CRANFIELD UNIVERSITY

PABLO KAISER LÓPEZ

SUSTAINABLE WATER MANAGEMENT FOR SWEETCORN IN SENEGAL

SCHOOL OF APPLIED SCIENCE
MSc by Research

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Academic Year: 2011 – 2012

Supervisor: Dr. Tim Hess
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ABSTRACT

Water consumption is a global concern, especially in the agriculture sector in sub-Saharan countries, where 70% of abstraction is for agricultural use. This study was undertaken to evaluate the role of scientific scheduling in reducing the irrigation water applied to sweetcorn without compromising the quality of the product in semi-arid conditions. The experimental site was located at SCL farm (northwest part of Senegal) (latitude 16.12ºN; longitude 16.24ºW and 7 m above sea level) in sandy soils.

Three experimental fields were drip irrigated, and equally fertigated, in locations with varying characteristics: unstructured soil (dunes) (Field A), sediments (Field B) and with high groundwater (Field C). The weekly irrigation schedule was developed according to the measured daily crop evapotranspiration (ETc) and periodic measurements of wetting patterns in each field. The schedule aimed to apply water to match ETc and keep the wetted depth close to the estimated root depth in each field.

The water consumption in the farm was reduced by 20% on average (23%, 15% and 39% in fields A, B and C respectively), compared to the previous season's records. Despite reducing the amount of water, the cob yield and quality were similar to SCL expectations. The Irrigation Water Use Efficiency obtained in fields B and C (2.4 and 3.4 kg/m^3) were higher than in the previous season (2.1 kg/m^3 on average); although in field A it was lower (1.1 kg/m^3) due to its low plant density and low yield due to nematode attack.

The application of scientific scheduling has allowed similar yield and quality values to be obtained compared to the previous (roughly similar climatically) season, while reducing the water consumption, improving the water efficiency and resulting in other cost savings in manpower, fertiliser and energy.

Keywords:

Sweetcorn, *Zea mays*; drip irrigation; sandy soil; semi-dry; wetting patterns; irrigation water use efficiency; export quality and yield.

ACKNOWLEDGEMENTS

I would like to thank Tim Hess for his help, support and supervision during the development of this thesis. Without his assistance, this project would not have been as successful.

I would also like to express my gratitude to the entire SCL staff who facilitated my work during my stay at Diama, with special mention to Mactar, Ousseinon and all the irrigation team, Ouley, Bruno, Jean-Pierre, Philippe, François Celine and Michael.

J'aime aussi faire un grand merci à les Frouin (Vesta, Lucie, Thomas, Jean et Céline) qui ont rendu mon séjour au Sénégal plus agréable et m'ont aidé dans tout ce qu'ils pouvaient. Je vous remercie beaucoup! Ne vous oublierai jamais!

Finally I would like to dedicate thank this thesis to my family and friends back home for your support and help in the difficult moments. Of course, I would like to have a special mention to Angie, without your support and patient the development of this thesis would not have been possible. *Ευχαριστώ πολύ!*

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LIST OF ABBREVIATIONS

AWC	Available Water Capacity
ET	Evapotranspiration
ETc	Crop evapotranspiration
ETo	Reference Evapotranspiration
FAO	Food and Agriculture Organization
FC	Field Capacity
IWUE	Irrigation Water Use Efficiency
Kc	Crop factor
SCL	Société de Culture Légumière
PWP	Permanent Wilting Point
WUE	Water Use Efficiency

1 INTRODUCTION

1.1 General background

As freshwater resources in the world are finite and the predictions for the global human population growth are high (between 9 and 10 billion people by 2050), the development of a proper water management may be crucial (Bloom, 2011). It will be essential in the African continent where the amount of internal renewable water resources is only 9% of the global freshwater, compared to 45 and 15% in American and European continents, respectively (FAO, 2012). Moreover, in African countries, in the next 40 years, a population growth by a half of the global growth is expected (Bloom, 2011).

The global use of water is divided into three sectors: agricultural, municipal and industrial. The water consumption depends on the needs of the country. As a global average, the agricultural sector is responsible for using the highest amount of freshwater (70%), mainly for irrigation. In Sub-Saharan African countries, this value is increased up to 87% (FAO, 2012).

There are several techniques to reduce the water consumption in the agricultural sector such as, improvement of the application efficiency (up to 60% of water reduction), changes in irrigation practices (up to 30%), development of drought-resistant crops (up to 50%) or even recycling of treated sewage effluent (around 10%) (Battilani, 2010).

The development of modern irrigation systems is becoming important in arid and semi-arid regions with limited water resources. These new systems focus on improving water use efficiency (WUE) and crop yield by decreasing the water percolation beneath the root zone (Bozkurt *et al.,* 2011b; Cavero *et al.,* 2000). Drip irrigation is the actual irrigation system that provides greater advantages over more traditional practices such as surface or sprinkler irrigation due to its low water loses by runoff, deep percolation or evaporation (Bozkurt *et al.,* 2006; Shock, 2006).

Sweetcorn (*Zea mays*) has high water requirements and it is very susceptible to water stress, hence it is important to study a proper irrigation water management for this specific crop (Cavero *et al.,* 2000).

1.2 Société de Culture Légumière

Société de Culture Légumière (SCL) is a company which has cultivated different crops in the north of Senegal since 2007. Senegal is located in the West side of the African continent. The company is located in Diama, 30 km north of the city of Saint Louis, which is located in the Northeast of the country (Picture 1).

Picture 1.1 Senegal map (Source: CIA, 2011)

SCL started with a small piece of land and now has around 500 ha divided into 5 different farms: Diama, Djama, Agrinord, Agroval and Bango. The soils in those farms are predominantly sandy. Most of the crops cultivated are aimed at the export market, which implies that apart from high yields it is also very important to harvest a high quality product. The main crops that SCL grows are: sweetcorn, butternut squash, peanut, asparagus and sweet potatoes. At SCL, sweetcorn as other crops are cultivated during the dry season, so they rely on the irrigation to grow.

1.2.1 Climate

Senegal has a tropical climate. This climate is divided into two different seasons. The dry season, from November to May, is dominated by high temperatures, few precipitations and strong and dry winds with suspended dust from the Sahara desert (Harmattan wind). The wet season, from June to October, is dominated by higher mean temperatures because of the increase in the minimum temperatures, high humidity and precipitation (CIA, 2011; TuTiempo, 2012).

The annual precipitation varies by area. In Saint Louis, the average annual precipitation does not exceed more than 300 mm (Figure 1.1) (CIA, 2011).

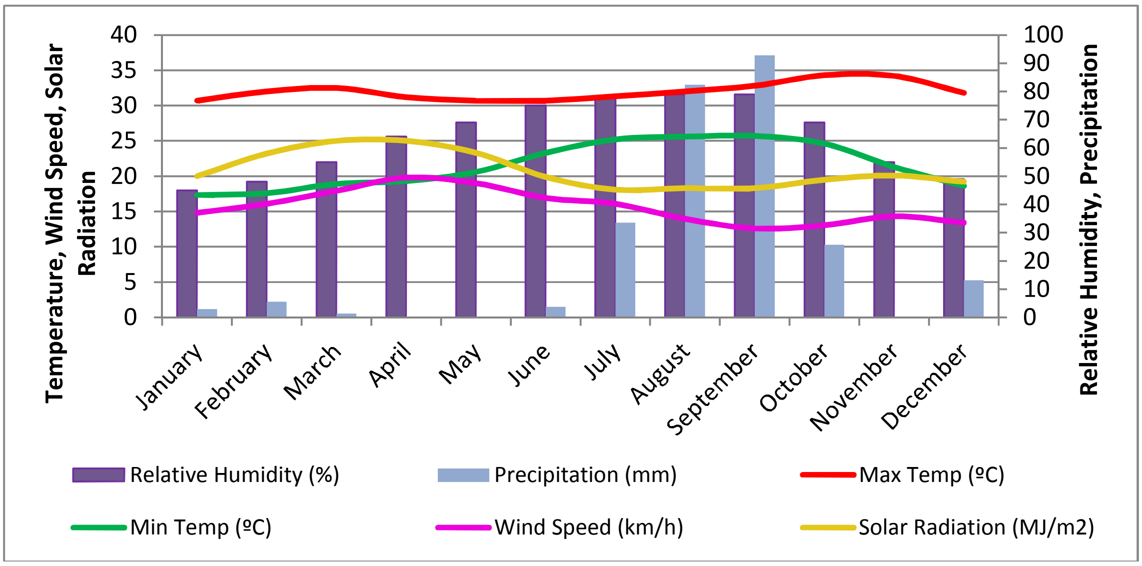


Figure 1.1 Climate characteristics of Saint Louis airport (Latitude: 16.05 ºN; Longitude: 16.45 ºW and altitude: 4 m) (1982 – 2011) (Source: TuTiempo, 2012)

1.2.2 Irrigation system

SCL has installed two different irrigation techniques among its farms. In Diama, Bango and Agroval it is drip irrigated while in Djama and Agrinord it is pivot irrigated.

In Diama the system is fertigated. This means that the fertiliser is mixed and dissolved into the water before being applied to the crop through the irrigation system. The farm has a primary fertiliser station, where the fertiliser is added to the irrigation system equally for the whole farm. And a secondary fertiliser station at each irrigation section where they may adjust the plant fertilisation needs at each crop stage. At the end of the crop season, all the crops are equally fertilised.

1.2.3 SCL concerns

The main concern that the company had in terms of irrigation, was that their irrigation management at the farm was sub-optimal. This means that there were some areas in which over-irrigation was causing water and fertiliser to be lost by drainage, whilst at the same time there were other areas which were under-irrigated, leading to a big plant stress and consequently yield and quality reduction. According to Hess (2011), the irrigation water applied to sweetcorn exceeded the crop water requirement (ETc) by 50 – 100%.

Over-irrigation is not only a present problem. It also may lead to a future problem because the water with the fertiliser is being stored in the soil. This phenomenon may increase the groundwater table and, consequently, increase the salinity of the soil and pollute it, restricting the correct development of the roots of the crop, thus resulting in a decrease in the yield and quality of the final production.

1.3 Stay at SCL

My stay in Senegal was for almost four months (12th of January – 2nd of May). During these months I worked on my research, collecting and analysing data. However, I also assisted the company in areas such as irrigation consultancy for other farms (pivot and drip irrigation), improvement of the irrigation management at Diama farm, measure and control of the groundwater table and other small tasks (Further details in Appendix F).

1.4 Aim and Objectives

The overall aim of this research is to evaluate the role of scientific irrigation scheduling in reducing the water use applied to sweetcorn without compromising the quality of the product by using a case study from Senegal. The objectives of this study are:

- To develop a new irrigation schedule according to the irrigation wetting patterns and the local climatic conditions.
- To assess the impact of these new irrigation schedules on sweetcorn yield, quality and IWUE.
- To assess the sweetcorn production grown under a scientific scheduling regime with regard to the existing practises in the farm.

2 LITERATURE REVIEW

In this chapter we look at the published literature in connection with the research which will develop as more is learned about: characteristics of the crop and its relation to the water; characteristics of the irrigation system; water behaviour in the soil and an understanding of its wetting patterns; and a general study of the layout of the system.

2.1 Agronomy of sweetcorn

As irrigation scheduling depends basically on the type of crop, amongst others, it is important to specify the crop characteristics, the possible problems that can happen and the different water requirements of the plant throughout the crop season.

Sweetcorn (*Zea mays*) is a variety of maize with high sugar content, as a result of natural recessive mutations, and its consumption, compared to maize, is fresh (Schultheis, 1994). It is a warm season crop and does not germinate well in soils of temperatures below 13 – 15 ºC. It grows better in lights soils, as sandy (Haynes *et al.,* 2002). It is a plant with a high water requirement compared to others and it is susceptible to water stress because the root system is relatively sparse, affecting growth, development and physiological process of the plant, which may reduce biomass and, ultimately, yield (El-Hendawy *et al.,* 2008a; Payero *et al.,* 2009). Crop cycle length of sweetcorn in arid conditions is 90 days, but may vary because of weather conditions. In hotter and more humid areas, the cycle would be reduced and viceversa (Allen *et al.,* 1998).

The depth of the roots depends on the irrigation frequency and the soil aeration. In a non-stress situation, the plant takes the water and nutrients from the upper parts of the soil but when there is water stress, the roots penetrate deeper, looking for available water (Coelho and Or, 1999; Oktem, 2006). It is at tasseling that the roots are at their largest. Even if the theoretical depth of sweetcorn roots is more than 90 cm, it has been found that in sandy soils they do not go deeper than 60 cm. According to the research developed by Laboski *et al.* (1998), at tasseling, in sandy soil 94% of total root length was 60 cm from the soil surface and 85% within the first 30 cm. The water uptake pattern simulation of Assouline (2002) and the soil observations of El-Hendawy and Hokam (2007) indicate that the water consumption by sweetcorn roots occurs throughout the 75 cm soil depth. But, it is within the first 25 cm soil profile that the plants extract most of the water. El-Hendawy and Hokam (2007) observed that, in sandy soils, there was relative drying within the first 25 cm and soil moisture was lower than the permanent wilting point (PWP), which also may indicate that some of the moisture was subject to evaporation from the soil surface. Other studies observed that corn grown in sandy-loam soils extracted most of the soil moisture within the first 35 cm (Oktem *et al.,* 2003; Panda *et al.,* 2004).

Plant density election for a proper yield depends on different factors such as soil type or the irrigation applied. In general, the planting recommendations for sweetcorn are 75 cm between rows with an in-row spacing of 23 cm (58,000 pl/ha). El-Hendawy *et al.* (2008a) studied the yield of different densities of corn in sandy soils and semiarid conditions. The characteristics for low densities (48,000 pl/ha), were better than those for higher densities (71,000 and 95,000 pl/ha). However, the density of 71,000 pl/ha obtained the best grain yield (8,892 kg/ha). For high densities (95,000 pl/ha), the problem was found to be that the humidity of the soil was closer to the wilting point, leading to water stress during the sensitive growth stages. For my study it is not only important that a good final yield is obtained, the final quality of the yield is very important too. As the conditions at El-Hendawy *et al.* (2008a) experimental site are similar to mine, the plant density recommended would be between 48,000 and 71,000 pl/ha, finding an attempt to achieve a balance between yield and quality.

Apart from the different plant densities, there are diverse theories regarding alternative planting methods. Viswanatha *et al.* (2002) studied the yield of sweetcorn in sandy loam soils during a summer in India, applying two planting methods: the conventional (60 cm x 30 cm) and the paired planting (45-90-45 cm x 30 cm). The research showed that the conventional layout had better results on fresh yield (20.07 t/ha; 31% higher than with the paired one) and WUE (3.9 kg/m^3) applying the same amount of water.

Fertiliser is an additional nutrient for the plant; therefore its specific amount depends on the chemical composition of each soil. In the case of sweetcorn, the plant needs high levels of nitrogen and moderate amounts of potassium and phosphorus (Haynes *et al.,* 2002). El-Hendawy and Hokam (2007) studied the yield and the WUE with different nitrogen applications and irrigation frequencies for corn. The results showed that the greater amount of nitrogen applied (380 kgN/ha), the greater the final yield and the grain characteristics are improved for high irrigation frequencies. Opazo *et al.* (2008), also reached the same conclusion for sweetcorn harvested in Chile, obtaining the highest yield by applying 240 kg N/ha.

The water requirements for good plant development depend heavily on weather and soil conditions. Table 2.1 has summarised some irrigation recommendations for corn and sweetcorn in different areas and soil conditions.

Table 2.1 Some water recommendations for corn and sweetcorn according to the location and soil characteristics

Country	Soil texture	Water recommendations (m^3/ha)
Oregon, USA [a]	Sandy	4,500 – 5,200
Zaragoza, Spain [b]	Loamy	4,000 – 5,500
Tanzania [c]	Clay-Loam	4,000 – 5,100
Changwu, China [d]	Loamy	3,840 – 4,000
Colby, Indonesia [e]	Silt-Loam	3,000 – 4,600
Texas, USA [f]	Silty-clay	4,000 – 4,500
Bangalore, India [g]	Sandy-Loam	5,000 – 5,500
Turkey [h]	Clay	5,000 – 6,000

Source: a Braunworth, 1987; b Cavero *et al.,* 2000; c Igbadun *et al.,* 2007; d Kang *et al.,* 2000; e Khan *et al.,* 1997; f Ko and Piccinni, 2009; g Viswanatha *et al.,* 2002; h Yazar *et al.,* 2002.

As it is possible to appreciate in Table 2.1, water recommendations for growing corn and sweetcorn are, on average, between 4,000 - 5,000 m^3/ha in almost any part of the globe.

Studies have been made regarding the calculation of the proper amount of water than needs to be supplied in accordance with the percentage of each evapotranspiration (ET) in corn (Bozkurt *et al.,* 2011a; El-Hendawy *et al.,* 2008a). In both pieces of research, they recommended a water treatment of 80% ET (5,030 m^3/ha and 4,762 m^3/ha, respectively), in the case of water scarcity. Although, the best results, in both studies, were with 100% ET. Both studies agreed that with treatments of 80% ET and higher, the soil water content was not lower than the soil field capacity at each location.

Despite the final irrigation choice, it is important to control the correct amount of water applied at each crop stage, in order to avoid unfavourable effects on final yield. In sweetcorn, water stress is reported to be especially significant at flowering, silking and pollination stages (Bozkurt *et al.,* 2006; El-Hendawy *et al.,* 2008a). Garcia y Garcia *et al.* (2009) reported that during the growing season, the water requirements for sweetcorn rapidly increase from about 40% of the crop evapotranspiration (ETc) during early growth to 110% of ETc at peak growth, with a decrease of 100% of ETc during the final two weeks prior to harvest for fresh market.

For instance, if the water reduction takes place at flowering there is a reduction in the number of cobs and grains per plant, whereas if it occurs at post-pollination there is decrease in the size of the grains. NeSmith and Ritchie (1992) have reported that a water reduction at those stages may lead to a reduction in maize yield above 90%. Nevertheless, when there is a stress event in the early vegetative growth stages, the maize is moderately insensitive to water stress because the water demand is not high and the plants are able to adapt to water stress conditions (Çakir, 2004).

As a final recommendation, applying good practices, the final yield of fresh sweetcorn expected should be equal to or higher than 55,000 cobs per ha, for a plant density of 50,000 pl/ha (≥1.1 cobs/pl) (Haynes *et al.,* 2002). Fresh cob characteristics depend on the variety of sweetcorn selected. In the case of Garrison (sweetcorn selected for the research), the maximum length expected is between 19 – 21 cm and the diameter between 5.0-5.5 cm (Syngenta, 2012).

As the values of irrigation and yield may vary from one place to another, to compare system efficiency the term WUE is used. WUE refers to the number of kilograms produced per m^3 of water needed for growth. Also, another concept exists that is related to the actual production per m^3 of water applied, irrigation water use efficiency (IWUE). The value of WUE is affected by multiple factors such as, genotype, agricultural practises, weather conditions, available soil water content and soil texture (Garcia y Garcia *et al.,* 2009). In arid and semi-arid areas, increasing WUE is a way to increase the agricultural production where water resources are less attainable (Kashiani *et al.,* 2011). Any crop grown in semi-arid conditions, where the final yield and quality of the harvest rely on the irrigation, the value of WUE may vary considerably. For sweetcorn grown in south-east Turkey the value of WUE was very low and it ranged from 1.18 - 1.36 kg/m^3 (Oktem *et al.,* 2003; Oktem, 2006; Oktem, 2008). In other areas where the water needs for the plant are supplied also by rainfall, this value increases considerably up to 10 kg/m^3 (Garcia y Garcia *et al.,* 2009; Viswanatha *et al.,* 2002).

2.2 Plant water demand

Plants, as any living being, need water for their correct development. In the case of an agricultural holding that has an aim to sell the final product and obtain benefits, the application of the correct amount of water becomes a very important factor.

In agriculture, plant water need is determined by the ETc. ET is the sum of water evaporation from the soil surface and crop transpiration. ET depends on weather conditions, type of crop and management and environmental conditions (Allen *et al.,* 1998). Consequently, crop evapotranspiration refers to the amount of water lost through ET.

The calculation of the ET for each crop is not easy, therefore it is being calculated a reference ET (ETo). The concept of ETo is being introduced to study the evaporative demand of the atmosphere independently of crop type, crop development and management practices. It is affected only by climatic parameters, so, ETo is a climatic parameter and it can be computed from weather data. It expresses the evaporation power of the atmosphere at a specific location and time of year and it does not take into consideration the crop characteristics and soil factors. FAO recommend a specific method to calculate the ETo: Penman-Monteith equation.

As ETo does not consider any crop factors, to calculate the ETc it is necessary to multiply the ETo by a crop factor (Kc). FAO has calculated the specific value of Kc for each crop as well as the value for the stages during the crop cycle (Initial, development, final). The formula used to determine the value of ETc is the following (Allen *et al.,* 1998):

$$ETc = ETo\ x\ Kc$$

To determine the theoretical value of ETc, FAO has developed computer software, *CropWat 8.0*, which determines ETc according to the site climate records and crop and soil characteristics. This software also provides a daily irrigation schedule for the crop cycle for different management conditions (FAO, 2006). This software provides a very good approximation of water requirements for any crop in any environment and its daily irrigation schedule. The limitation of this irrigation model is that it does not provide or predict the water movement and the soil moisture during the season which may vary the daily irrigation.

Apart from the calculation regarding the plant water need, for the irrigation, it is important to determine also the movement of the water into the soil and its moisture. For that, Cranfield University has developed software, called *WaSim,* which models the soil water balance and, also, the plant development based on ETo calculation, irrigation applied and crop and soil characteristics. The main limitation of this software is that the water balance model, at least with the current study characteristics, was not similar to the real field water movement. Because of that, it was only used to model the root development in the soil.

The application of these two programmes will help to develop a proper irrigation schedule and a better understanding of the water movement into the soil in the present research.

2.3 Irrigation: Drip Irrigation

Irrigation, as a main concept, is the artificial application of water to the soil which is mainly used for agricultural crops to increase yield, keep crops cool under excessive heat and prevent freezing. It makes agriculture possible in areas previously unsuitable for intensive crop production. With the proper irrigation system it is possible to obtain optimum quality and quantity crop production per unit area (Oktem, 2006). There are four primary systems of irrigation: Surface, Sprinkler, Drip or Trickle and Sub-surface (US EPA, 2012).

In surface irrigation, water flows directly over the soil surface. The surface can be flooded or the water is applied through furrows between the rows. With sprinkler irrigation, the water is sprayed over the soil surface as rain on the crop. In case of drip irrigation, the water is supply directly onto or below the soil surface through the emitters which control the water flow. The last system, sub-surface irrigation, delivers the water directly to the plants root zone below the soil surface and the water is absorbed upwards (US EPA, 2012).

In the case of sweetcorn, the irrigation systems most used are surface, sprinkler (pivot system for high land extension) and drip (above or below soil surface) irrigation. Normally, excessive water application causes water loss as surface run-off or deep percolation below the root zone (El-Hendawy *et al.,* 2008b). In the literature there are studies comparing those techniques.

A drip irrigation system has been studied in detail in recent years because of its high efficiency in comparism to other systems i.e. surface, sprinkler or pivot (Bozkurt *et al.,* 2006; Oktem, 2006). For instance, Abd El-Wahed and Ali (2012) and Viswanatha *et al.,* (2002), showed that the application of drip irrigation in sweetcorn produced better results in terms of yield and WUE than sprinkler and furrow irrigation. Abd El-Wahed and Ali (2012) obtained 24 and 38% more yield and WUE, respectively, with drip irrigation rather than sprinkler in sandy soils in Libya. On the other hand, Ebrahimi *et al.* (2011), compared sweetcorn yield in Iran between furrow and sprinkler irrigation. These results showed that sweetcorn yield applying sprinkler irrigation was 20% higher than furrow.

A drip irrigation system is more complex than other irrigation systems but more efficient. The different parts of the system are: pump unit, control head, filters (avoid clogging), main and submain lines, laterals and emitters or drippers (Figure 2.1).

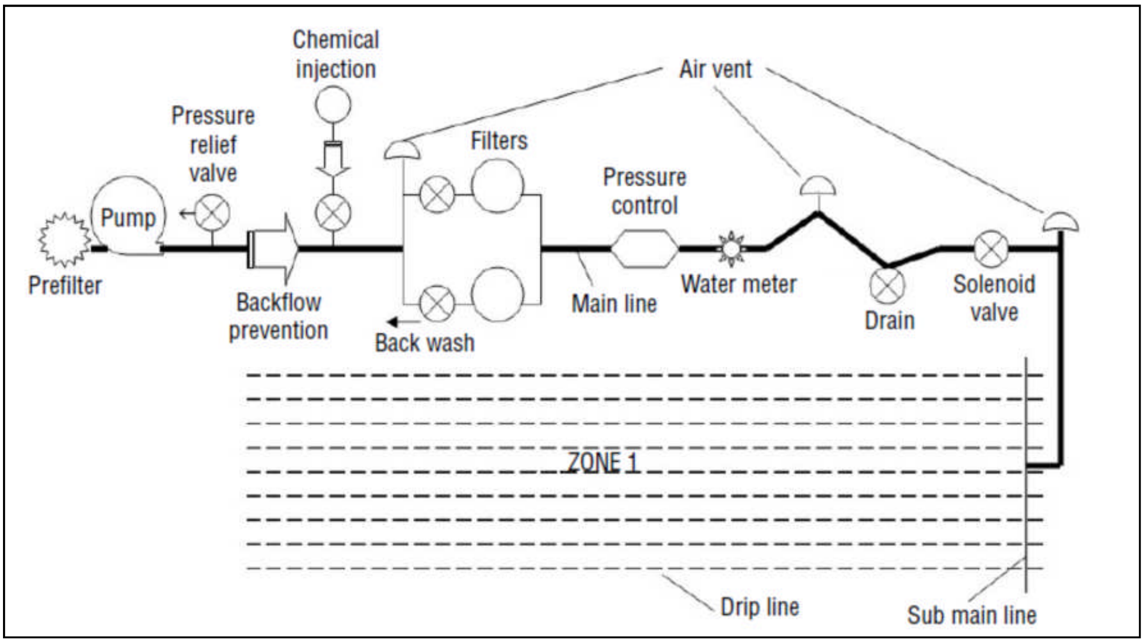


Figure 2.1 Scheme of the layout of a drip irrigation system (Source: Shock, 2006)

Drip irrigation advantages and limitations are summarised in Table 2.2.

Table 2.2 Advantages and limitations of drip irrigation system

(Source: Shock, 2006)

Advantages	Limitations
High efficiency (low evaporation, runoff and deep percolation)	High initial costs
High adaptation to different fields and topography	Clogging if water is not properly filtered
Possibility of fertigation with minimal waste of fertiliser	Short life of the drip lines
High uniformity in water distribution	Extra cleanup costs after harvest
Reduce risk of diseases and better weed control	
Low work pressure → Low energy costs	
Moisture within the root zone can be maintained at field capacity	

With the drip irrigation system there are two main drip line layouts: above ground or below ground near the roots system. For instance, Coelho and Or (1999), studied the root density and the water uptake pattern of corn in silty loam soils applying those two layouts. They saw that the root density and the wetting pattern at the first 30 cm from the surface (subsurface drip line depth) was slightly higher with buried than surface drip irrigation. As studies have indicated, subsurface drip irrigation has better results in corn, in terms of root density and water uptake. However, the final grain yields were similar (Payero *et al.,* 2009).

The main advantage of the buried drip irrigation system is that it allows for better root distribution and avoids water evaporation from the ground surface, thus saving water on the farm. However, its management and costs are higher than surface drip irrigation. Also, during the first crop stage it is important that the correct amount of water is applied to the seeds. Due to the low capillarity of sandy soils (in comparism to others soil textures) it would be advisable to avoid using it to install subsurface drip irrigation, because this type of soil limits the upwards movement of the water from the drip line up to the surface.

Surface drip irrigation mean efficiency is 90% in the case of optimal farm water management, which increases WUE, IWUE and final yield considerably (Battilani, 2010). This high efficiency is based on how the system applies the water to the soil. In the case of sweetcorn, the literature has shown that this irrigation system has better results in terms of water use and final yield than other irrigation systems (Abd El-Wahed and Ali, 2012; Ebrahimi *et al.,* 2011; Viswanatha *et al.,* 2002).

Drip irrigation high efficiency is related directly to the reduction of the irrigated water evaporation, deep percolation, surface runoff and to the direct application of water and nutrients in the most active root zone (Brouwer *et al.,* 2001). For a given discharge rate, irrigation frequency is the main factor in drip irrigation management (El-Hendawy *et al.,* 2008a). It has a direct effect on soil water behaviour, root distribution under the emitter, the quantity of water uptake by the roots and the amount of water drained under the root zone (Assouline, 2002; Coelho and Or, 1999; Thorburn *et al.,* 2003; Wang *et al.,* 2006). Because of this, different irrigation frequencies may have a direct repercussion in the WUE and crops yields, although the total amount of water applied is the same. El-Hendawy *et al.* (2008b) showed that, applying the same total irrigation, high frequency irrigations (once every 2 days) produced better yield and quality results in sandy soils than low frequencies (once each 4 or 5 days).

An excessive or insufficient application of water at each irrigation may have a negative impact on system efficiency or final yield. High irrigation frequencies, one or more per day, could provide better conditions for water uptake by roots, while it decreases the irrigation efficiency and increases labour and energy costs (Jordan *et al.,* 2003; Wan and Kang, 2005). Alternatively, low frequencies may cause stress before the next irrigation, especially in sandy soils, because the amount of water applied per irrigation may be higher than the water holding capacity of the soil resulting in significant water percolation below the root zone (El-Hendawy *et al.,* 2008a). Consequently, frequent irrigation events avoid the large oscillation in plant water stress caused by infrequent irrigations (El-Hendawy *et al.,* 2008b).

In the literature, several studies have focused on irrigation frequency. Most have studied the behaviour of the plant-water system with once per day irrigation frequencies or less (Bozkurt *et al.,* 2006; El-Hendawy and Schmidhalter, 2010; El-Hendawy *et al.,* 2008b; Garcia y Garcia *et al.,* 2009; Oktem, 2006; Wan and Kang, 2005) but there is a lack of information regarding higher frequencies, more than once per day, which will be applied in this research.

According to El-Hendawy *et al.* (2008b), it is shown that for corn grown in sandy soils, within the first 25 cm there is a general lack of water, independent of the frequency, with values below the Permanent Wilting Point (PWP), before the next irrigation. This research explains that phenomenon as, not only all the available soil water at this depth was consumed, but also some of the soil water was subject to evaporation from the soil surface. On the other hand, in the next

25 cm the soil water content increased drastically only in higher frequencies cases (once per two or three days), while in the lowest frequency case (once every five days) it was still close to PWP. At a depth of 75cm, the results were the opposite, which was indicated by the fact that there was more water percolation in low frequencies because the amount of water applied was higher than might be retained in this type of soil. Nevertheless, in higher frequency applications the small amount of water applied at each irrigation event was enough to wet the root zone without resulting in water drainage. However, it is important to find a proper irrigation frequency. High daily frequency may create a very humid zone in the most superficial roots what may reduce the oxygen diffusion into the soil affecting the activity of the crop enzymes and thus weakening crop photosynthesis and also inhibits the development of the leaf surface area which at the end is shown as a yield reduction. This issue is more frequent in soils with higher clay content (El-Hendawy and Schmidhalter, 2010).

In contrast, it is important to take into account that when the soil water content is insufficient for the plant, the development of the roots is limited and roots hair are damaged, which limit farther the water uptake process. However, when the soil is wet i.e. high irrigation frequencies, the roots expand quickly and the cells in the periderm expand correspondingly. So, apart from that, with high irrigation frequencies there is more water available for the roots, also the roots are able to take more water because they find it more easily, causing increases in WUE and IWUE (El-Hendawy et al., 2008b).

2.4 Soil-water relations: Wetting patterns

After the election of drip irrigation as the most suitable irrigation technique for sweetcorn, in order to programme an optimal irrigation frequency and timing it is necessary to understand the water movement in the soil after an irrigation event?

Unlike the surface or sprinkler irrigation, drip irrigation only wets part of the soil root zone, which may be as low as 30% of the soil wetted by other methods (Brouwer *et al.,* 2001). In drip irrigation, the wetted shape under the emitter is called wetting pattern and it is characterised by its width and depth. This shape depends on the soil hydraulic properties (Figure 2.2), the discharge of the emitter and the quantity of the water applied (Figure 2.3), the crop and its growth stage and the environmental conditions (Assouline, 2002; Hartz, 1999; Keller and Bliesner, 1990; Li *et al.,* 2004; Thabet, 2008; Thorburn *et al.,* 2003; Zur, 1996).

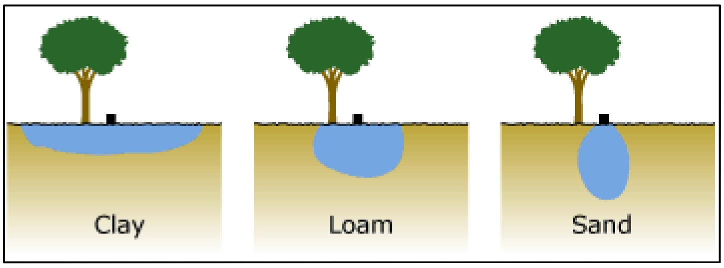


Figure 2.2 Wetting patterns of drip irrigation in clayey, loamy, and sandy soils (Idealize) (Source: WateReuse Foundation, 2007)

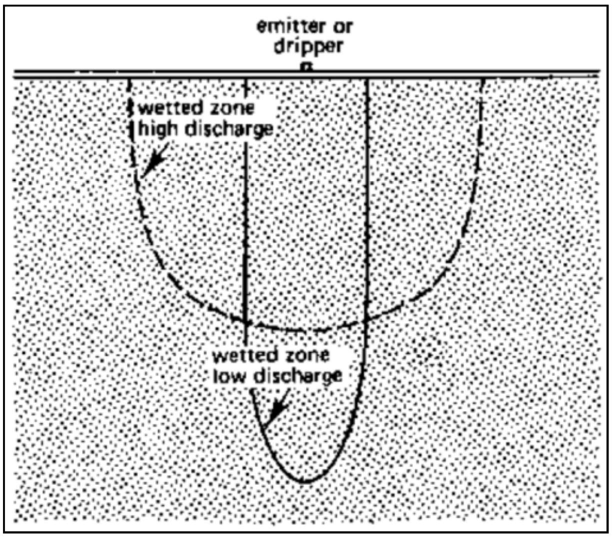


Figure 2.3 Wetting patterns for sandy soil with high and low discharge rates (Source: Brouwer *et al.,* 2001)

Water, as with any fluid, is almost continuously moving in the soil. Water movement can be in any direction depending on conditions. It moves downwards by gravity (infiltration) after an irrigation or rain event. It moves upwards to evaporate from soil surface and, also, it moves horizontally. Depending on the soil type, each movement can be more important than others.

Water flows through the open pores between soil particles. These pores vary in size and number depending on the soil. For instance, silty and clayey soils generally have smaller pores but many more than sandy soils. Because of that, when silty and clayey soils are filled with water, these soils contain more total water than sandy soil with all its pores filled (Gardner, 1988).

Two main forces move liquid water through the soil pores: gravity and adhesion. Gravity causes a downward force on water. When a soil is near saturation, the large pores are filled and water moves rapidly through them. When it is not saturated, the larger pores are unfilled and contribute little to the flow. In the unsaturated soils, in which more crops grow, the main force moving the water is adhesion. This force, together with cohesion causes water molecules to hang together, makes water move on particle surface and through the fines pores.

These are the same forces that cause water to rise by capillarity. Capillarity refers to the ability of a liquid to flow in narrow spaces without the assistance of, and in opposition to external forces such as gravity. It occurs because of inter-molecular attractive forces between the liquid and solid surrounding surfaces. If the diameter of the pore is sufficiently small, then the combination of cohesion and adhesive forces between the liquid and soil particles act to lift the liquid. In hydrology, capillarity is responsible for moving groundwater from wet areas to dry areas of the soil. In clay soils this phenomenon occurs more slowly but covers a greater distance (more than 80 cm up to several meters) in contrast to sandy soils, where it happens faster but not over more than 50 cm (Brouwer *et al.,* 1985).

Different types of soil lead to varying speeds of water movement through pore spaces, called hydraulic conductivity (cm/h). Hydraulic conductivity depends, basically, on porous media: size, distribution and connectivity. For instance, in clay soils, even though it has more pores, these are smaller and the hydraulic conductivity is lower than in sandy soils (Table 2.3).

Table 2.3 Range of hydraulic conductivity depending on soil texture

(Source: Landon, 1991)

Soil texture	Hydraulic conductivity (cm/h)
Sand	6 - ≥ 50
Silt	2 – 6
Clay	< 0.25 - 2

The ability and the speed of water to traverse the soil depend on multiple factors. In sandy soils, where the bulk density (1.40 – 1.60 gr/cm^3) and the infiltration are relatively high, (and it is unusual to have compaction), the water flows faster than in clay soils (Brouwer *et al.,* 1985; Landon, 1991; USDA, 2001). For instance, if there is a layer of clay in a sandy soil, when the water reaches the clay, the very fine pores of this layer resist water flow and its penetration is very slow. The same effect happens if there is a layer with higher compaction made by the plough (Gardner, 1966).

The wetting pattern is divided into two different zones: a saturated area close to the emitter and a zone where the water content decreases towards the wetting front (Figure 2.4). Assouline (2002) has studied the behaviour of the wetting pattern in sandy-loam soils using different discharge rate (8, 2 and 0.25 l/h) applying the same total irrigation for all treatments (555 mm). The results showed that, the yields obtained were not significantly different but 2 and 8 l/h discharges had the best soil water distribution.

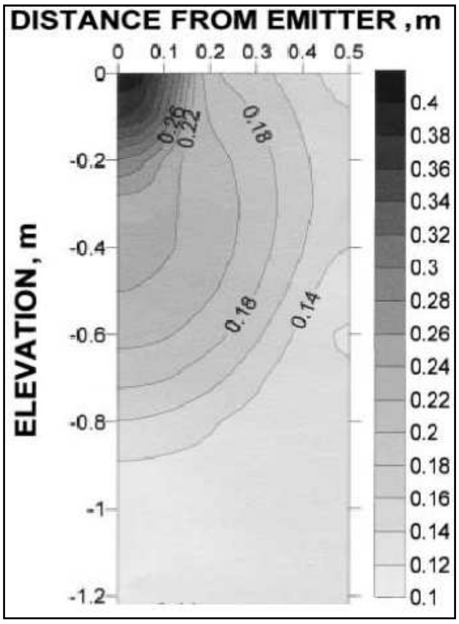


Figure 2.4 Simulated water distribution in sandy-loam soil (Discharge: 2 l/h)

(Source: Assouline, 2002)

In order to prevent water and nutrient losses and increase the system efficiency, sit is more convenient to increase the emission rate (l/h), or the frequency (i.e. reducing the days between irrigations). It makes the wetted soil diameter bigger and the wetted depth smaller (Assouline, 2002; Moncef *et al.,* 2002) (Figure 2.3).

The largest width of the volume allows the maximum space between emitters and the distance between lines, while the depth would have to agree with the actual depth of the root zone at each stage (Zur, 1996).

In the literature there are several examples of how to calculate the wetting pattern dimensions by the application of different empirical equations. Even though those equations will not be applied in this research, they provide a better understanding to the behaviour of the water movement into the soil.

Width depends on the volume applied and the emitter discharge, whilst depth depends on the volume applied and the hydraulic conductivity (Keller and Bliesner, 1990; Schwartzman and Zur, 1986). Keller and Bliesner (1990) showed that the ratio between the width and depth of the wetted soil volume tended to decrease with an increase in the hydraulic conductivity of the soil.

Li *et al.* (2004) discussed that, for a given volume applied, an increase of the application rate allowed for greater water distribution in the horizontal direction, while a decrease of that rate allowed greater water distribution in the vertical direction, which is particularly significant in light textured soils. It is important to take into account that this study was taken without plant water uptake.

2.5 Irrigation system layout

After understanding the behaviour of the water in the soil and the crop characteristics, the next step is to design the system layout. From the literature it is possible to find different systems and theories depending on farm characteristics. Once a fixed emitter discharge has been chosen, it is then possible to choose a design that provides for the correct distance between lines, distance between emitters, and distance between the plants, which will have a direct effect in the plant density (Thorburn *et al.*, 2003). Also, it is important to determine the amount of water that will need to be applied, comparing it with the ETc value.

The most frequently used distance between lines for sweetcorn in sandy soil is 75 cm and between the emitters is 30 cm (Cavero *et al.,* 2000; El-Hendawy and Schmidhalter, 2010; Hassanli *et al.,* 2009; Mansouri-Far *et al.,* 2010). However, those distance may change depending on soil and crop characteristics (Assouline, 2002; El-Hendawy *et al.,* 2008a; Oktem, 2006; Garcia y Garcia *et al.,* 2009; Mansouri-Far *et al.,* 2010; Viswanatha *et al.,* 2002). Bozkurt *et al.* (2006) investigated the optimum spacing between lines, keeping the plant line spacing of 70 cm in clay soils, according to final yield results. The different drip line distances used in this research were 70, 140 and 210 cm. The grain yield obtained with the separation of 140 cm was the highest (9,790 kg/ha), while the 70 cm separation obtained the lowest grain yield (8,566 kg/ha). They observed that, in clay type soils, for a plant line distance of 70 cm, the most recommendable distance between drip lines was 140 cm. This type of soil allows for a greater distance to be kept between drip lines because it retains more water in the soil and thus, the high horizontal water movement also enables the root zone to be wet even if it is not under the emitter (Figure 2.2).

Apart from the distance between lines and emitters, there are different theories regarding the drip disposition in respect of the plant. The most frequently applied is for the drip line to be placed near the plant but there are other theories which put the drip line between the plant line (Bozkurt *et al.,* 2011a).

We now understand the difficulty in achieving the optimum parameters in the irrigation system. It is because of this that several studies are now taking place in this field in order to better understand the different factors which take place in the system. In order to know if the parameters studied reach the required need it is important to make comparisons between the final yield responses.

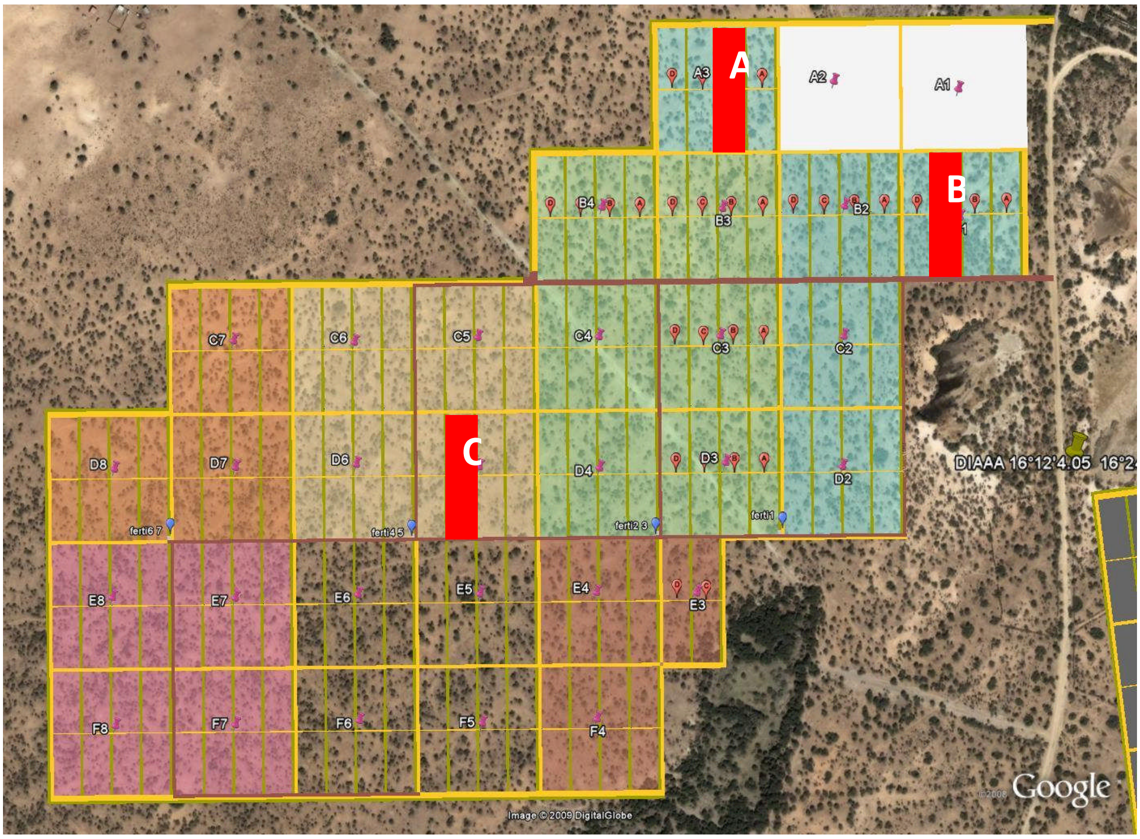
Consequently, a correct irrigation frequency is one which minimises the amount of water wasted below the root zone, provides the required daily plant water to the root zone and keeps a high soil matric potential around the roots to decrease plant water stress between irrigations (El-Hendawy *et al.,* 2008b).

Most of the literature reviewed was focused on the study of drip irrigation in maize for grain. This research may provide a better understanding in the performance of the drip irrigation applied in fresh market sweetcorn, which is more sensitive to water stress and has a shorter crop cycle than maize, in dry weather conditions.

3 MATERIALS AND METHODOLOGY

3.1 Experimental site

This study was carried out between January and April of 2012 in a farm located in Diama, in the region of Saint Louis, Senegal (latitude 16.12ºN; longitude 16.24ºW and 7 m above sea level). The farm belongs to the company called “Société de Culture Légumière” (SCL).



Picture 3.1 Map of Diama farm at SCL and the fields of the study (A, B and C)

The irrigation system at Diama is divided into eight different sections and each section is divided into different blocks, which are divided into four fields of approximately one hectare each (Picture 3.1).

The farm is characterised by three types of soils: soils without structure (dunes), soils composed of sediments and soils with the level of the groundwater table near the surface. Because of this, three fields were chosen (Picture 3.1). Field A

(Field in Block A3 for SCL irrigation layout code) of the research was chosen in the north of the farm where there was a dune. Field B (Field in Block B1 for SCL irrigation layout code) was situated in the east of the farm where the soil was of good structure but was composed mostly by sediments. Field C (Field in Block D5 for SCL irrigation layout code) was situated in an area with high groundwater table (Picture 3.2). The dimensions of each field were 212 m by 48 m (Approximately one hectare).

Picture 3.2 Soils at each field (A, B and C, respectively)

3.1.1 Soil characteristics

The texture of soil in the fields was classified according to particle size distribution method (ISO 11277, 1998) which determines the size particles by a combination of sieving and sedimentation. The infiltration rate of the soil was measured *in situ* using the double-cylinder infiltrometers. The cylinders were made by recycling old steel pipes. The diameters of the cylinders were 16 cm for the inner one and 32 cm for the outer one. Both had a height of 40 cm. They were buried 20 cm into the soil in order to avoid horizontal movement of the water (Picture 3.3). Two tests were conducted at each field to provide a representative value of the whole field.

Picture 3.3 Double-ring infiltrometer installed in the farm

The bulk density was calculated by the core method (Landon, 1991). This method consists of taking a core sample of soil using a cylinder of a known volume and drying it afterwards. The cylinder was recycled from a plastic pipe of 6.8 cm of diameter and 5 cm of height which leads to a volume of 182.3 cm^3. The samples were taken from the first 25 cm and were then dried in the oven. The formula used to calculate the bulk density ($\rho_{b,}$ g/cm^3), is the following:

$$\rho_b = \frac{M}{V}$$

Where:

- M is the oven dry weight of soil (g)
- and V is the volume of soil (cm^3).

Also it was calculated the soil porosity (S.P., %) using the following equation:

$$S.P.(\%) = 1 - (\frac{\rho_b}{\rho_p})$$

Where:

- ρ_p is the density of the particle, which is assumed to be approximately 2.65 g/cm^3.

Field Capacity (FC) and the PWP tests have been done according to (ISO 11274, 1998) methods. This method consists in applying a suction of 5 kPa for FC and 1,500 kPa for PWP to a sample of saturated soil, allowing it to reach equilibrium and to then measure the water content of the sample. The available water content (AWC) was calculated as:

$$AWC = FC - PWP$$

Some soil characteristics relevant to irrigation are summarised in Table 3.1. The type of soil in the three fields was classified as sandy. The AWC was 5.1, 7.8 and 4.3% in fields A, B and C, respectively. The soil pH was from 8 to 9. The CEC change between fields, from 9 to 30 meq/kg.

Table 3.1 Soil characteristics of the experimental soil site

Field	Sand (%)	Silt (%)	Clay (%)	Mean* Infiltration rate (cm/h)	ρ_b (g/cm^3)	S.P. (%)	FC (%)	PWP (%)
A	97.2	2.6	0.2	13.9	1.44	45	6.3	1.2
B	94.2	4.4	1.4	12.7	1.50	43	9.2	1.4
C	98.1	1.9	<0.05	7.2	1.53	42	4.9	0.6

* Full infiltration details in Appendix A

3.1.2 Climate

For the period from October 2011 to January 2012, the climate data was collected from the records of a weather station installed in the farm (latitude 16º 12’ N and longitude 16º 24’ W and 7 meters above sea level). The weather station was recently installed in the farm and in order to check its proper operation, this climate data was compared to the climate records from a fixed weather station installed in Saint Louis´ airport (Latitude: 16.05 ºN, Longitude: 16.45 ºW and altitude: 4 m). The airport is located 17 km to the south from the farm and closer to the Atlantic Ocean (TuTiempo, 2012). The data from the airport did not provide the solar radiation, so it was calculated with the Hargreaves approximation (Allen *et al.*, 1998):

$$R_s = k_{Rs}\, x \sqrt{(T_{max} - T_{\min)}}\, x\, R_a$$

Where:

- R_s is the solar radiation (MJ/m^2);

- k_{Rs} is the adjustment coefficient (ºC$^{-0.5}$) and it was selected 0.19 ºC$^{-0.5}$ because the station was near the coast;
- R_a is the extraterrestrial radiation coefficient which depends on the month and the latitude (MJ/m^2 per d);
- Tmax is the maximum air temperature (ºC)
- and Tmin the minimum air temperature (ºC).

3.1.3 Previous crop season

In order to have a base comparison with the results obtained in the current research, the first task was to collect data from the previous sweetcorn season in Diama farm. This season started in October - November of 2011 and finished in January of 2012. The data collected was related to local weather, irrigation records in sweetcorn in Diama farm and its final crop yield. The irrigation and yield data of the farm was provided by SCL.

3.2 Experimental design

3.2.1 Agronomic practises

The variety of sweetcorn selected for this research was Garrison. It was provided by Syngenta®. Before sowing, germinations tests took place of which 90 – 95% of seeds germinated. At the time of planting, the first 20 cm of soil was dry. In the three fields, the crops were planted in rows which had a distance of 75 cm and a distance of 25 cm between plants giving an ideal plant density of 56,000 plants per hectare. The seeds were planted by an integral planter machine at 4 cm of depth.

The different stages of sweetcorn during the crop season and the final length of the cycle are provided in Table 3.2. The harvest took place over a period of time because of the heterogenic maturity at each field.

Table 3.2 Crop development stages at each field

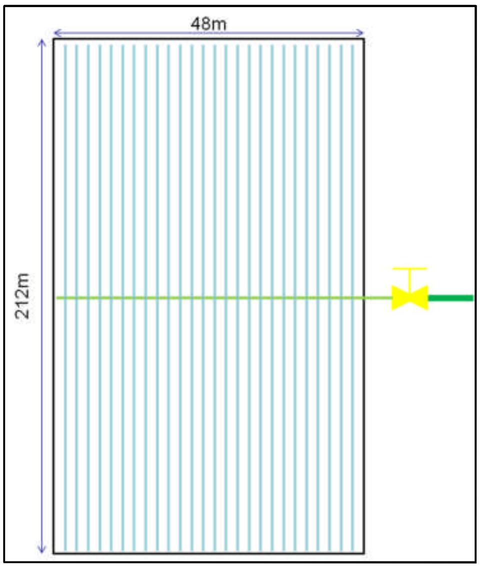
Field	Sowing	Emergence	2-3 Leaves	Tasseling	Pollination	Harvest	Cycle length
A	25th Jan	1st Feb	9th Feb.	18th March	22nd March	14 - 20 April	86 days
B	20th Jan	26th Jan	1st Feb.	12th March	18th March	11 - 15 April	86 days
C	1st Feb	6th Feb	9th Feb.	22nd March	26th March	19 - 21 April	81 days

3.2.2 Irrigation system layout

The irrigation layout in the field was the same as that used by SCL in previous seasons, surface drip irrigation. The distance between drip lines was 75 cm and 30 cm between emitters. 65 drip lines were installed in the field B and 66 in plots A and C. The water source of the drip lines was located in the middle of the plot, leading to double drip lines per plot (Picture 3.4).

The irrigation system is fertigated, which means that the fertiliser is mixed and dissolved into the water before being applied to the crop through the irrigation section. Because of this, the type of the drip tape used was t-type provided by John Deere, which is very resistant to clogging. It worked at 1 bar of pressure. The nominal discharge of the drip tape selected was 4.44 mm/hr per dripper.

The three fields had the same amount of fertiliser applied at the end of crop season. The fertiliser application began the third week after sowing in each field. Independently of the number of daily irrigations, one or two (depends on the date after sowing) of the applications were always fertigated, and the others, in case there were more, were irrigated with clean water. The final amount of fertiliser applied at each field was 200, 110 and 300 kg/ha of NPK. The farm has a primary fertiliser station, where the fertiliser is added to the irrigation system equally for the whole farm. There is also a secondary fertiliser station at each irrigation section, where plant fertilisation needs may require adjustments at each crop stage.



Picture 3.4 Irrigation layout of the field

The irrigation system was installed with a primary big filtration system just after the addition of fertiliser and small filtration devices at each field just before. The small ones were cleaned before any irrigation event.

The irrigation system was manually operated so that the amount of water can be varied from the initial irrigation programmed. Therefore, to monitor the irrigation system adequacy, nine water meters were installed in fields A and B, and eight in field C the 4th of February (Picture 3.5). Daily readings were collected to compare the water applied with the irrigation scheduled.

Picture 3.5 Water meter installed at each field

The irrigation frequency was the same in the three fields. It has varied from once a day at the beginning of the crop season to four times a day in the peak crop season. Each application time was scheduled for 30 minutes. This was according to how SCL programmed the irrigation in order not to change the one that they were working with. The amount of water applied each time was 2.2 mm.

3.3 Irrigation schedule

The calculation of the daily irrigation schedule was not a very complex method, but it needed to be periodically reviewed. Before the start of the study, sweetcorn water needs were calculated by *CropWat 8.0* software (FAO, 2006). This schedule provided a primary idea of how much water sweetcorn needs everyday at this location. According to Allen *et al.* (1998), the daily ETc was calculated as:

$$ETc = ETo \ x \ Kc$$

It was then adapted to fit the actual irrigation criteria of the farm (2.2 mm per irrigation), as the research was not developed for a research farm. The values of Kc chosen were adapted to the local climatic conditions (Allen *et al.,* 1998) (Table 3.3). This schedule was calculated with long-term climate data from a weather station 17 km away. So, it needed some daily control.

Table 3.3 Values of Kc for Sweetcorn at each stage (Source: Allen *et al.,* 1998)

Crop stage	Kc (FAO)	Kc adjusted for SCL conditions
Initial	0.35	0.35
Development	1.15	1.21
Final	1.05	1.05

Once the irrigation started, the schedule was controlled, and sometimes modified, by the daily climate records, recorded at the farm weather station, and the wetting patterns of the irrigation into the soil. Immediately after the sowing, 8 mm of water was applied in order to create a wet bulb around the seed, helping its initial growth. Two days without irrigation were followed.

The daily climate records were collected from an automatic weather station installed in the farm by the company a few months before. It provided the daily ETo but, by a method different to the Penman-Monteith equation. The necessary data was collected in order to calculate the ETo by using Penman-Monteith method from the weather station (Maximum and minimum temperature, ºC; humidity, %; wind speed, km/h; precipitation, mm; and solar radiation, MJ/m^2). Because of that, in order to see the correlation between both ETo, a regression statistical analysis was conducted.

To conclude the irrigation schedule adaptation, the wetting patterns were checked twice per week before the irrigation at each field, beginning the second week after sowing and continuing until harvest. This allowed the control of the water infiltration depth and its comparison with the roots. Although some root samples were measured after the harvest at each field, during the crop season they were estimated by *WaSim* (software developed by Cranfield University) because it was not possible to check them from the trenches.

The dimensions of the fields were big with regard to research purposes (212 x 48 m) they were not completely flat and the soil composition could very well vary. So, for the measurement of the wetting patterns, at each field, two trenches were dug at each side of the field (North and South) to provide a mean measure of the field.

For instance, the topography factor was important for the development of the irrigation schedule in field C, where the groundwater table was of significant importance. In the north side of the field, the water table was exceptionally high (closer than 40 cm from soil surface) while, in the south side it was not possible to appreciate it in the first 80 cm. Because of that, in the north side of field C after the 14th of February and in the south side after 14th of March it was not possible to obtain a clear measurement of the wetted pattern because they were touching the groundwater table.

Each trench was 50 cm of width, 100 cm of length and 80 cm of depth and was dug 10 cm away from the plant rows (Picture 3.6).

Picture 3.6 One of the trenches dug (left) and one example of a wetted pattern (right)

3.4 Yield and quality

To check the cob characteristics and its quality the harvest method of SCL was followed. Their harvest system is manual and it is done over two days. For the research, 250 cobs were randomly picked from each field during the first picking. In the second picking the aim was to pick the same amount of cobs but it was not possible to pick 250 cobs again in the three fields because there were an insufficient number of cobs left.

Each cob was subjected to the following tests: weighed with and without the leaves with a weight scale, the length measured with a tape measure and the diameter (in the middle point) with a precision meter, and the number of rows of grain counted (Picture 3.7). Those characteristics were statistically compared using the Student´s t-test.

The export requirements by SCL were:

- For first quality export product, the length of the cob must be above 15 cm
- For second quality export product, the length of the cob must be between 13 and 15 cm

- Cobs with a length below 13 cm are not allowed to be exported
- Regardless of the length, the number of rows of grain per cob must be 14 or above to be exported
- No export is allowed if there is any impurity or problem in the cob that may limit its trade i.e. immaturity, fecundation, any kind of pollution (worms) or dehydration.

Picture 3.7 Cob tests during the analysis

The final yield was calculated as the total number of cobs harvested per field multiplied by the mean cob weight of the samples picked.

The data provided by SCL for the previous crop season was an approximation of their real production because of the lack of measurement techniques. Nowadays, they have improved those techniques and yield records are more precise.

3.5 Water use efficiency

To evaluate the performance of the applied irrigation schedule and the yield efficiency, the water use efficiency (WUE, kg/m^3) and irrigation water use efficiency (IWUE, kg/m^3) were calculated with the following equations (El-Hendawy *et al.,* 2008b):

$$WUE\ (\frac{kg}{m^3}) = \frac{Y}{ET_c}$$

$$IWUE\ (\frac{kg}{m^3}) = \frac{Y}{I}$$

Where:

- Y is the economic yield (kg/ha),
- ETc is the crop water use (m^3/ha)
- and I is the irrigation applied (m^3/ha).

The water footprint (litres/cob) was also calculated in order to know how many litres of water should be applied to produce one cob of sweetcorn in these climate conditions. The equation to calculate is the following:

$$Water\ footprint = \frac{I}{Z}\ x\ 10^{-3}$$

Where:

- I is the irrigation applied (m^3/ha)
- and Z is the number of cobs per ha

4 RESULTS

In this chapter the results obtained are described. They are organised into four sections: Climate, irrigation scheduled, yield and quality, and WUE. In each section, the data collected from the previous crop season (October 2011 – January 2012) and the data obtained during the research (January – April 2012) is explained and compared.

4.1 Climate

During the previous crop season (October 2011 – January 2012) the climate data was collected from the weather station installed in the farm and from Saint Louis airport (Table 4.1; Full details of Diama climate records in this period are summarised in Appendix B).

During that period, the mean maximum and the mean minimum temperatures were quite similar in both places (2 and 1% higher at the airport, respectively). The biggest differences between both weather stations were in mean relative humidity, mean wind speed and mean solar radiation which were 10, 35 and 22% higher in the airport, in that order.

Table 4.1 Monthly climate data from SCL weather station and St Louis Airport (October 2011- January 2012) (Values between brackets: difference with the 30 years long-term data)

Month	Mean Daily Max. Temp (ºC)	Mean Daily Min. Temp (ºC)	Mean Daily Rel. Humidity (%)	Mean Daily Wind Speed (km/h)	Mean Daily Solar Radiation (MJ/m^2)	Total Rainfall (mm)
SCL station						
October	36.1 (+1.8)	24.6 (0.0)	64 (-5)	7.4 (-5.7)	19.3 (-0.2)	3 (-22)
November	34.5 (+0.3)	19.8 (-1.5)	52 (-3)	7.7 (-6.6)	18.1 (-2.0)	0.8 (+0.7)
December	30.7 (-1.1)	17.5 (-1.1)	38 (-11)	6.8 (-6.6)	18.4 (-0.8)	0 (-13.1)
January	31.1 (+0.4)	16.3 (-1.0)	38 (-7)	6.9 (-7.9)	17.0 (-3.0)	0 (-2.9)
St Louis Airport station						
October	35.3 (+1.0)	24.9 (+0.3)	70 (+1)	10.4 (-2.7)	20.3 (+0.8)	4.1 (-20.9)
November	35.0 (+0.8)	20.0 (-1.3)	61 (+6)	11.5 (-2.8)	21.7 (+1.6)	0.0 (-0.1)
December	32.3 (+0.5)	18.1 (-0.5)	38 (-11)	11.0 (-2.4)	20.0 (+0.8)	0.0 (-13.1)
January	31.7 (+1.0)	17.1 (-0.2)	45 (0)	11.2 (-3.6)	21.0 (+1.0)	0.0 (-2.9)

During the research, the climate data was collected only from the weather station installed in the farm (Table 4.2; Full details of Diama climate records in this period are in Appendix B).

Even though the local weather characteristics did not vary substantially from the long-term ones (Saint Louis airport), the regression analysis proves that there is less than 5% of probability of having the same values in both places. Because of that, the ETo was calculated with the daily data from the farm and not with the long-term ones.

Table 4.2 Average monthly climate data from SCL weather station (January – April 2012) (Values between brackets: difference with the 30 years long-term data from the airport)

Month	Mean Max. Temp (ºC)	Mean Min. Temp (ºC)	Mean Rel. Humidity (%)	Mean Wind Speed (km/h)	Mean Solar Radiation (MJ/m^2)	Total Rainfall (mm)
January	31.1 (+0.4)	16.3 (-1.0)	38 (-7)	6.9 (-7.9)	16.9 (-3.0)	0.0 (-2.9)
February	30.0 (-2.0)	16.5 (-1.1)	42 (-6)	6.3 (-9.8)	15.0 (-8.2)	0.2 (-5.4)
March	33.1 (+0.6)	18.7 (-0.2)	48 (-7)	6.2 (-11.7)	17.9 (-7.1)	5.0 (+3.7)
April	30.9 (-0.3)	18.5 (-0.8)	62 (-2)	10.1 (-9.7)	18.6 (-6.4)	0.0 (-0.1)

Daily climate records from the farm during the sweetcorn season are plotted in Figure 4.1. For instance, it is important to emphasise in this figure the unusual rainfall event which happened on 28th of March. Even though the mean humidity in those months was lower than the long-term average, before and after the rainfall event, the humidity had values similar to the wet season (July – August - September) where the humidity reached average values higher than 80% (Figure 1.1).

Also during this period, the maximum temperatures were lower than the long-term mean values in this month (March). Normally the average is between 30 and 35 ºC whilst the minimum temperatures had expected values for the season.

In addition, it is interesting to see how the maximum temperature, the solar radiation and the wind dropped during the rainfall event, while the relative humidity increased dramatically a few days before that event.

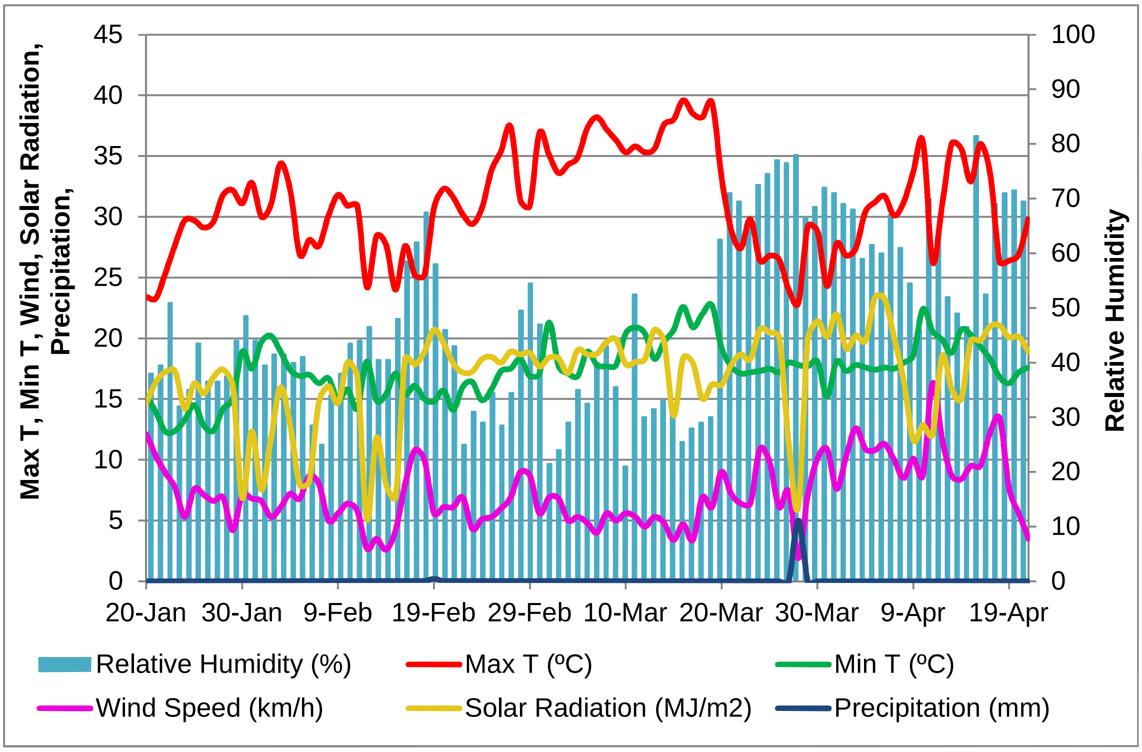


Figure 4.1 Climate data from Diama weather station (January – April 2012)
(latitude 16.12ºN; longitude 16.24ºW and altitude: 7 m)

As ETo from SCL weather station was not calculated by Penman-Monteith equation, it was analysed using the one from SCL station and the one calculated by the Penman- Monteith equation with the data from the station, to see the connection (Figure 4.2).

The regression analysis proves that there exists more than a 95% probability of obtaining significantly similar ETo values from any of both sources. The regression equation and the correlation between them are as follows:

$$y = 1.056x + 0.1136$$

$$R^2 = 0.78$$

In this equation, the values 1.056 and 0.1136 are not significantly different from the ideal linear equation where they should be 1 and 0, respectively. Because of this, the following calculation of ETc, for the irrigation schedule in the three fields, was done with the ETo calculated by the station software.

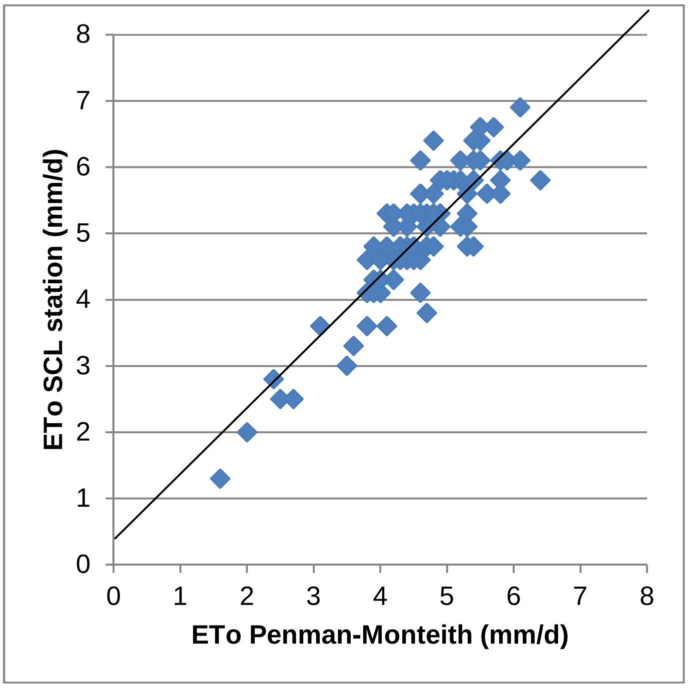


Figure 4.2 Comparison between the ETo calculated by SCL weather station and by Penman-Monteith equation (from 20/01 to 21/04 of 2012)

The mean ETo during the previous season and the study seasons were 5.16 and 4.96 mm/d, respectively. Daily ETo was very similar between both seasons (Figure 4.3).

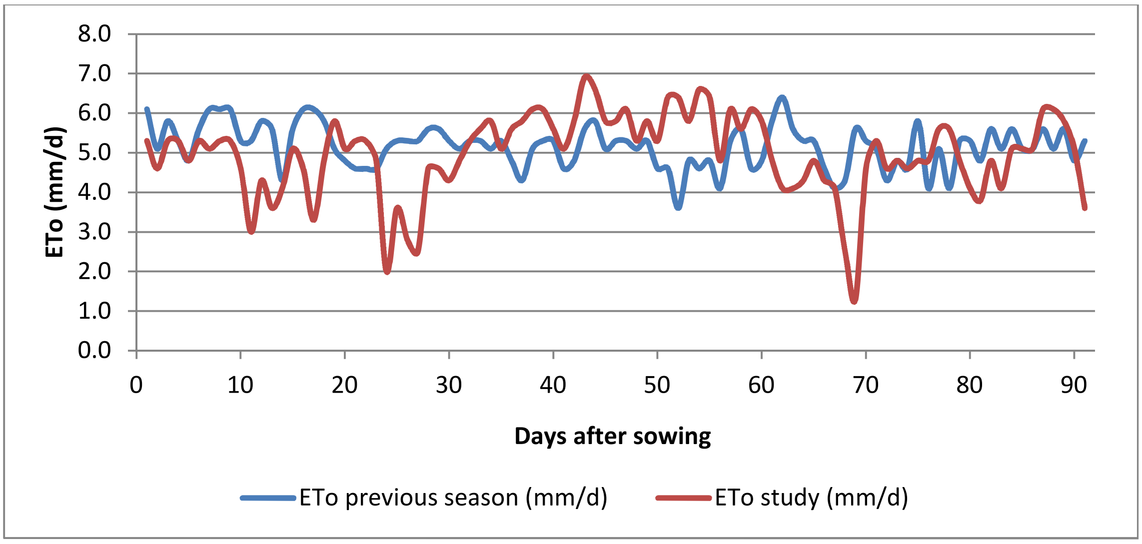


Figure 4.3 Comparison of the ETo during the study with the ETc from the previous crop season

4.2 Irrigation schedule

The total amount of water scheduled for sweetcorn in the period October 2011 – January 2012 was 392,126 m^3 for the entire farm. In that season, 70 hectares of land were cultivated and the average of the water scheduled was 5,602 m^3/ha. Table 4.3 shows the irrigation schedules and the ETc in fields A, B and C recorded in the previous crop season.

Table 4.3 Irrigation schedule records and ETc at SCL in fields A, B and C (October 2011 – January 2012)

Field	ETc (m^3/ha)	Irrigation scheduled (m^3/ha)
A	3,480	6,129
B	3,490	5,345
C	3,060	5,821

The significant differences between the ETc and the irrigation scheduled (76, 53 and 90%, in fields A, B and C, respectively) may be explained by the fact that during the maximum water demand from the plant (average of 6 mm/d), the average irrigation scheduled was 12.3, 10.8 and 13.3 mm/d in fields A, B and C, respectively (Figure 4.4).

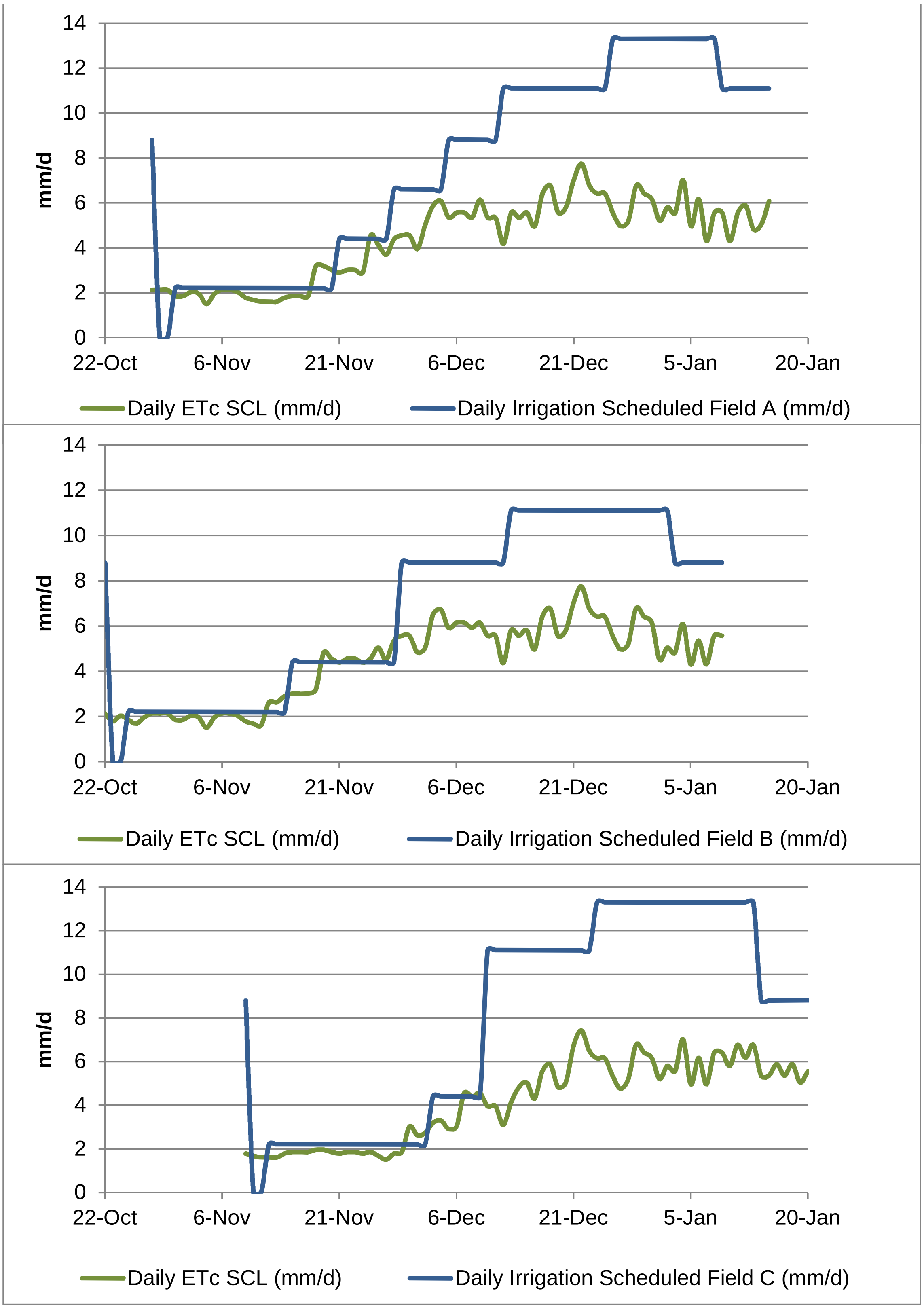


Figure 4.4 Daily values of ETc and Irrigation scheduled in fields A, B and C respectively (22nd October 2011 – 20th January 2012)

In comparison to the previous sweetcorn season, during the research season, the total amount of water scheduled for the whole farm was 438,956 m^3 programmed for 98 hectares. On average the irrigation scheduled was 4,479 m^3/ha. This value was 20% lower than in the previous season.

For the development of the new irrigation schedule the results have been organised in the methodology explained in Chapter 3.

A. CropWat 8.0 schedule

The base of the research irrigation schedule was developed by CropWat 8.0 software according to farm specifications. Figure 4.5, indicates the irrigation schedule recommended by CropWat for sweetcorn grown in these conditions. Applying this irrigation model, the maximum daily irrigation would be 9.9 mm/d and the final water consumption would be 5,556, 5,566 and 5,074 m^3/ha in fields A, B and C, respectively.

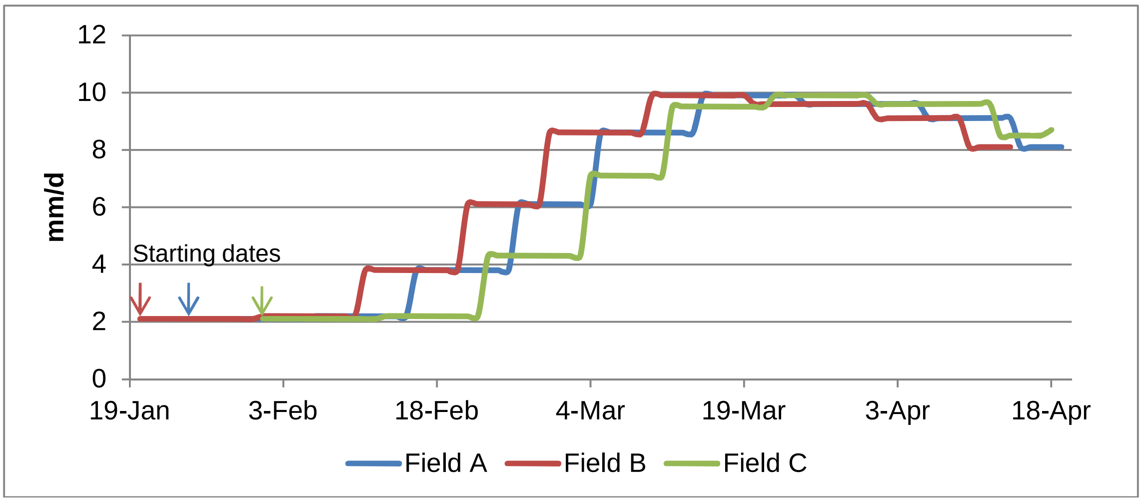


Figure 4.5 Irrigation schedule developed by CropWat for each field (January – April 2012)

B. Wetting pattern

As the collection of daily ETo in the farm, wetting pattern measurement took an important role for the development of the irrigation schedule. It was essential at field C because of its high groundwater table.

Figure 4.6 shows the mean wetted front depth compared to the predicted root depth (Full details of wetting patterns records are in Appendix C). Only in field C was the mean wetted front depth value not plotted because of the high groundwater table, which allowed for measuring until 14th of February and 16th of March on the north and south side of the field, respectively.

In field A, the wetted pattern was constantly under the root depth, and the maximum distance between them was 23 cm on 28th of February. In field B, during the first 40 days, the wetting pattern was very close to the root depth; and on occasions above it. After this period, with the increase of water applied, the wetting front dropped to under the roots with a maximum distance between them of 20 cm. The depth of the pattern in field C was measured below the roots until the 15th of February and then remained above. The final root depth was 60 cm in fields A and B and 70 cm in field C.

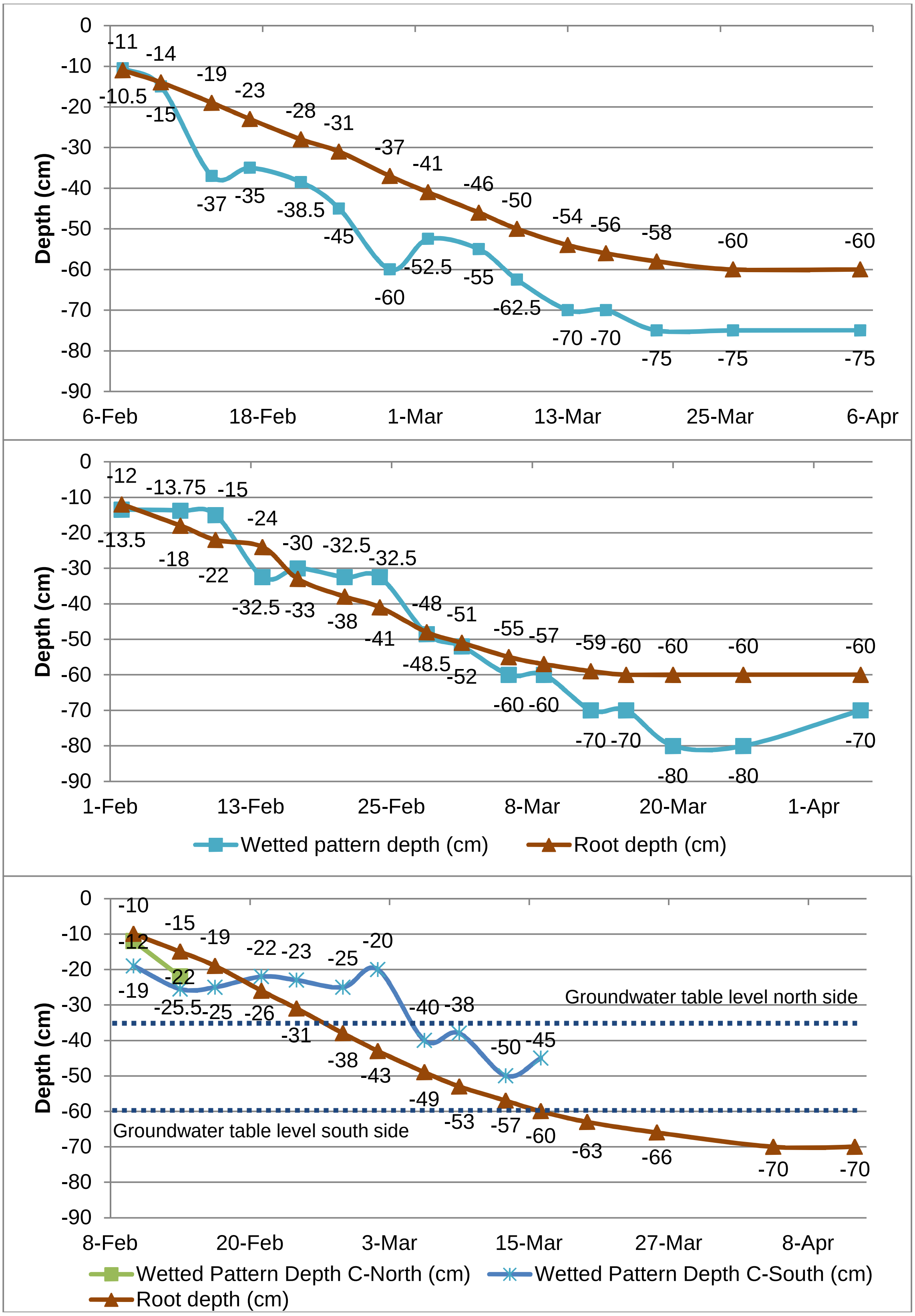


Figure 4.6 Comparison between mean wetted pattern and predicted root depth throughout the crop season in fields A, B and C, respectively

C. Irrigation schedule

After the adaptation of CropWat irrigation model to the irrigation farm's characteristics and the climate and wetting pattern analysis, the final irrigation schedule, at each field, is plotted in Figure 4.7 (Full details of daily irrigation schedule are in Appendix D).

In the three fields, the irrigation attempted to be as close as possible to the ETc. The mean application during the highest plant water needs at fields A, B and C was 7.8, 7.5 and 6.5 mm/d, while the mean ETc was 5.7, 6 and 5.6 mm/d, respectively. Comparing this period with the previous season (Figure 4.4), the irrigation applied was 37, 31 and 51% lower at field A, B and C, respectively. At the end of the crop season, in the three fields, the water scheduled was lower than the ETc.

Daily climate modifications were made throughout the season. The most important one being during the rainfall event (28th of March), when the ETc was 1.57 mm/d and the irrigation was stopped.

Also modifications from wetting patterns readings were important in the three fields. For instance, in field C, during the initial period, the irrigation of 2.2 mm/d was applied during four weeks rather than three, as in fields A and B. Also, it was attempting to keep the maximum daily irrigation in 6.6 mm/d, compared to fields A and B where it was 8.8 mm/d.

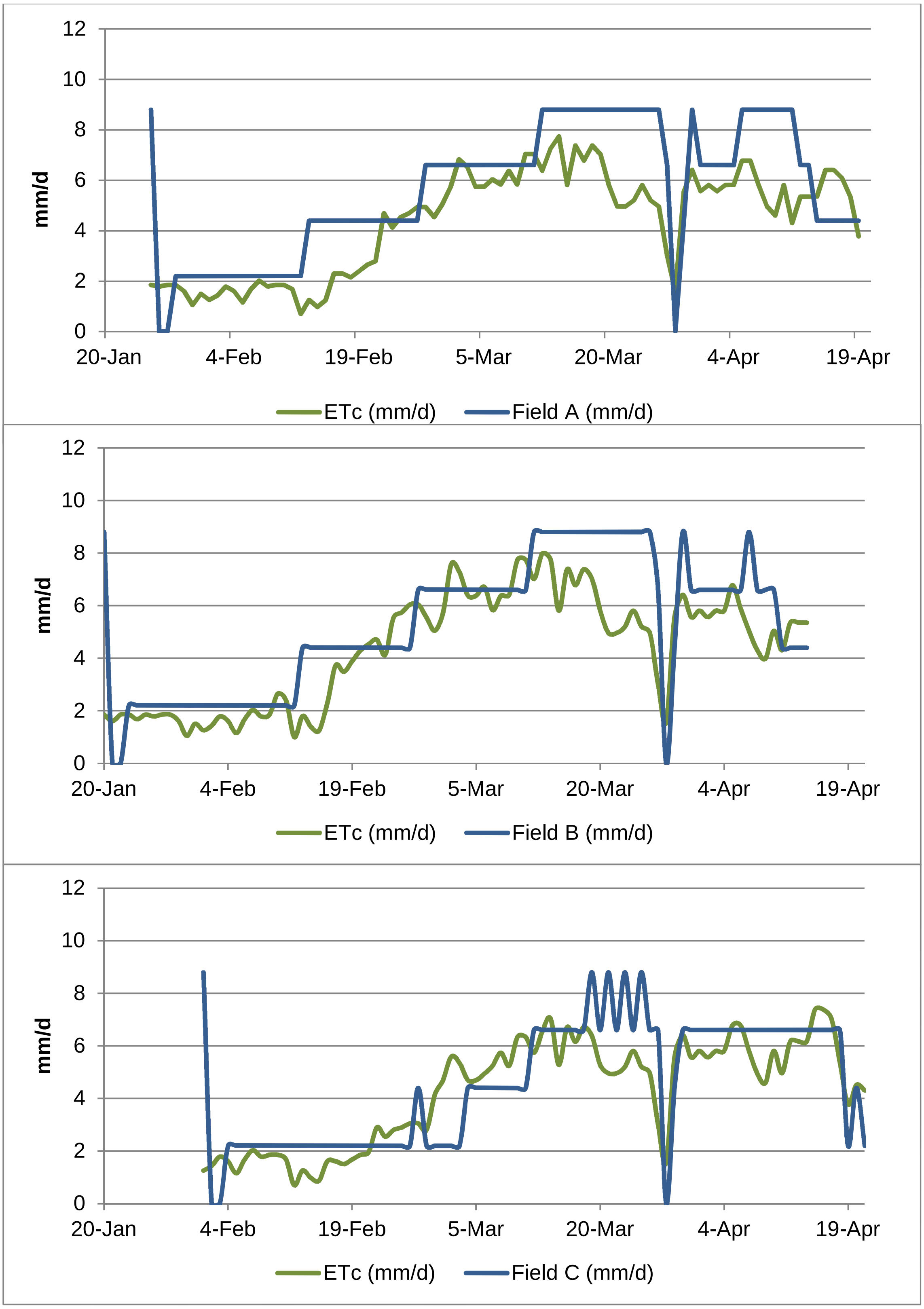


Figure 4.7 Daily values of ETc and Irrigation scheduled in fields A, B and C respectively (January – April of 2012)

Table 4.4 shows the ETc, the differences between the irrigation scheduled and the irrigation applied and the adequacy of the irrigation system. In the three fields the adequacy of the system was very high.

Table 4.4 ETc, irrigation scheduled and applied and their adequacy at each field

Field	ETc (m^3/ha)	Irrigation Scheduled (m^3/ha)	Irrigation Applied (m^3/ha)	Adequacy between irrigations
A	3,849	4,840	4,735	98%
B	3,837	4,530	4,530	100%
C	3,490	3,610	3,576	99%

4.3 Yield and quality

According to the data provided by SCL, during the previous crop season, the production exported of sweetcorn in Diama farm was around 12,000 kg/ha cultivated. Of the exported production, 89% was considered as first quality and 11% as second quality.

During the study season, the yield was reconsidered with regard to the number of cobs harvested per hectare and plant performance (Table 4.5). Field C produced the highest yield, but field B had the best export quality. In comparison to the previous season, field C produced the amount of sweetcorn expected while field B achieved quality values according to SCL expectations. In plant performance, fields B and C obtained the best results. Those results were almost double compared to field A.

The difference between cobs harvested in the first picking was very large among the three fields. Field C had a higher number of total cobs harvested and 87% of them were harvested during the first picking. In fields A and B only 80 and 77% were harvested in the first picking, respectively.

Table 4.5 Plant density, yield and export quality at each field

Field	Plant density (pl/ha)	Number of cobs harvested			Yield (kg/ha)	Plant yield (kg/pl)	Cobs per plant	Quality export (%)	
		1st picking	2nd picking	Total				1st	2nd
A	38,691	19,965	4,868	24,833	5,349.0	0.138	0.64	77	23
B	42,764	35,255	10,230	45,485	11,034.7	0.258	1.06	82	18
C	49,891	48,276	7,233	55,509	12,317.3	0.247	1.11	77	23

Table 4.6 shows the total average characteristics of the cob in each field after harvest, as well as the characteristics at each picking (Full details of cob characteristics are in Appendix E). On average, the three fields had good cob characteristics. In field B, the length and the diameter of the cobs were bigger than the other two fields, making the weight of the cobs in field B, 13 and 10% higher than in fields A and C, respectively. The lack of information related to cob characteristics from the previous season has made this comparison impossible.

Due to the fact that the amount of cobs harvested at each picking was different (Table 4.5); another important yield comparison was the cobs characteristics between different pickings. The characteristics of the cobs after the harvest were better in the first picking than in the second, except in field B. In fields A and C, the second cob was generally shorter on average but it kept approximately the same diameter. In field B, the second picking was 1.2 mm thicker. The length reduction was 20, 8 and 27% in fields A, B and C, respectively. Also, in the second picking the weight of the leaves was less with a reduction of 7, 5 and 8% compared to the first picking in fields A, B and C, respectively.

Table 4.6 Cobs characteristics at each picking and at each field

	Weight with leaves (gr)	Cob weight (gr)	Length (cm)	Diameter (cm)	Nº rows	Cobs harvested
Field A	**282.5^a**	**215.4^a**	**15.3^a**	**4.83^a**	**18.5^a**	**482**
1st picking	292.2^a	214.3^a	16.6^a	4.80^a	19.0^a	250
2nd picking	271.2^a	216.7^a	13.8^a	4.87^a	17.8^a	232
Field B	**318.1^b**	**242.6^b**	**16.2^b**	**4.98^b**	**19.3^b**	**500**
1st picking	327.2^b	241.0^b	16.8^b	4.92^b	19.1^a	250
2nd picking	308.8^b	244.2^b	15.6^b	5.05^b	19.5^b	250
Field C	**280.4^a**	**221.9^c**	**15.6^a**	**4.88^c**	**18.6^a**	**304**
1st picking	289.1^a	225.4^c	16.2^c	4.88^b	18.4^c	250
2nd picking	238.6^c	204.7^c	12.8^a	4.89^a	19.3^b	54

Within columns, means with the same letter are not significantly different at $p<0.05$, according to Student´s t-test.

The last important factor in crop production is the export quality (Figure 4.8). The three fields had similar and good export quality in the first picking, while in the second one there were bigger differences between the three fields and not very good final export quality on average. Finally field B exported 91% of its production, which was 5 and 1% more than in fields A and C, respectively.

The cobs quality in field A dropped in the second picking (25% in the first quality) but increased by 9, and 17% in the second one and no export, respectively. In the case of field C it was worse. The percentage of first quality dropped by 54%, whereas the percentage of second quality and no export cobs increased by 34 and 19%, correspondingly. In terms of quality of only the cobs exported, 77% was exported as first quality in fields A and C, while in field B this value increased up to 82% (Table 4.5).

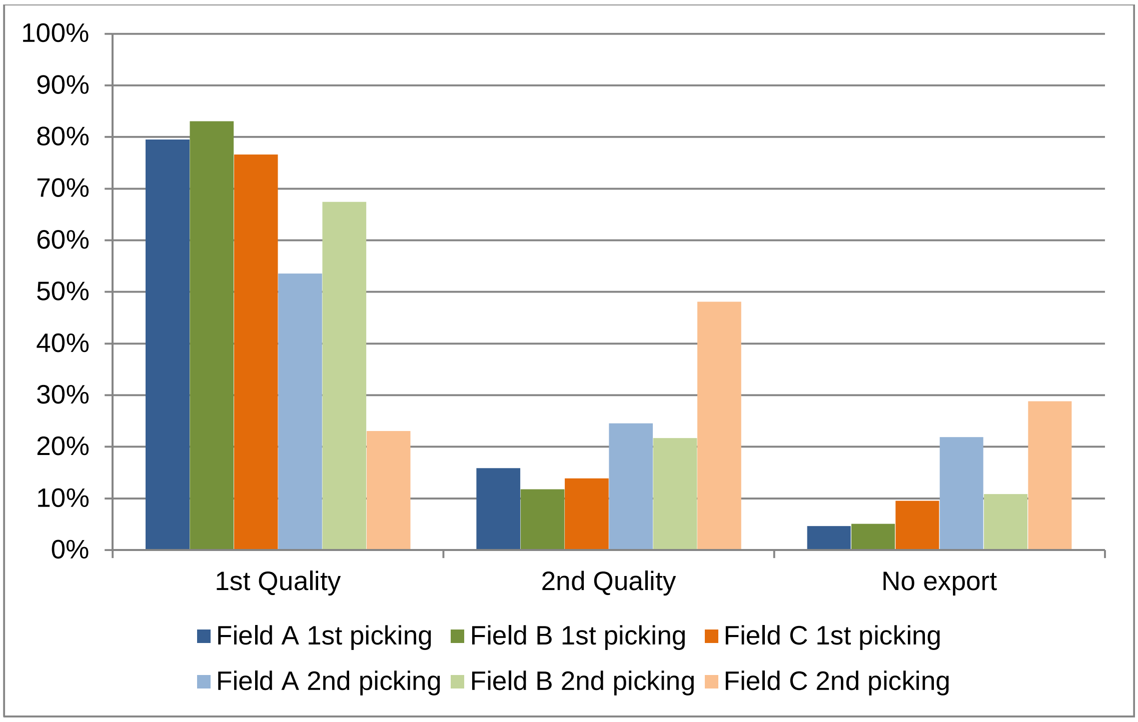


Figure 4.8 Cobs export quality at each picking in fields A, B and C

4.4 Water use efficiency

During the previous crop season, the values of WUE and IWUE were 3.4 and 2.0 kg/m^3 in field A; 3.4 and 2.2 kg/m^3 in field B; and 3.9 and 2.1 kg/m^3 in field C, respectively.

The values from the research are summarised in Table 4.7. The field with better water efficiency was field C with values of WUE and IWUE of 3.5 and 3.4 kg/m^3. The plant water needs were 64 litres of irrigation to produce one cob in field C, whilst in fields A and B 126 and 36 litres more were applied respectively.

Table 4.7 Water use efficiency characteristics at each field

Field	ETc (m^3/ha)	Irrigation applied (m^3/ha)	Yield (kg/ha)	WUE (kg/m^3)	IWUE (kg/m^3)	Water footprint (litres/cob)
A	3,849	4,735	5,349.0	1.4	1.1	190
B	3,837	4,530	11,034.7	2.9	2.4	100
C	3,490	3,576	12,317.3	3.5	3.4	64

Comparing both crop seasons results, only in fields B and C was the IWUE improved (10 and 62%, respectively). The WUE had similar values in both seasons but field A was 59% lower.

Table 4.8 provides a summary of the results obtained during the research as well as the data provided by SCL from the previous crop season. The data shown from the previous season came from the farm. The number of cobs harvested during the previous season was calculated from the average yield and the average weight of a cob (230 gr).

Table 4.8 Summary of the results obtained during the research and the previous crop season

	Field A	Field B	Field C	Previous season
Soil characteristics	Unstructured	Sediment	High groundwater	Farm average
Bulk density	1.44	1.50	1.53	1.49
AWC%	5.1	7.8	4.3	5.7
Infiltration rate (cm/hr)	13.9	12.7	7.2	11.3
Plant density ha (m^2)	38,691 (3.87)	42,764 (4.28)	49,891 (4.99)	50,000 (5,00)
Yield				
Kg/ha fresh	5,349	11,035	12,317	12,000
(Calc. at 25% d.m.)	(1,337)	(2,759)	(3,079)	(3,000)
1st quality yield (Kg/ha)	3,584	8,276	8,252	10,680
Total cobs	24,833	45,485	55,509	52,174
Cobs/plant	0.6	1.06	1.11	1.04
Water info				
ETc m^3/ha	3,848	3,837	3,490	3,343
Irrigation m^3/ha	4,735	4,529	3,576	5,602
WUE fresh kg/m^3	1.4	2.9	3.5	3.6
IWUE fresh kg/m^3	1.1	2.4	3.4	2.1
WUE dm kg/m^3	0.35	0.72	0.88	0.9
IWUE dm kg/m^3	0.28	0.61	0.86	0.5
Kg fresh/mm Irri/ha	11.3	24.4	34.4	21.4
Litres irri/cob	190	99	65	107
Litres ETc/cob	155	84	63	64
Kg fresh mm ETc/ha	13.9	28.7	35.3	35.9
Kg fresh mm irri/ha	11.3	24.4	34.4	21.4

5 DISCUSSION

In this chapter the results obtained during the research and the methodological limitations are discussed. The previous analysis of the farm characteristics has contributed to understanding the characteristics and the irrigation techniques at SCL as well as being able to compare the results of the research with those from the previous sweetcorn season.

5.1 Climate

The climate data analysis was made to calculate the ETo during both seasons and to check if it was possible to predict an irrigation schedule applying long-term climate data for the farm.

The analysis made during the previous season (October 2011 – January 2012) shows that, the climate data recorded at St. Louis airport and at the farm, during the same period, had some differences (Table 4.1). The distance between the two places (approximately 17 km) cannot explain these differences. However, they can be justified due to the proximity of the airport to the Atlantic Ocean, which may increase some climate characteristics, such as wind speed and relative humidity. The difference in terms of solar radiation may be explained by the Harmattan wind. The farm is very close to the desert and the wind brings clouds of dust from the desert, limiting the solar reception by the weather station sensor.

To demonstrate these climate differences between the weather stations, the regression analysis made between each of the climate characteristics shows that there is almost no chance of there being the same weather conditions. Hence, the climate data from the airport was used only as a climate reference owing to the lack of long-term climate data in the farm. The final ETc was calculated from the ETo obtained by the weather station installed in the farm (Figure 4.2).

Looking at the ETo during both seasons (Figure 4.3), it is possible to see that the climate characteristics in the farm were similar between both crop seasons.

The mean daily ETo was 4% higher during the previous season than during the study. With similar ETo, the plant water needs should be similar between seasons too, as well as the irrigation applied.

5.2 Irrigation schedule

According to the previous section, sweetcorn water needs during both crop seasons should be similar (Figure 5.1). The mean ETc in the farm, during the previous season, was 3,343 m^3/ha (10% lower than the research one). This means that at least the farm mean irrigation applied in the previous season should be lower or equal to the irrigation applied during the research.

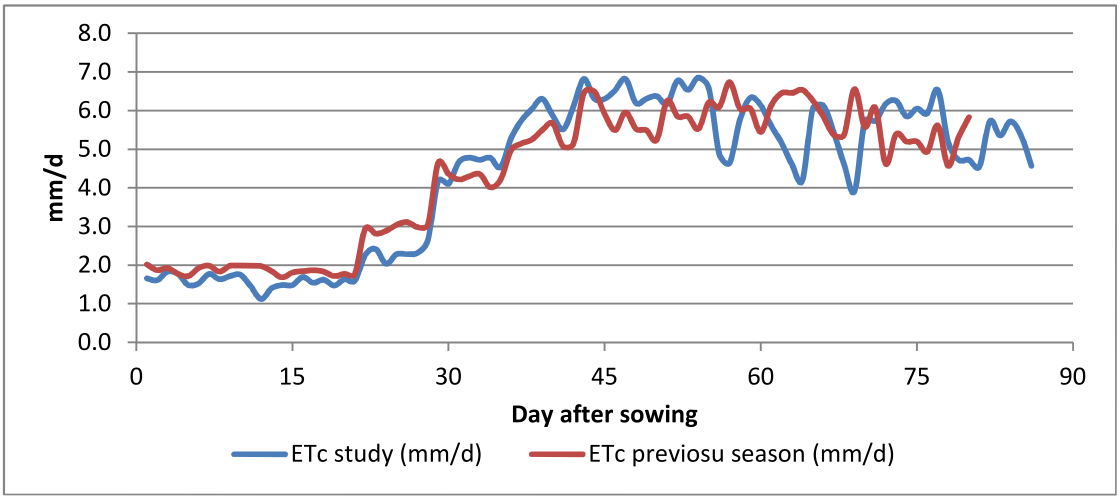


Figure 5.1 Comparison of the ETc during the study with the ETc from the previous season

The average irrigation applied in the farm during the previous season was 5,602 m^3/ha. This value differed by around 15% more than the literature recommendations, which advises to irrigate around 4,500 - 5,000 m^3/ha in a sandy soil and dry climate area (Table 2.1). In the particular case of the three fields of the study (A, B and C; Table 4.3), they were 25, 11 and 18% over-irrigated according to the literature recommendations for this climate and soil conditions, respectively.

This previous irrigation analysis shows that the three fields of the study were irrigated with more water than would be expected for the location and climate conditions during that period. To help this assertion, Figure 4.4 shows the difference between the actual ETc and the irrigation scheduled in the three fields of the study. The over-irrigation period took place mainly during the highest water demand from the plant (December 2011 – January 2012). According to the mean ETc during that period (6 mm/d), fields A, B and C were daily irrigated 55, 46 and 52% more, respectively. At the end of the season, the final irrigation scheduled was 43, 35 and 47% more than the ETc, in fields A, B and C, respectively (Table 4.3).

Only by comparing the recommendations it was clear that the fields were over-irrigated but there was not a specific irrigation recommendation for this farm. So the need for a new irrigation schedule was essential to verify how much water was wasted in the farm.

The sweetcorn from the research was irrigated, as farm average, with 4,479 m^3/ha (20% lower than in the previous season). In the particular cases of the three fields studied (fields A, B and C), they were irrigated 23, 15 and 39% less than in the previous season, respectively.

This high irrigation reduction was possible because of the daily climate analysis and the periodical checking of the wetting patterns. The purpose of the new irrigation schedule was to keep the amount of daily irrigation as close as possible to the daily ETc (Figure 4.7). During the research, the maximum daily irrigation scheduled was 8.8 mm/d and not 12.6 mm/d (Figure 4.4) as was found to be the average in the three fields during the previous season. In both seasons the maximum ETc never reached values higher than 7 mm/d (Figure 5.1). So, the irrigation of 12.6 mm/d represents an increment of 80% of sweetcorn water needs grown in those conditions. At the end, during the research, the final water applied in fields A, B and C was 23, 18 and 2% more than the ETc, respectively (Table 4.4).

Compared to the previous season, the differences between the irrigation applied and the ETc during the study were much smaller. Although the target of the daily irrigation schedule was to be as close as possible to the daily ETc, the farm irrigation system did not allow it. This is because the irrigation system only allowed an irrigation multiple of 2.2 mm, so most of the time it was irrigated above the plants water needs (Figure 4.7).

There is an enormous cost involved in the running of this high irrigation (energy, fertilizer, manpower...), which has increased farm expenditure with issues such as the possibility of future soil contamination or a rise of the groundwater table. The latter is a very important issue in the farm, mainly in the central area around field C where the groundwater table is very high (40 cm from the soil surface). Soil analysis conducted in the farm years ago has shown that there was no groundwater table within the first two meters of soil. Also, analysis made of the water from the groundwater table shows that water salinity was higher than the one from natural water because of the fertilisation applied. As a result, it is demonstrated that this water comes from the over-irrigation from previous years.

One of the important effects that the high groundwater table may have on the crop is its death by root anoxia due to the possible flooding of the root zone. Also, due to its high salinity it may dehydrate the root cells limiting the water and nutrient absorption.

As field C was chosen in the area of high groundwater table, it was assumed that the plants were withdrawing part of their water needs from the groundwater table helping to reduce the irrigation applied in the field compared to fields A and B (Table 4.4). This assumption explains also why, during some periods the irrigation scheduled was lower than the ETc (Figure 4.7). This supposition would not be possible to make if the wetting patterns of the trenches had not been assessed.

Wetting patterns analysis was important for the development of the irrigation schedule in the three fields but it was essential in field C. As was expected from the literature reviewed (Li *et al.,* 2004), the wetting front penetrated more (Figure 4.6) when the amount of water applied increased (Figure 4.7).

This analysis helped to keep the irrigation of 2.2 mm/d, for the initial stage, during four weeks in field C, rather three weeks in fields A and B (Figure 4.7) and recognise the moment that the roots could touch the groundwater table (Figure 4.6). For the three fields the wetting patterns measurement was useful to develop the irrigation schedule at the moment of maximum ETc. According to the previous irrigation in the farm (Figure 4.4) and also, according to the irrigation schedule developed by CropWat (Figure 4.5), the irrigation at this stage would be higher. But, the measurement of the wetting patterns proved that the front of the pattern at this stage was below the predicted roots depth (Figure 4.6), so it was not necessary to increase the irrigation more than 8.8 mm/d

In field C, the distance between the groundwater table to the soil surface was not homogenous along the field because of its irregular topography. In the north side of the field, it was closer to the surface (less than 40 cm), so most of the roots could withdraw it at maximum root development. However, in the south side, it was farther (around 60 cm) so only at the end of the crop season could a few roots could take water from there. Because of that, the irrigation schedule during the maximum ETc was not easy to set. The large dimensions of the field made it difficult to provide the correct irrigation for the whole field, so a schedule suitable for both sides was attempted The final schedule for this period was to alternate the irrigation of 6.6 mm/d one day with the one of 8 mm/d the following day for nine days (Figure 4.7). The low infiltration rate of field C and the high groundwater table meant that the wetting patterns in the south side of the field were above the predicted root depth, compared to field A, where the infiltration rate was almost double.

Also, it is interesting to observe that the root depth among the three fields was not the same. In fields A and B it was around 60 cm as was expected from the literature (Laboski *et al.,* 1998), while in field C it was 70 cm. This higher root depth at field C might have two explanations. The first could be that when the irrigation applied is slightly limited; the roots go deeper, trying to find water (Coelho and Or, 1999; Oktem, 2006). And the second may be because of the high groundwater table, the roots grow downwards because they feel the soil moisture which is moving upwards from the groundwater table.

The measure of wetted patterns and root depth by this trench method presented some limitations. Due to the fact that the trench was dug near the emitter, the water distribution into the soil could have altered because there was less soil around the emitter where the water could move. Also the water of the trench surface may have evaporated with the effects of the sun leading to a false measurement. In addition it was difficult to see the maximum root depth, although it was measured after harvest and it was on average 60 cm in fields A and B and 70 cm in field C (Figure 4.6). Despite these limitations, with the characteristics of the farm and its technical resources, it was the only feasible way to monitor and control them.

At the end, field C had the lowest water application among the three fields. Fields A and B were irrigated with 4,735 and 4,530 m^3/ha, respectively. The irrigation in field C was around 1,000 m^3/ha less than in fields A and B. This difference was supposed to be supplied by the groundwater table. The final amount of fertiliser applied was the same in the three fields, as in the previous crop season.

In case that the irrigation schedule was developed by CropWat recommendations, the final water consumption would be 18, 23 and 42% higher than the actual irrigation applied during the study, in fields A, B and C, in that order (Figure 4.5). The drawback of the application of this schedule model is that it was run using the long-term climate data from Saint Louis airport. So, according to the climate data recorded from the farm, the sweetcorn water needs would be higher, as the long-terms climate records were higher during the study period (Table 4.2). This model was used only to provide a guide as to previous sweetcorn water needs for those climate and soil conditions. Then this schedule was modified, as it was explained, checking the ETo and the wetting patterns. So, it is demonstrated that this model will require adaptations for each specific area and conditions, if it is used with the long-term climate data.

In conclusion, this water reduction of 20% for the whole farm was due to the adaptation of the sweetcorn water needs to each specific field characteristics. The water needs from the sweetcorn in both seasons was similar (Figure 5.1), so this water reduction was achieved by understanding the over-irrigation during the previous crop season.

The over-irrigation is a general problem in agricultural companies which are looking for profit. As is evident at SCL, the companies are afraid to lose yield and quality from the final product. They think that by increasing the irrigation these problems will be solved.

5.3 Yield and quality

The purpose of this section is to verify if the new irrigation schedule was able to produce sweetcorn on the farm with similar characteristics as in the previous crop season. The lack of information from the previous season makes it more difficult to achieve an accurate comparison between the seasons.

During the research, the final yield has been affected, mainly, by plant density reduction at each field (Table 4.5). Field A suffered more from density reduction (31% lower comparing to the initial plant density) leading to a final yield of 5,349 kg/ha (52% and 57% lower than in fields B and C, respectively).

The high plant density reduction in field A occurred because of the attack of a nematode plague. According to SCL description, the nematodes type was *Pratylenchus.* This genus of nematodes attacks the roots of the plants. They reduce root growth or inhibit root development by forming local lesions on young roots or kill off the plant completely. Moist temperate and sandy soils are ideal conditions for its development (Castillo and Vovlas, 2007).

Field B was also affected in a small area by the nematodes, leading to a plant density reduction (24% lower comparing to the initial plant density) and consequently a lower yield (11,034.7 kg/ha; Table 4.5) according to SCL expectation (12,000 kg/ha; 1.04 cob/pl; Table 4.8). The final yield harvested at Field C (12,317.3 kg/ha; Table 4.5) was the only one above SCL expectation with a final production of 1.11 cob/pl.

In the previous season, the number of cobs harvested per hectare and the number of cobs per plant were 52,174 and 1.04, respectively (Table 4.8). Those values were estimated without density reduction (no data available), so probably they would be lower in a no-ideal situation.

However, it was Field B that produced a better plant yield (0.258 kg/pl; Table 4.5), cob characteristics (Table 4.6) and harvest quality (Figure 4.8). According to the literature reviewed, the small length and weight of the cobs in field C, compared to field B (Table 4.6), might be due to higher plant density or lower irrigation applied after the pollination, so it may have been necessary to increase, up to 8.8 mm/d, the irrigation applied after the 26th of March, just for a few days (Figure 4.7) (Bozkurt *et al.*, 2006; El-Hendawy *et al.*, 2008a).

According to the seed supplier (Syngenta, 2012), the cob length in the three fields was lower than expectation (19-21cm), while the cob diameter was around their expectations (5.0 cm). It was field B that produced better final cob characteristics (16.2 cm of length and 4.98 cm of diameter).

The two picking analyses, in terms of cobs characteristics (Table 4.6) and cob export quality (Figure 4.7), show that the second picking was a good harvest option only in Field B. In Field A, the characteristics were not very good, but it was still profitable to do it. However, in Field C, it was not possible to harvest the same amount of cobs as the other two fields because in the first picking it was harvested the majority (Table 4.5); of the cob characteristics were not very good for exporting (Figure 4.7). The results show that the second picking practice needs to be revised at each field to verify whether it is or not profitable to do it. The right time to harvest is one of the most important decisions to make in agriculture business. It is possible to trust all the production or increase considerably the farming costs if the day chosen to harvest is too late or soon.

In this section, the lack of available cob data from previous seasons has meant that the only comparison feasible to make was in terms of cobs export quality. In previous seasons, the export quality expectations (89% as first quality) were slightly higher than during the research, although the way that SCL had to check it was not very accurate. Field B had the best export quality among the three fields. Of the total cobs harvested, only 8% were considered as “no export” quality, while in fields A and C, it was 13% (Figure 4.8).

5.4 Water use efficiency

As the ETc in both seasons was similar (Figure 5.1), the amount of water used by the crop should be similar too. In the previous season, the irrigation scheduled was 40% higher than the ETc, compared to the 17% higher during the research, as farm average. This approximation to the ETc during the research, it was reflected with 20% water use reduction compared to the previous season.

As one purpose of the development of a new irrigation schedule was to match the irrigation applied to the plant water needs, it is being reflected in the difference between the WUE and the IWUE. Even if those ratios were different among the fields, they were similar within each field compared to the previous season (Table 4.8). The differences between WUE and IWUE were 21, 17 and 3%, at fields A, B and C, respectively; while in the previous season the mean difference was 42%. That means that, finally, during the research the irrigation applied was closer to the ETc than during the previous season, although only in fields B and C harvested more kilograms of sweetcorn per m^3 of water applied than in the previous season (Table 4.8).

Among the three fields of the research, the one with highest values of WUE and IWUE was field C (3.5 and 3.4 kg/m^3; Table 4.7). The WUE was similar to the estimation from the previous season but the IWUE was higher (3.6 and 2.1 kg/m^3, respectively; Table 4.8). The low values of WUE and IWUE in fields A and B were due to the low yield, although those values at field B were higher than in field A. This increment of the IWUE is very important in arid and semi-arid areas where there is a lack of available water resources (Kashiani *et al.,* 2011).

Also, this analysis may be made by the comparison between the amount of water needed to grow one cob of sweetcorn and the actual irrigation applied to grow it (Table 4.8). During the previous season, this difference was 43 litres of water, while during the research none of the fields reached that difference (35, 15 and 2 litres per cob in fields A, b and C, respectively). These values confirm the previous statement: during the research the amount of water applied coincide more to the sweetcorn water needs, than in the previous season.

According to the literature, the WUE of crops is affected by genotype, management, weather conditions, available soil water content and soil texture (Garcia y Garcia *et al.,* 2009). In the study, the only variable among the three fields was the available soil water content and the higher water table in field C, so higher soil water content lower water needs for the plant. If the yield had been similar in the three fields, the IWUE in fields A and B would have been similar too, but the one from field C would have been higher because of its higher soil water content.

In the literature those values vary depending on, basically, weather conditions and irrigation management. In areas where the irrigation is combined with either high soil water content or rainfall, the WUE is higher (4.0 – 10.0 kg/m^3) (Garcia y Garcia *et al.,* 2009; Viswanatha *et al.,* 2002). On the other hand, in areas where the water supply relies only on irrigation those values are lower, from 1 - 2 kg/m^3 (Oktem, 2006; Oktem, 2008).

In the end, the most efficient field, in terms of water use, was field C, although it is important to take into account that it was assumed that the plants were absorbing water from the groundwater table. It produced 38% more kilograms of sweetcorn per m^3 of water applied than in the previous season, and 68 and 29% more than in fields A and B, respectively. For a standard field without external water source (rainfall or groundwater table), the values of IWUE would be as in field B (2.4 kg/m^3).

5.5 Methodological limitations

The main difference between this study and most of the studies of the literature is that this was carried out in the farm of a company, SCL and not in a research centre. In a research centre it is possible to adapt the system to the research characteristics, but in this case it was the opposite. It was necessary to adapt the research characteristics to the system, limiting a lot the different irrigation variables, as for instance irrigation frequency and timing.

Apart from these system limitations, the way to answer the purpose of the research changed once I arrived at the farm. The initial idea of how to compare the results from their irrigation practices with those from the research was different as it is described in this paper. This idea consisted of comparing two by two the three fields selected in the farm during the same season. It meant that each of the selected fields (A, B and C) had one field together with very similar soil characteristics. The only difference would be that one field would be irrigated according the new schedule, while the other one would be scheduled by SCL. Apart from the problems that would be incurred in terms of irrigation practices, the company realised that, despite applying less water the plant development remained the same, even better in some areas (Field C). Because of this the company switched their irrigation schedule to the one in the research. It then became impossible to compare the final yield and quality in the same season because at the end it was decided to compare the results of the current study with data from the previous crop season.

The next problem that appeared was that the company did not have the information I required, in terms of yield and quality, to compare correctly the data from both seasons. Consequently, some of it was an approximation of their available data; other information was estimated from other data and also from farm expectations. During my stay at the farm, the company started to change their habits in terms of calculating the yield and quality per field in a more accurate way.

Even if in Senegal, sweetcorn is grown during part of the dry season and the weather conditions do not change a lot, in irrigation it is better to compare water needs, yield and quality data in similar conditions. It could be better to compare data from different years but during the same period or from the same period of the year.

As it was said before, in this research the research was adapted to the system. The irrigation system of the farm presented some limitations in terms of timing and frequency of the irrigations for the research. The timing was fixed as 2.2 mm of water irrigated at each application (30 minutes) with no possible variations. Also, this system had discharge limitations, as it was not possible to irrigate at the same time more than one field per block and each section has a water discharge limitation of 134 m^3/h, so the frequency was affected too. These system characteristics have limited the correct adaptation of the irrigation to the ETc (Figure 4.7).

In terms of the periodical irrigation, adaptation to the current situation by the wetting patterns measured in trenches, presented some limitations too. The water distribution below the emitter could change. As half the soil was removed, the effective flow rate into the soil was doubled, and the soil had double the amount of water to move. Also, due to the high temperatures, some water from the trench surface could be evaporated leading to a different measurement compared to the real one. In an attempt to avoid this problem, the wetting patterns measurements were taken for the first time, in the morning, before the irrigation.

This methodology is not the most accurate way to provide evidence of the water movement into the soil, but despite this limitations, with the characteristics of the farm and their technical resources, it was the most appropriate and feasible solution. In research carried out in a research centre, the control of the water movement into the soil would be done by neutron probes installed in different parts of the field.

There was an advantage to staying on the farm for the period of the research and being able to check the correct development of the project, however there were some drawbacks in that I was unable to attend courses or workshops for the correct presentation and analysis of the results obtained.

Limitations of the presented study had shown that for a further research it is necessary to use a proper replicated block experiment to compare different irrigations applications (e.g., 120, 100 or 80% ETc) in order to find the amount of water which would have the best yield and quality results.

6 CONCLUSION

In this study, it has been demonstrated that for the development of a water efficient irrigation schedule it is essential to adapt it to the current climate and soil site characteristics. For instance, the wetting pattern analysis was indispensable for the correct development of the irrigation schedule at field C.

The results show that, by applying this methodology, it has reduced the global farm water consumption up to 20%, compared to the existing practices. In the particular cases of fields A, B and C, the water reduction was 23, 15 and 39%, respectively. These water reductions could also reduce farm costs such as manpower, fertiliser and energy used; and avoid future soil pollution.

The final yield and quality obtained was similar to SCL expectations. Field B harvested the best cob quality (82% exported as first quality) and field C the highest yield (12,317.3 kg/ha and 55,509 cobs/ha). Compared to the previous season, the IWUE in fields B and C was incremented 14 and 62%, respectively; while in field A, it was 48% lower due to its low yield.

The adaptation of the irrigation schedule to the wetting patterns and the climate conditions, has demonstrated that it is possible to obtain similar results of yield and quality, saving water and other productions costs. Therefore, if SCL switch to this methodology it will produce similar yield and quality as in previous seasons but with lower crop costs.

The methodology presented in this study has contributed to a better understanding of the behaviour of drip-irrigated sweetcorn in semi-arid areas.

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APPENDICES

Appendix A Infiltration rates

A.1 Field A

Table A.1 Infiltration rate test I in field A

Local time	Interval (mins)	Cumulative time (mins)	Depth of water in the infiltrometer (cm)	Intake (cm)	Cumulative intake (cm)	Infiltration rate (cm/hr)	
						Immediate	**Mean**
16:05	0	0	17				
	1	1	16.5	0.5	0.5	30	30
	1	2	16.1	0.4	0.9	24	27
	1	3	15.8	0.3	1.2	18	24
	1	4	15.5	0.3	1.5	18	22.5
	1	5	15.2	0.3	1.8	18	21.6
	2	7	14.6	0.6	2.4	18	21
	2	9	14.1	0.5	2.9	15	20.14
	2	11	13.7	0.4	3.3	12	19.12
	2	13	13.3	0.4	3.7	12	18.3
	2	15	12.9	0.4	4.1	12	17.7
	5	20	11.8 – 17	1.1	5.5	13.2	17.29
	5	25	16.2	0.8	6.3	9.6	16.65
	5	30	15	1.2	7.5	14.4	16.47
	10	40	12.9 – 14.5	2.1	9.6	12.6	16.2
	10	50	12.3 – 17.1	2.2	11.8	13.2	15.91
17:05	10	60	14.9	2.2	14	13.2	15.76
	15	75	11.5 – 16.6	3.4	17.4	13.6	15.64
	15	90	13.4	3.2	20.6	12.8	15.48
	15	105	10.2 – 17	3.2	23.8	12.8	15.34
18:05	15	120	13.6	3.4	27.2	13.6	15.25
	15	135	10.1 – 16.5	3.5	30.7	14	15.19
	15	150	12.9	3.6	34.3	14.4	15.15
	15	165	9.2 – 16.3	3.7	38	14.8	15.13
19:05	15	180	12.3	4	42	16	15.17

Table A.2 Infiltration rate test II in field A

Local time	Interval (mins)	Cumulative time (mins)	Depth of water in the infiltrometer (cm)	Intake (cm)	Cumulative intake (cm)	Infiltration rate (cm/hr)	
						Immediate	**Mean**
9:15	0	0	17.7	0			
	1	1	17.5	0.2	0.2	12	12
	1	2	17.2	0.3	0.5	18	15
	1	3	16.9	0.3	0.8	18	16
	1	4	16.7	0.2	1	12	15
	1	5	16.4	0.3	1.3	18	15.6
	2	7	16	0.4	1.7	12	15
	2	9	15.7	0.3	2	9	14.14
	2	11	15.3	0.4	2.4	12	13.87
	2	13	15	0.3	2.7	9	13.33
	2	15	14.6 – 18.4	0.4	3.1	12	13.2
	5	20	17.6	0.8	3.9	9.6	12.87
	5	25	16.7	0.9	4.8	10.8	12.7
	5	30	15.7	1	5.8	12	12.65
	10	40	13.8 – 18.0	1.9	7.7	11.4	12.56
	10	50	16	2	9.7	12	12.52
10:15	10	60	14.1 – 19	1.9	11.6	11.4	12.45
	15	75	16	3	14.6	12	12.423
	15	90	12.9 – 19	3.1	17.7	12.4	12.422
	15	105	16	3	20.7	12	12.421
11:15	15	120	12.9 – 19	3.1	23.8	12.4	12.4
	15	135	15.9	3.1	26.9	12.4	12.49
	15	150	12.6 – 19	3.3	30.2	13.2	12.53
	15	165	15.9	3.1	33.3	12.4	12.52
12:15	15	180	12.6	3.3	36.9	13.2	12.55

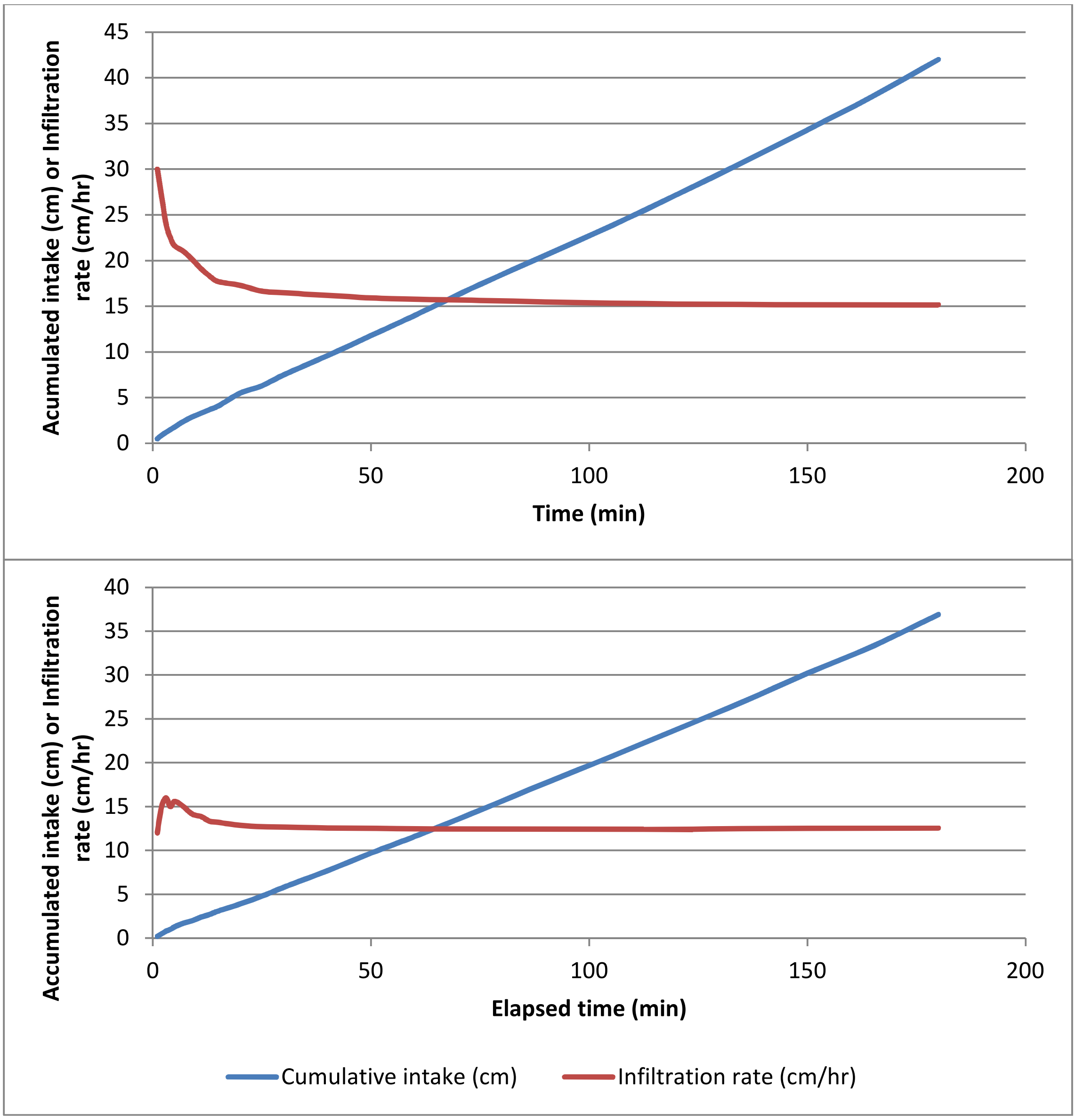

Figure A.1 Accumulated intake and infiltration rate in field A. Test I and II respectively.

A.2 Field B

Table A.3 Infiltration rate test I in field B

Local time	Interval (mins)	Cumulative time (mins)	Depth of water in the infiltrometer (cm)	Intake (cm)	Cumulative intake (cm)	Infiltration rate (cm/hr)	
						Immediate	Mean
9:00	0	0	20.5				
	1	1	20	0.5	0.5	30	30
	1	2	19.8	0.2	0.7	12	21
	1	3	19.5	0.3	1	18	20
	1	4	19.2	0.3	1.3	18	19.5
	1	5	19	0.2	1.5	12	18
	2	7	18.5	0.5	2	15	17.5
	2	9	18	0.5	2.5	15	17.14
	2	11	17.5	0.5	3	15	16.9
	2	13	17	0.5	3.5	15	16.7
	2	15	16.5	0.5	4	15	16.5
	5	20	15.5	1	5	12	16.1
	5	25	14.5 – 21	1	6	12	15.75
	5	30	20	1	7	12	15.46
	10	40	17.9	2.1	9.1	12.6	15.26
	10	50	15.7	2.2	11.3	13.2	15.12
10:00	10	60	13.7 – 21	2	13.3	12	14.93
	15	75	17.9	3.1	16.4	12.4	14.78
	15	90	14.8 – 21	3.1	19.5	12.4	14.64
	15	105	18.1	2.9	22.4	11.6	14.48
11:00	15	120	15.2 – 21	2.9	25.3	11.6	14.34
	15	135	18.4	2.6	27.9	10.4	14.15
	15	150	15.6 – 21	2.8	29.8	11.2	14
	15	165	18.4	2.6	32.4	10.4	13.86
12:00	15	180	15.6	2.8	35.2	11.2	13.75

Table A.4 Infiltration rate test II in field B

Local time	Interval (mins)	Cumulative time (mins)	Depth of water in the infiltrometer (cm)	Intake (cm)	Cumulative intake (cm)	Infiltration rate (cm/hr)	
						Immediate	**Mean**
16:10	0	0	16	0			
	1	1	15.3	0.7	0.7	42	42
	1	2	15	0.3	1	18	30
	1	3	14.7	0.3	1.3	18	26
	1	4	14.5	0.2	1.5	12	22.5
	1	5	14.2	0.3	1.8	18	21.6
	2	7	13.9	0.3	2.1	9	19.5
	2	9	13.6	0.3	2.4	9	18
	2	11	13.3	0.3	2.7	9	16.9
	2	13	13	0.3	3	9	16
	2	15	12.8	0.2	3.2	6	15
	5	20	12.1 – 16.1	0.7	3.9	8.4	14.4
	5	25	15.4	0.7	4.6	8.4	13.9
	5	30	14.5	0.9	5.5	10.8	13.67
	10	40	13.1	1.4	6.9	8.4	13.3
	10	50	11.4 – 16	1.7	8.6	10.2	13.1
17:10	10	60	14.6	1.4	10	8.4	12.26
	15	75	12.1 – 16	2.5	12.5	10	12.6
	15	90	13.7	2.3	14.8	9.2	12.43
	15	105	11.2	2.5	17.3	10	12.3
	15	120	9 – 15.2	2.2	19.5	8.8	12.13
	15	135	13.1	2.1	21.6	8.4	11.95
	15	150	10.8	2.3	23.9	9.2	11.83
	15	165	8.3 – 15.5	2.5	26.4	10	11.75
18:10	15	180	13.4	2.1	28.5	8.4	11.61

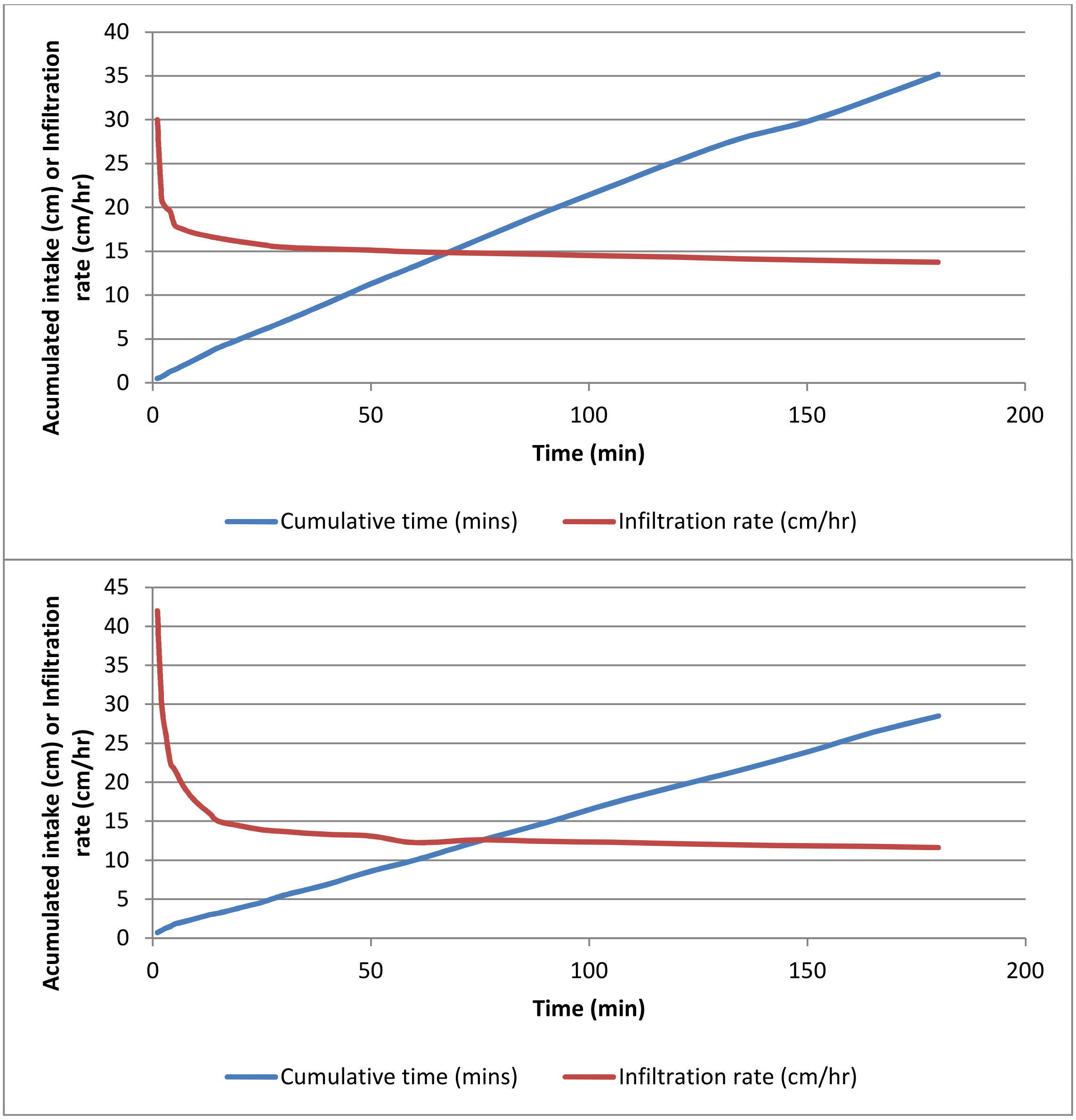

Figure A.2 Accumulated intake and infiltration rate in field B. Test I and II respectively.

A.3 Field C

Table A.5 Infiltration rate test I in field C

Local time	Interval (mins)	Cumulative time (mins)	Depth of water in the infiltrometer (cm)	Intake (cm)	Cumulative intake (cm)	Infiltration rate (cm/hr)	
						Immediate	**Mean**
9:20	0	0	22	0	0	0	0
	1	1	21.8	0.2	0.2	12	12
	1	2	21.5	0.3	0.5	18	15
	1	3	21.2	0.3	0.8	18	16
	1	4	20.9	0.3	1.1	18	16.5
	1	5	20.7	0.2	1.3	12	15.6
	2	7	20.6	0.1	1.4	3	13.5
	2	9	20.5	0.1	1.5	3	12
	2	11	20.3	0.2	1.7	6	11.25
	2	13	20.1	0.2	1.9	6	10.66
	2	15	20	0.1	2	3	9.9
	5	20	19.8	0.2	2.2	2.4	9.22
	5	25	19.3	0.5	2.7	6	8.95
	5	30	18.9	0.4	3.1	4.8	8.63
	10	40	18.3	0.6	3.7	3.6	8.3
	10	50	17.7	0.6	4.3	3.6	7.98
10:20	10	60	17	0.7	5	4.2	7.74
	15	75	16.2	0.8	5.8	3.2	7.48
	15	90	15.2 – 20.5	1	6.8	4	7.29
	15	105	19.6	0.9	7.7	3.6	7.09
11:20	15	120	18.7	0.9	8.6	3.6	6.92
	15	135	17.7	1	9.6	4	6.78
	15	150	16.7	1	10.6	4	6.65
	15	165	15.9	0.8	11.4	3.2	6.5
12:20	15	180	14.9	1	12.4	4	6.4

Table A.6 Infiltration rate test II in field C

Local time	Interval (mins)	Cumulative time (mins)	Depth of water in the infiltrometer (cm)	Intake (cm)	Cumulative intake (cm)	Infiltration rate (cm/hr)	
						Immediate	**Mean**
9:20	0	0	16.2	0	0	0	0
	1	1	15.9	0.3	0.3	18	18
	1	2	15.6	0.3	0.3	18	18
	1	3	15.4	0.2	0.8	12	16
	1	4	15.2	0.2	1	12	15
	1	5	15.1	0.1	1.1	6	13.2
	2	7	14.8	0.3	1.4	9	12.33
	2	9	14.5	0.3	1.7	9	11.71
	2	11	14.3	0.2	1.9	6	11
	2	13	14	0.3	2.2	9	10.77
	2	15	13.8	0.2	2.4	6	10.3
	5	20	13.1	0.7	3.1	8.4	10.13
	5	25	12.6	0.5	3.6	6	9.78
	5	30	12	0.6	4.2	7.2	9.58
	10	40	11.0 – 16.0	1	5.2	6	9.33
	10	50	14.9	1.1	6.3	6.6	9.15
10:20	10	60	13.9	1	7.3	6	9.01
	15	75	12.1 – 16.0	1.8	9.1	7.2	8.91
	15	90	14.5	1.5	10.6	6	8.74
	15	105	12.9	1.6	12.2	6.4	8.62
11:20	15	120	11.3	1.6	13.8	6.4	8.51
	15	135	9.8 – 16.0	1.5	15.3	6	8.39
	15	150	14.6	1.4	16.7	5.6	8.26
	15	165	13.3	1.3	18	5.2	8.13
12:20	15	180	11.9	1.4	19.4	5.6	8.03

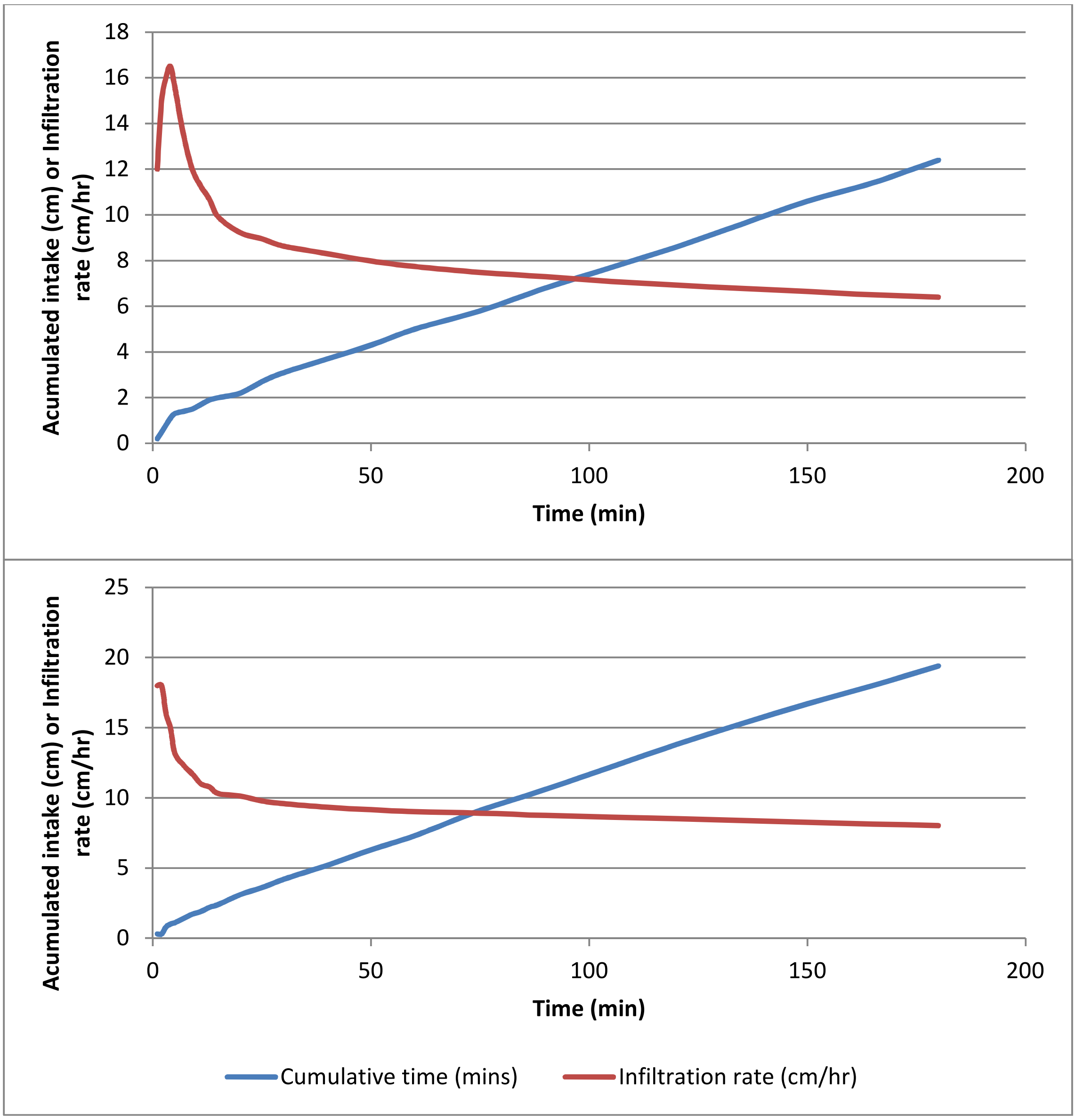

Figure A.3 Accumulated intake and infiltration rate in field C. Test I and II respectively.

Appendix B Climate data from the experimental site

Data available in the CD attached as “Appendix B – Climate data from the experimental site”.

Appendix C Wetting patterns records

Data available in the CD attached as “Appendix C – Wetting patterns records”.

Appendix D Daily irrigation schedule

Data available in the CD attached as “Appendix D – Daily irrigation schedule”.

Appendix E Cob characteristics

Data available in the CD attached as “Appendix E – Cob characteristics”.

Appendix F Work at SCL farm

My stay in Senegal was from the 12th of January to 2nd of May of 2012. Before the first seeding (Field B - 20/01/2012), I collected all the data available from the previous crop season (climate, irrigation and yield data) and I did all the soil test that I could do *in situ* (Infiltration rate, bulk density and soil porosity) in the three fields.

From the first seeding, until the last day of harvest (Field C – 21/04/2012), the research procedure was not very complex. Every day, I collected the irrigation and climate data from the previous day. And twice a week, I checked and measured the wetting patterns at each field. At the end of the harvest, I measured and evaluated the cobs harvested from the three fields.

As I had free time, I also worked for SCL in different tasks most of them, related to the irrigation:

- Irrigation consultant: as the research was focused only in drip irrigation, the three farms of the company, where it is irrigated by pivot, would not be studied. Because of that we move several times to the different areas in order to find a solution of their high irrigation at each farm.
- Irrigation management at Diama farm: apart of working on the scheduling for my research, I helped the person in charge of the irrigation at SCL to prepare their weekly schedule at Diama farm and its variations in case that the weather had changed.

  Apart of that, I become the responsible of the correct irrigation management at Diama farm. I had to supervise the employees in charge of the manual operated irrigation (around 20) being the link between them and my supervisor at SCL.
- Groundwater table mapping: as one area of Diama farm had the problem of the high groundwater table, I was also the responsible to map it and control it. The company had dug few piezometers in the farm, but most of them did not work. Therefore, by digging some trenches along the farm it was possible to measure it, in a very simple

way in order to have a scheme of its shape. After that, the technical manager at SCL and I were thinking the best way to install a simple device in order to allow a periodical control of the groundwater table, mainly, in the most risky area.

- I also did small tasks on the farm not related to irrigation, as measure the process station building and draw it by CAD software.