 1986; Avila, 1987). In addition, basal fertilizer and micro-nutrient application was included to facilitate improved crop growth. The fields were subjected to a soybean-maize rotation over two seasons. Soybeans were fertilized as the maize treatments except for N which was added at 40 kg ha⁻¹.

Table 3. 3 Selected soil properties (0-15 cm) for the fields used for short term experiments in Murewa established in 2007.

	pH (CaCl ₂)	Sand (%)	Silt (%)	Clay (%)	OC (%)	Total N (%)	C:N ratio	Total P (mg/kg)	CEC (cmol _c /kg)
Sandy HF	5.0	88.5	5.2	6.3	0.69	0.09	7.6	313.0	6.5
Sandy OF	5.2	89.0	3.2	7.8	0.60	0.09	6.7	475.5	7.0
Clayey HF	5.1	47.0	27.1	25.9	1.80	0.18	10.0	250.0	25.9
Clayey OF	4.7	31.0	37.9	31.1	1.11	0.13	8.5	238.0	30.9

Note: HF = homefield, OF = outfield

3.3 General Management of the Experimental Fields

Maize variety SC 525 and Safari soybean varieties were planted on the experimental sites. Land was first prepared by conventional ploughing using ox-drawn ploughs. Maize plant population of 44 444 plants/ ha was used at 0.9 m x 0.25 m inter- and intra- row spacing while soybean plant population was targeted at 444 000 plants/ha at 0.45 m inter-row spacing respectively. Manure was broadcast first and then incorporated into the soil to between 0-10 cm depth using hoes. Samples of the manure used were obtained by randomly taking 10 sub-samples using a hoe from the cattle manure heaps, homogenously mixing them and getting a representative sample. The representative samples were taken to the laboratory for N, P, OC, sand and ash determination (Table 3.4). At sowing a basal fertilizer compound D (N; P₂O₅; K₂O: 7; 14; 7) was applied to the short term fields at the rates described in section 3.2.2. Ammonium nitrate (AN, 34.5 % N) fertilizer was split applied as top dressing at 3 and 6 weeks after crop emergence (WAE) for maize. Weed control was done manually using hand hoes just before fertilizer top dressing (AN).

Table 3. 4 Characteristics of the cattle manure used over the two seasons

Season applied	% OC	% ash	% sand	% P	% N
2007/2008	43	26	32	0.148	1.73
2008/2009	44	36	20	0.133	1.92

3.4 Soil sampling for field characterisation

The soil samples for field characterization were obtained in all fields prior to planting in the 1st season. Ten sub-samples were randomly sampled from each block and thoroughly mixed to obtain a representative composite sample. Therefore, 3 composite samples were obtained per field. The soil samples were then air-dried, and sieved to pass through a 2 mm sieve before the analyses could be carried out.

3.4.1 Soil pH

Soil pH was determined using calcium chloride (CaCl_2). Soil and 0.01 M CaCl_2 were mixed in the ratio 1:5 and the mixture was shaken using a mechanical shaker for 30 minutes. After shaking the mixture was allowed to settle and pH measured from the supernatant suspension using a pH meter standardised at pH 4.0 and pH 7.0 (Anderson and Ingram, 1993).

3.4.2 Soil texture

Air-dried soil (40 g) passed through a 2 mm sieve was weighed into a beaker and 100 ml of 5 % sodium hexametaphosphate added together with 500 ml of distilled water to bring the mixture to the mark. The mixture was shaken on a mechanical shaker overnight to achieve chemical dispersion. The mixture was then transferred to a 1000 ml cylinder and distilled

water added to bring the volume to the mark. The solution was mixed by inverting the cylinder carefully 10 times after which a hydrometer was carefully inserted exactly four and half minutes later. A hydrometer reading was taken exactly 5 minutes later to obtain the density of clay and silt ($< 20 \mu\text{m}$ diameter) in suspension. After 2 hours another reading reflecting the density of clay only was obtained (silt had settled). Each time readings were taken, the temperature of the suspension was noted. Percent silt and clay in the soil were then calculated using the initial amount of soil and by adjusting for temperature (Okalebo *et al.*, 2002). Percent sand was calculated as the difference between 100 and the total percentage sum of silt + clay.

3.4.3 Soil organic carbon

Organic carbon was determined using the modified Walkley-Black method (Houba *et al.*, 1989). One gram of previously air-dried soil sieved through a 0.5 mm sieve was added to a conical flask, oxidized using potassium dichromate, sulphuric acid and external heating applied for 1 hour to achieve maximum oxidation. The mixture was then titrated against ferrous ammonium sulphate using diphenylamine indicator which changed colour from black through purple and then blue-green at the end point.

3.4.4 Total N and P determination

The digestion of the soil samples (0.5 g) was based on a Kjeldhal digestion of the material to leave a sulphuric acid solution (Okalebo *et al.*, 2002). The digestion mixture was made up of selenium powder as a catalyst, lithium sulphate, hydrogen peroxide and concentrated sulphuric acid. The mixture was digested in a block digester at 360°C until the solution was colourless after which it was removed from the digester and allowed to cool. The solution was diluted with 25 ml distilled water and allowed to cool. The volume was made up to the

100 ml mark with distilled water and the solution allowed to settle in order to obtain aliquots for colorimetric determination of N and P using a spectrophotometer.

3.4.5 Cation exchange capacity determination

Ammonium acetate solution (100 ml, at pH 7) was added to 5 g of air-dried soil and the mixture shaken for 1 hour before it was filtered. The residue on the filter paper was washed with absolute alcohol and transferred to a Kjeldhal flask. Distilled water, sodium chloride (NaCl), antifoam mixture, 1 N sodium hydroxide (NaOH), a few anti-bumping granules and a small amount of zinc filings were added. After shaking these together and allowing mixture to settle, the suspension was distilled into CO₂ free 5 N HCl in a conical flask which contained methyl red indicator. Distillation was continued until the indicator changed from pink to green. The CEC of the soil was calculated using back titration (Summer and Miller, 1996).

Chapter 4

Effects of Soil Fertility Management Practices on Selected Soil Physical Properties of Two Contrasting Soils in Murewa Smallholder Farming Area

4.1 Introduction

Manure is often credited with improving soil physical properties with benefits such as reduced run-off and erosion (Gilley and Risse, 2000; Wortmann and Walters 2006), reduced bulk density, increased micro- and macro-porosity and increased hydraulic conductivity. Addition of manure also results in increased soil organic carbon due to increased formation of water stable aggregates associated with an increase in particulate organic matter (Oades, 1984; Six *et al.*, 2000). Moreover, soil carbon sequestration through enhanced aggregation is an important strategy to mitigate the increased concentration of atmospheric CO₂ (Shrestha *et al.*, 2007).

Soil aggregate size distribution and stability are important indicators of soil physical quality (Castro Filho *et al.*, 2002), reflecting the impact of land use and soil management on aggregation or degradation. However, not only is soil management the only factor influencing soil quality, soil texture is another key determinant of soil quality as it moderates the behaviour of several soil processes, including SOM dynamics, aggregate formation dynamics and C sequestration (Kettler *et al.*, 2001).

It is therefore important to study the impacts of soil fertility management on soil physical properties in an attempt to improve crop yields and promote sustainable farming methods. Many different methods exist for measuring aggregate stability. Among them some of the widely used ones include Yoder (1936), Kemper and Rosenau (1986) and Li Bissonnais (1996). Using different methods helps give information about the stability of aggregates to different forces and the breakdown mechanisms, which is an indicator of the soil's susceptibility to erosion (Barthes and Roose, 1996).

The aim of this study was to determine the effects of cattle manure and inorganic fertilizer application to soil on SOC, bulk density, aggregate stability and aggregate protected carbon on differently managed fields (homefields and outfields) in the short and long term. It was hypothesized that SOC, bulk density, aggregate stability and aggregate protected carbon would improve with manure application.

4.2 Materials and Methods

Experiments 1 and 2 which are the long-term and short-term trials respectively were used. Details of the general description of the experimental sites and their management are given in sections 3.2.1 and 3.2.2 in the preceding chapter while laboratory procedures are detailed below.

4.2.1. Soil sampling, pre-treatment and storage

Soil sampling was done in April after harvest for both experiments in 2008 and 2009.

Sampling cores of 5 cm diameter and height of 5 cm were used to obtain undisturbed samples

from a depth of 0-10 cm for bulk density determination in plough layer. Disturbed composite samples from each treatment, replicated three times, were randomly obtained for aggregate stability, aggregate protected carbon and SOC at a depth of 0-15 (plough layer) cm using a spade. The samples were air dried, sieved through 4.75, 2 and 0.5 mm sieves and packaged in khaki bags and stored for subsequent analyses of SOC and water stable aggregates.

4.2.1 Soil Organic Carbon (SOC)

Organic carbon was determined following the method detailed in section 3.4.3.

4.2.2 Water stable macro-aggregation and macro-aggregate protected carbon determination

Water stable aggregates were determined following a method by Barthes and Roose (1996) where 4 g of air dried samples passed through a 2 mm sieve were immersed in deionised water for 30 minutes and then wet sieved through a 0.2 mm sieve with a Yoder machine for 6 minutes. A sample of aggregates > 200 µm was oven dried at 105°C, the dry fraction (F > 200 µm) was then weighed and dispersed in 0.05 M NaOH solution for 30 minutes for sand correction. The coarse sand fraction (CS) was oven dried and weighed. Stable macro aggregate index (Ima) was defined as:

$$I_{ma} = 1000(F > 0.200 - CS) / (g DM - CS) \quad (4.1)$$

Where DM = dry matter of the sample determined after oven drying at 105°C.

g = mass of soil sample used in grams

Aggregates for aggregate protected carbon were obtained using a wet sieving technique. The aggregates were obtained by sieving the soil through 4.75 mm sieve and retained on a 2 mm sieve. Fifty grams of air-dried 2-4.75 mm aggregates were placed on a nest of sieves with pores 250 μm and 53 μm (Franzluebbers and Arshard, 1997), and the sieves were gently immersed into a tank of distilled water such that the bottom of the top sieve just touched the water in the wet sieving machine. The aggregates were allowed to wet for 30 minutes and then the wet sieving machine was switched on to run for 10 minutes. The sieves were gently removed and placed on top of an oven (30°C) with newspapers underneath to dry the aggregates. Two aggregate treatments were established (i) intact > 250 μm aggregates and (ii) crushed > 250 μm aggregates (to pass through a 250 μm screen using pestle and mortar). Sub samples of aggregate treatments (5-10 g) were carefully weighed into jars. The soil was then moistened to field capacity (approximately 55 %) and incubated in the constant temperature room at 25 °C in sealed jam jars containing CO₂ traps (0.1M NaOH). Samples were corrected for moisture after every 3 days. The CO₂ traps were changed on days 3, 7, 14, and 21 and the respired C was measured by titration with HCl using phenolphthalein indicator (Beare *et al.*, 1994).

The carbon content of the soil samples was calculated as follows:

$$\text{mg C} = (\text{B}-\text{V}).(\text{NE}) \quad (\text{Stotzky, 1965}) \quad (4.2)$$

where B =volume (ml) of the standard acid needed to titrate the trap solution from the blanks

V=volume (ml) of the standard acid needed to titrate the trap solution from the sample flasks.

N =normality of the acid, in milliequivalents mL⁻¹

E = the equivalent weight of carbon in CO₂, given as 6 as the data was expressed in terms of C (i.e. mg CO₂-C)

The macro aggregate protected and unprotected carbon was then calculated as follows:

$$\text{Unprotected } C_{\min(t)} = \text{intact aggregate } C_{\min(t)}$$

$$\text{Protected } C_{\min(t)} = \text{crushed aggregate } C_{\min(t)} - \text{intact aggregate } C_{\min(t)}$$

Where $C_{\min(t)}$ is the cumulative C mineralized at time t (days) from uncrushed and intact aggregates (Beare *et al.*, 1994).

4.2.3 Bulk density

Undisturbed core samples were taken from a depth of 3 -8 cm to characterize the plough layer (0-15 cm) . This was done by scrapping approximately 3 cm from the surface soil and the metal cores (5 cm diameter and height) were gently pushed deep into the soil until they were totally filled with soil. A hoe was then used to dig them out and soil on both ends of the core was gently scrapped away with a knife until it was leveled out. Both ends of the cores were closed using lids and then transported to the laboratory.

In the laboratory, the cores were weighed, put in an oven at 105°C and dried to constant mass. When there was no weight change, the soil was removed from the cores and the mass of the empty cores measured. The difference between mass of core + dry soil and mass of empty core gave the oven dry mass of soil only. Bulk density was calculated as:

$$\text{Bulk density} = \frac{\text{Mass of oven dry soil}}{\text{Volume of soil core}} \quad (4.3)$$

4.2.4 Statistical Analyses

Analysis of variance was conducted using Genstat 7.1 statistical package. A two-way ANOVA was used to analyse for differences between fertility treatments, field types and

fertility treatment x field-type interactions. The least significant difference (LSD) at $p < 0.05$ was used to differentiate between statistically different means. Further, the Pearson's correlation coefficient was used to investigate the relationships between SOC and the measured physical parameters after which regression functions were determined if correlations were found to be significant.

4.3 Results

4.3.1 Soil Organic Carbon

Soil fertility treatment significantly increased SOC on both sandy and clay soil (Fig. 4.1a &c). Soil organic carbon was significantly ($p < 0.05$) lower in the control than the initial SOC content of the fields when the experiment was started and the margin was greater on the homefield owing to the higher initial SOC content. Initial differences in SOC observed between the homefields and outfields (Zingore, 2006) were no longer evident after 6 years on both soil types. In the short-term, cattle manure application significantly ($p < 0.05$) increased SOC relative to the initial soil SOC and control on the clay fields. Furthermore, there was a significant ($p < 0.05$) difference between the homefield and outfield (Fig. 4.1b).

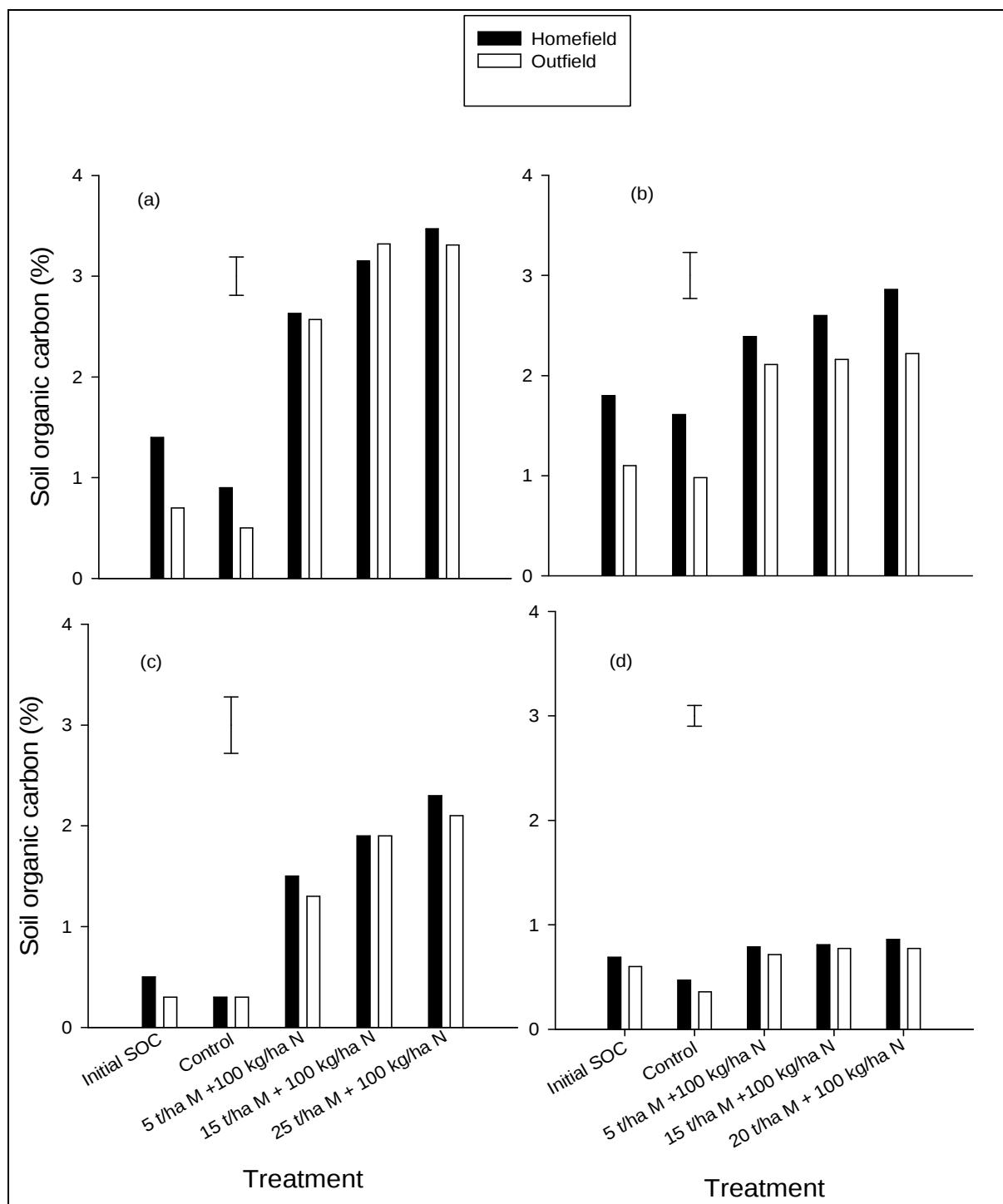


Figure 4.1: Soil organic carbon levels in the plough layer (a) long-term clay soil (b) short-term clay soil (c) long-term sandy soil (d) short-term sandy soil. The bar shows the LSD at $p = 0.05$. HF is homefield and OF is outfield.

Soil fertility treatment did not significantly increase SOC on the sandy short-term fields and SOC ranged between 0.4-0.9 %. The short-term sandy homefield and outfield were not significantly different (Fig. 4.1d)

4.3.2 Bulk density

Cattle manure application did not have a significant effect on bulk density ($p > 0.05$) on both soils. Bulk density ranged between 1000 -1100 kg m⁻³ for the clay soils while in sandy soils it ranged between 1300 – 1550 kg m⁻³. On the other hand, bulk density on the sandy outfield was significantly higher than the homefield possibly because of its greater proportion of the heavier sand particles (Table 3.1). In the short-term fields, bulk density was relatively higher on the clay outfield than homefield, though not significantly. Bulk density ranged between 1000-1300 kg m⁻³ and fertility treatment did not result in any significant differences. The short-term sandy soils did not show any significant change in bulk density after 2 years of cattle manure application (Fig.4.2d). Bulk densities ranged between 1350 and approximately 1500 kg m⁻³.

4.3.3 Water stable macro-aggregation

Soil fertility treatments on the clay long-term fields had a significant effect ($p < 0.05$) on aggregate stability as measured by macro-aggregation index (Fig. 4.2a). Macro aggregation indices on the long term clay sites were between 139-179 % higher on the 25 t ha⁻¹ manure treatments than where no manure was applied on both homefield and outfield. However, there were no significant differences between field types on the long term fields. Addition of manure on the short term clay fields resulted in significantly higher macro aggregation indices (between 98-119%) on the manure treatments relative to the control (Fig. 4.2c) while between the homefield and outfield no significant differences were observed.

Manure application on the sandy soils did not induce any significant increase in macro aggregation indices on both long term and short-term fields. Macro-aggregation index ranged from 55-102 on the long-term sites compared to short term sites' 70 to 120. Field type had no significant ($p > 0.05$) effect on both long-term and short-term fields.

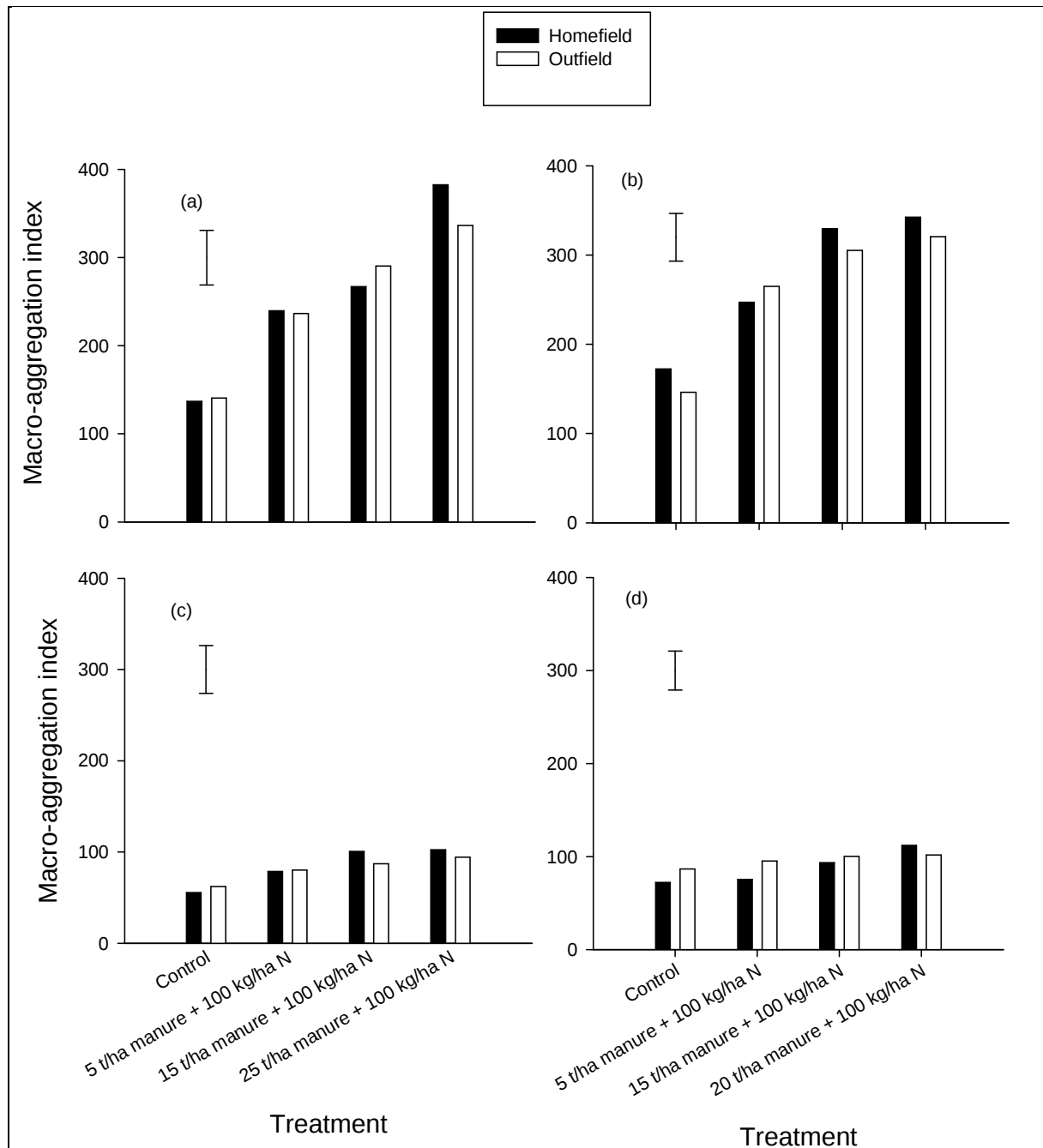


Figure 4.2 :Macro aggregation indices on (a) long-term clay soil (b) short-term clay soil (c) long-term sandy soil (d) short-term sandy soil. The bar shows the LSD at $p = 0.05$.

4.3.4 Macro-aggregate Protected Carbon

Macro-aggregate protected carbon was only determined in clay soils because the aggregates were absent in sandy soil. Cattle manure significantly increased ($p < 0.05$) macro-aggregate protected carbon in manure treatments compared to control on both homefield and outfield (Fig 4.3a) on clay long-term soils. The same trend was shown for macro-aggregate protected carbon in the short term fields (Fig 4.3b). However, in the short term, applying cattle manure at 5 t ha^{-1} did not result in significant differences in macro-aggregate protected carbon relative to the control on both field types. There was a significant difference when cattle manure was applied at $\geq 15 \text{ t ha}^{-1}$.

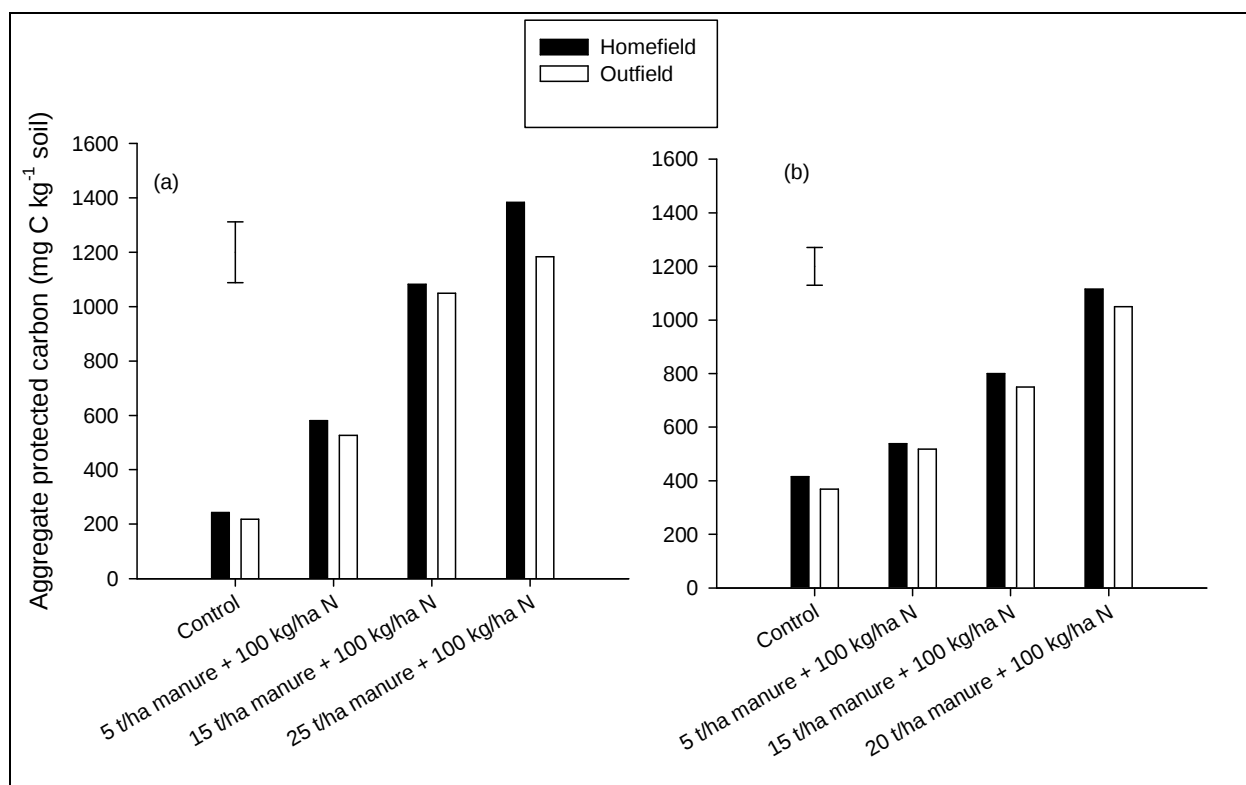


Figure 4.3: Macro-aggregate protected carbon on clay fields after (a) 6 years (b) 2 years. The vertical bar denotes the LSD at $p = 0.05$.

4.3.5 Regression relationships between SOC, aggregate stability and aggregate protected carbon

No regressions were done for the sandy soils as there were no significant differences in bulk density and Ima after cattle manure additions both in the long-term and short term implying that other factors such as primary composition other than SOC were responsible for soil structure.

Regression functions of SOC with macro-aggregation indices and aggregate protected carbon were used to analyse the variability in the physical properties caused by SOC. In the clay soils, aggregate stability and aggregate protected carbon showed a highly positive linear relationship with SOC which explained 85 % and 82 % of the variability respectively (Fig. 4.4a & b). Other possible relationships such as curve linear and quadratic gave lower R^2 values. The short-term clay fields also showed positive increases in macro-aggregation index ($R^2 = 0.81$) and aggregate protected C ($R^2 = 0.57$) with increasing SOC (Fig. 4.4a & b).

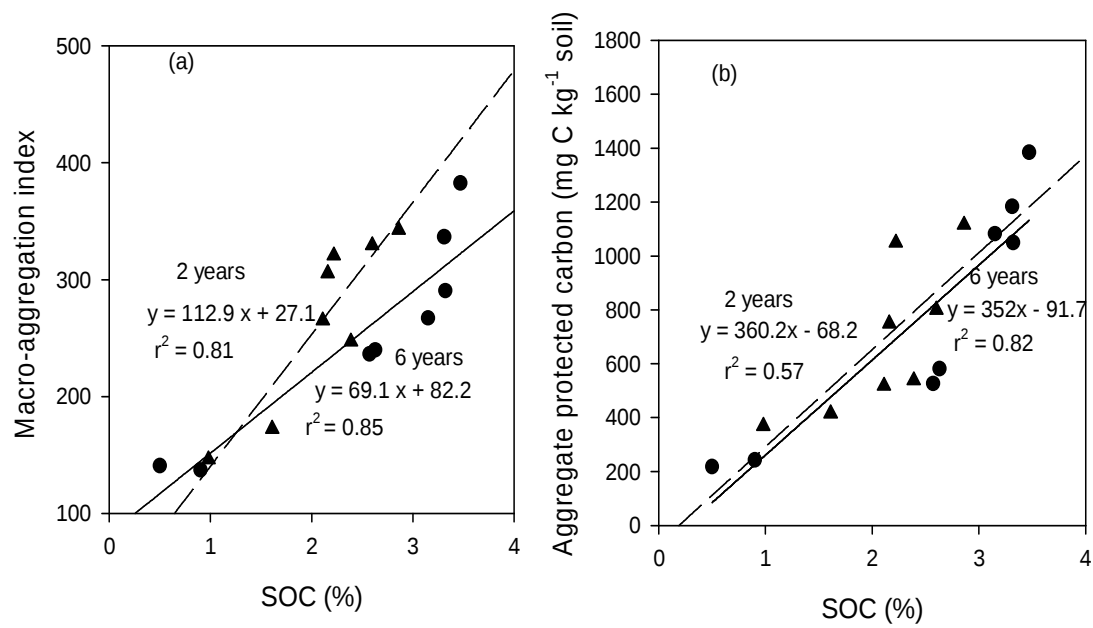


Figure 4.4: Regression relationships between SOC and (a) aggregate stability and (b) aggregate protected carbon on long-term and short-term clay fields

4.4 Discussion

4.4.1 Soil organic carbon

Soil organic carbon was significantly higher where cattle manure was added relative to the control treatments on long-term fields. Despite the initial differences between the homefields and outfields arising from long-term site specific soil management by the farmer (Bationo *et al.*, 2006; Zingore, 2006) SOC was found to be similar in HF and OF after 6 years of same cattle manure application rates. Increase in SOC concentration in manure and inorganic fertilizer treatments could be as a result of organic matter addition through cattle manure application and enhanced crop growth with higher root biomass (Acharya *et al.*, 1988; Mikha and Rice 2004). Similar results confirming the importance of management practices that prioritize C addition to coarse textured soils of Zimbabwe through organic C resources application have been reported (Chivenge *et al.* 2007). Organic carbon content in the soil is closely associated with clay and silt contents and clay types, which influence the stabilization of organic carbon (Bationo *et al.*, 2006; Chivenge *et al.*, 2007) and this partly explains the differences in SOC levels reached in clay and sandy soils receiving the same quantities of cattle manure in this study.

In the short-term fields, cattle manure application significantly increased SOC on the clay fields only. Similar results of significant increase in SOC after 2 years of farmyard manure application at 30 and 60 t ha⁻¹ have been reported (Shirani *et al.*, 2002) while increases in one season have been reported by Haynes and Naidoo, (1998) and Nyamangara *et al.*, (2001). The clay homefield showed higher SOC relative to the outfield owing to the initially higher levels of SOC accumulated over time. On the other hand, the sandy short-term fields' SOC was marginally increased after cattle manure addition. Response to fertilization were similar on

both fields on sandy short-term fields owing to the lack of fertility variability at the beginning of the experiment.

4.4.2 Bulk density

The lowest bulk density was observed at 25 t ha⁻¹ cattle manure indicating an improvement in aggregation and amount of pore space (Schjønning *et al.*, 1994; Hati *et al.*, 2006) although the decrease was not significant compared to other fertility treatments. On the other hand, the sandy outfield was significantly higher than the homefield possibly because of its greater proportion of the coarse sand particles while fertility treatment did not show any significant ($p>0.05$) effect on bulk density.³⁴

After 2 years of cattle manure application, the outfield on the clay soil showed relatively higher bulk densities than the corresponding homefield, and the highest bulk density was 1265 kg m⁻³ in the control on the outfield. This difference was attributed to the effects of manure application to the homefield from past management. The sandy soils did not show any significant change in bulk density after 2 years of manure application. Similarly, Nyamangara *et al.*, (2001) reported some lack of consistency in bulk density with 3 years of cattle manure application on a Zimbabwean sandy soil containing 6 % clay, indicating the poor responses of the soils to manure application.

4.4.3 Water stable macro-aggregation

Cattle manure application increased macro-aggregation index on both long- and short-term clay soils, a trend that was consistent with SOC observed for the same soils. Generally, SOC is a basic factor affecting aggregate stability (Elliot, 1986) through increased microbial

proliferation and the resulting binding of clay- and silt sized particles and micro-aggregates by mucilages into macro-aggregates (Oades, 1984; Six *et al.* 2000). Nyamadzawo (2004) and Su *et al.*, (2006) reported a strong relationship between SOC and aggregate stability, confirming the importance of SOC in aggregation. Consistent with these findings, SOC could explain 85 % and 81 % of the variation in Ima on the clay long term and short term fields respectively. In other experiments, water stable aggregates (WSA) were found to be highest in manure + NPK treatments compared to compost, inorganic fertilizer only and control treatments (Hati *et al.*, 2006; Shirani *et al.*, 2002). Mikha and Rice (2004) also reported significant increases in aggregates greater than 2000 μm with manure addition which was attributed to the input of additional fresh organic residue and available C to the soil resulting in enhanced microbial activity and production of polysaccharides (Tisdall and Oades, 1982) which then act as binding agents (Tisdall and Oades, 1982; Haynes and Francis, 1993). Furthermore, addition of manure could have increased the macro-faunal population such as earthworms which are known to improve aggregation and nutrient cycling (Lee and Foster, 1991; Bossuyt *et al.*, 2005). This is achieved through the secretion of mucus in their guts which may strengthen bonds between organic and soil mineral components when they ingest the organic matter and soil (Martin and Marinissen, 1993).

There was no significant ($p>0.05$) effect of farmer management (field-type) on aggregate stability after 6 years of manure application indicating that initial differences were a result of differential resource allocation targeting the homefield at the expense of the outfield. Manure application can therefore be considered as an option of restoring fertility on degraded outfields.

On the sandy soils, manure addition did not result in any increase in Ima despite the significant differences in SOC. Regardless of manure application, clay +silt content seemed to have greater effect on quantity of stable aggregates as indicated by similar aggregation indices in all fertility treatments on sandy soils. The greater proportion of water stable aggregates on the clay soils relative to the sands was a result of the limited carbon protection capacity of sands due to low clay contents. Similar results were reported by Kemper and Koch (1966) who showed that aggregate stability increased to a maximum level depending on the clay and free Fe-oxides.

4.4.4 Macro-aggregate protected carbon

A significant increase in macro-aggregate protected C was observed between the control and subsequent manure application rates in the order of control < 5 < 15 < 25 t ha⁻¹ manure. In the short-term experiment, there was a significant difference when manure was applied at ≥ 15 t ha⁻¹. The comparison of C respired from crushed (ground with mortar) and uncrushed WSA showed that crushing increased amount of C mineralised. Increased respiration in crushed samples resulted from breaking down of stable aggregates and organic matter fractions increasing their surface area and accessibility to microbial attack. Physical protection of carbon by aggregates is accomplished by formation of physical barriers between microbes, enzymes and their substrates therefore increasing SOM (Edwards and Bremner, 1967; Tisdall and Oades, 1982; Six *et al.*, 2000). The crushing of aggregates therefore, increased the carbon by exposing the plant roots, hyphae and mucilages that hold together the macro aggregates and micro-aggregates (Oades, 1984) to breakdown by enzyme action.

SOC explained 82 % of the variation in aggregate protected carbon on the long-term fields and only 57 % on the short term fields. The high correlation between SOC and aggregate

protected carbon was a result of development of stable aggregates over time with cattle manure addition. Elliot (1986); Beare *et al.*, (1994) and Mikha and Rice (2004) reported significantly greater proportions of labile C associated with macro-aggregates than micro-aggregates and they concluded that macro-aggregates therefore, contribute more to nutrient cycling than micro-aggregates.

4.4.5 Regression relationships between SOC, aggregate stability and aggregate protected carbon

In the clay soils, aggregate stability and aggregate protected carbon showed highly positive linear relationships with SOC. The observed increase in SOC due to manure application caused an increase in the stability of aggregates which in turn resulted in increased C protected within macro-aggregates. Soil organic carbon showed a significant negative linear relationship with bulk density, indicating that bulk density decreased as organic carbon increased after 2 and 6 years of manure application. Other studies have also reported highly positive linear relationships between SOC and stability of aggregates, and negative linear relations with bulk density (Evrendilek *et al.*, 2004; Heusher *et al.*, 2005; Hati *et al.*, 2007 ; Wang *et al.*, 2010).

4.5 Conclusion

This study indicated that equal cattle manure and inorganic fertilizer application on HFs and OFs allows for the restoration of degraded clay soils after 6 or more years. Spatial variabilities were therefore a short-term phenomenon on clay soils unlike in sandy soils which did not show any positive response to cattle manure application. Manure application showed limited effects on physical properties on the sandy soils probably because of the very

low clay content (6–13 %) limiting the stabilization capacity of the soils, but acted more as a source of nutrients and modified the soil bio-chemical environment. In the clay soils it acted as both a source of nutrients and optimized the soil bio-physical environment. Therefore, manure application rates greater than or equal to $15 \text{ t ha}^{-1} \text{ year}^{-1}$ are recommended for soil structure build-up and maintenance in clay soils while in sandy soils rates $5 \text{ t ha}^{-1} \text{ year}^{-1}$ would be more efficient for the purpose of complementing the inorganic fertilizers and to regulate and reduce acidity in sandy soils. The hypothesis that different manure rates combined with inorganic fertilizer lead to improved SOC, bulk density, aggregate stability and aggregate protected carbon was therefore rejected as improvements were only reported in some physical properties in the clay soil while only SOC was improved on the sandy soil.

Chapter 5

Soil hydraulic properties as influenced by soil fertility management on two contrasting soils in Murewa

5.1 Introduction

Smallholder farmers have over time found widespread use of locally available forms of organic nutrient resources such as woodland litter, green manures, composted materials, crop residues and cattle manure (Campbell *et al.*, 1998; Mapfumo and Giller, 2001). However, cattle manure is the one that is mostly used as it is found at the homestead where the cattle are kept and therefore it is readily available especially for livestock owners (Mtambanengwe and Mapfumo, 2005). It is often applied as supplement and/ or complement to inorganic fertilizers which are usually scarce under smallholder farming systems. As a nutrient reservoir, it is often a poor source as it has a high C:N ratio (N concentration relative to lignin and polyphenols) and high sand concentrations due to poor grazing and handling (Materechera, 2010). There is therefore need to study its complementary role in developing soil fertility technologies as it has low turn-over rates and subsequently it is a good precursor to SOM build-up.

SOM binds soil particles together into aggregates and improves soil structure that favours the downward flow of water into the soil (Boyle *et al.*, 1989). Long-term cattle manure application has been found to improve soil physical properties including bulk density, aggregate stability, infiltration rates (Hati *et al.*, 2006) and water retention (Schjønning *et al.*, 1994; Rose 1991). According to Letey (1985), water content or potential is the key variable

of the soil physical parameters directly related to crop productivity. Therefore it is important to investigate the effects that cattle manure application has on the soil hydraulic properties of soils variable in soil fertility.

In Zimbabwe Nyagumbo (2002), Thierfelder and Wall (2009) evaluated the impact of reduced tillage and conventional tillage on infiltration rates and crop water availability while Nyamadzawo *et al.*, (2008) evaluated the changes in infiltration rates and hydraulic conductivity under a maize-fallow rotation using improved fallows. These studies all addressed different contexts that include comparisons between tillage practices and types of improved fallows. This study dwells on the hydraulic properties of differently managed fields (homefields and outfields) to complement the work that has been done on the chemical aspects and nutrient use efficiencies (Scoones and Toulmin, 1999; Tittonell *et al.*, 2005; Zingore, 2006). The aim of the study was to investigate the effects of cattle manure application to homefields and outfields (farmer induced fertility gradients) on steady state infiltration rates, porosity, unsaturated hydraulic conductivity and soil moisture retention characteristics. The hypothesis tested was that the hydraulic properties under study improve with increasing manure application rates over time and in the long-term there are no differences between HFs and OFs.

5.2 Materials and Methods

Experiments 1 and 2 which are the long-term and short-term trials respectively were used. Details of the general description of the experimental sites and their management are given in sections 3.2.1 and 3.2.2. All field measurements were done in May up to July in 2009, after harvesting. Soil sampling for moisture retention characteristics determination was also done after crop harvest in May 2009 using metal sampling cores.

5.2.1 Infiltration Rates measurement

Double rings and tension infiltrometers were used to measure infiltration rates and hydraulic conductivity (Anderson and Ingrams, 1993). Measurements were conducted from May to July (after harvest) on both long term and short term clayey fields on the control, 20 t ha⁻¹ and 25 t ha⁻¹ manure treatments only for short-term and long-term fields respectively. Unfortunately, measurements could not be done on short-term sandy fields as the owner of the farm quickly ploughed the fields soon after harvest despite our efforts of letting our intentions known. The time needed to reach steady state infiltration rate was long therefore field measurements were done on the two extreme treatments but in all replications due to budget constraints. The method entailed first clearing stover from the surface from subplots of 1.5 x 1.5 m² areas. Metal rings (30 cm and 60 cm inner and outer diameters respectively and height 30 cm) were driven into the soil for about 15 cm using a rubber hammer and then filled with water to a height of 13 cm and water was allowed to infiltrate (Fig. 5.1a). Refilling was done each time water dropped by 5 cm, taking note of the water level before refilling. Water levels in both rings were maintained at the same level. Measurements were stopped when the time required to infiltrate a certain volume of water remained constant. Cumulative infiltration was then calculated from differences in depth recordings according to a method by Landon (1984). Infiltration data from the double ring measurements was fitted to the

Kostiakov's infiltration model (Hillel, 1982) which gave the best fit ($R^2 > 0.90$) compared to other models. The Kostiakov model which was used is given in equation 5.1

$$F = at^b \quad (5.1)$$

where F is the infiltration in (cm hr^{-1}), the constant a represents the cumulative infiltration after time t of infiltration and constant b gives an indication of the relative importance of time to infiltration.

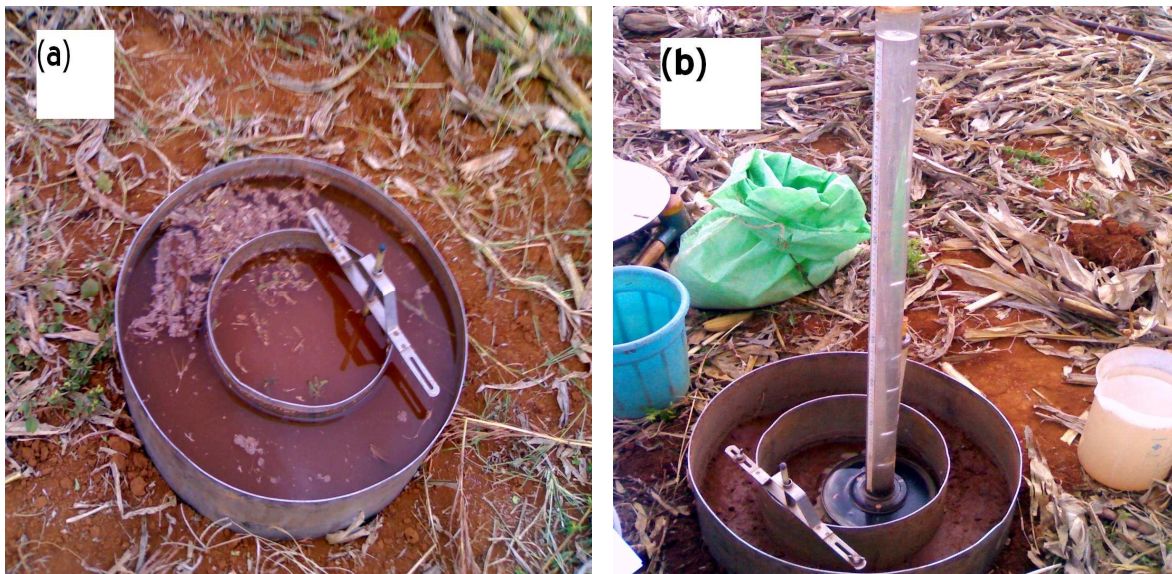


Figure 5.1: Photo showing (a) infiltration measurements using a double ring infiltrometer (b) Tension infiltrometer measurements soon after double ring measurements used to obtain porosity parameters

5.2.2 Porosity measurement

Measurements were taken soon after double ring infiltrometer measurements using a tension infiltrometer and the soil was assumed to be saturated (Fig. 5.1b). Hydraulic contact between the porous ceramic materials of the tension infiltrometer's cap and the soil matrix was facilitated through a thin layer (0.02 mm) of fine grain silica sand cap placed on the surface of the soil. Tension infiltration measurements were conducted at 5 and 10 cm therefore

involving pores with diameter $< 600 \mu\text{m}$ and $< 300 \mu\text{m}$ respectively. These pores are important because they transport most water in the soil under high water potential (Nyamadzawo *et al.*, 2008). Pore sizes were estimated from the capillary equation (Eq. 5.2) Watson and Luxmoore, (1986):

$$R = \frac{-2\sigma \cos \alpha}{\rho g h} \approx \frac{-0.15}{h} \quad (5.2)$$

where : σ is the surface tension of water, α is the contact angle between water and the pore wall (assumed to be 0), ρ is the density water , g is the acceleration due to gravity, r is the pore radius and h is the head (cm H₂O).

Applying the capillary equation (Eq. 5.2) at 5 cm, minimum pore radius was 0.03 cm. Macropore conductivity (K_m) was calculated as the difference in ponded infiltration rate (K_p) and infiltration rate at (K_f) at 5 cm. The maximum number of effective macropores per unit (N) area at 5 cm tension was given by:

$$N = 8\mu K_m / \pi p g (0.03)^4 \quad (5.3)$$

Where μ is the viscosity of water (ML⁻¹T⁻¹), K_m is the macropore conductivity.

The total effective macroporosity θ_m (m³ m⁻³) was calculated by multiplying the maximum number of effective macropores per unit area (N) by the cross sectional area of the pores using minimum pore radius. At 5 cm tension, it was given by :

$$\theta_m = N\pi r^2 = N\pi (0.03)^2 \quad (5.4)$$

Where: θ_m is the total effective porosity.

5.2.3 Unsaturated hydraulic conductivity using a tension infiltrometer.

Measurements for unsaturated hydraulic conductivity were taken from initially dry soil (Fig. 5.2). A tension infiltrometer (20-cm diameter base plate; CSIRO,1988) was calibrated as outlined in the user manual (CSIRO, 1988) before the measurements were conducted. Tensions of 5 and 10 cm which exclude pores > 0.06 and > 0.03 cm in diameter were used during measurements. The measurements were carried out as described in section 5.2.2 and tension was adjusted by increasing the depth of air entry tube in the water from 5 cm and 10 cm (CSIRO, 1988).

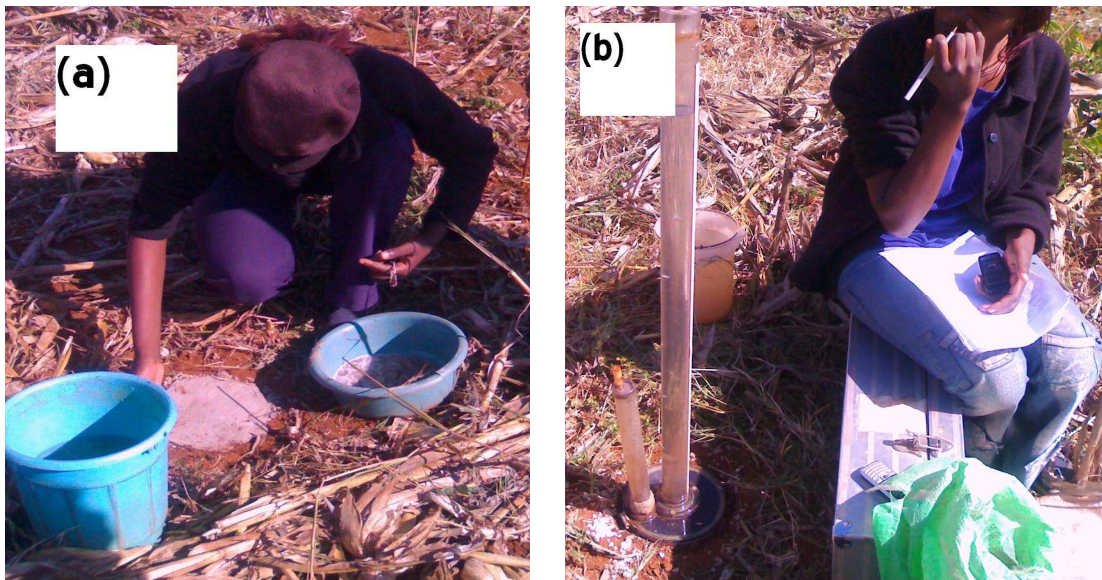


Figure 5.2: Photo showing (a) preparation of the sand cap using fine sand for placement of tension infiltrometer (b) measuring of unsaturated hydraulic conductivity using the tension infiltrometer on an initially dry soil.

(a) Sorptivity

Sorptivity (S_o) was calculated from the early time data through plotting of volume flux of water ($Q/\pi r^2$) against the square root of time ($\sqrt{t}$). The slope of the straight line portion gave the sorptivity with units of length/ ($\sqrt{t}$) (CSIRO, 1988). Sorptivity was required for the calculation of hydraulic conductivity.

(b) Steady state flow rate

Steady state flow rate was found by plotting the cumulative infiltration during the last part of the infiltration (using the last 10 readings) as a function of time. The slope of this line gave the steady state flow rate ($q/\pi r^2$).

(c) Hydraulic conductivity (K_o)

The hydraulic conductivity of the soil at the potential at which the measurement was made was calculated from:

$$K_o = q/\pi r_o^2 - 4bS_o^2/\pi r_o (\theta_o - \theta_n) \quad 5.5$$

Where; K_o = hydraulic conductivity, ($q/\pi r^2$) is the steady state flow rate, S_o is the sorptivity, r_o is the radius of the ring, θ_o is the volumetric moisture content at the measurement potential, θ_n is the volumetric moisture content at initial potential, and b is a dimensionless constant whose values lie between 0.5 and $\pi/4$, (CSIRO, 1988).

(d) Macroscopic capillary length and mean pore size

The macroscopic capillary length (λ_c) which is a flow weighted mean soil-water potential (White *et al.*, 1992) was derived from the sorptivity, hydraulic conductivity, and the volumetric water content at the measurement potential and initial potential using equation 5.6

$$\lambda_c = bS_o^2 / (\theta_o - \theta_n)K_o \quad (5.6)$$

Macroscopic capillary length (λ_c) and a predetermined soil constant of 7.4 were then used to calculate the characteristic mean pore size, which is a soil structure index (White and Sully, 1987) using the relationship in equation 5.7 (CSIRO, 1988).

$$\lambda_m = 7.4 / \lambda_c \quad (5.7)$$

5.2.3 Soil moisture retention determination

Undisturbed core samples were taken from a depth of 3-8 cm . This was done by scrapping approximately 3 cm from the surface soil and the metal cores (5 cm diameter and height) were gently pushed deep into the soil until they were totally filled with soil. A hoe was then used to dig them out and soil on both ends of the core was gently scrapped using a knife until it was leveled out. Both ends of the cores were closed using lids and then transported to the laboratory. The soil samples were subjected to suctions of 5, 10, 100, 200 and 1500 KPa in the laboratory. For the lower suctions (5 and 10 KPa) the tension table was used (Rose, 1966). A nylon cloth was securely tied to one end of the sampling core containing the soil sample using a rubber band. The samples were then placed into a wetting tray with foam rubber close to saturation and allowed to soak overnight. The following day the cores were placed on a tension table set at a suction of 5 kPa and the cores were monitored every 2 days by weighing them until there was no change of weight in successive weighings. Once equilibrium had been established the equilibrium weight was recorded and the cores placed onto a tension table at 10 kPa and the same process repeated. The weight of the core, rubber band and nylon cloth were also determined for use in the gravimetric moisture content determination of the soil samples (Baruah and Barthakur, 1998). For higher suctions pressure plates were used (Klute, 1986). Sample retaining rings were placed on ceramic plates, and

then portions of soil samples from 5 and 10 kPa determinations were put in them. The samples were then saturated with an excess of water in the ceramic plates for 24 hours after which the ceramic plates were placed into the pressure chambers, and the desired pressure applied. A burette filled with distilled water was attached to the outflow tube to ensure through its readings that outflow had ceased after which the soil samples were quantitatively transferred to pre-weighed metal trays weighed, oven dried at 105⁰C for 24 hours weighed again and the weights recorded. Gravimetric moisture content of the soil was calculated as:

$$\text{Soil water \%} = \frac{\text{Mass of water}}{\text{Mass of oven dry soil}} \times 100 \quad (5.8)$$

Where, mass of water = mass of wet soil – mass of oven dry of soil

mass of dry soil = (mass of dry soil + tray) - mass of empty tray

Volumetric moisture content was calculated by multiplying gravimetric moisture content by bulk density. Bulk density was obtained from the measurements done in section 4.2.3 of chapter 4.

5.2.4 Statistical analysis

Steady state infiltration rates, hydraulic conductivity, macroscopic capillary length, mean pore sizes, total effective porosity and pore density were analysed for significant differences using two way ANOVA where cattle manure application was used as the fertility treatment and field type (HF or OF) were the two sources of variation. Analysis of variance on moisture retention characteristics was done for each pressure level. Genstat 7.1 statistical package was used and significance level was tested at 5 % with LSDs (least significant differences) being used to differentiate between statistically different means.

5.3 Results

5.3.1 Steady state infiltration rates

Infiltration rates were 238% and 129% higher with 25 t ha⁻¹ cattle manure application than control on long-term clay homefield and outfield respectively (Table 5.1). On the short-term clay fields, infiltration rates were increased by at least 30 % with 20 t ha⁻¹ cattle manure application over control, while no changes in steady state infiltration rates were observed with manure application ($p>0.05$) on sandy soils after 6 years. Steady state infiltration rates were obtained by fitting the data points to the Kostiakov model which gave a good fit ($R^2 > 0.90$) on all fields types and soil types.

Table 5.1 Steady state infiltration rates using the Kostiakov-type model

Treatment	Steady state infiltration rates (cm hr ⁻¹)			
	Clay fields		Sandy fields	
Long-term fields	HF	OF	HF	OF
Control	6.2 ^a	8.3 ^a	15.2 ^a	18.6 ^b
25 t ha ⁻¹ M +100 kg ha ⁻¹ N	22.4 ^c	16.5 ^b	16.8 ^{ab}	24.7 ^c
LSD (P < 0.05)	3.3		2.4	
Short-term fields				
Control	17.0 ^a	22.6 ^a		
20 t ha ⁻¹ M +100 kg ha ⁻¹ N	41.3 ^c	30.8 ^b		
LSD (P < 0.05)	6.1			

Note: means in the same column and under the same parameter followed by the same superscript are not significantly different at P = 0.05. HF = homefield and OF = outfield

5.3.2 Total effective porosity and pore density

Pore density and total effective porosity of pores $< 600\ \mu\text{m}$ that were included in the transport process at 5 cm were almost 3 times and more than 1.7 times higher in $25\ \text{tha}^{-1}$ cattle manure than control in long-term clay homefield and outfield respectively (Table 5.2a). In addition, cattle manure at this rate significantly increased pore density and total effective porosity of pores $< 300\ \mu\text{m}$ by between 1.8 to 2.8 times on the clay soils after 6 years (Table 5.2a). Pore density was lower at 5 cm tension and increased as tension was increased to 10 cm implying that pores of radius $< 300\ \mu\text{m}$ were more dominant than those of radii $< 600\ \mu\text{m}$ which are involved in the transport process at 5 cm.

Short-term clay fields' pore density and total effective porosity were between 1.2 to 2.8 times higher in $20\ \text{tha}^{-1}$ cattle manure plots than control at both 5 and 10 cm tension (Table 5.2b). There were also significant fertility and field type treatment effects ($p < 0.05$). The homefield's pore density and total effective porosity were 11 % greater than the outfield. Compared to the clay long term fields pore density and total effective porosity were generally higher on the short term fields.

The sandy fields' pore density and total effective porosity were not significantly different ($p > 0.05$) as a result of manure application for 6 years (Table 5.2c).

Table 5.2a Pore density and total effective porosity on long-term clay fields

Treatment	Pore density (m^{-2})		Total effective porosity (m^3m^{-3})	
	5 cm	10 cm	5 cm	10 cm
Control (HF)	429 ^a	6892 ^a	12 ^a	152 ^a
25 tha^{-1} M + 100 kgha^{-1} N (HF)	1130 ^b	19540 ^b	32 ^b	431 ^b
Control (OF)	565 ^a	9699 ^a	16 ^a	231 ^a
25 tha^{-1} M + 100 kgha^{-1} N (OF)	975 ^b	17528 ^b	27 ^b	387 ^b
LSD ($P < 0.05$)	383	4637	11	102

Note: means in the same column followed by the same letter are not significantly different at $P = 0.05$

Table 5.2b Pore density and total effective porosity on short-term clay fields

Treatment	Pore density (m^{-2})		Total effective porosity (m^3m^{-3})	
	5 cm	10 cm	5 cm	10 cm
Control (HF)	1164 ^a	19274 ^a	102.8 ^a	425 ^a
20 tha^{-1} M + 100 kgha^{-1} N (HF)	3228 ^b	55362 ^c	285.0 ^d	1222 ^c
Control (OF)	1650 ^b	27398 ^a	145.7 ^b	605 ^a
20 tha^{-1} M + 100 kgha^{-1} N (OF)	2313 ^c	38514 ^b	204.2 ^c	850 ^b
LSD ($P < 0.05$)	462	9109	41	201

Note: means in the same column followed by the same letter are not significantly different at $P = 0.05$

Table 5.2c Pore density and total effective porosity on long-term sandy fields

Treatment	Pore density (m^{-2})		Total effective porosity (m^3m^{-3})	
	5 cm	10 cm	5 cm	10 cm
Control (HF)	68 ^a	995 ^a	22 ^a	78 ^a
25 tha^{-1} M + 100 kgha^{-1} N (HF)	55 ^a	1399 ^a	19 ^a	123 ^a
Control (OF)	72 ^a	1223 ^a	25 ^a	108 ^a
25 tha^{-1} M + 100 kgha^{-1} N (OF)	60 ^a	1238 ^a	23 ^a	109 ^a
LSD ($P < 0.05$)	19	181	6	22

Note: means in the same column followed by the same letter are not significantly different at $P = 0.05$

5.3.3 Unsaturated hydraulic conductivity, macroscopic capillary length and mean pore sizes

Hydraulic conductivity (K_o) was significantly ($p < 0.05$) higher in 25 t ha⁻¹ manure treatments relative to where no manure was applied on homefield and outfield of clay long-term fields at 5 cm, while at 10 cm there was no difference (Table 5.3a). Hydraulic conductivity, macroscopic capillary length (λ_c) and mean pore sizes (λ_m) all improved by at least 1.2 times with manure addition at 25 tha⁻¹ at 5 cm tension. Transmission at 5cm was through pores between 380-600 μ m while at 10 cm it was through pores < 300 μ m, consequently, K_o was lower at 10 cm since transmission occurred through smaller sized pores.

Table 5.3a Unsaturated hydraulic conductivity (K_o) , macroscopic capillary length and mean pore sizes on the clay long term fields

Treatment	K_o cm h ⁻¹		Macroscopic capillary length (mm)		Mean pore size diameter (mm)	
	5 cm	10 cm	5 cm	10 cm	5 cm	10 cm
	tension	tension	tension	tension	tension	tension
Control (HF)	1.83 ^a	2.14 ^a	19.62 ^a	24.80 ^a	0.38 ^a	0.29 ^a
25 tha ⁻¹ M + 100 kg N ha ⁻¹ (HF)	3.00 ^c	2.34 ^a	12.89 ^c	24.50 ^a	0.58 ^c	0.30 ^a
Control (OF)	2.03 ^a	1.85 ^a	15.49 ^b	25.20 ^a	0.48 ^b	0.29 ^a
25 tha ⁻¹ M + 100 kg N ha ⁻¹ (OF)	2.34 ^b	1.87 ^a	12.33 ^c	25.50 ^a	0.60 ^c	0.29 ^a
LSD (P< 0.05)	0.31	0.86	3.55	11.02	0.10	0.18

Note: means in the same column followed by the same letter are not significantly different at P = 0.05. K_o is unsaturated hydraulic conductivity.

On the clay short-term fields, unsaturated hydraulic conductivity was significantly higher in 20 tha⁻¹ manure treatment on the homefield (1.57 cmhr⁻¹) at 5 cm, while at 10 cm there were no significant changes (Table 5.3b). Further, K_o was significantly lower in the outfield

relative to homefield by between 17 – 26 %. Macroscopic capillary length and mean pore sizes were however not significantly different between fertility treatment and field type.

Table 5.3b Unsaturated hydraulic conductivity (K_o) , macroscopic capillary length and mean pore sizes on the clay short-term fields

Treatment	Ko cm h ⁻¹		Macroscopic capillary		Mean pore size diameter		
			length (mm)		(mm)		
	5cm	10cm	5	cm 10cm	5	cm 10cm	
	tension	tension	tension	tension	tension	tension	
Control (HF)	1.49 ^{ab}	1.28 ^a	16.10 ^a	28.80 ^a	0.46 ^a	0.26 ^a	
20 tha ⁻¹ M + 100 kgha ⁻¹ N (HF)	1.57 ^b	1.58 ^a	14.00 ^a	27.00 ^a	0.53 ^a	0.28 ^a	
Control (OF)	1.14 ^a	1.02 ^a	18.10 ^a	32.00 ^a	0.43 ^a	0.23 ^a	
20 tha ⁻¹ M + 100 kgha ⁻¹ N (OF)	1.15 ^a	1.32 ^a	12.80 ^a	25.30 ^a	0.58 ^a	0.30 ^a	
LSD (P< 0.05)	0.37	0.42	9.29	11.66	0.22	0.12	

Note: means in the same column followed by the same letter are not significantly different at P = 0.05. K_o is unsaturated hydraulic conductivity.

Hydraulic conductivity, macroscopic capillary length and mean pore sizes were all not significantly ($p > 0.05$) changed by manure application for 6 years (Table 5.3c) on sandy fields.

Table 5.3c Unsaturated hydraulic conductivity (K_o) , macroscopic capillary length and mean pore sizes on the sandy long-term fields

Treatment	K_o cm h ⁻¹		Macroscopic capillary length (mm)		Mean pore size diameter (mm)		
	5	cm	10cm	5cm	10cm	5cm	10cm
	tension	tension	tension	tension	tension	tension	tension
Control (HF)	2.21 ^a		1.73 ^a	187.39 ^a	161.65 ^a	0.04 ^a	0.05 ^a
25 tha ⁻¹ M + 100 kg N ha ⁻¹ (HF)	2.29 ^a		1.96 ^a	119.27 ^a	242.63 ^a	0.06 ^a	0.03 ^a
Control (OF)	1.55 ^b		1.54 ^a	113.47 ^a	105.35 ^a	0.07 ^a	0.07 ^a
25 tha ⁻¹ M + 100 kg N ha ⁻¹ (OF)	1.99 ^b		1.96 ^a	167.84 ^a	165.52 ^a	0.05 ^a	0.05 ^a
LSD (P< 0.05)	0.47		0.31	73.00	84.20	0.03	0.03

Note: means in the same column followed by the same letter are not significantly different at P = 0.05. K_o is unsaturated hydraulic conductivity

5.3.4 Moisture retention characteristics

Manure application at 25 t ha^{-1} resulted in a significant volumetric moisture content increase ($p < 0.05$) of between 10-12 % at 5 kPa and between 6-7.5 % at 10 kPa on clay long-term field (Fig 5.1a). In addition, moisture retained at 5 kPa in the clay short-term homefield was higher in the manure treated plots than control (Fig 5.1b). At higher suctions of 33, 100, 200 and 1500 kPa moisture retained was not significantly different between the fertility treatments on both long- and short-term fields. Although volumetric moisture content was not significantly changed at 1500 kPa, if field capacity was assumed to be at 10 kPa, available water capacity was higher in 25 t ha^{-1} cattle manure treatment than in control in the clay long-term fields by between 7-10 %.

On the sandy long-term fields moisture retained ranged between 2-20 % and there was no significant difference between treatments at any given suction (Figure 5.1c).

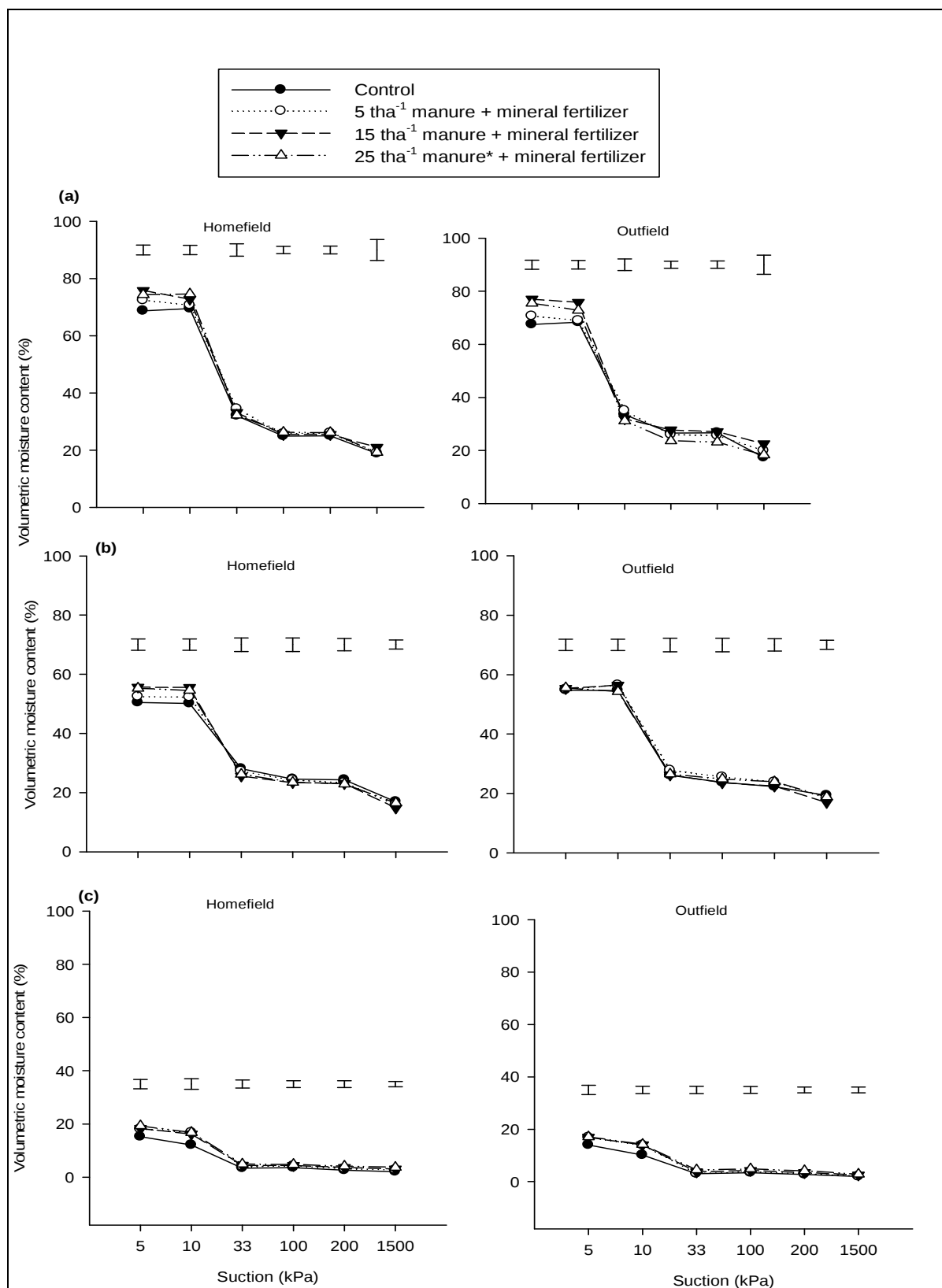


Figure 5.3. Moisture retention characteristics for (a) long-term clay (b) short-term clay and (c) long-term sandy fields. The vertical bars represent the LSD at $p < 0.05$. * 20 tha^{-1} manure on short-term fields

5.4 Discussion

5.4.1 Steady state infiltration rates

Application of 25 tha^{-1} cattle manure + mineral fertilizer in the clay long-term clay trial increased steady state infiltration by 3 times in homefield and 2 times in outfield when compared to the control. The responses in short-term trial were also significant but of a lesser magnitude. Homefields were more responsive to fertilization compared to outfields an indication of the underlying fertility variability due to the preferential fertility management. The increase in steady state infiltration rates was attributed to the improved soil structural stability and effective porosity. Higher infiltration rates on the manure plots were also ascribed to possible preferential flow of water in root channels due to concomitantly higher root biomass generation with organic and inorganic fertilization (Christensen, 1988).

Increased steady state infiltration rates translate to less run-off therefore making available more water in the soil for crop use. Positive responses of ponded infiltration to manure have been reported in other studies (Ekwue, 1992; Hati *et al.*, 2007). However, no changes in steady state infiltration rates were observed with cattle manure application on the sandy soil trials and this was attributed to lack of stable aggregates due to the low clay content (< 15 %) of the soils.

5.4.2 Pore density and total porosity

Pore density of pores < 600 μm that were included in the transport process were lower in the control treatments relative to the 25 tha^{-1} cattle manure treatments on clay long-term trial, subsequently, total effective porosity at the equivalent pressure head was lower. The

difference indicated the effect of cattle manure addition on soil porosity compared to no manure application. Cattle manure improved pore density and effective porosity as a result of improved soil aggregation. The response at 10 cm tension for pores $< 300\ \mu\text{m}$ was significant but of a lesser extent. This indicated that finer porosity was less susceptible to changes in management (Eynard *et al.*, 2004).

On the short-term clay fields pore density and total effective porosity were significantly different between fertility treatments and field type and there was an interaction between fertility and field type. Manure applied at $20\ \text{t ha}^{-1}$ resulted in the highest pore density than the other treatments. The results were however not consistent with ponded infiltration rates and unsaturated hydraulic conductivity at similar pressure head which could have been due to possible collapse of the soil structure under the tension infiltrometer (Watson and Luxmoore, 1986) since the measurements were conducted on saturated soil soon after double ring measurements.

The effect of cattle manure application and field treatment were however not significantly different on the sands after 6 years implying limited cattle manure effects on soil physical properties on sandy soils which could be attributed to the poor SOC stabilizing capacity due to the sandy nature ($> 85\%$ sand fraction) of the soil.

5.4.3 Unsaturated hydraulic conductivity, macroscopic capillary length and mean pore sizes

Infiltration rates under tension reflect differences in soil porosity, pore size distribution and stability (Eynard *et al.*, 2004). In this study measurements were conducted at 5 cm and 10 cm tensions which refer to pores $< 600\ \mu\text{m}$ and $< 300\ \mu\text{m}$ equivalent cylindrical diameter pores

active in water transmission, respectively. Mean pore size in 25 t ha⁻¹ cattle manure was significantly larger than in control at 5 cm tension which implied that cattle manure improved soil aggregation and consequently the size of pores conducting water under high potential. Consequently, hydraulic conductivity was higher in the manure treatments at 5 cm than in control treatments in the long-term clay fields. The increase in hydraulic conductivity with manure application was attributed to increased mean pore sizes and pore continuity due to better aggregation. Manure has been reported to increase soil organic matter, which binds soil particles together into aggregates, and this improves soil structure and favours downward flow of water into soil (Boyle *et al.*, 1989; Abrisquetta *et al.*, 2006).

A higher proportion of very fine macropores in grass > no-till > tillage treatments in a study by Eynard *et al.*, (2004) indicated greater biological activity, similarly, more macropores in manure treatments possibly suggested greater biological activity compared to plots where no manure was added. Hydraulic conductivity was directly affected by λ_c and λ_m and this was reflected in the consistency of results obtained for K_o , λ_c and λ_m in the clay long-term fields.

The sandy soil showed marginal changes in hydraulic properties after 6 years of manure application compared to no manure plots possibly because of low carbon stabilizing capacity and hence little structural change with manure. Consistent with steady state infiltration rates and effective porosity, hydraulic conductivity was not significantly different between treatments on the sandy long-term fields.

5.4.5 Moisture retention characteristics

Volumetric moisture content was significantly higher in 25 t ha⁻¹ cattle manure treatments than in control on long-term clay soils at 5 and 10 kPa suctions. The soil water retention

characteristic relates soil water potential to water content and can be used to assess water availability to plants since it expresses the water holding capacity of the soil (Nyamangara *et al.*, 2001). It can be used to assess changes in soil structure and management (Connolly, 1998). The effects of application of cattle manure to the soil were evident at the lower suctions because structural changes occur at lower suctions while at higher suction water retention is texturally controlled (Hillel, 1982). Available water capacity measured at 10 kPa as field capacity and 1500 kPa as permanent wilting point was approximately 55 and 50 % in 25 t ha⁻¹ manure and control plots respectively on the long-term clay field. This difference indicated that plants in the manure treatment would have more water available for uptake compared to control. Water holding capacity is controlled primarily by the number of pores and their size distribution and the specific surface area of the soils (Haynes and Naidoo, 1998). At higher suctions of 33, 100, 200 and 1500 kPa moisture retained was not significantly different between the fertility treatments. Soil texture (clay content) which is not affected by manure application is more important in controlling the volume of small and intra-aggregate pores (Hall, 1991). Marginally significant differences were observed in the short-term clay field at 5 kPa but at higher suctions and at all suctions in the outfield, there were no significant differences in moisture content.

Nyamangara *et al.*, (2001) reported significantly improved water retention with manure application in the first year at low suctions below 10 kPa in a loamy sand soil in Zimbabwe. In other long-term studies (Hati *et al.*, 2007; Chakraborty *et al.*, 2010) combinations of inorganic and farmyard manure resulted in increased moisture retention than sole inorganic fertilizer and control plots below 50 and 33 kPa respectively. In contrast, the sandy long-term fields did not show significant differences in moisture retention between treatments and these results were consistent with results obtained for infiltration rates as well as porosity and pore

size distribution owing to the little response observed between this soil type and SOM stabilization which in turn affects soil structure parameters.

5.5 Conclusion

Manure application in combination with inorganic fertilizer improved clay soil's physical properties and consequently soil's hydraulic properties. Increased steady state infiltration rates, hydraulic conductivity and moisture retention transform to increased available water capacity which is vital for crop growth and productivity. On clay soils manure application improved very fine macroporosity and subsequently the amount of water infiltration and retention in the soil. Equal cattle manure application resulted in improved physical environment, for both homefield and outfields in the long term. On the sandy soil, there were marginal effects of manure application on porosity and hydraulic conductivity after 6 years of addition possibly due to poor soil structure and low carbon stabilization capacity of the soil. The hypothesis that selected soil hydraulic properties improve with increasing manure application and that HFs and OFs have similar properties was therefore accepted for clay soils but rejected for the sandy soils.

Chapter 6

Investigating the effects of soil fertility management practices and selected soil physical properties on crop yields and crop water productivity through modelling

6.1 Introduction

A third of the African population faces widespread hunger and chronic malnutrition and is exposed to a constant threat of acute food crisis and famine (Haile, 2005). The most affected are rural households whose livelihoods are heavily dependent on traditional rain-fed agriculture. Arid and semi-arid or sub-humid zones are characterized by low erratic rainfall of below 700 mm per annum and inter-annual rainfall variability from 50-100 % and 20-50 % in the arid and semi-arid zones respectively (http://www.iisd.org/casl/ASALProject_Details. 25.02.10). Consequently, droughts are one of the risks affecting agricultural productivity and household food security (Haile, 2005). These effects are further compounded by the increasing global warming and the ultimate effect of climate change. Increasing efficiency of water use by crops is key to improving crop yields in these regions (Hatfield *et al.*, 2001).

Water use efficiency (WUE), represents a given level of biomass or grain yield per unit of water used by the crop (Hatfield *et al.*, 2001). It can also refer to a range of observations, gas exchange by individual leaves for a few minutes to grain yield for the whole season. In agriculture, it is linked to the effectiveness of the use of precipitation and as such the concept of crop water productivity (CWP) has evolved from what is traditionally referred in literature as water use efficiency (WUE) (Steduto and Albrizio, 2005). In physical terms, CWP refers

to the ratio of the product, which is usually the weight biomass of harvestable component (fresh or dry) to that amount of water depleted or applied (Kijne *et al.*, 2002) expressed in terms of cumulative transpiration (Hillel, 1982) or cumulative evapotranspiration. Crop water productivity is thus governed by the same parameters influencing WUE.

Musick *et al.*, (1994) reported increased wheat yield with soil modifying management strategies resulting in increased WUE. Modification of the soil surface will lead to changes in the soil water balance in terms of soil water evaporation and infiltration into the soil profile (Hatfield *et al.*, 2001) and therefore have potentially positive impacts on WUE and/ or CWP. Organic amendments such as manure are reported to increase soil organic matter (SOM) which binds soil particles together into aggregates thereby improving soil structure which favours the downward flow of water into the soil (Boyle *et al.*, 1989; Hudson, 1994).

Numerous studies have been conducted on the various aspects of crop yield to water relations (Dorenbos and Kassam, 1979; Hatfield *et al.*, 2001; Zhang *et al.*, 2003). Most studies have used actual evapotranspiration (Zwart and Bastiaansen, 2004) because transpiration is difficult to measure at field scale (Kijne *et al.*, 2002) and also because transpiration and evapotranspiration are strongly correlated particularly after complete canopy formation. Further, given the problems associated with measuring the various components of the field water balance, it is easier to make use of modelling (Cassa *et al.*, 2000).

Aquacrop, a yield-response to water model developed by FAO provides a method of estimating attainable yield under water- limiting conditions in arid and semi-arid environments (Raes *et al.*, 2008). Yield is calculated on the basis of water stress that occurs during each critical stage of development using K_y factor (Dorenbos and Kassan, 1979). As

compared to other crop models, Aquacrop has a significantly smaller number of parameters and a better balance between simplicity, accuracy and robustness (Steduto *et al.*, 2008). Its driving growth engine is expressed in the equation 2.5.

In addition, correlation and multiple linear regression techniques have been used to identify the important soil properties affecting crop yields. The use of such techniques, offers opportunities of determining soil factors affecting crop yields on which to base management decisions. This process is complex due to the interactions among various factors (Ayoubi *et al.*, 2009). However, the problem of correlation among variables can be circumvented by using multi-variate techniques, such as principal component analysis (PCA) and factor analysis (FA) (Hair *et al.*, 1987; Kaspar *et al.*, 2004).

6.2 Materials and Methods

Experiments 1 and 2 which are the long-term and short-term trials respectively were used. Details of the general description of the experimental sites and their management are given in sections 3.2.1 and 3.2.2. In this study observed crop yields were measured over two seasons (2007-08 and 2008-09) on the short and long-term experimental fields. Aquacrop model was used to obtain actual cumulative transpiration which was used to calculate crop water productivity on the long term fields. Modelling was not done on short-term fields due to financial constraints experienced in the second season. Multiple linear regression techniques were used to model the soil physical properties with the largest effect on crop yields within the experimental management regimes

6.2.1 Grain yield

Harvest for grain yield determination was done from the net plots (1.8x2 m²) for each treatment. A crop moisture meter was used to measure moisture content of the grain at harvest. The fresh weight was then standardized by adjusting to 12.5% and 11 % moisture content for maize and soybean respectively.

6.2.2 Crop water productivity modelling using AquaCrop

There are four modules involved when modelling using AquaCrop and they are the weather, soil, crop and management modules.

6.2.2.1 Estimating Evapotranspiration (ET)

Reference Evapotranspiration (ET₀) was calculated from the FAO Penman-Monteith equation (Equation 6.1) (Allen *et al.*, 1998). Daily weather data of maximum, minimum daily temperature, solar radiation, net radiation, relative humidity and horizontal wind speed at 2 m were obtained from the nearest meteorological station in Marondera, approximately 60 km away from the site while rainfall was measured onsite using rain gauges. The weather data was processed into daily values and used to calculate ET₀ using a submodel within the model.

$$ET_0 = \frac{0.408(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (6.1)$$

Where, ET₀ is the reference evapotranspiration (mm day⁻¹), R_n is the net radiation at the crop surface (MJ m⁻² day⁻¹), G is the soil heat flux density (MJ m⁻² day⁻¹) which is considered

negligible on a daily time scale, T is the mean daily air temperature at 2 m height ($^{\circ}\text{C}$), u_2 is the wind speed at 2 m height (m s^{-1}), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), Δ is the slope of saturation vapour pressure temperature relationship ($\text{kPa } ^{\circ}\text{C}^{-1}$) and γ is the psychrometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$).

6.2.2.2 Soil parameters used to simulate evaporation

Soil samples for field capacity, permanent wilting point, available water content moisture retention characteristics in the surface horizons were obtained as undisturbed cores in April 2008 soon after harvest (section 4.2.1). Field capacity (FC) was determined at 10 KPa for medium to heavy textured soils, while permanent wilting point (PWP) was determined at 1500 kPa following guidelines by Landon, (1984) (section 4.2.3). Available water capacity was obtained as the difference in volumetric moisture content at FC and PWP. Volumetric moisture was obtained from the relationship:

$$\theta_v = \theta_g \cdot \rho_b / \rho_w \quad (6.2)$$

Where θ_v is volumetric moisture content, θ_g is the gravimetric moisture content and ρ_b is the bulk density of the soil obtained in section 4.2.3. ρ_w is density of water.

Soil profile descriptions for the two experimental sites were done close to the experimental fields (approximately 1-1.5 m away to avoid disturbing the experimental plots) to determine soil profile characteristics. The profile characteristics are given in Appendix 2. Horizon thicknesses together with the textural classes were then used to define the sub-surface soil water characteristics of FC, PWP, AWC for the replicate treatments under study using pedotransfer functions within the model. AquaCrop performed a water balance that kept track of daily incoming and outgoing water fluxes through pedotransfer functions that simulated

run-off (through curve number), infiltration, internal drainage or redistribution, deep percolation and capillary rise in the soil profile.

6.2.2.3 Crop parameters used to simulate transpiration

The crop parameters required to input into the crop module included date of sowing, date of harvest, length of the growing season, crop coefficient (K_c) and rooting depth. Records for dates of sowing and harvest dates were recorded when these activities were carried out and length of the growing season was calculated as the number of days from date of sowing until harvest date. Crop coefficient (K_c) was obtained from the SeedCo crop manual (2004) where it is provided by the producer Seed Company of Zimbabwe for the different seed varieties that they produce. Rooting depth was determined immediately after harvesting the maize crop by digging pits up to 0.7 m adjacent to the control and 25 t ha⁻¹ manure treatments which was a destructive method, therefore only the extreme treatments were considered in modelling CWP. The crop parameters were then used to simulate transpiration.

6.2.2.4 The management module

Field management practices that included soil mulch, ploughing, ridges and soil fertility were specified in the model. These were based on actual field management practices that were done in the fields. For the control plots no external amendments were added therefore nothing was specified, while fertilizers and manure use were specified for the fertilizer treatments.

6.2.3 Validation of AquaCrop Model

To validate AquaCrop model, actual soil moisture content of the soil was measured and compared with simulated moisture content. Actual soil moisture was determined gravimetrically using the auger method. The soil samples were augured from each horizon as determined in the profile descriptions and up to 60 cm on clay soils because of hindrances by stones and boulders beyond this depth (Appendix 2). Moisture content was measured at planting, 2 weeks after crop emergence (WAE), 6 WAE , 10 WAE and 14 WAE. Soil samples from each replicate were augured, stored in labelled plastic sampling bags which were securely tied and transported to the laboratory. In the laboratory they were immediately weighed and oven dried at 105 °C for at least 24 hours. The actual soil moisture content data was obtained as the mean for the 3 replicates for each treatment and was plotted against simulated moisture content and the R^2 statistic was obtained through a simple regression analysis. In addition, two statistical criteria namely, normalized deviation (ND) and model efficiency (EF) were used to further evaluate the model (Beaudoin *et al.*, 2008).

$$ND = \frac{\sum_{i=1}^n Oi - \sum_{i=1}^n Si}{\sum_{i=1}^n Oi} \quad (6.1)$$

$$EF = \frac{\sum_{i=1}^n (Oi - \bar{O})^2 - \sum_{i=1}^n (Si - Oi)^2}{\sum_{i=1}^n (Oi - \bar{O})^2} \quad (6.2)$$

Where Si is simulated moisture content, Oi is observed and $\bar{O}$ is the mean observed value.

6.2.4 Calculation of crop water productivity

Water productivity in this study was defined as the ratio of harvestable grain yield to cumulative transpiration. The validated AquaCrop model was used to estimate daily actual crop transpiration and cumulative transpiration for the entire growing season. This was achieved through a simple water budget submodel to account for the water inputs and outputs into the root zone. Actual grain yield used for CWP calculation was the same as that obtained from the net plots (section 6.5).

6.2.5 Principal components analysis theory

Principal component analysis is an exploratory method that helps learn from the data about interrelations between variables and objects (Sena *et al.*, 2002). It aims at data reduction through linear combinations of the original variables (Marten and Naes, 1989). The resulting principal components (PCs) or factors account for the maximum variance within the data set and can be utilized to represent the whole data set in a simpler manner (Sena *et al.*, 2002). The PCs are orthogonal and independent therefore it is possible to investigate the interrelations among the variables through the respective variable loadings. The size of the variable loadings in relation to the considered PC is a measure of the importance of that variable for the PC model. Total variance of each PC is defined as eigenvalue (Swan and Sandilands, 1995) and PCs or factors with eigenvalues ≥ 1 (Bredja *et al.*, 2000) and those that explained at least 5 % of the variation in the data (Wander and Bollero, 1998) are retained for the subsequent regression analyses.

6.2.5.1 Multiple regression modelling

The method used involved use of principal component analysis (Jagadamma *et al.*, 2008). Analysis of variance (ANOVA) of soil physical properties including SOC, bulk density, aggregate stability, aggregate protected carbon, steady state infiltration rates, unsaturated hydraulic conductivity and total effective porosity was done using Genstat 7.1 statistical package in preceding chapters (chapter 4 & 5). Only those properties that showed significant differences ($p < 0.05$) between fertility and field-type treatments were used in the multiple regression analysis in this study. All retained physical properties were subjected to correlation analysis using the Pearson Product Moment Correlation in Sigma plot 11.0 to identify associations between soil properties and crop yields. Principal component analysis was used to eliminate multi-collinearity between variables that have common underlying effects (Ayoubi *et al.*, 2009) on maize grain yields. Soil properties constituting a PC or factor were selected based on the correlation coefficients or variable loadings in that factor (Sharma, 1996; Johnson and Wichern, 1992). Soil properties with variable loadings > 0.4 were chosen to be included in the factors as there are no established rules to help decide what a 'large' variable loading is (Mallarino *et al.*, 1999). If the variable loading was > 0.4 in more than one factor, it was included in the factor having the highest coefficient value for that property. The resulting groups of factors which were mutually orthogonal and uncorrelated (Sena *et al.*, 2002) were then used in multiple regression modelling. Multiple regressions were performed using SigmaPlot 11.0 statistical package.

6.3 Results

6.3.1 Rainfall data

A total of 811 mm and 672 mm of rainfall was received during 2007-08 and 08-09 seasons respectively. The rainfall pattern was almost similar for the two years, although slight differences were observed during some months. Most of the rainfall was received during the month of January in 2007-08 while in 2008-09 distribution was almost even. The rainfall received in 2007-08 fell within the average range (800-1000 mm) for the region while below average rain was received in the season of 2008-09.

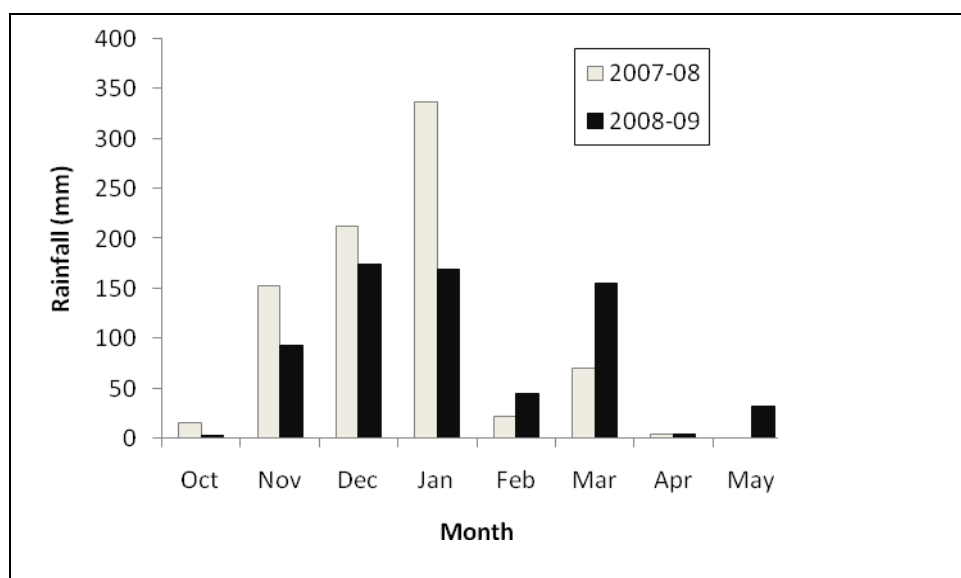


Figure 6.1: Rainfall distribution in Murewa , 2007-08 and 2008-09 seasons

6.3.2 Observed Grain Yields

6.3.2.1 Grain yield on the long-term fields

Maize grain yield was increased ($p < 0.05$) by at least 2.8 times on clay soils when fertilizer was applied at 100 kg ha^{-1} in combination with at least 5 t ha^{-1} cattle manure compared to control (Table 6.1). Amongst the cattle manure application rates, 5 t ha^{-1} yielded significantly

lower than 15 and 25 tha^{-1} while there was no statistical difference between application at 15 and 25 tha^{-1} (Table 6.1).

On the other hand, sandy soil's grain yields significantly increased by at least 3.5 times with 5 tha^{-1} cattle manure compared to control. Mean grain yield for 5, 15 + 25 tha^{-1} cattle manure rates in 2007-08 season was 2.5 tha^{-1} and 1.84 tha^{-1} on clay and sandy soil respectively. Compared to the mean yield on control plots (0.6 clay and 0.17 sandy tha^{-1}) the change in grain yield due to fertilizer and cattle manure application was twice greater on sands than clay soil. Generally grain yield was higher in 2008-09 season (maximum of 4.7 tha^{-1}) than 2007-08 (Table 6.1), although rainfall was higher in the former season, probably due to other factors such as early planting in the latter season.

Table 6. 1 Observed maize grain yield for two seasons on the long-term fields

<u>Clay long-term maize grain yield (t ha^{-1})</u>				
	2007-08		2008-09	
Treatment	HF	OF	HF	OF
Control	0.53 ^a	0.65 ^a	0.9 ^a	0.9 ^a
5 t ha^{-1} M +100 kg ha^{-1} N	1.58 ^{ab}	1.85 ^b	3.4 ^b	2.7 ^b
15 t ha^{-1} M +100 kg ha^{-1} N	3.32 ^c	2.08 ^b	4.5 ^c	4.2 ^{bc}
25 t ha^{-1} M +100 kg ha^{-1} N	3.35 ^c	2.99 ^{bc}	4.7 ^c	4.3 ^c
LSD	1.15		0.8	
<u>Sandy long-term maize grain yield (t ha^{-1})</u>				
	2007-08		2008-09	
Treatment	HF	OF	HF	OF
Control	0.26 ^a	0.07 ^a	0.4 ^a	0.2 ^a
5 t ha^{-1} M +100 kg ha^{-1} N	0.93 ^b	1.43 ^{bc}	2.3 ^c	0.75 ^b
15 t ha^{-1} M +100 kg ha^{-1} N	1.74 ^c	2.44 ^d	3.3 ^d	1.9 ^c

25 t ha ⁻¹ M + 100 kg ha ⁻¹ N	1.97 ^c	2.5 ^d	3.3 ^d	2.3 ^c
LSD	0.59		0.53	

Values in the same column followed by the same letter are not significantly different at $P < 0.05$.

6.3.2.2 Grain yield on the short-term fields

Soybean grain yield on clay fields significantly ($p < 0.05$) increased from control (mean 1.2 t ha⁻¹) by 75 % when mineral fertilizer only was applied and by at least 87.5 % when mineral fertilizer was applied with at least 5 t ha⁻¹ cattle manure. Unlike long-term fields, addition of cattle manure at rates between 5-20 t ha⁻¹ for one season did not result in any significant yield differences amongst the manure rates (Table 6.2). Mean soybean grain yield on sandy soils was 0.7 t ha⁻¹ in control with an increase of 100 % and 143 % with addition of mineral fertilizer only and fertilizer combined with at least 5 t ha⁻¹ cattle manure respectively. Generally, yields between homefields and outfields were in the same range, therefore the trend observed was in the order varied as clay HF $\approx$ clay OF $>$ sandy HF $\approx$ sandy OF.

In the second season, maize grain yield on clay soil increased by 3.5 times and at least 4 times with sole mineral fertilizer and combined cattle manure and fertilizer respectively over control ($P < 0.05$). Maize grain yields were higher on clay (2.5 – 4.5 t ha⁻¹) than sandy soils (1.8 - 2.9 t ha⁻¹). Addition of mineral fertilizer and 20 t ha⁻¹ cattle manure significantly out-yielded application between 5-15 t ha⁻¹ cattle manure (Table 6.2). On all field types, the control yielded less than a tonne per hectare (Table 6.2).

Table 6. 2 Soybean and maize grain yields on the short-term fields during the two seasons

<u>Clay Short-term grain yield (t ha⁻¹)</u>				
	2007-08 (Soybean)		2008-09 (Maize)	
Treatment	HF	OF	HF	OF
Control	1.26 ^a	1.14 ^a	0.90 ^a	0.50 ^a
Mineral fertilizer only	2.05 ^b	2.14 ^{bc}	2.50 ^b	2.73 ^b
5 t ha ⁻¹ M + mineral fertilizer	2.29 ^{bc}	2.20 ^{bc}	3.79 ^c	2.68 ^b
10 t ha ⁻¹ M + mineral fertilizer	2.34 ^{bc}	2.49 ^{bc}	4.00 ^{cd}	2.88 ^b
15 t ha ⁻¹ M + mineral fertilizer	2.94 ^{bc}	2.59 ^{bc}	4.38 ^{cd}	3.26 ^{bc}
20 t ha ⁻¹ M + mineral fertilizer	3.07 ^c	3.00 ^c	4.43 ^d	3.69 ^c
LSD	0.90		0.71	

<u>Sandy short-term grain yield (t ha⁻¹)</u>				
	2007-08 (Soybean)		2008-09 (Maize)	
Treatment	HF	OF	HF	OF
Control	0.92 ^a	0.50 ^a	0.85 ^a	0.74 ^a
Mineral fertilizer only	1.80 ^b	1.20 ^a	1.88 ^b	1.98 ^b
5 t ha ⁻¹ M + mineral fertilizer	1.90 ^{bc}	1.56 ^{ab}	2.20 ^{bc}	1.83 ^b
10 t ha ⁻¹ M + mineral fertilizer	2.23 ^{bc}	1.59 ^{bc}	2.62 ^{bc}	1.92 ^b
15 t ha ⁻¹ M + mineral fertilizer	2.42 ^c	1.90 ^{bc}	2.34 ^{bc}	2.11 ^b
20 t ha ⁻¹ M + mineral fertilizer	2.66 ^c	2.10 ^c	2.92 ^c	2.44 ^{bc}
LSD	0.71		0.79	

*mineral fertilizer refers to application rates: N, P, K, Ca, Mg, Zn and B at 100, 30, 29, 20, 10, and 5 kg ha⁻¹ respectively. For soybean N was @ 40 kg ha⁻¹

6.4.1 Crop parameters used in the model to simulate transpiration

The sandy fields were planted at the beginning of December 2007 and as a result the length of growing days was longer than for the clay soils which were planted later in the same month. The difference in planting dates could have played a significant role in the resultant predicted and observed yields as the amount of precipitation used would inevitably be different. The same seed variety was planted and therefore the crop coefficient and growth stages were the same. Rooting depth depends on a number of factors such as availability of moisture, nutrients and ease of penetration, therefore for the two soil types and fertility treatments there were differences in rooting depth (Table 6.3).

Table 6. 3 Crop parameters used to simulate crop transpiration during 2007-08 season on both clay and sandy soils.

Crop parameter	Clay sites		Sandy sites	
	Control	25 t/ha manure + 100 kg/ha N	Control	25 t/ha manure + 100 kg/ha N
Sowing date	23.12.07	23.12.07	03.12.07	03.12.07
Harvest date	01.05.08	01.05.08	24.04.08	24.04.08
Length of growing season (days)	131	131	143	143
K _c during the crop development stages	0.3 (I), 1.2 (M), 0.6 (L)	0.3 (I), 1.2 (M), 0.6 (L)	0.3 (I), 1.2 (M), 0.35 (L)	0.3 (I), 1.2 (M), 0.35 (L)
Growth stages (days)	I (20), CD (40), M (50), 30 (L)	I (20), CD (40), M (50), 30 (L)	I (20), CD (40), M (50), 30 (L)	I (20), CD (40), M (50), 30 (L)
Measured rooting depth (m)	0.38	0.65	0.38	0.7

Where I is the initial growth stage, CD is crop development stage, M is mid-season and L is the late season stage as given in the SeedCo manual. K_c is the crop coefficient

6.4.2 Soil parameters used to simulate evaporation

The soil parameters were used to generate daily incoming and outgoing fluxes in the water balance. The soil parameters that were used included field capacity, permanent wilting point, saturation water content. Clay soils showed higher water contents compared to the sandy soils which retained less water (Table 6.4). The separation of evapotranspiration into soil evaporation and crop transpiration was done to avoid the confounding effect of non-productive consumptive use of water through evaporation (Raes *et al.*, 2008).

Table 6. 4 Initial soil parameters used to simulate crop transpiration on clay soils.

Soil parameter	Control			25 t/ha manure + 100 kg/ha N		
	1 st layer	2 nd layer	3 layer	1 st layer	2 nd layer	3 layer
Layer thickness (m)	0.13	0.25	0.20	0.13	0.25	0.20
Textural class	Clay	Clay	Clay	Clay	Clay	Clay
Saturation water content (vol %)	50	60	68	53	64	69
FC (vol %)	31	33.5	33.5	33	35	36
PWP (vol %)	17.4	17.4	17.4	18	18	18
Curve No.	75			75		

Table 6.5 Initial soil parameters used to simulate crop transpiration on sandy soils

Soil parameter	Control				25 t/ha manure + 100 kg/ha N			
	1 st layer	2 nd layer	3 rd layer	4 th layer	1 st layer	2 nd layer	3 rd layer	4 th layer
Layer thickness (m)	0.14	0.36	0.23	0.47	0.14	0.36	0.23	0.47
Textural class	Coarse loamy sand	Coarse loamy sand	Coarse loamy sand	Coarse sandy loam	Coarse loamy sand	Coarse loamy sand	Coarse loamy sand	Coarse sandy loam
Sat water cont* (vol %)	38	38	37.6	35	38	38	38.4	41
FC (vol %)	12	12	12.8	18	26	26	27	34

PWP (vol %)	4	4	7.8	10	8	8	8.3	10
Curve No.	65							

Sat water cont* is saturation water content

6.5 Validation of AquaCrop model

The R^2 value obtained from the regression relationship between observed and simulated root zone water content was 0.75 which was highly positive and significant ($p < 0.0001$). The values obtained for ND and EF were 0.08 and 0.57 respectively as calculated from the equations 6.1 and 6.2 respectively. Calibration was considered as adequate since the values fell within acceptable limits of $ND < 0.1$ and $EF > 0.5$ (Beaudoin *et al.*, 2008), therefore the validity of the water balance sub-model of AquaCrop in simulation of root zone moisture content was confirmed.

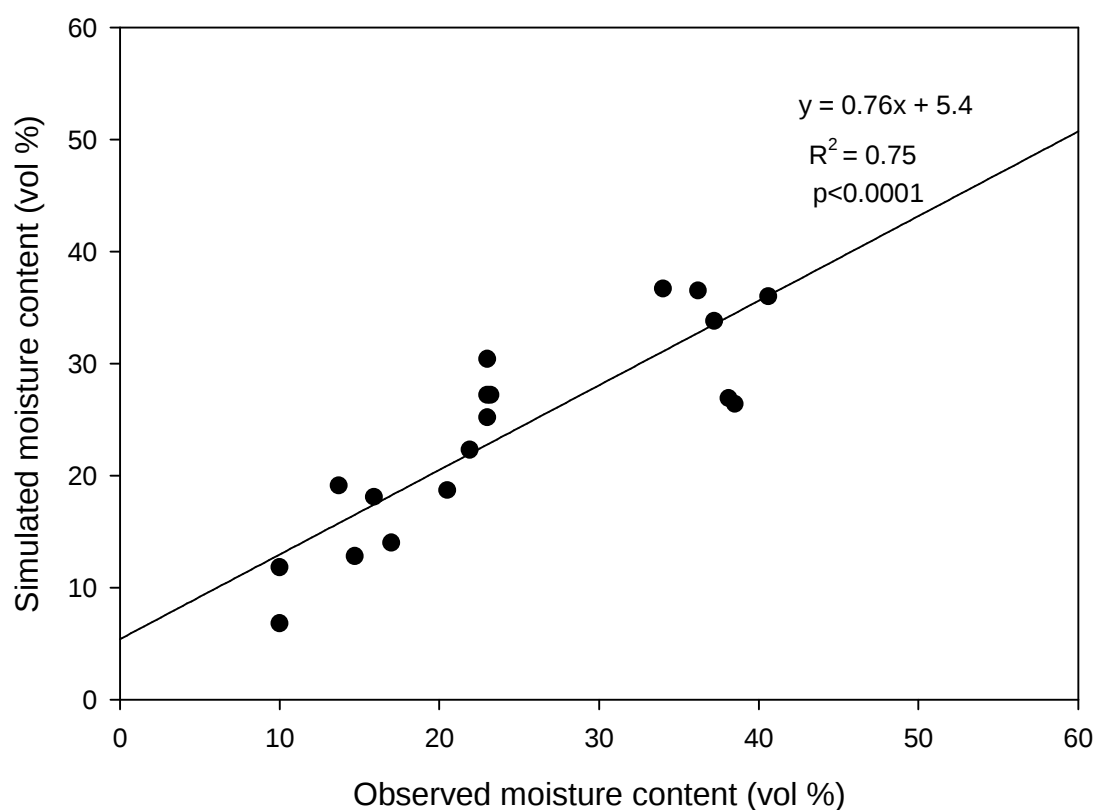


Figure 6.2: Regression graph between observed and simulated root zone moisture content

6.6 Crop water productivity

Crop water productivity expressed per cumulative transpiration was significantly increased by more than 5 times in plots where cattle manure was added at 25 t ha^{-1} than control plots on clay soil. On the other hand, sandy soils' CWP was at least 4 times higher in 25 t ha^{-1} cattle manure relative to control. There were however no significant differences in CWP between the two field types on sand while on the clay soil cattle manure application increased CWP by 25 % more on the homefield than outfield (Fig 6.3).

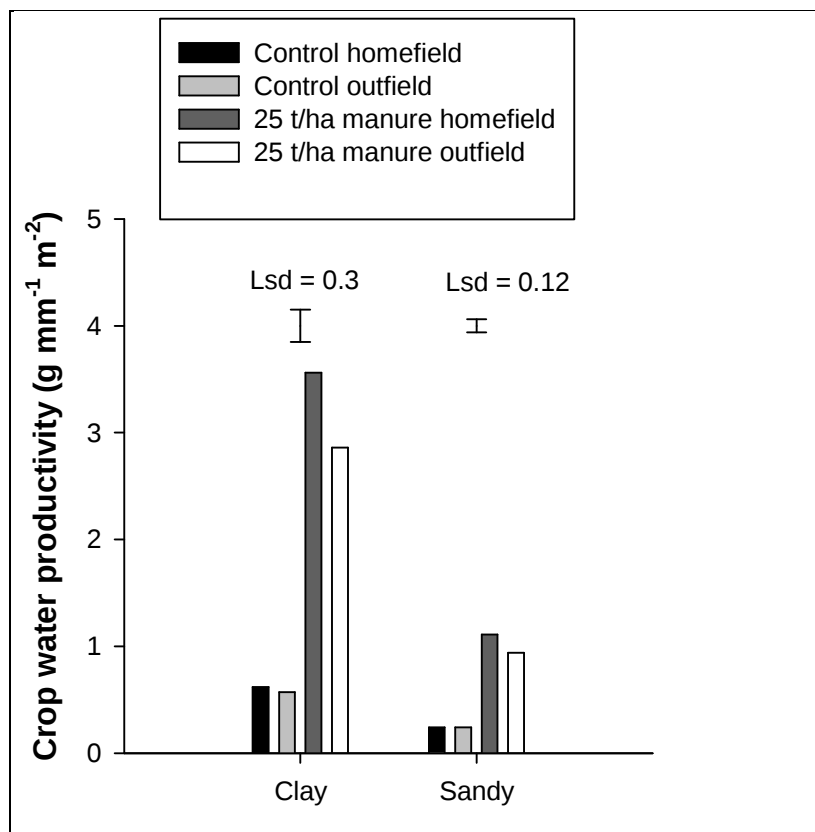


Figure 6.3: Crop water productivity using actual transpiration on long-term clay and sandy soils.

6.7 Multiple regression modelling

6.7.1 Multiple regression modelling on the long-term clay fields

On the long-term clay fields the soil physical properties that were considered for correlation analysis were SOC, Ima, aggregate protected carbon (APC), steady state infiltration rates as well as hydraulic conductivity and total effective porosity at 5 cm which showed significant changes with fertility management (Chapter 4 & 5). Maize grain yield was significantly and positively correlated to SOC, Ima, i.rates and porosity ($r^2 > 0.68$) (Table 6.5).

Table 6.6 Pearson's correlation coefficients and *p* values for soil properties and maize grain yield on the long-term clay field

	Ima	APC	i.rates	Porosity	Ko	Yield
SOC	0.66 <i><0.001</i>	0.12 <i>0.61</i>	0.83 <i><0.001</i>	0.72 <i>0.05</i>	0.32 <i>0.32</i>	0.68 <i><0.001</i>
Ima		0.21 <i>0.33</i>	0.83 <i><0.001</i>	0.82 <i><0.001</i>	-0.08 <i>0.80</i>	0.85 <i><0.001</i>
A PC			0.41 <i>0.19</i>	0.50 <i>0.09</i>	0.06 <i>0.84</i>	0.14 <i>0.51</i>
i.rates				0.86 <i>0.001</i>	0.21 <i>0.51</i>	0.93 <i><0.001</i>
Porosity					0.05 <i>0.88</i>	0.84 <i><0.001</i>
K _o						0.10 <i>0.75</i>
Yield						1

Values in italics are *p* values. SOC, soil organic carbon; Ima, macro-aggregation indices; APC, aggregate protected carbon; i.rates, steady state infiltration rates; TEP, total effective porosity; K_o, hydraulic conductivity

When these soil properties were subjected to PCA loading factors > 0.4 were obtained in one factor (factor 1) which explained 59.9 % of the variation (Table 6.6). Factor 2 and factor 3 had small eigenvalues of 0.99 and 0.91 respectively and consequently could not be used in the regression equation. Factor 1 was used in mapping the regression model that best explained variation in maize grain yield with respect to the soil physical properties studied. The model was highly significant ($p < 0.001$, $r^2 = 95.3$). The best fit model included Ima and steady state infiltration rates, while SOC and total effective porosity were not retained. The regression equation was given by:

$$\text{Yield} = 0.01(\text{Ima}) + 0.15(\text{steady state infiltration rate}) - 1.6 \quad (6.3)$$

Table 6.7 Principal components for the clay long-term field

Variable	Factor		
	Factor 1	Factor 2	Factor 3
Initial eigenvalue	3.59	0.99	0.92
Proportional variance explained (%)	59.90	-	-
Cumulative variance explained (%)	59.90	-	-
SOC	0.46	-0.26	0.30
Ima	0.47	0.22	0.26
APC	0.25	0.21	-0.88
i.rates	0.51	-0.05	0.03
TEP	0.49	0.15	-0.07
K _o	0.10	-0.90	-0.23

SOC, soil organic carbon; Ima, macro-aggregation indices; APC, aggregate protected carbon; i.rates, steady state infiltration rates; TEP, total effective porosity; K_o, hydraulic conductivity

6.7.2 Multiple regression modelling on the long-term sandy fields

Soil organic carbon, steady state infiltration rates (i.rates) and hydraulic conductivity showed a significant change in long-term sandy fields under fertility and field-type treatment as measured in the preceding chapters (Chapter 4& 5). Correlation analysis showed a positive and significant relationship between yield and SOC only ($p < 0.05$, $r = 0.89$). Consequently, linear regression was performed between the two, and a simple linear model (equation 6.4) was obtained. The correlation matrix is given in appendix 1.

$$\text{Yield} = 1.41(\text{SOC}) - 0.24 \quad (6.4)$$

6.7.3 Multiple regression modelling on the short-term clay fields

The soil properties that were considered for correlation on the short-term clay fields included SOC, macro-aggregate stability (Ima), aggregate protected carbon (APC), steady state infiltration rates, total effective porosity (TEP) and hydraulic conductivity. Maize grain yield was positively correlated with SOC, Ima, APC, steady state infiltration rates and total effective porosity ($r^2 > 0.78$). When subjected to a multiple regression analysis multicollinearity existed between Ima and APC, and also between steady state infiltration rate and total effective porosity (Appendix 1). The correlated variables were pooled together to form one factor that explained 89.6 % of the total variance in grain. A simple linear regression analysis between this factor and yield gave the model in equation 6.5 ($p < 0.05$, $r^2 = 0.7$).

$$\text{Yield} = 1.25 + 3.6 \times 10^{-6} (\text{pooled factor}) \quad (6.5)$$

No regression analyses were done for the short-term sandy fields due to lack of significant changes on soil physical properties under soil fertility and field-type effects (chapter 4 & 5).

6.8 Discussion

6.8.1 Grain yields

Manure application and mineral fertilizer increased maize grain yield by at least 2.8 times on clay soils and by more than 3.5 times on sandy soil compared to control. Organic resources are considered crucial for sustainable crop production in smallholder farming systems. According to Giller (2002), crop yields are increased under combined organic and inorganic fertilization due to (i) addition of multiple nutrients including P, base cations and micronutrients, (ii) improvement of the physical properties and (iii) the improvement of synchrony between the availability of N and its demand by crops.

The higher grain yields on clays were partly attributed to better fertility and higher SOC, pH, CEC (Grant, 1981) on such soils than on the inherently infertile granite derived sandy soils (Nyamapfene, 1991). Similar results, where clay soils have shown better yields than sands were also reported by Zingore *et al.*, (2008) working in the same area.

There was a steeper yield gradient between control and mineral fertilizer + manure treatments on sandy soils than clay soils, yield increase was twice as high in sands than clay and was credited to the ability of clay soils to support plant life better than sands even without external fertilizer application due to inherent fertility.

Soil fertility gradients initially reported by Zingore (2006) were reduced after 6 years of mineral fertilizer + cattle manure application to both homefields and outfields. This implies that resources not limiting, it can take at least 6 years to reclaim outfields to productivity. However, with the scarcity of manure and the poor quality of manure (Mugwira and

Murwira, 1998; Mtambanengwe and Mapfumo, 2006; Materechera, 2010) within farm fertility variability will probably remain a characteristic of smallholder farmers fields. It was noted that 15 and 25 tha^{-1} cattle manure application resulted in similar crop yields, therefore it is efficient to apply the scarce manure resource at the lower rate and achieve greater area coverage.

Cattle manure + mineral fertilizer also significantly increased soybean yield in one season. These results show that it is necessary to apply fertiliser to legumes contrary to the traditional farmer practices where legumes are mostly cropped without or with little fertilizer (Zingore, 2006). The use of rhizobia inoculants is on the other hand an economic way that can be used to boost soybean productivity in smallholder farming systems. This has the advantage of possibly increasing farm income since most legume crops are grown for marketing. In addition, increased biomass production results in large biomass additions of the N rich residues to the soil and utilization of residual fertility by the next crop in the rotation cycle.

6.8.2 Crop water productivity

AquaCrop's water balance sub-model was satisfactorily calibrated and validated for Murewa climatic conditions. Three methods were used in the validation process. The R^2 value obtained when simulated soil moisture data was regressed against actual moisture content was significant, showing the strength of the water balance sub-model in simulating actual root zone moisture content. Further, the model was quantitatively validated using normalized deviation (ND) and model efficiency (EF) and the values obtained were within acceptable limits therefore AquaCrop was accepted for estimation of actual transpiration.

Crop water productivity was significantly higher in 25 t ha⁻¹ manure + 100 kg ha⁻¹ N treatment than control on both soil types. Expressed as a function of transpiration, CWP gives the amount of harvestable yield that can be realized for every mm of water that is lost through transpiration. Water consumption in the form of transpiration occurs at a cost to crop growth. However, it is beneficial in that it occurs when the plant's stomata open to allow assimilation of CO₂, which is a raw material in carbohydrate formation during the process of photosynthesis. Therefore, crop transpiration is more beneficial to the crop when for the same amount of water lost, more harvestable yield is realized. In this study more than 4 times more grain was predicted to be produced when 25 t ha⁻¹ cattle manure + 100 kg ha⁻¹ N was added to the soil compared to control.

Crop water productivity values obtained for actual transpiration were consistent with other values reported in literature. Dujmovich *et al.*, (1996) reported CWP (grain to transpiration) values between 2.33-5.86 g mm⁻¹ m⁻² under sub-humid conditions of Argentine while Zwart and Bastiaansen, (2004) reported values between 0.2-3.99 g mm⁻¹ m⁻² (grain to evapotranspiration) in literature from Latin American continents and some examples from Africa. In Zimbabwe values between 7.7- 9.5 g mm⁻¹ m⁻² were reported for maize in Harare by Magodo (2007), although it is of importance to note that these values were obtained using a water balance model (BUDGET). Furthermore, the difference with values obtained in this study could be due to the fact that experiments by Magodo (2007) were done under irrigation conditions in a commercial farm *vis-a-vis* rainfed conditions in smallholder farming areas in this study.

Application of fertilizer and manure could have increased crop growth and root development than no application (Hati *et al.*, 2006). This implied that the crops could utilize soil water

from deeper horizons which on the other hand could not be accessed by shallow rooted plants in control. Increased crop growth implied better canopy cover which consequently reduced water loss from the soil surface as evaporation.

The results obtained in this study conform to the adaptation mechanisms recommended by Rockström *et al.*, (2003) for increased CWP. These include increased plant water availability through maximum rainfall infiltration, minimizing of unproductive water losses (evaporation, run-off), and increased soil water holding capacity and maximized root depth. Further, experiences in Burkina Fasso have shown that water management alone is not enough in CWP improving strategies, but soil fertility management plays an important a role too, greater CWP was realized with fertilizer application than supplementary irrigation alone (Rockström *et al.*, 2003).

6.8.3 Multiple regression analysis

Correlation analysis among soil variables showed that there were significant correlations between SOC, macro-aggregation indices, aggregate protected carbon, steady state infiltration rates and effective porosity. It further, highlighted the significant correlation existing between the soil parameters and maize grain yield.

Existence of correlations amongst the soil properties caused multi-collinearity to be reported when the soil parameters were subjected to multiple regression analysis with yield. Principal component analysis provided a rational criterion for including and arranging correlated variables in multiple regression models relating yield with soil parameters (Ayoubi *et al.*,

2009). Strong and positive correlation between SOC and macro-aggregation indices were reported, while steady state infiltration rates was correlated with total effective porosity. A resulting factor arising from the combined effect of the correlated parameters explained 59.9 % of the variation in grain on clay long-term field. Chakraborty *et al.*, (2010) also reported very strong and positive correlation between aggregation indices and SOC. These results are further substantiated by the findings of Acharya *et al.*, 1988 and Hati *et al.*, (2006) who reported increased aggregation with long-term application of mineral fertilizer and manure. Consequently, maize grain yield for the study sites in the specified season could be predicted from the soil parameters including SOC, Ima, steady state infiltration rates as shown by the regression model (Equation 6.3). Significant positive correlations between maize grain yield and SOM, water stable aggregates (WSA) and available water capacity have also been reported by Shuckla *et al.*, (2004).

In contrast to clay soils, sandy soil's grain yield could be predicted from SOC only ($p < 0.05$; $r = 0.89$) because there was no improvement in the measured soil physical properties with increase in cattle manure application.

The soil physical properties studied in this study could partially explain the variance in crop yield and the remaining variance could have belonged to non-measured variables such as chemical properties, biological properties and management practices such as weed control within the fields.

6.9 Conclusion

Combined cattle manure and mineral fertilizer application is important to increase crop water productivity therefore it can be used as mitigation measure to dissipate the effects of poor and erratic rainfall in semi-arid areas of Zimbabwe. In terms of grain yield, efficient cattle manure application rate after 6 years was at 5 t ha⁻¹ on the sandy soil, while for the clay soil 15 t ha⁻¹ achieved both improved soil physical properties and crop yields. Soil organic carbon, macro-aggregation indices, total effective porosity and infiltration rates explained the greatest variation in grain yield on clay soils therefore soil fertility management that attempts to attain optimum physical health will result in improved crop yields. In contrast, concomitant yield increases were attained with SOC increases on sandy soils. It should however be noted that for recommendations to be made across sites, based on CWP and multiple regression modelling a wide range of climatic conditions, field and soil types have to be considered, therefore the results obtained in this study are only valid for the specified fields and season. The hypothesis that inorganic and organic fertilizer application improves yields to similar levels on homefields and outfields was therefore accepted. Also the hypothesis that cattle manure application improves CWP over no application was accepted. However, not all physical properties analysed were necessary in modelling crop yields on clay and sandy soils as hypothesized, therefore the hypothesis was rejected.

Chapter 7

General discussion, conclusions and recommendations

7.1 Discussion and conclusions

7.1.1 Cattle manure application and the soil physical environment

Combined cattle manure and inorganic fertilizer application significantly increased SOC of both clay and sandy fields in the long-term. Initial differences between homefields and outfields were no longer evident after 6 years of equal application of cattle manure and inorganic fertilizer. In the short-term, SOC was significantly increased by manure and fertilizer application on the clay soils and this was attributed to increase in organic matter through manure application and enhanced crop growth with higher root biomass (Mikha and Rice, 2004).

Macro-aggregation index and aggregate protected carbon were improved with manure application in the clay soils. Highly positive and significant relationships were found between SOC, Ima and aggregate protected carbon ($r^2 > 0.57$) indicating the importance of SOC in aggregate formation in clay soils. Sandy soils did not show significant changes in aggregate stability despite change in SOC implying that SOC was not the only limiting factor in structure build-up possibly clay + silt content seemed to have greater bearing on aggregate formation. This was in line with results from a study by Kemper and Koch (1966) that aggregate stability increases to a maximum level with clay content and free Fe-oxides content and consequently, soils with low clay content have low aggregation indices. The potential of

cattle manure to maintain soil physical fertility was thus limited by the soil type amongst other factors.

This study also showed that changes in soil physical properties in long-term clay soils were accompanied by improvement in soil hydraulic properties that included steady state infiltration rates, pore density, total effective porosity, unsaturated hydraulic conductivity and the mean pore sizes of pores involved in water transmission at 5 cm potential. Cattle manure application increased steady state infiltration rates by increasing the mean pore size diameter of pores involved in the transport process from 430 μm in control to 560 μm in 25 tha^{-1} manure treatment. This change was accompanied by an increase in pore density per square meter of the mean sized pores at the potentials at which the measurements were conducted which resulted in more water which infiltrated into the soil.

Further, the advantages of cattle manure addition to clay soils were demonstrated by the increased soil water retained at 5 and 10 kPa suctions. The difference between control and treatments where cattle manure was applied meant that more water was available for crop uptake in the manure plots. Of interest was the demonstrated increase in crop water productivity in manure plots compared to control, both in clay and sandy soils. This clearly revealed that benefits of cattle manure application to soils go beyond increasing nutrient availability only but also increase water availability and improve crop water productivity. This is particularly important especially devising ways of mitigating the effects of mid-season dry spells which are a results of increasing climate variability.

Besides supplying multiple nutrients, cattle manure induced pronounced positive responses of soil physical properties on clay soils. Large amounts of cattle manure $\geq 15 \text{ tha}^{-1}$ were required

for significant improvement of soil physical properties. However, these amounts may not be sustainable for most smallholder farmers who apply 1 to 5 t ha⁻¹ yr⁻¹. In Zimbabwe, however, recommended rates are between 10 to 12 t ha⁻¹ (Mugwira and Shumba, 1986; Avila, 1987) which is close to 15 t ha⁻¹ application rate which significantly improved clay soil's physical properties in this study. It therefore imperative to recommend manure management strategies that result in the concentration of the scarce manure resource in small areas where there will be a positive impact of the manure on soil physical properties.

7.1.2 Cattle manure and inorganic fertilizer application on crop yields

Application of inorganic and organic fertilizer significantly improved maize and soybean grain yields on both clay and sandy soils. Crop response to sole mineral fertilizer application in the first and second season in short-term experiments did not significantly differ with the lower cattle manure rates (5 - 15 t ha⁻¹) which could be a result of slow mineralization of the manure. Manure application has been reported as key to maintaining crop productivity due to its multiple benefits which include multiple nutrient supply, reduction of soil acidity and improvement of soil physical properties if the clay + silt content are not limiting. On sandy soils, application of cattle manure at 5 t ha⁻¹ would be ideal as no improvements to physical properties are expected because of the very low clay + silt content of the soil used in this study.

7.1.3 Use of modelling in soil water studies

AquaCrop proved to be a useful tool in modelling of actual transpiration. Calibration of the model using the climate data obtained from Marondera which was the nearest weather station resulted in the model passing all the three criteria that were used to validate it. Modelling using AquaCrop helped partition evapotranspiration to transpiration and evaporation. Crop

water productivity therefore was expressed as a function of the actual water that was used towards harvestable biomass formation. The differences in CWP between 25 t ha⁻¹ cattle manure application and control were reflective of all other benefits that are coupled with cattle manure application. The importance of the model was in that it used a minimum number of climatic factors which were quite easily accessed. It can therefore be usefully used to obtain crop water productivity trends which can be used to inform farmer's management decisions to mitigate against unreliability of rainfall in rain-fed agricultural systems.

7.1.4 Regression modelling of soil physical that most significantly affected crop yields

Regression analyses performed between SOC, soil physical properties and maize grain yield revealed that macro-aggregation, steady state infiltration rates, aggregate protected carbon and SOC were the most significant yield predictors in clay soils. In contrast, only SOC was used to predict yield on sandy soils due to lack of positive ameliorative response of physical properties in the sandy soils studied. Factor analysis was very effective in dealing with collinearity amongst soil properties which were closely related in the field. Adding cattle manure to clay soils improved the physical properties which in turn partially accounted for the increase in grain yield but SOC only was enough to predict yield variation due to cattle manure application on sandy trials in this study. This study was important towards evaluation of the most sensitive soil physical properties that influence crop yield, therefore making it necessary to carry out further studies that can be synthesized to obtain general recommendations that have a wide applicability.

7.2 Recommendations

This study showed that crop yields were significantly improved with combined cattle manure and mineral fertilizer application. It is recommended that farmers should strive to apply cattle manure to their fields annually to increase SOC, improve soil physical properties and CWP. Cattle manure application rates at 5 t ha⁻¹ year are recommended in the sandy soils to complement the inorganic fertilizers while in clay soils in cases where cattle manure is not a major limitation, optimal rates at least 15 t ha⁻¹ were recommended. Alternatively, if cattle manure resources are too limited to be spread equally on all fields, judicious and consistent application to selected fields at low rates over longer time frames (> 6 years) should eventually result in improved soil physical health and crop yields. In addition, spot application of cattle manure in conservation agriculture basins achieves the high concentration required for significant improvement of soil physical and hydraulic properties.

7.3 Areas of Further Research

There is need to explore other options such as agroforestry legumes and crop rotations including grain legumes with fertilizer to minimise nutrient mining from the outfields since this study focussed on soil fertility restoration using cattle manure and mineral fertilizer.

Studies based on reduced tillage might be worth exploring on the outfields so as to promote SOM build-up through reduced mineralization in the outfields. Furthermore, the use of basins under conservation agriculture combined with spot manure application should also be pursued as an option to restoring fertility to depleted outfields.

There is also need to continue managing the long-term experiments at the current fertilizer application rates and in the long run SOC data can be used to assess when C-saturation levels

will be reached for the soil types and therefore evade making recommendations that would eventually result in excess C that will be free and not contribute to aggregate development and overall structure enhancement.

Further research work using the crop water balance model to predict CWP and regression modelling of soil physical properties with the most significant effect on crop yields across different sites with different climatic conditions, soil types and time scales are required to as to develop a systematic way to predict the effects of various soil management practices.

There is also need to investigate the effects of macro-faunal activities on soil physical and hydraulic properties such as aggregate formation which can also be influenced by cattle manure application in the experimental fields to help in the attribution of observed effects.

It is also important to carry out work to establish the critical level of clay + silt below which application of manure will not result in significant improvement in soil physical properties due to poor physical stabilization.

References

- Abrisquetta JM, Plana V, Franco JA & Ruiz-Sanchez MC 2006.** Effects of tillage and water pressure head on the hydraulic properties of a loamy soil surface. *Spanish Journal of Agricultural Research* 4: 180-186
- Acharya CL, Bisnoi SK & Yaduvanhi HS 1988.** Effect of long-term application of fertility and organic amendments under continuous cropping on soil physical and chemical properties in an Alfisol. *Indian Journal of Agricultural Science* 58: 509-516
- Alegre C & Rao MR 1996.** Soil and water conservation by contour hedging in humid tropics of Peru. *Agriculture, Ecosystems and Environment* 57: 17-25
- Allen RG, Pereira LS, Raes D & Smith M 1998.** Crop evapotranspiration. Guidelines for computing crop water requirements. *FAO Irrigation and Drainage Paper* 56. FAO, Rome, Italy 300 p
- Alvaro-Fuentes J, Cantero-Martinez C, Lopez MV, Paustian K, Denef K, Stewart CE & Arrue JL 2009.** Soil aggregation and soil organic carbon stabilization: Effects of management in semi-arid Mediterranean agro-ecosystems. *Soil Science Society Of America Journal* 73: 1519-1529
- Anderson JM & Ingram JSI 1993.** Tropical Soil Biology and Fertility: A Handbook of Methods, 2nd edn. CAB International, Wallingford, UK
- Avila M 1987.** Integrating livestock with cropping systems. proceedings of a workshop on cropping in the semi-arid areas of Zimbabwe, 24-28 August 1987, Harare, Zimbabwe
- Ayoubi S, Khormali F & Sahrawat KL 2009.** Relationships of barley biomass and grain yields to soil properties within a field in the arid region: use of factor analysis. *Soil and Plant Sciences* 59:107-117
- Barthe's B, Albrecht A, Asseline J, De Noni G & Roose E 1999.** Relationship between soil erodibility and topsoil aggregate stability or carbon content in a cultivated Mediterranean

Highland (Aveyron, France). *Communications in Soil Science and Plant Analysis* 30: 1929-1938

Barthes B & Roose E 1996. The stability of aggregates an indicator of the sensitivity of the ground streaming and erosion: Validation on several scales. *Soil Science Society of America Journal* 60: 888-894

Baruah TC & Barthakur HP 1998. A textbook of soil analysis. Vikas Publishing House, Private limited, New Delhi, India, p 334

Bastianssen WGM, van Dam JC & Droogers P 2003. Refocussing irrigation water management. In: van Dam JC, Malik RS (eds). *Water productivity of irrigated crops in Sirsa district, India-Intergration of remote sensing, crop and soil models and geographical information systems*. WUR/CCSH AU/IWMI/Water watch, Wageningen p 12-16

Bationo A, Kihara J, Vanlauwe B, Waswa B & Kimetu J 2006. Soil organic carbon dynamics, functions and management in West African agro-ecosystems. *Agricultural Systems*. doi: 10.1016/j.agsy.2005.08.011

Beare MH, Cabrera ML, Hendrix PF & Coleman DC 1994. Aggregate protected organic matter pools in conventional - and no-tillage soils. *Soil Science Society Of America Journal* 58:787-795

Beaudoin N, Launay M, Sauboua E, Ponsardin G & Mary B 2008. Evaluation of the soil crop model STICS over 8 years against “on farm” database of Bruyeres catchment. *European Journal of Agronomy* 29: 45-57

Bennie ATP & Woyessa YE 2004. Impact of cultivation practices on multiple uses of water in the Alemaya catchment, eastern Ethiopia. *Proceedings of the International conference on water resources of arid and semi-arid regions of Africa*, Gaborone, Botswana. 3-6 August 2004

- Bossuyt H, Six J & Hendrix PF 2005.** Protection of soil carbon by micro-aggregates within earthworm casts. *Soil Biology and Biochemistry* 37: 251-258
- Bouwer H 1986.** Intake rate: Cylinder infiltrometer p825-843. In: Klute A (ed) *Methods of soil analysis: Part 1, 2nd ed.* Agronomy monogram 9. ASA and SSSA. Madison, WI
- Boyle M, Frankenberger WT & Stokzy LH 1989.** The influence of organic matter on soil aggregation and water infiltration. *Journal of Production in Agriculture* 2: 290-299
- Bredja JI, Moorman TB, Karlen DL & Dao TH 2000.** Identification of regional soil quality factors and indicators in Central and Southern high plains. *Soil Science Society of America Journal* 64:2115-2124
- Burns RL, Cook DJ & Phillips RE 1971.** Influence of no tillage on soil moisture. *Agronomy Journal* 73: 593-596
- Campbell BM, Bradley PN & Carter SE 1994.** Sustainability and peasant farming systems: Some observations from Zimbabwe 13 pp. International Institute of Environmental Technology and Management, Stockholm Environment Institute, Stockholm, Sweden
- Campbell CA, McConkey BG, Biederbeck VO, Zentner RP, Curtin P & Peru MR 1998.** Long-term effects of tillage and fallow- frequency on soil quality attributes in a clay soil in semi arid south-western Saskatchewan. *Soil and Tillage Research* 46: 135-144
- Carter S & Murwira H 1995.** Spatial variability in soil fertility management and crop response in Mutoko communal area, Zimbabwe. *Ambio*. 24: 77-84
- Cassa R, Russel G & Cascio B 2000.** Estimation of evapotranspiration from linseed in Italy. *Agriculture for Meteorology* 104: 289-301
- Castro Filho C, Lourenco A, Guimaraes MDF & Fonseca ICB 2002.** Aggregate stability under different soil management systems in red Latosol in the state of Parana, Brazil. *Soil and Tillage Research* 65: 45-51

- Celik I, Ortas I & Kilic S 2004.** Effects of compost, mycorrhiza, manure and fertilizer on some physical properties of a Chromoxerert Soil. *Soil and Tillage Research* 78:59-67
- Chakraborty D, Garg RN, Tomar RK, Dwivedi BS, Aggarwal P, Singh R, Behera UK, Thangasamy A & Singh D 2010.** Soil physical quality as influenced by long-term application of fertilizers and manure under maize-wheat system. *Soil Science* 175: 128-136
- Chikowo R 2004.** Nitrogen cycling in Agroforestry systems of sub-humid Zimbabwe: Closing the Loop. PhD Thesis, Wageningen University, Wageningen, the Netherlands
- Chikuvire JT 2000.** An evaluation of soil fertility management of field niches in Mutoko communal area, Zimbabwe. Mphil Thesis, University Of Zimbabwe, Harare
- Chivenge PP, Murwira HK, Giller KE, Mapfumo P & Six J 2007.** Long-term impact of reduced tillage and residue management on soil carbon stabilization: Implications for conservation agriculture on contrasting soils. *Soil and Tillage Research* 94: 328-337
- Christensen BT 1988.** Effects of manure and mineral fertilizer on the total carbon and nitrogen contents of soil size fractions. *Biology and Fertility of Soils* 5: 304-307
- Connolly RD 1998.** Modelling effects of soil structure on the water balance of soil-crop systems: a review. *Soil and Tillage Research* 48: 1-19
- CSIRO 1988.** CSIRO Disc Permeameter Instruction Manual. Canberra 44 p
- Darwish OH, Persaud N & Marters DC 1995.** Effects of long-term application of animal manure on physical properties of three soils. *Plant and Soil* 176:289-295
- de Wit CT 1958.** Transpiration and crop yields. Verslandbowik Onderz, 64-67. Institute of Biology and Chemistry research on field crops and herbage, Wageningen, the Netherlands
- Dembele I, Kone D, Soumare A, Coulibale D, Kone Y, Ly B & Katler L 2000.** Fallows and field systems in Dryland Mali. In: Hilhorst T & Muchena F (Eds) Nutrients On The Move. Soil Fertility Dynamics In African Framing Systems. *International Institute For Environment And Development, London, Pp* 83-102

- Doorenbos J & Kassam AH 1979.** Yield response to water. *Irrigation and Drainage Paper* 33. FAO, Rome, Italy 193 p
- Doreenbos J & Pruitt WO 1977.** Crop water requirements. *Irrigation and Drainage Paper* No. 24, FAO, Rome
- Dujmovich MN, Bonsiomo C & Conflanone A 1996.** Evapotranspiration efficiency of corn grown under rainfed conditions. In: Camp (eds) *Proceeds of International Conference on evapotranspiration and irrigation scheduling*, ASCE, Texas
- Edwards AP & Bremmer JM 1967.** Microaggregates in soils. *Journal of Soil Science* 18: 64-73
- Ekwue EI 1992.** Effects of organic and fertilizer treatments on soil physical properties and erodibility. *Soil and Tillage research* 22: 199-209
- Elliot ET 1986.** Aggregate structure and carbon, nitrogen and phosphorus in nature and cultivated soils. *Soil Science Society of America Journal* 50: 627-633
- Evrendilek F, Celik I & Kilic S 2004.** Changes in soil organic carbon and other physical soil properties along adjacent Mediterranean Forest, Grassland and Cropland Ecosystems In Turkey. *Journal Of Arid Environments* 59:743-752
- Eynard A, Schumacher TE, Lindstrom MJ & Malo DD 2004.** Porosity and pore-size distribution in cultivated Ustolls and Usterts. *Soil Science Society of America Journal* 68: 1927-1934
- Franzluebbers AJ & Arshad AM 1997.** Soil microbial biomass and mineralization of carbon of water stable aggregates. *Soil Science Society of American Journal* 61
- Franzluebbers AJ 2002.** Soil organic matter stratification ratio as an indicator of soil quality. *Soil Tillage and Research* 66: 95-106
- Giller KE 2002.** Targeting management of organic resources and mineral fertilizers: Can we match scientists' fantasies with farmers' realities. In: Vanlauwe B, Sanginga N, Diels J,

Merckx R (Eds). Balanced nutrient management systems for the moist Savanna and Humid Forest Zones Of Africa. *CAB International, Wallingford, Pp 155-171*

Gilley JE & Risse LM 2000. Runoff and soil loss as affected by the application of manure. *Trans ASAE 43: 1583-1588*

Grant PM 1981. The fertilization of sandy soils in peasant agriculture. *Zimbabwe Agricultural Journal 78: 169-175*

Groenewald Y 2009. Malawi's fertile plan: smallscale farmers help the country to thrive. Mail Guard, 25(3) June 19-25, p 27. <http://www.mg.co.za>. Accessed 7.10.2010

Haile M 2005. Weather patterns, food security and humanitarian response in sub-Saharan Africa. *Philosophical Transactions of the Royal Society London Board of Biological Sciences 360: 2169-2182*

Haileslassie A, Preiss JA, Veldkamp E & Lesschen JP 2007. Nutrient flows and balances at the field and farm scale: Exploring effects of land-use strategies and access to resources. *Agricultural Systems 9: 459-470.*

Hair JF, Anderson JRE & Tatham RL 1987. Multivariate data analysis with readings. 2nd edn. Macmillan Publishing Co, New York, USA

Hall 1991. Relationship between moisture retention characteristics of other soil properties for Zimbabwean soils. *Zimbabwe Journal of Agricultural Research 29: 53-63*

Hatfield JL, Saucer TJ & Prueger JH 2001. Managing soils to achieve greater water use efficiency: Review. *Agronomy Journal 93: 271-280*

Hati KM, Mandal KG, Misra AK, Ghosh PK & Bandyopadyyay KK 2006. Effect of inorganic fertilizer and farmyard manure on soil physical properties, root distribution and water-use efficiency of Soybean in Vertisols of Central India. *Bioresource Technology 97: 2182-2188*

- Hati KM, Swarup A, Dwivedi AK, Misra K & Bandyopadhyay KK 2007.** Changes in soil physical properties and organic carbon status at the top soil horizon of a Vertisol of Central India after 25 years of continuous cropping, fertilization and manuring. *Agriculture, Ecosystem and Environment* 119:127-134
- Haynes RJ & Francis GS 1993.** Changes in microbial biomass carbon, soil carbohydrates and aggregate stability induced by growth of selected crop and forage species under field conditions. *Journal of Soil Science* 44:665-675
- Haynes RJ & Naidoo R 1998.** Influence of lime, fertilizer and manure application of soil organic matter content and soil physical conditions: A Review. *Nutrient Cycling In Agroecosystems* 51: 123-137
- Heuscher SA, Brandt CC And Jardine PM 2005.** Using Soil Physical And Chemical Properties To Estimate Bulk Density. *Soil Science Society Of America Journal* 69:51-56
- Hillel D 1982.** Advances in irrigation. Volume 1. Academic press, Inc, London. Pp 62-69
- Hillel D 1982.** Introduction to Soil Physics 2nd Ed. Academic Press, Orlando, Florida
- Houba VJG, van der Lee JJ, Novazamsky I & Waling I 1989.** Soil and Plant Analysis, Part 5. Wageningen Agricultural University, The Netherlands
- Hudson BP 1994.** Soil organic matter and available water capacity. *Soil Water Conservation* 49: 189-194
- Igbadun HE, Mahoe HF, Tarimo AP & Salim BA 2006.** Crop water productivity of irrigated maize in Mkoji sub-catchment of the Great Ruaha River Basin, Tanzania. *Agricultural Water Management* 85: 141-150
- Jagadamma S, Lal R, Hoeft RG, Nafziger ED & Adeo EA 2008.** Nitrogen fertilization and cropping system impact on soil properties and their relationship to crop yield in the Central corn belt, USA. *Soil and Tillage Research* 98:120-129

- Jama B & Pizarro G 2008.** “Agriculture in Africa: Strategies to improve and sustain smallholder production systems. Reducing the impact of poverty on health and human development.” *Scientific approaches. Oxford, Blackwell Publishing* 1136: 1176-1182
- Johnson RA & Wichern DW 1992.** In: Applied multivariate analysis. 3rd ed. Prentice Hall inc. Englewood cliffs, NJ. 642 p
- Kaspar TC, Fenton DJ, Colvin TS, Karlen DL, Jaynes DB & Meek DW 2004.** Relationships of corn and soybean to soil and terrain properties. *Agronomy Journal* 96: 700-709
- Kemper WD & Koch EJ 1966.** Aggregate stability of soils from Western Unites States and Canada. *Technical Bulletin No.1355.* Agricultural Research Services USDA in co-operation with Colorado Agricultural Experimental Station, Pp 1-52
- Kemper WD & Rosenau RC 1986.** Aggregate stability and size distribution. Pp 425-442. In: Klute A (ed) *Methods of Soil Analysis: Part 1*, 2nd ed. *Agronomy Monogram* 9. ASA and SSSA. Madison, WI
- Kettler TA, Doran JW & Gilbert TL 2001.** Simplified method for soil particle-size determination to accompany soil-quality analyses. *Soil Science Society of America Journal* 65: 849-852
- Kijne JW, Barker R & Molden D (eds) 2003.** Water productivity in agriculture: limits and opportunities for improvement. CAB International
- Kijne JW, Twong TP, Benne J, Bouman B & Oweis T 2002.** Ensuring food security via improvement in crop water productivity- challenge program for food and water. CGIAR, Colombo pp 1-42
- Klute A & Dirkson C 1986.** Hydraulic conductivity and diffusivity. In: Klute A (ed) *Methods of soil analysis, Part 1.* Pp 687-734. 2nd edn. *Agronomy Monograph*, volume 9. American Society of Agronomy, Madison, WI, USA

- Kostiakov AW 1932.** On the dynamics of the coefficient of water percolation in soils and the necessity for studying it from a dynamic point of view for purposes of amelioration. Trans 6th Communication. *International Society of Soil Science Russia Part A*: 17-21
- Landon JR 1984.** Tropical soil manual. A handbook for soil survey and agricultural land evaluation in tropics and subtropics. Booker Agricultural International Limited, London. pp 35-70
- Larson WE & Pierce FJ 1994.** The dynamics of soil quality as a measure of sustainable management. Pp 37-51. In: Doran JW (ed) Defining soil quality for a sustainable environment. *Soil Science Society of America special publication 35*. SSSA and ASA, Madison, WI
- Le Bissonnais Y 1996.** Aggregate stability and assessment of soil crustability and erodibility: 1. Theory and methodology. *European Journal of Soil Science* 47: 425-437
- Lee KE & Foster RC 1991.** Soil fauna and soil structure. *Australian Journal of Soil Research* 29: 745-776
- Letey J 1985.** Relationship between soil physical properties and crop production p 227-294. In: Stewart BA (ed) *Advances in Soil Science Volume 1*, Springer-Verlag, New York
- Levy GJ and Miller WP 1997.** Aggregate stability of some south-eastern US soils. *Soil Science Society of America Journal* 61: 1176-1182
- Luxmoore RJ 1981.** Micro-, meso- and macro-porosity of soil. *Soil Science Society of America Journal* 45:671
- Magodo L 2007.** Determination of water productivity of maize varieties grown in Zimbabwe. MSc thesis, department of Physics, University of Zimbabwe, 152 p
- Mallarino AP, Oyarzabal EZ & Hinz PN 1999.** Interpreting within-field relationships between crop yields and soil and plant variables using factor analysis. *Precision Agriculture* 1:15-25

- Mapfumo P & Giller KE 2001.** Soil fertility management strategies and practices by smallholder farmers in Semi-Arid Areas of Zimbabwe. ICRISAT, FAO, Bulawayo, Zimbabwe
- Marshall TJ 1959.** Relations between water and soil. *Technical communications No. 50*, Commonwealth Bureau of soils, Harpenden, UK
- Martens H & Naes T 1989.** Multivariate calibration. Wiley, New York, USA. Pp 97-108
- Martin A & Marinissen JCY 1993.** Biological and physic-chemical processes in excrements of soil animals. *Geoderma* 56: 331-347
- Materechera SA 2010.** Utilization and management practices of animal manure for replenishing soil fertility among smallscale crop farmers in semi-arid farming districts of the North West Province, South Africa. *Nutrient Cycling in Agroecosystems* 87: 415-428
- Mbagwu JSC & Bazzoffi P 1989.** Properties of soil aggregates as influenced by tillage practices. *Soil Use and Management* 5: 180-188
- Mead R & Curnow RN 1986.** Statistical methods in agriculture and experimental biology. Chapman and Hall, London, pp 183-185
- Mikha MM & Rice CW 2004.** Tillage and manure effects on soil and aggregate-associated carbon and nitrogen. *Soil Science Society of America Journal* 68: 809-816
- Morin J & Benjamin Y 1977.** Rainfall infiltration to bare soils. *Water Resources Research* 13: 813-817
- Mtambanengwe F & Mapfumo P 2005.** Organic matter management as an underlying cause for soil fertility gradients on Smallholder Farms In Zimbabwe. *Nutrient Cycling In Agroecosystems* 73:227-243
- Mugwira LM & Murwira HK 1997.** Use of cattle manure to improve soil fertility in Zimbabwe: Past and current and future research needs. Soil Fertility Network for Maize-Based Cropping Systems in Malawi and Zimbabwe, working paper 2. Pp 1-33

- Mugwira LM & Murwira HK 1998.** A review of manure as soil fertility amendment in Zimbabwe: Some perspectives. In SR Waddington, JDT Kumwenda, D Hikwa & F Tagwira (eds). *Soil Fertility Research for maize based farming systems in Malawi and Zimbabwe. Soil Fertility Net and CIMMYT-Zimbabwe*, Harare. Pp 195-201
- Mugwira LM & Shumba EM 1986.** Rate of manure applied in some communal areas and the effect on plant growth and maize grain yield. *Zimbabwe Agriculture Journal* 83: 99-104
- Mulla DJ, Huyck LM & Reganold JP 1992.** Temporal variation in aggregate stability on conventional and alternative farms. *Soil Science Society of America Journal* 65:1620-1624
- Murage EW, Karanja NK, Smithson PC & Woomer PL 2000.** Diagnostic indicators of soil quality in productive and non-productive smallholders fields of Kenya's Central Highlands. *Agricultural Ecosystems and Environment* 79:1-8
- Murwira HK, Swift MJ & Frost PGH 1995.** Manure as a key resource in sustainable agriculture: A case study of communal area farming systems in Zimbabwe. A keynote address. In: Powell JM, Fernandez-Rivera S, Williams TO & Renard C (eds). *Livestock and sustainable nutrient cycling in farming systems of SSA, Vol II. International Livestock Centre for Africa (ILCA) Proceedings, Addis Ababa, Ethiopia. Pp 131-148*
- Musick JT, Jones OR, Stewart BA & Duseck DA 1994.** Water-yield relationships for irrigated and dryland wheat in the United States, Southern plains. *Agronomy Journal* 86: 980-986
- Ncube B, Twomlow SJ, Dimes JP, van Wijk MT & Giller KE 2009.** Resource flows. Crops and soil fertility management in smallholder farming systems in semi-arid Zimbabwe. *Soil Use and Management* 25: 78-90
- Nyagumbo I 2002.** Effects of three tillage systems on seasonal water budget and drainage of two Zimbabwean soils under maize. DPhil thesis, Department of Soil Science and Agricultural Engineering, University of Zimbabwe.

Nyamadzawo G 2004. The effects of improved fallows and tillage management on soil and water conservation in a sandy soil. Mphil Thesis. University of Zimbabwe. Pp 121

Nyamadzawo G, Nyamugafata P, Chikowo R & Giller K 2008. Residual effects of fallows on selected soil hydraulic properties in a kaolinitic soil subjected to conventional tillage (CT) and no tillage (NT). *Agroforestry systems* 72: 161-168

Nyamangara J, Gotosa J, Mpofu SE 2001. Cattle manure effects on structural stability and water retention capacity of a Granitic soil in Zimbabwe. *Soil and Tillage Research* 62: 157-162

Nyamapfene KW 1991. Soils of Zimbabwe. *Nehanda Publishers (PVT)LTD, Harare, Zimbabwe*

Oades JM 1984. Soil organic matter and structural stability: Mechanisms and implications for management. *Plant and Soil* 76:319-337

Okalebo JR, Gathua KW & Woomer PL 2002. *Laboratory Methods of Soil and Plant Analysis: A Working Manual*. 2nd Ed. TSBF-CIAT and Sacred Africa, Nairobi, Kenya

Palm CA, Myers RJK & Nandwa SM 1997. Combined use of inorganic and organic nutrient sources for soil fertility maintenance and replenishment. In: Buresh RJ, Sanchez PA, Calhoun F (eds.). *Replenishing Soil Fertility in Africa*. *Soil Science Society of America Special Publication No 51*. Madison, Wisconsin, USA, pp193-217

Papendick RI, Lindstrom MJ & Cochran VL 1973. Soil mulch effect on seedbed temperature and water during fallow in eastern Washington. *Soil Science Society of America Proceedings* 37: 307-314

Probert ME, Keating BA, Thompson JP & Parton WJ 1995. Modelling water, nitrogen and crop yield for a long-term fallow management experiment. *Australian Journal of Experimental Agriculture* 35: 941-950

- Prudencio CY 1993.** Ring management of soils and crops in the West African Semi-Arid Tropics: The case of the Mossi Farming System In Burkina Fasso. *Agriculture Ecosystems and Environment* 47: 237-264
- Raes D 2002.** BUDGET- soil and water balance model. Reference manual. Version 5.0. Department of Land Management. Faculty of Agriculture and Applied Biological sciences. KU. Leuven, Belgium
- Raes D, Geerts S, Kipkorir E & Wellens J 2005.** Simulation of yield decline as a result of water stress with robust soil water balance model. *Agriculture and water management*
- Raes D, Steduto P, Hsiao TC, Fereres E & Heng L 2008.** AquaCrop calculation procedure, prototype version. FAO, Rome, Italy, 64 p
- Rockström J, Barron J & Patrick F 2003.** Water productivity in rainfed agriculture: Challenges and opportunities for smallholder farmers in drought prone Tropical Agro-ecosystems. In: Kijne JW, Barter R & Molden D (eds). *Water productivity in agriculture: limits and opportunities for improvement*. CAB International. Pp 145-162
- Rodel MGW, Hopley JDH & Boultonwood JN 1980.** Effects of Nitrogen, kraal compost and maize stover on the yields of maize grown on a poor granite soil. *Zimbabwe Agriculture Journal* 77: 229-232
- Rose DA 1991.** The effect of long-continued organic manuring on some physical properties of soils. In: Wilson WS (ed) *Advances in Soil Organic Water Research, Special Publication no 90*. Royal Society of Chemistry, Cambridge pp 197-205
- Schjonning P, Christensen BT & Cartensen B 1994.** Physical and chemical properties of a sandy loam receiving animal manure, mineral fertilizer or no fertilizer for 90 years. *European Journal of Soil Science* 45: 257-268
- Schlesinger WH 1997.** Biogeochemistry: An analysis of Global Change, 2nd edn. Academic Press, San Diego

- Scoones I & Toulmin C 1999.** Soil nutrient budgets and balances water use policy? *Managing African Soils* no. 6, 23 p
- Scott HD 2000.** Soil physics: Agricultural and environmental applications. Iowa State University Press, Ames, IA
- SeedCo 2004.** SeedCo Agronomy Manual, SeedCo limited, Harare, Zimbabwe
- Sena MM, Frighetto RTS, Valarini PJ, Tokeshi H & Poppi RJ 2002.** Discrimination of management effects on soil parameters by using principal component analysis: a multivariate analysis case study. *Soil and Tillage Research* 67: 171-181
- Sharma S 1996.** Applied multivariate techniques John Wiley and Sons, New York. Pp 1-493
- Shirani H, Hajabbasi MA, Afyuni M & Hemmat A 2002.** Effects of farmyard manure and tillage systems on soil physical properties and corn yield in Central Iran. *Soil and Tillage* 68:101-108
- Shrestha BM, Singh BR, Sitaula BK, Lal R & Bajracharya RM 2007.** Soil aggregate- and particle –associated organic carbon under different land uses in Nepal. *Soil Science Society of America Journal* 71: 1194-1203
- Shuckla MK, Lal R & Ebinger M 2004.** Principal component analysis for predicting corn biomass and grain yields. *Soil Science* 169: 215-224
- Six J, Bossuyt H, Degryze S & Denef K 2004.** A history of research on the link between (micro) aggregates, soil biota and soil organic matter dynamics. A Review. *Soil Tillage and Research* 79: 7-31
- Six J, Elliot ET & Paustian K 2000.** Soil macro-aggregate turn-over and micro-aggregate formation: A mechanism for carbon sequestration under no-tillage agriculture. *Soil Biology and Biochemistry* 32:2099-2103
- Steduto P & Albrizio R 2005.** Resource use efficiency of efficiency of field grown sunflower, sorghum, wheat and chickpea. *Agriculture for Meteorology* 130: 269-281

- Steduto P, Raes D, Hsiao TC, Fereres E, Heng L, Izzi G & Hoogeveen J 2008.** AquaCrop: a new model for crop prediction under water deficit conditions. *Options Mediterraneennes* 80: 285-292
- Stoorvogel JJ & Smaling EMA 1998.** Research on soil fertility decline in tropical environments: Integration of spatial scales. *Nutrient Cycling in Agroecosystems* 50: 151-158
- Stoorvogel JJ, Smaling EMA & Jansen BH 1993.** Calculating soil nutrient balances in Africa at different scales 1. Supra-national scale. *Fertilizer Research* 35: 227-235
- Stotzky G 1965.** Microbial respiration. In: Black CA (eds.). *Methods of Soil Analysis*. Vol 2. *American Society of Agronomy, Monograph No.9, Madison, USA*. Pp 1550-1572
- Su YZ, Wang F, Suo DR, Zhang ZH & Du MW 2006.** Long-term effect of fertilizer and manure application on soil-carbon sequestration and soil fertility under the wheat-wheat-maize cropping system in northwest China. *Nutrient Cycling in Agroecosystems* 75: 285-295
- Summer ME & Miller WP 1996.** Cation exchange capacity and exchange coefficients. In: Weaver RW, Angles S, Bottomley P, Bezdicsek D, Smith S, Tabatabai A & Wollum (eds). *Methods of soil analysis. Part 3. Chemical methods, Soil Science Society of America of Agronomy: 1201-1229*. Madison, Wisconsin, USA.
- Swan ARH & Sandilands M 1995.** Introduction to geological data analysis. Blackwell, London. Pp 1-446
- Swartenrubler D & Olson TC 1961.** Sandy model study of the buffer effects of double rings infiltrometer. *Soil Science Society of America Proceedings* 25:5-8
- Thierfelder C & Wall PC 2009.** Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe. *Soil and Tillage Research* 105: 217-227
- Tisdall JM & Oades JM 1982.** Organic matter and water stable aggregates of soils. *Journal of Soil Science* 62: 141-163

- Tisdall JM 1994.** Possible role of soil micro-organisms in aggregation of soils. *Plant and Soil* 159: 115-121
- Tittonell P, Vanlauwe B, Leffelar PA, Shepherd KD & Giller KE 2005.** Exploring diversity in soil fertility management of smallholder farms in Western Kenya: II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. *Agriculture, Ecosystem and Environment* 110:166-184
- van der Meer FBW, Twomlow SJ, Bruneau PMC & Reid I 1998.** Weeding impact on semi-arid soil water regimes: A quantitative approach. *AgEng* 98: 24-27
- Van Noordwijk M, Schhonderbeek D & Kooistra MJ 1993.** Root- soil contact of grown winter wheat. *Geoderma* 56: 277-286
- Vincent V & Thomas RG 1960.** An agricultural survey of Sourthern Rhodesia. Part I. Agro-ecological survey. Government Printers, Salisbury
- Vogel H 1992.** Morphological and hydrological characteristics of gleyic granitic soils and their potential for crop production. A case study from Zimbabwe. *Soil Technology* 5: 303-317
- Wander MM & Bollero GA 1999.** Soil quality assessment of tillage impacts in Illinois. *Soil Science Society of America Journal* 63:961-971
- Wang ZM, Zhang B, Song KS, Liu DW & Ren CY 2010.** Spatial variability of soil organic carbon under maize monoculture in the Song-Nen Plain, North-East China. *Pedosphere* 20: 80-89
- Watson KW & Luxmoore RJ 1986.** Estimating macroporosity in Forest Watershed by use of tension infiltrometers. *Soil Science Society of America Journal* 50: 578-582
- Wauchope RD & Burgon B 1993.** Pesticides runoff studies towards a new protocol. Agrochemical research in the 1990's. Pp 273-285
- White I & Sully MJ 1987.** Macroscopic and microscopic capillary length and time scales from field infiltration. *Water Resources Research* 23:1514-1522

- White I, Sully MJ & Perroux KM 1992.** Measurement of surface soil hydraulic properties: disk permeameters, tension infiltrometers and other techniques. In: Topp GC, Reynolds WD, Green RE (eds). *Advances measurement of soil physical properties: Bringing Theory in to Practice*. Soil Science Society of America, Inc, Madison, Wisconsin, USA
- Wilcocks TJ & Cornish GA 1988.** Understanding soil physical constraints to rainfed crop production in semi-arid SADCC regions. FAO soil testing, management and fertilizer use seminar and training course. Jokioinen, Finland, July 10-24, 1988 pp 57-68
- Wilson GV & Luxmore RJ 1988.** Infiltration, macroporosity and mesoporosity distributions on two forested watersheds. *Soil Science Society of America Journal* 52: 329-335
- Wiyo KA 1999.** Effect of tied ridging on soil water status and maize under Malawi conditions. Unpublished Ph.D. Thesis. Katholieke. University of Leuven, Belgium
- Woomer PL, Bekunda MA, Karanja NK, Moorehouse T & Okalebo JR 1998.** Agricultural resource management by smallholder farmers in East Africa. *Natural Resources* 34:22-33
- Wortmann CS & Walters 2006.** Phosphorus runoff during four years following composted manure application. *Journal of Environmental Quality* 35: 651-657
- Yoder RE 1936.** A direct method of aggregate analysis of soils and study of the physical nature of erosion losses. *Journal of American Society of Agronomy* 28: 337-351
- Young MDB & Gowing JW 1996.** "The Parched-Thirst model. User guide version 1.0." University of Newcastle, Newcastle. 44 pp
- Zhang B and Horn R 2001.** Mechanisms of aggregates stabilization in Ultisols from sub-tropical China. *Geoderma* 99: 123-145
- Zhang Y, Kendy E, Quing Y, Yunjun S & Hongyong S 2003.** Effects of soil water deficit on evaporation- crop yield and water use efficiency in North China plain. *Agricultural Water Management* 64: 107-122

- Zingore S 2006.** Exploring diversity within smallholder farming systems in Zimbabwe: Nutrient use efficiencies and resource management strategies for crop production. PhD Thesis Wageningen University, Wageningen, The Netherlands. 271 p
- Zingore S, Delve RJ, Nyamangara J & Giller KE 2008.** Multiple benefits of manure: The key to maintenance of soil fertility and restoration of depleted sandy soils on African smallholder farms. *Nutrient Cycling in Agro-ecosystems* 80:267-282
- Zingore S, Murwira HK, Delve RJ & Giller KE 2007.** Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. *Agriculture, Ecosystems and Environment* 119: 112-126
- Zwart SJ & Bastiaansen WGM 2004.** Review of measured crop water productivity values for wheat, rice and cotton and maize. *Agricultural Water Management* 69: 115-133

Appendix 1

Regression analyses results for the long-term sandy fields and short-term clay fields

Long-term sandy field

Cell Contents:

Correlation Coefficient

P Value

	i.rates	Ko	Yield
SOC	0.476	0.460	0.889
	0.524	0.540	0.00317

i.rates	-0.374	0.285
	0.626	0.715

Ko	0.574
	0.426

Yield	1
-------	---

Linear Regression

Data source: Data 1 in Pearson's correlation (LT sandy)

$$\text{Yield} = -0.239 + (1.411 * \text{SOC})$$

R = 0.889 Rsqr = 0.790 Adj Rsqr = 0.755

Standard Error of Estimate = 0.610

	Coefficient	Std. Error	t	P
Constant	-0.239	0.482	-0.496	0.638
SOC	1.411	0.297	4.747	0.003

Analysis of Variance:

	DF	SS	MS	F	P
Regression	1	8.396	8.396	22.531	0.003
Residual	6	2.236	0.373		
Total	7	10.632	1.519		

Normality Test (Shapiro-Wilk) Passed (P = 0.899)

Constant Variance Test: Passed (P = 0.423)

Power of performed test with alpha = 0.050: 0.886

Short-term clay fields
Pearson' correlation (ST clay)

Cell Contents:
Correlation Coefficient
P Value

	Ima	APC	i.rates	TEP	Ko	Yield
SOC	0.902 0.00217	0.752 0.0315	0.853 0.147	0.849 0.151	0.553 0.447	0.958 0.000184
Ima		0.887 0.00334	0.892 0.108	0.886 0.114	0.250 0.750	0.937 0.000599
APC			0.902 0.0978	0.896 0.104	0.197 0.803	0.787 0.0204
i.rates				1.000 0.000119	0.275 0.725	0.919 0.0813
TEP					0.280 0.720	0.913 0.0869
Ko						0.284 0.716

Yield

Multiple Regression

Data source: Data 1 in Pearson' correlation (ST clay)

$$\text{Yield} = -2.519 + (1.500 * \text{SOC}) + (0.00962 * \text{Ima}) - (0.000374 * \text{APC})$$

$$R = 0.973 \quad \text{Rsqr} = 0.947 \quad \text{Adj Rsqr} = 0.907$$

Standard Error of Estimate = 0.460

	Coefficient	Std. Error	t	P	VIF
Constant	-2.519	0.709	-3.550	0.024	
SOC	1.500	0.706	2.125	0.101	5.705
Ima	0.00962	0.00804	1.196	0.298	11.600
APC	-0.000374	0.00137	-0.273	0.799	4.964

Warning: Multicollinearity is present among the independent variables. The variables with the largest values of VIF are causing the problem.

Analysis of Variance:

	DF	SS	MS	F	P
Regression	3	15.017	5.006	23.677	0.005
Residual	4	0.846	0.211		
Total	7	15.862	2.266		

Column	SSIncr	SSMarg
SOC	14.548	0.955
Ima	0.453	0.302
APC	0.0157	0.0157

The dependent variable Yield can be predicted from a linear combination of the independent variables:

	P
SOC	0.101
Ima	0.298
APC	0.799

Normality Test (Shapiro-Wilk) Passed (P = 0.951)

Constant Variance Test: Passed (P = 0.120)

Power of performed test with alpha = 0.050: 0.998

Principal components analysis

*** Latent Roots/ eigenvalues ***

1	2	3
2.695	0.249	0.056

*** Percentage variation ***

1	2	3
89.85	8.29	1.86

*** Trace ***

3.000

*** Latent Vectors (Loadings) ***

	1	2	3
APC	-0.56485	0.72723	0.38998

Ima	-0.59799	-0.03506	-0.80074
SOC	-0.56865	-0.68550	0.45468

Linear Regression

Data source: Data 1 in Pearson' correlation (ST clay)

Yield = 1.251 + (0.00000359 * SOC*Ima*APC)

R = 0.839 Rsqr = 0.704 Adj Rsqr = 0.655

Standard Error of Estimate = 0.884

	Coefficient	Std. Error	t	P
Constant	1.251	0.548	2.282	0.063
col(10)×col(5)	0.00000359	0.000000950	3.780	0.009

Analysis of Variance:

	DF	SS	MS	F	P
Regression	1	11.171	11.171	14.286	0.009
Residual	6	4.692	0.782		
Total	7	15.862	2.266		

Normality Test (Shapiro-Wilk) Passed (P = 0.561)

Constant Variance Test: Passed (P = 0.233)

Power of performed test with alpha = 0.050: 0.778

Appendix 2

Murewa (Ward 28) soil profile descriptions

Clay site

Site characterisation

Coordinates	: 17°51.098' S, 31°34.360' E
Elevation	: 1360 m
Geology	: Dolerite
Surface features	: Stones and boulders
Vegetation	: <i>Brachystegia spiciformis</i> , <i>B. boemii</i> and <i>Piliostigma thonningii</i>
Landuse	: Cultivated to maize previous season
Slopes	: Gently undulating, 4-5 % on pediment

Profile description

0-13 cm	Dark reddish brown (2.5YR 3/3m); moderately developed medium sub-angular blocky; slightly hard dry, friable moist, sticky and plastic wet consistence; clay; good permeability and well drained; numerous very fine roots; clear smooth transition to:
13-38 cm	Dark reddish brown (2.5YR 3/3m); moderately developed medium sub-angular blocky; slightly hard dry, friable moist, sticky and plastic wet consistence; clay; good permeability and well drained; fairly numerous very fine roots; gradual smooth transition to:
38-68 cm	Dark reddish brown (2.5YR 3/3m); moderately developed medium sub-angular blocky; slightly hard dry, friable moist, sticky and plastic wet consistence; clay; good permeability and well drained; occasional fine roots; gradual smooth transition to:
> 68 cm	Stony and bouldery

Particle size and pH Analysis Results

Depth (cm)	0-13	13-38	38-68
Lab No.	S319	S320	S321
DM %	100	100	100
Texture	C	C	C
Clay %	48	64	67
Silt %	18	13	14
Fine sand %	26	17	14
Medium sand %	6	4	3
Coarse sand %	2	2	2
pH (CaCl ₂)	5.0	5.2	5.0

Sandy site Site characterisation

Coordinates	: 17°49.517' S, 31°32.988' E
Elevation	: 1274 m
Geology	: Granite
Surface features	: Gravel and small stones on surface
Vegetation	: <i>Terminalia sericea</i> dominant plus <i>Azanza garckeana</i> , <i>Psedolachnostylis maprouneifolia</i>
Landuse	: Cultivated to maize previous season
Slopes	: Gently undulating, 3-5 % on pediplain

Profile description

0-14 cm	Brown (10YR 5/3m); weakly developed fine sub-angular blocky; soft dry, very friable moist, non sticky and non plastic wet consistence; coarse grained loamy sandy; good permeability and well drained; fairly numerous very fine roots; clear smooth transition to:
14-50 cm	Light yellowish brown (10YR 6/4m); moderately developed medium sub-angular blocky; soft dry, very friable moist, slightly sticky and slightly plastic wet consistence; coarse grained loamy sand; good permeability and well drained; few fine roots; clear smooth transition to:
50-73 cm	Yellowish brown (10YR 5/4m); weakly developed fine sub-angular blocky; soft dry, very friable moist, slightly sticky and slightly plastic wet consistence; coarse grained loamy sand; rapid permeability and well drained; gravel and common small quartz stones; occasional fine roots; gradual smooth transition to:
73-120 cm	Yellowish brown (10YR 5/6m); massive breaking to moderately developed medium sub-angular blocky; slightly hard dry, friable moist, slightly sticky and slightly plastic wet consistence; coarse grained sandy loam; good permeability and well drained; gravel and common small parent material stones; occasional very fine roots

Particle size and pH Analysis Results

Depth (cm)	0-14	14-50	50-73	73-120
Lab No.	S326	S327	S328	S329
DM %	100	100	100	100
Texture	cLS	cLS	cLS	cSaL

Clay %	5	9	4	15
Silt %	5	5	8	8
Fine sand %	22	25	46	18
Medium sand %	28	27	11	15
Coarse sand %	40	34	31	44
pH (CaCl ₂)	3.6	3.4	4.0	5.1

