

FINAL REPORT

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QUANTIFYING THE EFFECTS OF CONSERVATION AGRICULTURE (CA) PRACTICES ON SOIL AND PLANT PROPERTIES

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LIST OF ABBREVIATIONS

AMF	Arbuscular mycorrhizal fungi
API	Animal Production Institute
ARC	Agricultural Research Council
C	Carbon
CA	Conservation agriculture
CT	Conventional tillage
EC	Electrical conductivity
FH	Fertilizer, high applications level
FL	Fertilizer, low application level
GCI	Grain Crops Institute
IPCC	Intergovernmental Panel on Climate Change
ISCW	Institute for Soil, Climate and Water
K	Potassium
MC	Maize/cowpea intercropping system
MM	Maize monoculture cropping system
MS	Maize/soybean rotation cropping system
N	Nitrogen
NWM	Neutron water meter
OM	Organic matter
P	Phosphorus
PPRI	Plant Protection Research Institute
RT	Reduced tillage
SOM	Soil organic matter
SWC	Soil water content

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EXECUTIVE SUMMARY:

Quantifying the effects of conservation agriculture¹

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Conservation agriculture (CA) is a sustainable farming system that is gaining momentum as more and more farmers convert to CA. Conservation agriculture is a sustainable management system that optimises yields and reduces input costs. For many farmers the rising fuel cost and the pressure on resources, such as water and arable land, increase the pressure to consider alternative farming methods. However, there are also challenges when switching from conventional farming practices to CA. Weed composition and dynamics, for instance, change under different tillage systems; commercial farmers might need new implements such as no-till planters which would result in high initial capital expenses; overall management becomes more adaptive and farmers need to be skilled; compaction could be a problem in certain soil types in the absence of tillage; and lack of appropriate or available cover crops complicates CA implementation, especially in the drier regions of South Africa. Despite these challenges, the rewards are high. Conservation agriculture improves soil water-holding capacity, reduces erosion, improves the nutrient status and structure of the soil, and could cut input costs. But to achieve these improvements, all three aspects of CA, *viz.* minimal tillage, multi-cropping and permanent soil cover, must be incorporated. The combined effect of incorporating all three aspects is a build-up of soil organic matter (SOM) which is really the driving force behind all the improved qualities associated with CA.

To evaluate the effect of CA on soil and plant properties, the Agricultural Research Council (ARC) initiated the Zeekoegat on-station, dryland field trial in 2007. The trial, which continued for 6 years, was conducted just north of Pretoria at Zeekoegat, Roodeplaat, on a Shortland soil form with a clayey texture (51% clay). An iron-manganese oxide concretion layer occurs at varying depths of 500-1000 mm throughout the trial area. The area receives an average annual rainfall of 704 mm. The trial was designed to compare conventional farming practices (ploughing and

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monoculture) with various CA aspects (reduced tillage, permanent soil cover and multi-cropping systems). It was statistically laid out in a randomised complete block design, with tillage as the main factor. Other treatments included cropping systems (maize monoculture, maize/cowpea rotation, maize/soybean rotation, maize/cowpea intercropping, maize/oats intercropping and maize/vetch intercropping), as well as fertilizer application (optimal and low fertilizer levels). In terms of tillage, the soil was prepared as follows: conventionally tilled plots were ploughed with a mouldboard plough, disked and then a tine implement was used to draw furrows for planting; whilst on the reduced tillage plots, only furrows were drawn for planting. In the first 3 years these furrows were made by hoes, but due to the time-consuming nature of this procedure, a tractor was used in the last 3 years of the trial. Planting was done by hand with a specialised no-till planter.

Various properties were measured, including soil chemical properties (such as soil nutrients, carbon sequestration and greenhouse gas emissions), soil physical properties (such as aggregate stability, soil penetration resistance, soil water content and soil temperature), soil biological properties (such as microorganisms, nematodes and mycorrhizae) as well as agronomic properties (grain yields, biomass and weeds). All the results were statistically analysed.

In this trial, the results were initially very positive in favour of CA. For the first 3 years, maize that was planted with intercrops (especially the legume intercrops such as grazing vetch or cowpea) outperformed monoculture maize. Maize grain yields under reduced tillage systems were higher than on conventionally tilled soils, but not all the CA treatments performed equally well. The maize/oats intercropping, for instance, did no better than the maize monoculture. This could possibly be because oats were not suitable for the specific area and as a result grew very poorly, generating inadequate biomass. Since biomass is the driving force behind CA, the poor biomass production resulted in less optimal improvements under CA treatments. The first two trial seasons received high rainfall and the crops performed well. In the other four seasons, however, rainfall was either low or poorly distributed throughout the season, resulting in very low yields. Another observation was that in the last three seasons, crop yields under reduced tillage were lower than under conventional tillage. It was hypothesised that topsoil compaction in the absence of ploughing was responsible for poor crop performance. On average, the maize grain yields for the six trial seasons were very similar for the different tillage systems, with 2.9 ton/ha for reduced tillage and 3.1 ton/ha for conventional tillage. Although this indicates that

there was no significant difference between the two tillage systems, it must be kept in mind that less inputs were required for the reduced tillage plots than conventionally tilled plots.

Soil samples were taken once a year at various depths (0-5, 5-10, 10-30 and 30-60 cm) and analysed for a variety of elements (such as P, NO₃, NH₄, Ca, Mg, Na, K, total N and total C). Statistical analysis of the data showed that cropping system, and to a lesser degree, tillage and fertilizer, were responsible for increased nutrient status in certain plots. As expected, it was especially nitrogen that significantly increased under maize/legume cropping systems.

Soil organic carbon was measured as an indicator of organic matter build-up in the soil, and a steady increase in organic C was observed over the course of the 6 years under reduced tillage, while in conventionally tilled soils the organic C was more or less stable. This concurs with results obtained by other researchers. A build-up in organic C indicates a build-up in SOM which is one of the aims of CA. Soil water content reacted positively to CA practices and soil water was consistently higher under reduced tillage compared to conventional tillage. Soil water conservation is increased by an intact soil profile, as well as organic matter that covers the soil surface. Soil temperatures were cooler under reduced tillage, probably due to higher water content and protection from extremes in air temperature by the SOM surface cover.

Reduced tillage proved to be beneficial for aggregate stability and water-holding capacity. Reduced tillage leads to increased aggregate stability, as well as increased soil organic C and N, both of which play constituent roles in aggregate formation and stabilisation. Aggregate stability leads to improved water retention relationships with positive effects on infiltration, drainage and soil aeration. When measuring the soil water content, this effect was confirmed, when higher soil water contents were consistently measured under reduced tillage compared to conventional tillage practices.

Soil penetration resistance was also measured as an indicator of possible soil compaction. This was done in the final season, and results indicated that a topsoil layer of increased soil penetration resistance occurred in the reduced tillage soils. Topsoil compaction is a risk in the absence of tillage, and could explain the poorer yields under reduced tillage in the final few years. Higher soil penetration resistance could negatively affect root development and also negatively affect germination, biomass production and grain yield. These results highlight the

importance of adaptive farming systems, and the value of knowing the soil and applying correct management practices.

Weeds were monitored for three consecutive years, to determine the dynamics of weed populations under CA compared to conventional farming practices over time. It was found that tillage practices can affect both the biomass as well as the diversity of weeds. Cultivation year and the cultivation year x tillage interaction significantly affected weed biomass. Weed biomass and species diversity increased under reduced tillage while under conventional tillage, weed biomass had a slight downward trend and species composition was similar over the 3 years.

In terms of nematodes and mycorrhizae, results were mostly inconclusive or insignificant as a result of a large number of variables and the short time-span over which the data is compared. The significance of results obtained from the nematology study was that this is one of very few medium-term field trials in which nematodes were monitored for changes as a result of farming practices. One of the most important observations is that it takes far longer to observe a definite trend than was expected by researchers until now. Mycorrhizae, glomalin and spore counts were similarly slow to react to different farming systems. Glomalin levels increased under all treatments and tillage practices, as a result of inoculation in 2010/11. Slight increases in arbuscular mycorrhizal fungi spores were initially counted under reduced tillage, but towards the end of the trial, spore count was higher under conventional tillage. Crop rotations and intercropping with legumes had a positive effect on spore count.

Soil microbes are more sensitive to changes in and to the soil. As soon as soils are tilled, or rotational crops or different mulches are introduced, the soil microbes react to that change. In this trial the results showed that reduced tillage favoured higher microbial activity (faster conversion of carbon and phosphorus in the soil) and diversity than with conventional tillage, depending on the crops planted. This implies that soil quality can be increased by planting the right crops, or combination thereof, with reduced tillage.

Emissions of the greenhouse gas (GHG) carbon dioxide (CO₂) were measured over a number of years. Although comparison of emissions across the years is difficult since different methods have been used and tested, it can be concluded that CO₂ emissions from conventionally tilled soils were higher than from reduced till soils. A relatively strong correlation exist between CO₂ emissions and soil water content, while a weak correlation between CO₂ and temperature was

also measured. The results for GHG emissions are preliminary and will be explored further using modelling.

In conclusion it can be said that conservation agriculture is a complex system that consists of various aspects. In this study, reduced tillage in combination with various crop rotations and intercropping systems was compared to conventionally tilled soils and maize monoculture practices. Since not just one type of CA can be practised, the results are presented in terms of tillage and cropping systems. After careful sampling, analysis and interpretation of 6 years of data, it can be concluded that reduced tillage could increase soil organic matter, water-holding capacity and aggregate stability. Multi-cropping, especially with legume crops such as cowpea and vetch, successfully improved soil N content and soil organic C content as well as aggregate stability. The research team feels confident that we were able to quantify the positive effects of CA on soil and plant properties. But part of the conclusion is also that CA is not a recipe that can be followed towards successful farming, but more of an adaptive learning process. Conservation agriculture provides a system whereby each farmer can apply what works, and pick the best practices from the CA 'basket' to suit their specific needs.

1 RESEARCH BRIEF

In 2007 the ARC-Institute for Soil, Climate and Water (ARC-ISCW) initiated a medium-term research project to quantify the effects of conservation agriculture on soil and plant properties. The original main question that needed to be addressed was: What is the role of the key principles of CA, especially different diversified cropping systems, to contribute to the soil health processes to help restore desired agro-ecosystem functions? The project's aim was initially very broad, and the secondary objectives that were deemed necessary over the short and medium term were as follows:

1. To implement, monitor and evaluate on-station research methods investigating the contribution of CA practices on crop-soil processes and systems.
2. To improve our basic knowledge and skills of new and innovative basic and systems research methods on plant-soil systems, which include elements of soil biology, soil nutrient cycling and soil water dynamics.
3. To improve the awareness of the contribution of CA practices to food security and soil productivity to a broader group of stakeholders.
4. To improve capacity of, and collaboration between researchers in the ARC-ISCW and other institutes.

An on-station field trial was developed and laid out on the ARC's experimental farm at Zeekoegat, north of Pretoria, with the assistance of the ARC-Animal Production Institute (ARC-API). At the onset of the project the only funding was core research funding made available by the ARC-ISCW. But as the project continued, external funding from the Maize Trust was also obtained. The project coordination, planning and basic data collection was the responsibility of the ARC-ISCW. Over the years the project grew as more researchers joined the team, adding their expertise and contributing data from their studies to the overall project.

The research team view the project as a great success, both in terms of its original objectives as well as the specific objectives that were continuously added. The field trial was successfully planned, laid out and maintained during its 6-year duration. Even though climatic conditions resulted in poor yield in some years, data was still collected, analysed and prepared for various publications and presentations. Vast volumes of data have been collected on a variety of aspects over the course of the project, contributing to basic knowledge and skills. Awareness on CA was promoted through a number of information days, radio and television talks, as well as popular articles, pamphlets and posters. The capacity of the ARC researchers who participated has been

improved, while researchers from different ARC institutes were not only collaborating successfully with one another, but also with people from other institutions, such as universities, industries and farmers. Throughout the years there were many people who were involved and contributed to the success of this project, as listed in Table 1-1.

Table 3.1-1: Research team and collaborators

NAME	CAPACITY	INSTITUTION	TIME INVOLVED
Research team			
Dr Hendrik Smith	Initiated project & Project leader	Grain SA	2007-2008
Ms Corrie Swanepoel	Project leader Researcher	ARC-ISCW	2007-2014
Dr Danie Beukes	Mentor Researcher	ARC-ISCW	2007-2014
Mr Johan Habig	Researcher	ARC-PPRI	2008-2014
Dr Susan Koch	Researcher	ARC-PPRI	2008-2014
Dr Mariette Marais	Researcher	ARC-PPRI	2008-2014
Dr Antoinette Swart	Researcher	ARC-PPRI	2008-2014
Mr Gerrie Trytsman	Advisor & Pasture scientist	ARC-API	2007-2014
Students and supervisors			
Ms Wendy Seggota	MSc, Mycorrhizae	ARC-PPRI & Rhodes	2008-2014
Prof Jo Dames	Supervisor	Rhodes University	2008-2014
Ms Reedah Mampana	MSc, Soil water and temp	UP	2009-2014
Prof Martin Steyn	Supervisor	UP	2009-2014
Mr Conrad Baker	M.Inst Agrar, Weed science	UP	2013-2014
Prof Casper Madikadze	Supervisor	UP	2013-2014
Technical assistance			
Mr Michael Kidson	Technician	ARC-ISCW	2007-2014
Mr Martiens Mmamadisha	Assistant	ARC-ISCW	2007-2014
Mr Jan Manganje	Foreman	ARC-API	2007-2013
API farm team	Labourers	ARC-API	2007-2013
Statisticians			
Ms Marie Smith	Biometrician	ARC-Biometry Unit	2007-2008
Ms Nicolene Thiebaut	Biometrician	ARC-Biometry Unit	2008-2014
Mr Frikkie Calitz	Biometrician	ARC-Biometry Unit	2009-2014
Reviewers and administrative coordination			
Dr Thomas Fyfield	Reviewer, proof-reading & Research team (NWM)	ARC-ISCW	2007-2014
Prof Robin Barnard	Reviewer & mentor	ARC-ISCW	2007-2014
Dr Goodman Jezile	Reviewer	ARC-ISCW	2009-2014
Prof Ian McDonald	Coordinator with MT	ARC-GCI	2007-2008
Prof Graham Thompson	Coordinator with MT	ARC-GCI	2009-2014
Ms Paula Kruger	Coordinator at GCI	ARC-GCI	2007-2014
Ms Adri Laas	PR	ARC-ISCW	2007-2014
Funders			
Maize Trust			2008-2014
ARC-ISCW			2007-2013

Contributions changed from year to year, depending on the capacity of the researchers, or the study duration and objectives of students. Subject-specific objectives originated as more researchers joined the project, including the following:

1. To quantify the effect of reduced and conventional tillage practices as well as various cropping systems on **maize grain yield**.
2. To compare **biomass production** under conventional farming systems with CA practices.
3. To evaluate the effects of tillage practices and CA cropping systems on soil **aggregate stability** and associated soil properties.
4. To compare **soil water content and soil temperature** under CT and RT practices.
5. To determine the effect of various conservation agricultural facets on soil **microbial dynamics**.
6. To monitor, over an extended period, the succession of **nematodes** in some of the reduced tillage and conventional tillage treatments.
7. To determine the effect of tillage on **AM fungi spore number, root colonisation and glomalin concentration**.
8. To verify a method of measuring **greenhouse gas emissions** from agricultural soils and to determine the effect of farming practices on GHG emissions.

Knowledge dissemination occurred throughout the duration of the project in many formats, including presentations, articles (popular and peer-reviewed), information days, TV/radio talks, as well as pamphlets and posters. A detailed list is given in Appendix 1 whilst Table 1-2 provides a summary of these outputs.

Table 3.1-2: Summary of outputs from Zeekoegat CA project

Year	Poster/oral presentation	Scientific report	Popular article	Peer-reviewed article	Thesis / Chapter	TV/Radio talk	Information Day / Workshop	Pamphlet / Flyer
2009		1	2			1	2	2
2010	6	2	1			1	1	1
2011	5	1		1				
2012	3	1				1	1	
2013		1		2				
2014	4	1		3	2	2		
Total	18	7	3	6	2	5	4	3
<i>Due</i>	>5		>4	>3	2			

QUANTIFYING THE EFFECTS OF CONSERVATION AGRICULTURE (CA) PRACTICES ON SOIL AND PLANT PROPERTIES



2 INTRODUCTION

Crop failure, low yields and food insecurity are prevalent in many parts of Africa and South Africa. This is not just a consequence of climatic variability but also agricultural drought, which is the result of land degradation, incorrect agricultural practices, reduced infiltration and subsequent low soil water availability and crop failure (Rockström & Steiner, 2003). Optimum soil conditions are associated with increased soil organic matter, increased soil water and optimal soil temperature and can be obtained by good farming practices such as conservation agriculture (Hobbs, 2007).

Conservation agriculture (CA) is a sustainable management system that improves soil physical, chemical and biological properties, while at the same time reducing input costs, soil erosion and water pollution (FAO, 2007). Combining the three principles of CA, which are permanent organic soil cover, diversified cropping systems (including cover crops and crop rotations) and minimum soil disturbance, results in the increase of soil organic matter (SOM) (Hobbs, 2007; Dumanski *et al.*, 2006). An increase in SOM subsequently leads to other advantages such as increased infiltration, aggregate stability and better water-holding capacity (FAO, 2007; Dumanski *et al.*, 2006; Bot & Benites, 2005) and moderate soil temperatures (Lal, 1974). Plant residues or mulch that cover the soil surface protect the soil from sealing and crusting by raindrops, increasing rainwater infiltration and reducing runoff (Bot & Benites, 2005) and temperature extremes (Lal, 1974), thereby enhancing green water productivity and providing increased insurance against drought (Dumanski *et al.*, 2006).

However, CA is a complex system, with various aspects and components. A number of studies suggest that a soil and nutrient management strategy based on a broader range of ecosystem processes is worthy of further investigation (Drinkwater & Snapp, 2007; Graves *et al.*, 2004; Clark *et al.*, 1998). The approach is inclusive of various disciplines as influenced by management practices such as CA, and that in turn also influence the soil and plant growth under these systems. This study aims to measure a wide range of disciplines, including soil physical and chemical properties, soil biological properties and agronomic aspects of a CA system compared to conventional farming systems.

3 MATERIALS AND METHODS

Baseline information

An on-station field trial was conducted at Zeekoegat, north of Pretoria, South Africa (25° 36' 55" S, 28° 18' 56" E). The experimental soil was classified as borderline between a Hutton and a Shortland form with moderately fine to medium blocky structure and clay texture, with underlying Gabbro. Some A horizon properties were: clay texture (clay = 46%); pH (H₂O)=6.0; P (Bray-1) = 16; K mg/kg, Ca and Mg = 632, 1206 and 248 mg/kg, respectively; organic C = 1.2%; and CEC = 12.6 cmol_c/kg. An iron-manganese oxide concretion layer occurs at varying depths of 500-1000 mm throughout the trial area.

Trial layout

The trial was laid out as a split-plot randomised complete block design replicated three times. Each replicate was split into two tillage systems (whole plots) and then each whole plot (reduced tillage [RT] and conventional tillage [CT]) was further subdivided into 12 treatments (6 cropping systems x 2 fertilizer levels), giving a total of 72 plots. The cropping systems were: maize monoculture, maize/cowpea rotation, maize/soybean rotation, and maize/cowpea intercropping, maize/oats intercropping and maize/vetch intercropping. Fertilizer was applied at a high level according to the fertilizer application guidelines, and at a low level, which is 50% of the high application. Plot dimensions were 7.2 m x 8 m with 0.9 m planting rows. (See details of trial treatments and layout in Appendix 5.1 and 5.2 respectively.)

Soil preparation

At the onset of each season, all crop residues from the previous season were flattened and slashed. The CT plots were ploughed with a mouldboard plough and then disked with a disk harrow. Furrows were drawn with a four tine cultivator frame on both the CT and RT plots. On the RT plots, only furrows were drawn for planting (0.9 m apart). In the first 3 years these furrows were made by hoes, but due to the time-consuming nature of this practice a tractor was used in the last 3 years of the trial. Planting was done by hand with a specialised no-till planter.

Fertilizer application

The original trial layout included two levels of fertilizer application: high input (F2) and a low input (F1), at 50% of the high input rate. A similar level of fertilizer application rate was selected for legumes, but with different fertilizers to account for the nitrogen fixing abilities of legumes.

Fertilizer levels were determined annually based on soil analysis. A target yield of 4 ton/ha was estimated, taking into account the rainfall and soil type and depth (FSSA, 2007).

Nitrogen was applied accordingly, at a total rate of 70 kg/ha. But, according to the Pannar Production Guideline series for Maize (Pannar, undated), if fertilizer is band applied, application should not exceed 40 kg N/ha. It was therefore decided that at planting, N fertilizer in the form of Limestone Ammonium Nitrate (LAN (28)) would be applied at 42 kg/ha, with a follow-up fertilizer application of 28 kg N/ha. A total of 70 kg N/ha would thus be applied, in accordance with the Fertilizer Guidelines (FSSA, 2007).

Phosphorus (Supergrow (20.3%)) was applied at 65 ton P/ha in accordance with the Fertilizer Handbook (FSSA, 2007); however, it is also advised that P should be applied to maintain soil P. The removal of P through crop harvest should be replenished at a rate of 4 kg P per ton of maize removed. This application was done by annually determining the amount of P removed by multiplying the maize grain yield with 4 ton P. Phosphorus was therefore applied at this rate (to replenish P removed from harvesting) during planting in November/December, and the remaining P (as indicated by the Fertilizer Handbook) would be applied during top-up in January.

The soil K levels were very high at 485-662 mg/kg and as a result no K was added.

Planting

Main crop

Planting usually commenced by the end of November or early December, after the first significant rain of the season was received. The cropping sequence is outlined in Table 3-1.

Table 3.1-1: Cropping systems and crops planted in seasons 1 to 6

Cropping system	Season 1	Season 2	Season 3	Season 4	Season 5	Season 6
	2007/08	2008/09	2009/10	2010/11	2011/12	2012/13
1. Monoculture	Maize	Maize	Maize	Maize	Maize	Maize
2. Rotation	Cowpea	Maize	Cowpea	Maize	Cowpea	Maize
3. Rotation	Soybean	Maize	Soybean	Maize	Soybean	Maize
4. Intercrop	Maize/cowpea	Maize/cowp	Maize/cowp	Maize/cowp	Maize/cowp	Maize/cowp
5. Delayed intercrop	Maize/oats	Maize/oats	Maize/oats	Maize/oats	Maize/oats	Maize/oats
6. Delayed intercrop	Maize/vetch	Maize/vetch	Maize/vetch	Maize/vetch	Maize/vetch	Maize/vetch

Standard row spacing (0.9 m) was used for the monoculture and crop rotation treatments, while tramline rows (1.8 m spacing between maize) were used for all the intercropping plots. Three rows of cowpea were planted in the 1.8 m space between maize rows.

A yellow maize cultivar (6P/110) from Pannar was used. It was aimed to plant maize at a density of 37 000 plants/ha. Two seeds were planted in each hole to ensure good germination. Three weeks after planting, maize seed was replanted where poor germination had occurred whilst double maize plants were removed.

Intercrop

There were six intercropping treatments in each block: maize (*Zea mays*) with cowpea (*Vigna unguiculata*) intercropping under low fertilizer (treatment 4) and high fertilizer (treatment 10); maize with delayed oats (*Avena sativa*) intercropping under low fertilizer (treatment 5) and high fertilizer (treatment 11); and maize with grazing vetch (*Vicia dasycarpa*) delayed intercropping under low (treatment 6) and high (treatment 12) fertilizer.

The cowpea intercrop was planted about 3 weeks after the main crops. A mixed cowpea variety was used. Manual labour was used to make furrows and plant seeds, while the delayed intercrops (oats and vetch) were planted as soon as adequate rainfall had been received in February.

3.1 Ad hoc activities during growing season

During the growing season two types of activities took place: maintenance and data collection. Maintenance included weeding, applying herbicides and pesticides, and also 'replant' of crops. Weeding included a combination of chemical and manual control. Prior to planting, the trial was treated twice with both glyphosate (such as Roundup) and S-metolachlor (such as Dual Gold) herbicides to treat both broadleaf and grass weeds. After crop emergence only manual weeding took place. This was done two or three times during the growing season using handheld hoes.

Although this was a dryland trial, it was necessary to irrigate once due to exceptionally low rainfall (Swanepoel *et al.*, 2013).

Data collection

Data collection during the season became more diverse as more researchers joined the team.

This included the following:

- General soil sampling – once a year in October.
- Yield determination – upon harvesting.
- Biomass determination – middle of the growing season (March).
- Leaf samples – once in the growing season after the cobs formed (February).
- Soil water measurement using a neutron water meter – weekly measurements during the growing season, and two-weekly measurements during the winter period.
- Soil water measurement using capacitance probes - data was downloaded twice a month.
- Gravimetric soil water measurement for calibration purposes.
- Sampling for nematodes – before planting and again in January.
- Sampling for soil microbes – before planting and twice in the growing season.
- Sampling for mycorrhizae – once during the growing season.
- Greenhouse gas emission sampling – CO₂ directly after rainfall episode (x2).
- Soil aggregate stability.

Statistical analyses

Most statistical analyses were done by the ARC-Biometry Unit. A split-plot analysis of variance (ANOVA) over two tillage systems was done using Genstat 14.1 to test for differences between high and low fertilizer levels as well as six cropping systems. The data was normally distributed with acceptable homogeneous variances. The means were separated using Fishers' unprotected t-test least significant difference (LSD) at the 5% level of significance (Snedecor & Cochran, 1980).

3.2 Harvesting

Main crops were only harvested in May/June each year, with the exception of very dry years, when harvesting occurred as early as March. During the dry years when maize cob formation was poor and the plants were starting to dry out prematurely, the cobs were harvested to prevent any insect damage or other losses. Maize cobs were harvested by hand and 2 x 5 m rows were selected in each plot. The maize plants were counted and the cobs were removed, placed in a marked bag and transported to the ARC-ISCW. The residue of the maize, cowpeas, oats and vetch was left on the field as mulch. Prior to planting, the crop remains were flattened using a knife edge roller.

The harvested maize samples were threshed by using hand maize strippers. The grain was weighed and moisture content determined using a grain moisture analyser, Farmex Moisture Master. The ideal grain moisture content is 12.5%. After the grain was weighed, the average yields were calculated by converting the sample to 1 hectare. The grain moisture content was taken into account using the following equation: $(1 - (\text{ave \% seed moisture} - 12.5\%))/100 * (\text{yield/ha})$. Final results were expressed as yield/ha.

3.3 Biomass determination

Biomass was determined during the active growing season, usually in February for maize, cowpea and soybean, while the winter crops (oats and vetch) were determined in July to August. A 1 m² square grid was used. Two sub-samples were taken per plot (thus 2 m² was sampled). Crops in the square metre were removed at the ground, bagged and transported to the ARC-ISCW, where they were oven-dried at 50 °C. The dried plant material was weighed to determine the dry mass. Biomass values were converted to ton/ha. In the case of intercropping (treatments 4 and 10), the combined total biomass of the maize and cowpea was used.

3.4 Soil sampling

General soil sampling took place once a year just before planting. Each of the 72 plots was sampled at four different depths, namely 0-5, 5-10, 10-30 and 30-60 cm. A soil auger was used and two auger holes were made, one in the main row and one in between rows. Soil layers of each depth were then mixed on a plastic sheet to get a composite sample that would be representative of the plot. The soil was transferred to marked plastic bags and transported to the Analytical Services laboratory at ARC-ISCW.

At the laboratory, the soil was dried and sieved prior to analysis. The following elements were analysed: pH, resistance, P, Ca, K, Mg, Na, NO₃-N, NH₄-N, total N, total C and organic C. The results were sent to the ARC-Biometry Unit for statistical analysis. Variance in the data was tested with the ANOVA model using GenStat.

3.5 Leaf sampling

Leaf samples were taken each February. A transect across each plot was made and five maize plants in this transect were sampled, usually excluding the first and last row. Sampling took place just after the cobs had formed and the leaf 'opposite and below' the cob was removed. When

there was more than one cob, the largest cob was selected and the leaf 'opposite and below' was sampled. Legume leaves were sampled from the top where relatively new growth occurred. The composite samples were transferred to a clearly marked paper bag and transported to the ARC-ISCW laboratory for analysis. At the laboratory, leaves were first washed to remove any soil particles and then oven-dried. Leaves were analysed for N, P, Ca, Mg, K, Cu, Fe, Zn and S.

3.6 References

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4 RESULTS AND DISCUSSION

4.1 Climatological observations

For the purpose of evaluating long-term climatological observations, data from the ARC-ISCW Rooodeplaas automatic weather station at a bearing of 72° from true north (north east) and at 4.1 km distance from the trial site was used. Elements recorded on an hourly basis included rainfall, radiation, humidity and air temperature, while evaporation was calculated using the Blaney-Criddle equation. In November 2012 a Texas automatic rain gauge was installed at the trial site (Zeekoegat) which provided continuous rainfall data. Large seasonal and monthly variation in rainfall is evident (Fig. 4.1-1). Table 4.1-1 gives a summary of the total rainfall, minimum and maximum temperature in the growing as well as the fallow periods for all six trial seasons.

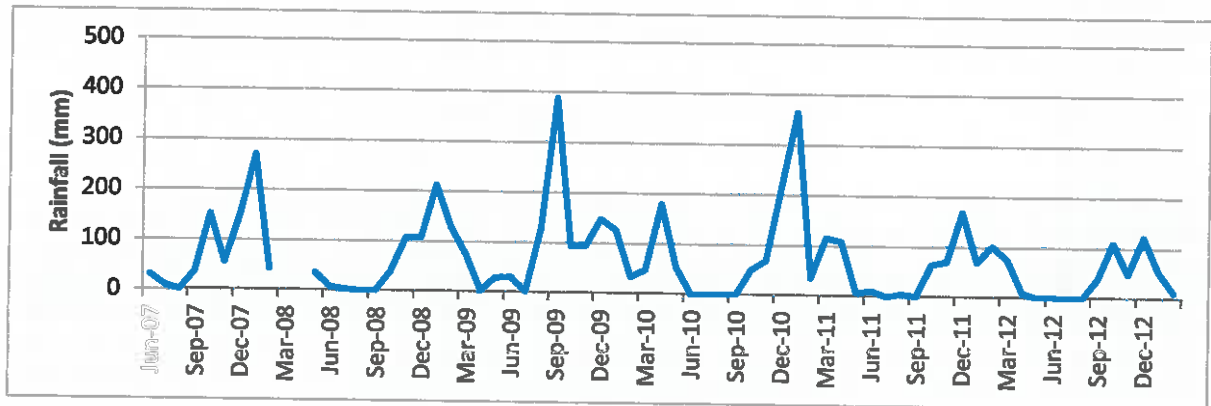


Figure 4.1-1: Rainfall distribution (monthly rainfall in mm) for six seasons at Zeekoegat.

Table 4.1-1: Rainfall, minimum and maximum temperatures during the fallow, vegetative and reproductive periods of the six growing seasons at Zeekoegat

	2007/08			2008/09			2009/10			2010/11			2011/12			2012/13		
	Fp	Vp	Rp	Fp	Vp	Rp	Fp	Vp	Rp	Fp	Vp	Rp	Fp	Vp	Rp	Fp	Vp	Rp
Rainfall	282	462	36	155	447	106	732	306	279	118	648	244	150	333	88	264	270	175
Temp min	8.3	15.9	8.4	8.2	17.0	9.6	7.8	16.6	12.0	8.0	16.5	10.9	6.6	16.7	9.7	7.3	16.3	9.5
Temp mx	25.3	28.4	24.8	26.5	29.6	26.5	25.1	29.7	26.2	26.4	28.9	26.1	25.6	30.2	27.5	25.5	30.4	26.8
Fp:	Fallow period (June-November)																	
Vp:	Vegetative period (December-February)																	
Rp:	Reproductive period (March-May)																	
Rainfall:	Total rainfall in mm for each period																	
Temp min:	Minimum temperature (°C)																	
Temp mx:	Maximum temperature (°C)																	

4.2 Yield

Various factors could affect crop yields, including total rainfall, rainfall distribution (maize is more sensitive during the vegetative period and a dry spell of 10 days could significantly affect the yield), temperature, nutrient availability and compaction. In this trial, the yield varied considerably across the six seasons, and was mostly affected by rainfall distribution during the growing season rather than total seasonal rainfall (Fig. 4.2-1 A). With the exception of one season, a relatively strong correlation between yield and January rainfall was obtained (Fig. 4.2-1 B). In the first two seasons the rainfall was adequate and well distributed for optimal crop production. However, in the last four seasons, rainfall was either low or poorly distributed, resulting in poor germination or poor cob formation for maize, and subsequent low yields. Plate 4.2-1 illustrates the crops during the six growing seasons.

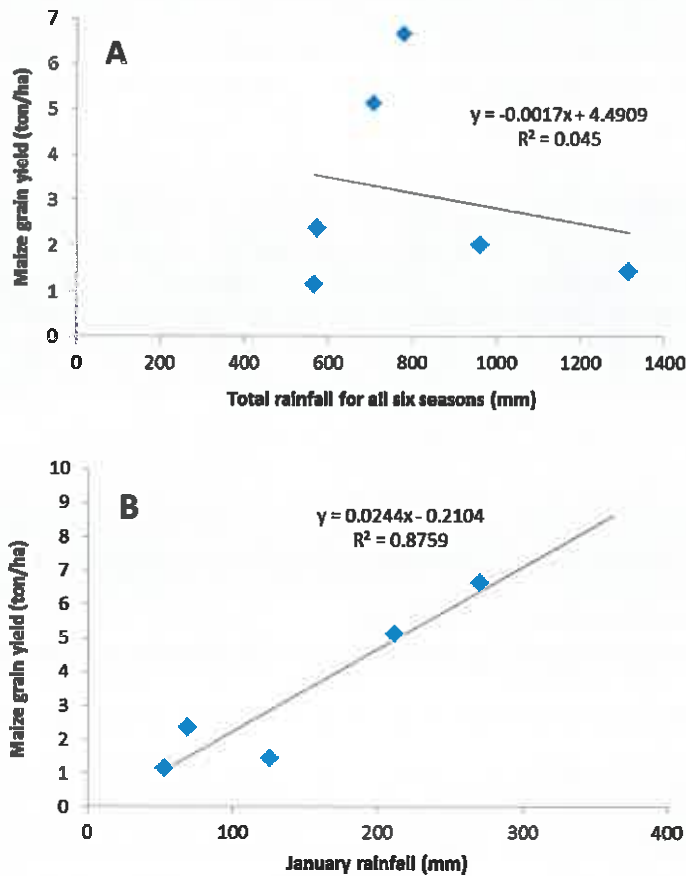


Figure 4.2-1: Correlation between yield and total seasonal rainfall (A) for all six seasons and January rainfall (B) for seasons 1, 2, 3, 5 and 6.

Season 1: 2007/08



Season 2: 2008/2009



Season 3: 2009/10



Season 4: 2010/11



Season 5: 2011/12



Season 6: 2012/13



Plate 4.2-1: Crops in seasons 1 to 6.

Conservation agriculture practices such as tillage and cropping systems also had an effect on maize grain yield. Tillage initially had a slightly positive effect, although not significant, for the first three seasons (Fig. 4.2-2), but negatively affected yields in the last three seasons. This was most likely as a result of topsoil compaction in the absence of tillage under RT soils (see section 5.5). The effect of cropping systems on yields was evident with leguminous intercrops or crop rotations, such as vetch and cowpeas, that had the most beneficial effect (Fig. 4.2-3). These crops did not only significantly improve the nitrogen content of the soil, it also conserved soil water by providing better soil cover than maize monoculture. In this trial, the fertilizer effect was negligible, probably because the water availability due to low rainfall was more limiting than nutrient supply.

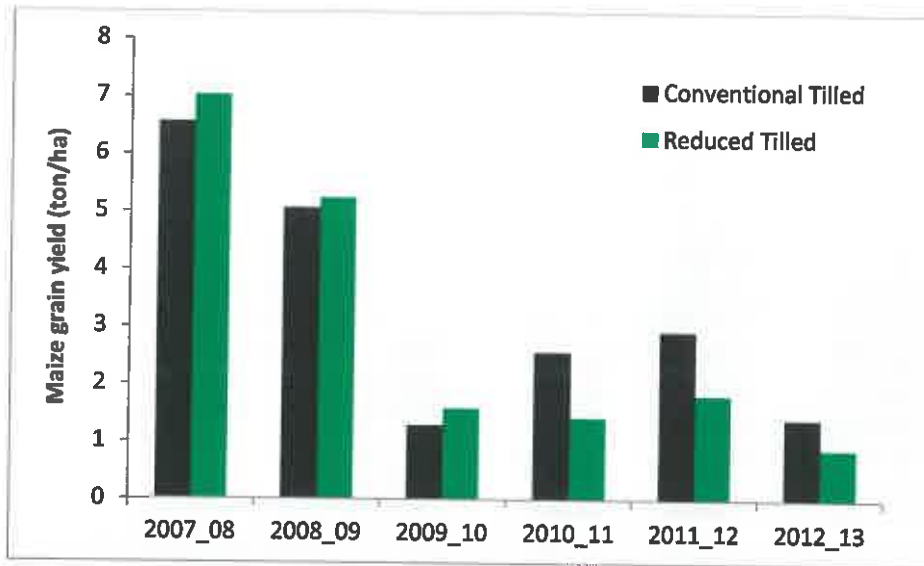


Figure 4.2-2: Effect of tillage systems on maize grain yield for six growing seasons at Zeekoegat.

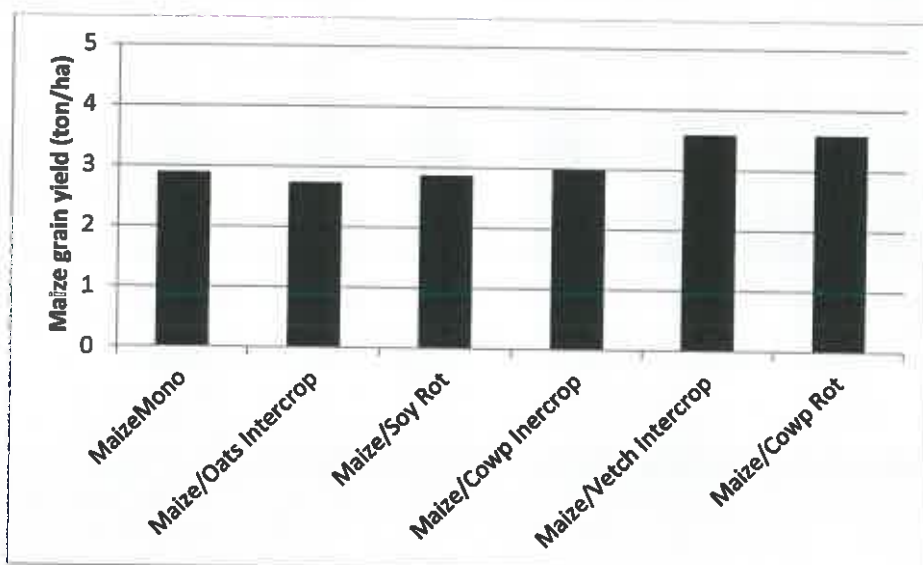


Figure 4.2-3: Effect of cropping systems on maize grain yields.

4.3 Biomass

Comparisons between consecutive years are difficult because of the rotation cropping systems. Every second year, maize as well as the various intercrops were planted on all plots, while every other year, the legume rotation was planted on all the rotation plots. Furthermore, maize monoculture was planted in full stands, while intercropping systems were planted in tramlines with 1.8 m row spacing. Data for total biomass exists from 2009/10 to 2012/13. In Fig. 4.3-1 total biomass is compared across years and cropping systems.

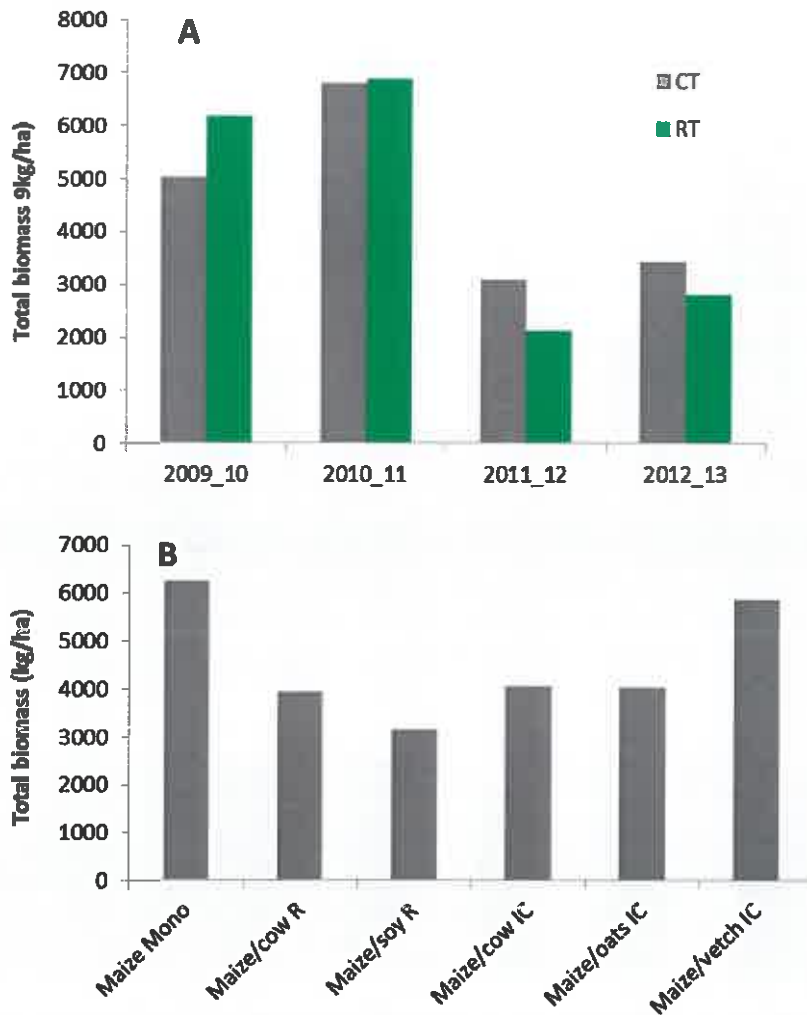


Figure 4.3-1: Total biomass expressed in (A) years and (B) cropping systems.

Total biomass from the 'maize' years of the rotation systems (2010/11 and 2012/13) was higher than the previous year in which the legume crops were planted (2009/10 and 2011/12). The biomass under RT was initially higher but was outperformed by CT at the end. As with grain yield, this can be explained by topsoil compaction in the absence of tillage. Higher soil penetration resistance values were measured under RT soils, leading to poorer root development, which in turn led to poor plant growth as well as low yields.

Total biomass from maize-based systems, such as maize monoculture, was the highest. Overall the biomass from the rotational systems (maize/cowpea and maize/soybean rotations), produced the lowest biomass. This is because the mass of the legumes planted during the

'legume' years was much lower than that of maize. Intercropping systems included maize, but it was planted at 50% density compared to that of maize monoculture stands, reducing the total biomass for these systems. The maize/vetch cropping system was most beneficial to grain yields as well as biomass production. Vetch was a very effective cover crop that completely covered the soil surface, thereby conserving soil water, while adding to soil nutrients by fixing nitrogen. The improved soil health supported better maize growth, which added to the relatively high biomass produced under this cropping system.

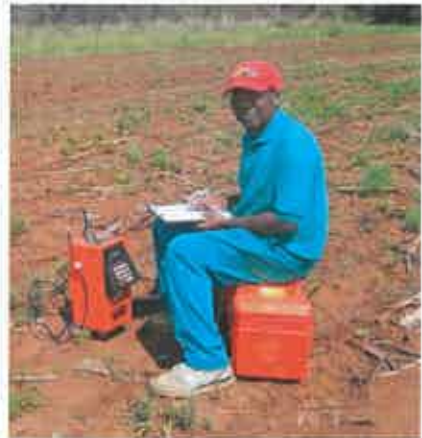
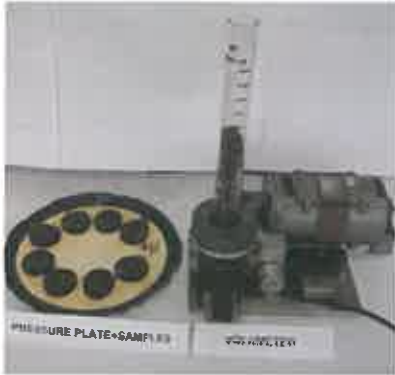
4.4 Soil nutrient dynamics

Most nutrients or soil properties showed no clear trend over time. Phosphorus did respond to fertilizer application, with higher P values measured under the high fertilizer treatments. Nitrogen levels, including total N, NO₃ and NH₄, improved most years as a result of cropping systems, specifically the maize/vetch intercropping and the maize/legume rotation treatments. Significant differences were observed in most years for K, Ca, Mg and Na, but these changes were not consistent over time, and each year resulted from different factors (tillage, cropping systems, fertilizer application, or a combination thereof). Cropping systems was mostly responsible for changes in nutrient dynamics, possibly because different crops utilise nutrients differently. Organic C showed a steady increase as a result of tillage systems at both the 0-5 cm and 5-10 cm soil depths. This effect was less pronounced in the final year, due to low biomass production and subsequent low C returns to the soil.

4.5 Leaf analysis

Nutrient uptake was measured by analysing nutrients in maize leaves. Results showed that nutrient uptake responded very well to cropping systems. Initially the highest nutrient uptake was from the maize/cowpea rotation systems. Towards the end of the trial, the maize/vetch cropping system outperformed that of other cropping systems and maize from this cropping system had significantly higher nutrient values in the leaves. In contrast, maize monoculture generally showed the lowest nutrient uptake. Legume intercropping or crop rotations, in this case cowpea or vetch, proved to be most beneficial for improved nutrient uptake in maize.

5 RESEARCH ACTIVITIES



5.1 Soil Physical Properties: Soil Aggregate Stability

The effects of conservation and conventional agricultural practices on soil aggregate stability and related properties

DJ Beukes

ARC-ISCW

Introduction

It is well known that crop rotation and reduced tillage induce higher soil carbon (C) and nitrogen (N) levels compared to conventional tillage practices (Havlin *et al.*, 1990; Rasmussen & Collins, 1991). Under reduced tillage, of course, there is a maximum retention of crop residues on the soil surface. It is also well documented that soil organic matter (SOM) increases soil aggregate stability (Greenland *et al.*, 1962; Chaney & Swift, 1984; Christensen, 1986). Franzluebbers (2004) reported that the topsoil fraction of water-stable aggregates was higher under no-till than under conventional tillage. Franzluebbers (2004) also reported that fine-textured soils have a higher inherent level of macro-aggregation because of the cohesive nature of highly reactive clays. Soil organic matter exerts a positive influence on the soil microbial biomass, which mediates processes of SOM turnover, nutrient cycling and soil aggregation (Rasmussen & Collins, 1991). The formation and stabilisation of soil aggregates is a function of the nature and configuration of organic compounds, such as polysaccharides, carbohydrates and proteins. These compounds are produced by the micro-flora functional groups (e.g. cellulose decomposers, nitrifying bacteria, mycorrhizae) and microbial enzymatic activity during the decomposition of SOM. The beneficial effect of SOM on soil structure is virtually attributed to these compounds. The organic compound-clay association is a complex material, involving the complexation of organic polymers with polyvalent cations (Turenne, 1982). In his study, Chan (1989) found a similar result, namely that most of the bondings responsible for clay aggregation were pyrophosphate extractable and were therefore organic polymers complexed with polyvalent metal ions. In a review by Six *et al.* (2004), they came to the conclusion that micro-aggregates, rather than macro-aggregates, protect SOM in the long term, and that macro-aggregate turnover is a crucial process influencing the stabilisation of SOM. The contribution of AM to aggregate formation and stabilisation lies in the proliferation of the soil by its hyphae, as well as the excretion of a glyco-protein (glomalin) that acts as a bonding agent (Miransari *et al.*, 2007).

A number of techniques are available to determine aggregate stability, *viz.* the wet sieve (Greenland *et al.*, 1962), turbidity (Williams *et al.*, 1966), permeability (Williams & Cooke, 1961)

and stability methods (Leo, 1963). However, these methods are laborious, time consuming and impractical when large numbers of samples have to be analysed. To quantify the effects of conventional and CA practices, it was decided to use the simple and fast “volumeter” method as originally described by Srzednicki & Keller (1984) and slightly modified by Beukes (1987). However, testing and calibration was needed to determine: (1) whether the method will be sensitive enough; (2) the soil matric potential at which the largest differences in aggregate volumes are obtained; and (3) the number of knocks at which constant aggregate volumes are obtained.

The aim of this study was to evaluate the medium-term effects of CA and conventional cultivation practices on: (1) relationships between topsoil properties related to soil aggregate stability, (2) soil aggregate stability, and (3) possible arbuscular mycorrhizal fungi (AMF) activity vs. soil aggregate stability in the rhizosphere. The study was done on a CA field trial over four experimental seasons, i.e. from 2008/09 to 2011/12, at the Zeekoegat Experimental Station (25° 36' 52.6" S, 28° 18' 52.8" E). The results from individual seasons, as well as trends over seasons, will be presented and discussed.

Materials and Methods

Baseline information

The experimental design is outlined under Materials and Methods (section 3). In the present study a statistical unit of 24 plots comprising the two tillage systems, two cropping systems (monoculture maize=C1, maize/cowpea intercropping=C4) and two fertilizer levels (Low=F1, High=F2), replicated three times, was utilised.

Technique testing and calibration

A composite air-dry soil sample from the 0-30 mm layer of plots 17 (CT, F1C1) and 11 ([RT, F2C4]), as well as of the undisturbed natural grass ley alongside the experimental plots was taken. A mass of 100 g of structure fragments of 5-15 mm diameter were carefully taken from each bulk sample in duplicate, saturated with distilled water on a ceramic plate, and subjected to 5 kPa pneumatic pressure (Klute, 1986). After equilibrium between pressure and water content was attained, the sample was carefully and quantitatively transferred to the graduated glass cylinder of the “volumeter” and subjected to a series (50-1100) of small, vertical knocks, with sample volumes recorded after each series of knocks. Thereafter duplicate samples were taken to determine gravimetric soil water content (Gardner, 1986). The whole procedure was repeated

for measurements at 10, 20, 30 and 40 kPa pressure (for plot 17 (CT) measurements were only done at 10 kPa pressure). At equilibrium the matric potential (expressed as a negative entity) at which the water is held in the soil sample is numerically equal to the pneumatic pressure that was applied.

Field sampling

Composite undisturbed soil samples from the 0-50 mm layer (topsoil) on each of 24 plots, representing the two tillage practices and the F1C1, F1C4, F2C1 and F2C4 fertilizer/crop system treatments, respectively, were taken in August at the end of each experimental season. Care was taken to preserve aggregates and soil fragments during the sampling and transporting process.

Laboratory analysis

Triplicate sub-samples, each with a mass of 100 g of structure fragments of 5-15 mm diameter, were carefully taken from each composite plot sample. One sub-sample per plot was ground and sieved (2 mm) for chemical analyses, while the remaining two samples were saturated with distilled water on a ceramic plate, and subjected to 10 kPa pneumatic pressure (Klute, 1986). After equilibrium between pressure and water content was attained, the samples were carefully and quantitatively transferred to the graduated glass cylinder of the "volumeter" and subjected to 500 vertical knocks, and the consolidated aggregate volumes recorded. The latter property is regarded as a measure of soil aggregate stability: the larger the aggregate volume, the more stable the soil aggregates are against deformation. Thereafter samples were taken from the duplicate "volumeter" samples to determine gravimetric soil water content (Gardner, 1986). Soil organic C (Walkley-Black), total N and inorganic N ($\text{NH}_4\text{-N}$, $\text{NO}_3\text{-N}$) were determined on the prepared sub-samples according to the procedures of Allison (1965), Bremner (1986) and The Non-Affiliated Soil Analysis Work Committee (1990), respectively.

Rhizosphere aggregate stability (2009/10)

An AMF study was conducted by Ms W Sekgota and Dr S Koch from the ARC-Plant Protection Research Institute. Soil aggregates (about 10-25 mm diameter) were collected during the 2009/10 season from the rhizosphere of 12 selected plots and were subjected to the same laboratory procedures as for the topsoil aggregate stability determinations. As the rhizosphere aggregate stability determinations were regarded as a pilot study, no soil chemical or statistical analyses were performed.

Multi-seasonal (2008/09-2011/12) trends in soil properties

In order to observe trends over time of soil properties, mean values per property were calculated for the four crop systems (F1C1, F1C4, F2C1 & F2C4) per experimental season and the results displayed graphically.

Statistical analysis

Statistical analysis entailed ANOVA using Genstat (Genstat for Windows, 2009) to test for LSDs at $P < 0.05$ between treatments for the various soil properties. Simple linear regression analyses (Gomez & Gomez, 1984) were performed to determine the statistical relationships between the various soil properties. The regression coefficient “b” was tested with the Student’s t distribution, while the linear correlation coefficient “r” was tested against tabular r values (Gomez & Gomez, 1984).

Results and Discussion

Technique testing and calibration

2008/09: In Fig. 5.1-1 (left) sample volumes at 10 kPa pressure of RT and CT treatments are compared. Typically of more stable soil aggregates, RT gave somewhat higher sample volumes. The small differences could be due to the fact that the trial was only in its first experimental year. For the remainder of the results, comparisons were made between the RT and the grass ley samples. In Fig. 5.1-1 (right) aggregate volumes of grass ley were compared to RT samples as a function of the number of knocks, as well as the various equilibrium pressures. Two features can be noted: (1) under the grass ley more stable aggregates (higher aggregate volumes) were measured than under the RT treatment, and (2) aggregate volumes tended to an equilibrium from 500 knocks onwards. Future measurements could, therefore, be made at 500 knocks. It can be concluded that the “volumeter” method is suitable to measure soil aggregate stability differences among treatments for this particular experimental soil.

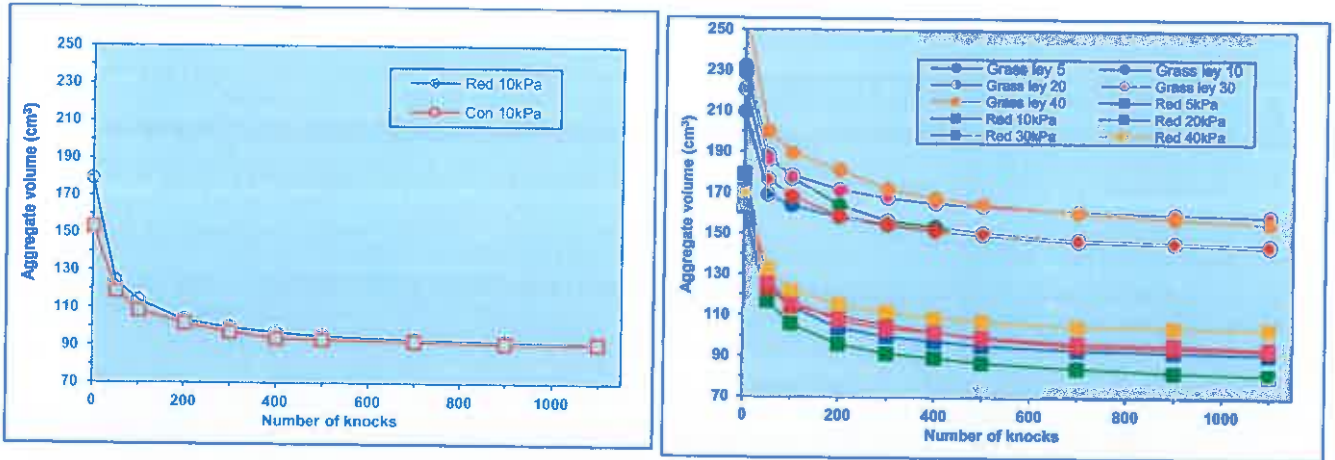


Figure 5.1-1: Comparison of aggregate volumes of RT and CT at 10 kPa pressure (left); Comparison of aggregate volumes of grass ley and RT at various pressures (right).

The difference in soil aggregate volumes of the grass ley and RT samples at the various number of disintegration steps (knocks) can be used as a measure of relative aggregate stability. It can be argued that the larger the differences among treatments, the higher the probability would be to obtain statistical significance. Fig. 5.1-2 (left) shows that the largest differences were obtained at 10 kPa pressure, or -10 kPa matric potential, between 200 and 1100 knocks. It is, therefore, recommended to test aggregate stability of the various tillage and crop residue treatments at this matric potential. Fig. 5.1-2 (right) shows that the RT soil samples had higher water contents at the various matric potentials than the grass ley samples. An explanation for this result can be that the more stable grass ley aggregates with more macro-pores drained more freely with resultant lower water contents.

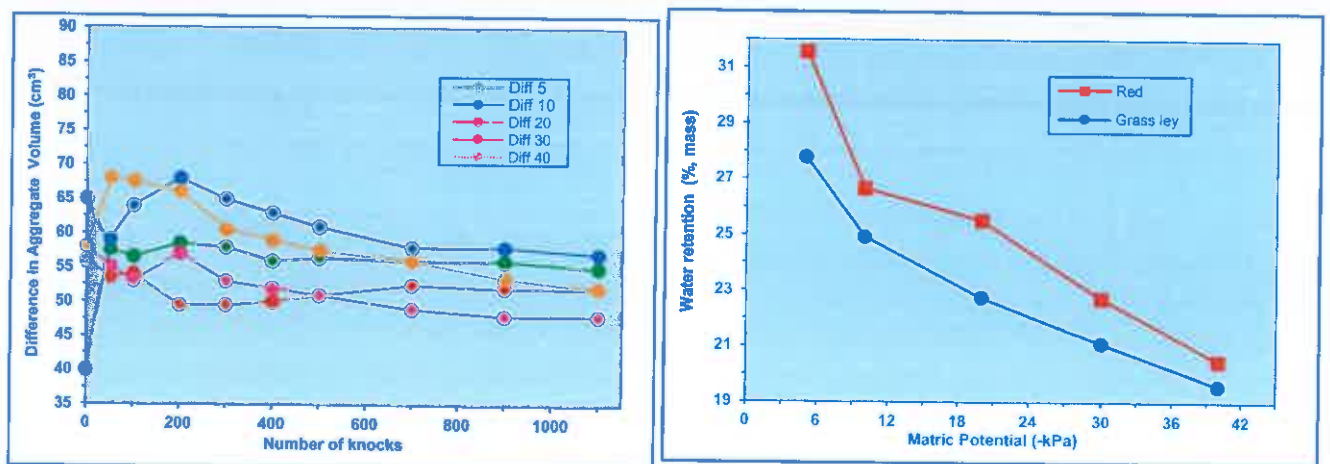


Figure 5.1-2: Differences in aggregate volumes (left); Effect of matric potential on soil water content (right).

Relationships between soil properties

2008/09: Statistical data for the relationships between the various soil properties is given in Table 5.1-1, while the estimated regression lines and the observed data are plotted in Fig. 5.1-3. The t-test values for the regression coefficients indicate that the linear responses of (1) aggregate volumes to changes in total soil N, (2) soil water retention to changes in aggregate volumes, and (3) inorganic N to changes in soil organic C were significant to highly significant. Significant to highly significant correlation coefficients (r) were calculated for the particular relationships (Table 5.1-1). No statistically significant relationships could be derived for aggregate volume vs. soil organic C. Graphical displays of the relationships in Fig. 5.1-3 show good and poor “closeness of fit” (indicated by magnitude of the r values) between the estimated regression lines and the observed points. Note the negative relationship between soil water retention and aggregate volume, indicating that the more stable the soil aggregates were, the more easily drainable larger soil pores were formed with resultant lower soil water contents.

Table 5.1-1: Statistical data for relationships between soil properties (2008/09)

Description ¹ (Y vs X)	Calibration Equation (Y = a + bX)	Valid X range	Degrees of freedom	t test for regress coeff (b)	Variance explained (R ² , %)	Correlation coeff (r)
AV vs SOC	Y = 74.40720 + 31.39711X	1.07 ≤ X ≤ 1.46	22	1.59NS	9	0.3068NS
AV vs Soil N	Y = 85.94342 + 289.52525X	0.0547 ≤ X ≤ 0.1347	22	2.46*	20	0.4449*
AV vs Inorg N	Y = 109.76975 + 0.28281X	4.9 ≤ X ≤ 30.25	22	0.96NS	4	0.1911NS
SWR vs AV	Y = 42.05224 - 0.14296X	92 ≤ X ≤ 140	22	-4.62***	35	-0.5943**
Soil N vs SOC	Y = 0.02920 + 0.05322X	1.07 ≤ X ≤ 1.46% C	22	0.02NS	11	0.3384NS
Inorg N vs Soil N	Y = -11.14636 + 260.30749X	0.0547 ≤ X ≤ 0.1347	22	3.69**	35	0.5919**

¹AV = Aggregate volume; SOC = Soil organic carbon; Soil N = Total soil nitrogen; SWR = Soil water retention at 10 kPa; Inorg N = Inorganic NH₄ + NO₃-N

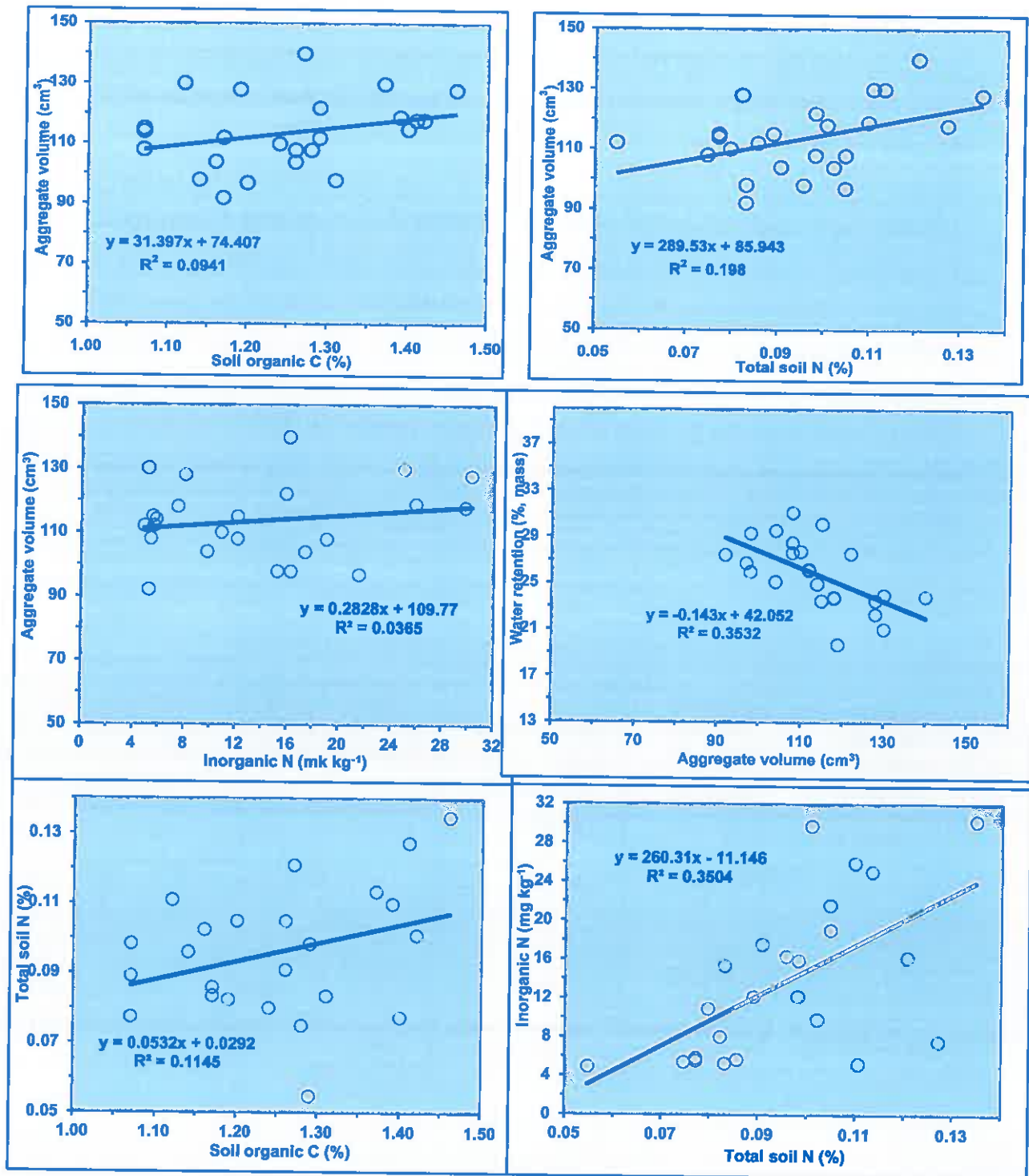


Figure 5.1-3: Linear relationships between soil properties (2008/09).

2009/10: Statistical data for the relationships between the various soil properties is given in Table 5.1-2, while the estimated regression lines and the observed data are plotted in Fig. 5.1-4. The t-test values for the regression coefficients indicate that the linear responses of (1) aggregate volumes to changes in soil organic C, (2) soil water retention at 10 kPa to changes in aggregate volumes, and (3) inorganic N to changes in total soil N are significant to highly significant. The R² values indicate that between 0.2 and 59% of the variation in the dependent variable (Y) was accounted for by the respective linear functions. Highly significant correlation coefficients (r) were calculated for the particular relationships (Table 5.1-2). No statistically significant relationships could be derived for aggregate volume vs. total soil N and inorganic soil N, respectively. Graphical displays of the relationships in Fig. 5.1-4 shows good and poor “closeness of fit” (indicated by magnitude of the r values) between the estimated regression lines and the observed points. Note the negative relationship between soil water retention and aggregate volume, indicating that the more stable the soil aggregates were, the more easily drainable larger soil pores were formed with resultant lower soil water contents.

Table 5.1-2: Statistical data for relationships between soil properties (2009/10)

Entity ¹ (Y vs X)	Calibration Equation (Y = a + bX)	Valid X range	Degrees of freedom	t test for regress coeff (b)	Variance explained (R ² , %)	Correlation coeff (r)
AV vs SOC	Y=7.01700 + 73.62600X	1.20<=X<=1.67	22	4.13***	41	0.6423**
AV vs Soil N	Y=86.753 + 221.60606X	0.0597<=X<= 0.1412	22	1.45NS	8	0.2821NS
AV vs Inorg N	Y=98.42393 + 0. 89275X	3.50<=X<= 27.75	22	1.51NS	9	0.2940NS
SWR vs AV	Y=46.53241 - 0.17897X	88<=X<=149	22	-7.44***	59	-0.7686**
Soil N vs SOC	Y=-0.03458 + 0.09734X	1.20<=X<= 1.67	22	0.05NS	45	0.6671**
Inorg N vs Soil N	Y=10.60694 + 11.90679X	0.0597<=X<= 0.1412	22	0.23NS	0.2	0.0460NS

¹AV = Aggregate volume; SOC = Soil organic carbon; Soil N = Total soil nitrogen;

Inorg N = Inorganic NH₄ + NO₃-N; SWR = Soil water retention at 10 kPa

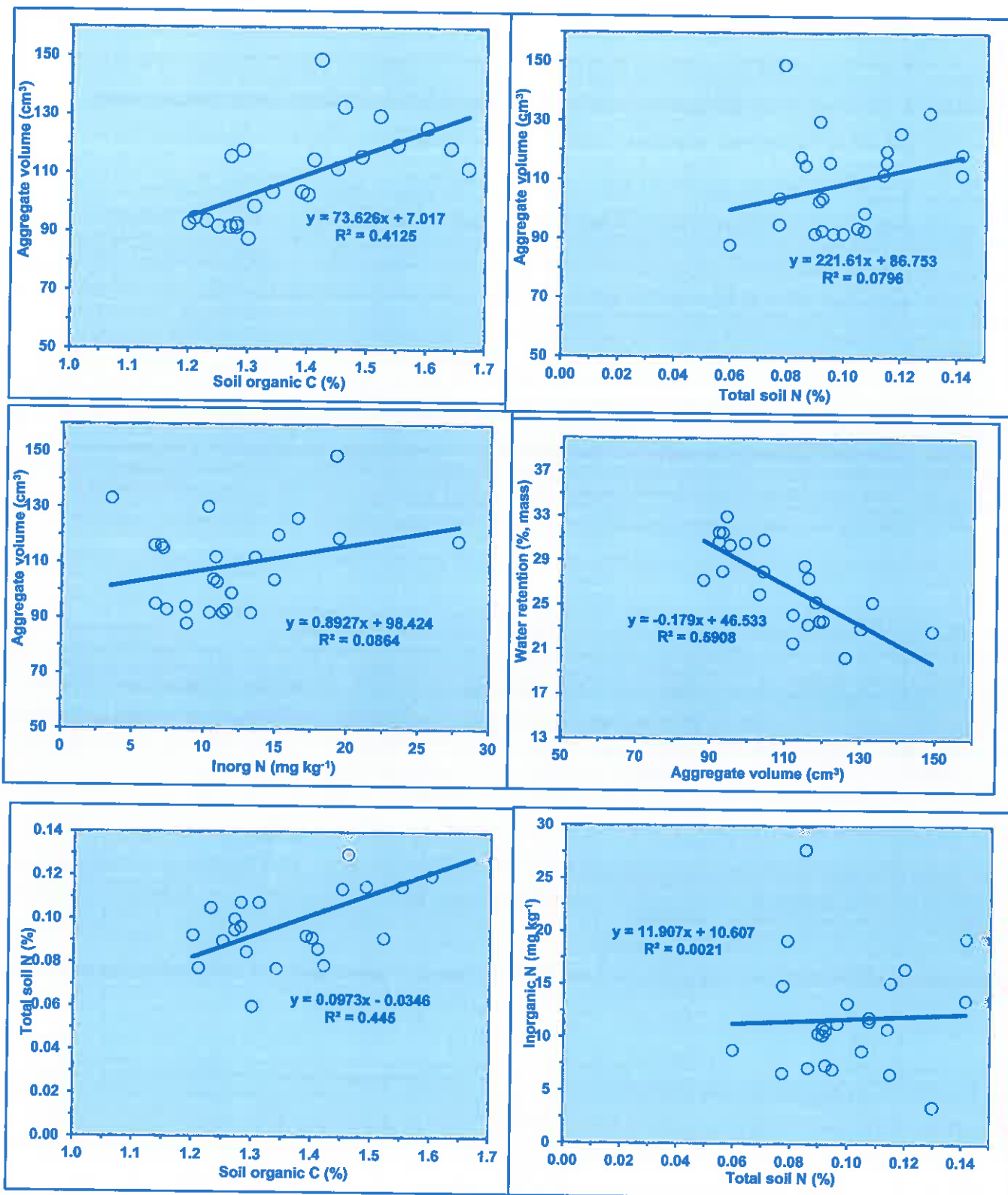


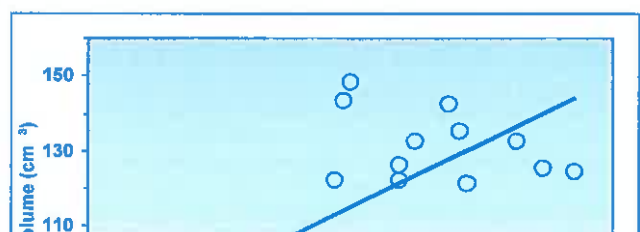
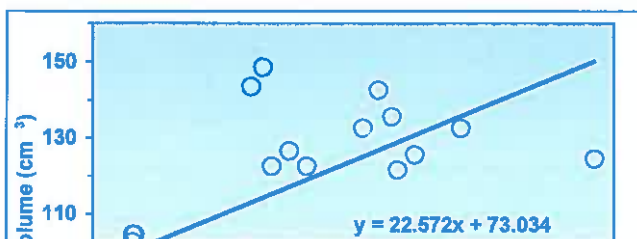
Figure 5.1-4: Linear relationships between soil properties (2009/10).

2010/11: Statistical data for the relationships between the various soil properties is given in Table 5.1-3, while the estimated regression lines and the observed data are plotted in Fig. 5.1-5. The t-test values for the regression coefficients indicate that the linear response of aggregate volume to changes in soil organic C, total soil N and inorganic soil N, is highly significant. The t-test values for the regression coefficients indicate that the linear response of soil water retention at 10 kPa, to changes in aggregate volume, is highly significant. Similarly, the linear response of inorganic soil N to changes in total soil N is highly significant. The R² values in Table 5.1-3 indicate that between 29 and 97% of the variation in the dependent variable (Y), is accounted for by the respective linear functions. Highly significant correlation coefficients (r) were calculated for all linear relationships. Graphical displays of the relationships in Fig. 5.1-5 show good and poor “closeness of fit” (indicated by magnitude of the r values) between the estimated regression lines and the observed points. Note the negative relationship between soil water retention and aggregate volume, indicating that the more stable the soil aggregates were, the more easily drainable larger soil pores were formed with resultant lower soil water contents.

Table 5.1-3: Statistical data for relationships between soil properties (2010/11)

Description ¹ (Y vs X)	Calibration Equation (Y = a + bX)	Valid X range	Degrees of freedom	t test for regress coeff (b)	Variance explained (R ² , %)	Correlation coeff (r)
AV vs SOC	Y = 73.03362 + 22.57228X	1.07<=X<=3.42	22	5.30***	54	0.7322**
AV vs Soil N	Y = 59.01437+ 426.71557X	0.085<=X<=0.199	22	5.78***	58	0.7607**
AV vs Inorg N	Y = 84.71592+ 1.6185X	9.50<=X<=36.25	21	3.05**	29	0.5352**
SWR vs AV	Y = 47.88697 - 0.18071X	83<=X<=148	22	-8.50***	67	-0.8192**
Soil N vs SOC	Y = -0.49173 + 17.88121X	0.085<=X<=0.199	22	0.12NS	97	0.9828**
Inorg N vs Soil N	Y = 4.26976+ 102.31963X	0.085<=X<=0.199	21	3.30**	31	0.5542**

¹ AV = Aggregate volume; SOC = Soil organic carbon; Soil N = Total soil nitrogen; Inorg N = Inorganic NH₄ + NO₃-N; SWR = Soil water retention at 10 kPa



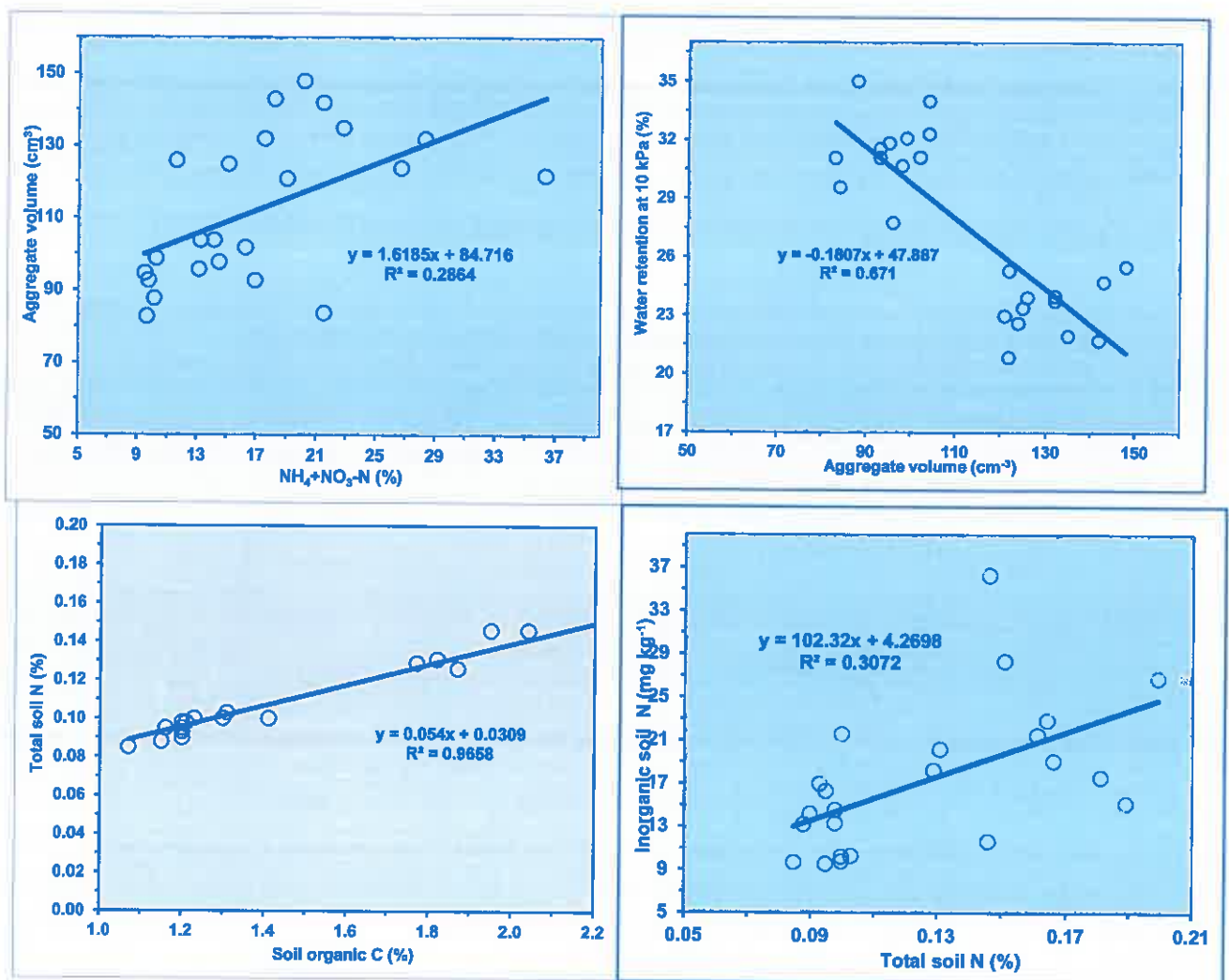


Figure 5.1-5: Linear relationships between soil properties (2010/11).

2011/12: Statistical data for the relationships between the various soil properties is given in Table 5.1-4, while the estimated regression lines and the observed data are plotted in Fig. 5.1-6. The t-test values for the regression coefficients indicate that the linear response of aggregate volume to changes in soil organic C and total soil N, respectively, is highly significant. Similarly, that the linear response of soil water retention at 10 kPa to changes in aggregate volume is highly significant. The t-test values for the regression coefficient of aggregate volume vs. inorganic soil N, as well as that of total soil N vs. soil organic C are not significant. The R² values in Table 5.1-4 indicate that between 9 and 82% of the variation in the dependent variable (Y), is accounted for by the respective linear functions. Highly significant correlation coefficients (r) were calculated for all linear relationships, except for aggregate volume vs. inorganic N and inorganic N vs. total soil N. Graphical displays of the relationships in Fig. 5.1-6 show good “closeness of fit” (indicated by magnitude of the r values) between the estimated regression lines and the observed points. Note the negative relationship between soil water retention and aggregate volume, indicating that the more stable the soil aggregates were, the more easily drainable larger soil pores were formed with resultant lower soil water contents.

Table 5.1-4: Statistical data for relationships between soil properties (2011/12)

Description ¹ (Y vs X)	Calibration Equation (Y = a + bX)	Valid X range	Degrees of freedom	t test for regress coeff (b)	Variance explained (R ² , %)	Correlation coeff (r)
AV vs SOC	Y = 50.82160 + 42.03826X	1.09<=X<=2.48	22	5.01***	51	0.7134**
AV vs Soil N	Y = 17.14361+ 777.72784X	0.0946<=X<=0.1650	22	5.45***	55	0.7422**
AV vs Inorg N	Y = 89.55541+ 1.01705X	14.35<=X<=48.28	22	1.94NS	14	0.3675NS
SWR vs AV	Y = 39.98869 - 0.11752X	84<=X<=159	22	-4.89***	43	-0.6561**
Soil N vs SOC	Y = 0.05103 + 0.04771X	1.09<=X<=2.48	22	0.06NS	82	0.9075**
Inorg N vs Soil N	Y = 8.06327 + 116.53597X	0.0946<=X<=0.1650	22	1.56NS	9	0.3078NS

¹AV = Aggregate volume; SOC = Soil organic carbon; Soil N = Total soil nitrogen; Inorg N = Inorganic NH₄ + NO₃-N; SWR = Soil water retention at 10 kPa

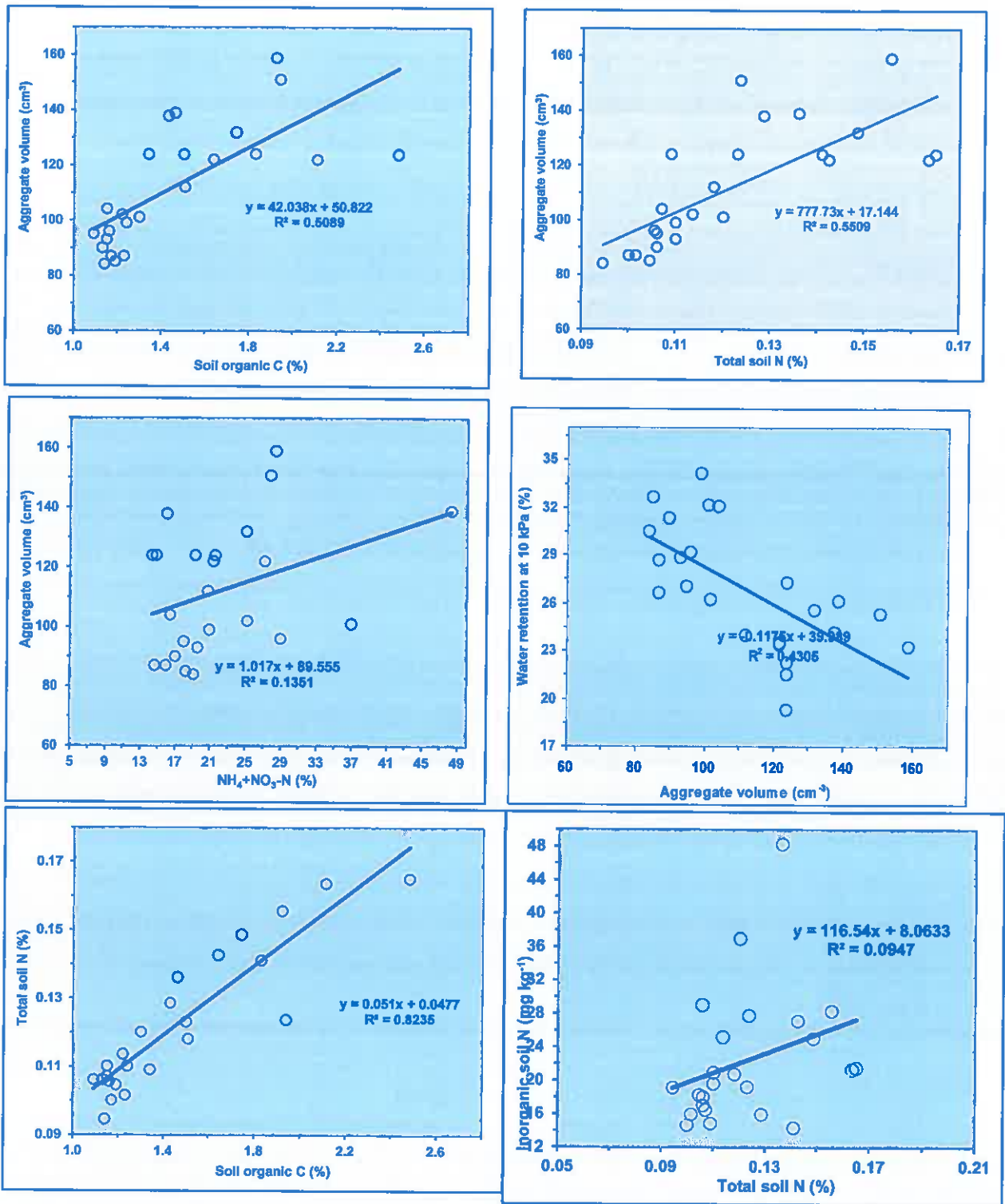


Figure 5.1-6: Linear relationships between soil properties (2011/12).

Statistical comparison of treatment effects

For all experimental seasons only three components of the ANOVAs for aggregate volumes and associated properties, viz. the (1) F probability values, (2) mean values of the various properties, and (3) tests for least significant differences will be presented in tables, while only results on the main sources of variation viz. tillage, fertilizer and crop system will be displayed graphically.

2008/09: Reduced tillage induced higher aggregate volumes, and hence higher aggregate stability, compared to CT (Table 5.1-6: 122.3 vs. 105.0 cm³; Fig. 5.1-7 (left)). Although this result was not statistically significant (Table 5.1-5: F=0.10), it was still very encouraging and confirms results reported by, for example, Havlin *et al.* (1990). Significantly (Table 5.1-5), higher water retention at 10 kPa pressure was recorded for CT, compared to RT (Table 5.1-6: 27.71 vs. 23.90%; Fig. 5.1-7 (right)). In practice this result has the implication that due to more stable soil aggregates under RT the soil is better drained with a higher infiltration rate, and would have better aeration. The statistically higher water retention of F1 compared to F2 cannot be explained yet.

The higher organic C content under RT (Table 5.1-6: 1.324 vs. 1.177; Fig. 5.1-8 (left)) is almost statistically significant (Table 5.1-5: F = 0.057). The higher soil C under RT is probably due to the retention of crop residues, providing soil microbes of an essential source of energy to produce the polysaccharides and carbohydrates that bind with clay particles to form stable soil aggregates (Turenne, 1982). Although not statistically significant, there are trends that total soil N and inorganic N contents are higher under RT than under CT (Table 5.1-6; Fig. 5.1-8 (right)). Unique relationships exist between organic C and total soil N, depending *inter alia* on the type and amount of crop residue input, as well as the type and intensity of tillage (Rasmussen & Collins, 1991).

Table 5.1-5: F probability of analyses of variance (2008/09)

Source of variation	Aggr vol	Water ret at 10 kPa	Org C	Total N	Inorg N
Tillage	0.100	0.047*	0.057	0.231	0.433
Fert	0.191	0.018*	0.945	0.103	0.705
Crop system	0.627	0.397	0.235	0.862	0.873

* Statistically significant at F probability < 0.05

Table 5.1-6: Mean values and test for least significant difference (2008/09)

Source of variation	Treatment	Soil property				
		Aggr vol (cm ³)	Water ret (%)	Org C (%)	Total N (%)	Inorg N (mg/kg)
Tillage	RT	122.3 ^a	23.90 ^a	1.324 ^a	0.1003 ^a	15.0 ^a
	CT	105.0 ^a	27.71 ^b	1.177 ^a	0.0912 ^a	12.6 ^a
Fert	F1	111.6 ¹	26.60 ¹	1.252 ¹	0.0894 ¹	13.2 ¹
	F2	115.8 ¹	25.01 ²	1.249 ¹	0.1021 ¹	14.4 ¹
Crop system	C1	112.9 ¹	26.06 ¹	1.273 ¹	0.0951 ¹	13.5 ¹
	C4	114.4 ¹	25.55 ¹	1.228 ¹	0.0964 ¹	14.0 ¹
LSD _{0.05}	Till	25.49	3.68	0.1586	0.0231	10.39
	Fert	6.55	1.26	0.0769	0.0157	6.56
	Crop	6.55	1.26	0.0769	0.0157	6.56

Column values followed by the same type of symbol are not statistically different at P<0.05

LSD_{0.05} : Least significant difference at 5% probability level

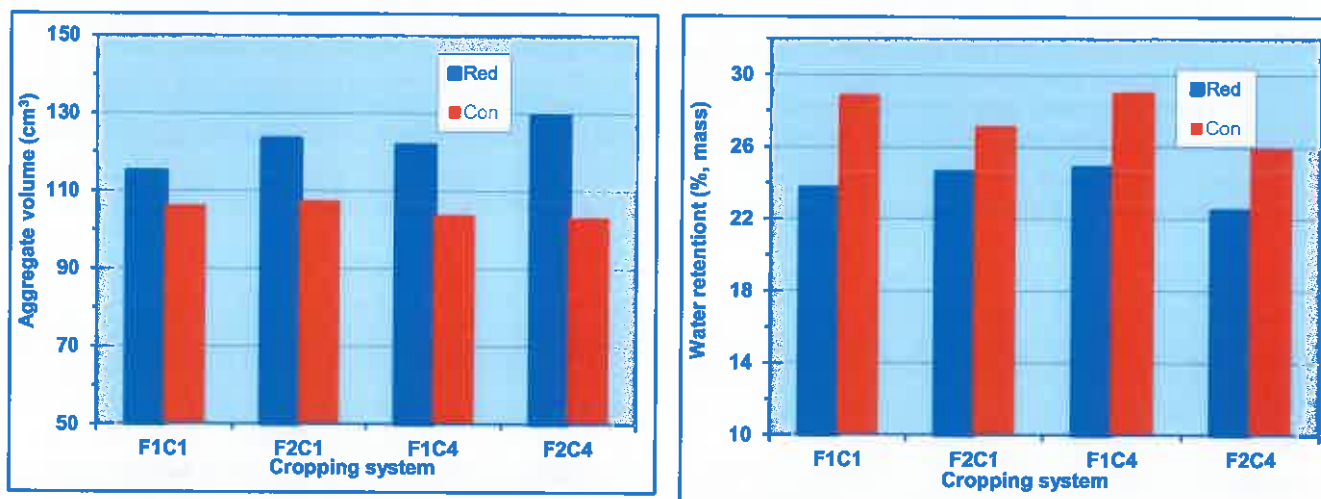


Figure 5.1-7: Soil aggregate volumes (left) and water retention at 10 kPa (right) (2008/09).

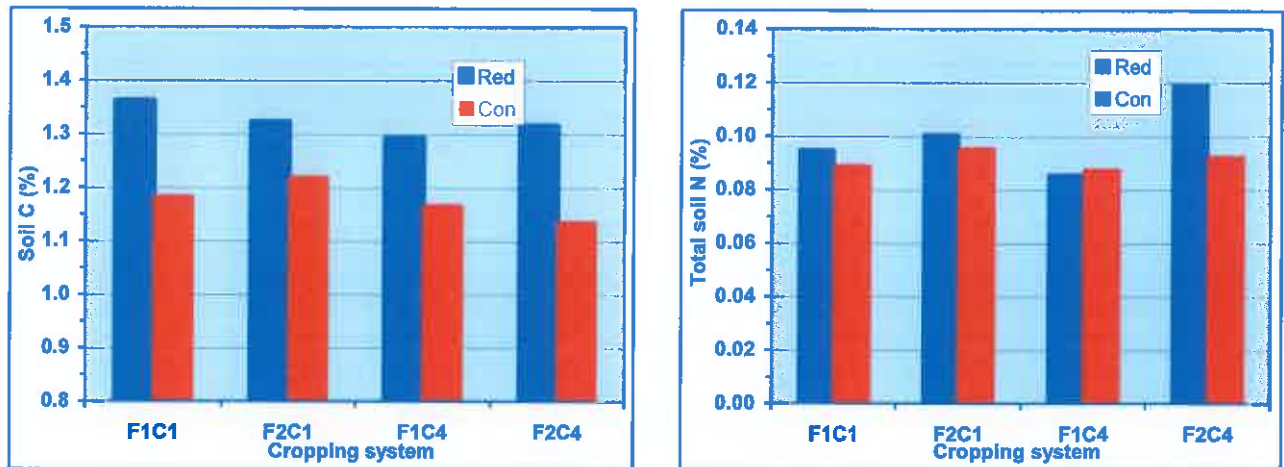


Figure 5.1-8: Soil organic C (left) and total soil N (right) (2008/09).

2009/10: Reduced tillage induced significantly higher aggregate volumes, and hence higher aggregate stability, compared to CT (Table 5.1-8: 122.2 vs. 95.8 cm³; Fig. 5.1-9 (left)). Significantly (Table 5.1-7), higher water retention at 10 kPa pressure was recorded for CT, compared to RT (Table 5.1-8: 29.96 vs. 24.10%; Fig. 5.1-9 (right)). In practice this result has the implication that due to more stable soil aggregates under RT the soil is better drained with a higher infiltration rate, and would have better aeration.

The higher organic C content under RT (Table 5.1-8: 1.481 vs. 1.288; Fig. 5.1-10 (left)) is statistically not significant (Table 5.1-7: $F = 0.187$) – a result that is disappointing because of the expectation that soil C storage would have been significant after three seasons of CA practices and RT. Theoretically it would be expected that the retention of crop residues under RT would provide soil microbes of an essential source of energy to produce the polysaccharides and carbohydrates that bind with clay particles to form stable soil aggregates (Greenland *et al.*, 1962). Although not statistically significant, there is a trend that total soil N is higher under RT than under CT (Table 5.1-8; Fig. 5.1-10 (right)). Inorganic N contents under RT are almost significantly higher (Table 5.1-7: $F = 0.058$, Fig. 5.1-9) compared to CT.

Table 5.1-7: Summary of analyses of variance (2009/10)

Source of variation	F probability				
	Aggr vol	Water ret at 10 kPa	Org C	Total N	Inorg N
Tillage	0.003***	0.019*	0.187	0.315	0.058
Fert	0.204	0.800	0.717	0.693	0.723
Crop system	0.093	0.845	0.904	0.926	0.781

*** Statistically highly significant at F probability < 0.01

* Statistically significant at F probability < 0.05

Table 5.1-8: Mean values and test for least significant difference (2009/10)

Source of variation	Treatment	Soil property				
		Aggr vol (cm ³)	Water ret (%)	Org C (%)	Total N (%)	Inorg N (mg/kg)
Tillage	RT	122.2 ^a	24.10 ^a	1.481 ^a	0.1092 ^a	13.1 ^a
	CT	95.8 ^b	29.96 ^b	1.288 ^a	0.0912 ^a	10.5 ^a
Fert	F1	107.3 ¹	27.17 ¹	1.378 ¹	0.0990 ¹	11.3 ¹
	F2	110.6 ¹	26.90 ¹	1.391 ¹	0.1015 ¹	12.3 ¹
Crop system	C1	111.2 ¹	26.93 ¹	1.387 ¹	0.0999 ¹	11.4 ¹
	C4	106.8 ¹	27.14 ¹	1.383 ¹	0.1005 ¹	12.2 ¹
LSD _{0.05}	Till	6.46	3.56	0.4199	0.0583	2.75
	Fert	5.27	2.31	0.0734	0.0135	5.50
	Crop	5.27	2.31	0.0734	0.0135	5.50

Column values followed by the same type of symbols are not statistically different at P < 0.05

LSD_{0.05}: Least significant difference at 5% probability level

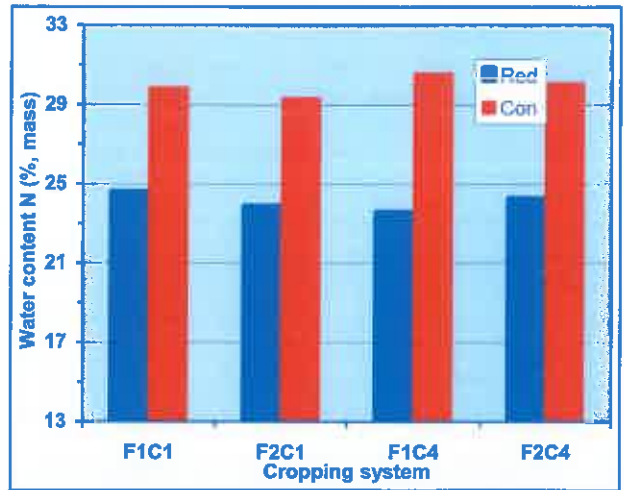
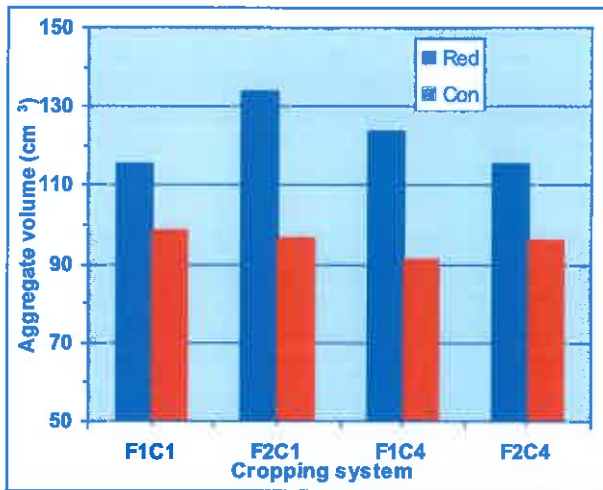


Figure 5.1-9: Soil aggregate volumes (left) and water retention at 10 kPa (right) (2009/10).

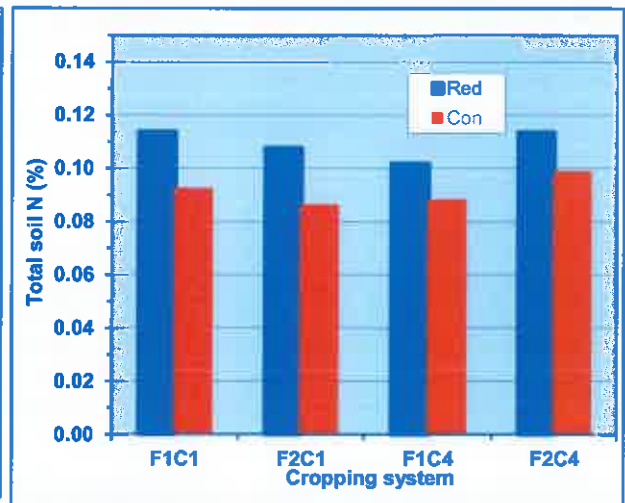
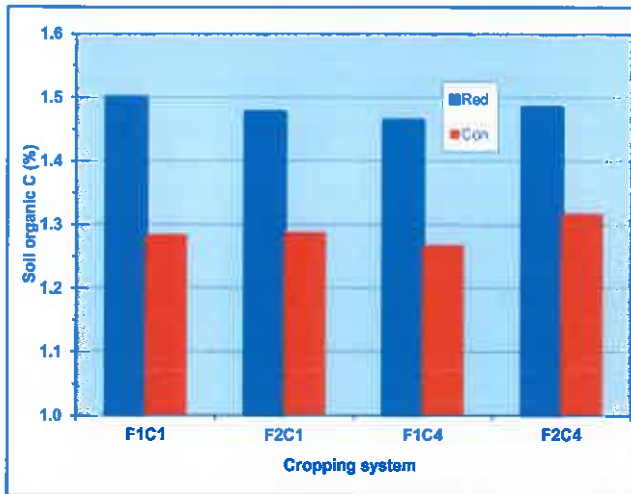


Figure 5.1-10: Soil organic C (left) and total soil N (right) (2009/10).

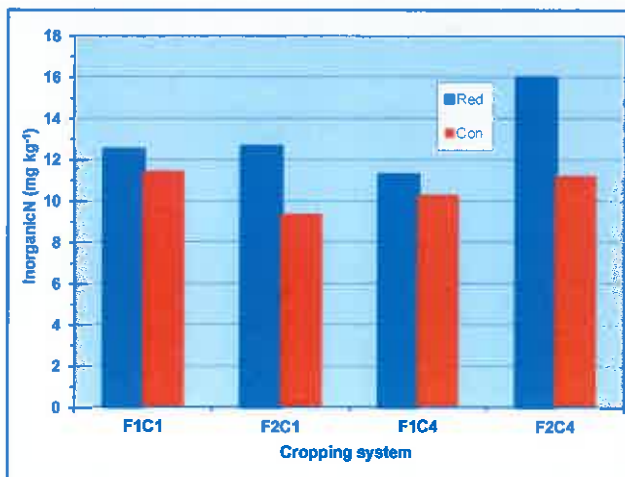


Figure 5.1-11: Inorganic soil N as function of treatments (2009/10).

Rhizosphere aggregate stability

From Fig. 5.1-12 no clear effects of the various CA components on rhizosphere aggregate volumes (stability), or water retention, are discernable. Apparently the spore counts were very low (data not included) with the result that little, if any, AMF proliferation of the soil by its hyphae, as well as the excretion of glomalin that acts as a bonding agent, was discernable.

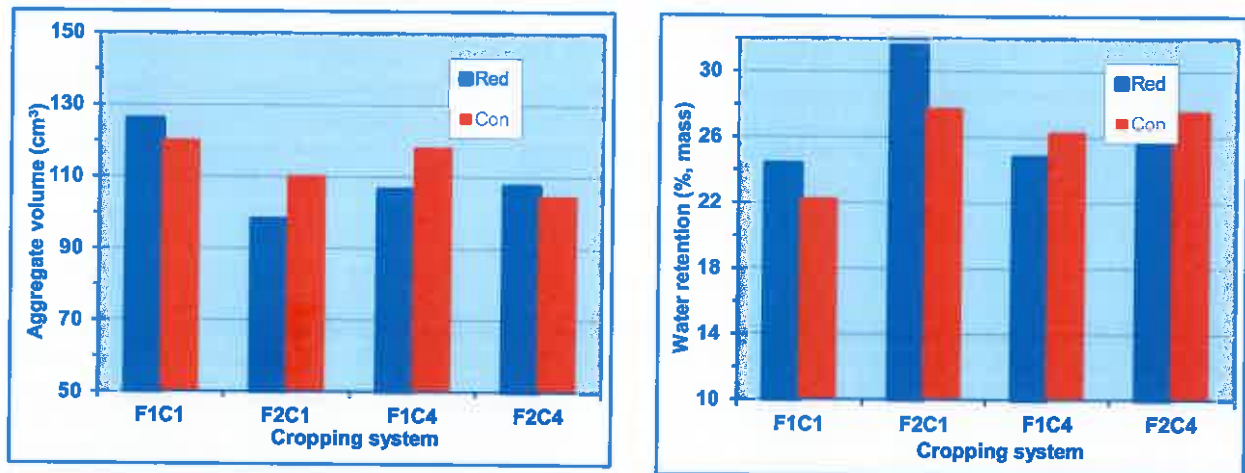


Figure 5.1-12: Rhizosphere aggregate volumes (left) and water retention (right) (2009/10).

2010/11: The higher organic C content under RT (Table 5.1-10: 2.318 vs. 1.220 (CT); Fig. 5.1-13 (left)) is statistically significant (Table 5.1-9: $F = 0.030$). Theoretically it could be expected that the retention of crop residues under RT would provide soil microbes of an essential source of energy to produce the polysaccharides and carbohydrates that bind with clay particles to form stable soil aggregates (Greenland *et al.*, 1962). The higher total N content under RT (Table 5.1-10: 0.1574 vs. 0.0954 (CT); Fig. 5.1-13 (right)) is statistically significant (Table 5.1-9: $F = 0.027$). There is a trend, although not statistically significant, that inorganic N contents are higher under RT than under CT (Fig. 5.1-14, left) compared to CT. Although not statistically tested, RT gave higher C/N ratios than CT (Fig. 5.1-14 (right); Mean: 14.7 vs. 12.8).

Reduced tillage induced significantly (Table 5.1-9) higher aggregate volumes, and hence higher aggregate stability, compared to CT (Table 5.1-10: 131.0 vs. 94.9 cm³; Fig. 5.1-15 (left)). Significantly (Table 5.1-9) higher water retention at 10 kPa pressure was recorded for CT, compared to RT (Table 5.1-10: 31.52 vs. 23.43%; Fig. 5.1-15 (right)). In practice the latter result has the implication that due to more stable soil aggregates under RT, the soil is better drained with a higher infiltration rate, and would have better aeration.

Table 5.1-9: Summary of analyses of variance (2010/11)

Source of variation	F probability				
	Org C	Total N	Inorg N	Aggr vol	Water ret at 10 kPa
Tillage	0.030*	0.027*	0.204NS	<0.001***	0.003**
Fert	0.982NS	0.438NS	0.480NS	0.382NS	0.213NS
Crop system	0.114NS	0.024*	0.113NS	0.417NS	0.842NS

*** Statistically highly significant at F probability<0.001; ** Statistically highly significant at F probability<0.01; * Statistically significant at F probability<0.05

Table 5.1-10: Mean values and test for least significant difference (2010/11)

Source of variation	Treatment	Soil property				
		Org C (%)	Total N (%)	Inorg N (mg/kg)	Aggr vol (cm ³)	Water ret (%)
Tillage	RT	2.318 ^a	0.1574 ^a	25.1 ^a	131.0 ^a	23.43 ^a
	CT	1.220 ^b	0.0954 ^b	13.2 ^a	94.9 ^b	31.52 ^b
Fert	F1	1.770 ¹	0.1246 ¹	20.6 ¹	111.8 ¹	27.06 ¹
	F2	1.768 ¹	0.1283 ¹	17.8 ¹	114.1 ¹	27.90 ¹
Crop system	C1	1.863 ¹	0.1323 ¹	15.9 ¹	111.9 ¹	27.54 ¹
	C4	1.674 ¹	0.1205 ¹	22.5 ¹	114.0 ¹	27.41 ¹
LSD _{0.05}	Till	0.8353	0.0447	27.45	3.53	1.98
	Fert	0.2421	0.0099	8.45	5.40	1.39
	Crop	0.2421	0.0099	8.45	5.40	1.39

Column values followed by the same type of symbols are not statistically different at P<0.05

LSD_{0.05} : Least significant difference at 5% probability level

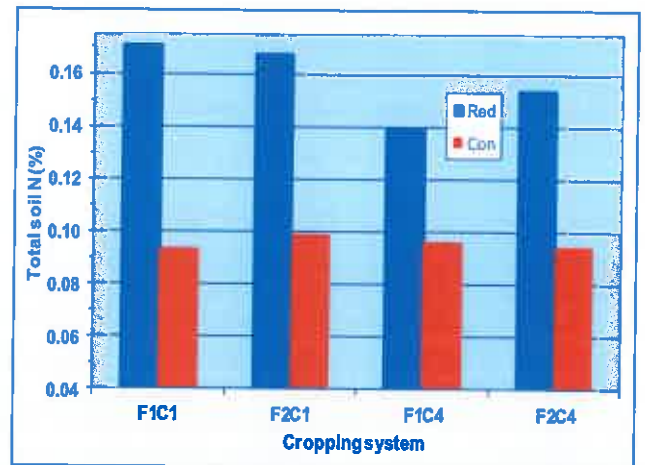
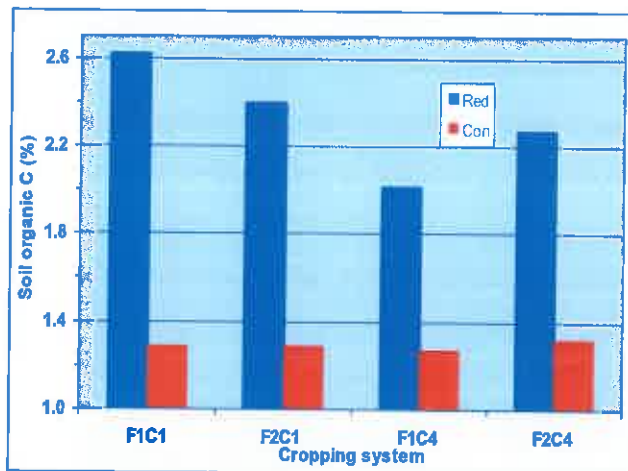


Figure 5.1-13: Soil organic C (left) and total soil N (right) (2010/11).

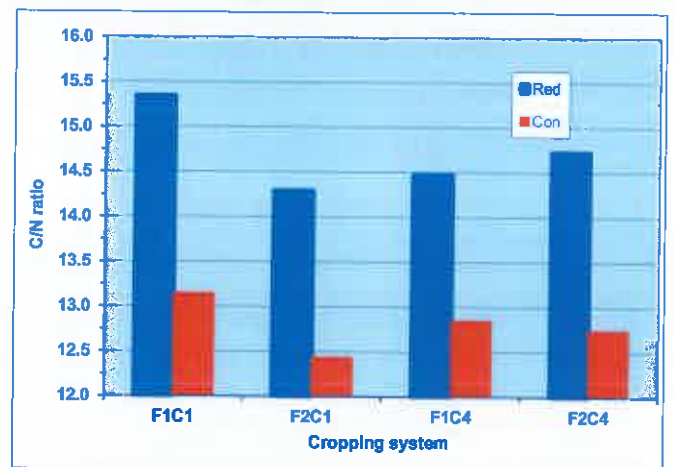
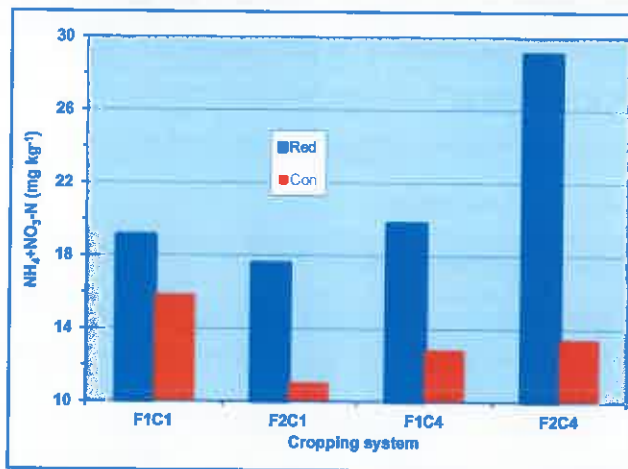


Figure 5.1-14: Inorganic soil N (left) and C/N ratios (right) (2010/11).

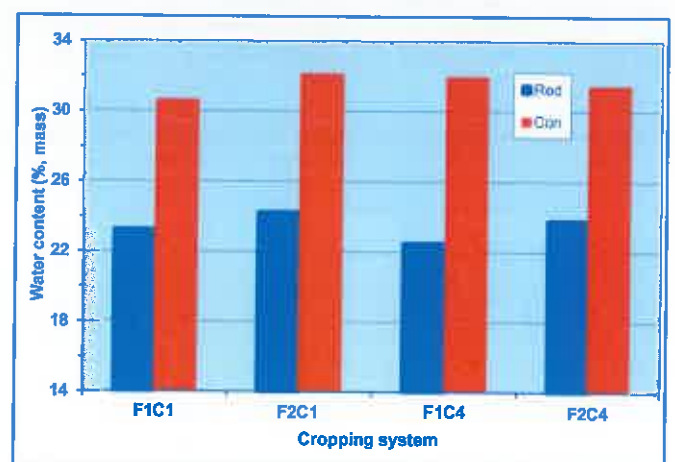
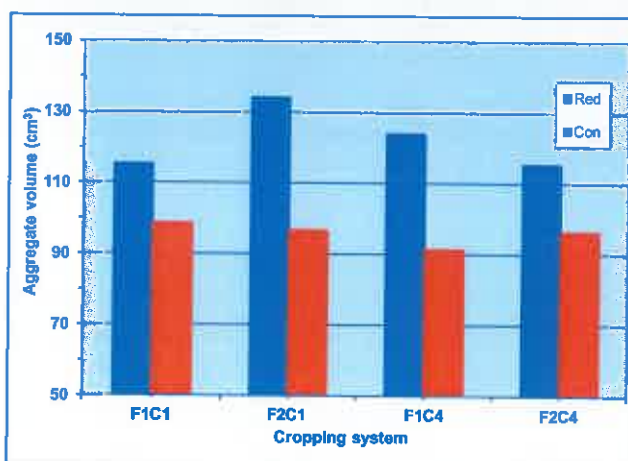


Figure 5.1-15: Topsoil aggregate volumes (left) and water retention at 10 kPa (2010/11).

2011/12: The higher organic C content under RT (Table 5.1-12: 1.740 vs. 1.181) compared to CT; Fig. 5.1-16 (left)) is statistically highly significant (Table 5.1-11: $p = 0.003$). Theoretically it could be expected that the retention of crop residues under RT would provide soil microbes of an essential source of energy to produce the polysaccharides and carbohydrates that bind with clay particles to form stable soil aggregates (Greenland *et al.*, 1962). The higher total N content under RT (Table 5.1-12: 0.1379 vs. 0.1066 (CT); Fig. 5.1-16 (right)) is statistically highly significant (Table 5.1-11: $p = 0.010$). There are trends, although not statistically significant, that: (1) inorganic N contents are higher under RT than under CT (Fig. 5.1-17, left) compared to CT; and that (2) C/N ratios are higher under RT than under CT (Fig. 5.1-17, right).

Reduced tillage induced significantly (Table 5.1-11: $p = 0.005$) higher aggregate volumes, and hence higher aggregate stability, compared to CT (Table 5.1-12: 130.9 vs. 93.6 cm³; Fig. 5.1-18 (left)). Significantly (Table 5.1-11: $p = 0.003$) lower water retention at 10 kPa pressure was recorded for RT, compared to CT (Table 5.1-12: 23.73 vs. 29.87%; Fig. 5.1-18 (right)). In practice the latter result has the implication that due to more stable soil aggregates under RT, the soil is better drained with a higher infiltration rate, and would have better aeration.

Table 5.1-11: Summary of analyses of variance (2011/12)

Source of variation	F probability (p)					
	Org C	Total N	Inorg N	C/N Ratio	Aggr vol	Water ret at 10 kPa
Tillage	0.020*	0.010**	0.337NS	0.092NS	0.005**	0.003**
Fert	0.806NS	0.807NS	0.480NS	0.899NS	0.343NS	0.581NS
Crop system	0.005**	0.091NS	0.113NS	0.087NS	0.366NS	0.196NS

** Statistically highly significant at F probability < 0.01; * Statistically significant at F probability < 0.05;

NS: Statistically not significant

Table 5.1-12: Mean values and test for least significant difference (2011/12)

Source of variation	Treatment	Soil property					
		Org C (%)	Total N (%)	Inorg N (mg/kg)	Aggr vol (cm ³)	C/N Ratio	Water ret (%)
Tillage	RT	1.740 ^a	0.1379 ^a	23.7 ^a	130.9 ^a	12.60 ^a	23.73 ^a
	CT	1.181 ^b	0.1066 ^b	20.9 ^a	93.6 ^b	11.10 ^a	29.87 ^b
Fert	F1	1.452 ¹	0.1216 ¹	20.6 ¹	110.5 ¹	11.82 ¹	27.00 ¹
	F2	1.469 ¹	0.1230 ¹	24.0 ¹	114.0 ¹	11.88 ¹	26.59 ¹
Crop system	C1	1.581 ¹	0.1273 ¹	22.2 ¹	113.9 ¹	12.24 ¹	26.30 ¹
	C4	1.340 ¹	0.1172 ¹	22.4 ¹	110.6 ¹	11.46 ¹	27.29 ¹
LSD _{0.05}	Till	0.3482	0.01354	9.56	11.15	2.124	1.45
	Fert	0.1515	0.01202	7.33	7.73	0.915	1.57
	Crop	0.1515	0.01202	7.33	7.73	0.915	1.57

Column values followed by the same type of symbols are not statistically different at P<0.05

LSD_{0.05} : Least significant difference at 5% probability level

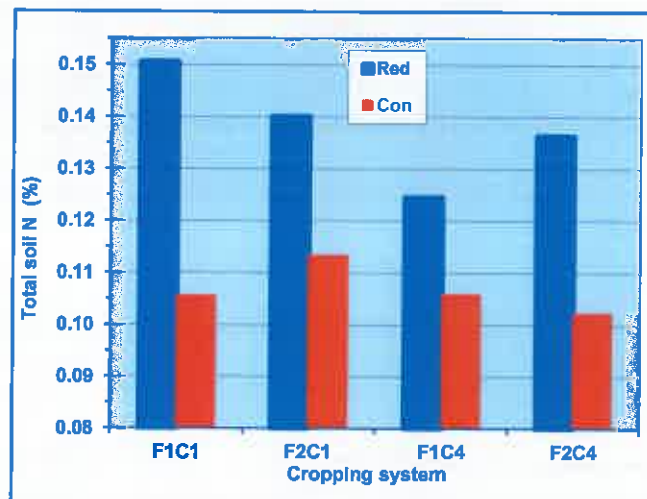
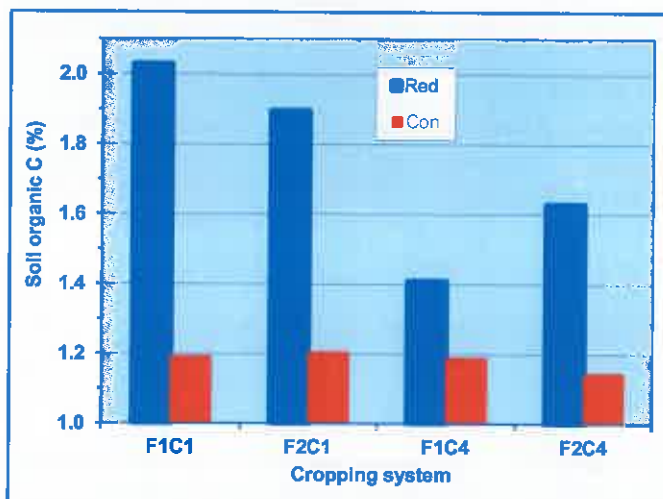


Figure 5.1-16: Soil organic C (left) and total soil N (right) as function of treatments (2011/12).

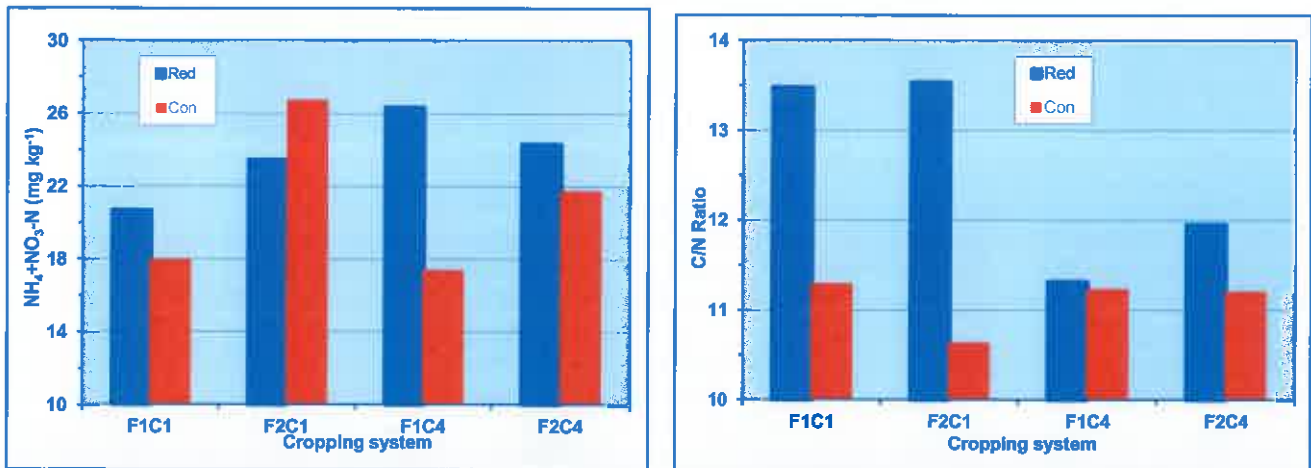


Figure 5.1-17: Inorganic soil N (left) and C/N ratios as function of treatments (2011/12).

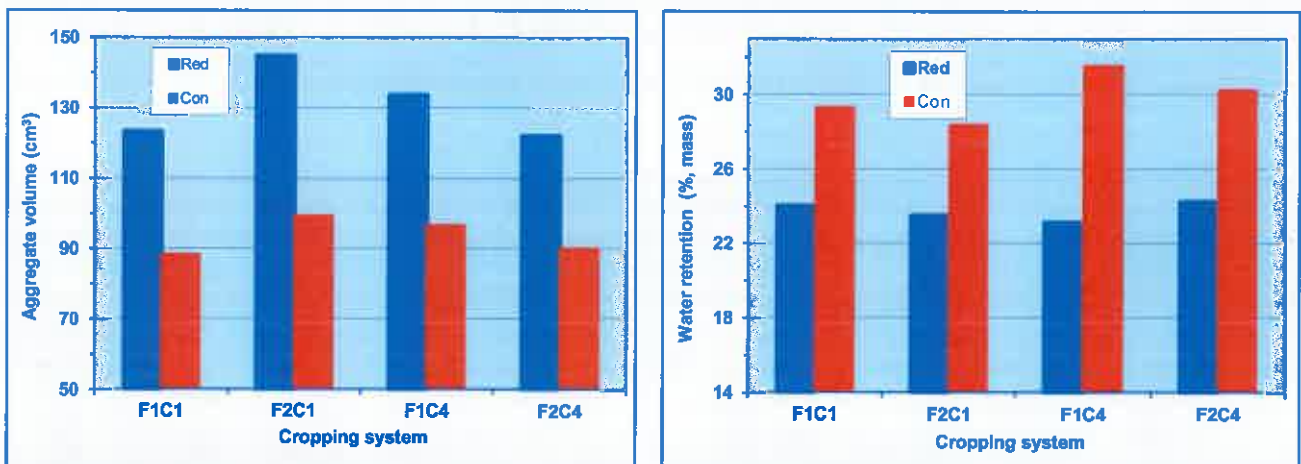


Figure 5.1-18: Soil aggregate volumes (left) and water retention at 10 kPa (2011/12).

Multi-seasonal (2008/09-2011/12) trends in soil properties

The temporal trends in soil organic C and total N under RT showed an initial increase, followed by a leveling off, while under CT these properties showed a decline. Aggregate volumes (aggregate stability) increased moderately under RT. Of significance is that aggregate stability decreased over time under CT. Temporal water retention under RT decreased slightly, while under CT an increase followed by a leveling off can be observed (Fig. 5.1-19).

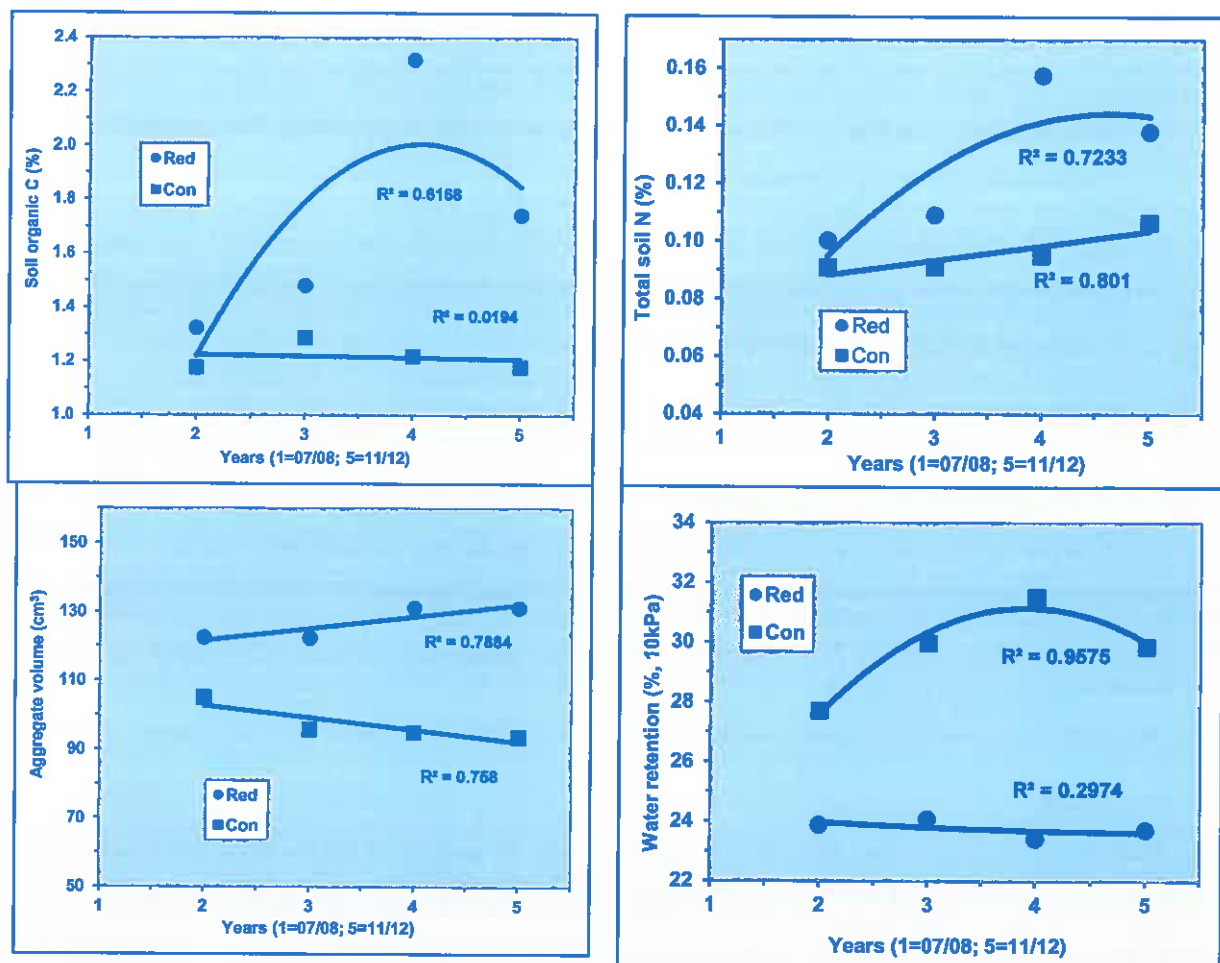


Figure 5.1-19: Temporal effects of tillage practice on soil properties (2008/09-2011/12).

Conclusions and Recommendations

Evaluating the four experimental seasons individually, it can be concluded that:

- Significant linear relationships could be established between soil aggregate volume (stability) and soil properties, such as soil organic C and N, C/N ratios, as well as water retention, that play a role in soil aggregate formation and stability.
- A significant linear relationship could also be established between soil organic C and N.
- The positive relationship between total soil N and inorganic N has the implication that a saving in N fertilizer is possible under CA compared to CT practices.
- Compared to CT, certain CA practices led to increased soil aggregate stability, soil organic C and N, C/N ratios, as well as inorganic N. The first three components play constituent roles in aggregate formation and stabilisation.
- Aggregate stability led to improved water retention relationships with envisaged positive effects on infiltration, drainage and soil aeration.

- No clear effects of the various CA components on rhizosphere aggregate volumes (stability), or water retention, were discernable. Apparently the spore counts were too low to enhance AMF proliferation of the soil by its hyphae, as well as the excretion of glomalin that acts as a bonding agent.
- Clear multi-seasonal trends were visible: under RT, soil organic C and N markedly increased in a curvi-linear trend over time. While aggregate stability under RT linearly increased over time, it decreased under CT.

The following recommendations can be made:

- RT practices, whereby the maximum amount of crop residues are retained in dryland crop farming, are recommended in order to enhance soil aggregate stability.
- The role of micro, meso and macro soil biota such as bacteria, fungi (e.g. mycorrhizae) and earthworms in the formation and stabilisation of soil aggregates should be more intensively studied.

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5.2 Soil Physical Properties: Soil Water I

The effects of conservation and conventional agricultural practices on soil water content

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Introduction

A dryland field trial on conservation agriculture (CA) was conducted on the Zeekoegat Experimental Station (25° 36' 52.6" S, 28° 18' 52.8" E). The goal of the study was to quantify the effects of various CA practices on soil and plant properties in comparison with conventional cultivation practices. Focus areas included soil (aggregate stability, soil water and temperature, nutrient dynamics and greenhouse gas emissions), plant (biomass, grain yield, leaf analyses and weeds) and biological (nematodes, soil bacteria, mycorrhizae and root pathogens) parameters. The study was conducted over six experimental seasons, from 2007/08 to 2012/13. In the present study the medium-term effects of CA and conventional cultivation practices on temporal soil water fluctuations, as well as soil profile water storage at specific points in time, will be evaluated over a period of five experimental seasons, i.e. 2008/09 to 2012/13. The results from individual seasons, as well as trends over seasons, will be presented and discussed.

For the measurement of soil water content (SWC) a variety of methods are available such as gravimetric, nuclear, electromagnetic tensiometric and hygrometric. Two of these methods, *viz.* nuclear (neutron scattering) and electromagnetic (capacitance technique), were used in the present study. The instruments, their installation, calibration and processing of readings are presented and discussed.

Materials and Methods

Baseline information

The experimental design is outlined under Materials and Methods (section 3). In the present study a statistical unit of 36 plots was utilised for the neutron water meter measurements, comprising the two tillage systems, two fertilizer levels (Low=F1, High=F2), and three cropping systems (monoculture maize=C1, maize/soybean rotation=C3, maize/cowpea intercropping=C4), replicated three times. For the capacitance probe measurements a unit of 18 plots was utilised.

Theoretical background of instrumentation

Neutron scattering method

Certain nuclides, or atoms, emit radiation by spontaneous transformation, or by bombardment, of their nuclei by alpha, beta or neutron particles, or by electro-magnetic radiation such as gamma or X-rays. The neutron water meter (NWM) makes use of a combined Americium-Beryllium ($^{241}\text{Am}-^9\text{Be}$) radioactive source that emits neutrons at a rate of 135 000 high energy (5.05 MeV) neutrons per second. The mechanism of emission is based on the radioactive ^{241}Am emitting alpha particles that bombards the Be nuclei to emit neutrons. When a NWM probe is lowered into the soil, these neutrons collide with atomic nuclei (such as that of H), are slowed down, loses energy and are scattered (change direction). These so-called thermalised neutrons get detected by a BF_3 (gas) detector in the NWM probe and are registered as counts on an electronic scaling unit. If the assumption is made that almost all H in the soil is from water, the registered counts can be regarded as a direct measure of SWC. The thermalised neutrons, in turn, may collide and get captured by atomic nuclei from elements such as Fe, K, B, Cl, Cd and Li. This aspect needs to be taken into consideration during the calibration of a NWM on a specific soil (Friedlander & Kennedy, 1949; Overman & Clark, 1960; Overman, 1963; The Radiochemical Centre, 1966).

Capacitance method

Soil dielectric properties can be assessed by a frequency domain measurement. Since the dielectric constant of water (80) is much greater than that of air (1) or soil solids (3-5), the measurement of a composite soil dielectric constant is primarily a function of SWC. The capacitance probe has apart from its electronic circuitry, data capturing and transmitting facilities, as well as temperature thermistors, also capacitor units embedded at regular intervals in an aluminium tubing. These capacitors operate at a frequency of about 150 MHz. The surrounding medium (soil and tube) responds by oscillating at a similar frequency, but some of the energy is stored in the soil (due to its capacitance), and the respondent frequency is reduced. The probe measures this shift in frequency (ranging from about 15-45 MHz), which increases with increasing SWC because of the effect of the dielectric constant of water on the composite soil dielectric constant. By definition, capacitance is a linear function of the dielectric constant (Tomer & Anderson, 1995; Seyfried & Murdock, 2001).

Field installation of NWM access tubes and capacitance probes

NWM: Aluminium access tubes to facilitate NWM readings were installed annually at about two weeks after planting (first week of December) on the 36 selected plots on the plant row of the main crop (see Appendix 5.2). Two installation methods were used: (1) In 2009/10 a 2100 mm steel pipe (42 mm diameter) with a hardened sharp tip was knocked into the soil to a depth of at least 1200 mm using an electric jack hammer (Kango 950K) powered by a Robin generator RGL 3500 (3.5 kW). The pipe was extracted using a HS-E 1.5 ton chain pulley hanging from a 2 m high tripod. Due to the occasional occurrence of an almost impenetrable concretion layer, shallower depths than 1200 m had to be contended with. An access tube was inserted in the hole and seated using the jack hammer. However, due to the mentioned constraint, this installation method was discontinued after the first season. In all subsequent seasons a hand auger (42 mm diameter) was used to drill holes to a depth of at least 1300 mm, followed by the insertion of the access tubes. After installation all the tubes were cut to protrude 100 mm above the soil surface, and then covered with an empty cool drink can to prevent rain water entering the access tube. All access tubes were removed annually before the onset of the next growing season to facilitate tillage and planting operations.

Capacitance probes: Commencing in December 2009, probe installation was done annually at about two weeks after planting (first week of December) on 18 selected plots on the plant row of the main crop (see Appendix 5.2). A specially designed hand auger was used to bore holes to a depth of 900 mm on the plant row of the main crop on the selected plots. Water was used during the augering process to ease the extraction of the soil. Using the extracted soil, a slurry was prepared and poured into the hole before the probes were inserted to ensure a good contact between the soil and the probes. All capacitance probes were removed annually before the onset of the next growing season to facilitate tillage and planting operations.

Field calibration of NWMs

In this study a Geoquip Waterman NWM was calibrated on the Zeekoegat CA field trial. A CPN 503DR Hydroprobe NWM was also calibrated in a correlation study using the Waterman calibration data. Both instruments utilise an “universal” calibration procedure to convert counts (readings) to water content (mm) per depth increment. This procedure, however, gives dubious values due to the absence of using *in situ* bulk density values for the conversion of counts to either water content (mm) per depth increment or volumetric SWC (%). Both NWMs facilitate the taking of readings as direct counts, making it possible for an *in situ* field calibration. The following calibration procedure was followed for the Geoquip Waterman NWM:

1. Field calibration procedures were carried out on five dates (September 2010-September 2011) and on four plots (except September 2010) from each replicate (Table 5.2-1).
2. Six standard counts (readings) were taken, as specified by the manufacturer, before, as well as after all calibration readings were taken. The mean of the 12 counts was calculated for further use.
3. Readings were taken at depths of 150, 300, 600, 900 and 1200 mm, allowing a counting time of 16 seconds.
4. All readings were converted to count ratios after division by the mean standard count.
5. Simultaneously, soil samples were augered within a radius of *ca.* 300 mm (Williamson & Turner, 1980) from the access tube at depth intervals of 0-225, 225-375, 375-525, 525-750, 750-1050 and 1050-1350 mm, and SWCs gravimetrically determined (Gardner, 1986).
6. In order to calibrate the NWM for volumetric SWC, soil bulk density at each of the depth intervals mentioned in step (5) had to be determined. The latter operation was performed on 8-10 December 2010. One profile pit per replicate/block was dug (see positions in Fig. 5.2-1) and core samples (volume 295.4 cm³) taken in duplicate in the centre of each depth interval by excavating in a step-like way a side wall of the profile pit. These samples were transferred to paper bags and the procedure followed of Blake & Hartge (1986) to determine soil bulk density. A substantial amount of concretions (>2 mm diameter), varying with depth, was present. It was, therefore, decided to adjust soil bulk density values accordingly by subtracting gravel masses and volumes from the original soil core volumes and masses. Mean values for the duplicate samples were then calculated.
7. Gravimetric SWC values from step (5) were multiplied by the adjusted bulk density values to obtain volumetric SWC.
8. Because of the spatial variation in concretion, and hence in soil bulk densities, it was decided to calibrate the NWM per replicate (block) and per depth increment.
9. Simple linear regression analyses (Gomez & Gomez, 1984) were performed to determine the statistical relationships between NWM count ratios and volumetric water. The regression coefficient "b" was tested with the Student's t distribution, while the linear correlation coefficient "r" was tested against tabular r values (Gomez & Gomez, 1984).

Following the calibration of the Waterman, the following correlation procedure was used to calibrate the CPN 503DR Hydroprobe NWM:

1. On four occasions and on four plots per replicate (Table 5.2-2), simultaneous readings were taken with the Waterman and CPN NWMs and count ratios were calculated.

2. Linear regression analyses (Gomez & Gomez, 1984) were performed on the two sets of count ratios to obtain regression equations whereby CPN count ratios could be calculated from the Waterman count ratios obtained during its field calibration.
3. Using the volumetric SWC data obtained from the Waterman calibration and using the calculated CPN count ratios, calibration equations for the CPN NWM were calculated using the regression procedure of Gomez & Gomez (1984).

Table 5.2-1: Baseline data for Waterman NWM calibration

Date	Plot No.		
	Replicate 1	Replicate 2	Replicate 3
2 Sept 2010	7	29	56
	19	41	68
24 Feb 2011	4	29	49
	7	41	61
	16	34	56
	19	46	68
20 Apr 2011	4	29	49
	7	41	61
	16	34	56
	19	46	68
21 June 2011	4	29	49
	7	41	61
	16	34	56
	19	46	68
1 Sept 2011	4	29	49
	7	41	61
	16	34	56
	19	46	68

Table 5.2-2: Plots used for correlation study for CPN 503DR NWM calibration

Date	Replicate No.	Plot No.	Replicate No.	Plot No.	Replicate No.	Plot No.
12 Apr 2012	1	5	2	29	3	49
20 Apr 2012		6		34		56
27 Apr 2012		9		41		61
10 May 2012		10		46		68

Field calibration of capacitance probe capacitors

In this study AquaCheck capacitance probes were used. The calibration of the probe capacitors for gravimetric SWC (Gardner, 1986) was performed on 12 selected plots per depth increment while capacitor readings were recorded automatically (see Table 5.2-3 for plot selection and calibration detail). From Table 5.2-3 it can be seen that the same depth increment for SWC was

used for the calibration of the capacitors at both 100 and 200 mm depths. Statistical analysis entailed a simple linear regression analysis of the data in order to determine the relationship between SWC and capacitor reading. The regression coefficient “b” was tested with the Student’s t distribution, while the linear correlation coefficient “r” was tested against tabular r values (Gomez & Gomez, 1984).

Table 5.2-3: Capacitance probe soil water calibration information

Plot No.	4	7	16	19	29	34	41	46	49	56	61	68
Probe No.	2641	2303	4884	2301	5470	5465	2370	2220	4513	5276	4478	5294
Capacitor position (mm)	100		200		300		400		600		800	
Soil water depth increment (mm)	0-225		0-225		225-375		375-525		525-750		750-1050	
Calibration events	2 Sept 2010; 24 Feb 2011; 20 Apr 2011; 21 Jun 2011; 1 Sept 2011, 16 Feb 2012, 30 May 2012											

Routine measurement of SWC

Neutron water meter

The Geoquip Waterman NWM was used for routine measurement of SWC. Weekly or two-weekly readings (counts) were taken at depths of 150, 300, 600, 900 and 1200 mm on the 36 selected plots. The seasonal readings usually started in December, shortly after planting, and continued until harvesting, in June, the next year. In this report the measurements of five growing seasons, viz. 2008/09 to 2012/13, will be presented and discussed. Soil water content data for the 2008/09 and 2009/10 seasons were derived from NWM counts using the manufacturer’s calibration equation, while for the 2010/11 to 2012/13 seasons, NWM counts were converted to SWC expressed either as volumetric soil water percentage or as mm of water per depth increment, using the acquired calibration equations.

Capacitance probes

The data was periodically captured from the 18 installed capacitance probes (Table 5.2-4) with a hand-held data logger, transferred to a computer using Cropgraph software and subjected to quality control before converting readings to volumetric SWC with the acquired calibration equations. In this report the measurements of four growing seasons, viz. 2009/10 to 2012/13, will be presented and discussed.

Table 5.2-4: Capacitance probe installation data

Plot No.	4	5	7	16	17	19	29	34	35
Probe No. ¹	2641	2417*	2214 ² 2303 ^{3#}	4521 ⁴ 4884 ⁵	4504	2137 ² 2301 ³	5470	4510 ⁴ 5465 ⁵	4480*
Plot No.	41	46	47	49	56	60	61	68	72
Probe No.	2370	2220	2395	4513	5276	4475	4478	5294	5302

¹ Probe Nos. with no superscripts installed 2009/10-2012/13; ² Installation 2009/10-2011/12;

³ Installation 2012/13; ⁴ Installation 2009/10; ⁵ Installation 2010/11-2012/13

* No data generated in 2011/12 because of faulty probe or flat batteries

No data generated in 2012/13 because of faulty probe

Results and Discussion

Field calibration of NWMs

The concretion fractions present at the various depth layers for the three profile pits are presented in Table 5.2-5. Uncorrected and corrected soil bulk density values for the three profile pits are presented in Fig. 5.2-1. The correction/adjustment of soil bulk densities to compensate for gravel fractions had a profound effect on final bulk density values – the larger the amount of gravel, the larger the correction. For example, for the 525-750 mm layer of profile pit no. 1, the original bulk density of 1.57 g/cm³ was adjusted to 1.11 g/cm³ (Fig. 5.2-1) due to the presence of 54% concretions (Table 5.2-5). Furthermore, the concretion data, and consequently the soil bulk densities, exhibited great variation among the profile pits, and hence among the three experimental replicates/blocks, hence the decision to calculate calibration equations per replicate and per depth increment.

Table 5.2-5: Concretion fractions (>2 mm) of the experimental site

Soil layer (mm)	Concretion (%)		
	Profile Pit No. 1	Profile Pit No. 2	Profile Pit No. 3
0-225	5.5	0.6	0.9
225-375	14.1	1.4	2.7
375-525	37.5	1.5	3.6
525-750	53.6	3.2	4.5
750-1050	38.0	18.7	49.2
1050-1350	11.6	39.6	41.1

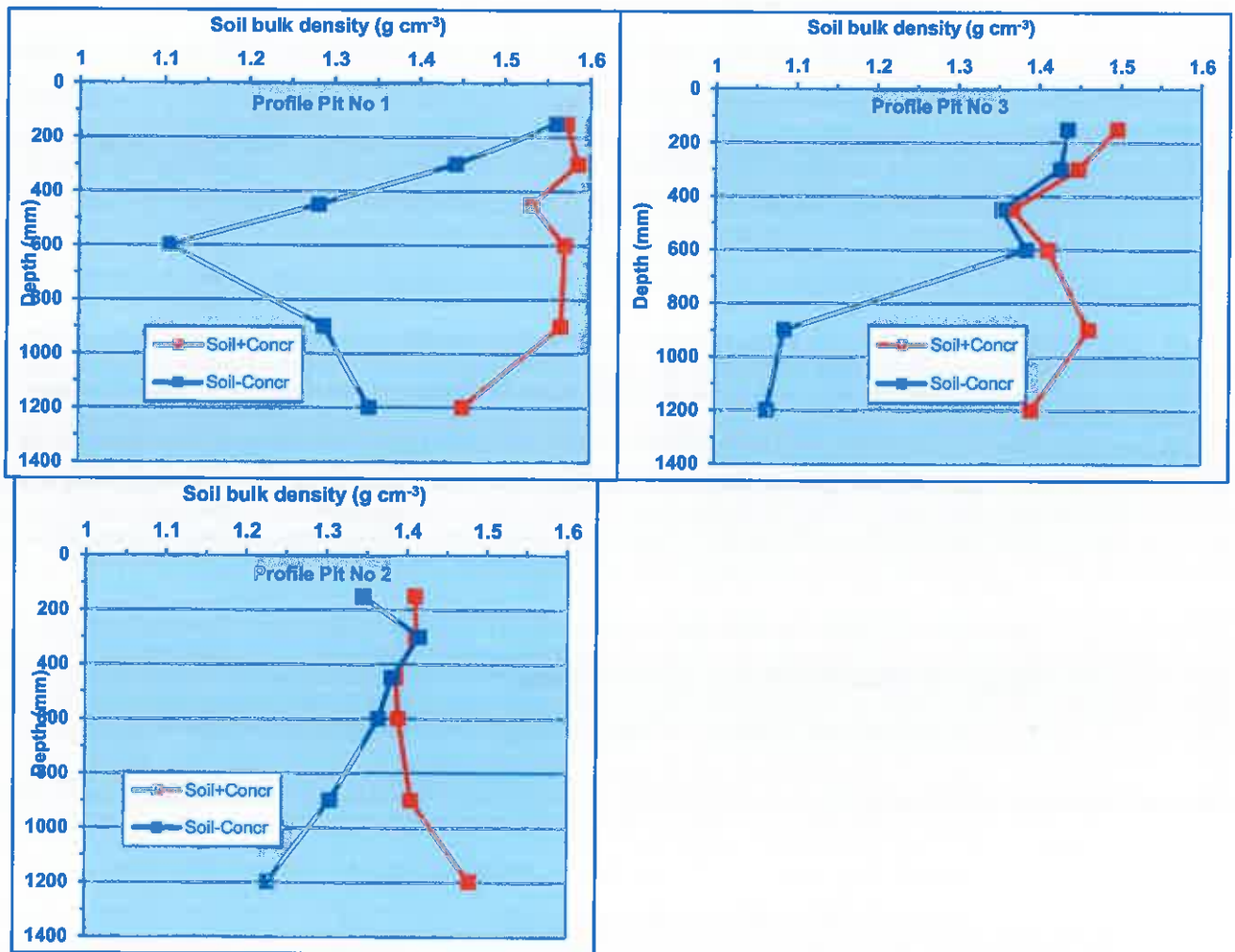


Figure 5.2-1: Soil bulk densities for profile pits 1-3.

Waterman NWM: Statistical data for the calibration per replicate and per depth increment of the Waterman NWM is given in Table 5.2-6, while calibration results are plotted in Fig. 5.2-2. From the latter results, the following observations can be made:

- The t-test values for the regression coefficients indicate that the linear response of volumetric SWC to changes in NWM count ratios is significant ($p < 0.05$) to highly significant ($p < 0.001$).
- The R^2 values indicate that 12-89% of the variation in volumetric SWC is accounted for by the linear function of NWM count ratios.
- Highly significant correlation coefficients (r) were calculated.
- The graphical displays of the calibration data show a good “closeness of fit” (indicated by magnitude of the r value) (Gomez & Gomez, 1984) between the estimated regression lines and the observed points.
- For all replicates the best calibration results were obtained for the 0-225 and 225-375 mm depth increments. The poorer calibration results for the deeper soil layers are probably caused by others factors such as the presence of Fe and Mn concretions (Table 5.2-5; section 5.3). Comparing replicates, the poorest calibration results were obtained for replicate 1, probably for the same reasons.

CPN Hydroprobe: The linear relationships that were established between the Waterman NWM vs. CPN Hydroprobe count ratios to facilitate the calibration of the latter NWM are displayed in Fig. 5.2-3. Because of the great variation exhibited by the concretion data, and consequently the soil bulk densities, among the profile pits (Fig. 5.2-1), and hence among the three experimental replicates/blocks, it was decided to calculate calibration equations per replicate and per depth increment. It was also decided to individually calibrate the capacitors of each probe. The calibration equations for the CPN Hydroprobe are given in Table 5.2-7. From the calibration results, the following observations can be made:

- In general good R^2 values, i.e. the variation in CPN count ratios accounted for by the linear function of Waterman count ratios, were obtained per replicate and per depth of reading (Fig. 5.2-3). However, poor R^2 values were obtained for some replicates and depths of reading (e.g. Rep 3; 150 mm depth), reflecting probably other factors (presence of concretions?) that affected the relationships.
- Because the CPN NWM calibration was linked to that of the Waterman NWM, the same statistical relationships (apart from the calibration equations) were established (Table 5.2-7).

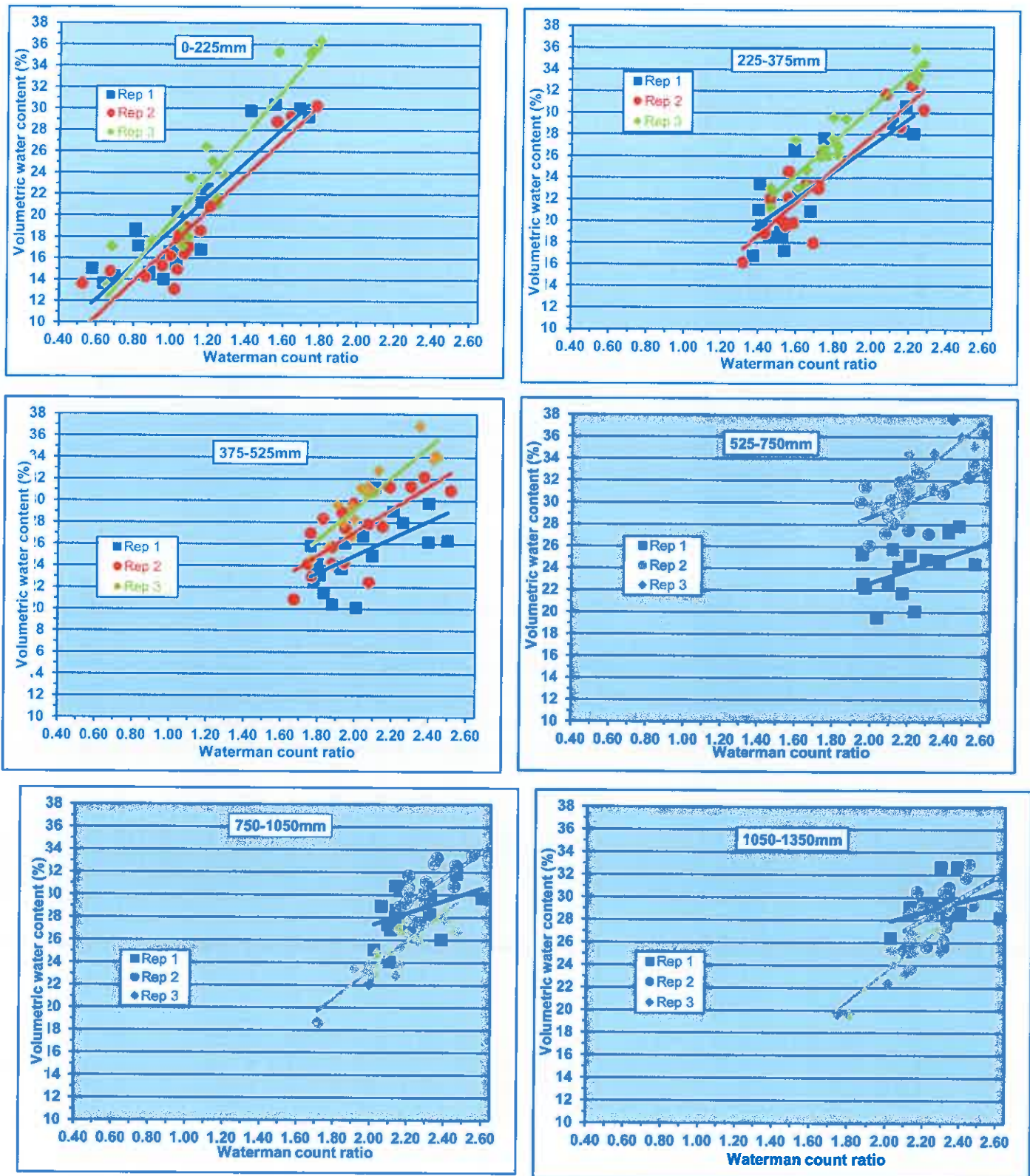


Figure 5.2-2: Calibration graphs for Waterman NWM.

Table 5.2-6: Statistical data for Geoquip Waterman calibration

Depth (mm)	Replicate	Calibration Equation ($Y = a + bX$) ¹	Valid X range	DF	t test for regress coeff (b)	Variance explained (R ² , %)	Correlation coeff (r)
0-225	1	Y = 2.49564+ 16.04726X	0.577238<=X<= 1.734262	16	9.67***	81	0.9001**
	2	Y = 0.57393+ 16.54319X	0.524431<=X<= 1.777845	16	15.23***	87	0.9335**
	3	Y = -1.18235+ 20.55269X	0.65736<=X<= 1.796005	15	13.75***	88	0.9389**
225-375	1	Y = 2.44319+ 12.28113X	1.372989<=X<= 2.222513	16	7.05***	66	0.8111**
	2	Y = -2.76471+ 15.29554X	1.320182<=X<= 2.277487	16	11.93***	80	0.8968**
	3	Y = -0.50703+ 15.48252X	1.465857<=X<= 1.656015	16	48.29***	89	0.9435**
375-525	1	Y = 8.92123+ 7.99709X	1.761350<=X<= 2.499346	16	3.90**	36	0.5975**
	2	Y = 5.64407+ 10.69232X	1.669803<=X<= 2.515052	16	5.99***	54	0.7365**
	3	Y = 0.59382+ 14.31391X	1.764492<=X<= 2.444372	16	43.69***	80	0.8941**
525-750	1	Y = 11.23627+ 5.72092X	1.956442<=X<= 2.518765	14	3.73**	29	0.5403*
	2	Y = 14.92461+ 6.87511X	1.947368<=X<= 2.727094	16	5.32***	38	0.6166**
	3	Y = 1.32449+ 13.83413X	2.005639<=X<= 2.599476	16	28.01***	73	0.8530**
750-1050	1	Y = 16.26127+ 5.50011X	2.021838<=X<= 2.60144	15	2.66*	16	0.3996NS
	2	Y = 4.33741+ 11.31514X	2.159774<=X<= 2.713351	16	11.02***	52	0.7206**
	3	Y = -2.28338+ 12.79494X	1.715326<=X<= 2.469895	16	11.55***	68	0.8266**
1050-1350	1	Y = 18.79427+ 4.48793X	2.029117<=X<= 2.623037	16	2.43*	12	0.3413NS
	2	Y = 7.21294+ 9.44631X	2.103187<=X<= 2.691754	16	4.84**	35	0.5901**
	3	Y = -3.11029+ 13.25370X	1.749924<=X<= 2.348168	16	18.20***	65	0.8038**

¹Y = Volumetric soil water content; ²X = NWM count ratio; * (p<0.05); ** (p<0.01); *** (p<0.001)

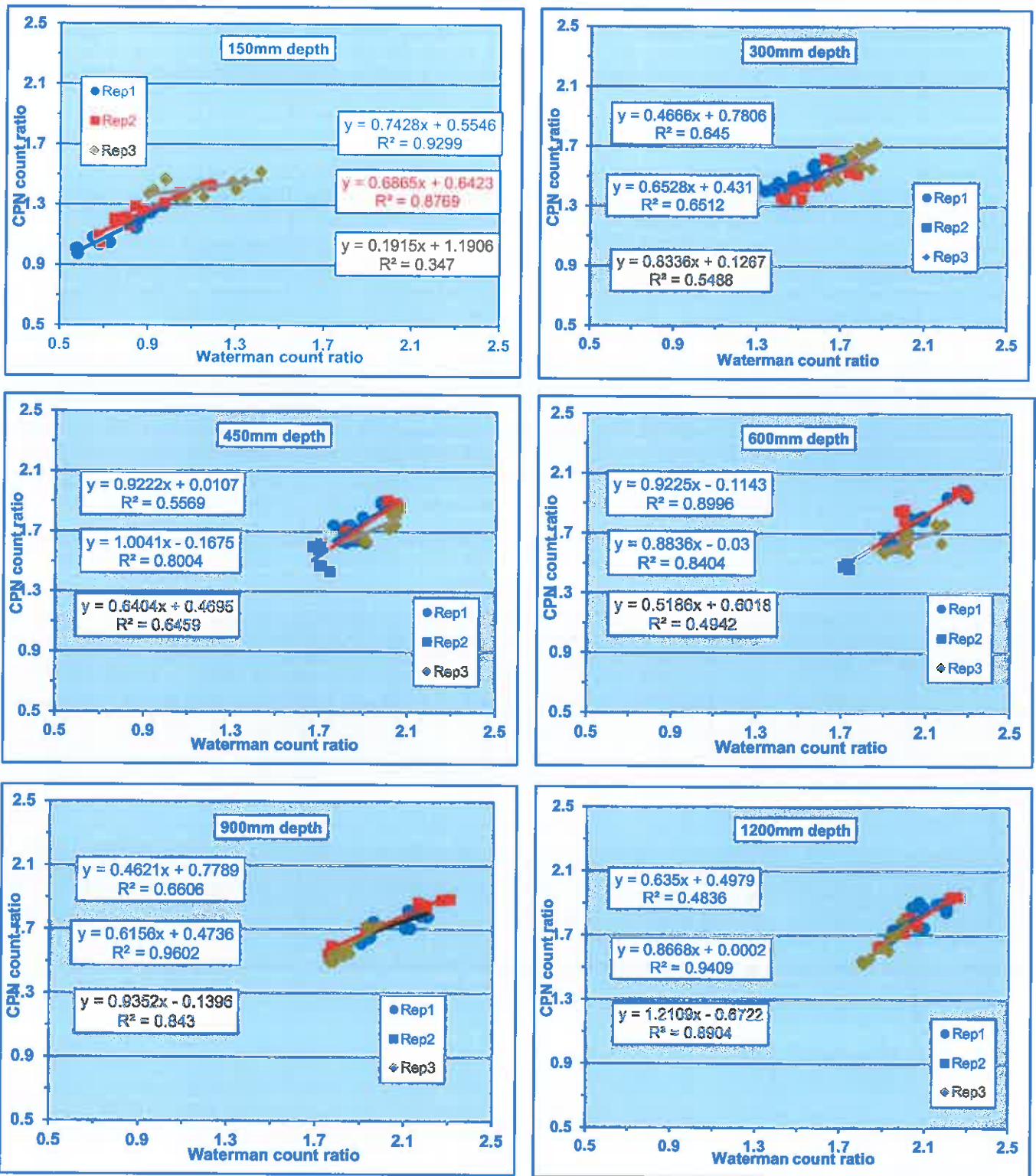


Figure 5.2-3: Linear relationships between NWM count ratios.

Table 5.2-7: Statistical data for CPN 503DR Hydroprobe calibration

Depth Increment (mm)	Replicate	Calibration Equation (Y = a + bX) ¹	Valid X range	Degrees of freedom	t test for regress coeff (b)	Variance explained (R ² , %)	Correlation coeff (r)
0-225	1	Y = -9.87783 + 21.98556X	0.984126 <= X <= 1.828637	16	9.67***	81	0.9001**
	2	Y = -12.23242 + 22.07230X	0.973261 <= X <= 1.912695	16	15.23***	87	0.9335**
	3	Y = -128.96319 + 107.32474X	1.316484 <= X <= 1.534535	15	13.75***	88	0.9389**
225-375	1	Y = 2.44319 + 12.28113X	1.372989 <= X <= 2.22513	16	7.05***	66	0.8111**
	2	Y = -13.69692 + 23.86945X	1.303973 <= X <= 1.917414	16	11.93***	80	0.8968**
	3	Y = -2.86023 + 18.57308X	1.348639 <= X <= 2.025213	16	48.29***	89	0.9435**
375-525	1	Y = 9.05963 + 8.54299X	1.632599 <= X <= 2.323437	16	3.90**	36	0.5975**
	2	Y = 7.15042 + 10.79051X	1.515008 <= X <= 2.352565	16	5.99***	54	0.7365**
	3	Y = 0.59382 + 14.31391X	1.764492 <= X <= 2.444372	16	43.69***	80	0.8941**
525-750	1	Y = 11.98616 + 6.18211X	1.689191 <= X <= 2.398719	14	3.73**	29	0.5403*
	2	Y = 14.96839 + 7.96007X	1.676442 <= X <= 2.349891	16	5.32***	38	0.6166**
	3	Y = -11.45404 + 24.72147X	1.639256 <= X <= 1.971567	16	28.01***	73	0.8530**
750-1050	1	Y = 7.28938 + 11.69738X	1.717668 <= X <= 1.990197	15	2.66*	16	0.3996NS
	2	Y = -4.36767 + 18.38067X	1.803157 <= X <= 2.143939	16	11.02***	52	0.7206**
	3	Y = 1.05203 + 12.83344X	1.45028 <= X <= 2.202586	16	11.55***	68	0.8266**
1050-1350	1	Y = 16.14888 + 6.59699X	1.781409 <= X <= 2.185452	16	2.43*	12	0.3413NS
	2	Y = 7.02556 + 11.02253X	1.819431 <= X <= 2.323833	16	4.84**	35	0.5901**
	3	Y = -0.17669 + 13.62568X	1.486851 <= X <= 2.068763	16	18.20***	65	0.8038**

¹Y = Volumetric soil water content; ²X = NWM count ratio; * (p<0.05); ** (p<0.01); *** (p<0.001)

Field calibration of capacitance probes

Calibration equations for the capacitance probes per replicate, per depth increment and per capacitor are given in Table 5.2-8. In Fig. 5.2-4 calibration results are displayed graphically for the capacitors at 100, 400 and 800 mm depths. Statistical results for the calibration lines of the 100 mm capacitors in Fig. 5.2-4 are presented in Table 5.2-9. Using the calibration results of Tables 5.2-8 and 9 as examples, the following observations can be made:

- The majority of the t-test values for the regression coefficients indicate that the linear response of capacitor readings to changes in volumetric SWC is significant ($p < 0.05$) to highly significant ($p < 0.001$).
- In general good R^2 values, i.e. the variation in capacitor readings accounted for by the linear function of volumetric soil water content, were obtained during the calibration procedures. However, the inconsistency in the calibration data is unexplainable. There is a tendency that poorer calibrations were obtained for the deeper (400, 600 and 800 mm) capacitors. Again, this phenomenon can also not be explained at this point in time.
- All capacitors per probe displayed different calibration equations. The implication is that there is no "universal" calibration per probe – capacitors need to be calibrated individually.
- When calibrations per replicate (block) are compared for the four calibration plots, large variations in capacitor readings are found at the same soil water contents. While the capacitors at 100 mm show similarity in slopes, there is almost no agreement among capacitors at 400 and 800 mm, with the latter being the worst.
- Statistically non-significant to highly significant correlation coefficients (r) were calculated.
- The graphical displays of the calibration data in Fig. 5.2-4 show a poor to a relatively good "closeness of fit" (indicated by magnitude of the r value) (Gomez & Gomez, 1984) between the estimated regression lines and the observed points.

