Technologies for improved water use efficiency in small-scale maize production in a semi-arid region

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Abstract

Alternative technologies to increase grain maize production under rainfed systems are urgently needed, considering the low grain yield in small-scale farming in countries such as Mozambique. Supplemental irrigation, fertiliser application and tillage methods are valuable available farming technologies. This thesis examined the impact of supplemental irrigation, fertiliser application and three tillage methods (hand hoeing, strip tillage, disc tillage) on maize grain yield. Studies on belowground biomass showed that most roots were concentrated in the upper 20 cm of the soil. Root abundance decreased down the soil profile, which can be genetically derived but also attributable to higher penetration resistance at greater depth. Tillage had a great effect on soil penetration resistance, but little effect on root growth and a limited effect on yield. Root to shoot ratio was high under rainfed conditions, due to low allocation of assimilates to aboveground traits under water stress. Degrees above canopy threshold (DACT, a water stress index) varied from 0 °C (no stress) to 17.1 °C (high stress). It was mainly affected by water supply and was negatively correlated with soil moisture, grain yield, thousand-grain weight and water use efficiency. Water use efficiency ranged from 0.16-0.60 kg m^{-3} (rainfed) to 0.45-1.09 kg m^{-3} (irrigated) and was negatively correlated with DACT in both seasons studied. Supplemental irrigation alone resulted in an average maize yield increase of 161% compared with rainfed maize and increased water use efficiency by 79%. Application of 48 kg ha^{-1} of nitrogen fertiliser alone increased grain yield by 31% compared with no fertiliser and increased water use efficiency by 18%. Crop modelling results suggested that the recommended nitrogen fertiliser rate (120 kg ha^{-1}) for maize in Mozambique is only suitable for irrigated maize or for regions with high, uniform rainfall.

Overall, the work in this thesis reveals scope for improving crop water use efficiency in semi-arid regions through better soil and water management practices.

Keywords: rainfed, supplemental irrigation, nitrogen, tillage, water use efficiency, leaf temperature, maize, APSIM

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Dedication

To myself, and my wonderful family

- Lindiwe, Yuran, Daniela and Elisa -

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Magaia, E., Arvidsson, J., Brito, R. and Joel, A. (2015). Maize root development and grain production as affected by soil and water management on a sandy soil in a semi-arid region of southern Mozambique. *Acta Agriculturae Scandinavica, Section B — Soil & Plant Science*, 1-12. doi: 10.1080/09064710.2015.1090624.

II Magaia, E., Famba, S., Wesström, I., Brito, R. and Joel, A. (2017). Modelling maize yield response to plant density and water and nitrogen supply in a semi-arid region. *Field Crops Research*, 205, pp 170-181. doi: 10.1016/j.fcr.2016.12.025.

III Magaia, E., Wesström, I., Brito, R. and Joel, A. (2017). Influence of soil water content on critical maize leaf temperature and effects on grain yield components under semi-arid conditions (Submitted manuscript)

Papers I-II are reproduced with the permission of the publishers.

The contribution of Emilio Magaia to the papers included in this thesis was as follows:

I-III Main author. Planned the analyses together with the co-authors. Performed part of the soil sampling and field data collection. Performed data analysis. Carried out the writing with the assistance of the co-authors.

Abbreviations

APSIM	Agriculture production system simulator
CRM	Coefficient of residual mass
d	Model agreement
DACT	Degrees above canopy threshold
DAS	Days after sowing
Dp	Deep percolation
EF	Modelling efficiency
ETa	Actual evapotranspiration
ETc	Crop evapotranspiration
FC	Field capacity
GY	Grain yield
LA	Leaf area
LAI	Leaf area index
MINAG	Ministry of Agriculture
MSM	Measured soil moisture
PAW_f	Fraction of plant-available water
R2	Blister stage
R4	Dough stage
RMSE	Root mean square error
RRMSE	Relative mean square error
SM	Soil moisture
V7	Seven-leaves stage
VT	Tasselling stage
WP	Wilting point
WUE	Water use efficiency

1 Introduction

Population growth and static maize grain yield in sub-Saharan Africa call for new technologies to increase water use efficiency in rainfed systems of this region. The main challenge is to feed the population with existing resources and prevailing agricultural technologies. Farmers currently use low levels of agricultural inputs, with hand tools for land preparation. Moreover, there is great interest in ways to increase maize grain yield through a combination of different soil and water management strategies in Southern Africa. In this region, most of agriculture practice is carried out under rainfed systems using inadequate production methods for food crop production that leads to low water use efficiency. However, it is recognised that rainfed agriculture plays, and will continue to play, a role in crop production (Rockström *et al.*, 2010). Maize yields in sub-Saharan Africa have been at the lower end of the global range for decades (Folberth *et al.*, 2013), probably because smallholder farmers use manual cultivation techniques and little or no purchased inputs or irrigation (FAO, 2010).

This thesis investigated the effect of different maize farming technologies (water supply, fertiliser application and tillage methods) on maize grain yield in a semi-arid region of Mozambique for a sandy loam soil. The water supply treatment consisted of rainfed and supplemental irrigation at 50% plant-available water. The fertiliser treatments consisted of no application of fertiliser and application of 48 kg N ha^{-1}, which is 40% of the recommended level for maize in Mozambique (Fato *et al.*, 2011). The tillage methods were hand hoeing, strip tillage and disc tillage. Knowledge of how these different technologies for soil and water management affect plant growth and grain yield is of particular importance for many countries in semi-arid regions of Africa (Tadele, 2017; Corbeels *et al.*, 2000) , such as Mozambique. Such knowledge is also needed to develop management practices for sustainable maize production in semi-arid regions and to set clear recommendations.

1.1 Aim and Objectives

The aim of this thesis was to study the possibilities to increase maize grain yield in rainfed agriculture. Different levels of water supply, fertiliser application and tillage methods to improve maize (*Zea mays* L.) production in southern Mozambique were tested. Water supply (irrigation and rainfed), fertilisation level (with and without fertiliser) and tillage methods (hand hoeing, strip tillage and discing) were combined in different treatments.

Specific objectives were:

i) To evaluate the effect of water supply, nitrogen fertiliser application and tillage methods on root and crop development;

ii) To quantify the crop water use efficiency of different field management strategies;

iii) To evaluate the relationship between maize leaf temperature and maize agronomic traits from flowering to blister crop stage;

iv) To formulate general recommendations for nitrogen fertiliser rate for rainfed and supplemental irrigation cropping.

2 Background

2.1 About Mozambique

Mozambique is located on the southern-east coast of Africa and has an extensive coastline of 2470 km, a land area of 801 590 km^2 and 36 million hectares of arable land (MINAG, 2008). Of Mozambique's 128 districts, 20 are highly prone to drought, 30 to flooding and another seven to both risks (MINAG, 2003). Agriculture is the main contributor to the economy, employing over 80% of the population (Cunguara *et al*., 2011) and contributing 25% of gross domestic product. With the current population growth, there is a need to improve productivity in the agricultural sector (de Sousa *et al.*, 2017). One way to increase water productivity is through irrigation, but in Mozambique existing irrigation technology is still unproductive (de Sousa *et al.*, 2017) and irrigation is not common practice among farmers (Benson *et al.*, 2014). The actual irrigation potential is 3 million hectares, of which currently only 90 000 hectares are under irrigation (surface and furrow mostly), in systems developed mainly in the 1950s (de Sousa *et al.*, 2017). Of these 90 000 hectares, around 20 000 are located in southern Mozambique, of which 2800 hectares (19%) are in the Maputo Province (de Sousa *et al.*, 2017).

Since 1996-97 onwards, maize, cassava, bean and sweet potato production has increased considerably in Mozambique (Cunguara *et al.*, 2011). However, this increase in productivity is due to land expansion and also because of rural population increase (returning refugees), and is not a consequence of increased agriculture productivity (Cunguara *et al.*, 2011). Maize is generally produced under rainfed conditions. Official statistics do not give detailed data on the irrigated maize area in the country. Mozambique has different agro-ecological zones. Northern regions are characterised by average maize yield between 734 and 945 kg ha^{-1}, while the agro-ecological zones in the south of the country are characterised by yields of around 400 kg ha^{-1} (Sitole, 2012).

2.2 Agriculture in semi-arid sub-Saharan Africa

The agriculture model in Africa is different from that in Asia and America (OECD/FAO, 2016). In sub-Saharan Africa, growth in agriculture occurs through land expansion and not by increasing land productivity (OECD/FAO, 2016). Agriculture is the main sector in sub-Saharan Africa, employing 65% of the workforce (Alliance for green revolution in Africa (AGRA), 2014). Rainfed agriculture is practised on 80% of agricultural land worldwide, but on 95% of agricultural land in sub-Saharan Africa (Bhatt *et al.*, 2006; Rockström *et al.*, 2003;). Therefore crop production in sub-Saharan Africa is failing to keep pace with rapid population growth (OECD/FAO, 2016).

It is recognised that water is the major limiting factor for crop production in semi-arid regions of Africa (Barron, 2004; Fox & Rockström, 2003). Semi-arid zones are characterised by receiving less than 500 mm of rainfall per year (Makurira, 2010) and this rainfall is poorly distributed (Ngigi, 2003). In such regions, crop yields continue to be very low compared with experimental (attainable) yields and simulated (potential) yields, resulting in a very significant yield gap between actual and attainable rainfed yields (Wani *et al*., 2009). Figure 1 shows the typical rainfall partitioning in a rainfed system. The challenge is to increase the amount of productive water (transpiration) (Makurira *et al.*, 2007), by means of soil management. Farmers in sub-Saharan Africa are classified as 'low resource' and they practise low input/low yield subsistence agriculture (Alliance for green revolution in Africa (AGRA), 2014).

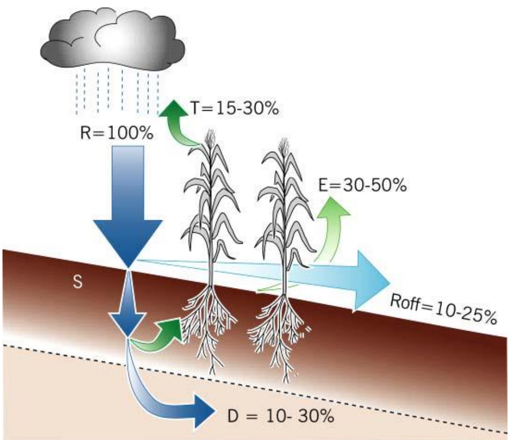

Figure 1. Rainfall partitioning in a typical rainfed system in a semi-arid region. R is rainfall, T is transpiration, E is evaporation, D is deep percolation and Roff is runoff. Source: Rockström *et al.* (2003).

The yield gap is largely explained by inappropriate soil, water and crop management options used at farm level, combined with persistent land degradation (Wani *et al.*, 2009). In sub-Saharan Africa, fertiliser use is very low compared with in other parts of the world. The average nitrogen fertiliser use is around 20 kg ha^{-1} for Africa and 3-5 kg ha^{-1} for sub-Saharan countries (Folberth *et al.*, 2013), while for Mozambique it is around 5 kg ha^{-1} (Chianu *et al.*, 2012). The rate of nitrogen compound fertiliser used in maize production ranges from 26 kg ha^{-1} in Malawi to 70 kg ha^{-1} in Zambia (Jeje *et al.*, 1999). The African Union (2006) called for more intensive use of fertiliser in Africa, to levels of 50 kg ha^{-1} by 2015.

Low utilisation of fertilisers in Africa can be attributed to inability to deliver appropriate recommendations and supplemental inputs in the right form to smallholder farmers (Sanginga & Woomer, 2013). The use of purchased inputs in Mozambican agriculture is also very limited. According to a national agriculture survey conducted in 2012, only a small proportion of farmers use any fertilisers or improved technologies (MINAG, 2012) (Table 1). For example, fertiliser use in Mozambique is concentrated mostly in cash crops such as sugar cane and tobacco (IFDC, 2012).

It is known that the use of improved seeds does not follow the use of fertilisers in many parts of Africa (Smale *et al.*, 2013). In Mozambique over 70% of cultivated land is used for maize production, followed by rice and millet (MINAG, 2012). Besides, a single fertiliser recommendation is used for wide areas, with no account taken of the environmental conditions and cash constraints (Smale *et al.*, 2013).

Table 1. *Percentage of farmers using different agricultural practices in Mozambique, 2002-2012*

Technology type	2002	2003	2005	2006	2007	2008	2012
Fertiliser (%)	3.8	2.6	3.9	4.7	4.1	3.8	2
Pesticide (%)	6.8	5.3	5.6	5.5	4.2	4.1	6.3
Improved maize seed (%)			5.6	9.3	10	9.9	8.7
Animal traction (%)	11.4	11.3	9.5	12.8	12	11.3	7.7
Irrigation (%)	10.9	6.1	6.0	8.4	9.9	8.8	8.1

Source: MINAG (2012)

2.2.1 Water management and water use efficiency

Water management in agriculture is a broad concept covering an increasingly wide range of technologies and practices available for improving water and land management (Namara *et al.*, 2006). *In situ* technologies are those that alter the rainfall partitioning of agricultural fields themselves, while external (*ex situ*) technologies concentrate runoff from uncultivated areas onto agricultural fields (Andersson *et al.*, 2009; Falkenmark *et al.*, 2001). Example of *in situ* techniques are the use of terraces, ditches, stones, vegetative bunds, mulching, conservation tillage (strip, minimum, reduced, *etc*.) (Namara *et al.*, 2006). In Zimbabwe, contour ridges with infiltration pits have been shown to increase long-term grain yields, an effect attributed to greater cumulative infiltration of water (Nyakudya *et al.*, 2014). In Ethiopia, strip tillage has been shown to increase grain yield compared with conventional tillage with the local wooden plough (*maresha*), an effect attributed in that case to increased infiltration and lower evaporation from soil (Temesgen *et al.*, 2012). *Ex situ* water management includes rainwater harvesting (Namara *et al.*, 2006; Falkenmark *et al.*, 2001), storage and/or supplemental irrigation (Andersson *et al.*, 2009). Stored runoff water can be used for supplemental irrigation in semi-arid regions (Barron, 2004). The use of *ex situ* water management has been proven to reduce the impact of dry spells in many parts of sub-Saharan Africa (Makurira, 2010; Barron, 2004).

Crop water use efficiency, also termed crop water productivity (Waraich *et al.*, 2011), is defined as the ratio of biomass accumulation expressed as carbon dioxide assimilation, total crop biomass or grain yield to the amount of water consumed, which can be expressed in transpiration (T), evapotranspiration (ET) or total water input to the system (I). In a water management context, the term water use efficiency (WUE) refers to crop production per unit of water used, with units such as kg grain ha^{-1} mm^{-1} or kg m^{-3} (Sadras *et al.*, 2012).

Crop water use efficiency depends on different factors, which include crop physiological characteristics, genotype, soil characteristics such as soil water-holding capacity, meteorological conditions and agronomic practices (Huang *et al.*, 2006). Improving water management and water use efficiency in rainfed crop production is an essential requirement for sustainable maize production (Asare *et al.*, 2011). To maximise WUE, there is a need to conserve water and to promote crop growth through optimising the timing of tillage, planting, fertilisation and pest control (de Pascale *et al.*, 2011). A shortage of soil moisture often arises in dry rainfed areas during the most sensitive growth stage of the crop, resulting in poor crop growth and low grain yield (Oweis & Hachum, 2009). Therefore supplemental irrigation using a limited amount of water during critical crop stages can improve yield and increase water productivity (Oweis & Hachum, 2009). Studies have found that irrigated maize has higher water use efficiency than rainfed maize (Kresović *et al.*, 2016; Hernández *et al.*, 2015). Supplemental irrigation also increases water use efficiency in maize (Barron, 2004; Rockström *et al.*, 2003). Sadras *et al*. (2012) reported values of water use efficiency ranging from 1.1 kg m^{-3} to 3.2 kg m^{-3} for irrigated maize and from 0.6 kg m^{-3} to 2.3 kg m^{-3} for rainfed maize.

Water use efficiency in maize can be increased by nitrogen application in environments with adequate rainfall or by the use of irrigation (Hernández *et al.*, 2015). Maculuve (2011) reported water use efficiency values ranging from 0.40 to 1.7 kg grain m^{-3} for two open-pollinated maize cultivars under rainfed fertilised treatments (120 kg ha^{-1} N) in a semi-arid region of Chokwe in Mozambique. For the same region, Sitoe (2011) reported values ranging from 0.24 kg grain m^{-3} (0 kg N ha^{-1}) to 1.19 kg grain m^{-3} (120 kg N ha^{-1}) using the maize cultivar Matuba. On light-textured soils in Zimbabwe, Kurwakumire *et al*. (2014) found WUE under rainfed conditions to range from 0.038 kg m^{-3} to 0.113 kg m^{-3} (control), while it ranged from 0.3 kg m^{-3} to 0.8 kg m^{-3} for crops receiving NPK fertiliser.

2.2.2 Maize grain yield in sub-Saharan regions

Maize is the staple food for sub-Saharan Africa, but this crop is still under-performing in most sub-Saharan countries except in some areas of South Africa (OECD/FAO, 2016; Bott, 2014). The main reasons for the low yield are soil constraints (44%), weeds including *Striga* spp. (19%) and drought (18%), but also inadequate crop nutrition (Bott, 2014). However, the yields obtained on research stations are 3- to 5-fold higher than those in farmers' fields (Barron, 2004). Smallholder farmers have limited access to capital, little schooling, are at the mercy of highly variable rainfall and suffer seasonal price fluctuations (FAO, 2010).

In Mozambique, the average maize yield is about 1.19 tons ha^{-1} (FAO, 2010). In semi-arid and sub-Saharan African, the yield gap is high not due to water scarcity *per se*, but rather to inefficient soil and water management (Rockström *et al.*, 2010). Maize is extensively and intensively cultivated in small-scale farming systems in Mozambique with rainfed agriculture. It is the second staple food (after cassava) and the most important cereal in Mozambique, followed by rice, wheat, sorghum and millet (Short *et al.*, 2013). Maize is largely grown as a subsistence crop and it is often cultivated as a dominant intercrop alongside grain legumes such as cowpea, beans, groundnuts and pigeon peas (Silici *et al.*, 2015). It is recognised that the low agricultural productivity in Mozambique is partly due to erratic rainfall distribution, disproportional aid to the agriculture sector compared with other sectors and low use of improved agricultural technologies (Cunguara & Moder, 2011).

According to FAO, (2010), the type of agriculture practised in Mozambique provides a precarious livelihood for smallholder farms, which are characterised by holdings of multiple small plots, multiple crops, low input use and low productivity.

One way to increase rain water use efficiency is through increasing water infiltration into the soil and reducing overland flow (Rockström & Valentin, 1997). Moreover, field experiments have shown that there is a possibility of grain yield increase in sub-Saharan Africa if adequate soil and water management are put in place (Temesgen *et al*., 2012; Barron 2004).

2.2.3 Tillage effects

Tillage is mechanical soil manipulation for the purpose of crop production, affecting soil water conservation, soil temperature, infiltration and evapotranspiration processes (Abolanle *et al.*, 2015). Tillage-induced changes in soil properties can influence evaporation, infiltration and how the water is redistributed within the profile after precipitation (Schwartz *et al.*, 2010). Tillage strongly influences pore size distribution, with soils under conventional tillage generally having lower bulk density and associated higher total porosity within the plough layer than no tillage (Lipiec *et al.*, 2006). After tillage infiltration is increased (Messing & Jarvis, 1993), but this can change after soil wetting and drying processes (Moret & Arrúe, 2007). Appropriate tillage operations are needed for better crop yield and, as a result, production increases (Memon *et al*., 2012). Around 2455 million hectares of land are cultivated in sub-Saharan Africa (Kienzle & Fao, 2013) and are dominated by small-scale farmers (Houmy *et al.*, 2013). In this region, 80% of the land is prepared by hand tools, 15% by draft animal power and the remaining 5% by tractor (Mrema *et al.*, 2008). Tillage operations are known to influence both the release and conservation of soil nutrients (Agbede & Adekiya, 2013).

Different tillage methods such as hand hoeing, strip tillage and conventional tillage have different impacts on the soil, affecting bulk density, moisture availability and temperature, and can influence both release and conservation of soil nutrients (Agbede & Adekiya, 2013). Tillage also exerts adverse effects on soil when it is performed under inadequate moisture conditions, or when inadequate tillage implements are used (Memon *et al*., 2012).

Tillage methods vary from no-till to full tillage. Tillage can also be classified as conservation or conventional tillage (FAO, 2000). Conservation tillage is known to be more beneficial than conventional tillage in terms of soil physical and chemical properties as well crop yields (Abolanle *et al.*, 2015; FAO, 2000). Strip tillage reduces the time required for land preparation and can also destroy the plough pan and thus increase infiltration (Temesgen *et al.*, 2012). Strip tillage can increase maize grain yield compared with disc tillage (Temesgen *et al.*, 2012). However, the strip tillage practised in an African context can differ from that in *e.g.* the USA, due to the low amount of residues and soil cover in African farming systems, which makes it difficult to apply the conservation tillage approach (Breton, 2009).

The relationships between crop yield, soil moisture and tillage are not completely understood and the results available are not consistent and vary from region to region. However, research throughout the world is providing increasing evidence of the value of producing maize without tillage (Ahmad *et al.*, 2010).

Compared with conventional tillage, maize yields under zero tillage production can be similar or even greater in some cases (Memon *et al.*, 2012). In other cases, conventional disc tillage followed by harrowing can result in higher soil moisture content than no till (Aikins & Afuakwa, 2012). This trend in soil moisture had been associated with increased yield in cowpea (Aikins & Afuakwa, 2012).

2.2.4 Root development

The architecture of the root system is related to its water and mineral uptake (Pagès & Pellerin, 1994). Root growth in the field is often slowed by a combination of soil physical stresses, including mechanical impedance, water stress, oxygen deficiency and sometimes also toxic chemicals (Bengough *et al.*, 2006). Root development in soils, especially during the early growth stages, can be considered vital for successful crop establishment, since roots can determine the content of water extracted for crop growth and for final grain yield (Sangakkara *et al.*, 2010). Root density generally declines exponentially with depth under well-watered conditions (Klepper, 1991). The well-watered zones in the soil are associated with lower amounts of available oxygen. Under irrigation conditions, the most critical soil property for root growth is oxygen diffusion rate (Klepper, 1991).

Root elongation occurs when root pressure exceeds mechanical impedance (Laboski *et al.*, 1998). Compaction from wheel traffic has often been found to influence adversely all stages of the crop growth, responses being particularly marked in the early phases of establishment (Soane, 1987).

Factors determining root mortality at the reproductive stage are largely unknown (Niu *et al.*, 2010). Distribution of materials to roots and shoots depends on plant species, environmental conditions and time in the growing season (Klepper, 1991). Plants respond to nitrogen availability by changing their root to shoot ratio (Ågren & Franklin, 2003). As a general rule, annual crop plants show high root to shoot ratio during germination and stand establishment and this decreases gradually during the growing season, especially in the reproductive stage (Klepper, 1991). Fertiliser generally stimulates shoot growth more than root growth and decreases root to shoot ratio (Bonifas *et al.*, 2005;Klepper, 1991).

2.2.5 Maize root development and penetrometer resistance

Maize root growth is negatively affected by compacted layers in the surface (*e.g.* agricultural traffic) and subsoil layers (Taboada & Alvarez, 2008). Root elongation rate decreases in response to both increasing penetrometer resistance and decreasing matric potential, but there is considerable variation between individual studies (Bengough *et al.*, 2011). Root elongation is halved by penetrometer resistance of between 0.8 MPa (cotton) and 2 MPa (maize and peanut), and by matric potential below -0.5 MPa for maize. There is recent evidence that penetrometer resistance in excess of 2 MPa occurs even in many relatively moist soils (*e.g.* matric potential of -100 kPa to -200 kPa), and that is sufficient to slow root elongation to less than half of its unimpeded rate (Bengough *et al.*, 2011).

Tillage affects not only penetrometer resistance values, but also soil water content and bulk density (Lampurlanés & Cantero-Martínez, 2000). Therefore, some studies have found that, in reality, the values measured by penetrometer can be higher than those exerted by roots in the soil (Bengough & Mullins, 1990). On the other hand, on untilled soil with high bulk density, roots can continue to grow deep even at high cone penetrometer values. This can be explained by the capacity of roots to follow the voids or biochannels in the soil (Bengough & Mullins, 1990). For that reason, root development in the soil profile can be explained from different points of view, ranging from soil water content to penetrometer resistance and tillage type and history of the soil.

2.3 Modelling maize yields

Models can help to organise specific data into knowledge and results. Many models have been tested in semi-arid regions of the world to predict maize grain yield under different management strategies. Crop modelling has been a significant focus of agricultural research since the 1960s (Jones *et al.*, 2016).

Crop growth models are increasingly being used as decision support tools to help optimise crop and soil management strategies. Such models need to be calibrated and validated for the site and crop cultivar of interest. There are many different models and each uses different parameters to simulate the cropping system. Nowadays, various models are commonly used for crop growth simulation in irrigated and non-irrigated environments. Models of agricultural systems are useful tools for understanding complex system interactions (Jones *et al.*, 2016). Models have been tested in Africa to evaluate crop production under a wide range of management systems (Masikati *et al*., 2014). Many studies have simulated the low-input farming systems common in sub-Saharan Africa (*e.g*. (Kisaka *et al*., 2015; Shamudzarira & Robertson, 2002; Robertson *et al.,* 2000). A major constraint in modelling work is the lack of reliable, comprehensive datasets for calibration and validation of crop models (Archontoulis *et al*., 2014).

The other important factor is the inclusion of weed effects in the modelling process (Matthews & Stephens, 2002). Model simulations have shown that application of only 50 kg nitrogen and 18 kg phosphorus ha^{-1}, which is less than one-third of the current level in high-input countries, would double maize yield in most areas of sub-Saharan Africa (Folberth *et al.*, 2013). The agricultural production system simulator model (APSIM) has been used in South and East African countries to explore possible management changes in smallholder systems (Roxburgh & Rodriguez, 2016). Studies have shown that APSIM can adequately simulate grain yield under different agro-climate conditions and enhance understanding of different farmers' strategies in maize cropping (Kisaka *et al*., 2015; Masikati *et al*., 2014; Famba, 2011; Shamudzarira & Robertson, 2002). For that reason, APSIM was chosen for the modelling work in this thesis.

2.4 Leaf temperature and water stress

A wide range of methodologies have been devised to manage irrigation scheduling and to detect stress signs in crops (Taghvaeian *et al.*, 2014). Canopy temperature has been used as an indicator of crop water stress, since the reduction in plant-available water results in lower transpiration rates and consequently higher canopy temperatures (Taghvaeian *et al.*, 2014; Jones *et al.*, 2009). Alderfasi & Morgan (1998) found a strong negative correlation between canopy temperature and leaf conductance in wheat, with higher leaf temperature observed in rainfed treatments. High leaf temperature affects pollen viability (Aslam *et al.*, 2015). The major effect of leaf temperature increase during kernel development is a reduction in photosynthesis and in translocation of assimilates, which impacts upon grain filling (Aslam *et al.*, 2015) and consequently on grain yield.

There are several indices available to transform canopy temperature to plant water status (Durigon & de Jong van Lier, 2013). Nowadays, infrared thermometry is used to assess soil-plant-water relations (DeJonge *et al.*, 2015; Jones *et al.*, 2009). This method is not destructive, is capable of measuring a single leaf or whole plant and is less expensive. Differences between canopy temperature and air temperature have been used to quantify water stress (DeJonge *et al.*, 2015; Yuan *et al.*, 2004; Tubaileh *et al.*, 1986) Crop water stress index (CWSI) is the best-known of these (Durigon & de Jong van Lier, 2013). Besides CWSI, there are other indices that relate plant water stress to canopy temperature, such as: degrees above non-stressed canopy (DANS), temperature-time threshold (TTT) and degrees above canopy threshold (DACT) (Carroll, 2015;Taghvaeian *et al.*, 2014). The DACT and DANS indices produce results that are just as effective as CWSI (DeJonge *et al.*, 2015). The advantage of DACT is that only measurements of canopy or leaf temperature are needed, which reduces the need for the complicated calculations required with CWSI (DeJonge *et al.*, 2015), making it easy for farmers to use. Understanding how soil water content affects maize canopy temperature and grain yield is of critical importance for field water management in semi-arid regions.

3 Material and methods

3.1 Site description

A three-year experiment was performed at the research station belonging to the Faculty of Agronomy and Forestry Engineering of Eduardo Mondlane University in Maputo, Mozambique. The experimental site is located in the northern part of the Maputo Province (25º19´08.0´´S, 032º15´55.3´´E) (Figure 2), in Moamba, Sábiè Administrative District Post, around 110 km from Maputo city. Sábiè lies within the semi-arid region of southern Mozambique (Reddy, 1986). It has two distinct weather seasons, warm and wet (October-March) and cold and dry (April-September), with mean annual rainfall between 400 and 600 mm and potential evapotranspiration of 1300 to 1700 mm per year (Reddy, 1984, 1986).

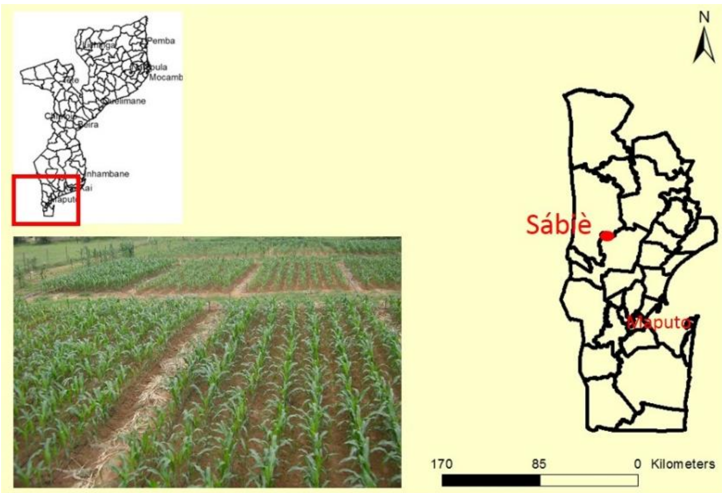

Figure 2. Location of the experimental site at Sábiè in the Maputo province, Mozambique, southern Africa.

The soil at the experimental site is a sandy loam that is classified as a Eutric Fluvisol in the FAO soil classification system (ESDAC, 2014; IUSS Working Group WRB, 2006). Some physical and chemical properties of the soil at the study site are presented in Table 2.

Figure 3 presents rainfall data for 25 years (1990-2015) at a weather station 15 km from the study site. The data show that the monthly long-term average in the region for the cropping season (October-March) is 425 mm. Rainfall amount in the three cropping seasons studied in this thesis corresponded to 95% (season 1), 88% (season 2) and 62% (season 3) of the reference average rainfall.

Table 2. *Soil water retention parameters, particle size distribution and chemical parameters at the experimental site. Field capacity (1 m), wilting point (150 m) and texture in % by weight.*

Physical parameters	Layer 1 (0-20 cm)	Layer 2 (20-40 cm)	Layer 3 (40-60 cm)
Field capacity (FC, mm mm^{-1})	0.213	0.186	0.224
Wilting point (WP, mm mm^{-1})	0.058	0.052	0.056
Saturated water content (SAT, mm mm^{-1})	0.402	0.421	0.464
Soil bulk density (BD, g cm^{-3})	1.39	1.26	1.29
Clay (%)	10.0	10.2	10.5
Silt (%)	13.4	11.5	12.1
Sand (%)	76.6	78.3	77.4
Soil pH(H_2O)	6.7	7.2	7.1
Ca^{+2} ($cmol^+$ kg^{-1})	2.49	2.67	2.90
Mg^+ ($cmol^+$ kg^{-1})	1.83	2.40	2.07
K^+ ($cmol^+$ kg^{-1})	0.39	0.10	0.13
Organic carbon (%)	0.45	0.36	0.36
N-NH_4^+ (ppm)	1.72	1.72	1.84
N-NO_3^- (ppm)	1.82	1.82	2.02

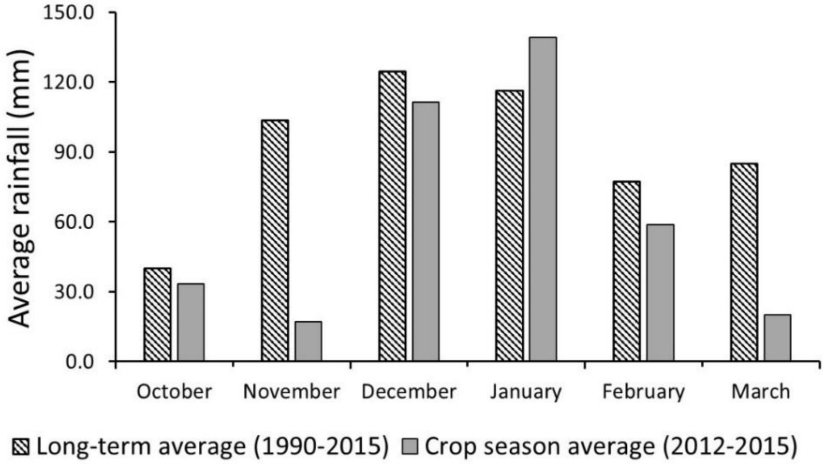

Figure 3. Crop season rainfall average and long-term rainfall distribution from October to March (1990-2015), measured at a weather station 15 km from the experimental site.

3.2 Experimental design

The field trials comprised a factorial experiment with a randomised complete block design on a sandy loam soil. The main treatments were: water supply (two levels), fertiliser application (two levels) and tillage (three methods). The water supply levels were rainfed (W1) and supplemental drip irrigation (W2). The fertiliser levels were without nitrogen (N) (F1) and with 40% of the recommended dose of 120 kg N ha^{-1} (F2). The tillage methods were hand hoeing (T1), strip tillage (T2) and disc tillage (T3). Each combination of treatments had three replicates. The plot size was 6.0 m x 14.0 m, each with eight rows of maize, and with 1 m between plots. The crop was Matuba, an open-pollinated maize cultivar common in Mozambique. Target plant density was 4.2 plants m^{-2}, with 0.3 m spacing within rows and 0.8 m spacing between rows.

The maize cultivar Matuba used is a drought-tolerant and high-yielding variety released in Mozambique (Fato *et al*., 2011).

For the water supply, two water levels were applied, rain-fed and supplemental irrigation at 50% of plant available water. In season 1 (2012/2013), irrigation timing was based on daily potential evapotranspiration measured with an Andersson evaporimeter (Casanova *et al.*, 2009; Hallgren, 1969) installed in the field. Irrigation amount was determined by measuring the change in water level from one day to the next in the Andersson evaporimeter (ET_0) and converting it to crop evapotranspiration (ET_c) using a crop coefficient (K_c) and accounting for precipitation and soil moisture on the previous day at a root zone depth of 80 cm. The soil moisture content in the beginning of the experiment was measured using a gravimetric method. A simple water balance (in mm) was drawn up using the following equation:

$$W_i - W_{i-1} + P_{tot} + G_e + I_{rr} = ET_C + D_p \quad \text{(Eq. 1)}$$

where W_i is soil moisture today, W_{i-1} is soil moisture content on the previous day, P_{tot} is total precipitation on the actual day, G_e is groundwater contribution (assumed to be zero), I_{rr} is irrigation demand, ET_c is crop evapotranspiration and D_p is deep percolation (assumed to be zero).

In season 2 (2013/2014) and season 3 (2014/2015), the irrigation scheduling was based on soil water depletion of 50% of plant-available water in the root zone. Soil moisture was monitored using profile probes (PR2, Delta-t Co., United Kingdom), with one access tube installed per plot, to 100 cm depth (Fig. 4). For water balance, 60 cm depth was chosen, since root studies showed no roots at depths below 60 cm. Supplemental irrigation was applied in the irrigated treatment only (W2), *i.e.* in 18 out of the 36 plots. In order to find the critical point for irrigation (50% of plant available water), the fraction of plant-available water (PAW_f) at each measurement occasion was calculated according to the equation:

$$PAW_f = \frac{MSM - WP}{FC - WP} \quad \text{(Eq. 2)}$$

where MSM is measured soil moisture (%vol.), WP is soil wilting point (%vol.) and FC (DUL) is soil field capacity (%vol.) (where FC-WP = PAW). Soil moisture was not measured during and directly after heavy rainfall, to avoid equipment damage and smearing of the soil surface.

Figure 4. Installing the access tubes in the beginning of the cropping season.

The recommended fertiliser rate for maize in Mozambique is 120 kg N ha^{-1} (Fato *et al*., 2011). Mineral fertiliser was applied three times during the cropping season in this thesis (at sowing as a starter and at the V7 (7 leaves) and VT (tasselling) stages), supplying a total of 48 kg N ha^{-1} (16 kg N ha^{-1} at each stage), which is 40% of the recommended amount of nitrogen for a potential maize yield of 6 ton ha^{-1}. NPK fertiliser (12-24-12) was applied as a starter, and then urea (46) was applied as a local side-placement fertiliser at the other crop stages (V7 and VT).

Hand hoeing is a normal farm practice in soil and land preparation in Mozambique and in the experimental treatment consisted of breaking up the soil with a traditional hoe to 5-7 cm depth. Strip tillage involved using a cultivator with two tines to a depth of approximately 20-25 cm and 15 cm cultivated width (Figure 5). Several passes were made in the same line in order to achieve the desired depth. In disc (conventional) tillage, a disc plough was used to a working depth of 20-25 cm depth, followed by disc harrowing. In most cases, farmers' fields are small or do not have any vegetation cover between cropping seasons. The residues from previous crops are used to feed animals or as kindling, or are naturally degraded. Thus the strip tillage practised in the experiment described in this thesis was without a vegetation cover. Most previous studies using strip tillage consider it to be a form of conservation tillage, where part of the soil is untilled and soil cover exists. In this thesis, the strip tillage had to be performed without soil cover, due to lack of residues. Thus it should be borne in mind that the lack of residues between the crop lines in this treatment may have had a high impact on the soil water balance.

Figure 5. Strip-tilled line with wheel between the strip-tilled rows (2013).

3.3 Soil sampling and survey

3.3.1 Soil sampling

Disturbed and undisturbed samples were taken to study the soil physical and chemical characteristics of the soil. Soil samples were taken in the middle of each 20 cm layer down to 1 m in the soil profile, i.e. at 10, 30, 50, 70 and 90 cm depth, over the whole experimental area. Disturbed soil samples were taken at six points on the diagonal of each block, in October 2012 (before first season). Disturbed samples were used to determine soil texture, soil nitrogen content, pH and carbon (C) content (details are presented in Papers I and II).
A pit was also dug to take undisturbed soil samples at the same depth intervals (with four replicates) and for soil profile description (Figure 6). The undisturbed samples were also used to determine the soil water-holding capacity and bulk density.

3.3.2 Soil penetration resistance (Paper I)

Soil penetration resistance (PR) measurements were carried out at the VT stage using an Eijkelkamp penetrologger to a maximum depth of 40 cm at 1-cm intervals. The cone had an area of 1 cm^2 and a 30° semi-angle. Five insertions were made in the crop line and five between crop lines in each plot. The measurements were made along the middle of each plot, perpendicular to the crop lines.

Figure 6. Pit used for soil profile description.

3.4 Belowground and aboveground biomass

3.4.1 Belowground and aboveground biomass (Paper I)

In root studies, vertical root abundance and root biomass were measured. Vertical abundance of maize roots was measured three times during the growing season (stages V7, VT and R4) in seasons 1 and 2.

The root distribution was measured using the profile wall method (Van Noordwijk *et al*., 2000; Böhm, 1979). The number of living roots was counted in an 8 cm x 8 cm grid (Figure 7). The grid was set parallel to the crop line along the excavated wall in the plant root system. The roots inside each square were counted and screened and subdivided into fine roots (<0.7 mm diameter) and coarse roots (>0.7 mm diameter) using a calliper.

The whole root system was excavated by shovel using an established method (Anderson, 1988; Böhm, 1979). The excavated roots were hand-washed with running water and liquid soap to remove any soil attached to the roots and rinsed with clean water. This process was done carefully to avoid losing air roots. After the cleaning process, the roots and the aboveground biomass were placed inside pre-labelled paper bags in a drying oven at 70 °C (Böhm, 1979) until there was no further change in weight.

Most previous root studies report values of root length density using an auger method followed by image processing (*e.g.* using ImageJ, WinRHIZO).

Separation of fine and coarse roots is a laborious process, but it gives an indication of the relative proportions and reduces the number of replicates needed, which could increase the accuracy of the method. Root abundance was only assessed in between the crop lines and parallel to the crop lines in the field. Moreover, in the hand hoeing and strip tillage treatments, there was difficulty in separating the roots of weeds and the roots of maize and also in separating coarse and fine roots.

Figure 7. Grid used to measure root system development. Each square measured 8 cm x 8 cm. Photo: Mario Chilundo (2012)

3.4.2 Aboveground studies (Papers I, II and III)

Biomass determination

The shoots were cut 2 cm above the soil (Anderson, 1988). Aboveground biomass was placed separately inside paper bags in a drying oven at 70 °C (Böhm, 1979) until there was no further change in weight. The shoots were chopped and oven-dried at the same temperature as the roots until constant weight.

Leaf area measurement

Two maize plants in the middle rows representing the specific crop stage were selected to determine non-destructive leaf area index (LAI). Expanded leaf area was measured once at tasselling (V7, VT and R4), by measuring length and maximum width of full expanded leaf blades (Lizaso *et al.*, 2003) and calculated as:

$$LA = L \times W \times 0.75 \quad \text{(Eq. 3)}$$

where LA is leaf area, L is leaf length, W is the maximum leaf width blade and 0.75 is the coefficient used for maize. Total leaf area was then divided by 0.24 m^2, the area assumed to be covered by each plant in the field. An area coefficient of 0.75 was adopted in this thesis. This coefficient does not account for the cultivar under study, and thus the results only give an indication of differences between treatments.

Leaf temperature and water stress index (Paper III)

Single leaf temperature was measured using a hand-held infrared camera (FLIR® Systems AB, E5) in the most critical stage for grain formation in maize (flowering to blister stage). Unshaded leaf temperature (Nielsen & Anderson, 1989) of five individual leaves was measured between 13:00 and 15:00 h in season 2 and season 3. These measurements were made when there was clear sky (Nielsen & Anderson, 1989). Images were taken from the start of flowering to the blister stage in both years (Zia *et al.*, 2013). The camera used in this study has thermal sensitivity <0.10 °C; emissivity 0.95; temperature range -20 to 250 °C; accuracy 2°C and resolution 320 x 240. The temperature of the plot was determined by averaging the temperature of the five leaves. The leaf temperature was then used to relate to soil moisture content.

The degrees above canopy threshold (DACT) index was calculated as (DeJonge *et al.*, 2015):

$$\text{DACT (h)} = \max\left[0, T_c\text{ (h)} - T_{\text{Critical}}\right] \quad \text{(Eq. 4)}$$

where T_c is leaf temperature and $T_{critical}$ is 28 °C (DeJonge *et al.*, 2015; O'Shaughnessy & Evett, 2010). The crop is not stressed if the temperature is below $T_{critical}$, where DACT is given a value of zero, indicating no stress.

Thermal images were analysed manually using the FLIR tool (Copyright © 1999-2013 FLIR Systems, Inc.). The box tool under FLIR was used to determine the average temperature area of interest in unshaded leaves.

Many studies relate canopy temperature to water stress in different crops. The very well-known crop water stress index (CWSI) is much more data demanding than the DACT method used in this thesis. Therefore studies with CWSI (DeJonge *et al.*, 2015; González-Dugo *et al.*, 2006) examine well-watered and well-fertilised treatments, which was not done in this thesis and where only the actual treatments were used to assess the leaf temperature in relation to water stress. Thus with only this approach, it was not possible to see the two extremes of water conditions, *i.e.* well-watered and with severe drought. Non-inclusion of relative humidity and wind speed in DACT is one of the main limitations of this method, as these two parameters can mask the outcome.

3.4.3 Grain yield determination

Maize was harvested at physiological maturity, in all seasons. A harvest area of 38.1 m^2 (11.9 m× 3.2 m), including the four middle lines, was selected for yield quantification. Harvesting was carried out by hand when all leaves and husks were dry. Cobs were separated from husks in the field and left to sun-dry. The grain was then separated from the cobs and sun-dried again to a moisture content of around 15.5%, determined using a Mini GAC grain moisture tester (Dickey-John®, USA). The final plot yield (PlotGY) was then adjusted corresponding to a water content of 15.5% (Dobermann, 2005b).

3.5 Water use efficiency

Two approaches were used to calculate actual evapotranspiration (ET_a). For season 1, only soil moisture at sowing and end of the crop season was available while daily rainfall and irrigation were measured. For seasons 2 and 3 daily soil moisture was available while daily rainfall and daily irrigation were measured.

For all seasons WUE for maize grain was estimated as (Kresović *et al.*, 2016; Hernández *et al.*, 2015; Kang *et al.*, 2000):

$$\mathrm{WUE} = \frac{GY}{ET_a} \qquad \text{(Eq. 5)}$$

where GY is maize grain yield and ET_a is seasonal crop water use (in mm).

In season 1, ETa was calculated as:

$$ET_a = \Delta\mathrm{SWC} + P_r + I_r - Dp \qquad \text{(Eq. 6)}$$

where ∆SWC is the difference between soil moisture in the 0-80 cm soil layer at sowing and soil moisture at harvest, Pr_i is precipitation in mm, Ir_i is irrigation in mm and D_p is deep percolation. For season 1, D_p was considered to be zero (no soil data were available to calculate this parameter).

In seasons 2 and 3, more soil data were available and ETa (mm) was calculated as:

$$ET_a = \sum_{i=1}^{n}(Pr_i + Ir_i - Dp \pm (W_i - W_{i-1}) \qquad \text{(Eq. 7)}$$

where W_i - W_{i-1} is the change in soil water storage between two observation dates in mm.

After heavy rain or irrigation, the soil water content in the root zone can exceed field capacity, and then percolation occurs. Deep percolation (Dp) was estimated as the difference between total soil moisture at field capacity (MFC) and total measured soil moisture content at 0.6 m depth as:

$$\mathrm{Dp} = \mathrm{Max}\,(\mathrm{MSM} - \mathrm{MFC}; 0) \qquad \text{(Eq. 8)}$$

where MSM is total measured soil moisture in the root zone (0-60 cm). In this depth (60 cm), the total soil moisture at field capacity (MFC) is 124.6 mm. When total soil water content in the root zone is below field capacity, Dp = 0. It was also assumed that there was no runoff, since the area was flat and the soil well drained and with no influence of capillary rise. Mean seasonal ET_a was calculated by averaging the three replicates in the experiment.

3.6 Crop modelling (Papers III and IV)

The APSIM model (Agricultural Production System Simulator version 7.7; available at www.apsim.info/) was used to simulate crop production on sandy soils. APSIM is a software that enables crop and pasture to be dynamically simulated, with regard to residue decomposition, soil water and nutrient flow, erosion and soil and crop management (McCown *et al.*, 1996). Figure 8 presents a simple APSIM layout.

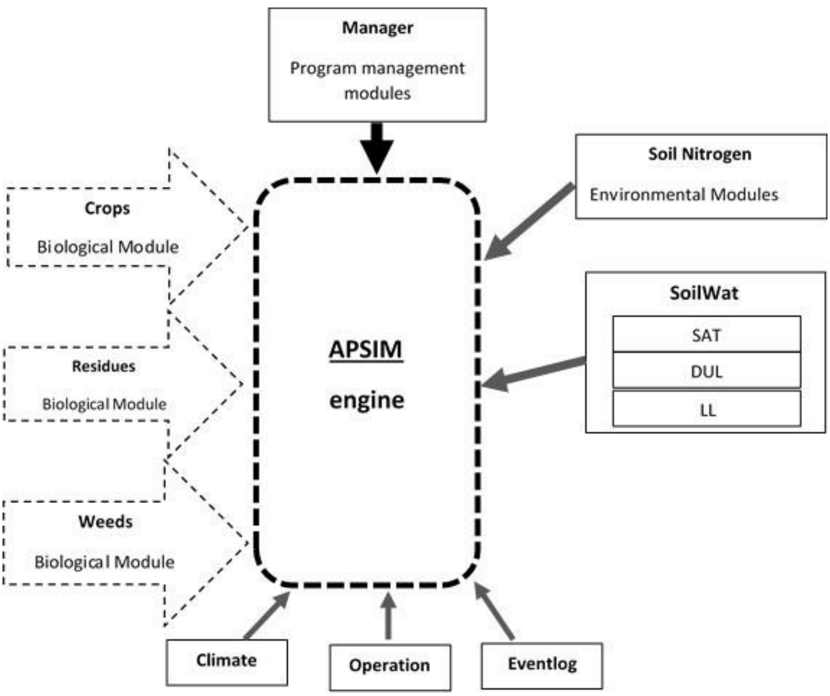

Figure 8. A simple layout structure of the agricultural production system simulator (APSIM) model.

In this modelling exercise, the aim was to simulate two water supply levels, 10 nitrogen fertiliser levels and one tillage method (disc tillage).

The structure and functionality of APSIM are described in detail by Keating *et al.* (2003) and McCown *et al.* (1996). Soil variables are simulated continuously as a function of weather and management (Probert *et al.*, 1998; McCown *et al.*, 1996). APSIM simulates water in two possible ways, a cascading module or using a Richard's equation module.

3.6.1 Calibration

Data obtained from field experiments were used to calibrate the model. The calibration process aimed to minimise the root mean square error (RMSE) between measured and predicted soil moisture, biomass and grain yield. Many of the parameters in the model were adjusted manually during the calibration process until the lowest RMSE of soil moisture and grain yield was achieved (Paper II). The calibration process was initialised with values reported in the literature. Reference values for calibrated parameters are presented in Papers II. Model calibration was initiated on 10 October in order to allow the model to stabilise soil water content before the start of the cropping period.

3.6.2 Modelling scenarios

The calibrated and validated APSIM model (Paper II) was used to determine the best fertiliser rate for different cropping and soil management systems. The main driver of crop growth in APSIM is climate. There was no complete dataset for the study site, so a 25-year climate rainfall and temperature dataset for a station 15 km from the site was used as input for APSIM. Solar radiation data were obtained from https://power.larc.nasa.gov/.

All scenarios included 25-year simulations with increasing nitrogen application rate at 12 kg increments (0 to 120 kg N ha^{-1}), three sowing densities (1, 4.2 and 8.4 plants m^{-2}) and two water supply levels (rainfed and supplemental irrigation).

The planting densities of 1 plant m^{-2} (low) and 8.4 plants m^{-2} (high) are commonly used by farmers in the region, while a density of 4.2 plants m^{-2} is the recommended standard density for maize. Only the planting density of 4.2 plants m^{-2} was validated against experimental data, while the other two (low and high) were used in 'virtual experimentation' through long-term modelling. In these simulations, weed pressure was not considered because the experiment was free of weeds (Papers II).

The APSIM maize module does not have script for application of NPK (12-24-12) as a fertiliser compound. For that reason, nitrogen and phosphorus were introduced separately. In all simulated scenarios, nitrogen and phosphorus were applied proportionally as NPK at sowing as a starter fertiliser and nitrogen as urea (46% N) as a topdressing.

3.6.3 Crop modelling statistics

To compare the outcome of the model, different statistical methods were used. These methods compared the observed data with simulated.

The RMSE (Eq. 9) and the relative mean square error (RRMSE) were used to determine the accuracy of the model (Heinemann *et al.*, 2012):

$$\text{RMSE} = \left[\frac{1}{n}\sum_{i=1}^{n}(Pi - Oi)\right]^{0.5} \quad \text{(Eq. 9)}$$

$$RRMSE = \frac{RMSE}{\bar{O}} \text{ x } 100 \quad \text{(Eq. 10)}$$

where the lower the error value, the better. The threshold values of RRMSE are set as (Jamieson, 1991): very good if RRMSE <10%, good if 10% < RRMSE < 20%, fair if 20% < RRMSE < 30% and poor if RRMSE > 30%.

The model efficiency (EF) was calculated as (Archontoulis & Miguez, 2015):

$$\text{EF} = 1 - \frac{\sum_{i=1}^{n}(Oi - Pi)^2}{\sum_{i=1}^{n}(Oi - \bar{O})^2} \quad \text{(Eq. 11)}$$

Model efficiency determines the relative magnitude of the residual variance ('noise') compared with the measured data variance and EF ranges between $-\infty$ and 1.0 (1 inclusive), with EF = 1 being the optimal value. Values between 0.0 and 1.0 are generally viewed as an acceptable level of performance, whereas values <0.0 indicate that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance (Moriasi *et al.*, 2007). The other measure of model efficiency is model agreement (d):

$$d = 1 - \frac{\sum_{i=1}^{n}(Oi - Pi)^2}{\sum_{i=1}^{n}(|Pi - \bar{O}| + |Oi - \bar{O}|)^2} \quad \text{(Eq. 12)}$$

The d parameter is dimensionless ($0 \leq d \leq 1$) and a value of 1 indicates good agreement between observed and measured data, while 0 indicates no agreement (Moriasi *et al.*, 2007).

While the above index indicates the difference between simulated and observed data, coefficient of residual mass (CRM) indicates whether the model is under- or over-estimating the data under study:

$$\text{CRM} = \frac{(\sum_{i=1}^{n} Oi - \sum_{i=1}^{n} Pi)}{\sum_{i=1}^{n} Oi} \qquad \text{(Eq. 13)}$$

A positive value indicates a tendency for underestimation and a negative value a tendency for overestimation (Antonopoulos, 1997):

3.7 Statistics

3.7.1 ANOVA

Minitab 16.2.4 (Minitab Ltd, United Kingdom) was used for statistical analyses. Analysis of variance (ANOVA) was used to evaluate the influence of different treatments (water, fertiliser and tillage) on grain yield and biomass. Analyses of statistical significance were performed using the general linear model (GLM) procedure applied to a factorial design with the following model:

$$Y_{ijkl}=\mu+\alpha_i+\beta_j+\gamma_k+(\alpha\beta)_{ij}+(\alpha\gamma)_{ik}+(\beta\gamma)_{jk}+\delta_{ijk}+b_l+\varepsilon_{ijkl} \qquad \text{(Eq. 14)}$$

where μ is average, αi is the effect of level i of water factor b ($\alpha i = \mu i - \mu$) (where i= 1e 2), βj is the effect of level j of fertiliser factor ($\beta j= \mu j - \mu$) (where j= 1 e 2), γk is the effect of k level of tillage factor ($\beta j= \mu k - \mu$) (where k= 1, 2, e 3), $(\alpha\beta)_{ij}$ is the interaction factor between level i of water factor and level j of fertiliser factor, $(\alpha\gamma)_{ik}$ is the interaction factor between level i of water factor and level k of tillage factor, $(\beta\gamma)_{jk}$ is the interaction factor between level j of fertiliser factor and level k of tillage, $(\delta)_{ijk}$ is the interaction between level i of water factor, level j of fertiliser factor and level k of tillage factor, b_l is the block effect and ε_{ijkl} is the experimental error on each plot $\varepsilon_{ijk} \sim$ iidN (0, σ2). Differences between individual treatments were tested using Tukey's honest significant difference (HSD) test and taken as significant at $p<0.05$.

3.7.2 Pearson correlation

Correlation between DACT and total soil moisture from 0 to 60 cm was determined using Pearson correlation. The correlation coefficient assumes a value between -1 and +1. If one variable tends to increase as the other decreases, the correlation coefficient is negative, while if the two variables tend to increase together the correlation coefficient is positive. For a two-tailed test of the correlation: $H0: r = 0$ versus $H1: r \neq 0$, where r is the correlation between a pair of variables. Correlation values above 0.5 are more acceptable, such that values between 0.7-0.9 indicate a strong correlation between the variables under study.

4 Main Results

4.1 Rainfall distribution and soil moisture

The temporal distribution of rainfall differed between years. Figure 9 presents the cumulative rainfall distribution for seasons 1 to 3, starting 32 days before sowing. Total rainfall (from sowing to harvest) for seasons 1, 2 and 3 was 400.2, 373.4 mm and 307.4 mm, respectively. Daily temperature between seasons was slightly different, ranging from a minimum of 12.3 °C to a maximum of 41 °C, and differed only slightly in season 1 (range 12.3-39 °C), season 2 (13-40 °C) and season 3 (13.8-41 °C).

In seasons 1 and 2, maize germinated four days after sowing in both rainfed and supplemental irrigation. In season 3, in the supplemental irrigation treatment germination was also at 4 days after sowing (DAS), but in the rainfed treatment germination was at 34 DAS because of low rainfall. In all crop seasons, there was enough rainfall to produce biomass and sustain the crop from sowing to harvest. In the vegetative stage (from sowing to tasselling), the rainfed treatments received 121.6 mm in season 1 and 134 mm in season 2. From tasselling (VT) to start of grain filling (R2), the rainfall was 215.6 mm in season 1 and 15.4 mm in season 2. From start of grain filling to harvest, season 1 received 63.0 mm and season 2 received 223.9 mm.

Due to lag time of 34 DAS, in season 3 in vegetative stage (from sowing to tasselling) it was 194.5 mm and 155.1 mm, from tasselling (VT) to start of grain filling stage (R2) it was 58.2 mm and 53.3 mm and from start of grain filling to harvest the rainfall was 54.7 and 99 mm for the rainfed and irrigated treatments, respectively.

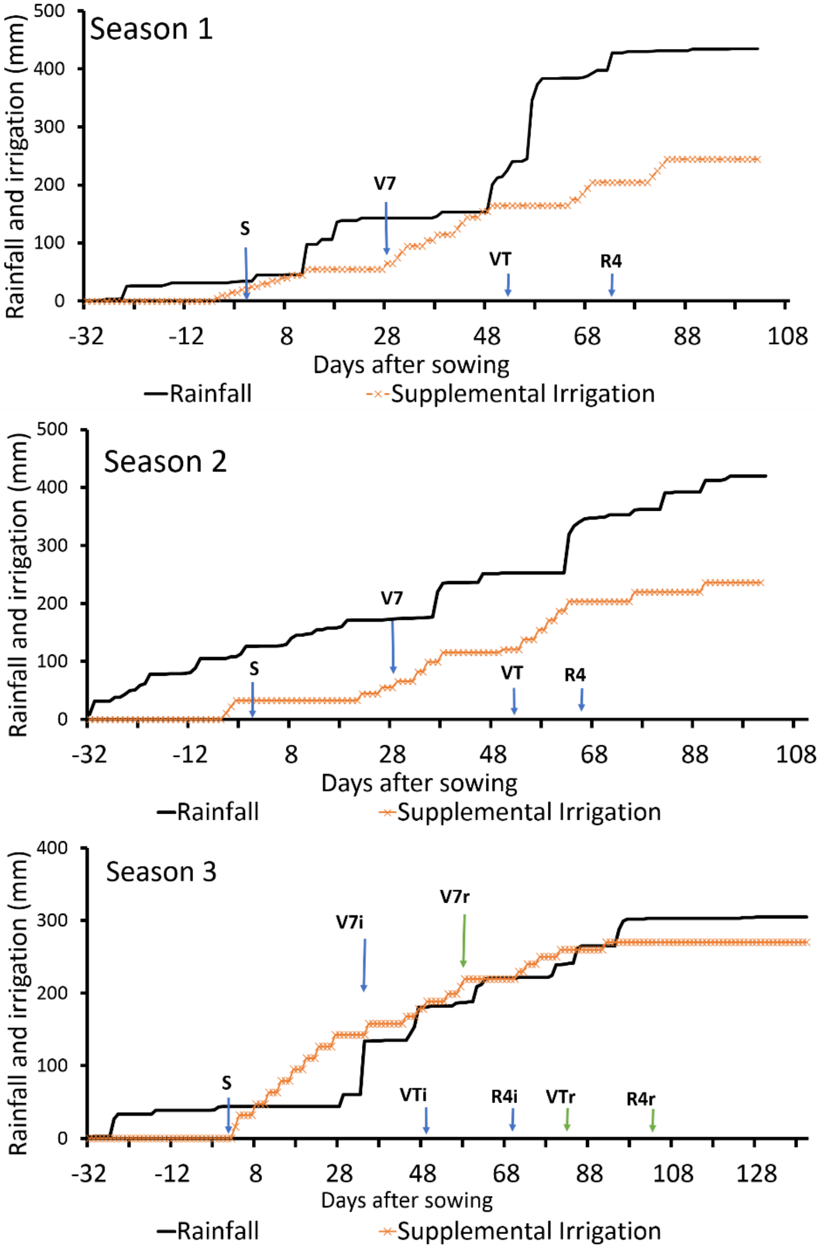

Figure 9. Cumulative rainfall and supplemental irrigation for crop seasons 1, 2 and 3. The letters S are sowing, V7 is with seven leaves, and VT is at tasselling and R4 at reproduction phase 4 and the letters (season 3) i stands for irrigation and r for rainfed.

4.1.1 Soil moisture trends (Papers II and III)

The rainfall before the start of crop season 2 impacted positively on soil moisture, such that in the beginning of season 2 soil moisture was higher than in season 3. Figure 10 presents soil moisture at different depths for hand hoeing tillage non-fertilised (W1F1T1) and hand hoeing fertilised (W1F2T1) for rainfed treatment. In the rainfed treatments, before tasselling in the treatment with hand hoe tillage and no fertiliser (W1F1T1), the highest soil moisture content was in the 20 cm layer, but after first major rainfall event (43.4 mm) more water moved down such that the soil moisture increased in the lowest soil layer. This pattern was followed along all cropping seasons. While in the fertilised plots of the hand hoe treatment (W1F2T1), the highest moisture content was observed at 40 cm depth throughout the cropping season.

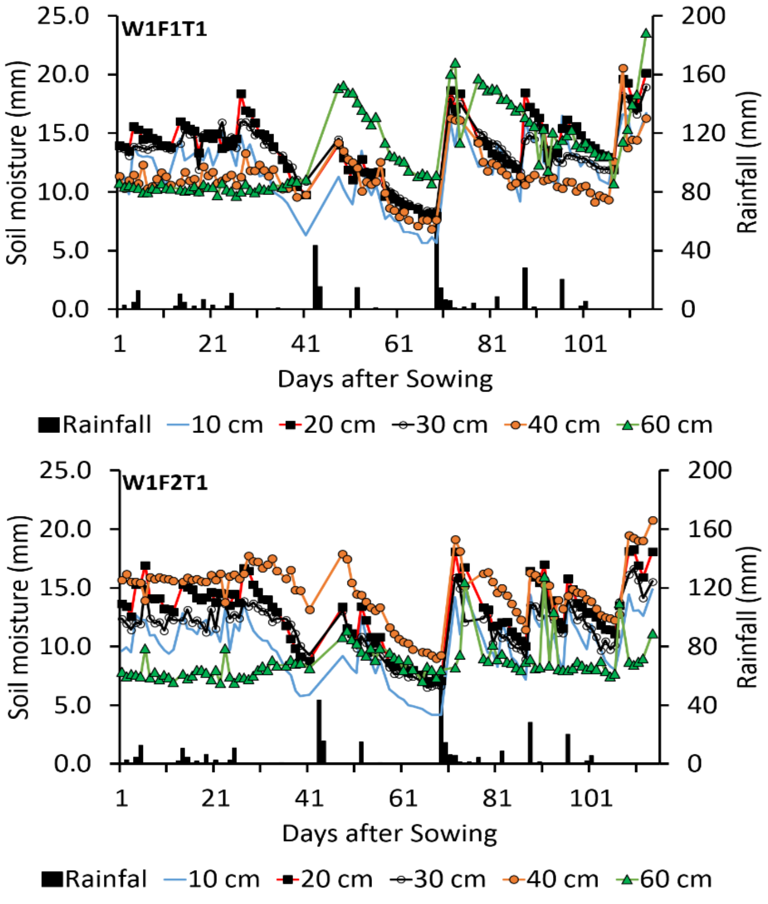

Figure 10. Season 2 soil moisture at different depths for the rainfed treatment (W1), combined with unfertilised (F1) and fertilised treatments (F2) for hand hoeing (T1)

Figure 11 presents the soil moisture for strip tillage in rainfed for season 2. In the strip tillage treatment, the upper depths studied (10 cm, 20 cm and 30 cm) contained most soil moisture until 45 DAS both for fertilised (W1F2T2) and non-fertilised (W1F1T2) treatments. This scenario changed when the system received 43.4 mm of rain. Thus depth 60 cm had a tendency to show the lowest soil moisture content throughout this crop season.

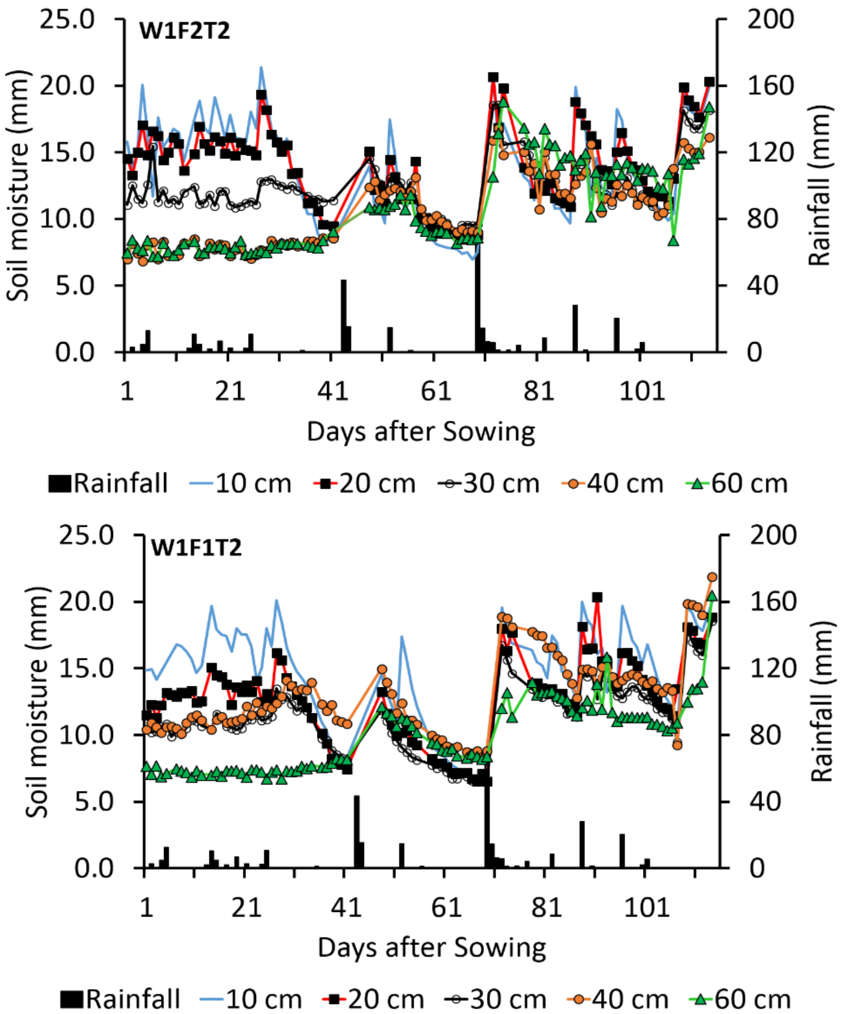

Figure 11. Season 2 soil moisture at different depths for the rainfed treatment (W1), combined with unfertilised (F1) and fertilised treatments (F2) for strip tillage (T2).

In the disc tillage-unfertilised treatment (W1F1T3) (Figure 12), most of the soil moisture was concentrated in the top four 10-cm depths in the first 30 DAS. The greatest depth (60 cm) showed increased soil moisture after the rain at 45 DAS and after that rain episode had the highest soil moisture content until the end of the crop season. After 45 DAS, most of the time, the top layer (10 cm) dried and had a lower soil moisture content than other layers until the end of the cropping season. The fertilised treatments under disc tillage (W1F2T3) displayed different behaviour to the unfertilised treatment. The highest soil moisture was observed in the first 10 cm and the lowest at 30 cm depth.

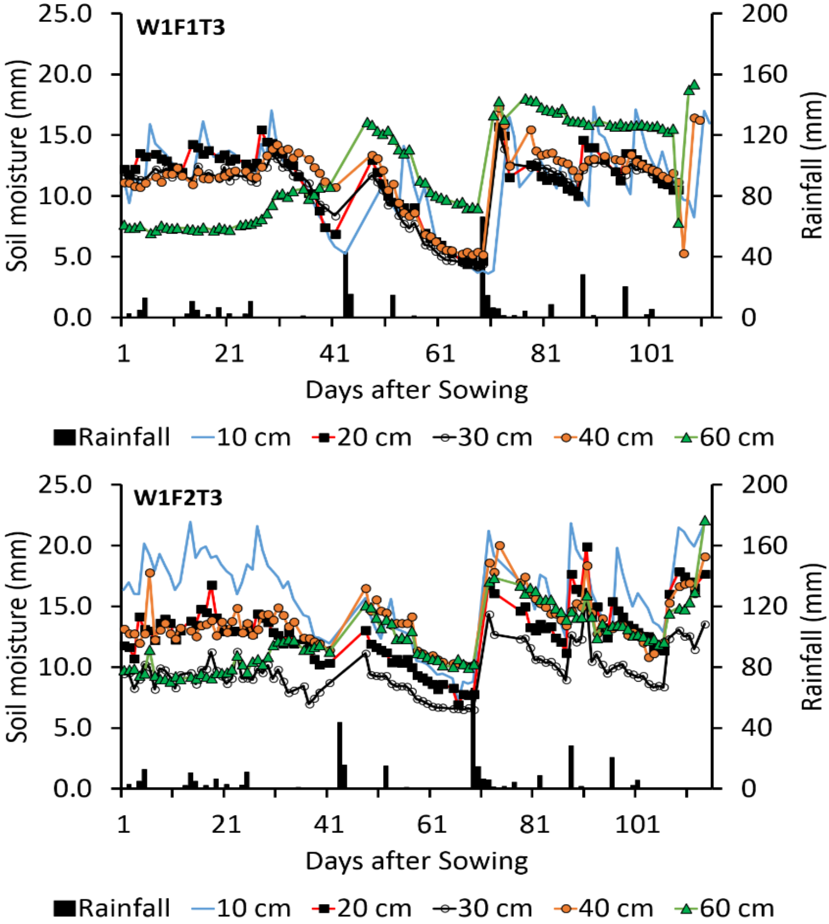

Figure 12. Season 2 soil moisture at different depths for the rainfed treatment (W1), combined with unfertilised (F1) and fertilised treatments (F2) for disc tillage (T3).

Supplemental irrigation was capable of maintaining high soil moisture content in most top layers (Figure 13, 14 and 15). In most of the cases, soil moisture at the greatest depth (60 cm) increased slowly during the cropping season. In hand hoeing treatment (W2F1T1 and W2F2T1) the top 10 and 20 cm depth had higher soil moisture throughout the cropping season (Figure 13). Therefore after 45 DAS, soil moisture increased in all layers due to 43.4 mm of rainfall that fell in the area. But in the W2F1T1 the deepest layer (60 cm) had a lower soil moisture content than the layers above. While for W2F2T1 the layer 40 cm presented the lower soil moisture content compared to others.

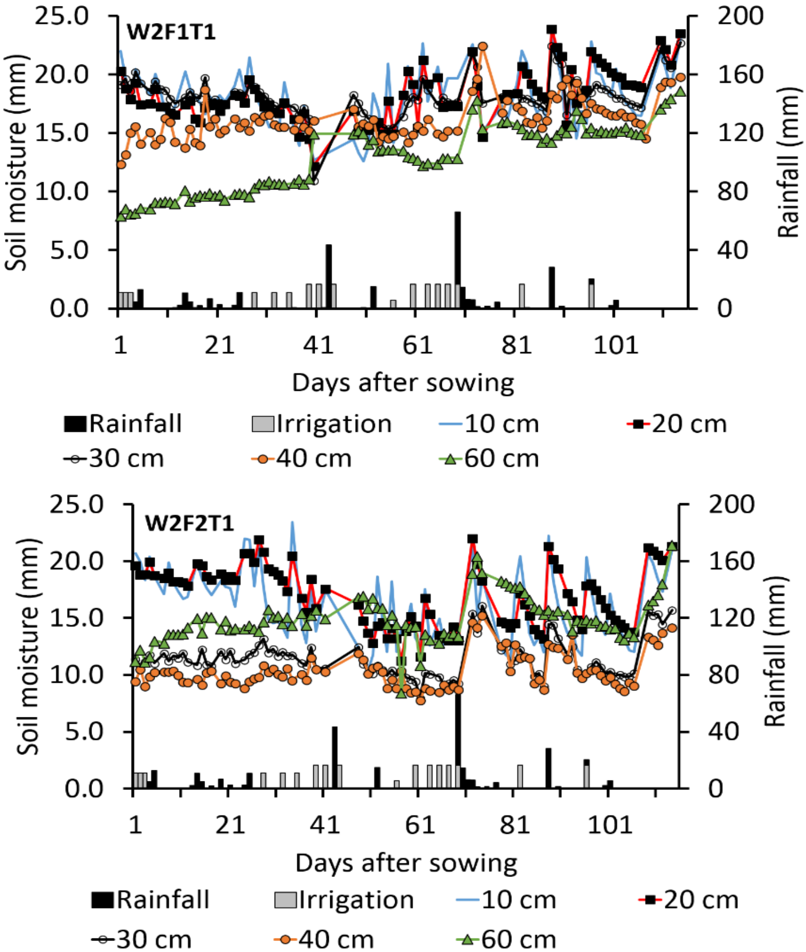

Figure 13. Season 2 soil moisture at different depths for the supplemental irrigation treatment (W2) combined with unfertilised (F1) and fertilised treatments (F2) for hand hoeing (T1).

Figure 14 presents the soil moisture for strip tillage treatments both for fertilised and unfertilised treatments in the irrigated treatment. In the unfertilised treatment (W2F1T2) and fertilised treatment (W2F2T2) the top 10 cm, 20 cm and sometimes 40 cm depths had higher soil moisture throughout the cropping season (Figure 14). But in the W2F1T2 the middle layer (30 cm) had a lower soil moisture content than the other layers. While for W2F2T2 the layer 60 cm presented the lower soil moisture content compared to the others.

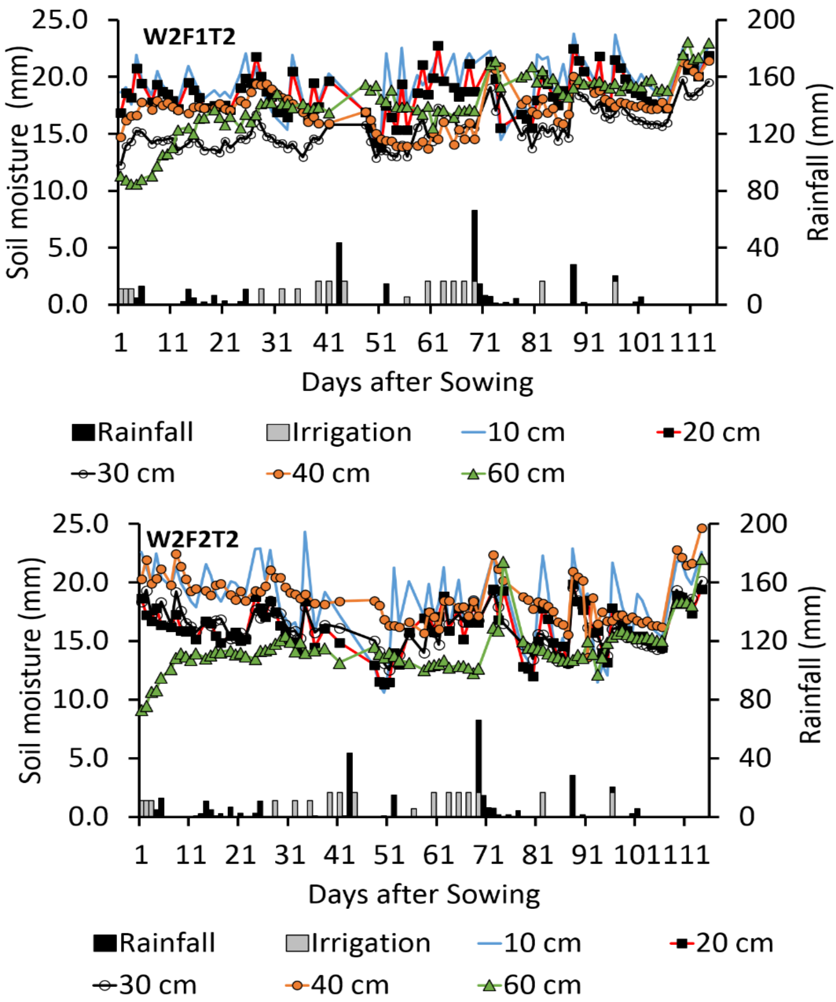

Figure 14. Season 2 soil moisture at different depths for the supplemental irrigation treatment (W2) combined with unfertilised (F1) and fertilised treatments (F2) for strip tillage (T2)

Figure 15 presents soil moisture for disc tillage both for unfertilised (W2F1T3) and fertilised (W2F2T3) treatments. In the unfertilised treatment soil moisture was most of the time higher in the lower depths (40 and 60 cm), while for fertilised treatments the higher soil moisture was most of the time in the layer 10, 20 and 40 cm depths.

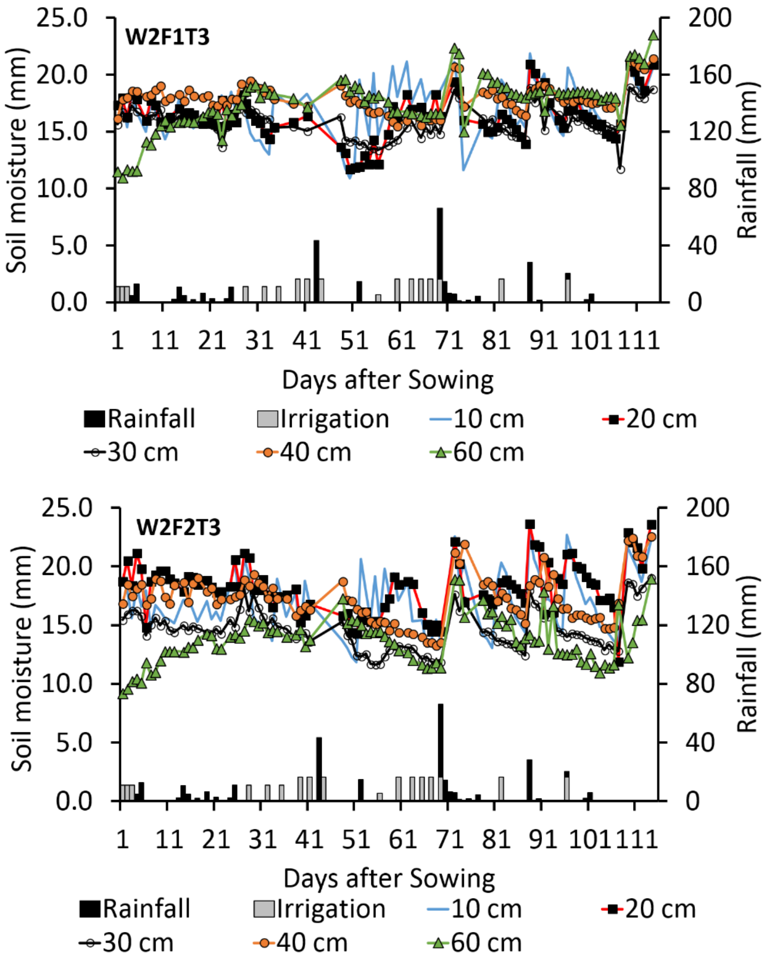

Figure 15. Season 2 soil moisture at different depths for the supplemental irrigation treatment (W2) combined with unfertilised (F1) and fertilised treatments (F2) for disc tillage (T3).

Before the start of season 3, the system received little rainfall, so at sowing the soil moisture content was low. Soil moisture changes at different depths in season 3 are presented in Figures 16, 17 and 18 (rainfed) and 19, 20 and 21 (supplemental irrigation).

At the beginning of the experiment, in the rainfed treatments, soil moisture was very low for all treatments. In all treatments under rainfed conditions, the highest soil moisture was in deeper soil layers rather than at 10 cm depth. There was an increase in soil moisture in all treatments after rainfall of 73.4 mm on 34 DAS. This rain positively affected all soil depths in all treatments. Therefore, even after this major rainfall event, the 10 cm and 20 cm depths showed a tendency to display lower soil moisture content than the other depths in most treatments. This was probably because this layer was in direct contact with the atmosphere, creating higher evaporation than at greater depths and were the layers with higher root density.

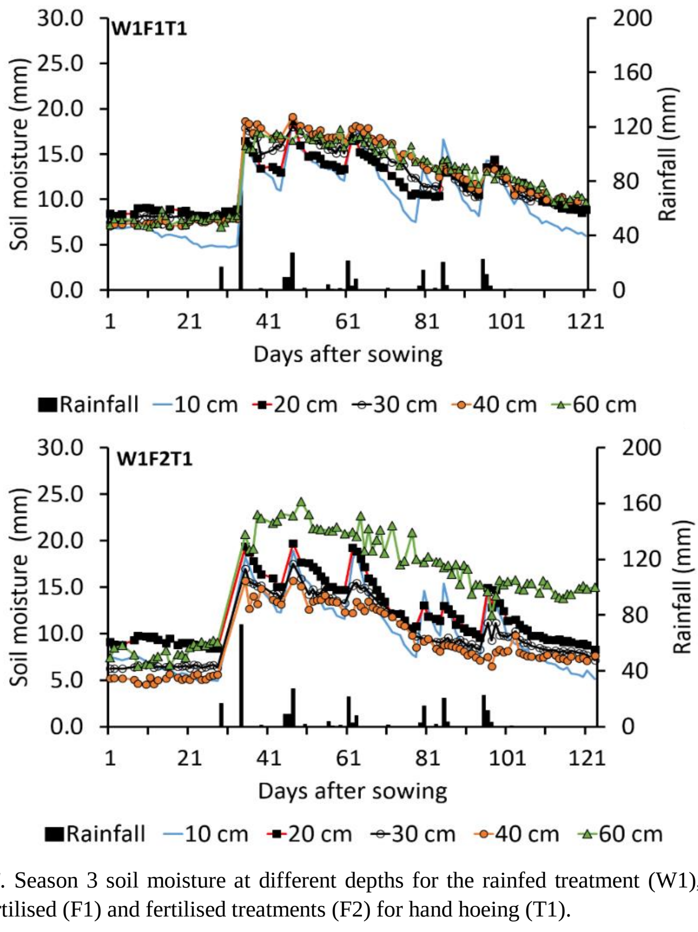

Figure 16. Season 3 soil moisture at different depths for the rainfed treatment (W1), combined with unfertilised (F1) and fertilised treatments (F2) for hand hoeing (T1).

The rainfall on 34 DAS also increased the soil moisture content at 60 cm soil depth. Soil moisture at 60 cm depth was highest throughout the crop season for hand hoeing fertilised treatment (W1F2T1) (Figure 16).For strip tillage, the highest soil moisture was at 40 cm depth, both for fertilised (W1F2T2) and unfertilised (W1F1T2) treatments (Figure 17).

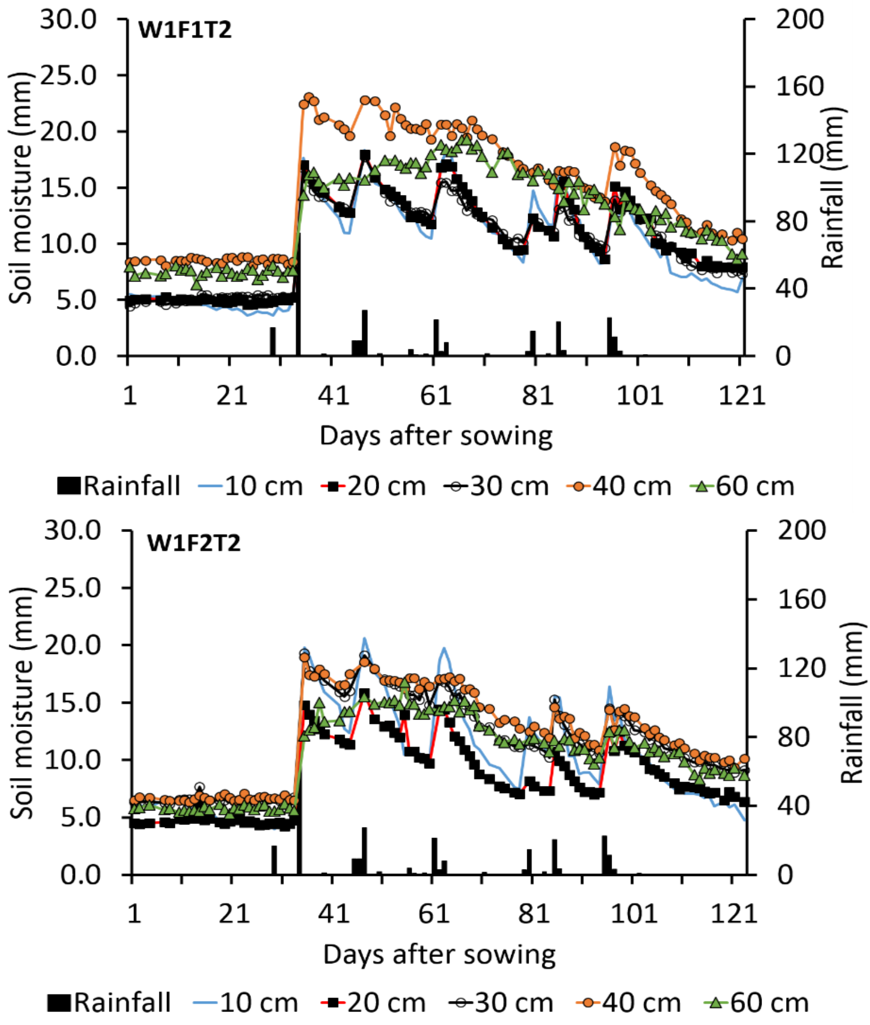

Figure 17. Season 3 soil moisture at different depths for the rainfed treatment (W1), combined with unfertilised (F1) and fertilised treatments (F2) for strip tillage (T2).

In season 3, the disc tillage-unfertilised treatment (W1F1T3) had higher soil moisture at greater depths (40 cm and 60 cm), while the disc tillage-fertilised (W1F2T3) treatment had the highest soil moisture at depths 30 cm and 40 cm.

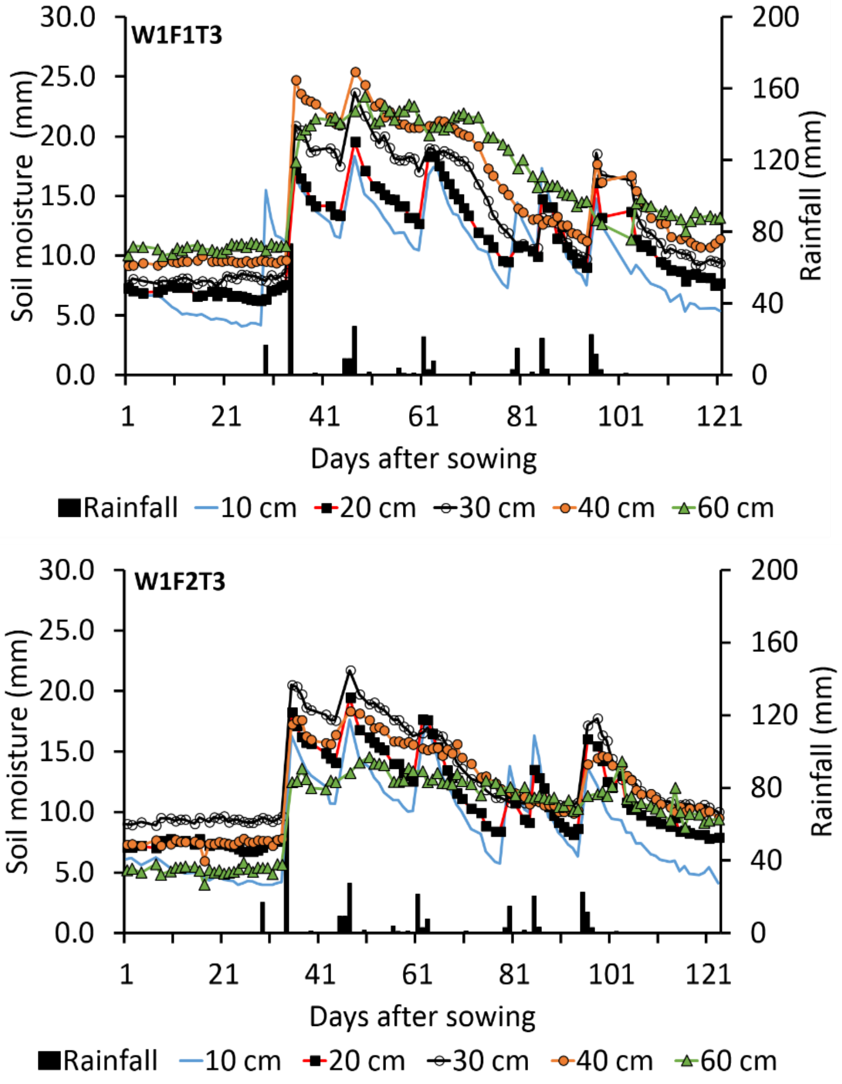

Figure 18. Season 3 soil moisture at different depths for the rainfed treatment (W1), combined with unfertilised (F1) and fertilised treatments (F2) for disc tillage (T3).

Water supply significantly affected soil moisture content at all depths. Moreover, there was a significant interaction between water supply and tillage method. Figures 19, 20 and 21 presents the soil moisture for supplemental irrigation in season 3.

In the irrigation treatments, the soil moisture content increased with irrigation. Thus supplemental irrigation was able to maintain high soil moisture at the upper 10 cm and 20 cm depths of W2F1T1, W2F2T1, W2F1T2 treatments (Figure 19 and 20). While for other treatments higher soil moisture was observed in deeper layer (60 cm).

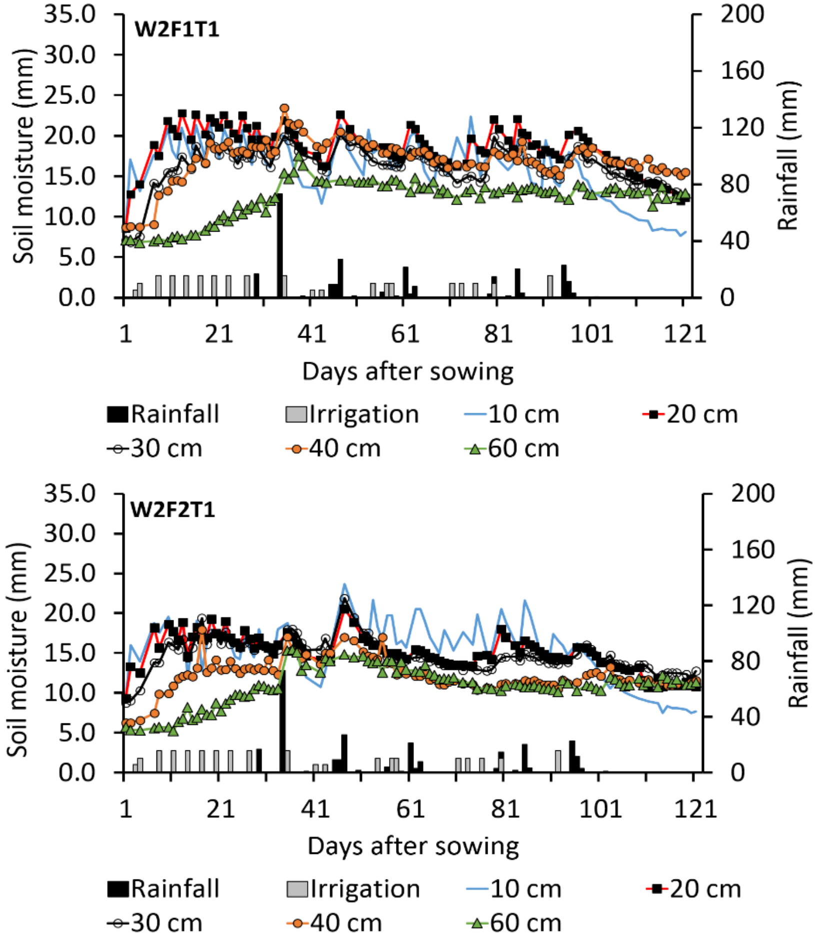

Figure 19. Season 3 soil moisture at different depths for the supplemental irrigation treatment (W2), combined with unfertilised (F1) and fertilised treatments (F2) for hand hoeing (T1).

In both hand hoeing treatments and in strip tillage without fertiliser (W2F1T2), the 60 cm depth had lower soil moisture than the other depths throughout the crop season. However, in the disc tillage treatment, 60 cm depth had the highest soil moisture content after the rainfall at 34 DAS.

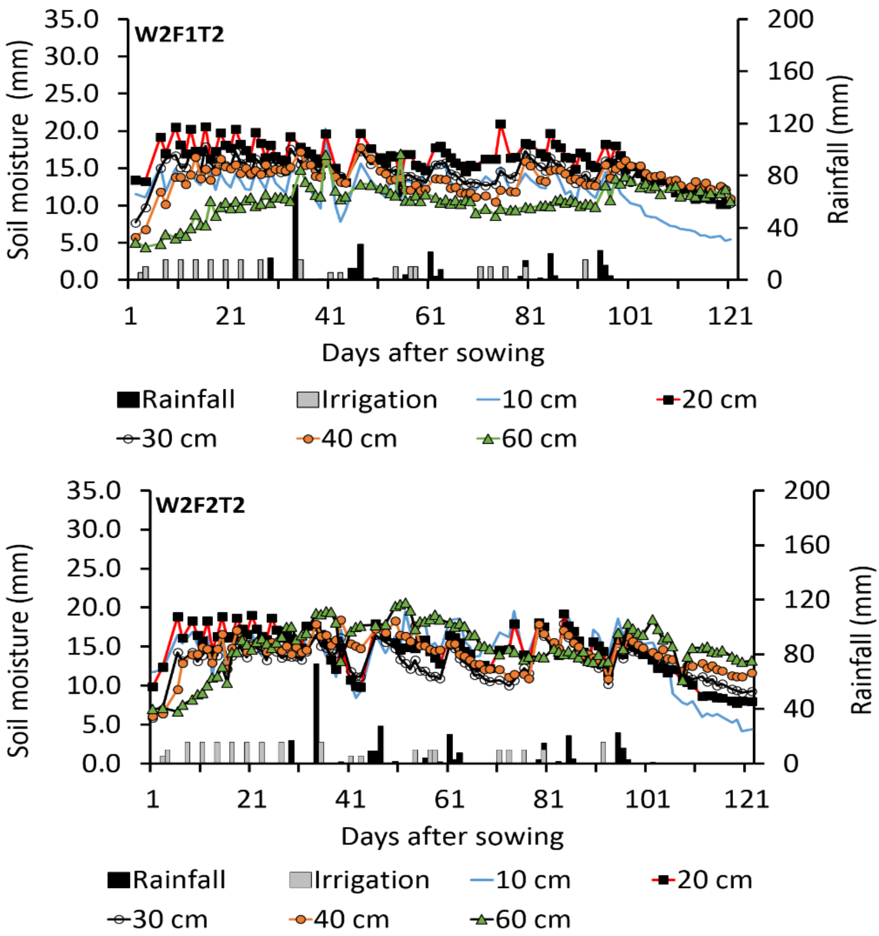

Figure 20. Season 3 soil moisture at different depths for the supplemental irrigation treatment (W2), combined with unfertilised (F1) and fertilised treatments (F2) for strip tillage (T2).

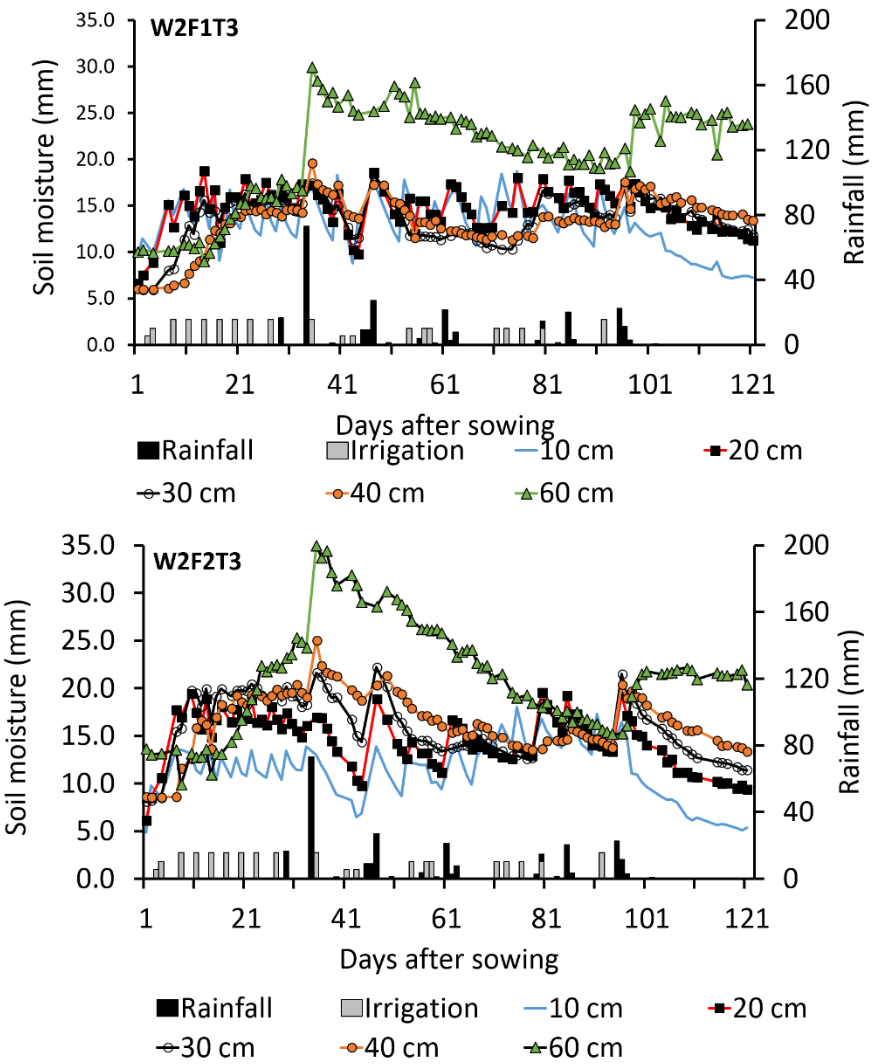

Figure 21. Season 3 soil moisture at different depths for the supplemental irrigation treatment (W2), combined with unfertilised (F1) and fertilised treatments (F2) for disc tillage (T3).

4.2 Soil penetration resistance and root abundance

Soil penetration resistance increased with soil depth in all seasons (Figure 22). In season 1, there was a marked difference between tillage methods. Values of penetration resistance in the first 15 cm of the treatment involving tillage by hand hoeing were higher than with disc tillage (in and between crop lines). Between 15 cm and 30 cm, the hand hoeing treatment had lower penetration resistance than disc tillage. The highest penetration resistance was observed in the first 15 cm of soil in between the crop lines in the strip tillage treatment. Between 15 cm and 30 cm depth, this pattern changed and the penetration resistance in strip tillage was below that in disc-tilled soil, both within the crop line and between crop lines. At the same time, values of penetration resistance in the crop line (0-15 cm) were similar to those in crop lines in the hand hoe tillage treatment. From 30 cm down, all tillage treatments showed higher penetration resistance, with slightly higher values for strip tillage between crop lines.

In season 2, the penetration resistance values were different from those in season 1. A marked difference was seen in strip tillage, where soil between the crop lines had higher values of penetration resistance than other tillage methods, while the crop line in strip tillage had the lowest values. The hand hoeing and disc tillage treatments had similar values of penetration resistance in the crop line. Similar behaviour was seen between crop lines under hand hoeing and disc tillage.

Penetration resistance values in season 3 were different from those in seasons 1 and 2. These differences were most pronounced in the disc tillage treatment compared with hand hoeing and strip tillage. Hand hoeing had similar values as in season 2. With hand hoeing, the values within crop lines (CL) and between crop lines (BCL) were higher than in strip tillage (crop lines) and disc tillage (within and between crop lines). As in seasons 1 and 2, in the crop lines in the strip tillage showed the lowest penetration resistance values and strip tillage between crop lines the highest values.

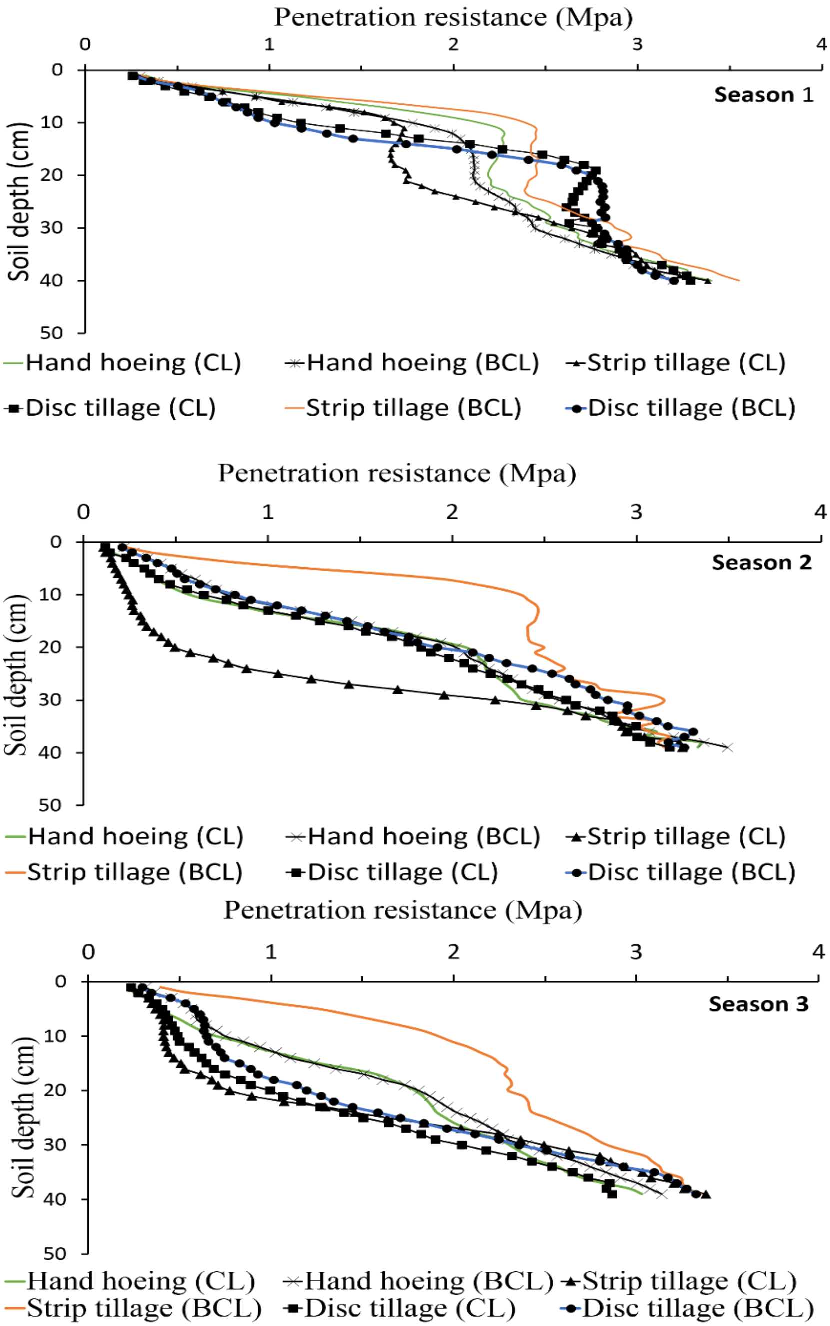

Figure 22. Change in soil penetration resistance (MPa) with depth. CL is crop line and BCL is between crop lines for season 1, 2 and 3.

Root studies are described in detail in Paper I. The overall finding was that the maximum root depth attained in both seasons studied (season 1 and 2) was 60 cm. Generally, most of the roots were concentrated in the top 20 cm of the soil profile (Paper I). Root abundance decreased down the soil profile and was negatively related to penetration resistance, an effect which can be genetically derived but also attributable to the higher penetrometer resistance in deeper layers.

4.3 Belowground and aboveground biomass

4.3.1 Root:shoot ratio

Root:shoot ratio changed during the cropping season (Table 3) due to changes in root or shoot dry matter (DM). In season 1, root and shoot DM increased during the cropping season for both rainfed and supplemental irrigation, but the rainfed treatment had a higher root:shoot ratio than the supplemental irrigation treatment. However, the root:shoot ratio values did not differ significantly ($p<0.05$) due to water supply at V7 and VT stages. Differences between root:shoot ratio in the fertiliser treatment were small and not statistically significant. Similarly, there were no significant differences in root:shoot ratio due to tillage method.

In season 2, root and shoot DM also increased during the cropping season (Table 3). Shoot dry matter in this season was significantly different ($p<0.05$) between water supply treatments, being larger in the supplemental irrigated treatments than in the rainfed treatments. Water supply was the experimental factor which had the largest impact on root and shoot growth. In most cases, root biomass was larger in the irrigated treatment, in several cases significantly larger ($p<0.05$). The increase in shoot biomass compared with root biomass in the irrigated treatments in the crop stage R4 reduced the root:shoot ratio, such that the irrigated treatments had a lower ratio than the rainfed treatment.

Table 3. *Season 1 and 2 root:shoot ratio (R:S) for maize at crop stage V7 (7 leaves), VT (tasselling) and reproductive stage R4. Means within columns followed by different letters are significantly different (p<0.05)*

	Season 1			**Season 2**		
	R:S_V7	R:S_VT	R:S_R4	R:S_V7	R:S_VT	R:S_R4
Water supply						
Rainfed	0.92a	0.73a	0.35a	0.58a	0.32a	0.37a
Irrigation	0.81b	0.69a	0.31a	0.65a	0.32a	0.19b
Fertiliser						
No fertiliser	0.87a	0.71a	0.35a	0.62a	0.35a	0.26a
Fertiliser (40%)	0.86a	0.71a	0.32a	0.61a	0.29a	0.31a
Tillage						
Hand hoeing	0.87a	0.72a	0.33a	0.61a	0.29a	0.31a
Strip	0.88a	0.67a	0.32a	0.63a	0.31a	0.34a
Discing	0.84a	0.75a	0.35a	0.60a	0.36a	0.20a
F-test probability						
Water supply	0.003	0.585	0.231	0.142	0.892	0.003
Fertiliser	0.892	0.929	0.401	0.727	0.081	0.481
Tillage	0.471	0.591	0.775	0.880	0.195	0.132
Water supply x Fertiliser	0.379	0.910	0.674	0.260	0.104	0.122
Water supply x Tillage	0.670	0.074	0.347	0.125	0.115	0.267
Fertiliser x Tillage	0.290	0.429	0.374	0.487	0.284	0.163

4.4 Leaf area index

In season 2, there was a significant ($p<0.05$) leaf area index (LAI) increase due to water supply (Figure 23A). The supplemental irrigation treatment had higher LAI than the rainfed treatment. Fertiliser application (Figure 23B) and tillage method (Figure 23C) were not significantly different in terms of leaf area index. Tillage factor did not affect LAI at any crop stage

In season 3 (Figure 24), water supply significantly affected LAI in crop growth stages VT and R4. Supplemental irrigation increased LAI significantly ($p<0.05$) (Figure 24A). Fertiliser application did not significantly ($p<0.05$) increase leaf area index (Figure 24B). Moreover, the differences in LAI between tillage methods were small and not statistically significant (Figure 24C).

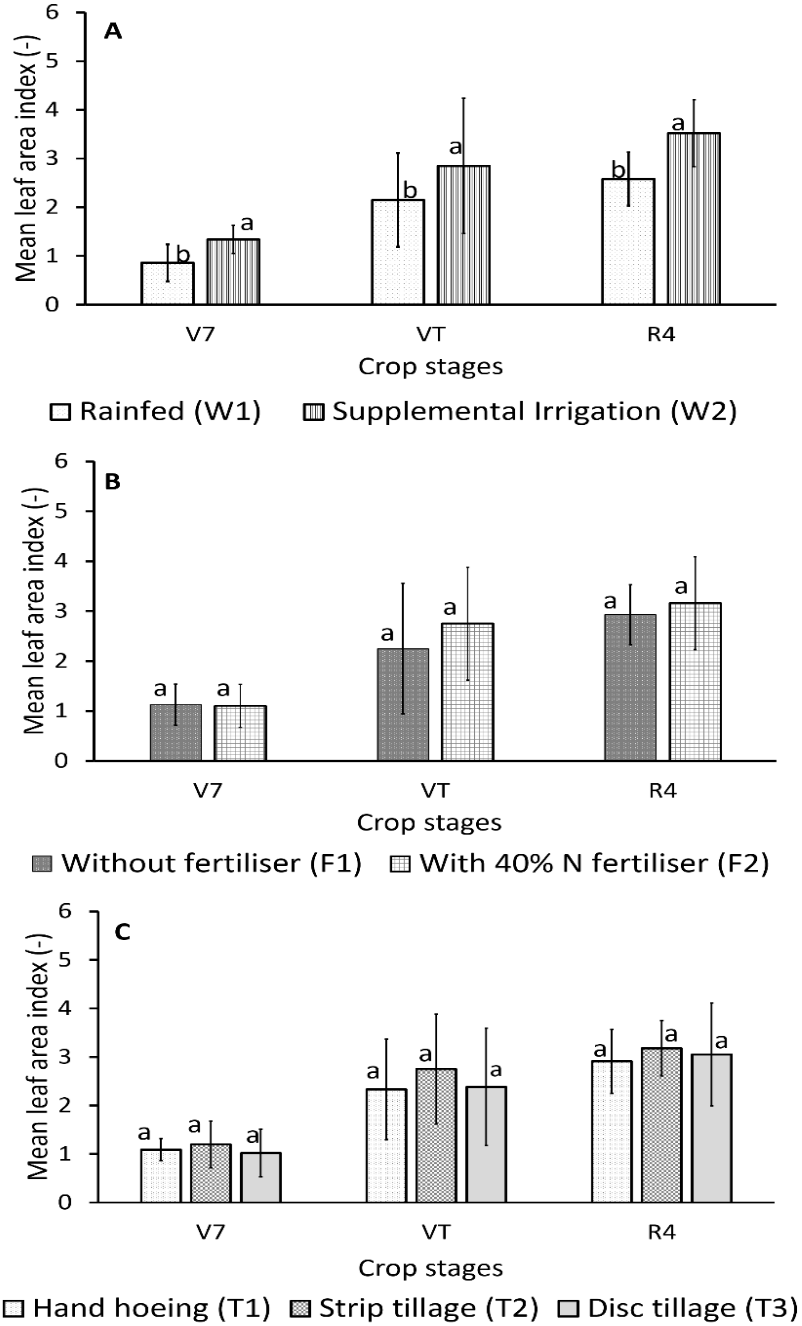

Figure 23. Season 2 single factor leaf area index. a) water treatment factor, b) fertiliser treatment and c) tillage treatment. Crop stage V7 is 7 leaves, VT tasselling and R4 reproductive stage R4. Means within columns followed by different letters are significantly different ($p<0.05$).

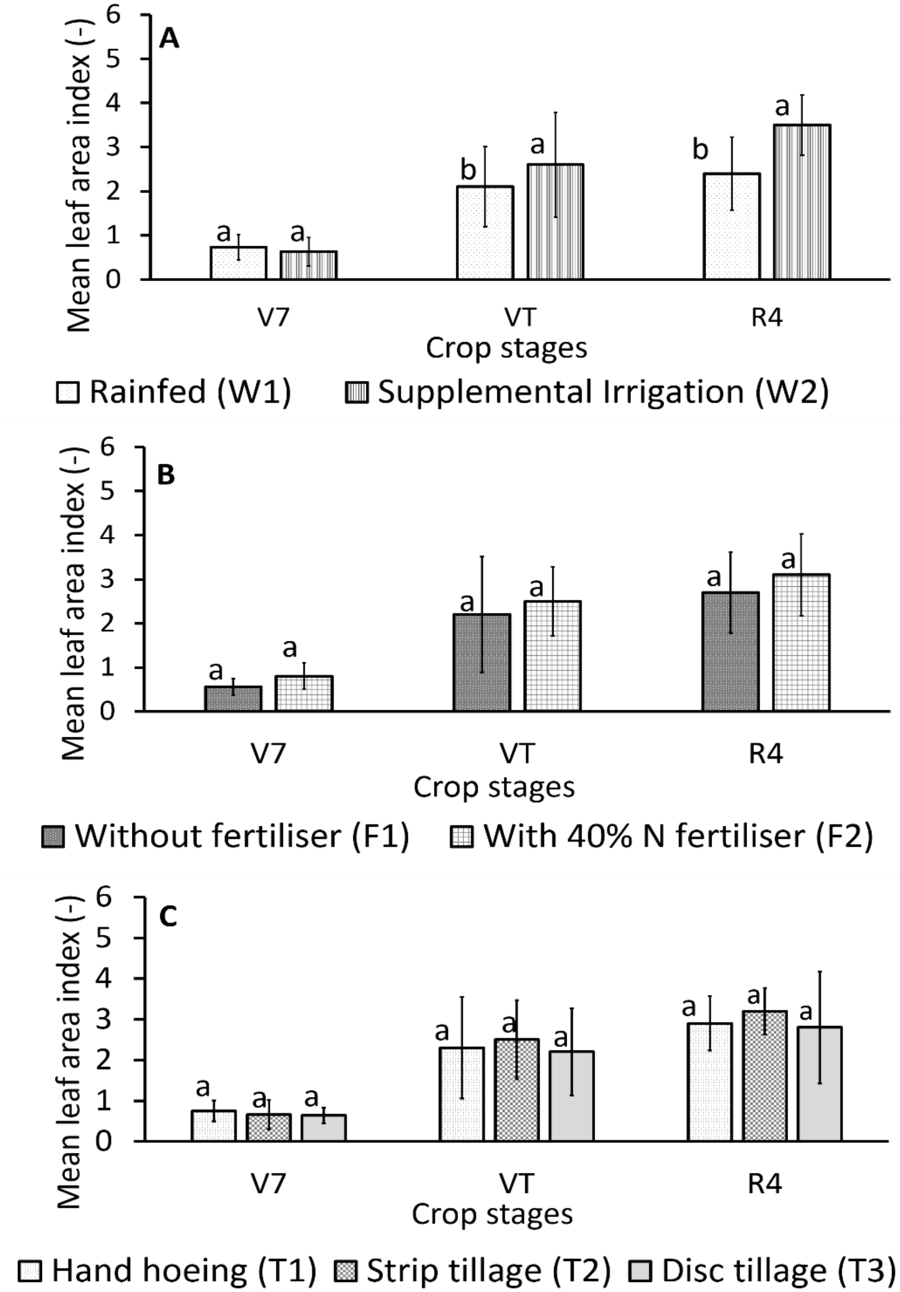

Figure 24. Season 3 single factor leaf area index. a) water treatment, b) fertiliser treatment and c) tillage treatment. Crop stage V7 is 7 leaves, VT tasselling and R4 reproductive stage R4Means within columns followed by different letters are significantly different ($p<0.05$)

4.5 Grain yield and water use efficiency

4.5.1 Grain yield (Papers I, II and III)

Supplemental irrigation and fertiliser alone increased grain yield in all seasons. Among the tillage methods, disc tillage gave higher yield than the other two methods, but differences between tillage methods were small in the last two seasons and not statistically significant. Cob development in the different water supply treatments in season 2 is shown in Figure 25 and grain yield in all seasons studied is presented in Figure 26. There were significant differences ($p<0.05$) in yield in the water and fertiliser treatments. In season 1, yield was lowest for hand hoeing, while it was intermediate for strip tillage. As with water supply treatment, nitrogen fertiliser application increased the grain yield in all seasons and the differences were statistically significant. There was also an interaction between water and fertiliser (Papers I, II and III).

Rainfall distribution in season 1 (2012/2013) was temporally more uniform than in the other two seasons. This created an environment for higher grain yield compared with the other two seasons. The lowest grain yield was found with hand hoeing in the rainfed treatment (1792 kg ha^{-1}) and the highest grain yield (4720 kg ha^{-1}) was found with disc tillage in the irrigated treatment. In season 1, supplemental irrigation increased grain yield by 921 kg ha^{-1}, while fertiliser application increased grain yield by 771 kg ha^{-1}. Strip and disc tillage increased grain yield compared with hand hoeing. However, the yield increase in strip tillage in relation to hand hoeing was small (328 kg ha^{-1}) and not statistically significant. The difference between grain yield in the disc and hand hoe treatments was 1059 kg ha^{-1} and statistically significant.

Season 2 had more irregular rainfall distribution than the other two seasons. Supplemental irrigation increased yield by 4117 kg ha^{-1}. Figure 25 shows the cobs from irrigated plots and from rainfed plots in season 2. The cobs in rainfed plots were barren, with low grain set (Figure 25B). Fertiliser application increased grain yield by 834 kg ha^{-1}. There was an interaction ($p<0.05$) between water and fertiliser. Disc tillage gave higher grain yield than strip and hand hoe tillage. Strip tillage reduced grain yield by 53 kg ha^{-1} compared with hand hoeing, while disc tillage increased grain yield by 135 kg ha^{-1} in relation to hand hoeing. The differences in grain yield in tillage treatments were small and not statistically significant.

As in season 2, in season 3 rainfall affected crop growth. Maize was sown in mid-November, as in previous seasons, but rainfall came 30 days later. Supplemental irrigation increased grain yield by 2577 kg ha$^{-1.}$ Fertiliser application also increased grain yield, by 702 kg ha^{-1}. There was an interaction between water and fertiliser. In this season, hand hoeing had higher grain yield than strip tillage (Figure 26). Moreover, the use of strip tillage reduced grain yield by 149 kg ha^{-1} compared with hand hoeing. Disc tillage gave 48 kg ha^{-1} higher grain yield than hand hoeing and 197 kg ha^{-1} higher grain yield than strip tillage.

Figure 25. Cob development under different water supply. a) no water stress from flowering to the blister stage, b) with water stress from flowering to blister stage (small and barren cobs).

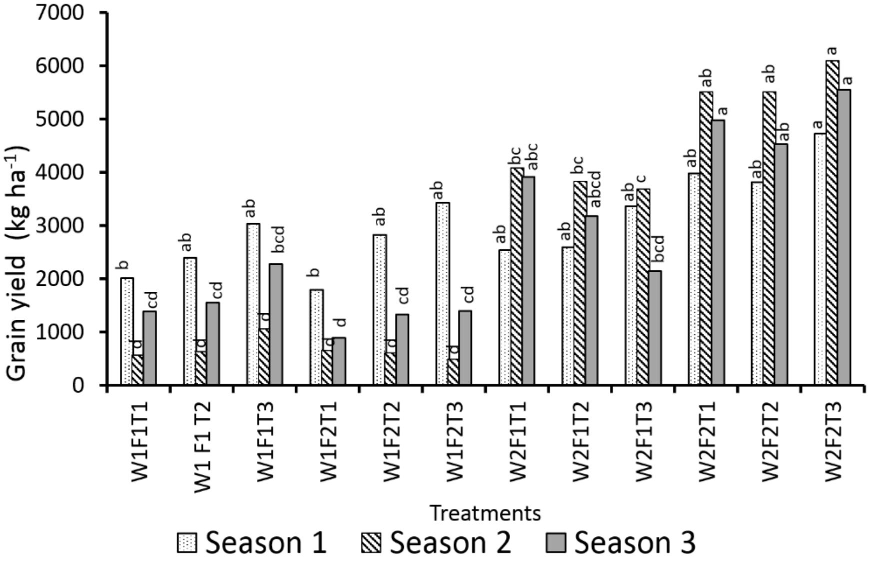

Figure 26. Grain yield in seasons 1-3. Treatments were: W1: rainfed, W2: supplemental irrigation; F1: without fertiliser, F2: fertilised with 48 kg N; T1: hand hoeing; T2: strip tillage and T3: disc tillage. Columns within seasons marked with different letters are significantly different ($p<0.05$).

In summary, the three-year study reported in Paper II showed that supplemental irrigation alone resulted in an average maize yield increase of 161%, while the application of fertiliser alone increased grain yield by 31%. Despite the lack of statistical significance between tillage methods, grain yield due to strip tillage compared with hand hoeing was only 1.6% higher, while for disc tillage in relation to hand hoeing the difference was 15%.

4.5.2 Water use efficiency

Water use efficiency for all treatments is presented in Table 4. In general, supplemental irrigation increased water use efficiency and a major increase was seen in the second season, while fertiliser application and tillage methods did not show clear trends in different seasons. In season 1, water use efficiency ranged from 0.48 kg m^{-3} (rainfed) to 0.73 kg m^{-3} (supplemental irrigated) (Table 4). In season 1, the differences in water use efficiency were small and not significantly different for water supply.

Table 4. *Water use efficiency (kg ha^{-1}) in cropping seasons 1-3. Means within columns followed by different letters are significantly different ($p<0.05$)*

	Season 1	**Season 2**	**Season 3**
Water supply (W)			
Rainfed (W1)	0.58a	0.21b	0.52b
Supplemental irrigation (W2)	0.61a	0.83a	0.91a
Fertiliser (F)			
No fertiliser (F1)	0.54b	0.48a	0.66a
Fertiliser (F2)	0.65a	0.56a	0.77a
Tillage (T)			
Hand hoeing (T1)	0.52b	0.50a	0.67a
Strip (T2)	0.57ab	0.48a	0.71a
Discing (T3)	0.70a	0.57a	0.76a
F-test probability			
Water supply	0.664	<0.0001	<0.001
Fertiliser	0.048	0.070	0.112
Tillage	0.026	0.224	0.589
Water supply x Fertiliser	0.020	<0.001	0.001
Water supply x tillage	0.666	0.919	0.354
Fertiliser x Tillage	0.995	0.856	0.525
W1 x F1	0.59ab	0.25c	0.60bc
W1 x F2	0.57ab	0.16c	0.45c
W2 x F1	0.48b	0.70b	0.72b
W2 x F2	0.73a	0.96a	1.09a

Supplemental irrigation increased water use efficiency by 5%, while fertiliser application increased it by 17%. The best option for increasing water use efficiency was a combination of supplemental irrigation and fertiliser.

In season 2, water use efficiency ranged from 0.16 kg m^{-3} (rainfed) to 0.96 kg m^{-3} (supplemental irrigated) (Table 4). Water use efficiency in the supplemental irrigation treatment was significantly higher (295%) than in the rainfed treatment. There was a very strong interaction between water and fertiliser in this season, and thus the irrigated fertilised treatment gave higher water use efficiency (0.96 kg m^{-3}) than the irrigated unfertilised treatment (0.70 kg m^{-3}). Hand hoe tillage gave higher water use efficiency than the other two tillage treatments, but the differences were small and not significantly different.

In season 3, water use efficiency ranged from 0.45 kg m^{-3} in rainfed and 1.09 kg m^{-3} in irrigated treatments (Table 4), *i.e.* it was 43% higher ($p<0.05$) in the irrigation treatment. The fertilised treatments and the tillage treatments were not significantly different in terms of water use efficiency in this season.

On average, supplemental irrigation alone increased water use efficiency by 79%. Moreover, application of nitrogen fertiliser alone increased water use efficiency by 18%. Strip tillage increased (2%) water use efficiency compared with hand hoeing, while disc tillage increased it (by 14%) compared with hand hoeing.

4.6 Maize leaf temperature (Paper III)

In season 2, single leaf temperature measurements were carried out from 13:00 to 15:00 h on 52, 54, 55, 59, 61, 62, 67 and 69 DAS. Figure 27 presents an example of measured leaf temperature on maize. The average daily relative humidity and solar radiation during the sampling period (12.00-15.00 h) was 69.9% and 670 Wm^{-2} respectively. In season 2, maize germinated at 4 DAS in both rainfed and supplemental irrigation. The amount of rainfall received was 134 mm from sowing to tasselling, 15.4 mm from tasselling (VT) to blister stage (R2) and 223.9 mm from blister stage to harvest. The amount of rain decreased from flowering stage (50 DAS) to blister stage (71 DAS), so that the total rainfall amount that the crop received at that stage was only 15.4 mm. This decrease impacted upon soil moisture content in the rainfed treatment. During the sampling period, the wind speed was on average 1.3 m s^{-1}.

The magnitude of DACT also increased when leaf temperature increased. In general, in the rainfed treatment the DACT increase followed soil moisture depletion and water stress. In both seasons studied, in treatments with supplemental irrigation DACT was always above zero (0).

In season 2 under rainfed condition, the highest DACT (17.1 °C) was observed on 69 DAS, the last day of measurement. In the irrigated conditions, most DACT values were below those in the rainfed treatment, as was expected. For that reason, DACT was not zero for any of the irrigated plots except at 59 DAS when, despite irrigation and low soil moisture content, the air temperature was below the critical temperature for DACT calculation (28 °C).

The main reason is probably that the air temperature at measuring time was 26.9 °C (10 minutes average, between 12.00 and 15.00 h), despite low soil moisture in the rainfed treatment and DACT does not respond to air temperature below 28 °C.

Water supply treatment gave significant differences ($p<0.05$) for all sampling occasions except 54 and 55 DAS. No significant differences ($p<0.05$) were found between nitrogen fertiliser application or tillage treatments. A strong negative correlation between soil moisture and DACT was observed.

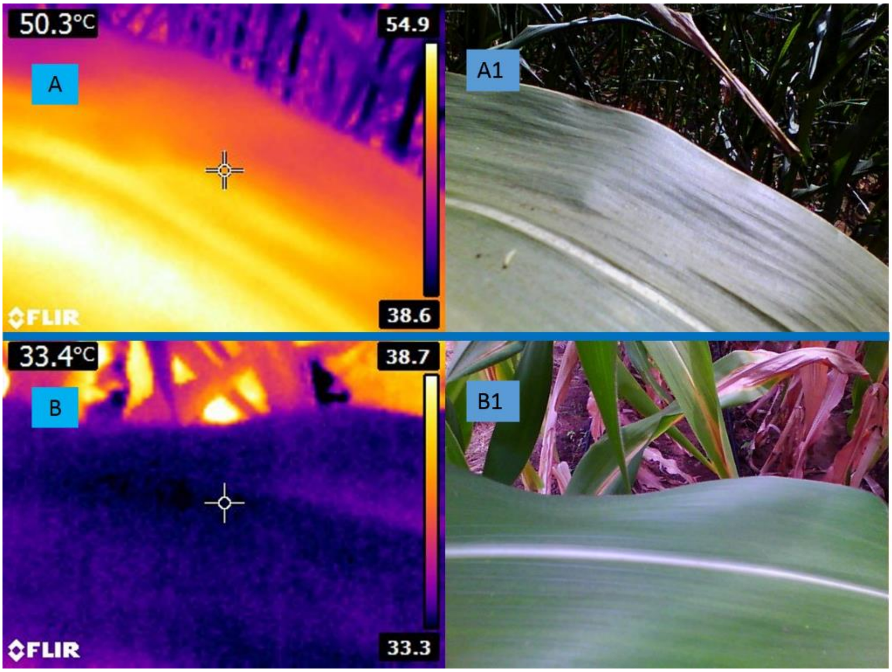

Figure 27. Maize leaf temperature. A) thermal image of a rainfed maize leaf (high temperature) and B) thermal image of an irrigated maize leaf (low temperature). A1 and B1 are the normal images of the rainfed and irrigated leaves, respectively. The cross in the middle of the leaf represents the target point, unshaded area.

The results showed that these two variables were well correlated on most days except for 54, 55 and 59 DAS, and on the last four measurement occasions there was a high negative correlation. This inverse relationship between DACT and soil moisture indicates that a soil water decrease increases leaf temperature and DACT.

In season 3, single leaf temperature measurements were carried out at 52, 56, 63, 65 and 69 DAS for the irrigated treatment and 74, 76, 77, 87, 90 and 91 DAS for the rainfed treatment, with a lag time of 30 days. These days were selected in order to measure the temperature in the same cropping stage for both rainfed and supplemental irrigation. The average daily relative humidity during the sampling period was 45% in rainfed treatments and 63.5% in irrigated treatments, while solar radiation for the same period was 740 Wm^{-2} and 570 Wm^{-2} in rainfed and irrigated treatments, respectively. In both crop seasons, after germination there was enough rainfall to produce biomass and sustain the crop from sowing to harvest. Rainfed treatments received 194.5 mm from sowing to tasselling, 58.2 mm from tasselling to blister stage (R2) and 54.7 mm from blister stage to harvest. Irrigated treatments received 155.1 mm from sowing to tasselling, 53.3 mm from tasselling to blister stage (R2) and 99 mm from blister stage to harvest. The average wind speed was 1.4 m s^{-1} and 1.1 m s^{-1} during sampling in rainfed and supplemental irrigation plots, respectively.

As seen in season 2, in season 3 DACT was higher in the rainfed than in the irrigated plots for all tillage treatments. DACT in the irrigation treatment was always different from zero. The highest value of DACT (14.7 °C) was found on the last measuring day. In season 3, water supply level again significantly ($p<0.05$) affected canopy temperature, and thus DACT.

4.6.1 Relationship between leaf temperature and maize agronomic traits

There was an inverse relationship between DACT, soil moisture, grain yield and water use efficiency (Table 5). There was a negative correlation between DACT and grain yield in both seasons. In season 2, soil moisture correlated negatively with DACT on all sampling days and the correlation was strong and significant ($p<0.05$) at the blister stage (61-69 DAS).

Table 5. *Relationship between degrees above canopy threshold (DACT) and soil moisture (SM), grain yield (GY) and water use efficiency (WUE) in season 2 and season 3*

	Crop season 2				**Crop season 3**		
Sampling (DAS)	DACT x SM	DACT x GY	DACT x WUE	Sampling (DAS)	DACT x SM	DACT x GY	DACT x WUE
52	-0.406s	-0.644***	-0.594***	52	-0.365ns	-0.343s	-0.303ns
54	0.073ns	0.169ns	0.157ns	56	-0.217ns	-0.568s	-0.600s
55	-0.213ns	-0.222ns	-0.234ns	63	-0.260ns	-0.362ns	-0.326ns
59	-0.181ns	-0.295ns	-0.133ns	65	-0.349ns	-0.334ns	-0.322ns
61	-0.646***	-0.643***	-0.667***	69	-0.168ns	-0.031ns	0.075ns
62	-0.609***	-0.791***	-0.779***	74	-0.270ns	-0.280s	-0.237ns
67	-0.514***	-0.601***	-0.592***	77	-0.118ns	-0.468s	-0.491s
69	-0.679***	-0.601***	-0.667***	87	0.104ns	0.252ns	0.216ns
				90	-0.238ns	0.337ns	0.369ns
				91	-0.285ns	0.418ns	0.458ns

***, **, s: significant at p < 0.0001 and 0.05; ns: not significant (p>0.05).

In season 3, the correlation between soil moisture and DACT was negative, but weak and not significant. Besides soil moisture, DACT also correlated with grain yield and water use efficiency (Paper III).

In season 2, the correlations between DACT and grain yield and water use efficiency were stronger and significant at the tasselling (52 DAS) and blister stage (61-69 DAS). The non-significance of the correlation of DACT with grain yield and water use efficiency on 54, 55 and 59 DAS can be related to the fact that DACT did not respond to climate (rainfall and air temperature) conditions on those days. In season 3, there was a negative correlation between DACT and grain yield on most sampling days, except at blister stage on the rainfed sampling days (87, 90 and 91 DAS). The correlation was significant at tasselling both for rainfed (74 and 77) and irrigation sampling days (52, 56 DAS).

4.7 Crop modelling (Papers II)

Overall model performance with the Matuba cultivar was good in simulating soil moisture, grain yield and biomass (details are presented in Paper II). The simulated soil moisture was in agreement with that observed in the field. The relative root mean square error (RRMSE) ranged from 9.3% to 19.3%, *i.e.* it was in the acceptable range for model prediction, while the results showed that the model underestimated the soil moisture content in the irrigation treatment and overpredicted it in the rainfed treatment. Model efficiency (EF) was positive for rainfed (0.10 to 0.48) and negative for irrigated (-1.9 to -2.9) treatments. The model agreement (d) for all treatments was always above 0.50. The model was able to predict the low grain yields observed in the rainfed treatments.

4.7.1 Multiple season simulation

In simulations of rainfed systems with low planting density (1 plant m^{-2}), grain yield did not increase with increasing fertiliser rate. With the standard plant population density (4.2 plants m^{-2}), grain yield responded well to increasing nitrogen fertilisation rate in all rainfed seasons included in the simulations except 1991/1992, 1993/94, 2004/2005 and 2006/2007. In those four seasons, total rainfall was 266.8 mm, 300.3 mm, 394 mm and 386 mm, respectively, *i.e.* below the long-term rainfall average of 425 mm. In rainfed cropping with high plant density (8.4 plants m^{-2}), 20% of simulated years resulted in grain yield below 1000 kg ha^{-1} and 12% of simulated years resulted in no grain yield.

With high planting density in the rainfed treatment, the number of seasons with no yield was higher than with the other planting densities. This suggests that it is unreliable to apply fertiliser with high planting density under rainfed. The scenarios showed that supplemental irrigation was able to increase and stabilise grain yield. Furthermore, irrigation was only beneficial at the recommended or higher planting densities.

In the simulations, nitrogen partial factor productivity (PFP(N)) was high for low nitrogen application rates (Paper II). On using the recommended PFP(N) threshold, the optimal fertiliser rate ranged from 41 to 102 kg ha^{-1} in the rainfed system and from 38 to 86 kg ha^{-1} in the irrigated system.

5 Discussion

5.1 Rainfall distribution and soil moisture

Rainfall in the study region in southern Mozambique is erratic and sometimes comes in storm events. There was occurrence of dry spells of at least five days in all seasons. In season 1, the rainfall was more evenly distributed despite some minor dry spells. In this season soil moisture was not assessed, but the crop parameters and grain yield showed that the distribution of rain did not influence crop growth. In seasons 2 and 3, the rainfall pattern was different from that in season 1. The longest dry spells were 15 days in season 2 (from tasselling to blister stage) and 30 days in season 3 (from sowing to germination in rainfed). The dry spell in season 2 impacted negatively on soil moisture content in the rainfed treatments, while in season 3 it impacted on germination timing. These results show that in the study region, there is a risk of having long or short dry spells that can have different impacts depending on the crop development stage. Dry spells that affect grain yield have also been observed in other studies in sub-Saharan Africa (Barron, 2004; Fox & Rockström, 2003). Many studies point out the importance of using supplemental irrigation as a strategy to stabilise crop growth and grain yields in arid regions (Rockström & Barron, 2007; Fox & Rockström, 2003; Rockström *et al.*, 2003).

Moreover, rainfall events in the study region were often of short duration and high intensity, *e.g*. rainfall events of 100 mm in 24 hours were observed. The main problem with high-intensity rainfall is that it is likely to generate runoff and is thus of little benefit to the growing crop. However, this runoff can be collected outside the field and used for supplemental irrigation (Makurira, 2010; Barron, 2004). Another strategy could be to address the rainfall partitioning in these systems. It is known that a reduction in soil evaporation and in field runoff (Makurira, 2010) can have a positive effect on soil moisture content and increase the available water for crop growth (Rockström *et al.*, 2003)

5.2 Penetration resistance and root abundance (Paper I)

Root concentration were higher in the top 0-20 cm depth. This higher root concentration in the topsoil (0-20 cm depth) can be attributed to higher soil moisture content in this layer and lower penetrometer resistance (<1.25 MPa) that did not restrict root growth. Similarly, Laboski *et al*. (1998) and Chilundo *et al*. (2017) found that the roots tend to concentrate more in upper soil layers and the amount of roots in those layers were related to impeding layers. In season 2, beside high penetrometer resistance, the restricted root distribution observed can also be attributed to reduced soil moisture at greater depth in the soil. Most cereal roots are affected when penetrometer resistance is between 1.25 and 2.0 MPa and there is severe root growth restriction at values above 3 MPa (Hazelton & Murphy, 2007). In season 1 (Figure 22), the threshold value penetrometer resistance of 1.25 MPa was found from 10 cm downwards, while in season 2 (Figure 22) it occurred from 15 cm downwards. Thus the penetrometer readings indicate that root elongation may have been negatively affected already from 10-15 cm depth.

5.2.1 Root:shoot ratio

Relative translocation of assimilates to roots and shoots changes depending on soil conditions in terms of water and nutrients. In this thesis, root biomass was greater than shoot biomass in most of the sampling periods. In particular, the proportion of root increase in relation to shoot was higher in the rainfed and unfertilised treatments. Maize invests more in roots than shoots when there is water or nitrogen stress. This reduction in root:shoot ratio was also found by Benjamin *et al*. (2014) and Sangakkara *et al*. (2010) in maize experiments.

The application of fertiliser also affected the root:shoot ratio. Fertiliser application in general increased shoot biomass more than root biomass, thus reducing the root:shoot ratio. Bonifas *et al*. (2005) also found a reduction in root:shoot ratio in fertilised maize.

However, the impact of tillage was not consistent in the two seasons, an effect that can be attributed to the different rainfall pattern. This agrees with findings by Sangakkara *et al.* (2010) for maize and Huck *et al*. (1983) for soybean that the root:shoot ratio in rainfed systems tends to be high because crops invest more in root dry matter in such systems. The large decrease in root:shoot ratio with time, especially for the maize grain filling (R4) stage, confirms findings by *e.g.* Klepper (1991) and Anderson (1988). This reflects the low allocation of assimilates to the root system in later growing stages.

5.3 Grain yield (Papers I, II, and III)

Grain yield in rainfed treatments was lower than in supplemental irrigation treatments. The maize in rainfed treatments also had lower LAI, aboveground biomass (Papers I and II) and grain yield compared with the maize in supplemental irrigation treatments (Papers I, II and III). This trend was similar in all sampling stages (growth stages V7, VT and R4). Water stress in the vegetative stage (from sowing to VT) reduced the growth of maize traits (root, leaf and biomass). Aslam *et al*. (2013) made a similar finding and attributed this to the fact that under water stress conditions, photosynthesis, transpiration and light interception are reduced, impacting the maize traits due to a reduction of translocated assimilates. Under supplemental irrigation, all these traits were improved compared with rainfed conditions.

Between flowering and R4 stage, the rainfed treatments also produced lower maize trait values (leaf and biomass) compared with the supplemental irrigation treatments. In season 1, the amount of rainfall during this stage and the values in daily water balance suggest that there was no water stress in this season. However, in seasons 2 and 3, between VT and R4 soil moisture was depleted and this affected the start of grain formation. In season 2, the soil moisture content was below 50% PAW most of the time, while in season 3 soil moisture was near 50% plant-available water. Drought stress at this crop stage (VT to R4) affects pollen viability, increases the anthesis to silking interval and reduces grain weight (Aslam *et al.*, 2015). In seasons 2 and 3, the maize cobs were small and barren in the rainfed treatments. Water stress in the flowering stage can lower the number of grains per cob due to pollen sterility, which results in poor grain set and reduced number of grains per cob (Hussain *et al*. 2013).

From flowering stage to blister stage (R2) in season 2, the air temperature was high and the site received only 15.4 mm of rainfall, and thus the atmosphere and crop demand at this stage drastically reduced the amount of moisture in the soil. In season 3 the system received 44 mm of rainfall, but the soil moisture content at this stage was above 50% plant-available water for half the time. As a result of water stress at this stage, grain yield was low compared with in supplemental irrigation. In field experiments, Çakir (2004) also found low grain yield as a consequence of drought stress at the flowering stage. Similar findings have been reported by Aslam *et al*. (2015) and Chen and Weil (2011).

Supplemental irrigation increased yield, but there was a marked difference between the effects in the three seasons. For example, in season 2 the grain yield difference between rainfed and irrigated was approximately 4100 kg, despite the total rainfall being similar in these two years. The benefit of supplemental irrigation in semi-arid regions has been highlighted by Barron (2004) and Fox and Rockström (2003).

For fertiliser application, there was a very strong interaction with water regime. In both seasons in which this was studied, fertiliser did not increase yield significantly in the rainfed system, while there was a large yield increase in combination with irrigation. These results imply that the outcome of fertilisation may be too unreliable in a rainfed system and that fertiliser should only be used in combination with irrigation. A strong interaction between water supply and fertiliser in terms of effects on yield has been found previously by Yin *et al.* (2014), Moser *et al.* (2006) and Bennett *et al.* (1989). It should also be noted that in all seasons, the yield level was relatively high without fertiliser in the irrigated treatment, indicating that mineralisation of nitrogen was probably high in the experiment.

The starting hypothesis in this work was that deeper tillage decreases penetration resistance and increases root growth and crop yield. There were generally small effects of tillage on root growth (Paper I). In the literature, the effects of strip tillage on crop yield of maize are inconsistent. For example, Al-Kaisi (2004) found no significant impact of strip tillage on grain yield, whereas others (Temesgen *et al.*, 2012; Mallarino & Pecinovsky, 2011) have reported higher yield for strip tillage than for conventional tillage, which they attributed to lower runoff and evaporation and not to improved conditions for root growth. There were also no significant interactions between tillage and the other treatments in Paper I, meaning that the outcome of tillage was not affected by fertiliser application or water regime. Thus there appears to be little need for loosening on this soil and tillage requirement should be determined by other factors, such as incidence of weeds.

5.4 Water use efficiency (Paper III)

In all seasons, water use efficiency increased due to supplementary irrigation. Low water use efficiency values under rainfed conditions were observed in this thesis, and the values found are comparable to those reported by Sitoe (2011) and Maculuve (2011) in Mozambique and Mudenda *et al.* (2016) in Zambia. Increased water use efficiency has previously been reported in irrigation treatments supplied with nitrogen fertiliser (Kresović *et al.*, 2016; Pandey *et al.*, 2000). This increase is related to a high level of interaction between fertiliser and irrigation that leads to good crop development, high leaf area index, good grain set and higher actual evapotranspiration (ETa) (Pandey *et al.*, 2000). These findings are in agreement with Hernández *et al.* (2015), Ogola *et* *al.* (2002) and Pandey *et al.* (2000). Overall, the results in Paper III suggest that soil tillage does not affect grain yield, and thus water use efficiency. In general, under rainfed conditions there was no benefit in terms of water use efficiency from applying nitrogen. This means that under rainfed semi-arid conditions, addition of fertiliser is not a good way to increase water use efficiency.

5.5 Fertiliser recommendations (crop modelling approach: Paper II)

The model used was able to simulate grain yield and biomass with good accuracy. The RRMSE for grain yield varied from 14.3% to 20%, the model efficiency (EF) from 0.97 to 0.99 and the model agreement (d) was 0.99. The APSIM model was able to simulate adequately grain yield in rainfed systems. These results are in agreement with modelling results in Zimbabwe (Shamudzarira & Robertson, 2002), Tanzania (Mkoga *et al.*, 2010), and Kenya (Kisaka *et al.*, 2015)

Multiple-season simulation generally showed a grain yield increase as a function of applied nitrogen, as also found elsewhere (Akponikpè *et al.*, 2010). The response to the applied fertiliser (extra kg grain per N kg applied) varied for different seasons. Similar results have been reported previously for a semi-arid region of Zimbabwe (Shamudzarira & Robertson, 2002).

Modelling showed no grain yield in some years for rainfed conditions. No or very low grain yield in these years was found to be related to erratic rainfall distribution in the cropping season and not to total amount received. This is common in semi-arid environments, *e.g*. Kamanga *et al.* (2013) and Barron *et al*. (2003) reported that in semi-arid regions, total failure of grain yield due to water stress can occur. For maize, this is exacerbated if the drought coincides with tasselling stage (Hussain *et al.*, 2013).

In all simulated years, the maize crop was able to germinate, but low rainfall and low soil moisture during the flowering stage had a negative impact on yield. According to Kamanga *et al.* (2013) and Paper I, in dry years yield is reduced even with adequate crop management and fertiliser application. High plant density (8.4 plant m^{-2}) reduced crop yield under rainfed conditions, with some years experiencing total lack of grain yield, confirming findings by Sangakkara *et al.* (2004). The modelling results showed that under high plant density, water depletion was high and exacerbated when the soil was not capable of supplying water during the flowering stage (Ren *et al.*, 2016). Low yield due to low soil moisture also occurred at the experimental site in season 2 (Paper I). The scenarios showed that supplemental irrigation was able to increase and stabilise grain yield. Furthermore, irrigation was only beneficial at the recommended or high planting densities. In the simulations, nitrogen partial factor productivity (PFP(N)) was high for low nitrogen application rates (details are presented in Paper II). According to Dobermann (2005), high PFP(N) can be related to crops using indigenous nitrogen. On using the recommended PFP(N) threshold, the optimal fertiliser rate ranged from 41 to 102 kg ha^{-1} in the rainfed system and from 38 to 86 kg ha^{-1} in the irrigated system. Similarly, in previous crop model simulations for rainfed small-scale cropping in Malawi (Kamanga *et al.*, 2013) and Zimbabwe (Shamudzarira & Robertson, 2002), the adequate fertiliser rate identified in simulations was below the national recommended nitrogen rate for maize for those countries.

5.6 Maize leaf temperature and maize traits (Paper III)

In both seasons studied, rainfed maize always showed higher DACT than irrigated maize. Similar results have been reported previously (Carroll, 2015). The increase in DACT due to leaf temperature increase is related to reduced transpiration by the leaf (Siddique *et al.*, 2000). The results in Paper III showed that soil moisture and DACT were well correlated on most days. Chávez (2015) also found a strong negative correlation between maize crop water stress index (CWSI) and soil moisture content, although there were days when this correlation was not significant ($p<0.05$). Similarly, DACT showed weak and negative correlations with soil moisture on some sampling days in season 2, despite soil moisture being below 50% plant-available water. On these days, the air temperature was below the threshold temperature (28 °C) used on DACT calculations. Similar results have been obtained elsewhere (Carroll, 2015). However, the correlation was negative and non-significant for the rest of the sampling period in season 2, in agreement with other studies (Taghvaeian *et al.*, 2014). Fertiliser level did not affect leaf temperature or DACT in season 2. These results suggest that nitrogen fertiliser does not affect DACT and/or confound the water impact. Similar results have been reported by Carroll (2015) under laboratory and field conditions.

In both seasons studied, there was no impact of primary tillage on DACT. In contrast, Eskandari *et al.* (2015) found a reduction in canopy temperature in conservation agriculture (no-till) compared with conventional tillage on clay soil, which they attributed to increased soil water retention. In both years, the experiment in Paper III had clear periods of wetting and drying. Wetting and drying periods lead to natural subsequent reconsolidation of soil properties (Moret & Arrúe, 2007; Green *et al.*, 2003). This soil reconsolidation effect is probably higher for the first rainfall event after sowing, leading to no difference between tillage treatments on sandy loam in Papers I and III.

In this thesis, there was a relationship between DACT and maize traits (grain yield, water use efficiency, thousand-grain weight). Zia *et al.* (2013) also found a linear relationship between canopy temperature and grain yield in maize cultivars, while Irmak *et al*. (1985) found a quadratic relationship between another water stress index (CWSI) and grain yield. In season 2, the irrigation treatment significantly ($p<0.05$) increased thousand-grain weight, by 17%, while fertiliser level and tillage methods had no significant effect. In season 3, both water and fertiliser levels significantly affected thousand-grain weight. Kernel weight is determined during the post-anthesis stage, according to Aslam *et al*. (2015). In both seasons, there was a soil moisture reduction in rainfed plots during grain filling. Under the rainfed treatment, soil moisture was between 50% plant-available water and wilting point at this crop stage, which affected grain filling. Vafa *et al*. (2014) also found a significant effect of drought stress at grain filling stage on thousand-grain weight in maize.

6 Conclusions

This thesis tested a combination of soil and water management technologies aimed at increasing maize grain yield in a semi-arid region of sub-Saharan Africa. The main conclusions of the work are:

- Root abundance decreased down the soil profile. This decrease was associated with higher penetrometer resistance at greater depth. Root and shoot dry matter were influenced mainly by water supply and fertiliser application.

- The best option to increase maize grain yield and water use efficiency on sandy loam soils under semi-arid conditions such as those studied here is through supplemental irrigation and fertiliser application. It is clear that there is a need to take a combined approach to water supply and fertiliser application.

- Leaf temperature between flowering and blister stage can be used as an indirect method to assess agronomic traits in maize.

- Modelling results indicated that the actual recommended nitrogen fertiliser rate for maize in Mozambique (120 kg ha^{-1}) is not suitable for rainfed semi-arid regions. The optimal fertiliser rate ranged from 41 to 102 kg ha^{-1} in the rainfed system and from 38 to 86 kg ha^{-1} in the irrigated system. Thus the fertiliser amount should be adjusted to climate variability, such that in very dry years application of fertiliser is suspended.

7 Implications for future research

This thesis presents results obtained in experiments in the semi-arid region of Sábiè, southern Mozambique. These results are important for low-input farming systems in the region, but may not be applicable to other agro-ecological regions of the country or other soil types. Thus the technologies studied here have to be tested in other regions with different soil types, crop cultivars and climate conditions, weed effects and cultivation systems (*e.g.* in consociations).

Different factors influence maize grain yield in the semi-arid region of Mozambique studied here. The results presented in this thesis indicate there is a potential for further grain yield increase due to supplemental irrigation and fertiliser application. The modelling scenarios showed that the actual fertiliser recommendation is not suitable for rainfed farming, which opens opportunities for further field experimentation to validate the results reported here.

Researchers have advocated the use of strip tillage as a way to conserve soil moisture, reduce soil erosion and increase grain yield, but the findings in this thesis did not support this recommendation.

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