Effects of irrigation and fertiliser management on water and nitrogen use efficiency in maize on a semi-arid loamy sandy soil

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Cover: Maize plants in a drip-irrigated plot during the hot-wet season at the experimental site, located in Sábie village in southern Mozambique
(photo: Mário Chilundo)

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Abstract

Understanding water and nitrogen redistribution in the soil profile is important to improve water and nitrogen use efficiency for sustainable agriculture. This thesis evaluates the interactions between water and fertiliser management factors affecting water and nitrogen use efficiency, based on field experiments on a semi-arid loamy sandy soil. The impact on maize (*Zea mays L.*) yield and other crop properties was also assessed. Cropping periods in two hot-wet seasons and two cold-dry seasons were compared. The treatments involved two irrigation methods (furrow and drip), two irrigation levels (full and reduced) and two top dressing nitrogen fertiliser types (quick-release and slow-release).

Overall, there were trends for better nitrogen uptake, water and nitrogen use efficiency and grain yield in the cold-dry than in the hot-wet season, especially under reduced irrigation. Furrow irrigation with reduced irrigation level tended to give higher grain and dry matter nitrogen use efficiency in both hot-wet and cold-dry cropping periods. Soil moisture distribution, water flow direction and deep percolation were primarily affected by irrigation method and irrigation level in the cold-dry season and by a combined effect of irrigation level and rainfall events in the hot-wet season. In both seasons, full irrigation level with quick-release nitrogen fertiliser was found to induce more net downward redistribution of water and nitrogen in the soil profile, irrespective of irrigation method. Reduced irrigation, particularly in the hot-wet season, resulted in less deep percolation. In the cold-dry cropping period, reduced irrigation combined with slow-release nitrogen fertiliser, resulted in longer nitrogen residence time at 30 and 60 cm depth, irrespective of irrigation method. Drip irrigation resulted in a moister soil profile overall in both seasons, and thus allowed better growth and elongation of coarse and fine roots, which were denser in the uppermost 56 cm of soil and reached a maximum depth of 80 cm.

These results indicate that reduced irrigation should be considered as a potential irrigation management option for semi-arid loamy sandy soil in both hot-wet and cold-dry seasons. Drip irrigation and slow-release nitrogen fertiliser may be suitable options for the cold-dry season.

Keywords: deep percolation, maize yield, root growth, nitrogen redistribution

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Dedication

To my wife Sónia and my children Naya, Kiyara and Mayro,
for their ceaseless love and support.

"It is not the quantity of water applied to a crop, it is the quantity of intelligence applied which determines the result – there is more due to intelligence than water in every case"

Alfred Deakin, 1890

"Water is the most perfect traveller, because when it travels it becomes the path itself!"

Mehmet Murat İldan

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 Chilundo, M., A. Joel, I. Wesström, R. Brito, and I. Messing (2016). Effects of reduced irrigation dose and slow release fertiliser on nitrogen use efficiency and crop yield in a semi-arid loamy sand. *Agricultural Water Management* 168, 68-77.

II Chilundo, M., A. Joel, I. Wesström, R. Brito, and I. Messing (2017). Response of maize root growth to irrigation and nitrogen management strategies in semi-arid loamy sandy soil. *Field Crops Research* 200, 143-162.

III Chilundo, M., A. Joel, I. Wesström, R. Brito, and I. Messing. Influence of irrigation and fertilisation management on the seasonal distribution of water and nitrogen in a semi-arid loamy sandy soil (submitted).

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The contribution of Mário Chilundo to the papers included in this thesis was as follows:

I, II, III Planned the study together with the co-authors. Implemented the study (*i.e*. experimental field work, sample collection and laboratory analysis). Carried out data analysis, interpretation and writing with frequent assistance from the co-authors.

Abbreviations

CP	Cropping period
CP-cd	Cold-dry season cropping period
CP-hw	Hot-wet season cropping period
D	Drip irrigation
DAS	Days after sowing
DM	Dry matter
ET_c	Crop evapotranspiration
ET_o	Reference evapotranspiration
F	Furrow irrigation
I_f	Full irrigation level
I_r	Reduced irrigation level
N	Nitrogen
NH4-N	Ammonium-nitrogen
NO3-N	Nitrate-nitrogen
N_q	Quick-release nitrogen fertiliser
N_s	Slow-release nitrogen fertiliser
NUE	Nitrogen use efficiency
R1	Maize silking stage (reproductive stage 1)
R6	Maize physiological maturity (reproductive stage 6)
SWD	Soil water depletion
V6-12	Six-leaf to 12-leaf vegetative growth stage
VT	Tasselling stage
WUE	Water use efficiency

1 Introduction

Efficient use of water and fertilisers by crops calls for revised or new agricultural crop management practices to sustain agricultural production (Shrestha *et al.*, 2010). This is a worldwide concern, not least in arid and semi-arid areas, which sustain about 14% of the global population (UN, 2011) and about 60% of the total population in sub-Saharan Africa (IAASTD, 2009). The increase in agricultural production in the world, including that in arid and semi-arid areas, has been achieved through application of modern agricultural technologies, comprising a combination of irrigation and heavy doses of fertiliser (Janmohammadi *et al.*, 2016; Hussain & Al-jaloud, 1995). As a result, as much as 40% of global food production derives from irrigated agriculture. However, a large amount of the irrigation water used is lost due to inappropriate irrigation practices (FAO, 2016a). This is the case, for example, in soils with excessive internal drainage and low water-holding capacity, such as sandy soils (McNeal *et al.*, 1995). Therefore, today's agriculture sector faces a complex series of challenges to cope with the demands for sustainable management and production, which entails an increase in food production to ensure food security while using less water per unit of output (Yihun, 2015), and reducing nitrogen (N) fertiliser losses through leaching. This is particularly important in sub-Saharan Africa, where a major expansion in irrigated agricultural area is expected to occur in the near future, since only 7.7 million ha out of a potential 38 million ha are currently in operation (FAO, 2016a). Mozambique, the study area in this thesis, has a potential of 3 million ha land suitable for irrigation, of which only 90000 ha are currently being used (MINAG, 2015), thus showing significant potential for expansion.

The fact that irrigation and N fertiliser management practices affect cereal production to a large degree (*e.g.* Shirazi *et al.*, 2014; Yin *et al.*, 2014) is important to consider as regards the expectations and needs in production. The simultaneous growing concern considering the environmental implications will require the development of best management practices that maximise water and N fertiliser use efficiency. Thus, a better understanding of the interactions between irrigation and fertiliser methods and application rates, as related to soil type and crop performance, and their seasonal dependency is essential for proper and efficient water and N fertiliser management, not least in semi-arid environments (Behera & Panda, 2009).

Like other crops, maize, one of the most widely grown cereals in the world together with rice and wheat (FAO, 2015), requires water and N for its maximum growth. However, excessive application of water is common in the dominant furrow-irrigated systems that represent more than 95% of the irrigated land in the world (FAO, 2016a; Alhammadi & Al-shrouf, 2013). This brings several disadvantages, especially the risk of high rates of water and N losses due to leaching (Zhou *et al.*, 2006), and thus low water and N use efficiency. On sandy soils, as a result of their coarse texture, excessive irrigation and fertiliser applications may result in substantial water loss through deep percolation and alarmingly high amounts of N, for example in the form of nitrate, into the groundwater (Hu *et al.*, 2008).

A good understanding of the influence of water and N fertiliser management options on water movement, N turnover and redistribution is important in order to improve water and N use efficiency while safeguarding high maize yield. This is particularly important in semi-arid sandy soils in developing countries with smallholder farming systems, where the spread of suitable improved management systems remains deficient.

2 Objectives and hypotheses

The overall aim of this thesis work was to study the interactions between water and N fertiliser management factors affecting water and N use efficiency, and their impact on maize (*Zea mays* L.) growth and yield, in experimental plots on a semi-arid irrigated loamy sandy soil in southern Mozambique. Reducing water and N losses is important in order to maximise maize yield, while safeguarding good quality harvested products and reducing potential environmental degradation. Specific objectives were:

- To quantify and evaluate soil water balance, nitrogen use efficiency and crop yield as affected by different irrigation and nitrogen fertiliser management options (Paper I)

- To quantify and evaluate maize root response (density and maximum rooting depth) to the interaction between irrigation and nitrogen management options (Paper II)

- To quantify and assess water and nitrogen redistribution in the soil profile, including potential water and nitrogen fluxes to the zone below the roots, as affected by different irrigation and nitrogen fertiliser management options (Paper III)

The main hypothesis was that the enhanced practices (combination of drip irrigation, reduced irrigation level and slow-release nitrogen fertiliser) compared to conventional practices (combination of furrow irrigation, full irrigation level and quick-release N fertiliser), reduces water and N losses below the root zone, improves water and N use efficiency and gives higher aboveground biomass, leaf area index and maize grain yield (Papers I and III).

A second hypothesis was that the use of enhanced practices increases maize root density and maximum rooting depth compared with conventional practices, and that the increase in root density improves grain yield, aboveground biomass and leaf area index (Paper II).

3 Background

3.1 Irrigation management and nitrogen transformations

The limited access to water in semi-arid areas during dry seasons or droughts constitutes a restricting factor for farming and for improving agricultural productivity (Xie *et al.*, 2013). Irrigation has often been regarded as a promising solution to boost agricultural productivity levels in several such regions (AGRA, 2013), but the limited availability of water calls for optimised management strategies. Such strategies need to respond to the growing needs for food production while giving best economic and environmental return per unit of water utilised (El-Wahed & Ali, 2013; Kang *et al.*, 2000).

Worldwide, more than 80% of the total area under irrigation is managed by surface irrigation, whereby water is spread over the field by gravity using basin, furrow or border strip techniques (WB, 2006). However, this irrigation method is recognised as being relatively inefficient in terms of water application, and often requires availability of large volumes of water (Tagar *et al.*, 2012). To cope with periods of water shortage, efficient use of irrigation water is becoming increasingly important and water-saving agriculture is an important option. Pressurised methods, such as sprinkler and drip irrigation, have proven to be successful in terms of water use efficiency and increased yield for a wide range of crops and environments (Ati *et al.*, 2012).

Well-scheduled irrigation programmes throughout the crop growing period, coupled with appropriate irrigation techniques that are applicable also in semi-arid environments, have been suggested in earlier studies (Tagar *et al.*, 2012; Hassanli *et al.*, 2009; Pereira *et al.*, 2002). As an example, 56% water savings, a 22% increase in yield and a two-fold increase in water use efficiency have been found for drip irrigation in comparison with furrow irrigation (Tagar *et al.*, 2012). However, the identification of best irrigation management strategies (methods, levels and timings) still remains an important issue in order to improve water management at farm level in semi-arid environments where water is scarce. Studies by Wallace & Gregory (2002) and later by Behera & Panda (2009) recommend focusing on strategies increasing yield per unit of water applied, while optimising N fertiliser management, as approaches to reduce deep percolation and leaching losses of N below the root zone. In African studies, similar issues to those described above have generally been identified and such studies highlight the need to improve water productivity in the smallholder irrigation context, including actual water consumption (Yokwe, 2009) and better irrigation and fertilisation management methods (Woltering *et al.*, 2011; Hess & Molatakgosi, 2009).

There is wide consensus in the literature that the temporal variation in soil moisture deriving from irrigation and precipitation events to a large degree controls most N transformations (symbiotic fixation, mineralisation, immobilisation, nitrification and denitrification) and fluxes (surface runoff, volatilisation and leaching) (Barakat *et al.*, 2016). Mineralisation is generally optimum in the presence of sufficient moisture in soil pores (Valé *et al.*, 2007). The frequent application of relatively small amounts of water, which is characteristic of drip irrigation, creates conditions for good continuous microbial activity, and thus for mineralisation and nitrification (Thorburn *et al.*, 2003a), with reduced or absent denitrification. However, less frequent application of relatively high amounts of water, which is characteristic of furrow irrigation, results in high variability in soil moisture conditions such as temporary saturated conditions, which are adverse for mineralisation (Thorburn *et al.*, 2003b) and favourable for denitrification (Sánchez-Martín *et al.*, 2008). The leaching in coarse-textured soils and soils with macropores (Zotarelli *et al.*, 2007) is likely to occur when soil water amount and rate exceed field capacity and potential evapotranspiration of the soil plant system or through preferential flow, especially in furrow irrigation (Santos *et al.*, 1997). However, the magnitude of N losses is also dependent on the form of N applied. Nitrate, for example, is mostly present in soil solution given its low adsorption to soil particles (Marchi *et al.*, 2016). Hence, nitrate can be expected to leach below the root zone in furrow irrigation during periods of excess soil moisture conditions or by preferential flow, given its tendency to be transported by convection. Studies have shown occurrence of vertical movement of nitrates to 70 cm below the emitter and, moreover, lateral movement up to 30 cm away from the application point in drip irrigation (Badr & El-Yazied, 2007), revealing a strong relationship between nitrate and water movements.

3.2 Impact of water and nitrogen management on water and nitrogen use efficiency

3.2.1 Definition of water use efficiency and nitrogen use efficiency

Water use efficiency (WUE) is defined in its simplest terms as the crop yield per unit of water use, while at a more biological level it is the amount of carbohydrate formed through photosynthesis per unit of transpiration (Howell, 2001). However, the term water use efficiency often gains a new meaning when used in irrigated agriculture. Bos (1985) proposed the term irrigation water use efficiency, defined as the difference in yield divided by the difference in evapotranspiration between irrigated and rainfed crop. Two terms can thus be distinguished: i) crop water use efficiency, which is the ratio between grain yield and actual crop evapotranspiration from sowing to harvesting, without distinction of water source (irrigation or rainfall) (Kresović *et al.*, 2016; Fairweather *et al.*, 2003), and ii) irrigation water use efficiency, representing the ratio between grain yield and water input, *i.e.* irrigation plus rainfall, from sowing to harvesting (Al-Jamal *et al.*, 2001).

Nitrogen is the most limiting crop nutrient for most non-legume production systems (Zotarelli *et al.*, 2007) and thus the most limiting in crop production. As a result, N fertilisers constitute a major component of fertilisation management in agriculture worldwide (He *et al.*, 2000). Efficient uptake of applied N by the crop is a major concern for farmers (Sato & Morgan, 2008), *i.e.* there is a need to improve N use efficiency. Nitrogen use efficiency (NUE) is the degree to which N is used by plants, and specifically refers to the efficiency by which crops produce biomass or harvested product from a unit of acquired N (Bell, 2014), or the grain or dry matter production per unit of N available in the soil (both native and applied) (Dobermann, 2005; Moll *et al.*, 1982). In some cases, the 'N' in NUE is used to denote 'nutrients', but in the present thesis NUE is used only to refer to nitrogen use efficiency. Nitrogen use efficiency is the product of two primary components (Moll *et al.*, 1982): i) the efficiency of absorption (uptake) (*i.e.* the ratio between total N in the plant at maturity and the total N supply), and ii) the efficiency with which the N absorbed is utilised to produce grain (*i.e.* ratio between maize grain yield and total N in the plant at maturity). Zhao *et al.* (2013) add two further definitions: i) agronomic NUE (ANUE), which is the ratio of the difference in grain yield between fertilised and non-fertilised plots to the total amount of nitrogen applied, and ii) physiological NUE (PNUE), which is the ratio of the difference in grain yield between fertilised and non-fertilised plots to the difference in plant N content between fertilised and non-fertilised plots.

3.2.2 Water and nitrogen use by maize

Maize is the third most important cereal crop after rice and wheat, and it is grown in a wide range of soil and climate conditions (Huang *et al.*, 2006). The total global harvested area in 2014 was about 185 million ha, producing about 1040 million Mg maize grain at a mean grain yield of 5.6 Mg ha^{-1} (FAO, 2016b). Maize is a highly water-demanding crop and can give grain yields of 10-12 Mg ha^{-1} when there are no limitations on water and nutrients. However, maize is very sensitive to water and nutrient stress. As an example, for a maize crop requiring 400-450 mm to attain maximum yield, a single irrigation omission during one of the sensitive growth stages, *i.e*. before anthesis, tasselling or silking and grain filling (Mansouri-Far *et al.*, 2010), has been shown to reduce final grain yield (by 30-40%), plant height, dry matter accumulation (Çakir, 2004), leaf area index and root growth (Pandey *et al.*, 2000b). Overall, maize water requirements are highest approximately two weeks before and two weeks after pollination (Bondesio *et al.*, 2006). There are indications that maize is relatively less sensitive to water stress when this occurs during early vegetative growth stages, given the relatively reduced crop evapotranspiration (Steduto *et al.*, 2012).

High yield in maize is closely associated with nitrogen application, but only where other inputs and management practices are optimal. Maize plants take up nitrogen only slowly during early growth stages (Roy *et al.*, 2006). However, the rate of uptake increases rapidly to a maximum before and after tasselling, when it can exceed 4 kg ha^{-1} day^{-1} (Roy *et al.*, 2006). For some hybrid varieties, and for a targeted yield of 6 Mg ha^{-1}, maize requires about 120 kg N ha^{-1}, 22 kg P ha^{-1} and 100 kg K ha^{-1} (FAO and IFA, 2000). The higher the yield target, the more N per Mg of grain will be required. For example, under irrigation and for a target yield of 10 Mg ha^{-1}, more than 220 kg N ha^{-1} may be required (Bondesio *et al.*, 2006). Nutrient availability and/or uptake, especially N, may also be modified by the level of water supply (Ercoli *et al.*, 2008). As a general rule of thumb, maize is likely to produce high yields when N fertiliser uptake is enhanced by relatively high soil moisture levels (Fapohunda & Hossain, 1990). A reduction in N uptake can thus be expected under limited soil moisture conditions, with negative impacts on the maximum attainable grain yield compared with high soil moisture conditions (Moser *et al.*, 2006).

3.2.3 Effect of irrigation methods on water use efficiency

The irrigated agriculture sector is the largest water user in the world, consuming about 80-90% of available freshwater (Steduto *et al.*, 2012), yet with poor water use efficiency, on average not exceeding 45% of the applied amount (Hamdy *et al.*, 2003). Numerous strategies are available for improving water use efficiency, including the use of improved irrigation methods (Huang *et al.*, 2006). In addition, water use efficiency can be improved with precise delivery systems for water conveyance, allocation and distribution (Hamdy *et al.*, 2003), since the application efficiency (*i.e.* the ratio between water used by the crop and that delivered to the field) of different irrigation methods varies: *e.g.* for surface (furrow) irrigation it is 60-90%, for sprinkler irrigation it is 65-90% and for drip irrigation it is 75-90% (Fairweather *et al.*, 2003). An improvement in water use efficiency can be achieved through more precise irrigation methods combined with appropriate irrigation scheduling, the latter based not only on crop water requirements but designed and managed to ensure optimal use of allocated water (Huang *et al.*, 2006). Furthermore, the soil texture may represent an important and determining factor for the performance of a particular irrigation method (Verbeten, 1998). Compared with furrow irrigation, drip irrigation can substantially improve water use efficiency by minimising deep percolation and evaporative losses of water (Jha *et al.*, 2016), particularly in sandy soils (Alhammadi & Al-shrouf, 2013). Thus, irrigation of sandy soils requires high attention to the timing and level of irrigation water applied, as increased application may result in deep percolation and leaching of nutrients below the root zone and later into the groundwater (Alhammadi & Al-shrouf, 2013) and thus in reduced water (and N) use efficiency.

There is a wide variation in maize irrigation water use efficiency values in the literature, and this variation is considered to be related to climate, irrigation practices and application of fertilisers. For example, Zwart & Bastiaanssen (2004) reported on an average global value of 1.8 kg m^{-3}, with a range from 0.22 to 3.99 kg m^{-3}. However, irrigation water use efficiency has been always regarded as superior for drip irrigation compared with furrow irrigation. For example, higher irrigation water use efficiency for drip irrigation (1.7-1.8 kg m^{-3}) than for furrow irrigation (1.4-1.5 kg m^{-3}) has been reported in a two-year study in an arid region (Hassanli *et al.*, 2009). Comparable ranges were reported by Karimi & Gomrokchi (2011), who found irrigation water use efficiency ranging between 0.92 and 1.68 kg m^{-3} under furrow irrigation and between 0.82 and 1.96 kg m^{-3} under drip irrigation. Furthermore, drip irrigation resulted in higher irrigation water use efficiency (ranging between 1.0 and 1.7 kg m^{-3}) compared with sprinkler irrigation (range 0.6-1.1 kg m^{-3}) under similar fertilisation strategies in a study in an arid region (El-Wahed & Ali, 2013). Using drip irrigation in a sub-humid region, Steele *et al.* (1994) indicated variation in irrigated water use efficiency from 2.03 to 2.86 kg m^{-3}.

3.2.4 Effect of nitrogen fertiliser type on nitrogen use efficiency

Increasing crop productivity in arid and semi-arid areas is widely recognised as difficult, partly due to such areas having a large proportion of degraded soils that are deficient in nutrients. The application of fertilisers to replenish nutrient uptake by crops has thus become a viable option to improve yields. When applied in excess or in a quick-release form, N is often cited as a major contributor to non-point source pollution, which may lead to elevated levels of nitrate into surface waters and groundwater (Zhao *et al.*, 2013; Stoate *et al.*, 2001). Large N fertiliser input levels generally result in low N use efficiency (Hu *et al.*, 2010). Therefore, many studies have reported on the need for proper and improved N fertiliser management, including appropriate N sources, rates and application timings, as well as proper irrigation management after fertilisation events (He *et al.*, 2012; Gross *et al.*, 1990). One interesting strategy is the use of slow-release and controlled-release N fertilisers. Slow-release N fertilisers are defined as stabilised organic N compounds from which nutrient release into the environment occurs at a slower rate than from common fertilisers (Shaviv & Mikkelsen, 1993). However, the rate, pattern and duration of release of slow-release fertilisers are not well-controlled, as they are strongly affected, among other factors, by soil conditions, such as moisture content, wetting and drying cycles, freezing and thawing, and biological activity (Shaviv, 1996). According to criteria of Trenkel (2010), at 25 °C standard temperature, a slow-release fertiliser should release no more than 15% of the nutrient in 24 hours following application, less than 75% in 28 days, and at least 75% during the manufacturer’s recommended total release time. In controlled-release fertilisers, on the other hand, the granules are coated with polymer or non-organic compounds aiming to regulate their release to the environment. In controlled-release fertilisers, the rate, pattern and duration of release are well-known and controllable during their formulation (Shaviv, 1996), a process that distinguishes them from slow-release fertilisers.

Slow-release and controlled-release N fertilisers have been used for many years (Shaviv, 2005), and are assumed to potentially reduce leaching of nutrients, especially nitrate-nitrogen, below the root zone and into the groundwater, in comparison with the application of conventional soluble N fertilisers (Sato & Morgan, 2008), thereby increasing N use efficiency (Arrobas *et al.*, 2011). For example, in experiments assessing the growth and N uptake of tomato, it was shown that slow-release fertilisers had an overall much smaller propensity to give rise to leaching than conventional ammonium nitrate fertiliser (Fan *et al.*, 2009). Nevertheless, even recognising the potential of slow-release fertilisers in reducing N leaching and/or increasing N use efficiency, studies have shown that up to 30% of the total N applied as slow-release fertiliser can be leached, especially from sandy soils (Wang & Alva, 1996). Concerning the influence on maize grain yields, increases in the order of 15-18% compared with conventional fertiliser have been reported in experiments in semi-arid areas with use of attapulgite-coated fertiliser, a slow-release fertiliser (Guan *et al.*, 2014).

Experiments with controlled-release fertilisers have also shown comparable results to those with slow-release fertilisers. A study with summer hybrid maize examining the effect of controlled-release fertilisers on agronomic N use efficiency reported a 68-120% increase in N use efficiency, *i.e.* a variation from 6.6 kg grain kg^{-1} N with application of conventional fertiliser to values ranging between 11.1 and 14.5 kg grain kg^{-1} N using controlled-release fertiliser (Zhao *et al.*, 2013). Comparable results were also found when polymer-coated N fertilisers (*e.g.* polyolefin-coated urea) were used to increase N uptake and N use efficiency by plants (Noellsch *et al.*, 2009). However, some studies have reported an absence of consistent improvement in N use efficiency deriving from controlled-release fertiliser use. For example, Grant *et al.* (2012) reported yield losses due to use of controlled-release fertiliser in comparison with non-coated urea. These losses were attributed to delays in release of N from the granule, thereby limiting its availability for crop growth. This is especially critical in maize, which has a high N demand.

Even considering the benefits of using slow or controlled-release fertilisers, the degree of measured N losses will remain being dependent on factors such as amount of applied N, type of applied fertiliser, soil type, soil temperature, soil moisture content, leaching regime (volume and frequency) and leachate collection method (repacked column, suction cups, *in situ* column, lysimeter or incubation) (Sato & Morgan, 2008; Hanafi *et al.*, 2000).

3.3 Redistribution of nitrogen in irrigated soils

On irrigated soils, crops are usually heavily fertilised (Hallberg & Keeney, 1993; Pratt, 1984), particularly on sandy soils which are less productive than other soils due to their relatively small amounts of nutrients and organic matter (Kelly & Ray, 1999). Therefore, assessment of the movements of N in irrigated soils, especially of nitrate, has been discussed in depth in the scientific community (Moreno *et al.*, 1996a). It is widely accepted that under irrigated conditions in arid and semi-arid environments, occasional drainage below the root zone is required to reduce the salt content in the soil profile, even though this may cause N losses when water input exceeds the amount consumed by crops (Gheysari *et al.*, 2009a). Some leaching of ammonium may occur in sandy soils, but only to a minor degree due to adsorption to the soil exchange complex (Moreno *et al.*, 1996a).

Several studies have reported increased N movements in sandy soils as a result of irrigation, with a consequent increase in N leaching below the root zone (*e.g.* Rong & Xuefeng, 2011; Hu *et al.*, 2008; Quiñones *et al.*, 2007). Excessive irrigation and N fertiliser application and high nitrate concentration in the irrigation water have been pointed out as the main factors determining high nitrate dynamics and leaching in sandy soils (Hu *et al.*, 2008). Quiñones *et al.* (2007) found that nitrate movements in the soil profile were lower under high frequency N application with drip irrigation than under low frequency N application combined with flood irrigation. Nitrate has also been shown to move below the root zone when irrigation rates exceed evapotranspiration (Cassel *et al.*, 1976). Rong & Xuefeng (2011) reported increased accumulation of nitrate at 0-100 cm depth when the irrigation level was 900 mm ha^{-1}, compared with 200-300 cm depth when irrigation level was 1200 mm ha^{-1}.

Based on these kind of findings, proposed strategies to reduce nitrate leaching below the root zone include: (i) split application of irrigation and fertilisers following crop growth stage requirements (Jia *et al.*, 2014), (ii) appropriate design and management of the irrigation system to coordinate it with rainfall (Klocke *et al.*, 1996), (iii) applying frequent low-level irrigation events to cope with the lower water-holding capacity of sandy soils (Smika *et al.*, 1977), (iv) use of fertigation under surface (Quiñones *et al.*, 2007) and subsurface (Thompason *et al.*, 2009; Lamm *et al.*, 2001) drip irrigation, (v) alternating partial root-zone irrigation with N fertilisation (Han *et al.*, 2016), and (vi) reduced irrigation level in relation to crop water requirements (Pandey *et al.*, 2000a).

A consistent conclusion from the literature tackling N movements in irrigated sandy soils is that irrigation level should be carefully controlled to prevent excessive N leaching through the soil zone (Prunty & Montgomery, 1991; Watts, 1990). However, it has also been acknowledged that it is almost impossible to reduce N leaching to zero in coarse-textured soils while maintaining adequate crop yields (Ritter, 1989). To reduce the risk of N leaching, better knowledge of integrated water application and N fertilisation management is needed. However, there is still a lack of systematic studies on integrated management of irrigation and N under different agricultural practices at field scale (Lv *et al.*, 2016; Simonne *et al.*, 2010; Moreno *et al.*, 1996a).

3.4 Effect of water and nitrogen on root development

The adaptation of irrigation systems to arid and semi-arid regions with limited water resources is especially important (Raj *et al.*, 2013), since any lack of sufficient soil moisture affects the growth and development of roots, which are vital for water uptake. The depth of root penetration into the soil and the degree of rooting, *i.e.* the root density in the soil volume under consideration, determine the amount of water and nutrient that can be extracted (Kuchenbuch *et al.*, 2006). Thus, deep rooting of crops is a key factor in achieving higher production (Al-Khafaf *et al.*, 1989).

Several studies focusing on the influence of soil physical properties on root development have been undertaken during recent decades (*e.g.* Magaia *et al.*, 2015; Laboski *et al.*, 1998; Materechera & Mloza-Banda, 1997; Ehlers *et al.*, 1983; Grimes *et al.*, 1972). Overall, the results show that penetration resistance is the main soil physical property controlling root penetration and growth. Since penetration resistance is dependent on soil moisture conditions, some studies have focused on the effect of soil moisture content on root growth and development (Sangakkara *et al.*, 2010; Kuchenbuch *et al.*, 2006; Aina & Fapohunda, 1986). They concluded that when soil moisture content increases, soil penetration resistance to the roots decreases and *vice versa*, and that first-order lateral average root length increases as initial seasonal soil moisture content is increased. Furthermore, water stress due to severe moisture deficit in the upper soil layers has been reported to increase root length and decrease root diameter (*i.e.* resulting in more fine roots), which improves potential water uptake by the roots (Li *et al.*, 2011). With increasing intervals between water supply events, root length, root weight density and penetration into deeper soil layers increases (Sangakkara *et al.*, 2010).

Gajri *et al.* (1989) showed that wheat root development was more extensive and rapid in a sandy loam than in a loamy sand, and that root growth was stimulated by early season irrigation and N application. Irrigation in a semi-arid sandy loam resulted in greater root and shoot growth and crop yield, increasing maize yield from 670 (non-irrigated) to 4780 kg ha^{-1} (Magaia *et al.*, 2015). This was particularly due to the positive correlation between grain yield and root weight density, as found in earlier studies (*e.g.* Wang *et al.*, 2014a). Drip fertigation practices have been shown to increase maize root horizontal spread and dry mass (*i.e.* inducing new secondary roots) in a sandy clay soil under a semi-arid tropical climate, while vertical rooting depth was higher under furrow irrigation (Raj *et al.*, 2013).

Plant root systems are known to be highly sensitive to nutrient availability and distribution in the soil. Overall, root elongation has been shown to be inhibited by high soil nitrate concentrations (Tian *et al.*, 2008), suppressing root growth into deeper soil layers and thereby reducing N use efficiency (Comfort *et al.*, 1988). Thus, the application of moderate quantities of N has been shown to favour root growth (Vamerali *et al.*, 2003) and, with low availability of N in soil, to improve root biomass (Wang *et al.*, 2009). Other studies claim that low N availability changes the morphology of the root system and causes less root branching (Eghball *et al.*, 1993). Similar contrasting responses to those described above have been shown in other studies (Wang *et al.*, 2014a; Yu *et al.*, 2014; López-Bucio *et al.*, 2003; Durieux *et al.*, 1994), possibly due to the variations in root architecture development in response to N application being largely dependent on soil type and crop species. As large amounts of organic matter and immobile nutrients are generally found in the upper soil layers, the majority of the roots of most crops generally tend to be concentrated in the upper 0-20 cm soil layer (Gregory, 1994).

3.5 Irrigated areas and maize production in Mozambique

In Mozambique, about 80% of the total population, the latter estimated at 26 million inhabitants in 2016 (INE, 2017), rely on small-scale rainfed agriculture for their livelihoods (Silici *et al.*, 2015). Thus, agriculture remains the key sector and has contributed to more than 23% of the country’s gross domestic product (GDP) for the past 10 years. The production system is dominated by the smallholder farm sector, which accounts for about 98% of the agricultural area, producing almost all the food crops, such as maize, cassava, rice and beans. Overall, smallholder farming is characterised by small fields (1.8 ha each on average), low inputs, inadequate equipment and low yields and returns (FAO, 2016a). The 2009-2010 agricultural census revealed that throughout the country more than 200000 farms used irrigation (INE, 2010).

Mozambique has over 36 million ha of arable land (Donovan & Tostão, 2010) with a potential irrigable land area of about 3 million ha, of which more than 181000 ha are currently equipped with irrigation infrastructure but only about 50% of this area is effectively under irrigation (MINAG, 2015). Of the total irrigated area, about 35000 ha are used for food crop production, while the remaining area is used for sugarcane (sugar and ethanol) production (MINAG, 2014b). Recent plans for expansion of irrigated areas in the country project a growth rate of between 1050 and 15000 ha year^{-1}, expecting to reach more than 377000 ha by 2040 and thus increase the current area four-fold (MINAG, 2015).

Most of the infra-structure and irrigated areas in Mozambique at present are located in the southern region (*i.e.* Inhambane, Gaza and Maputo provinces), mostly lying along floodplains dominated by sandy soils (MINAG, 2014a; MINAG, 2013a; MINAG, 2012). Smallholder ‘traditional irrigation’ systems are the dominant practice to date, while formal irrigation development programmes by government or private investment are more recent additions (FAO, 2016a). Basin irrigation is practised for rice and furrow irrigation for maize, other cereals and vegetables. Basin and furrow irrigation account for 42% of the total irrigated area in the country. Sprinkler irrigation is widespread within private companies, especially in sugarcane plantations, and represents 50% of the country’s total irrigated area. Drip irrigation is limited to a few small and medium-scale producers and is applied mainly to vegetable production, and accounts for 8% of the country’s total irrigated area (FAO, 2016a; MINAG, 2013b). Irrigation efficiency (*i.e.* the ratio between water made available to the crop and that supplied from the water source) is overall as low as 25-50%, mostly in surface-irrigated areas with smallholder farmers (FAO, 2005), and much of the water losses are due to surface runoff and deep percolation. In private farm companies, which mainly use sprinkler irrigation, irrigation efficiency rates are up to 70% (FAO, 2005).

The annual maize production in Mozambique has shown a slight increase in the past decade, from 1.2 million Mg in 2000 to 1.4 million Mg in 2014, but no distinction can be made between rainfed and irrigated production due to lack of statistical data. This increase is mostly due to the expansion in production area, since the average yield has remained almost constant, varying between 0.8 and 1.2 Mg ha^{-1}, in the same period (FAO, 2016b).

The average rate of fertiliser application in Mozambique is 8 kg ha^{-1} (mainly as NPK and urea), which is 50% of the average in sub-Saharan Africa (FAO, 2016b) and 5% of the average in European Union (WB, 2017). Only 4% of farmers currently apply fertiliser (MINAG, 2008). According to a study by Folmer *et al.*, (1998), Mozambique is estimated to lose on average about 122 kg ha^{-1} of N, 60 kg $ha^{-1}$of P_2O_5 and 116 kg ha^{-1} of K_2O per year through nutrient mining in agricultural soils resulting from cultivation without replenishment of nutrients, coupled with soil erosion and leaching of nutrients. Thus, increased and improved fertiliser use is strategically seen as a way to boost production for target crops, including maize, and thus meet the country’s goals by 2020 (MINAG, 2011).

With the current promotion and future adoption of intensive agricultural practices in Mozambique, fertiliser use is expected to increase to about 48 kg ha^{-1} of N, 11 kg ha^{-1} of P_2O_5 and 2.5 kg ha^{-1} of K_2O for a target maize yield ranging between 8 and 10 Mg ha^{-1} (IFDC, 2012). Likewise, considering the low irrigation efficiency and the dominant sandy soils in irrigated areas, improved irrigation and N fertiliser strategies will be required.

4 Materials and methods

4.1 Thesis framework

In this thesis, the effects of different water and N fertiliser management strategies on water and N use efficiency were analysed. The efficiency of water and N uptake by maize plants, the response of root development and their potential contribution for water and N recovery and the redistribution of nitrate and ammonium N in the soil profile were also examined. The studies, which are described in detail in Papers I-III, were focused on different parts of the soil-plant-atmosphere system, altogether contributing to water and N cycling (sources, uptake and sink). *Figure 1* illustrates how the three papers included in the thesis are connected, including the different water and N fertiliser strategies tested.

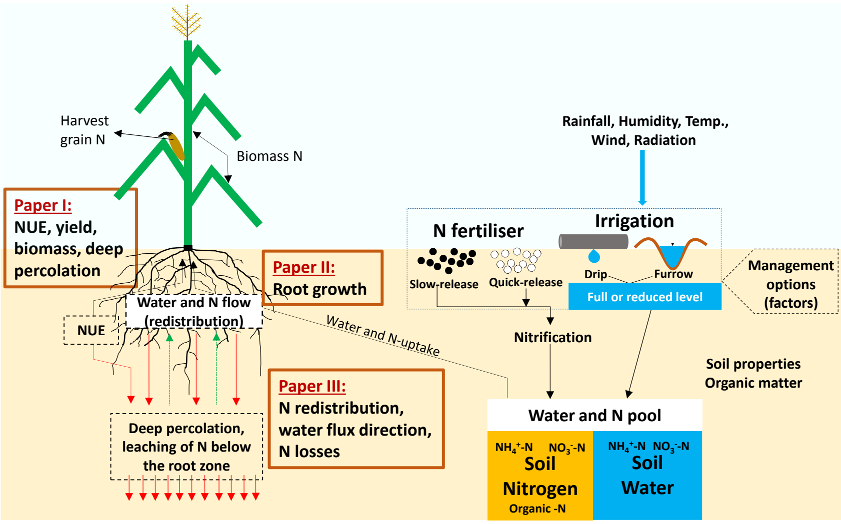

Figure 1. Schematic representation of the relationship between different components addressed in Papers I-III of this thesis.

4.2 Study area, site and experimental design

Papers I-III are all based on data collected in experimental studies carried out in Sábie (25°19’01” S; 32°15’53” E), a rural village located in Sábie Administrative Post in Maputo Province, southern Mozambique (*Figure 2*). The site is located on the experimental station of the Faculty of Agronomy and Forestry Engineering (FAEF), Eduardo Mondlane University (UEM). It is located 58 m above sea level and its soil characteristics and climate conditions are representative for southern Mozambique.

The site is characterised by a tropical steppe climate (Peel *et al.*, 2007) with two distinct seasons, a hot-wet season stretching from October to March and a cold-dry season from April to September (Reddy, 1984). Mean annual rainfall (1990-2015) measured at Corrumana climate station, located 15 km from the experimental station, is 620 mm and shows strong seasonality, with about 88% occurring in the hot-wet season, ranging between 39 and 131 mm month^{-1}, and 12% in the cold-dry season, ranging between 6 and 37 mm month^{-1} (*Figure 3*). Mean annual temperature in the region is 23 °C, with mean minimum temperature between 19 and 22 °C in the hot-wet season, and between 14 and 19 °C in the cold-dry season, while the mean maximum range is between 27 and 32 °C in the hot-wet season and between 24 and 29 °C in the cold-dry season.

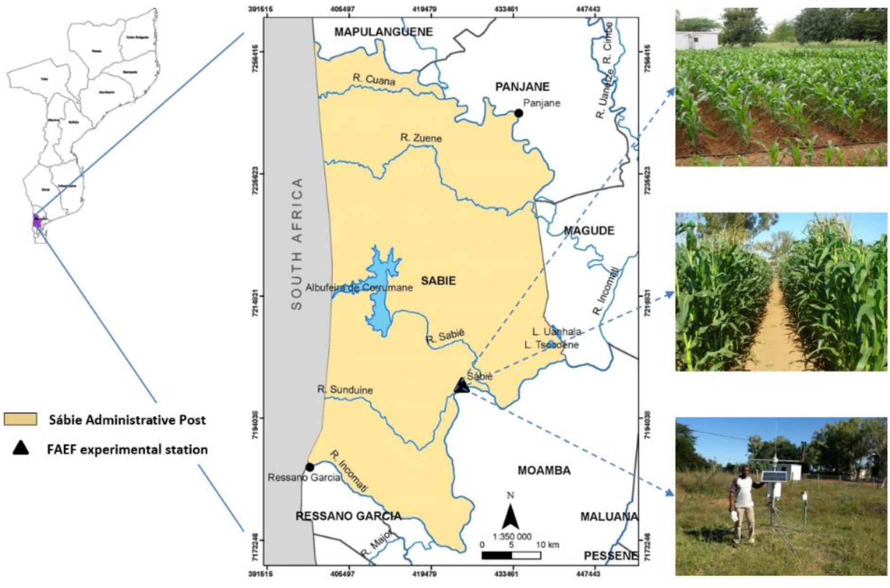

Figure 2. Map of Mozambique (left) and expanded view of Sábie Administrative Post (right), where the FAEF experimental station (▲) is located. Far right: Images from the experimental site. (Photos: Vicente Chaúque and Mário Chilundo)

Mean annual potential evapotranspiration is 1500 mm (Reddy, 1986), ranging between 134 and 159 mm month^{-1} in the hot-wet season and between 81 and 127 mm month^{-1} in the cold-dry season. The ratio of mean annual precipitation to mean annual potential evapotranspiration, or the aridity index, is 0.41, and thus the area is classified as having a semi-arid climate (UNEP, 1997). The crop growing period for rainfed crops (FAO, 1978) is in the hot-wet season, starting in November when the mean monthly rainfall exceeds half the mean monthly potential evapotranspiration, and stretches for five months up to March (*Figure 3*). In the cold-dry season, agricultural production is only possible with the use of irrigation, due to low rainfall.

The annual rainfall recorded at the FAEF experimental station during the period of the studies in this thesis from 2012 to 2015 ranged between 311 and 688 mm (*Figure 4*). In the hot-wet season 2012-2013, when the first study was performed, the monthly rainfall ranged between 18 and 246 mm, while the mean temperature ranged between 22 and 26 °C. The monthly rainfall was between 2 and 63 mm in the cold-dry season of 2013, with mean temperature ranging between 18 and 23 °C whereas in the cold-dry season of 2014, the monthly rainfall was between 0 and 21 mm and the mean temperature between 18 and 23 °C. In the hot-wet season 2014-2015, when the last study was performed, the monthly rainfall was between 2 and 137 mm, with mean temperature ranging between 23 and 28 °C. The climate deviations at the experimental station during the period of the studies were within the expected variations in the region.

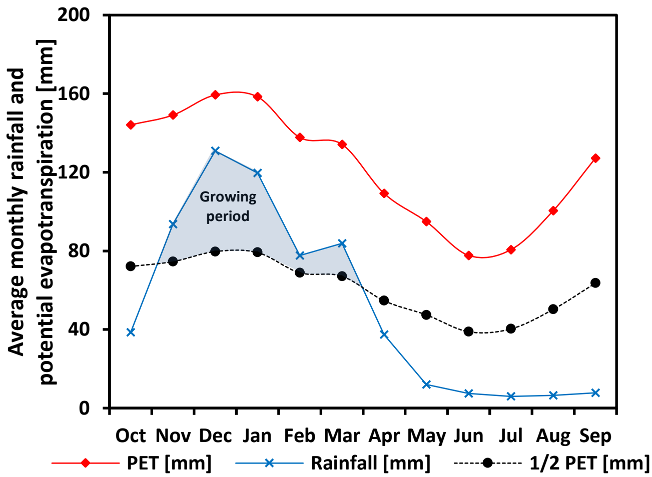

Figure 3. Average monthly rainfall and potential evapotranspiration (PET) (1990-2015) and the rainfed crop growing period (shaded area) for Sábie Administrative Post. Climate data were collected at Corrumana station (Ara-Sul, 2016) located 15 km from FAEF experimental station.

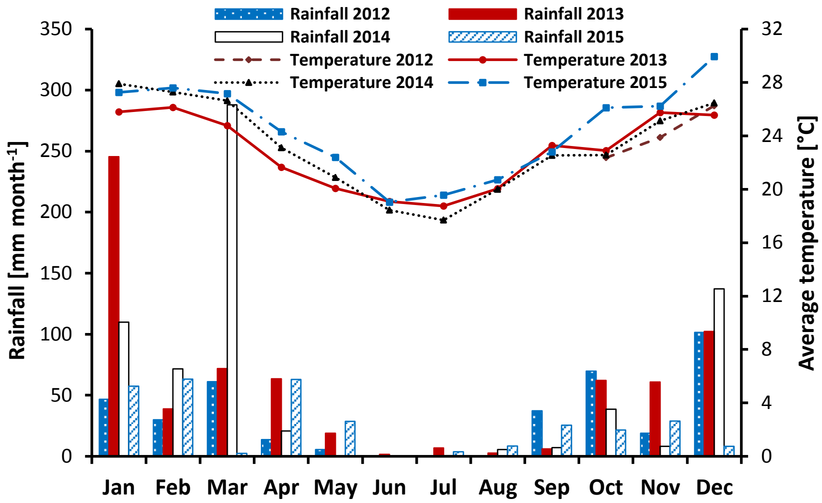

Figure 4. Observed monthly rainfall and mean air temperature for the period 2012-2015 at the FAEF experimental station in Sábie.

The soils in the area comprise deep stratified alluvial deposits with flat or almost flat topography (slope 0-2%), and are classified as Eutric Fluvisols in the FAO soil classification system (MINAG, 2013a; FAO/IUSS/ISRIC, 2006). The soils are generally deep (>4 m), with good to moderate internal drainage, and low natural fertility, and are classified as marginally suitable for agriculture and irrigation (MINAG, 2013a).

The soils at the experimental station had been under bush fallow for at least 10 years before the establishment of the first field experiment in 2012. Before the establishment of trial plots, soil samples were collected throughout the experimental site (0-80 cm depth) and analysed for physical and chemical properties, which constituted the baseline soil data (*Table 1*).

The soil texture was found to range on average from loamy sand to sandy loam, and the soil has neutral pH, low Kjeldahl N content, a very low to extremely low organic matter content, and low cation exchange capacity (Hazelton & Murphy, 2007). The available N content (nitrate (NO_3^--N, hereafter NO3-N) and ammonium (NH_4^+-N, hereafter NH4-N)), based on auger samples collected every 30 cm to a depth of 90 cm throughout the experimental site, ranged between 3.4 and 7.3 kg ha^{-1} for nitrate and between 2.2 and 4.3 kg ha^{-1} for ammonium.

A single soil profile pit excavated at the site revealed dry bulk density values ranging between 1.30 and 1.42 g cm^{-3}, particle density ranging between 2.63 and 2.66 g cm^{-3}, field capacity (at 1 m soil water tension) between 19.0

and 22.6% (v/v) and permanent wilting point (150 m soil water tension) between 5.0 and 5.8% (v/v).

Table 1. *Baseline soil properties at the experimental site (mean±standard deviation, n=24): sand and clay content, texture class, organic matter (OM), organic carbon (OC), Kjeldahl nitrogen (N_{Kj}), pH (in H_2O), electrical conductivity (EC), and cation exchange capacity (CEC), where % is percentage by weight. Water retention (percentage by volume) and dry bulk density from soil core samples in one pit (n=2).*

Depth [cm]	*Physical properties*					
				Water retention [%, v/v]		
	Sand [%]	Clay [%]	Soil texture class	Field capacity [1 m]	Wilting point [150 m]	Dry bulk density [g cm^{-3}]
0-20	80.7±4.0	10.2±1.8	Loamy sand	21.9	5.8	1.42
20-40	81.6±2.6	10.2±1.7	Loamy sand	19.3	5.2	1.31
40-60	80.7±2.1	10.7±1.6	Loamy sand	22.6	5.6	1.30
60-80	80.1±2.6	10.6±1.5	Sandy loam	19.0	5.0	1.34
	Chemical properties					
	OM [%]	OC [%]	N_{Kj} [%]	pH [H_2O]	EC [dS m^{-1}]	CEC [meq100 g)$^{-1}$]
0-20	0.85±0.38	0.49±0.22	0.06±0.03	7.00±0.28	0.44±0.28	7.32±1.82
20-40	0.65±0.28	0.38±0.16	0.06±0.03	7.12±0.24	0.37±0.12	7.33±1.25
40-60	0.68±0.25	0.39±0.15	0.07±0.04	7.26±0.33	0.39±0.18	7.59±1.07
60-80	0.64±0.16	0.37±0.09	0.06±0.04	7.23±0.25	0.42±0.14	7.81±1.24

In the hot-wet season, the Sábie cropping system in irrigated areas is dominated by maize, followed by vegetables (tomato, cabbage, green beans, pepper and cucumber), while during the cold-dry season the cropping system is dominated by vegetables, although maize is present on the majority of farms. Thus, maize was chosen for the experiments in this thesis due to its importance in the southern region and in Mozambique as a whole.

The studies reported in Paper I-III were based on a similar experimental set-up and obtained data for two to four cropping periods between 2012 and 2015. The first cropping period (CP), in the hot-wet cropping season (CP-hw1), was established and ran from November 2012 to March 2013, followed by the first cold-dry season cropping period (CP-cd1) from May to October 2013. The second cold-dry season cropping period (CP-cd2) ran from May to October 2014, and the second hot-wet season cropping period (CP-hw2) from November 2014 to March 2015.

The first hot-wet cropping period (CP-hw1) and the first cold-dry cropping period (CP-cd1) were used in Paper I. The second cold-dry cropping period (CP-cd2) and the second hot-wet cropping period (CP-hw2) were used in Paper III. Data from all cropping periods was used in Paper II.

The experiments entailed eight treatments, resulting from the combination of two irrigation methods, two irrigation levels and two top-dressing nitrogen fertiliser types, arranged in a 2x2x2 factorial system in a randomised complete block design with three blocks, the latter used as replicates (*Figure 5*). The irrigation methods were furrow (F) and drip (D). The irrigation levels were to meet at least the crop water requirements, full irrigation (I_f), and reduced irrigation (I_r) at 75% of full irrigation. The nitrogen fertiliser types were quick-release (N_q) and slow-release (N_s). The treatments assigned to each plot, resulting from the combination of the factor levels, are shown in *Figure 5*.

In each plot, composed of nine furrows and ridges, a medium maturation maize hybrid PAN67 was manually planted with a density of 41600 plants ha^{-1} on 10 November for the two hot-wet cropping periods and 10 May for the two cold-dry cropping periods. The crop has a cycle of approximately 110 days to maturation in the hot-wet season and 140 days in the cold-dry season,

Apart from the different treatments, all plots were treated equally. Soil preparation before establishment of CP-hw1 and CP-cd2 comprised conventional disc tillage to a depth of 20-25 cm, followed by disc harrowing to 12-15 cm depth. Before establishment of CP-cd1 and CP-hw2, no soil preparation was done other than the manual hoeing of weeds. Pests were controlled by spraying chemicals preventatively or on occurrence, according to Mozambican agricultural technical guidelines (UDA, 1982), while weeds were manually hoed on two occasions (*i.e*. at seven-leaf stage and before tasselling).

The N fertiliser treatments consisted of two fertilisers applied as top-dressing: (i) a quick-release urea with 46% N (N_q), which is the most commonly used mineral fertiliser in Mozambique, and (ii) an organic complex-coated slow-release Black Urea® with 46% N (N_s). According to the manufacturer (AN, 2014), the coating is meant to promote rapid population growth of heterotrophs around the fertiliser granule, which are stimulated to metabolise ammonium, thus making it less available to nitrifying bacteria. Furthermore, it is claimed that the normal N cycle takes over once the rhizosphere is generated by plant growth, making N available to the plant in both forms, *i.e*. as nitrate-N and ammonium-N. In total, 100 kg N ha^{-1} were applied to each plot for a target maize yield of 5.5 Mg ha^{-1} (Bondesio *et al*., 2006). Nitrogen was applied on three occasions per cropping period, as adapted from the Mozambican fertilisation regime for irrigated maize (UDA, 1982): 25% of total N as NPK compost (12:24:12) uniformly spread along the rows and hoed into the soil at the time of planting, 37.5% as top-dressing N_q or N_s manually incorporated into the soil beside the growing plants at 5 cm depth between the six-leaf vegatative stage (V6) and seven-leaf vegetative stage (V7), and 37.5% applied similarly at the tasselling stage (VT).

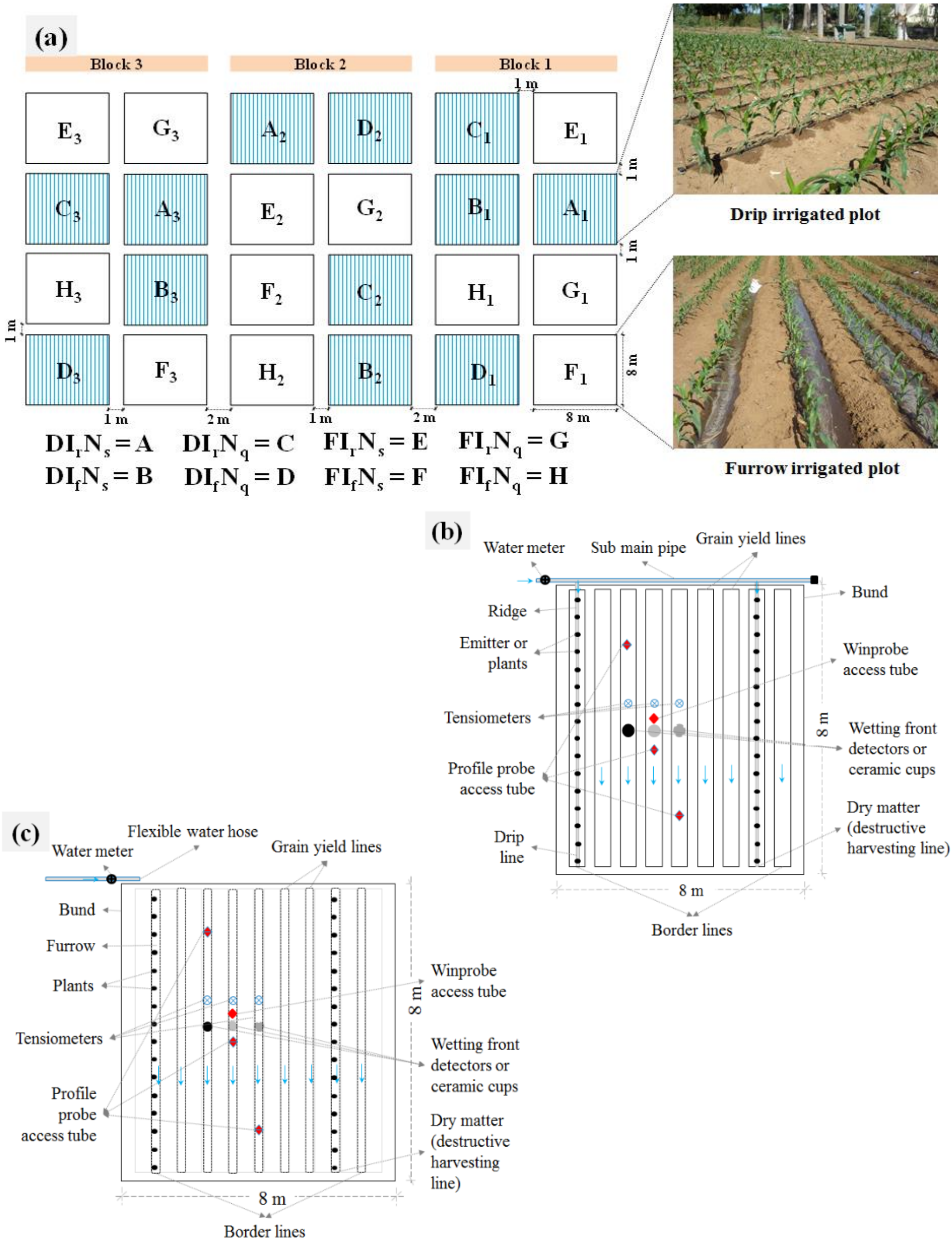

Figure 5. Generalised layout of the experiment set-up including, (a) the distribution of treatments among the blocks resulting from combinations of irrigation method (furrow – F or drip – D), irrigation level (full – I_f or reduced – I_r) and nitrogen (N) fertiliser type (quick-release – N_q or slow-release – N_s), (b) monitoring instrumentation in drip-irrigated plots and (c) in furrow-irrigated plots. A description of the instruments used in the different cropping periods and blocks is given in the running text.

To control the irrigation level, volumetric flow meters were attached to flexible hoses for furrow irrigation treatments and installed on the irrigation manifold pipes for drip irrigation treatments (*Figure 5*). For drip irrigation, Netafim® low-volume, pressure-compensating emitters spaced 30 cm apart along the line, delivering a maximum discharge of 1.0 L h^{-1} at 1 bar operating pressure, were used. In order to start the trials with similar soil moisture conditions and thoroughly wet the soil to values close to or above field capacity in the upper 60 cm, 40 mm water was applied as irrigation before sowing except in CP-hw1, in which 40 mm fell as rain before sowing. The irrigation scheduling was managed by calculating the daily soil water depletion through a simplified soil water balance (Allen *et al.*, 1998):

$$\mathrm{SWD_i} = \mathrm{SWD_{i-1}} + \mathrm{ET_{c,i}} - \mathrm{I_i} - \mathrm{P_i} \qquad \text{(Eq. 1)}$$

where SWD_i is soil water depletion at the end of day i (mm), SWD_{i-1} is soil water depletion at the end of the day before day i (mm), $ET_{c,i}$ is crop evapotranspiration on day i (mm) calculated as the product of crop growth coefficient (adapted from Allen *et al.* (1998) to local climate conditions) and reference evapotranspiration, I_i is the applied irrigation level on day i (mm) and P_i is the rainfall on day i (mm). The minimum value of SWD_i was zero, *i.e.* at field capacity, which was set as the starting boundary condition of each cropping period assuming that the root zone was at field capacity following initial cumulative rainfall or irrigation events prior to sowing. Surface runoff and capillary rise were neglected, due to the level to nearly level topography in the area and the deep groundwater level (>6 m). In furrow-irrigated plots, 30 mm of water were applied in the full irrigation treatments when SWD_i approached 30 mm, while 22.5 mm was applied in the reduced irrigation treatments. The drip-irrigated plots under full irrigation received 15 mm water when SWD_i approached 15 mm, while those under reduced irrigation received 11.25 mm. The irrigation frequency was therefore higher in drip-irrigated than in furrow-irrigated treatments but in total, treatments within irrigation level (full or reduced) received equal amounts of water.

4.3 General field measurements

4.3.1 Weather data

During all four cropping periods studied, meteorological data were collected from an automated weather station installed 40 m from the experimental site (Paper I-III). The set of parameters monitored on a daily basis included rainfall, solar radiation, wind speed at 2 m height, wind direction, relative humidity and air temperature. The daily rainfall, given its possible spatial variability, was also monitored within the experimental plots using UV-protected plastic rain gauges. These readings were later compared with readings made with the automated tipping bucket rain gauge (model TE525WS, Texas Electronics, INC, USA) in the automatic weather station. Following assessment of rainfall data from CP-hw1, the automatic rain gauge was used as the reference monitoring device in the remaining cropping periods due to the possibility of splitting night rainfall events according to the date of occurrence and the reduced demand for monitoring by staff. Rainfall and temperature data for 2012-2015 were as presented in *Figure 4*. Potential evaporation was manually monitored using an Andersson evaporimeter installed at 1.5 m height (Andersson, 1969) adjacent to the weather station.

4.3.2 Soil moisture content, soil water tension and soil water nitrogen concentration

Soil moisture content in the plots was monitored (from sowing to harvest) using WinProbe (Soilzone Solutes, Australia) and PR2 Profile Probe (Delta-T Devices Ltd, Cambridge, UK) devices (Papers II and III). WinProbe was used in periods CP-hw1 and CP-cd1, allowing readings at 10, 20, 30, 40 and 60 cm depth in one access tube placed in the centre of each plot (see *Figure 5*). A PR2 profile probe was used in CP-cd1, CP-cd2 and CP-hw2, with readings at the same depths as WinProbe, and additionally at 100 cm depth, at three different positions along the third, fourth and fifth lines (in CP-cd1) or in the centre of each plot, *i.e*. middle of the fourth line (in CP-cd2 and CP-hw2).

Daily soil water tension was monitored in the centre of each plot in the central block of the experimental site during CP-cd2 and CP-hw2 by means of tensiometers (Irrometer Company Inc., USA), installed at 30, 60 and 90 cm along the third, fourth and fifth lines (*Figure 5*) (Paper III).

Soil water N distribution in the profile in CP-hw1 and CP-cd1 was monitored using wetting front detectors (Agriplas, South Africa; Stirzaker & Hutchinson, 2005) installed in the centre of each plot at 20, 40 and 60 cm depth (Paper I). In CP-cd2 and CP-hw2 they were replaced by ceramic suction cup samplers (Irrometer Company Inc., USA) installed at 30, 60 and 90 cm depth in the centre of each plot (Paper III). Soil water samples in wetting front detectors and suction cups were extracted after irrigation or rainfall events. In the wetting front detectors, water samples were collected whenever the device showed a pop-up flag signalling that soil water had filled its cup. The extraction of soil water using ceramic suction cups in CP-cd2 was done 24 hours after an initial application of 10 kPa suction (*i.e*. a pressure of -10 kPa) before the start of irrigation or during a rain event, aiming to capture the fast-flowing water mainly in the macropores. After this first sample extraction at 10 kPa, the suction was increased to 30 kPa (*i.e.* a pressure of -30 kPa) for the next 36 hours for a second soil water extraction, to capture flow mainly in the mesopores. In CP-hw2, sample collection with suction cups was limited to application of 30 kPa suction, *i.e.* a pressure of -30 kPa applied just before start of irrigation or during a rain event, followed by sample extraction 36 hours after suction application, thereby capturing flow from both macropores and mesopores. After each collection, consecutive soil water samples per depth, extraction suction and treatment were mixed and frozen at -18 °C, and later colorimetrically analysed for nitrate, nitrite (NO_2-N) and ammonium using a portable RQflex reflectometer (Merk Millipore group, Germany). This is described in more detail in Papers I and III.

4.3.3 Soil and total plant nitrogen

Nitrogen content in the soil in all cropping periods was determined using soil samples collected from the 0-30, 30-60 and 60-90 cm layers (Papers I and III). One composite sample per layer, deriving from eight sub-samples spread throughout each individual plot, was taken prior to sowing, at seven-leaf growth stage (V7), 10-leaf stage (V10), silking stage (R1) and after physiological maturity (R6).

The mineral N content (NO3-N and NH4-N) was determined by titration with 0.01 M HCl on soil samples taken prior to sowing and after maturity in CP-hw1, CP-cd1 and CP-cd2 and, furthermore, from all crop growth stages in CP-hw2, after extraction with 2M KCl from frozen (-15 °C) samples and steam distillation as described by Keeney & Nelson (1982).

The Kjeldahl N procedure as described by Westerhout and Bovee (1985) was used to determine the total plant N content (Paper I and III), including grain N, after drying and milling the grain or plant material (passing through a 1 mm sieve).

4.3.4 Root mapping

Root mapping studies were carried out in detail, *i.e.* with measurements of root density and maximum rooting depth, in CP-hw1 and CP-cd1, while in CP-cd2 and CP-hw2 the measurements were limited to the maximum rooting depth (Papers I and II). The mapping was performed at three growth stages: seven-leaf (V7), silking (R1) and physiological maturity (R6). The modified profile wall method originally described by Böhm (1979) was used. On each mapping occasion, a 1.2 m deep trench was dug, centred and parallel to the plant rows, and a smooth vertical face (0.7 m x 1.2 m) was opened for root counting. Roots were uncovered by removing the surrounding soil over a thickness of approximately 5-10 mm using a blunt metal rod. Detailed root mapping was performed by counting visible roots using a frame (0.52 m x 0.52 m) composed of 36 square grids of 0.08 m x 0.08 m and 13 square grids of 0.08 m x 0.04 m placed on the wall face, covering a total area of 0.27 m^2 at each single observation and representing roots from 1.5 consecutive plants (*Figure 6*). Roots were classified into two sizes: coarse roots with diameter ≥0.7 mm and fine roots with diameter <0.7 mm (Ruta, 2008). The maximum rooting depth at each growing stage was taken as the length from the collar region to the tip of the deepest root.

4.3.5 Other variables sampled

At R1 growing stage during CP-hw1 and CP-hw2, soil penetration resistance was measured from the soil surface to 60 cm depth, with 10 replicates along the plant rows in each plot, using a hand-driven electronic Penetrologger (Eijkelkamp, Giesbeek, The Netherlands) (Paper II). In CP-hw1, measurements were made when soil moisture was close to field capacity (two days after a 138.4 mm rainfall event over three consecutive days), while in CP-hw2, the measurements were made in less wetted upper soil (six days after only 37.8 mm rain observed during two consecutive days). These measurements are described in more detail in Paper II. Progressive crop leaf area index (LAI) and aboveground dry biomass (DM) were determined at stages V7, R1 and R6 (Papers I and II).

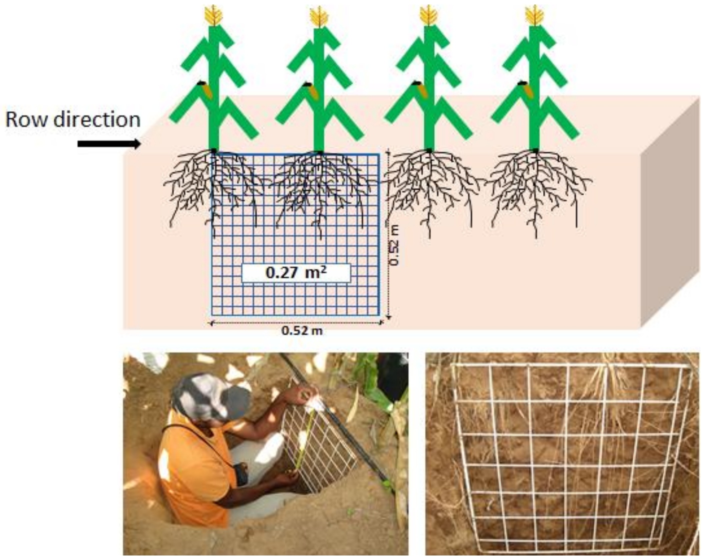

Figure 6. Sketch and overview of detailed mapping of roots (Paper II) with the aid of a frame (0.08 m x 0.08 m grid and 0.08 m x 0.04 m grid) for root counting. (Photos: Vicente Chaúque and Mário Chilundo)

Leaf area index was determined by scanning the plant leaves from two representative plants in each plot with a portable laser leaf scanner CI-202 (CID Bio-Science, USA) during CP-hw1 and CP-cd1. During CP-cd2 and CP-hw2 measurements were performed with a portable photosynthetically active radiation ceptometer LP-80 (Decagon Devices Inc., USA), by placing the sensor diagonally below the canopy in two consecutive maize rows between 10 and 14 h on clear-sky days. Aboveground dry biomass was determined (destructive measurement) by cutting two representative plants per plot at ground level, and mixing leaf blades, stalks, sheaths, tassels, husks and cobs. All the material was dried at 70 °C to constant weight.

Final grain yield (Papers I and II) was assessed by harvesting the central 6 m of two adjacent rows in each plot (see *Figure 5*), and weight was standardised at 15.5% kernel moisture content.

4.4 Calculations and data analysis

4.4.1 Reference evapotranspiration

The reference evapotranspiration (ET_o) (Papers I, II and III) in all cropping periods was estimated from Andersson evaporimeter (Andersson, 1969) data except during the first three weeks after sowing in CP-hw1, when ET_o was calculated from climate data using the Penman-Monteith equation (Allen *et al.*, 1998) using daily data from the automated weather station. The Andersson evaporimeter was chosen because it gave a direct manually performed measure of evaporation that could be used directly in the irrigation scheduling procedure and because the measurement is dependent on only one measuring device, whereas the Penman-Monteith equation is dependent on four electronic devices measuring radiation, air temperature, air humidity and wind speed.

In the irrigation scheduling procedures, the Andersson evaporimeter values were used as reference evapotranspiration. For the full irrigation level, this could result in a certain degree of over-irrigation and consequent percolation of water and N to the zone below the roots, which resemble the common farmer's irrigation practices. Hence, the criterion for the full irrigation level (I_f) was to meet at least crop water requirements, whereas the reduced level (I_r) was expected to supply more than 75%, but less than 100%, of the crop water requirements.

4.4.2 Irrigation water and nitrogen use efficiency

The irrigation water use efficiency (kg m^{-3}) was calculated for all cropping periods as the ratio between the maize grain yield and the seasonal irrigation water applied for a specific water treatment plus the rainfall amount.

The total mineral N available in the soil (N_T) (Papers I) was calculated as the sum of N applied as fertiliser (N_{fert}) plus initial mineral N before sowing (N_z) plus the N applied through irrigation water (N_{ir}) plus N deriving from soil organic matter mineralisation during the cropping period (N_{min}) plus atmospheric N deposition during the cropping period (N_{atm}). As a result, N use efficiency (kg kg^{-1} N_T) per treatment and at physiological maturity stage (R6) was calculated as the ratio between total aboveground dry matter biomass (DM) and N_T (NUE_{DM}) and between grain yield and N_T (NUE_G), the latter calculated after harvesting. Both NUE_{DM} and NUE_G integrate the efficiency of both native and applied N sources. Values for N_{fert}, N_z and N_{ir} were measured, whereas values assumed for N_{min} and N_{atm} are further explained in Paper I. A relatively large contribution of N_{min} was assumed for the first year since before the first experiment installation, the site had been under fallow for more than 10 years.

4.4.3 Stress days, flow direction and deep percolation

The number of stress days during CP-hw1 and CP-cd1 (Paper II) was defined from the days on which the soil moisture content was below the readily available moisture content in the root zone (RAW, mm), the latter calculated as (Benjamin *et al.*, 2014; Allen *et al.*, 1998):

$$\mathrm{RAW} = f \times (\theta_{FC} - \theta_{WP}) \times Z_r \qquad \text{(Eq. 2)}$$

where f is the fraction of available soil water content that can be depleted from the root zone before moisture stress, θ_{FC} is the fraction of soil water content at field capacity, θ_{WP} is the fraction of soil water content at wilting point, and Z_r is the rooting depth. For maize, the plants were considered to be under stress when 55% of the plant-available water had been consumed, *i.e. f set to* 0.55. Stress due to waterlogging (*i.e.* soil air deficiency) was not considered for days on which there was excess water (*i.e.* above field capacity), since stagnant water was not observed after irrigation or rainfall events and thus sufficient internal drainage could be assumed.

The daily water flow direction between the soil depths 30 and 60 cm, and 60 and 90 cm (Paper III), was estimated in the central block for CP-cd2 and CP-hw2 by calculating the hydraulic gradient ($\Delta H/\Delta z$, m m^{-1}) from the Darcy equation:

$$\frac{\Delta H}{\Delta z} = \left(\frac{h_1-h_2}{z_1-z_2}\right) + \left(\frac{g_1-g_2}{z_1-z_2}\right) \qquad \text{(Eq. 3)}$$

where ΔH is the total head difference, (h_1-h_2) is the water pressure head (-tension) difference and (g_1-g_2) the gravitational head difference, all three expressed over a specific flow path length (Δz=z_1-z_2). The flux was considered to be faster when soil water tension was below 20 kPa (*i.e.* above 50% plant-available water) at the flux destination depth, combined with a difference in total head between two consecutive depths. Slower or zero flux was considered when soil water tension was equal to or above 20 kPa (*i.e.* below 50% plant-available water) at the flux destination depth, combined with a difference in total head between these two depths (slower flux), or when there was no difference in total head between these two depths regardless of soil water tension (zero flux). The flow direction between 60 and 90 cm depth was used to assess the days with a potential risk of N losses to the zone below the roots (*i.e.* below 80 cm depth).

Daily deep percolation (DP_i, mm), *i.e.* the amount of water loss out of the root zone (Paper I), was calculated for CP-hw1 and CP-cd1 through the soil water balance approach considering the mass conservation principle (Moreno *et al.*, 1996b), and assuming absence of surface runoff and groundwater capillary rise:

$$DP_i = P_i + I_i - ET_{c,i} - D_{r,i} \qquad \text{(Eq. 4)}$$

where P_i is daily rainfall, I_i is daily irrigation, $ET_{c,i}$ is daily crop evapotranspiration and $D_{r,i}$ is the estimated change in soil water storage.

4.4.4 Estimation of nitrogen losses

The cumulative loss of total mineral N (Paper III) from the soil profile (0-90 cm depth) (N_{Tloss}, kg ha^{-1}), *i.e.* losses through leaching, volatilisation, denitrification, immobilisation in organic matter and ammonium adsorption in clay, were calculated for CP-cd2 and CP-hw2 from sowing to harvest through a N balance approach adapted from Sexton *et al.* (1996):

$$N_{Tloss} = N_{fert} + N_{min} + N_z + N_{ir} + N_{atm} - N_{plant} - N_{final} \qquad \text{(Eq. 5)}$$

where N_{fert} is the nitrogen input from mineral fertiliser application, N_{min} is the nitrogen input from mineralisation of organic matter, N_z is the mineral nitrogen (NO3-N + NH4-N) initially present in the soil (0-90 cm), N_{ir} is the nitrogen input from irrigation water, N_{atm} is the nitrogen input from atmospheric deposition, N_{plant} is the nitrogen uptake by the aboveground biomass, and N_{final} is the mineral nitrogen present in the soil after harvesting (0-90 cm). Values assumed for N_{min} and N_{atm} are further explained in Paper III.

4.5 Statistical analyses

The general linear model (Papers I and II) and general linear mixed model (Papers II and III) applied to the factorial design were used to assess the interaction or single effect of test factors on response variables, while the Tukey's Honestly Significant Difference (HSD) and Student's *t*-test were used for multiple and pair-wise mean comparisons with the significance level set at $p<0.05$ (Papers I-III). Linear regression and Pearson correlation analysis were used for detecting relationships between variables (Papers I-III). All statistical analyses were performed using Minitab 17 statistical software (Minitab Inc., State College, PA, USA).

5 Results

5.1 Effects of irrigation and nitrogen fertilisation strategy on deep percolation, grain yield, nitrogen uptake and nitrogen use efficiency (Paper I)

In Paper I, the first hot-wet cropping period (CP-hw1) and the first cold-dry cropping period (CP-cd1) were studied.

Potential nitrogen losses through deep percolation were found to be higher in the hot-wet period than in the cold-dry period, and this was associated with higher estimated deep percolation volumes in the hot-wet period (mean 127 mm) than in the cold-dry period (mean 12 mm). In the hot-wet period, deep percolation events mainly coincided with high rainfall events (*Figure 7*).

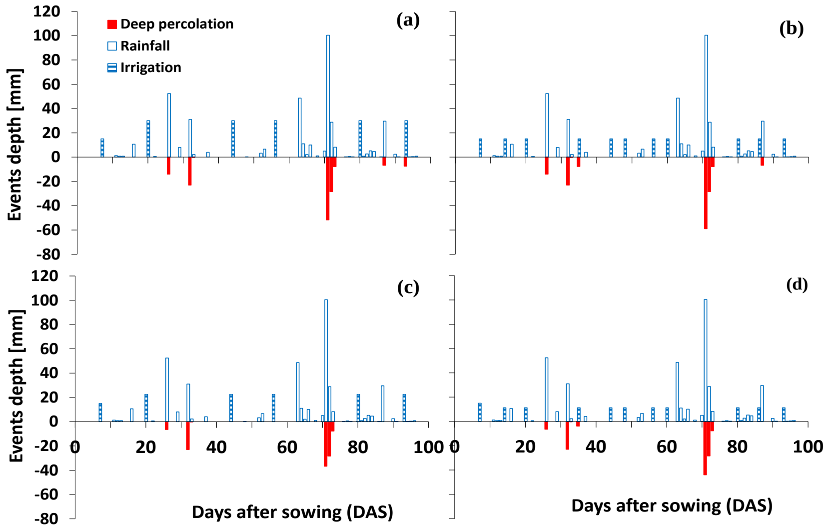

Figure 7. Deep percolation with full irrigation (I_f) (a and b) and reduced irrigation (I_r) (c and d) during hot-wet cropping period 1 for furrow (F) irrigation (a and c) and drip (D) irrigation (b and d) as influenced by rainfall and irrigation events.

Deep percolation events were estimated on seven occasions during the hot-wet cropping period and the cumulative amounts ranged between 103 mm (in reduced furrow irrigation (FI_r) treatments) and 147 mm (under full drip irrigation, DI_f) (*Table 2*). In this period, the first major deep percolation loss was estimated at 26 days after sowing (DAS) (14 mm), after a 52.4 mm rainfall event, while the highest loss was estimated at 71 DAS (59 mm) under DI_f treatments following a 100.4 mm rainfall event. At later stages, deep percolation events at 72 (28 mm) and 73 DAS (8 mm) were generally associated with relatively low-magnitude rainfall events (<30 mm) and high soil moisture conditions, mainly in full irrigation treatments (*Figure 7*). In the cold-dry period, deep percolation losses were only estimated to occur in a few low-level events totalling 12 mm, and were mainly associated with frequent irrigation events during the crop establishment, *i.e.* at early growth stages (first 33 DAS), when irrigation regime was similar in all treatments.

Both cropping periods displayed average maize grain yield of about 6 Mg ha^{-1}, but with a trend for higher yields in the cold-dry period than in the hot-wet period (the terms 'trend' and 'tend to' in this thesis are used when *p* values are near significance). In the hot-wet period, the highest observed yield was in treatment FI_rN_q (6.4 Mg ha^{-1}), while in the cold-dry period the highest yield was in treatment FI_fN_s (6.5 Mg ha^{-1}) (*Table 2*). Maize yield variation in both cropping periods showed trends for being explained only by the interaction between irrigation level and N fertiliser type.

The N uptake by maize overall ranged between 126 (treatment DI_rN_s) and 207 kg N ha^{-1} (treatment DI_rN_q) in the hot-wet period, and the values were overall higher per treatment in the cold-dry period, the latter ranging from 144 (treatment DI_fN_q) to 208 (treatment FI_fN_s) kg N ha^{-1} (*Table 2*). All N uptake values exceeded the N application rate in the system. No interaction effect between irrigation method, irrigation level and N fertiliser type on N uptake was found in either the hot-wet or cold-dry cropping period. However, in the cold-dry period, the irrigation level and the interaction between irrigation level and N fertiliser type tended to explain the variation in N uptake.

Maize aboveground dry matter N use efficiency (NUE_{DM}) was overall lower in the hot-wet period (mean 67.5 kg DM kg^{-1} N) than in the cold-dry period (mean 76.8 kg DM kg^{-1} N). In the hot-wet period, the highest NUE_{DM} was found in treatment DI_rN_q (75.9 kg DM kg^{-1}), while in the cold-dry period the highest NUE_{DM} was found in treatment FI_rN_q (93.2 kg DM kg^{-1}) (*Figure 8*).

Maize grain nitrogen use efficiency (NUE_G) was found to be similar in the hot-wet (mean 35 kg kg^{-1} N) and cold-dry period (mean 38 kg kg^{-1} N) (*Figure 9*). In the cold-dry period, irrigation method tended to better explain the variation in NUE_G, with higher NUE_G resulting from furrow irrigation treatments, while the interaction between irrigation level and N fertiliser type tended to explain the NUE_G variation in the hot-wet period.

Table 2. *Deep percolation (DP), N uptake, grain N, dry matter (DM) and grain yield (15.5% moisture) in hot-wet (CP-hw1) and cold-dry (CP-cd1) cropping periods as affected by irrigation method (furrow – F or drip – D), irrigation level (full – If or reduced – Ir) and N fertiliser type (quick-release N – N_q or slow-release N – Ns). N uptake, grain N, DM and grain yield values are given as mean±standard deviation, n=3.*

Cropping Period	Treatment	Water applied	DP	N uptake		Grain N		DM		Grain yield	
		[mm]	[mm]	[kg N ha^{-1}]		[kg N ha^{-1}]		[Mg ha^{-1}]		[Mg ha^{-1}]	
CP-hw1	FI_fN_q	551	139	164	±37	67.3	±3.9	11.4	±0.3	6.2	±0.7
	FI_fN_s	551	139	179	±46	64.0	±6.6	11.5	±1.3	5.6	±0.2
	FI_rN_q	513	103	202	±94	60.9	±4.8	12.6	±2.0	6.4	±0.5
	FI_rN_s	513	103	195	±29	62.2	±9.2	11.2	±1.1	5.4	±0.9
	DI_fN_q	551	147	154	±41	67.8	±9.6	11.2	±0.6	5.5	±0.6
	DI_fN_s	551	147	157	±75	71.5	±8.0	11.1	±1.4	6.1	±0.3
	DI_rN_q	513	114	207	±75	63.8	±25.0	12.4	±3.8	6.2	±1.0
	DI_rN_s	513	114	126	±30	71.1	±9.8	9.8	±1.3	5.8	±0.8
CP-cd1	FI_fN_q	565	12	162	±68	67.9	±23.2	10.2	±3.5	6.2	±2.2
	FI_fN_s	565	12	208	±9	74.3	±13.4	11.7	±1.3	6.5	±1.1
	FI_rN_q	452	12	207	±4	71.2	±10.3	12.7	±1.1	6.4	±0.3
	FI_rN_s	452	12	186	±55	64.1	±16.0	11.1	±1.0	6.2	±0.9
	DI_fN_q	565	12	144	±70	62.7	±1.9	8.9	±1.0	5.6	±1.2
	DI_fN_s	565	12	182	±22	62.4	±14.0	9.1	±0.6	5.6	±1.1
	DI_rN_q	452	12	193	±26	60.8	±17.0	10.8	±1.5	5.5	±1.7
	DI_rN_s	452	12	204	±21	69.0	±12.0	11.6	±2.6	6.3	±0.6

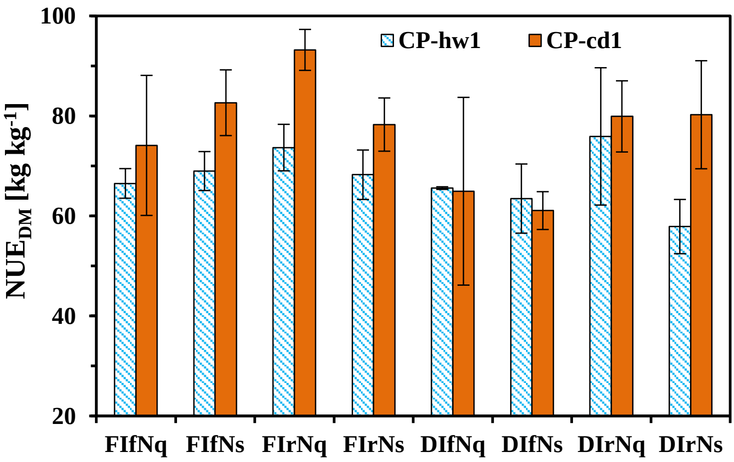

Figure 8. Maize aboveground dry matter nitrogen use efficiency (NUE_{DM}) with standard error of mean (bars) for hot-wet cropping period 1 (CP-hw1) and cold-dry cropping period 1 (CP-cd1), resulting from combinations of irrigation method (furrow – F or drip – D), irrigation level (full – I_f or reduced – I_r) and nitrogen fertiliser type (quick-release N – N_q or slow-release N – N_s).

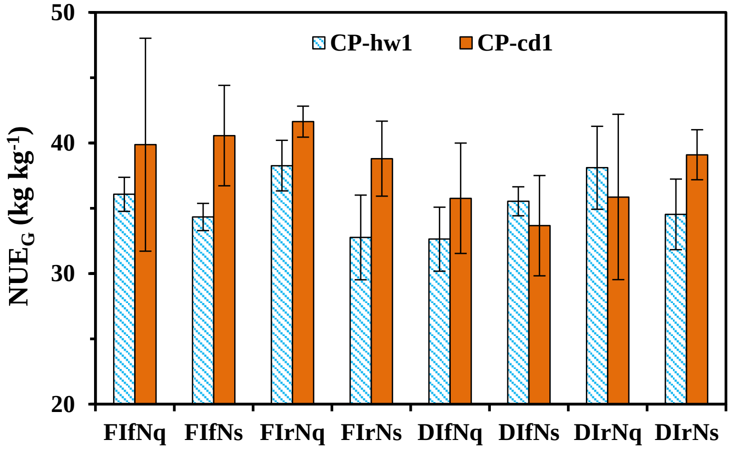

Figure 9. Maize grain nitrogen use efficiency (NUE_G) with standard error of mean (bars) for hot-wet cropping period 1 (CP-hw1) and cold-dry cropping period 1 (CP-cd1), resulting from combinations of irrigation method (furrow – F or drip – D), irrigation level (full – I_f or reduced – I_r) and nitrogen fertiliser type (quick-release N – N_q or slow-release N – N_s).

As for NUE_{DM} in the cold-dry period, the highest NUE_G was found in treatment FI_rN_q, with 42 kg kg^{-1} N. This was also the treatment resulting in the highest NUE_G in the hot-wet period, about 38 kg kg^{-1} N.

Overall, the use of furrow irrigation tended to give higher N use efficiency than drip irrigation, especially in the cold-dry cropping period. In addition, the reduction in irrigation level from the full to reduced irrigation treatment (I_f to I_r) tended to increase N uptake, N use efficiency and maize yield during both cropping periods, regardless of irrigation method and N fertiliser type. Overall, higher N use efficiency was observed in the cold-dry than in the hot-wet period (*Figure 8 and 9*). Slow-release N fertiliser did not give evidence of improving N use efficiency, N uptake or maize yield in either cropping period.

5.2 Root density and maximum rooting depth response to irrigation and nitrogen fertilisation strategy (Paper II)

In Paper II all four cropping periods were studied, *i.e.* both hot-wet cropping periods (CP-hw1, CP-hw2) and both cold-dry cropping periods (CP-cd1, CP-cd2). Detailed root mapping was performed in CP-hw1 and CP-cd1, while the maximum rooting depth was measured in all four cropping periods.

For CP-hw1 and CP-cd1 cropping periods, maize coarse roots were overall concentrated in the uppermost 48 cm (87% of root density) of the soil profile, while fine roots were mostly in the uppermost 56 cm (94%). Root density was not affected by the interaction between irrigation method, irrigation level and

N fertiliser type, given the few statistically significant effects. Root density distribution was explained by the variation in individual factors. In general, irrigation method affected growth and development of the maize root system in both hot-wet and cold-dry cropping periods, whereas the results were not robust regarding the effects of irrigation level or the interaction effect between irrigation method and irrigation level. For the irrigation method effect, for example, drip irrigation resulted in 33-153% higher coarse root density (*Table 3*) and 26-55% higher fine root density than furrow irrigation in deeper layers (16-64 cm) (*Table 4*), whereas furrow irrigation gave 21-40% higher coarse root density than drip irrigation in shallow layers (0-16 cm).

Table 3. *Mean density (number of roots per 100 cm^2) of coarse maize roots (≥ 0.7 mm) at three growth stages (V7, R1, R6) as affected by irrigation method (furrow – F, drip – D), irrigation level (full - I_f, reduced - I_r) and nitrogen fertiliser type (quick-release – N_q, slow-release – N_s) in four soil layers for hot-wet cropping period 1 (CP-hw1) and cold-dry cropping period 1 (CP-cd1). Means in each soil layer for different factors followed by different letters are significantly different at p<0.05. Values are mean of 12 observations for a particular factor.*

CP	Growth stage	Depth (cm)	Factors					
			Irrigation method		Irrigation level		N fertiliser type	
			F	D	I_f	I_r	N_q	N_s
hw1	V7	0-16	4.48	4.07	*3.73b*	*4.82a*	4.30	4.25
		16-32	2.56	3.06	2.88	2.75	*3.31a*	*2.31b*
		32-64	*0.06b*	*0.37a*	0.28	0.15	0.28	0.15
		64-96	-	-	-	-	-	-
	R1	0-16	5.79*a*	4.12*b*	4.68	5.22	5.04	4.87
		16-32	4.05	4.26	4.38	3.93	3.94	4.37
		32-64	*1.42b*	*1.89a*	1.67	1.63	*1.38b*	*1.93a*
		64-96	0.01	0.11	0.02	0.10	0.03	0.09
	R6	0-16	6.44a	4.78b	5.32	5.89	5.36	5.85
		16-32	5.38	4.95	5.20	5.13	4.96	5.37
		32-64	*1.55b*	*2.32a*	2.05	1.82	1.84	2.03
		64-96	0.00	0.11	0.02	0.09	0.03	0.09
cd1	V7	0-16	3.08	2.81	2.92	2.98	2.86	3.04
		16-32	*1.23b*	*1.89a*	1.64	1.48	1.46	1.66
		32-64	0.02b	0.19a	0.11	0.09	0.09	0.12
		64-96	-	-	-	-	-	-
	R1	0-16	*5.42a*	*4.47b*	5.08	4.80	4.94	4.94
		16-32	3.41	3.84	3.66	3.59	3.58	3.67
		32-64	0.58b	1.47a	1.09	0.96	1.01	1.04
		64-96	-	-	-	-	-	-
	R6	0-16	*5.06a*	*4.02b*	4.49	4.59	4.44	4.64
		16-32	3.87	3.24	3.39	3.72	3.70	3.41
		32-64	*0.62b*	*1.23a*	0.90	0.95	*0.80b*	*1.06a*
		64-96	-	-	-	-	-	-

Irrigation level had little effect on root density in either of the two first cropping periods (CP-hw1, CP-cd1). For coarse root density, for example, in the majority of cases, for all growth stages and both cropping periods, mean root density in the uppermost soil layer (0-16 cm) was higher with reduced than with full irrigation. Below 16 cm soil depth, however, in most cases full irrigation resulted in higher mean coarse root density than reduced irrigation. Conversely, for fine roots, the density differed between the cropping periods. In CP-hw1, reduced irrigation resulted in higher fine root density in the top layer (0-16 cm), and full irrigation tended to result in higher fine root density in deep layers, while in CP-cd2 the opposite was observed.

Table 4. *Mean density (number of roots per 100 cm^2) of fine maize roots (<0.7 mm) at three growth stages (V7, R1, R6) as affected by irrigation method (furrow – F, drip – D), irrigation level (full – I_f, reduced – I_r) and nitrogen fertiliser type (quick-release – N_q, slow-release – N_s,) in four soil layers for hot-wet cropping period 1 (CP-hw1) and cold-dry cropping period 1 (CP-cd1). Means in each soil layer for different factors followed by different letters are significantly different at p<0.05. Values are mean of 12 observations for a particular factor.*

CP	Growth stage	Depth (cm)	Factors					
			Irrigation method		Irrigation level		N fertiliser type	
			F	D	I_f	I_r	N_q	N_s
hw1	V7	0-16	17.59	22.12	*14.73b*	*24.97a*	19.51	20.19
		16-32	*8.27b*	*15.65a*	12.24	11.68	13.22	10.70
		32-64	*0.35b*	*1.59a*	1.40	0.54	1.31	0.63
		64-96	-	-	-	-	-	-
	R1	0-16	87.61	78.01	80.89	84.64	77.30	78.66
		16-32	*63.36b*	*79.74a*	76.56	66.55	67.64	75.47
		32-64	*25.37b*	*39.38a*	34.97	29.78	33.27	31.48
		64-96	0.21	2.97	0.54	2.64	2.01	1.17
	R6	0-16	74.50	70.70	69.38	75.82	79.35	65.85
		16-32	55.36	62.58	60.94	57.00	59.21	58.73
		32-64	*17.11b*	*25.81a*	21.46	21.47	21.45	21.48
		64-96	*0.18b*	*1.45a*	0.46	1.17	0.83	0.79
cd1	V7	0-16	19.49	24.41	22.87	21.04	*18.02b*	*25.89a*
		16-32	*6.77b*	*14.01a*	10.10	10.68	9.92	10.85
		32-64	*0.19b*	*1.32a*	0.37	1.14	0.79	0.72
		64-96	-	-	-	-	-	-
	R1	0-16	85.11	82.11	*91.69a*	*76.34b*	82.93	85.10
		16-32	54.78	50.51	57.70	47.59	52.61	52.68
		32-64	*15.50b*	*23.79a*	21.87	17.43	18.63	20.66
		64-96	0.15	0.42	*0.12b*	*0.45a*	0.23	0.34
	R6	0-16	73.40	72.95	*78.40a*	*67.95b*	75.83	70.53
		16-32	57.93	55.14	53.61	59.47	55.30	57.78
		32-64	*14.42b*	*22.03a*	17.18	19.28	17.63	18.82
		64-96	*0.14b*	*0.47a*	0.37	0.23	0.23	0.37

Application of slow-release N (N_s) fertiliser tended to result in higher root density and deeper coarse and fine roots than quick-release N (N_q) fertiliser in both cropping periods (CP-hw1 and CP-cd1) (*Table 3 and 4*). Given the seasonal effect on variation in root density between the hot-wet season and cold-dry season (see Tables 2 and 4 in Paper II), slow-release N resulted in overall higher grain yield and biomass in CP-cd1 than in CP-hw1, although no interaction between N fertiliser type and season was found.

The maximum rooting depth was overall greater in the first cropping periods studied (CP-hw1 and CP-cd1) than in the later periods (CP-cd2 and CP-hw2) (*Figure 10*). However, it was not affected by the interaction between irrigation method, irrigation level and N fertiliser type.

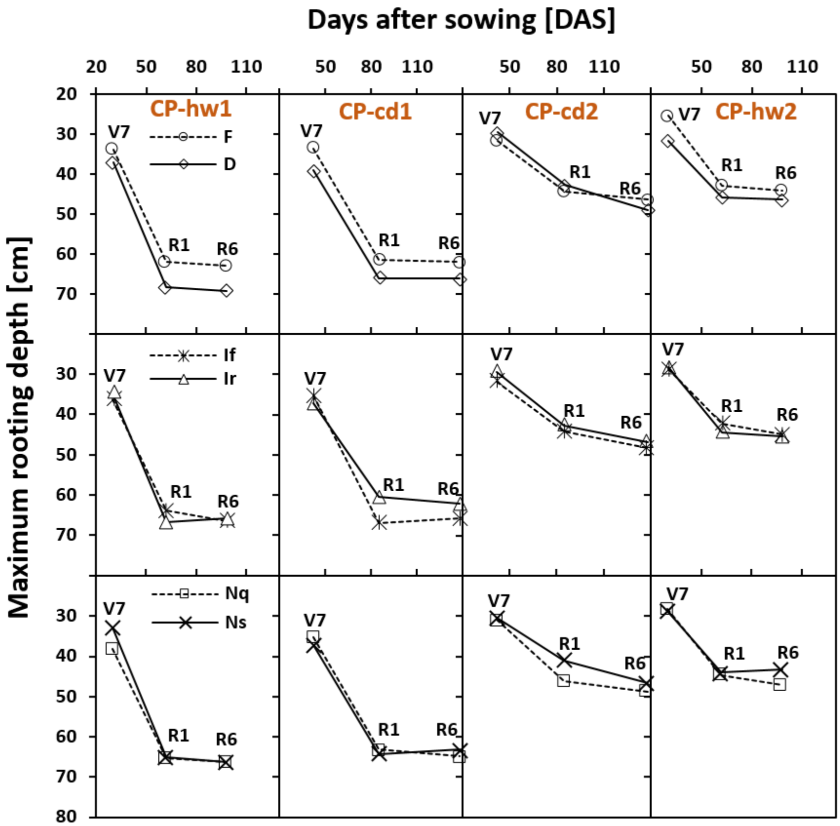

Figure 10. Variation in mean maximum rooting depth at three growth stages (V7, R1 and R6) as affected by irrigation method (drip – D or furrow – F), irrigation level (full – I_f or reduced – I_r) and nitrogen fertiliser type (quick-release N – N_q or slow-release N – N_s) in four cropping periods during the hot-wet seasons (CP-hw1, CP-hw2) and the cold-dry seasons (CP-cd1, CP-cd2). Each mean value per growth stage is a mean of 12 observations.

Considering all four cropping periods together, maximum rooting depth was overall deeper in drip than in furrow treatments at almost all growth stages studied (10 out of 12 assessed cases). Furthermore, in the majority of cases (eight out of 12 assessed), mean maximum rooting depth was greater in full than in reduced irrigation level in all cropping periods and growth stages. Moreover, deeper mean maximum rooting depth was generally associated with quick-release rather than slow-release N treatments throughout the growth stages (nine out of 12 cases).

Root density and maximum rooting depth showed few significant correlations with grain yield, biomass and leaf area index. However, higher maize root density generally tended to result in higher grain yield as observed in their generally positive relationship. Accordingly, of the four cropping periods studied, grain yield was affected by the interaction between irrigation method, irrigation level and N fertiliser type only in one period (*i.e.* CP-cd2), where the DI_fN_q treatment had 34% higher grain yield than the lowest in FI_rN_s treatment. In three of the four cropping periods, drip irrigation gave higher mean grain yield than furrow irrigation. In CP-hw2, drip irrigation showed 25% higher grain yield than furrow, while in CP-cd2 it was 13% higher (p<0.05 in both cases). These higher grain yields in drip irrigation were partly associated with the relatively higher root density in the soil profile compared with furrow irrigation treatments.

5.3 Soil profile water and nitrogen redistribution as affected by irrigation and nitrogen management (Paper III)

In Paper III the second cold-dry cropping period (CP-cd2) and the second hot-wet cropping period (CP-hw2) were studied.

Soil water and soil nitrate-N (NO3-N) and ammonium-N (NH4-N) concentrations in the soil profile were overall increased at depth under high soil moisture conditions resulting from the effect of the interaction between irrigation method, irrigation level and N fertiliser type. Compared with other factor combinations, the application of furrow or drip irrigation combined with full irrigation and quick-release N resulted in an increase in soil water nitrate-N at lower depths over time, thus suggesting movement of N from upper to lower layers in both the cold-dry and hot-wet period. This pattern was found in samples extracted at both 10 and 30 kPa tension, highlighting potential rapid soil water and N redistribution under saturated or near saturated conditions in macropores and mesopores as influenced by irrigation and N fertilisation regime. The application of reduced irrigation and slow-release N resulted in longer soil water nitrate-N residence time at 30 and 60 cm depth in the cold-dry period and partially in the hot-wet period. In the cold-dry period, the mean soil water nitrate-N concentration at 30 and 60 cm was 81% and 59% lower in I_fN_s and I_fN_q treatments, respectively, than in I_rN_s treatments, which had the highest values. In the hot-wet period a similar effect was found only at 30 cm depth, where I_fN_s treatments resulted in 85% less mean nitrate-N than the highest value in I_rN_s. Comparable results were found for soil water ammonium-N, with residence time in top layers being overall longer under reduced irrigation. Moreover, ammonium-N concentrations were in general, and in the entire soil profile, on average 44% higher in the cold-dry than in the hot-wet period.

The fast downward movement of soil water nitrate-N was evident in the hot-wet period (*Figure 11*), but in the cold-dry period the collected data did not allow similar visual analysis. During the days assessed, there was an overall increase in soil water nitrate concentration throughout the soil profile (*e.g.* between 28 and 37 DAS, and between 46 and 56 DAS). This increase was particularly evident in furrow-irrigated plots, regardless of irrigation level and N fertiliser type, in comparison with drip-irrigated plots. However, at later sampling occasions (*e.g.* from 61 to 64 DAS), the overall decrease in soil water nitrate-N concentration in upper layers was accompanied by a relative increase in nitrate-N at lower depths, *i.e.* 90 cm.

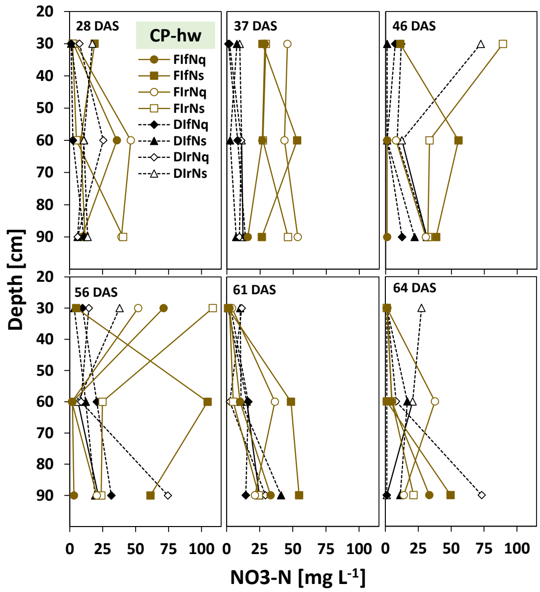

Figure 11. Soil water nitrate-nitrogen (NO3-N) at different soil depths for six sampling occasions during hot-wet cropping period 2 (CP-hw2), as influenced by a combination of irrigation method (furrow – F, drip – D), irrigation level (full – I_f or reduced – I_r) and nitrogen fertiliser type (quick - N_q release or slow – N_s). Each NO3-N value is a mean of three replicates.

The depth distribution of soil nitrate-N and ammonium-N showed large variations in the soil profile, *i.e.* the concentrations increased and decreased. The variation in soil nitrate-N in CP-hw was determined by the interaction between irrigation method and N fertiliser type, with higher soil nitrate-N in the 0-30 and 60-90 cm layers at 31 DAS associated with FN_s treatments, with similar results at 81 DAS for 0-30 and 30-60 cm layers (*see Table 2* in Paper III). After crop physiological maturity, the FN_s treatment gave the highest soil nitrate-N in the 0-30 cm layer, and FN_q the highest soil nitrate-N in the 30-60 cm, both with full irrigation. The highest soil nitrate-N in the 60-90 cm layer was seen in treatment DI_fN_s. For soil ammonium-N variation, no clear effect of the factors tested could be established. At 81 DAS, however, the interaction between irrigation method, irrigation level and N fertiliser type indicated that ammonium-N concentration variation in the soil profile might have been influenced by FI_f treatments, regardless of N fertiliser type. These treatments resulted in the lowest soil ammonium-N in the top layers (0-30 cm), and the highest at 30-60 cm and 60-90 cm, thus suggesting its depletion in upper layers and deposition in underlying layers.

The water flux direction in reduced irrigation treatments during both cold-dry and hot-wet period (*Figure 12*) was slower or zero on the majority of measuring occasions, as a result of relatively higher soil water tension and/or lack of differences in total hydraulic potential, with the exception of treatment FI_rN_q during the hot-wet period. The slower or zero flux under reduced irrigation was mostly found to be associated with furrow irrigation, with no influence of fertiliser type, in both the cold-dry and hot-wet period.

Upflow (faster flux), was also found to be associated with reduced irrigation treatments, irrespective of irrigation method and N fertiliser type, with relatively higher frequency in the hot-wet period than in the cold-dry period. The downflow (faster flux) was mainly estimated to occur in full irrigation level treatments, irrespective of the irrigation method or N fertiliser type. Full level drip irrigation treatments, in comparison with full level furrow irrigation, generally resulted in 33 to 91% more occasions with downflow from 30 to 60 cm depth, while from 60 to 90 cm depth the increase in downflow occasions ranged between 8 and 108%. This indicates conditions with a higher risk of potential losses of water and N with full level drip irrigation. Furthermore, the leaching risk was concentrated in the first 50 to 75 days after sowing in reduced level furrow and drip irrigation treatments, while it was spread throughout the cropping period in full level furrow and drip irrigation treatments.

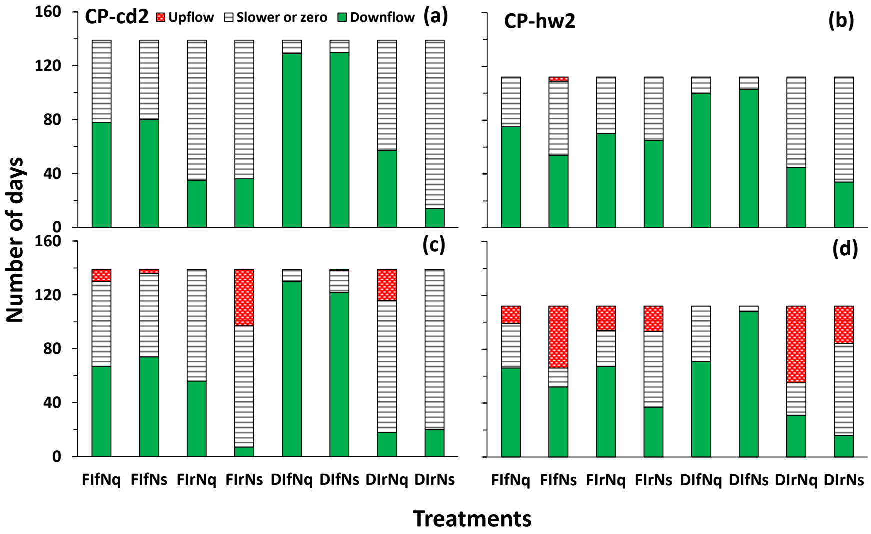

Figure 12. Variation in number of days with different flux directions (faster upflow or faster downflow, and slower or zero) in cold-dry cropping period 2 (CP-cd2) and hot-wet cropping period 2 (CP-hw2) between 30 and 60 cm depth (a and b) and between 60 and 90 cm (c and d) as affected by a combination of irrigation method (furrow – F or drip – D), irrigation level (full – I_f or reduced – I_r) and nitrogen fertiliser type (quick – N_q or slow – N_s release).

5.4 Irrigation water use efficiency

Of the four cropping periods studied, the highest irrigation water use efficiency values were obtained in the two cold-dry periods (1.42 kg m^{-3} in CP-cd1 and 1.40 kg m^{-3} in CP-cd2 under treatment FI_rN_q and DI_rN_s, respectively) (*Table 5*). Those treatments also resulted in the highest irrigation water use efficiency during the hot-wet cropping periods, but at lower values, *i.e.* 1.22 kg m^{-3} (CP-hw1) and 1.26 kg m^{-3} (CP-hw2), thus 10 and 14% lower than in cold-dry periods. The water use efficiency was mostly affected by irrigation level, whereas no effect of the interaction between irrigation method, irrigation level and N fertiliser type on irrigation water use efficiency was found. Thus, considering results from all cropping periods, reduced irrigation resulted in 12% higher water use efficiency than full irrigation.

Table 5. *Irrigation water use efficiency (kg m^{-3}) resulting from the combined effect of irrigation method (furrow – F or drip – D), irrigation level (full – I_f or reduced – I_r) and N fertiliser type (quick – N_q or slow – N_s release) in hot-wet cropping periods (CP-hw1 and CP-hw2) and cold-dry cropping periods (CP-cd1 and CP-cd2). Treatment means followed by different letter in each cropping period are significantly different at $p<0.05$. Values are mean of three observations.*

Treatment	Cropping period			
	CP-hw1	CP-cd1	CP-cd2	CP-hw2
F I_f N_q	1.09ab	1.10ab	0.93b	0.96ab
F I_f N_s	1.00ab	1.15ab	1.05ab	0.85b
F I_r N_q	1.22a	1.42a	1.31ab	1.05ab
F I_r N_s	1.02ab	1.37ab	1.17ab	0.85b
D I_f N_q	0.97b	0.99b	1.24ab	1.29a
D I_f N_s	1.09ab	0.99b	1.15ab	1.20ab
D I_r N_q	1.17ab	1.22ab	1.22ab	1.15ab
D I_r N_s	1.10ab	1.40ab	1.40a	1.26a

6 Discussion

6.1 Variation in soil moisture, potential water fluxes and water use efficiency (Papers I, II and III)

In general, sandy soils are known for their increased likelihood of losing water due to their higher degree of internal drainage and lower water-holding capacity compared with finer soils (Alhammadi & Al-shrouf, 2013; Yu *et al.*, 2013). The results obtained in this thesis, under loamy sandy soil conditions, indicated that soil moisture redistribution over time (Paper III), potential water flux (Paper III) and deep percolation (Paper I) were primarily affected by irrigation method and irrigation level during cold-dry cropping periods, and by the combined effect of irrigation method and level and rainfall pattern during hot-wet cropping periods. Overall, a less significant influence of N fertiliser type on soil moisture redistribution was detected (Paper III). In cold-dry cropping periods, rainfall contributed 2-9% of the total water input in the different treatments, while in hot-wet cropping periods the contribution of rainfall ranged between 52 and 73% of the total water input (Papers I and III). As a consequence, deep percolation events were estimated (*i.e.* from Eq. 4) to occur more often in the hot-wet periods, and, furthermore, to a larger degree in drip-irrigated treatments with full irrigation (*Figure 7* and *Table 6*). The presence of wetter entire soil profiles, as under full irrigation (*e.g.* in drip irrigation, with 16-20% v/v at 0-32 cm depth to about 16% v/v at 32-64 cm), or wetter deeper layers (*e.g.* in furrow irrigation, about 12-16% at 0-32 cm depth, >16% v/v at 32-64 cm) (Paper II) enabled a fast flux of water in heavy rainfall events. Comparable effects of rainfall events increasing deep percolation under irrigated conditions have been reported in other studies (Wang *et al.*, 2014b; Behera & Panda, 2009; Moreno *et al.*, 1996b). Furthermore, some studies have found that increases in deep percolation are primarily associated with the irrigation regime used (frequency and level), mostly at early crop growth stages before a deeper root system has been established, when water requirements are low (Linderman *et al*., 1976).

Table 6. *Rainfall (Prec., mm), irrigation (Irri., mm) and estimated deep percolation (DP, mm) during hot-wet cropping periods (CP-hw1 and CP-hw2) and cold-dry cropping periods (CP-cd1 and CP-cd2), as affected by the combination of irrigation method (furrow – F or drip – D) and irrigation level (full – I_f or reduced – I_r).*

Cropping periods	Irrigation method	Furrow (F)		Drip (D)	
	Irrigation level	Full (I_f)	Reduced (I_r)	Full (I_f)	Reduced (I_r)
CP-hw1	Prec	386	386	386	386
	Irri	180	143	180	143
	DP	139	103	147	114
CP-cd1	Prec	40	40	40	40
	Irri	525	412	525	412
	DP	12	12	12	12
CP-cd2	Prec	13	13	13	13
	Irri	528	415	528	415
	DP	4	1	4	1
CP-hw2	Prec	266	266	266	266
	Irri	240	188	240	188
	DP	41	14	52	25

Another important process determining deep percolation in the system studied may have been preferential flow of water in macropores, as recognised in previous studies (Bouma, 1981). This possibly occurred more in furrow irrigation, due to higher applied water amounts at each irrigation event (lower irrigation frequency), occasionally increasing hydraulic gradients and preferential flow. Moreover, in this thesis, a certain degree of over-irrigation was occurring with application of full irrigation level, and thus the relatively higher estimated deep percolation under full irrigation was somewhat expected. However, care is needed in irrigation management during hot-wet seasons, even with application of reduced irrigation, due to the large influence of rainfall.

The assessment of water flux direction in the second cold-dry and hot-wet cropping periods (Paper III), based on hydraulic gradient difference (Eq. 3), indicated that the use of drip irrigation combined with full irrigation level, in comparison with furrow irrigation combined with full irrigation level, resulted in 33 to 91% more days with downflow from 30 to 60 cm, while from 60-90 cm depth the increase ranged between 8 and 108%, thus indicating conditions for an increased risk of water and N losses below the root zone (*i.e.* 80 cm depth). Furthermore, the days with downflow were concentrated in the first 50-75 days after sowing in furrow or drip-irrigated treatments with reduced irrigation, while in furrow or drip-irrigated treatments with full irrigation they were spread throughout the cropping period.

More frequent irrigation with smaller amounts of water, similar to the scheduling with drip irrigation in this thesis, has been suggested as a strategy to reduce deep percolation in coarse-textured soils (Linderman *et al.*, 1976). However, the results in the present thesis indicate that this strategy may only be suitable during cold-dry cropping periods, *i.e.* under conditions with a reduced number of excess rainfall events. Moreover, concerns have been raised that drip irrigation cannot completely eliminate deep percolation and potential leaching of N below the root zone (Sui *et al.*, 2015; Vázquez *et al.*, 2006). Thus, recent research on strategies for irrigation in arid and semi-arid areas have focused on deficit irrigation as a way of obtaining significant water savings with a relatively small reduction in crop yield (Gheysari *et al.*, 2017), while increasing water use efficiency. In the present thesis, such an outcome was significant in the hot-wet cropping period, when the use of reduced irrigation level in comparison to full irrigation resulted in a reduction in deep percolation of 22% and 37% for furrow and drip irrigation, respectively (Paper I). In the cold-dry cropping period, however, the influence of reduced irrigation level on deep percolation was estimated to be minor, as a result of small estimated values.

An immediate consequence of deficit irrigation management as a strategy to reduce water and N losses is an increase in days with water stress, which will potentially translate into negative effects on plant growth (Ahmed *et al.*, 2014; Pandey *et al.*, 2000a). The estimates obtained in the present thesis indicated, as expected, that stress days (Paper II) were more frequent under reduced irrigation treatments than under full irrigation in both the hot-wet and cold-dry cropping periods (*Figure 13*). Based on irrigation water use efficiency (*Table 5*), the relatively higher values with reduced irrigation level compared with full irrigation in both hot-wet and cold-dry cropping periods apparently denoted a low impact of stress days on maize growth. Earlier studies in semi-arid environments found a comparable increase in irrigation water use efficiency when deficit irrigation was tested (El-Wahed & Ali, 2013; Mansouri-Far *et al.*, 2010; Hassanli *et al.*, 2009). Furthermore, irrigation water use efficiency values were expected to be lower in furrow irrigation compared with drip, as supported in the literature (Karimi & Gomrokchi, 2011), particularly under similar conditions. In the present work, the relative similarities in water use efficiency values in furrow and drip irrigation could be partly explained by the reduced length of furrows used in the experiments (*i.e.* 8 m), which allowed good water application control, in comparison with the generally longer furrows in on-farm irrigation management. Improvements in water use efficiency on shortening furrows from 40 to 10 m have been reported by Eshetu *et al.* (2009).

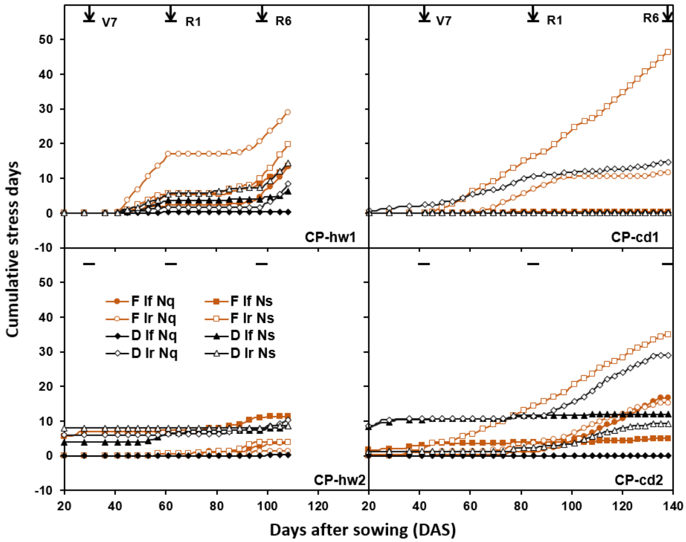

Figure 13. Effect of combination of irrigation method (furrow – F or drip – D), irrigation level (full – I_f or reduced – I_r) and N fertiliser type (quick – N_q or slow – N_s release) on cumulative days with water stress (stress days), *i.e.* days with soil moisture content below 55% of available water in hot-wet cropping periods (CP-hw1 and CP-hw2) and cold-dry cropping periods (CP-cd1 and CP-cd2). Arrows indicate key maize growth stages: V7 = seven-leaf stage, R1 = silking stage and R6 = physiological maturity.

6.2 Root density distribution in irrigated soil (Papers II and III)

Root density distribution was not affected by the interaction between irrigation method, irrigation level and N fertiliser type in either hot-wet or cold-dry cropping periods (Paper II). Overall, drip irrigation resulted in higher coarse and fine root densities in deeper soil layers (16-64 cm) than furrow irrigation, whereas furrow irrigation resulted in a shallower root system with a greater density at 0-16 cm depth than drip irrigation (*Tables 3 and 4*). It could be expected that under relatively drier upper layers, such as those observed in furrow-irrigated treatments, there could be some promotion of maize root growth (elongation and density) to deep layers (Sampathkumar *et al.*, 2012; Sangakkara *et al.*, 2010). Restriction of roots to top layers could be expected under drip irrigation due to the localised nature of wetting and the associated reduced wetted soil volume (Coelho & Or, 1999), compared with the larger spread and deepening of root distribution theoretically expected in furrow irrigation. However, the results in the present thesis indicated that root elongation in furrow-irrigated treatments was generally limited by the combination of longer drying periods between consecutive irrigation events in the upper soil layer, and consequently higher soil penetration resistance due to the temporarily reduced soil moisture content (Papers II and III). Another explanation for the lower root penetration to the lower soil layers could be that possible destabilisation of the soil structure caused by the run-on of irrigation water in furrow irrigation, with application of 22.5 to 30 mm of water in a single application event in the present work, may have resulted in a more compact topsoil (Bennie & Krynauw, 1985). This root development pattern is consistent with findings in previous studies on soils with similar or comparable texture and in similar environmental conditions (Bengough *et al.*, 2011; Gajri *et al.*, 1991). In contrast, in drip-irrigated treatments in the present work, the frequent irrigation, and thus better soil profile wetting, enabled the expansion and deepening of the maize root system, with an associated increase in the soil volume explored by roots for water and nutrient uptake.

The effect of slow-release N fertiliser on root growth under irrigated conditions has been reported in a few previous studies (Peng *et al.*, 2013; Zheng *et al.*, 2006). In the work presented in this thesis, application of slow-release N fertiliser generally did not explain the variation in maize root density in either the hot-wet or cold-dry cropping period (Paper II). However, during the cold-dry cropping period, in more than 77% of the cases assessed, slow-release fertiliser resulted in higher coarse and fine maize root density than quick-release fertiliser, thus representing a potential fertilisation option to promote root growth. One possible explanation for the better performance of the slow-release fertiliser in the cold-dry period compared with the hot-wet period might be the longer residence time of N in the soil profile under relatively cooler temperature (Paper III), thus allowing a better nutrition environment for root growth promotion. Similar N fertiliser responses have been reported in a previous study (Zotarelli *et al.*, 2008).

Deep rooting of crops is a key factor in achieving higher production levels because of its influence on water and nutrient uptake (Al-Khafaf *et al.*, 1989). The pattern of maize root deepening found in the present thesis was comparable to that in previous studies, where it is accepted that in overall terms, deepening of roots in the soil profile is favoured by good nutrition and adequate soil moisture conditions (Vamerali *et al.*, 2003). Other studies claim that low N availability changes the morphology of the root system and causes less root branching (Eghball *et al.*, 1993). Under favourable conditions, a major part of the root system is usually found in the top 20 cm of soil (Fageria & Moreira, 2011), as large amounts of organic matter and immobile nutrients are generally found there (Gregory, 1994). However, in the present thesis fine roots, for example, were largely concentrated in the uppermost 56 cm of the soil profile (Paper II). This spread and deepening or roots is thus believed to be a response to the quick redistribution of N in loamy sandy soil, especially with use of drip irrigation, full irrigation and quick-release N fertiliser, a combination which resulted in deeper maize roots overall.

6.3 Redistribution of nitrogen, grain yield response and nitrogen use efficiency (Papers I, II and III)

Relatively fast redistribution of N in the soil profile was found for soil water nitrate-N and ammonium-N on different sampling occasions in both cold-dry and hot-wet cropping periods. However, the nitrate-N concentrations were distinctly higher than those of ammonium-N and their distribution was influenced by the interaction between irrigation method, irrigation level and N fertiliser type (Paper III). This could be partly explained by the fast flow in soil macropores and mesopores (*i.e.* soil water extracted at 10 and 30 kPa suction) (Luxmoore, 1981; Bouma, 1981), resulting in a relatively fast flow variation in nitrate-N concentration on different sampling occasions and depths during both cropping periods. Consequently, it can be speculated that this relatively fast flow represents the primary path by which nitrate-N is translocated to deeper soil layers and to layers below the root zone, since nitrate-N is primarily held in solution (Schoonover & Crim, 2015). Furthermore, these risks were found to be increased when downflow occurred at early crop growth stages (Paper III).

Overall, the redistribution of soil water nitrate-N was more pronounced in hot-wet cropping period compared with cold-dry period, partly because of the favourable conditions for nitrification in hot-wet periods. In addition, the rapid uptake by the crop (*i.e.* due to the short crop cycle in the hot-wet periods) and the occurrence of relatively higher magnitude rainfall events, which increase soil moisture content, are other factors increasing N translocation (Wang *et al.*, 2014b). Furthermore, it should be acknowledged that the observed differences in soil water nitrate-N redistribution extracted at 30 kPa suction between cold-dry and hot-wet cropping periods, could be partly explained by the slightly different soil water sampling procedures used in the two cropping periods.

The results in this thesis showed also that overall, combining reduced irrigation with slow-release N fertiliser in either the cold-dry or hot-wet period, regardless of irrigation method, resulted in longer soil water nitrate-N residence time at 30 and 60 cm depth (Paper III), which represented the depth with the greatest concentration of roots (*i.e.* uppermost 56 cm) (Paper II). The reported delayed release of nutrients by slow-release fertilisers, ranging from 20 days to 18 months (Trenkel, 2010), coupled with reduced irrigation level could thus explain the soil water nitrate-N stability at 30 and 60 cm depth.

However, the nutrient release pattern of slow-release fertiliser is considered to be strongly dependent on microbial activity and properties that affect this activity, such as temperature and soil moisture content (Liu *et al.*, 2014). Thus, the relatively higher temperature and number of rainfall events in the hot-wet cropping periods, leading to temporary high soil moisture content (Papers I and III) seem to have negatively affected the performance of the slow-release N fertiliser compared with the conditions during the cold-dry cropping periods. This is because the rate, pattern and duration of N release in slow-release N fertiliser are not well controlled and N can be quickly released when high temperatures and excessive soil moisture occur simultaneously (Liu *et al.*, 2014).

The above processes governing soil water nitrate-N redistribution in the soil profile were reflected in the variations observed in bulk soil nitrate-N, although there were no clear patterns indicating that the combination of the three factors tested affected soil nitrate-N. However, regardless of irrigation method and N fertiliser type, treatments receiving full irrigation showed some accumulation of soil nitrate in the 60-90 cm layer at harvest.

The soil water ammonium-N concentration extracted at 30 kPa suction also showed some redistribution over time (Paper III). Mean concentrations were 44% higher in the cold-dry period than in the hot-wet, while full irrigation level in comparison with reduced irrigation accounted for depletion of ammonium-N in top layers, yet at lower magnitude compared with soil water nitrate-N. Lowering of the nitrification rate by the relatively lower temperatures in the cold-dry period (see *Figure 4*) could be a possible explanation for the overall higher soil water ammonium-N concentrations compared with the hot-wet period, since the optimum for nitrification is reported to be around 35 °C (Myers, 1975). As for soil water nitrate-N redistribution in the soil profile, the differences between soil water ammonium-N in the two cropping periods could also be attributed to differences in sampling procedure, as indicated earlier. Furthermore, previous studies have reported reduced ammonium-N adsorption in coarse-textured soils, due to their overall lower organic matter and cation exchange capacity (Blanchart *et al.*, 2007). Consequently, as the soil at the experimental site has a low organic matter content and low cation exchange capacity (*Table 1*), it can be speculated that the redistribution of soil water ammonium-N was mostly due to the effect of soil moisture variations. This was to some extent supported by the variation in bulk soil ammonium-N in the hot-wet cropping period, but complementary data on soil ammonium-N concentrations in the cold-dry cropping period were not available.

The study of N uptake by the crop throughout the first hot-wet and cold-dry cropping periods (Paper I) revealed that the uptake exceeded the estimated N application rate, with relatively higher N uptake per treatment in the cold-dry cropping period compared with the hot-wet. It may be deduced that at the experimental site, there was a large contribution from the fresh organic material following the long fallow (>10 years) prior to the experiments, especially for the first two cropping periods, and this contribution may have been underestimated. Another study on a sandy loam adjacent to the experimental site (50 m) found that maize grain yield was on average 2.5 Mg ha^{-1} in the first year (equivalent to CP-hw1) and 3.8 Mg ha^{-1} in the second year (equivalent to end of CP-cd1), in treatments receiving irrigation without fertiliser addition (Magaia *et al.*, 2015). This suggests a large contribution of native N to crop N uptake and final yield. In addition, no interaction effect between irrigation method, irrigation level or N fertiliser type was found on N uptake. Nevertheless, there were indications of better uptake with combined application of reduced irrigation with slow or quick-release fertiliser, mainly in the cold-dry cropping period. Furthermore, the translocation of N from vegetative organs to grain was low (*Table 2*), ranging between 30 and 56% in both cropping periods. Comparable low N translocation from vegetative organs to grain has been associated with excessive irrigation, which has been reported to increase plant N losses due to leaching or disruption of N translocation, mainly between anthesis and maturity growth stages (Xu *et al.*, 2005).

Grain yield is a direct consequence of the amount of N applied and N uptake by the crop (Zhao *et al.*, 2013; Dobermann, 2005). Overall, grain yield was affected by the interaction between irrigation method, irrigation level and N fertiliser type, and yield was 7% higher in cold-dry cropping periods than in hot-wet cropping periods (Paper II) (*Figure 14*). Even though no individual effect of factors was found, drip irrigation generally tended to give higher yield than furrow irrigation. The highest mean yield was found in drip irrigated treatments with reduced irrigation level and slow-release N fertiliser in the cold-dry periods. The relatively better yield in the cold-dry periods might be a result of the relatively slower N redistribution in the soil profile due to less influence of rainfall and temperature, and thereby a tendency for ammonium-N to increase in relation to nitrate-N. In the hot-wet season, there was possibly increased mineralisation and a tendency for nitrification to increase the conversion of ammonium into nitrate, which is highly mobile and may accompany the soil water to layers below the root zone to a higher degree than ammonium.

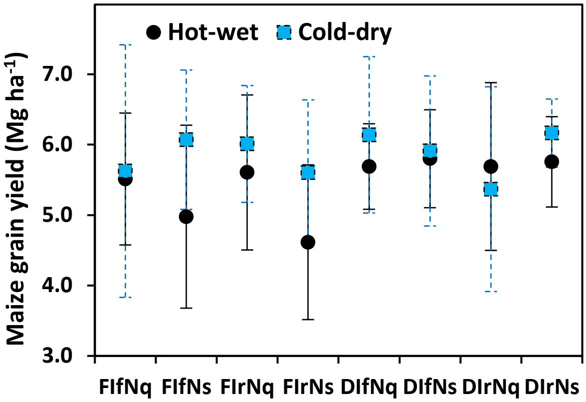

Figure 14. Maize grain yield in the hot-wet cropping period (CP-hw1 and CP-hw2) and cold-dry cropping period (CP-cd1 and CP-cd2) as affected by the combination of irrigation method (furrow – F, drip – D), irrigation level (full – I_f or reduced – I_r) and nitrogen fertiliser type (quick – N_q or slow – N_s release urea). The value per treatment is a mean of six observations, and bars represent the standard deviation.

The N use efficiency and its components (*i.e.* dry matter use efficiency (NUE_{DM}) and grain use efficiency (NUE_G)) were overall lower in the hot-wet cropping period than in the cold-dry period, partly confirming the expectations of less N losses during cold-dry than hot-wet cropping periods (Paper I). Furthermore, the results indicated a tendency for higher NUE_{DM} and NUE_G in the furrow-irrigated treatments under reduced irrigation level in both hot-wet and cold-dry cropping periods. Overall, higher N use efficiency would be expected under drip irrigation, as reported in earlier studies (Tagar *et al.*, 2012; Ayars *et al.*, 1999). In the experimental conditions employed in the present thesis, the better performance of furrow irrigation, which was especially apparent in the cold-dry cropping period, might be associated with the short furrow length used (8 m), which allowed good water application control, as mentioned earlier. Furthermore, N use efficiency was increased with the reduced irrigation level compared with the full level, thus yielding similar effects to those observed for irrigation water use efficiency in both cropping periods. This highlights the possibility of reducing irrigation level in semi-arid loamy sandy soils as a strategy to reduce water and N losses. Higher N use efficiency under deficit irrigation compared with full or over-irrigation has been reported in earlier studies (Ning *et al.*, 2012; Gheysari *et al.*, 2009b). Furthermore, other studies recommend not only a reduction in irrigation amount, but essentially the application of appropriate irrigation scheduling as a way of maximising N use efficiency and crop yield (Panda *et al.*, 2004). Given the positive effect of slow-release N fertiliser on root development in the cold-dry cropping period (Paper II), a similar response could be expected regarding N use efficiency, but this was not found to be the case. There was a tendency for slightly better NUE_{DM} and NUE_{G} under quick-release N fertiliser in both cropping periods. This might be explained by the influence of sources of N other than that applied as top dressing. Nevertheless, earlier studies have reported an increase in N use efficiency and N uptake by a summer maize crop treated with slow-release fertiliser compared with similar application of conventional fertiliser (Zhao *et al.*, 2013).

6.4 Evaluation of study methods and their implications for the results

Sound estimates of soil water balance, which are essential for proper irrigation management in experiments and on farms, require adequate determination and monitoring of its main components. Crop evapotranspiration under standard conditions, for example, which was essential for setting the irrigation scheduling during the field trials, is calculated as the product of experimentally determined crop coefficient (K_c) and standard reference crop evapotranspiration (ET_o) (Allen *et al.*, 1998). Different ET_o estimation methods are available and they all show wide variation (Djaman *et al.*, 2015; Weiß & Menzel, 2008). The FAO-Penman Monteith method is the most widely accepted and recommended approach (Allen *et al.*, 1998). However, this method has limitations in terms of the need for weather data, which are often not available in semi-arid regions. This is potentially a drawback for promotion of precision irrigation. In this thesis (Papers I, II and III), ET_o was estimated from Andersson evaporimeter (Andersson, 1969), which gives a direct, manually performed measurement of evaporation that can be used directly in irrigation scheduling, and is dependent on only one measuring device.

The Andersson evaporimeter device is described in detail by Messing (1998) and is composed of a Plexiglass cylinder (70 mm inner diameter, 70 mm high) with a water container in the lower 40 mm and vertical small holes in the upper 30 mm, and a lid (100 mm in diameter) that is solid on top but with holes on the sides through which water can evaporate (*Figure 15*).

Figure 15. Andersson evaporimeter. (Photo: Mário Chilundo)

It is thus a physical model, although admittedly crude, of a leaf with stomata in which there is a certain resistance to the evaporating water, whereas *e.g.* the more generally used class A pan has direct evaporation to the open air. The effect of this functional difference was shown by Messing (1998), who found that the ratio between Andersson evaporimeter and class A pan values varied between 0.8:1 and 1:1 at two meteorological stations in dry sub-humid and arid conditions. For humid cold temperate conditions, an approximate 0.7:1 relationship between evapotranspiration from an irrigated ley and Andersson evaporimeter values was found by Johansson (1969). In arid conditions an approximate ratio of 0.6:1 (warm summer period) and 0.9:1 (cooler winter period) was found between values from a Penman equation and Andersson evaporimeter (Messing, 1998). The use of Andersson evaporimeter values for the estimation of ET_o in the present thesis, which assumed a ratio of 1:1, may have resulted in a certain overestimation of ET_o and, as a consequence, irrigation events being more frequent than needed to meet the crop water requirements. Thereby, for full irrigation level, a certain degree of over-irrigation may have occurred, which to a certain degree resembled the conventional irrigation practice under semi-arid conditions on irrigated loamy sandy soils in Mozambique. This over-irrigation was of interest in the present work for evaluating deep percolation and leaching behaviour.

The soil moisture measurements during the cropping periods (Papers II and III) were made using the spot monitoring approach, where soil moisture readings were taken using portable probes in planted access tubes. Even though their potential use for real-time soil moisture monitoring has been largely supported in the literature (Bittelli, 2011; IAEA, 2008), access tube measurements may also introduce inaccuracies. The disturbance of soil during access tube installation and the potential for preferential flow along the tube represent some potential issues. In the present thesis work, gravimetric calibrations, installation of access tubes prior to cropping period start and increased frequency of monitoring were part of the strategy used to reduce possible sources of error.

The method used for the assessment of N dynamics in the soil profile also plays an important role for accurate description of soil N changes (Papers I and III). The full stop wetting front detectors used in the first hot-wet and cold-dry cropping periods, which have been reported to perform well under diverse conditions (Stirzaker & Stevens, 2004; Stirzaker, 2003), had low performance at 40 and 60 cm depth in the present thesis. This was explained by the generally weak wetting fronts at deeper layers, normally travelling with tensions higher than the designed threshold of the wetting front detectors to collect soil water (*i.e.* corresponding to soil water tension lower than 2 kPa)

(Stirzaker, 2008). Thus for the latter two cropping periods, wetting front detectors were replaced by ceramic suction cups. These devices are regarded to be suitable for monitoring N leaching in non-structured soils, such as sandy soils (Webster *et al.*, 1993). However, underestimations compared with values obtained using drainage lysimeter or soil coring methods have been reported (Zotarelli *et al.*, 2007). The fast water movement generally occurring in coarse-textured soils under extremely dry or wet conditions has been indicated as the major factor for N leaching underestimation using ceramic suction cups (Barbee & Brown, 1986). In the present work, in order to avoid these extreme sampling conditions, suction was established immediately before irrigation or following rainfall events, running over the period with fastest flows.

7 Conclusions

This thesis presents physical and chemical data on how the interactions between water and N fertiliser management factors affect water and nitrogen use efficiency, and their impact on maize growth and yield on a semi-arid irrigated loamy sandy soil:

The main conclusions are:

- Treatments with full irrigation level and quick-release N fertiliser, irrespective of the irrigation method (drip or furrow), had a greater number of deep percolation events, which mainly occurred at early crop growth stages when the maize root system was not well developed. In contrast, reduced irrigation, especially in hot-wet cropping periods resulted in fewer deep percolation events. Nitrogen uptake and N use efficiency tended to be higher in cold-dry cropping periods than in hot-wet periods, and furrow irrigation with reduced irrigation and quick-release N fertiliser gave higher N use efficiency. Overall, maize yield was higher in cold-dry cropping periods, mainly associated with reduced irrigation level, regardless of the irrigation method and N fertiliser type.
- In both hot-wet and cold-dry cropping periods, drip irrigation overall contributed to better soil profile wetting, resulting in higher maize root density and maximum rooting depth, whereas furrow irrigation resulted in a shallower maize root system, irrespective of irrigation level. The application of slow-release N fertiliser resulted in higher root density, particularly in the cold-dry cropping period.
- The interaction between full irrigation level and quick-release N fertiliser, irrespective of irrigation method, tended to result in lower N concentration in shallow soil layers and higher in deeper layers, thus acting as the main driver for net downward redistribution of N in the soil

profile. The application of reduced irrigation level and slow-release N fertiliser resulted in longer soil water nitrate-N and soil water ammonium-N residence time at 30 and 60 cm depth in the cold-dry cropping period, with some similar trends in the hot-wet cropping period.

- Compared to similar treatments with full irrigation level, the reduced irrigation level resulted in overall higher irrigation water use efficiency in cold-dry cropping periods than in hot-wet. The effects of irrigation method and N fertiliser type on irrigation water use efficiency were inconclusive.

8 Recommendations and future perspectives

This thesis demonstrated that reduced irrigation level can be of great importance in cold-dry cropping periods in semi-arid loamy sandy soils to reduce deep percolation and N losses while maintaining high water and N use efficiency and promoting high grain yield. However, further research is required, mainly to assess the performance of the reduced irrigation strategy when combined with drip irrigation and slow-release N fertiliser in long-term trials. Some further issues to be addressed in future research include:

- Assessment of best practice irrigation scheduling in hot-wet cropping seasons under loamy sandy soils, to reduce deep percolation, which was found to influence the magnitude of N losses below the root zone. This should include differentiated irrigation water deficit strategies following the crop growth stages, thus avoiding a water surplus at early growth stages when the root system is not well established.
- Assessment of slow-release and controlled-release N fertilisers in terms of their ability to increase nutrient availability in the soil profile, while increasing water and nitrogen use efficiency and grain yield. This should also include assessment of economic trade-offs and evaluation of the benefits of their use on agricultural fields, with particular emphasis on systems under loamy sandy soil.
- Evaluation of the best time to apply slow-release N fertiliser. This should include assessment of the release pattern of the fertiliser over time, including the effect of soil microbial population in loamy sandy soil on immobilisation and later release of N into the soil solution.
- In this thesis it was suggested that maize root growth was promoted by use of drip irrigation, irrespective of irrigation level and N fertiliser type. However, these results were obtained applying relatively high single irrigation events. Thus, more research would be required to understand the

response of root growth under lower irrigation levels, with higher irrigation frequency (e.g. daily irrigation scheduling).

- Research on possible better performance of furrow irrigation when furrows are shortened in length, as they were in the present study, compared with conventional practices, which would represent an important improvement in water and N management on small-scale farms in semi-arid areas.

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