The effects of saline irrigation water on the growth and development of bell pepper (*Capsicum annuum* L.) grown using a plasticulture system

By

Dagobiet Morales-Garcia

Department of Plant Science

McGill University

Montreal, Quebec, Canada

A thesis submitted to McGill University in partial fulfillment of the requirements of the degree of Doctor of Philosophy

August 2008

©Dagobiet Morales-Garcia 2008

To Angeles and my three sons:

Dagobiet Jr., Osmar and Adair

ABSTRACT

Salinity affects food production worldwide. Hence, appropriate management of saline water is important to reduce negative effects on plants, soils, and ultimately the groundwater. Peppers (*Capsicum annuum* L.) are moderately sensitive to salinity, and required a high water input to maximize yields. This project investigated the effects of varying levels of salinity (0.2 to 9.0 $dS \cdot m^{-1}$) and the use of drip irrigation and mulching as water management for peppers. During fruit development, stomatal conductance (g_s), transpiration (E) and photosynthesis (A) decreased as salinity increased. Mulched plants had higher g_s, E and A than the ones grown in bare soil. Growth was reduced by salinity but increased by mulching. Saline water levels above the control (0.2 or 0.5 $dS \cdot m^{-1}$) reduced marketable yield whereas mulched plants had higher marketable yields than plants grown in bare soil. Under limited salt leaching condition, mulched plants required less water at all levels of salinity than the ones grown in bare soil, resulting in less soil salinization. Effects of saline water on seedlings showed that final emergence was only reduced at salinities ≥ 3.5 $dS \cdot m^{-1}$. In general, growth (dry weight) and rates of g_s, E and A were reduced at ≥ 2.5 $dS \cdot m^{-1}$. Applying saline water (2.5 $dS \cdot m^{-1}$) at different growth stages with limited salt leaching, showed that plants grown in bare soil were slower than mulched ones to recover normal physiology after periods of saline irrigation. Saline irrigation applied from fruit set onwards decreased marketable fruit production whereas mulched plants increased yields regardless of saline irrigation treatments. Under field conditions, saline water caused slight decreases in g_s, E and A slightly when applied at flowering or fruit set rather than during vegetative growth. Mulched plants had higher rates of g_s, E and A than plants grown in bare soil. Yield of fully ripened fruits was higher in mulched plants regardless of saline irrigation treatments. Under limited salt leaching condition, mulched plants were able to limit the negative effects of saline water compared with the ones grown in bare soil.

RÉSUMÉ

La salinité affecte la production alimentaire partout dans le monde. Il est donc important de gérer adéquatement l'eau saline pour réduire les effets négatifs sur les plantes, le sol et les nappes souterraines. Le poivron (*Capsicum annuum* L.) est modérément sensible à la salinité et requiert une forte demande en eau pour maximiser les rendements. Ce projet visait à étudier les effets de différents niveaux de salinité (0.2 à 9.0 $dS{\cdot}m^{-1}$) et l'utilisation de l'irrigation goutte-à-goutte et de paillis pour la gestion de l'eau dans les champs de poivrons. Pendant la formation des fruits, la conduction des stomates (g_s), la transpiration (E) et la photosynthèse (A) ont diminué en fonction de l'augmentation de la salinité. Les plants sur paillis avaient de plus grandes g_s, E et A que les plants sans paillis. La croissance était réduite par la salinité mais augmentait avec le paillis. L'eau saline (0.2 ou 0.5 $dS{\cdot}m^{-1}$) a réduit le rendement vendable alors que les plants sur paillis avaient un meilleur rendement que les plants sans paillis. Sous des conditions limitées de lessivage des sels, les plants sur paillis ont nécessité moins d'eau à tous les niveaux de salinité que les plants sans paillis ce qui a réduit la salinisation du sol. Les effets de l'eau saline sur les semis ont réduit leur émergence seulement à des salinités de plus de 3.5 $dS{\cdot}m^{-1}$. En général, la croissance (poids sec) et les niveaux de g_s, E et A étaient réduits à 2.5 $dS{\cdot}m^{-1}$. L'application d'eau saline (2.5 $dS{\cdot}m^{-1}$) à différents stades de croissance, avec un lessivage des sels limité, a montré que les plants sans paillis croissaient plus lentement que les plants sur paillis pour retrouver une physiologie normale après une irrigation saline. L'eau saline appliquée avant la formation des fruits a diminué la production de fruits vendables alors que les plants sur paillis avait des rendements accrus sans égard au traitement d’eau saline. Sous des conditions de champ, l’eau saline a réduit légèrement g_s, E et A lorsqu’appliquée à la floraison ou à la formation des fruits plutôt qu’au stade végétatif. Les plants sur paillis avaient une niveau supérieur de g_s, E et A que sans paillis. Le rendement de fruits mûrs était plus important dans les plants sur paillis tout traitement d’eau saline confondu. Sous des conditions de lessivage des sels limités, les plants sur paillis ont limité les effets négatifs de l’eau saline comparé aux plants sans paillis.

ACKNOWLEDGEMENTS

I would like to greatly thank my supervisor Dr. Katrine A. Stewart for her guidance throughout my doctoral program at McGill as well as for her support and encouragement during the time I was writing this thesis. I also thank Professor Stewart for providing funds for my research and tuition fees at McGill.

I am indebted to the members of my Advisory Committee, Dr. Philippe Seguin, Dr. Chandra Madramootoo, and Dr. Donald L. Smith for their valuable comments and feedback during the years of my PhD program.

I am fully grateful to Michael Bleho and Richard Smith for their technical support during the course of my research program as well as for their friendship. Also, I wish to express my gratitude to other staff members of the Department of Plant Science, Carolyn Bowes, Roslyn James, Louise Mineau and Guy Rimmer for all services provided during my doctoral program.

Thanks to all my McGill friends for sharing ideas and leisure time. My gratitude goes to Juan Almaraz, José Moro and Geneviève Legault for their friendship. I also fully acknowledge Geneviève for the translation of the Abstract into French.

My family and I have greatly enjoyed living in the province of Quebec and visiting other places of Canada since we arrived in Montreal. One of the major reasons for that is that we have been enjoying our friendship with the following families: Hamel, Legault, Dean, Bordignon and Humber. Thank you all on behalf of my family.

My especial acknowledge goes to the National Council for Science and Technology (Mexico) for awarding me a scholarship to pursue my doctoral study at McGill. I am also thankful to the Postgraduate College in Agricultural Sciences (SLP Campus) for the support during my study at McGill.

I would like to thank the Alfaro Gonzalez family for their moral support to me and my family. My appreciation also goes to my parents Austreberto and Nereyda; to my brothers Noel, Enoy, Julio Alberto, Elmer and Tissot, as well as to my sister Angela for their continuous encouragement during my study. Finally, my deepest gratitude goes to my wife Angeles and to my children Daguito, Ossy and Addy for their unlimited support, encouragement and motivation to pursue my study at McGill.

TABLE OF CONTENTS

LIST OF TABLES

Chapter 3

Chapter 5

Chapter 6

Appendix A

LIST OF FIGURES

Chapter 3

Chapter 4

Chapter 6

Appendix A

CONTRIBUTIONS OF AUTHORS

This thesis comprises four scientific manuscripts presented in Chapters 3 to 6. The manuscript "Effects of saline drip irrigation and polyethylene mulch on the physiology, growth and yield of bell peppers" included in Chapter 3 is co-authored by Dagobiet Morales-Garcia, Katrine A. Stewart and Chandra Madramootoo; Ph.D. candidate, supervisor and advisor, respectively. I designed and carried out the experiments, collected data, conducted statistical analyses, and wrote the manuscript. Dr. Stewart provided financial support for the project, discussed the design of the project, and correct and edited the manuscript. Dr. Madramootoo participated in the discussion of the experiments and reviewed the manuscript. This manuscript will be submitted to the *International Journal of Vegetable Science*, a peer-reviewed journal.

The manuscript "Effects of saline water on growth and physiology of bell pepper seedlings" presented in Chapter 4 is co-authored by Dagobiet Morales-Garcia, Katrine A. Stewart and Philippe Seguin; candidate, supervisor and advisor, respectively. I designed and carried out the experiments, collected the data, conducted statistical analyses, and wrote the manuscript. Dr. Stewart provided funds for the project and was involved in discussions including the design of the project, and edited the manuscript. Dr. Seguin provided statistical advice and reviewed the manuscript. This manuscript has been published in the *International Journal of Vegetable Science* 2008, Vol 14, Number 2:121-138.

The manuscript "The timing of saline drip irrigation affects growth, physiology and fruit yield of bell pepper grown under mulch or bare soil condition" included in Chapter

5, I co-authored with Katrine A. Stewart and Philippe Seguin, supervisor and advisor, respectively. I set-up and carried out the experiment, collected and statistically analyzed the data, and wrote the manuscript. Dr. Stewart provided funds for the project and participated in the planning, revision and edition of the manuscript. Dr. Seguin participated in the planning and revision of the manuscript. This manuscript will be submitted to *Agricultural Water Management*, a peer-reviewed journal.

The last manuscript "Saline drip irrigation applied at different growth stages of two bell peppers cultivars grown with or without mulch in non-saline soil" is presented in Chapter 6, I share authorship with Katrine A. Stewart and Philippe Seguin, supervisor and advisor, respectively. I planned, designed, set-up and carried out the experiment, collected data, conducted statistical analyses, and wrote the manuscript. Dr. Stewart provided funds for the project and participated in the planning, revision and edition of the manuscript. Dr. Seguin provided help in statistical analysis and reviewed the manuscript. This manuscript will be submitted to the *International Journal of Vegetable Science*, a peer-reviewed journal.

Chapter 1

General introduction

The availability of good quality water for agricultural use is becoming scarce (Shannon et al., 2008). Only 2.5% of the total available water is considered to be fresh (about 35,000 million m^3), the remaining 97.5% in the oceans is highly saline (FAO, 2002). As human population increases so does the need for good quality water. In fact, in addition to drinking water, other water uses (e.g. recreational) are becoming equal to or more important than agricultural activities (Bouwer, 2002; Parsons, 2000; Shannon et al., 2008). Consequently, irrigation water that is available for agricultural use will be limited even in semihumid or humid areas, but especially in semiarid or arid regions where available water will be of poor quality and most probably saline in nature (Parsons, 2000; Shalhevet, 1994; Trout, 2000).

Irrigation has played a key role in terms of food production worldwide by increasing crop yield and quality. However, excessive irrigation can cause soil degradation primarily by increasing the soil salinity (Trout, 2000). Indeed, high levels of salinity have been reported as causing of the loss of 250,000 to 500,000 ha of irrigated land annually. The problem occurs primarily in arid and semiarid zones where a total of 100 to 110 million ha are reported as having problems related to salinization which could render them unusable for agricultural purposes (FAO, 2002). The problem is greatest in these areas due to the high level of evapotranspiration which concentrates salts, introduced via the irrigation water (secondary salinization) or as part of the original chemical composition of the soil (primary salinization), in the root zone (Chhabra, 1996).

Therefore, management of irrigation water must be studied in order to limit losses both in terms of plant productivity and soil due to salinity. This will be particularly important in semiarid regions where precipitation is low, evapotranspiration rates high, and in addition soils are frequently saline (Smedema and Shiati, 2002).

The first item in determining irrigation requirements is knowledge of the crop to be irrigated, its water requirements and in particular its response to salinity. Pepper (*Capsicum annuum* L.) a widely grown high value crop for domestic and export use (Bosland and Votava, 2000) requires large amounts of water (600-900 mm) in order to produce high quality fruit (Brouwer and Heibloem, 1986). Pepper is listed as being moderately sensitive to salinity (Maas, 1990), with high levels being reported to decrease shoot biomass and marketable yield (Chartzoulakis and Klapaki, 2000; De Pascale et al., 2003).

Attempts must be made to limit the amount of irrigation water applied without reducing yields and retaining that water in the soil to minimize the effects of salinity. The use of microirrigation (Parsons, 2000), in conjunction with plastic mulch, has proved to be efficient in conserving water (Lamont, 1996), and improving fruit yield in terms of quantity, quality, and earliness (Lamont, 2005; Tarara, 2000).

Currently, no research has been carried out on the physiological, growth and yield responses of pepper plants to using saline drip irrigation in a plasticulture system. Hence, the main objective of this project is to evaluate the effects of saline drip irrigation and polyethylene mulch on pepper plants as well as on soil salinity.

The following hypotheses have been elaborated for this project:

1. Saline drip irrigation is more deleterious to pepper plants grown under bare soil condition than under mulch condition based on physiology, growth and fruit production.
2. Use of polyethylene mulch reduces the plants water requirements regardless of the water quality while maintaining fruit production.
3. Under condition of minimal salt leaching, use of polyethylene mulch decreases soil salinization and concentrates salts evenly in the root zone compared with bare soil.
4. Bell pepper seedlings can tolerate certain levels of saline water ($\leq$2.5 dS·m^{-1}) without significant changes in physiological parameters and reductions in growth.
5. The phenological stage of development of bell peppers influences its response to saline irrigation.
6. Continual saline irrigation concentrates more salts in the soil than intermittent saline irrigation.

Chapter 2

Literature review

2.1 Water, a global perspective

In some parts of the world, especially poor countries, there is limited access to safe drinking water (Shannon et al., 2008). Indeed, the quality of consumed water is so low that water-transmitted diseases kill 12 million people annually (80% children) and another billion become ill (Bouwer, 1994; Bouwer, 2002).

As populations increase, less freshwater will be available for agricultural purposes. In areas with large urban populations, agriculture competes for good quality water not only for domestic consumption but also with other water uses, such as recreational areas like parks and golf courses; preserved wetlands, and fish and wildlife habitats (Bouwer, 2002; Parsons, 2000). FAO (2002) divided annual worldwide freshwater into three sectors namely agricultural (71%), domestic (9%), and industrial (20%). Currently, agriculture has the greatest share of the water pie. However, the increasing domestic and industrial pressure will in turn reduce the amount and the quality of the water available for agricultural use (Bouwer, 1994; Shannon et al., 2008).

One type of water that is currently available for agricultural use is groundwater. Groundwater represents about 30% of the total freshwater in the world (FAO, 2002). However, in dry regions aquifers are being overexploited at dangerous rates (Shannon et al., 2008; Smedema and Shiati, 2002). The quality of groundwater is often compromised. Agriculture is one of the major sources of pollution of groundwater mainly through the use of fertilizers, pesticides and by salts from saline irrigation. In addition, polluted groundwater if used as an irrigation source can in turn contaminate surface water (Bouwer, 2002).

Another available source for irrigation is wastewater after it meets the required quality parameters. Wastewater effluent commonly contains concentrations of N, P, and K of 50, 10 and 30 $mg \cdot L^{-1}$, respectively, as well as micronutrients and organic matter (FAO, 2002) and as such can be successfully use for irrigation of non-horticultural crops, such as sunflowers (Papadopoulos and Stylianou, 1991). Wastewater is recommended for industrial, municipal and recreational uses rather than potable use and irrigation of horticultural crops due to the high economic cost to purify the water, public perception as well as religious concerns (Bouwer, 1994).

The assessment of the quality of the irrigation water in question, including wastewater, should consider the electrical conductivity (EC), total dissolved solids (TDS), the sodium adsorption ratio (SAR), pH and the levels of nitrate, and bicarbonate, as well as those of microelements, such as copper, zinc, manganese, molybdenum, arsenic, selenium, lead and boron; and chemical products such as fungicides, insecticides and herbicides, to ensure that they are below risk levels of toxicity for wildlife and will not pollute surface and groundwater thereby compounding the problem (Ayers and Westcot, 1985; Martínez Beltrán, 1999; Pratt and Suarez, 1990; Trout, 2000).

Regardless of the water source, water salinity should be measured routinely to determine the quality of the irrigation water. Salinity, the concentration of several dissolved salts (Na^+, Mg^{2+}, Ca^{2+}, K^+, Cl^-, SO_4^{2-}, HCO_3^-, NO_3^-, and CO_3^{2-}), can be referred to in terms of mass of salts in a unit volume of water ($mg \cdot L^{-1}$). For agricultural purposes, it is evaluated in units of EC ($dS \cdot m^{-1}$) (Rhoades et al., 1999). The EC is a measure of the ability of a soil, water, or solution to conduct electricity, and is proportional to the salt concentration (Rhoades, 1996).

Rhoades et al. (1992) roughly classified non-saline and saline water. According to these authors, water with an electrical conductivity (EC_w) of ≤ 0.7 dS·m^{-1} or ≤ 500 mg·L^{-1} is classified as a drinking water quality because it is non-saline, and therefore is good quality water for irrigation; whereas water with an EC_w of 0.7-2 dS·m^{-1} or 500-1500 mg·L^{-1} is slightly saline for irrigation. Using the same scale of measurement, groundwater can be classified as moderately saline (EC_w of 2-10 dS·m^{-1}; 1500-7000 mg·L^{-1}), highly (EC_w of 10-25 dS·m^{-1}; 7000-15000 mg·L^{-1}) and very highly saline (EC_w of 25-45 dS·m^{-1}; 15000-35000 mg·L^{-1}). In comparison, seawater generally has an EC_w value higher than 45 dS·m^{-1} or more than 45000 mg·L^{-1} of salts. However, this classification of saline water should not be agronomically applicable as indicated by their classes because crops differ in the tolerance to salinity. For example, two irrigation waters with EC_w of 2 and 9 dS·m^{-1} belong to the same moderately saline class but are expected to cause light and severe yield reductions, respectively, in a moderately sensitive crop to salinity like pepper. Therefore, the aforementioned classification of saline water is not used in the present thesis.

There have been proposals to blend the use of drainage or saline water with good quality water, where two water sources varying in quality are available. Shalhevet (1994) and Shannon and Grieve (2000) mentioned general suggestions for irrigation management when using more than one source of water. One is to blend poor quality water (saline, drainage) with good quality water to achieve a level tolerated by the selected crop without a reduction in yield (Maas, 1990). Another possibility is alternate the water source for each irrigation; to irrigate first with good followed by poor quality water and repeating the sequence through out the growth of the crop. This arrangement should be followed only if the level of poor quality water is tolerable by the crop. The last option is to use low quality water only at non-salt sensitive growth stages of the crop to avoid any decreases in yield. This will only work if the tolerance to salinity at different growth stages is known for the crop in question. The convenience of reusing water depends on the crop tolerance to salinity and other ions; agricultural infrastructure and equipment to blend or alternate irrigation water; chemical, biological and physical composition of the water sources; the irrigation system and price of the water (Dinar et al., 1986; Shalhevet, 1994; Shannon and Grieve, 2000).

2.2 Plants growing in a saline environment

Definition of plant tolerance to salinity may change depending on the agronomic or ecological importance of the plant. Within an agronomic context, plant salt tolerance is referred to as the capability of a plant to withstand the effects of salt concentration in the root-zone or within the plant with none or minimum reductions in growth or yield (Maas, 1990; Shannon and Grieve, 1999). From an ecological perspective, plant tolerance to salinity is the capability of a plant to complete its life cycle in a saline environment (Parida and Das, 2005).

According to their capacity to grow in a high saline environment, plants are classified as either halophytes or glycophytes. Halophytes are plants well adapted to high saline environments (Flowers and Flowers, 2005; Sairam et al., 2006) which, for optimal growth, require salt concentrations higher (ranging from 20-500 mM NaCl) than those found in non-saline soils or mediums (Hasegawa et al., 2000). As oppose to halophytes, glycophytes are plants that do not tolerate salt concentrations to the same extend as halophytes (Flowers and Flowers, 2005; Sairam et al., 2006). Unfortunately, most crops, including grain and vegetables, are glycophytes (Borsani et al., 2003; Flowers and Flowers, 2005; Sairam et al., 2006). For example, the majority of vegetable crops are classified as sensitive and moderately sensitive to salinity (Ayers and Westcot, 1985; Shannon and Grieve, 1999; Shannon and Grieve, 2000).

Plants have developed three mechanisms to adapt to a saline environment: a) tolerance to osmotic stress, b) exclusion of Na^+ and Cl^-, and c) tolerance to Na^+ and Cl^- accumulated in tissues (Munns and Tester, 2008). Salt tolerance conferred through these adaptations is a multigenic trait and hence complex (Flowers and Flowers, 2005; Sairam et al., 2006; Shannon, 1997). Analysis and studies of salt stress at the whole plant level (Munns and Termaat, 1986; Munns and Tester, 2008; Schleiff, 2008; Shannon, 1997) or cellular and molecular levels (Binzel and Reuveni, 1994; Borsani et al., 2003; Hasegawa et al., 2000; Parida and Das, 2005; Sairam and Tyagi, 2004; Sairam et al., 2006; Yeo, 1998; Zhu, 2001) have contributed to understanding salt tolerance.

The responses of plants to salinity over time follow two phases: a) osmotic effects caused after salts, concentrated outside the roots, surpass a threshold level; and b) ionic effects caused by accumulation of salts within the plants up to toxic levels (Munns and Tester, 2008). In the first phase, osmotic stress leads to decreases in soil water potential, thus reducing the plant water uptake (Munns, 2002); at this phase, cell expansion of roots and young leaves is reduced and stomatal closure is induced, and hence growth is negatively affected (Munns and Tester, 2008). The second phase occurs when salts concentrate at a toxic level in the old leaves because salts cannot longer be compartmentalized in the vacuole; this phase takes more time to develop relative to the osmotic phase and negatively affect growth by limiting supply of carbohydrates to the growing cells (Munns, 2002; Munns and Tester, 2008).

Additionally, increasing salt concentration in saline soils, especially NaCl, may also cause antagonistic effects with other ions of major importance to plant nutrition (Flowers and Flowers, 2005; Grattan and Grieve, 1999) by altering important cationic and anionic ratios such as Na^+/K^+, Na^+/Ca^{2+}, Cl^-/NO_3^- (Shannon, 1997). When Ca^{2+} is found in low concentrations in the soil, relative to a high concentration of Na^+, uptake of Ca^{2+} by plants can negatively be affected (Läuchli, 1990). Similarly, Munns and Termaat (1986) reported that high levels of Cl^- in the soil may inhibit uptake of NO_3^- and result in a nitrogen deficiency.

Exposure of plants to unfavorable environmental conditions may decrease their salt tolerance. For instance, tolerance is generally higher when a crop grows in a temperate and humid environment compared with a hot and dry environment (Maas, 1990). Both factors can be controlled under greenhouse conditions when irrigating with certain levels of saline water to avoid a loss in yield. Romero-Aranda et al. (2002) found that increasing the relative humidity in a greenhouse, the negative effects of salinity (50 mM NaCl) causing yield reduction of tomato plants were alleviated.

Increasing air temperature, especially in low humidity conditions, decreases the salt tolerance of plants (Shannon et al., 1994), while increasing soil temperature up to a certain level increases salt tolerance. Dalton et al. (1997) in a hydroponic experiment compared the effects of root zone temperatures of 18 °C and 25 °C, on shoot biomass yield of tomato plants growing at 14 levels of salinity (0 to 140 mM Cl^-) using a 2:1 $NaCl/CaCl_2$ molar ratio of saline solution. Results from this experiment suggested that plants growing at a higher root zone temperature (25 °C) had significantly greater biomass and yield than plants grown at 18 °C. Since root zone salinity threshold increased with soil temperature, it might be plausible to use saline irrigation water of about 64 mM Cl^- in those areas with high radiation and warm soil condition rather than in temperate areas with cool soil or during cloudy days (Dalton et al., 2001).

2.3 The pepper crop

Pepper, a member of the Solanaceae, family is an herbaceous warm-season crop sensitive to frost (Decoteau, 2000; Wien, 1997). Pepper is grown perennially in tropical areas whereas in temperate climate it is grown as an annual (Decoteau, 2000; Wien, 1997). The genus *Capsicum* comprises 25 wild and five domesticated species (Bosland and Votava, 2000). Among the domesticated peppers, *Capsicum annuum* is the most important agriculturally and economically (Rubatzky and Yamaguchi, 1997). Peppers are economically high-value vegetables, prized for their flavour, colour, vitamin C content, and pungency (McMahon et al., 2002). Fruits of *C. annuum* are generally classified according to their features, such as color, shape and pungent; or to their use (dry or fresh consumption) (Decoteau, 2000). The most important characteristic of pepper fruits is flavor (Rubatzky and Yamaguchi, 1997), and consequently, the main classification is pungent (hot) or non-pungent (sweet). Examples of pungent or hot types are jalapeño, serrano, ancho, mirasol, pasilla, cayenne, piquin and de Arbol, whereas for non-pungent or sweet comprise bell, pimiento, Cuban and squash (Bosland and Votava, 2000).

The pepper phenology can be divided into five stages: germination, vegetative growth, flowering, fruit set, and fruit development and maturation (Wien, 1997).

- Seed germination. Peppers, dicotyledonous plants, demonstrate epigeal germination. Optimal germination occurs at 25 ºC (Bosland and Votava, 2000; Wien, 1997). The germination periods last 6-10 days at 30 ºC but they can be longer at 15 ºC (Rubatzky and Yamaguchi, 1997).
- Vegetative growth. Depending on the temperature and genotype, *Capsicum annuum* usually develops a main stem with eight to fifteen leaves exhibiting monopodial growth prior appearance of the first flower bud. When the first flower bud develops on the main stem, two dichotomous branches are produced. Each branch produces one or two leaves and terminates in a flower, after which, the pattern is repeated. However, one of the dichotomous branches is suppressed in further divisions resulting in sympodial growth (Bosland and Votava, 2000). Day and night temperatures at 25-27 ºC and 18-20 ºC, respectively, are optimum for pepper vegetative growth (Wien, 1997).
- Flowering. Flowering in starts with a single or two flowers on the main stem and continues at each additional node in a geometric progression (Bosland and Votava, 2000). Pepper flowers are self-pollinated (Wien, 1997). At anthesis, the flower opens within three hours of sunrise and remains open for less than 24 hours. Between one to ten hours after the flower opens the anthers dehisce (Bosland and Votava, 2000; Wien, 1997). Maximum number of flowers in pepper plants were found to be greatest at 24 ºC and 21 ºC day and night temperatures, respectively; lower temperatures delays flowering rate (Bakker,

1989) whereas night temperatures above 24 ºC causes flower drop (Bosland and Votava, 2000).

- Fruit set. Fruit growth depends on the ovule growth (Bosland and Votava, 2000; Wien, 1997), and it begins with the ovary formation at flower differentiation (Wien, 1997). As fruit is set (initial swelling of the ovary) and starts to develop, it decreases subsequent fruit set and flower production at the upper nodes of the plant (Bosland and Votava, 2000). Maximum fruit set can be obtained if day temperature is between 16-20 ºC and night temperature is between 12-15 ºC (Bakker, 1989); no fruit set occurs when pepper plants grow at mean temperatures lower than 16 ºC or higher than 32 ºC (Bosland and Votava, 2000).
- Fruit development and maturation. The length and weight (fresh and dry) of fruits follow a sigmoid growth curve (Marcelis and Hofman-Eijer, 1995). Fruits compete with themselves and with other parts of the plant for assimilates during this reproductive phase (Ali and Kelly, 1992; Hall, 1977), and represent about 50% of the plant dry matter (Miller et al., 1979). Commercially, the fruit green stage is consider ripe but it is immature physiologically (Bosland and Votava, 2000; Wien, 1997). Day and night temperature of 28 ºC and 23 ºC, respectively were found to produce fruits with the greatest fresh weight (Polowick and Sawhney, 1985). Optimum mean temperature for fruiting is reported to be between 18-26.5 ºC (Decoteau, 2000).

2.4 Effect of salinity on the growth and development of peppers

Germination (radicle appearance) of pepper seeds is not affected within a certain range of salinity. Chartzoulakis and Klapaki (2000) reported that salinity of 7.1 $dS \cdot m^{-1}$ (50 mM NaCl + half strength Hoagland solution) delayed germination of pepper seeds but not reduced its final percentage; however, salinity at 12.6 and 17.8 $dS \cdot m^{-1}$ (100 and 150 mM NaCl) reduced germination. Pepper seeds imbibed in salt solutions (Na or $NaCl{:}CaCl_2$ 1:1 ratio on a molar basis) of up to 100 mM (~10 $dS \cdot m^{-1}$) were able to germinate (Palma et al., 1996; Smith and Cobb, 1991). Using a different saline solution (Na/Ca+Mg 2:1 ratio on an equivalent basis), Miyamoto et al. (1985) found that final germination was not reduced when salinity was ≤23 $dS \cdot m^{-1}$ but was inhibited at higher salinity (32 $dS \cdot m^{-1}$). However, the radicle is more sensitive during its development when exposed to a saline solution of 50 mM NaCl (5.9 $dS \cdot m^{-1}$) at which reductions of about 52% were found by Chartzoulakis and Klapaki (2000). For this reason, salinity affects seedling emergence more than germination (Miyamoto et al., 1985; Yildirim and Guvenc, 2006).

The sensitivity to salinity progresses during vegetative growth stage of bell peppers. Chartzoulakis and Klapaki (2000) found that at the vegetative stage (6 weeks after planting), leaf area, plant height, and biomass of two bell pepper cultivars (Sonar and Lamuyo) decreased at salinity levels of 4.1 $dS \cdot m^{-1}$ (25 mM NaCl) or higher. Palma et al. (1996) reported reductions in dry weight of bell pepper seedlings when treated with saline water of 5.4 and 10 $dS \cdot m^{-1}$ (50 and 100 mM NaCl, respectively) during 84 days. Similar findings we found by Yilmaz et al. (2004) who reported that the relative growth rate (RGR) for fresh and dry weights of roots and shoots of bell pepper seedlings (cultivars: Demre, Çetinel 150 and Ilica 256) treated with different levels of salinity (0, 50, 100 and 150 mM NaCl) for 30 days (following a 30-d period with no salinity) were reduced at 50 mM NaCl or higher levels. Differences in the response to different levels of salinity could have been due to genotypic variation. All aforementioned studies involved a few bell pepper genotypes. When a large number of genotypes are grown under saline condition, this variation may be more noticeable. Aktas et al. (2006) evaluated 102 pepper genotypes in response to salinity [100 mM NaCl (10.9 $dS \cdot m^{-1}$) added to the nutrient solution] during 10 days starting at the 6-7 true leaf stage (vegetative; 14 days after transplanting) in greenhouse conditions. They were able to classify tolerance or sensitiveness to salinity by using a leaf symptom score. After classifying all genotypes, the authors selected six tolerant and six sensitive genotypes to salinity to carry out a second experiment following the same procedure, and increased the salinity to 150 mM NaCl (15.4 $dS \cdot m^{-1}$) in addition to the nutrient solution. The main finding of this research is that sensitive genotypes accumulated more Na^+ in the shoots than tolerant ones; thus suggesting that a certain level of a Na^+ exclusion mechanism was activated in tolerant genotypes. However, it remains a question whether this trend for tolerant genotypes could be maintained throughout growth until fruit growth stage.

No study has been conducted to evaluate the response, in terms of fruit production, of bell peppers to saline irrigation applied at different growth stages. Instead, constant salinity levels have been applied throughout growth to evaluate their effects on yield.

Agronomically, pepper is listed as moderately sensitive to salinity having a yield reduction threshold at 1.5 $dS \cdot m^{-1}$ of electrical conductivity of the soil saturated extract (EC_e) (Maas, 1990) or 1.0 $dS \cdot m^{-1}$ of EC_w of the irrigation water (Rhoades et al., 1992).

High levels of salinity have been reported to decrease shoot biomass and marketable yield under different irrigation systems.

Tadesse et al. (1999) in greenhouse conditions used a nutrient film technique (NFT) to irrigate pepper plants with various levels of KCl saline solutions (4, 6, 8 and 10 $dS \cdot m^{-1}$) added to the Cooper basic nutrient solution (2 $dS \cdot m^{-1}$). They found that all levels of saline solutions (≥ 4 $dS \cdot m^{-1}$) decreased yield following a quadratic relationship.

De Pascale et al. (2000) applied five levels of NaCl saline water (0.5, 2.3, 4.4, 8.5 and 15.7 $dS \cdot m^{-1}$) combined with three drip irrigation levels (100, 75, and 50% of the evaporation rate) plus a non-irrigated control to pepper plants. These authors indicated that plant growth and fruit yield were reduced at 8.5 $dS \cdot m^{-1}$ or higher, with an increase in the number of non-marketable fruit when salinity was more concentrated in the irrigation water. They reaffirmed a threshold value of 1.4 $dS \cdot m^{-1}$, similar to that reported by Maas (1990). In addition, the authors mentioned that N, P, K, Mg and S levels in pepper leaves were similar for saline and non-saline treated plants. In fact, Ca concentration in the leaves increased significantly when saline water level was between 0.5 and 4.4 $dS \cdot m^{-1}$ and blossom-end rot (BER) was prevented within this range.

Chartzoulakis and Klapaki (2000) using a hydroponic system evaluated the response of two pepper hybrids (Sonar and Lamuyo) to several levels of salinity 1.2, 2.4, 4.1, 7.1, 12.6, and 17.8 $dS \cdot m^{-1}$ (0, 10, 25, 50, 100 and 150 mM NaCl, respectively, added to a half-strength Hoagland solution). At fruiting, salinity greater than 2.4 $dS \cdot m^{-1}$ significantly reduced total fruit yield compared to the control (1.2 $dS \cdot m^{-1}$) treatment. Significant reductions in the number of fruit and the average fruit weight were obtained at

7.1 $dS{\cdot}m^{-1}$ or higher levels of salinity compared to the control and lower levels of salinity.

Patel et al. (2000) used lysimeters and a subirrigation system to evaluate the responses of pepper plants and soil salinity buildup to two water table depths (0.4 and 0.8 m), three levels of saline water (1, 5 and 9 $dS{\cdot}m^{-1}$) and four types of fertilizer rates (N1PK, N2PK, N1K and KP) applied at planting (35 and 70 kg $N{\cdot}ha^{-1}$ for N1, and N2, respectively; plus 200 kg $P{\cdot}ha^{-1}$ of P, except for N1K; and 230 kg $K{\cdot}ha^{-1}$ of K) and flowering (35 and 70 kg $N{\cdot}ha^{-1}$ for N1 and N2, respectively) stages of peppers grown on a sandy soil. The lack of nitrogen fertilization significantly decreased fruit yield and a maximum value was reached when all nutrients were applied (N1PK or N2PK) without causing salt build-up in the soil. Also, they concluded that salinity did not negatively affect green pepper yield because soil solution salinity was below 4.0 $dS{\cdot}m^{-1}$ in the upper root zone (30 cm depth).

Navarro et al. (2002) evaluated the yield of sweet peppers hydroponically grown in greenhouse condition in response to four levels of sulphate (Na_2SO4) or chloride (NaCl) salinity (3, 4, 6 and 8 $dS{\cdot}m^{-1}$) added to Hoagland solution (2 $dS{\cdot}m^{-1}$). All salinity levels reduced total and marketable yield; however, chloride salinity resulted more deleterious for marketable fruit yield than sulphate salinity within the 4 to 6 $dS{\cdot}m^{-1}$ range. Both types of salts reduced fruit size and number of marketable quality.

De Pascale et al. (2003) applied four irrigation treatments [non-saline control (0.5 $dS{\cdot}m^{-1}$), and saline water of 4.4 $dS{\cdot}m^{-1}$ and 8.5 $dS{\cdot}m^{-1}$, and a drought stress treatment] to drip-irrigated pepper plants grown under field conditions. Water salinity reduced total and marketable yields as well as the mean fruit weight but not the number of fruits per plant. The negative effect of the drought treatment was equivalent (total yield) to or higher (marketable yield) than that of the high water salinity (8.5 $dS \cdot m^{-1}$).

Pepper fruits are an important source of antioxidants (Howard et al., 2000; Marin et al., 2004), which are compounds (e.g. phenolics, ascorbic acid, and carotenoids) that, when consumed in adequate amounts, have protective effects in the body against human diseases including cancer, diabetes and cardiovascular diseases (Kaur and Kapoor, 2001). Navarro et al. (2006) studied the effects of three different concentrations of NaCl (0, 15 and 30 mM added to a basic nutrient solution) on pepper fruits harvested at three different ripening stages (green, turning red and red) from plants grown hydroponically under greenhouse conditions. They found that the antioxidant activity was highest in red fruits compared to the other two ripening stages; and that the general effects of salinity on antioxidant compounds in fruits were ripening state-dependent with salinity at 15 mM NaCl being favorable when fruits were harvested in the red state. In average, salinity decreased ascorbic acid but increased antioxidant activity in the lipophilic fraction (LAA) and lycopene. No salinity effects were detected on antioxidant activity in the hydrophilic fraction (HAA), ß-carotene, sugars or total phenolics.

Some strategies have been followed to ameliorate the effects of salinity in pepper fruit production. For example, Colla et al. (2006) studied the effects of using *Salsola soda*, a halophyte, as a desalinating companion plant to peppers drip-irrigated with two levels of saline water (4.0 and 7.8 $dS \cdot m^{-1}$, NaCl added to a Hoagland solution) under greenhouse conditions. They found that the highest total and marketable pepper yield was significantly obtained in treatments with pepper + *S. soda* irrigated with 4.0 $dS \cdot m^{-1}$ compared to treatments of pepper grown alone at any salinity level or pepper + *S. soda* at

7.8 $dS \cdot m^{-1}$. The use of *S. soda* as a companion plant at 7.8 $dS \cdot m^{-1}$ did not improve yield compared with pepper grown alone.

Another approach to cope with the negative effects of NaCl salinity on pepper yield has been focused towards fertilization with N, P, and K to inhibit Na uptake by plants. Kaya and Higgs (2003) found that pepper yield was only reduced by 16% when the saline soil (NaCl 3.5 $g \cdot kg^{-1}$ soil, 7.2 $dS \cdot m^{-1}$) contained supplementary urea at 0.4 $g \cdot kg^{-1}$ soil; compared to the non-saline control. Greater yield reductions were found when supplementary urea was at 0.2 $g \cdot kg^{-1}$ of saline soil (41%) or none urea in saline soil (52%). Regular fertilization rates were of 300, 200 and 250 $mg \cdot kg^{-1}$ for N (ammonium sulphate), P and K (mono-potassium phosphate) for all treatments. A similar experiment was carried out by Kaya et al. (2003) to evaluate the effect of supplementary potassium phosphate added at the rates of 136 and 272 $mg \cdot kg^{-1}$ to the saline soil, in addition to the regular fertilization rates [300, 100 and 250 $mg \cdot kg^{-1}$ for N (ammonium sulphate), P and K (mono-potassium phosphate), respectively] for all treatments. The plants grown in saline soil treated with the high rate of supplementary potassium phosphate had similar marketable and total yield to that of the non-saline control and greater yield than plants grown in saline soil without or with the low supplementary potassium phosphate. The previous approach, however, should avoid excessive fertilization that increases soil salinity. Villa-Castorena et al. (2003) found that a high nitrogen fertilization rate (200 $kg \cdot ha^{-1}$) in saline soils (sandy loam, $EC_e \geq 4$ $dS \cdot m^{-1}$) increased soil salinity and consequently decreased pepper yield.

A different strategy to alleviate negative effects of salinity on plants involves the management of the saline water for irrigation to leach salts in the soil solution out of the root zone by adding an excess of water. Using a flat-roof screenhouse (30% black shading) in field condition, Assouline et al. (2006) found that pepper plants, irrigated with saline water (4.2 $dS \cdot m^{-1}$) by using drip irrigation (1.6 $L \cdot h^{-1}$) on a daily (once a day) or high frequency (10 times or pulses per day) basis, had greater yield reductions (17 and 14%, respectively) when the amount of water applied was equivalent to the rate of the crop evapotranspiration (ET_c) rather than using 25% more water of the ET_c rate at either frequency (average of 8.6% yield reduction); relative to the yield obtained by plants irrigated with non-saline water via drip irrigation (daily or high frequency) at the ET_c rate.

It is important to point out that the amount of water required for salt leaching and thus to maintain relatively high yields depends on water salinity; the higher the level of water salinity the greater the amount of irrigation water required, consequently it may become eventually an unsustainable practice (Ben-Gal et al., 2008).

Frequency of irrigation plays an important role in root zone salt accumulation. When a low irrigation frequency (initiated at 32% drainage remaining) was employed to irrigate pepper plants, grown in greenhouse conditions, with water containing 6 $mM \cdot L^{-1}$ NaCl (plus a nutrient solution of 1.9 $dS \cdot m^{-1}$), a higher and progressive salt accumulation in the recycle drainage of a closed-cycle hydroponic system was observed compared to employing a high irrigation frequency (initiated at 65% drainage remaining); consequently, pepper yield was ameliorated under high frequency irrigation (Savvas et al., 2007).

The general responses of peppers to a saline environment have shown that growth (plant biomass, leaf area), measured at fruit harvest, decreased with increasing salinity

(De Pascale et al., 2003; Navarro et al., 2003; Tadesse et al., 1999). Similarly, some physiological parameters like leaf water potential (Ψ_w), turgor potential (Ψ_p), and osmotic potential (Ψ_π) (Bethke and Drew, 1992; De Pascale et al., 2003; Navarro et al., 2003; Tadesse et al., 1999) or stomatal conductance (g_s), transpiration (E) and photosynthesis (A) (Bethke and Drew, 1992; Chartzoulakis and Klapaki, 2000; De Pascale et al., 2003; Navarro et al., 2003) decreased with increasing levels of salinity. A decrease in g_s may subsequently reduce E and A primarily by osmotic effects in the root zone (Munns, 2002) or by increasing accumulations of Na^+ and Cl^- in the leaves causing chloroplast damages (Bethke and Drew, 1992; Chartzoulakis and Klapaki, 2000).

2.5 Plasticulture as a management system for horticultural crops

Plasticulture is a system used to grow plants by creating or modifying the microenvironment of the crop growing area by means of plastic polymer materials to shorten or extend the growing season (Lamont, 2005; Lamont, 1996). Included under the plasticulture umbrella are the uses of agricultural plastics for windbreaks, soil sterilization, as well as for pest and weed management. Two major components of plasticulture in horticulture that have become popular are drip irrigation, which often includes a fertigation system, and polyethylene mulch (Lamont, 2005).

2.5.1 Drip irrigation

Increases in crop yield associated with the use of drip irrigation could be attributed to: 1) localized application of water to the crop root zone which results in the reduction of water loss by evaporation, runoff, and deep percolation, which in turn increases water use efficiency and controls weed; 2) control of irrigation frequency, which reduces fluctuation in soil moisture and limits water stress and; 3) the possibility of applying fertilizers in solution (fertigation) along with the irrigation water (Dasberg and Or, 1999; Mmolawa and Or, 2000).

Among irrigation methods, drip irrigation is best suited when saline or marginal water is the available source because less amount of water with frequent application are delivered to the root zone (Mmolawa and Or, 2000), and not directly on the plant, thus avoiding foliage burning (Shannon et al., 1997). The amount of the saline water that should be applied via the drip system depends on the water quality, soil properties and crop tolerance to salinity (Dasberg and Or, 1999).

2.5.2 Responses of pepper plants to drip irrigation

The benefits of using a drip irrigation system to supply water to the pepper crop have been recognized since almost three decades (Beese et al., 1982; Horton et al., 1982). Currently, commercial pepper production is routinely drip irrigated (Bosland and Votava, 2000). It is known that the pepper crop require large amount of water to produce high quality yield (Brouwer and Heibloem, 1986); therefore, using less water than the crop demands may confer a certain degree of water stress in plants. For example, Beese et al. (1982) found that applying 20% less that the control (100% of the crop evapotranspiration, ET_c), pepper plants produced less biomass and had lower yields than plants receiving more water (20 or 40% more of the ET_c) because water was limited during their vegetative growth.

Wierenga and Hendrickx (1985) using drip irrigation found that applying 20% more water than that of the ET_c maximized fruit yields. However, yields decreased when plants were either over (40% more than ET_c) or under irrigated (60-80% less than ET_c). They concluded that an appropriate water supply was needed to reach maximum fruit yields. Also, these authors reported that drought stressing the plants at any growth stage did not improve the fruit yield per unit of water applied, and therefore, did not contribute to saving irrigation water.

Madramootoo et al. (1993) evaluated the effect of four drip irrigation rates (50, 100, 150 and 200 mm in 1987; and 70, 120, 170 and 220 mm in 1988; in addition to 405 and 301 mm of rainfall in 1987 and 1988, respectively) on pepper yield for a period of June to September. Results indicated that highest yields were for plants receiving 200 or 220 mm of irrigation water in addition to rainfall as these values met full evapotranspiration requirements. As the amount of irrigation decreased so did the yield.

Drip irrigation increases water use efficiency as less water could be used to maintain high yields. Kang et al. (2001) in a greenhouse experiment, separated the roots of potted hot pepper plants into two and applied drip irrigation by: 1) alternating irrigation between the two sets of roots, 2) irrigating one set, and 3) irrigating both set of roots at the same time. Using the alternating irrigation system saved water without reducing either yield or biomass. This treatment increased water use efficiency when soil moisture was maintained at 65% field capacity (θ_f) compared to 55% of θ_f.

Sezen et al. (2006) examined the effects of various irrigation regimes consisting of three irrigation intervals [cumulative pan evaporation of 18-22 mm (3-6 days), 38-42 mm (6-11 days), and 58-62 mm (9-15 days)] and three crop coefficients, K_c (0.50, 0.75 and

1.00) on bell pepper yield. These authors found that the shorter the irrigation interval (3-6 days) and the larger the K_c (1.00), the higher the fruit yield with improved quality.

2.5.3 Mulch

The increase in quantitative and qualitative yield of crops grown using polyethylene mulch has been associated with increases in soil temperature and soil moisture conservation.

The increase in soil temperature under a mulch is a reflection of the climatic conditions and type of mulch used. Black polyethylene mulch absorbs radiation and provides limited soil warming and controls weed growth while clear polyethylene transmits the radiation which results in greater soil warming but does not control weeds. Infrared-transmitting (IRT) mulch heats the soil like a clear mulch and controls weeds like a black polyethylene (Lamont, 1996). Regardless of the type of mulch used it is critical that there is direct contact between the mulch and the soil in order to enhance heat transmission (Lamont, 1996; Tarara, 2000).

Aziz (1994) working in South-western Quebec reported higher mean soil temperatures under IRT polyethylene mulch compared with silver or black mulch as well as bare soil. He also mentioned that the polyethylene-mulched soil conserved more moisture than did the bare soil. Allen et al. (1998) suggested that mulched plants use less water since evaporation from the soil is reduced by the use of a polyethylene mulch. Therefore, the depletion of soil water under such conditions may be caused mainly by plant transpiration (Kirnak et al., 2003). Soil moisture is expected to decrease gradually and be more homogeneous in the root zone under mulching condition compared with bare soil.

2.5.4 Response of pepper plants to polyethylene mulch

It is well recognized that the use of polyethylene mulch, particularly black, enhance growth and development of peppers (Brown and Channell-Butcher, 2001; Decoteau et al., 1990; Gough, 2001; Locher et al., 2005; Siwek et al., 1994).

A similar trend has been observed for total, marketable and early marketable yields and fruit quality of peppers grown under mulch condition compared to the ones grown in bare soil (Aziz, 1994; Brown and Channell-Butcher, 2001; Locher et al., 2005; Monette and Stewart, 1987; Porter and Etzel, 1982; Siwek et al., 1994). Enhancements of pepper growth and yield have been primarily due to improved soil temperature and retention of soil moisture. These two conditions are also favorable for nutrient uptake by plants grown on mulch. For example, yield resulted improved when nitrogen fertilization was applied to pepper plants grown on mulch, relative to the yield of those grown in bare soil condition both under optimal soil moisture condition (Locascio et al., 1985) or even when a certain water stress was imposed (Kirnak et al., 2003).

Salts in solution move downward when over-irrigation occurs and, subsequently, salinize soils, groundwater or other body waters downstream (Trout, 2000). Although no information is available on the effects of polyethylene mulch on the dynamics of salt leaching, mulching the soil could help to minimize the effects of salinization of soils and water. Mulching the soil surface can limit the leaching of nitrate toward deeper layers of the soil profile; and therefore, decrease groundwater pollution. Romic et al. (2003)

conducted a two-year field experiment with drip-irrigated bell pepper to test the effect of two types of mulch (black polyethylene and biodegradable cellulose) and bare soil on nitrate leaching. The use of the black polyethylene mulch significantly reduced nitrate leaching followed by the biodegradable cellulose mulch compared to nitrate leaching occurred in bare soil. However, the decreased efficacy of the cellulose mulch in preventing nitrate leaching, especially when rainfall rate was high (768 mm), was due to its characteristics to decompose and disintegrate being a paper material.

2.6 Final remarks

If saline water is to be used to irrigate peppers, a high value crop moderately sensitive to salinity, water management strategies must be developed to minimize both plant stress and salinization of the soil environment, thus preventing significant yield reduction. For these reasons, this project focused on the use of saline water applied via drip irrigation alone or in combination with polyethylene mulch to evaluate its effects on sweet pepper plant growth, development and yield, as well as on the plant physiology, water use efficiency and soil salinization.

Preface to Chapter 3

It is well recognized that availability of good quality water for agriculture, particularly for irrigation, will become scarce as a consequence of increasing demands by other water users such as for human consumption, industry and recreation. Therefore, water of low quality, e.g. saline, will likely be left for crop irrigation. Since bell peppers are sensitive to salinity, it is important to carry out studies to evaluate the effects of saline water on these plants while optimizing water use regardless of the water quality. In Chapter 3, the use of saline water, applied through drip irrigation to bell pepper plants growing on mulch or bare soil, was evaluated in terms of its effects on plant physiology, growth and yield, as well as soil salinity.

The manuscript is co-authored with Katrine A. Stewart, and Chandra Madramootoo. Participation of each author is described in the "Contributions of Authors" section. Tables and figures are presented at the end of this chapter, and references are listed in Chapter 10. Information from this manuscript will be submitted to the *International Journal of Vegetable Science* for peer review. Copyright transfers from co-authors are shown in Appendix B.

Chapter 3

Effects of saline drip irrigation and polyethylene mulch on the physiology, growth and yield of bell pepper

Dagobiet Morales-Garcia [(1)], Katrine A. Stewart [(1)], and Chandra Madramootoo [(2)]

[(1)] Department of Plant Science and [(2)] Department of Bioresource Engineering,

Macdonald Campus of McGill University.

21,111 Lakeshore Road, Ste. Anne de Bellevue, Quebec, H9X 3V9, Canada

3.1 ABSTRACT

Experiments were carried out under greenhouse conditions to evaluate the effects of saline irrigation (ranging from 0.2 up to 9.0 $dS{\cdot}m^{-1}$, and from 0.5 to 4.5 $dS{\cdot}m^{-1}$, respectively) and polyethylene mulch [black or green infrared-transmitting (IRT)] on the physiology, growth and yield of sweet peppers (*Capsicum annuum* L.). Mulched plants required less water at all levels of salinity than plants grown in bare soil; consequently, the soil in which they were grown had a decreased salinity. Stomatal conductance, transpiration and photosynthesis significantly decreased with increasing levels of salinity at the time of fruit development. Mulched plants had significantly higher rates of stomatal conductance, transpiration and photosynthesis than plants grown in bare soil. Generally, growth (fresh and dry weights, leaf area and number) was reduced by higher levels of saline water but increased by mulching. Salinity levels above the control (0.2 and 0.5 $dS{\cdot}m^{-1}$) significantly reduced total and marketable yield, agronomic water use efficiency (WUE_a), and harvest index. Mulched plants had greater WUE_a and significantly higher marketable yields than plants grown in bare soil. Fruit size and pericarp thickness were significantly reduced with increasing salinity, whereas fruit total soluble solids (TSS) increased.

Keywords: salinity, plastic mulch, *Capsicum annuum* L., stomatal conductance, transpiration, photosynthesis, WUE, electrical conductivity

3.2 INTRODUCTION

Worldwide, salinity affects 20% of the 230 million ha of irrigated land (FAO-AGL, 2000). Occurrence of soil degradation by salinity is primarily located in arid and semiarid regions (FAO, 2002), where, additionally, water is not only of poor quality but also scarce (Martínez Beltrán, 1999). Problems in quality and availability of irrigation water extend into humid areas, due to increasing competition among water users (Parsons, 2000; Shalhevet, 1994). Globally, agriculture accounts for 71% of the total water use (FAO, 2000). Therefore, improvement in the management of agriculture to maximize water use is required. Among irrigation systems, drip irrigation is one of the most efficient systems for water delivery and especially suitable for high cash value crops (Locascio, 2005). This system offers the advantage of reducing the surface area exposed to evaporation, thus diminishing water consumption (Dasberg and Or, 1999; Skaggs, 2001). Drip irrigation, also allows for the use of saline water (Dasberg and Or, 1999) and/or the inclusion of soluble fertilizers in the irrigating solution, e.g. fertigation (Bar-Yosef, 1999). In order to reduce the amount of water required, drip irrigation is often used in combination with mulch (Lamont, 1996). Mulching the soil with polyethylene films reduces crop water consumption by minimizing evaporation (Kirnak et al., 2003). Soil moisture is retained longer under mulch and hence less water is required to maintain soil moisture at a given level (VanDerwerken and Wilcox-Lee, 1988). In addition to reducing the amount of water used, there is the possibility of using poorer quality water (2 to 10 $dS \cdot m^{-1}$) (Rhoades et al., 1992), which must be studied. This is becoming more critical as the supply of high quality water is limited and expensive in semiarid and arid areas. However, before this option is considered feasible, the tolerance of each crop to salinity must be determined. Peppers (*Capsicum annuum* L.) require large amounts of water (600-900 mm) in order to produce high quality fruit yield (Brouwer and Heibloem, 1986) and are moderately sensitive to salinity. Rhoades et al. (1992) reported a yield reduction threshold of 1.0 $dS{\cdot}m^{-1}$ of the irrigation water for furrow irrigated peppers. Beyond this threshold, each $dS{\cdot}m^{-1}$ increase caused a 14% yield decrease (Ayers and Westcot, 1985). Plant response to salt has also been reported to be influenced by soil temperatures; for example, tomatoes grown at higher root zone temperature had a higher salt tolerance than their cooler counterparts (Dalton et al., 1997). Locher et al. (2005) attributed the significant improvement in growth and yield of mulched pepper plants, relative to plants grown in bare soil, to increases in soil temperature.

The general response of crops to surface (Dehghanisanij et al., 2006) and subsurface (Ayars et al., 1999) drip irrigation has been investigated, resulting in enhancement of saline water use (Dehghanisanij et al., 2006; Oron et al., 1999) and reduction of soil salinity (Hanson and May, 2004). However, the effects of a plasticulture system using saline water delivered via surface drip irrigation in combination with polyethylene mulch on pepper have, as yet, not been determined. Therefore, the objective of these experiments was to examine the effects of saline drip irrigation and polyethylene mulch on the physiology, growth, yield, and water use of bell pepper.

3.3 MATERIALS AND METHODS

3.3.1 Plant material

Pepper seeds (*Capsicum annuum* L. var. Red Knight X3R) (Petoseed, Oxnard, CA, USA) were sown 1 February 2003 (Experiment 1) and 13 October 2003 (Experiment 2) in 72-cell trays (semi-pyramidal cells of 4 cm x 2 cm x 6 cm, volume 60 cm^3) containing a peat-based substrate (Promix Bx, Premier Horticulture, Rivière-du-Loup, QC, Canada). This cultivar was chosen as it has a large blocky bell, early maturity and a bright red uniform colour, and it is well adapted to southeast and northeast of North America (Wehner, 2002). After the appearance of the first true leaves, plants were watered as required, and fertilized weekly for 3 weeks with 15 mL/plant of a nutrient solution including (in $mg{\cdot}L^{-1}$) 200 N, 88 P, and 166 K, 0.2 B, 0.5 Cu, 1.0 Fe, 0.5 Mn, 0.005 Mo, and 0.5 Zn; and then for approximately another 2 weeks with 20 mL/plant including (in $mg{\cdot}L^{-1}$) 400 N, 176 P, 332 K, 0.4 B, 1.0 Cu, 2.0 Fe, 1.0 Mn, 0.01 Mo, and 1.0 Zn (Plant Products, Brampton, ON, Canada). Seedlings, 18 cm tall with six true leaves, were transplanted into pots on 1 April 2003 (Experiment 1) and 18 December 2003 (Experiment 2) to initiate the experiment.

3.3.2 Experimental design and treatments

The 5 x 3 factorial experiments in a completely randomized design consisted of five levels of the saline irrigation and three levels of mulch, resulting in 15 treatment combinations replicated eight times. Each plant served as an experimental unit.

The levels of the irrigation water salinity were: 0.2 (control), 1.5, 4.0, 6.5 and 9.0 $dS{\cdot}m^{-1}$ (Experiment 1); and 0.5 (control), 1.5, 2.5, 3.5 and 4.5 $dS{\cdot}m^{-1}$ (Experiment 2). Concentrations of calcium (Ca^{2+}), sodium (Na^+) and chloride (Cl^-) for each salinity level are presented in Table 3.1. Stock saline solutions (100 L) were made up based on a $NaCl{:}CaCl_2$ 2:1 ratio on a molar basis (Dalton et al., 1997). The saline solutions had a value of 0.7 as the ratio of $Na^+/(Na^+ + Ca^{2+})$, which is within the range (0.1-0.7) found for most saline waters used to irrigate major horticultural crops around the world (Grattan and Grieve, 1999). The salts NaCl (Fisher Scientific, Whitby, ON, Canada) and $CaCl_2$ (Anco Chemicals, Maple, ON, Canada) were added to tap water with an electrical conductivity (EC_w) of 0.2 $dS \cdot m^{-1}$ and adjusted using a portable conductivity-meter (Model TDSTestr4TM, Oakton, Singapore) with automatic temperature compensation until the appropriate level was reached.

The mulch levels were bare soil, black polyethylene mulch (Climagro, Plastitech, St-Remi, QC, Canada), and green infrared-transmitting (IRT) polyethylene mulch (Polyon-Barkai, Polywest, Encinatas, CA, USA).

3.3.3 Experimental set up and plant management

Experiments were carried out in a greenhouse with air temperature of 25-27 °C day and 18°C night; relative humidity 65-75%; photoperiod 13 h with a light intensity of 700 $\mu moles \cdot m^{-2} \cdot s^{-1}$; and 365 $\mu L \cdot L^{-1}$ carbon dioxide.

The sandy loam soil (70% sand, 18% silt and 12% clay) used was mixed with a peat-based growing media (Promix Bx, Premier Horticulture, Rivière-du-Loup, QC, Canada) at a ratio of 1:1 (Experiment 1) and 2:1 v/v (Experiment 2). The soil-mix (henceforth referred to as soil) was placed into 120 10-L black plastic pots (24 cm inside diameter x 22.5 cm height, Nursery Supplies, Orange, CA, USA). Mulches were placed directly on the soil surface, stretched and taped to the rim of the pots and holes (16 cm^2) cut in the centre of the mulch for the transplant. Pots were spaced 55 cm between and 45 cm within rows.

A drip irrigation system was used to deliver water to all plants. Each treatment (eight plants) had an independent irrigation line consisting of rigid polyethylene pipe (1.24 cm inside diameter) with eight on-line pressure compensating snout drippers with an emitter discharge rate of 1.1 $L{\cdot}h^{-1}$ (Netafim, Fresno, CA, USA). To deliver water to each plant, a spaghetti tube (3 mm inside diameter) was connected to each dripper, and secured with an angled stake into soil. Each level of saline solutions or non-saline water was stored in a plastic container (120-L capacity) and pumped (operating pressure of 50 kPa) using a submergible pump (Model PE-2H-PW, Little Giant Pump, Oklahoma City, OK, USA) to three irrigation lines (for each mulch level) which had independent valves each. Each saline water level was gradually increased within the first week following transplanting until the corresponding saline irrigation level was reached.

The time to irrigate was based on soil moisture. Time domain reflectometry (TDR), a non-destructive method to measure soil water content, was used to monitor soil moisture. Three-rod (stainless steel, 21 cm length, 3 mm thickness, and separated 4 cm apart) probes were horizontally installed at depths of 5, 10 and 15 cm, respectively, into three randomly selected pots per treatment, giving a total of 45 pots. The three-rod probes were connected to a TDR Tektronix Cable Tester (Model 1502B, Tektronix, OR, USA) using a coaxial cable for measurements of the apparent length (m) of probes embedded in the soil, X_w, as graphically indicated on the TDR screen. The X_w values were then used to calculate the dielectric constant (electric transmissivity), ε_b, of a soil matrix by the following formula (Topp et al., 1980):

$$\varepsilon_b = \left(\frac{X_w}{L}\right)^2 \qquad \text{(Eq. 3.1)}$$

where L is the actual length of the probes (m) embedded in the soil. Soil moisture was calculated by the following equation (Topp et al., 1980):

$$\theta_v = -5.3\times10^{-2} + 2.9\times10^{-2}\varepsilon_b - 5.5\times10^{-4}\varepsilon_b{}^2 + 4.3\times10^{-6}\varepsilon_b{}^3 \text{ (Eq. 3.2)}$$

where θ_v is the volumetric soil water content ($m^3 \cdot m^{-3}$).

Irrigation was applied when 40% (Experiment 1) and 30% (Experiment 2) of the plant available water (PAW, 0.26 and 0.24 $m^3 \cdot m^{-3}$ for Experiments 1 and 2, respectively) had been depleted. The amount of water applied at irrigation was calculated by the following formula:

$$I = (\theta_f - \theta_s)\, V_s \qquad \text{(Eq. 3.3)}$$

where I is the irrigation requirement (L/plant), θ_f is the soil moisture at field capacity (0.42 and 0.35 $m^3 \cdot m^{-3}$ at −30 kPa of soil matric potential, for Experiments 1 and 2, respectively), θ_s is the instantaneous soil moisture at the irrigation time ($m^3 \cdot m^{-3}$), V_s is the volume of soil to be wetted (L/pot). To calculate the irrigation requirement, I, in this experiment, the previous formula was modified from that used for calculating the total available water in the root zone by Allen et al. (1998):

$$TAW = 1000\,(\theta_f - \theta_{wp})\, Z_r \qquad \text{(Eq. 3.4)}$$

where TAW is the total available water in the root zone (mm), θ_f is the soil moisture at field capacity ($m^3 \cdot m^{-3}$), θ_{wp} is the soil moisture at wilting point ($m^3 \cdot m^{-3}$), and Z_r is the zone root depth (m).

An organic insecticide (Safer's Trounce®, Charlottetown, PE, Canada) and insect predators [Gall midge (*Aphidoletes aphidimyza*), parasitic wasps (*Aphidius colemani*), ladybugs (*Adalia bipunctata*) and predatory mites (*Amblyseius cucumeris*, *Amblyseius degenerans*) (Biobest Biological Systems, Leamington, ON, Canada)] were used to control infestation of aphids and mites (Experiment 1). No insect problems occurred during Experiment 2; however, all the predator species were also introduced as a preventive measure.

Nitrogen was applied at pre-plant (NH_4NO_3, $NH_4H_2PO_4$, KNO_3) and five weekly (NH_4NO_3) applications to give a total of 100 kg·ha^{-1} (Table 3.2) starting 30 DAT. Phosphorus ($NH_4H_2PO_4$) and potassium (KNO_3) were applied at preplant (40 kg·ha^{-1}). The fertilization rate was based on a population density of 24,700 plants/ha. At fruit set, plants were staked and tied.

3.3.4 Data collection

Two copper-constantan thermocouples (Scott, 2000) installed in three pots per treatment at soil depths of 5 and 15 cm, respectively, were used to measure soil temperature. The thermocouples were connected to a datalogger (CR10, Campbell Scientific, Logan, UT, USA) to store data averaged on an hourly basis.

Measurements of net CO_2 assimilation (photosynthesis), leaf transpiration, and stomatal conductance were taken biweekly from transplanting until the first harvest for Experiment 1 or at fruiting stage [141days after transplanting (DAT)] in Experiment 2 by using a portable photosynthesis meter (Model LI-6400, LI-COR Biosciences, Lincoln, NE, USA). Based on previous reports (Chartzoulakis and Klapaki, 2000; De Pascale et al., 2003), the fourth fully expanded leaf of three plants per treatment was selected for these physiological measurements carried out between 1100 and 1400 h.

Water use efficiency was calculated according to Gregory (2004):

$$WUE_a = \frac{Y}{I} \qquad \text{(Eq. 3.5)}$$

where WUE_a is the agronomic water use efficiency (g·L^{-1}), Y is the fruit yield (g/plant) and I is the amount of water applied by irrigation (L/plant).

Mature red fruit were harvested weekly, counted, weighed (g/plant) and graded based on the following market classifications:

- Marketable grade 1. Fruit weight ≥ 100 g (Aziz, 1994; Rigby, 1988) with uniform shape and less than 3 small scratches (Aziz, 1994)
- Marketable grade 2. Fruit weight ≥ 80 g (Jolliffe and Gaye, 1995) but ≤ 100 g with uniform shape and less than 3 small scratches (Aziz, 1994)
- Non-marketable or culls. Fruit weight ≤ 80 g or any fruit weight with damage (≥ 3 small scratches; blossom end rot, scratching, sunscald) and/or anomalous shape (Aziz, 1994; Rigby, 1988).

Fruit length (cm) and width (cm) were measured by a caliper. Fruit total soluble solids (TSS) were determined at ambient temperature in mature fruit juice (3-5 mL) using a hand refractometer with a capacity from 0 to 32% Brix grade (ATC-1E, Atago, Japan).

At final harvest (~180 DAT), the number of leaves and immature fruit were counted and leaf area calculated using a leaf area meter (Delta-T devices, Cambridge, England). Fresh weights of roots (four plants per treatment), stems, leaves and both mature and immature fruits were taken and a fresh root to shoot ratio calculated by the formula:

$$R/S = \frac{FWR}{FWS} \qquad \text{(Eq. 3.6)}$$

where *R/S* is the fresh root to shoot ratio, *FWR* is the fresh weight of roots (g/plant) and *FWS* is the fresh weight of shoot (stems + leaves + fruits) (g/plant). Then the plant parts were oven-dried at 70°C for 72 h and dry weights taken.

Harvest index was determined on a fresh basis according to the following formula:

$$HI = \frac{Ym}{FWS} \qquad \text{(Eq. 3.7)}$$

where *HI* is the harvest index (dimensionless), and *Ym* is the marketable yield (g/plant).

Soil samples were collected from three pots per treatment (45 pots) at the end of the experiment for soil salinity determinations. Six subsamples were obtained with a cylindrical auger from each of three predetermined layers (0-7, 7-14 and 14-21 cm) of the soil profile in the pot, and then mixed and further divided into three parts. Two-thirds were kept for measurements of the electrical conductivity of the soil/water extracts 1:5 ratio ($EC_{1:5}$) and the last third was used to make a composite sample from three soil layers of three pots per treatment (15 composite samples) for electrical conductivity of the saturation soil paste extract (EC_e). Then the soil samples were air-dried for laboratory determinations of $EC_{1:5}$ and EC_e following the procedures of Rhoades (1996). Initial soil salinity levels were 0.84 and 0.73 $dS{\cdot}m^{-1}$ of EC_e for Experiments 1 and 2, respectively.

Based on the results of the first experiment a number of modifications to the original design were incorporated. These included a change in determining when to irrigate. In order to avoid water stress in the high salinity treatments under conditions of high evapotranspiration (Allen et al., 1998), plants were irrigated at 70% of the PAW remaining in the soil instead of 60%. The levels of salinity were changed to 0.5 $dS{\cdot}m^{-1}$ (control), 1.5, 2.5, 3.5, and 4.5 $dS{\cdot}m^{-1}$ (Table 3.1).

3.3.5 Statistical analysis

Data from each experiment were analysed separately due to the differences in salinity levels and the established threshold of the PAW depletion. Analyses of variance (ANOVA) were carried out using the statistical analysis system (SAS) software (SAS Institute, Cary, NC, USA) for each variable. When the F ratio from the ANOVA was significant, a Tukey's multiple mean comparison test (P=0.05) was performed. Information is presented on the main factors: saline irrigation and mulching; interactions between the two are only presented when significant.

3.4 RESULTS

3.4.1 Soil conditions

Soil temperature was slight but significantly and consistently higher with IRT mulch compared to black mulch or bare soil throughout the growing period (Figures 3.1 and 3.2). During vegetative growth, soil temperature was higher under a black mulch than in bare soil (Figure 3.1). However, the temperature gap narrowed after flowering, fruit set and fruiting growth stages likely because the canopy covered the mulch so the sun did not hit it directly (Figure 3.1). When averaged over the entire season, it was found that soil temperatures under a black mulch were higher in the night and morning but lower between 12 h and 20 h relative to bare soil (Figure 3.2).

Soil moisture was depleted faster in the control (bare soil) than mulched treatments. Therefore, plants grown in bare soil were irrigated more frequently. Mulched plants used approximately 30 and 15% less water than the ones grown in bare soil treatment in Experiments 1 and 2, respectively (Table 3.3). As the salinity of the irrigation water increased, the amount of water used by the plant decreased. Irrigation requirements were reduced by 11, 20, 38, and 52% at salinity levels of 1.5, 4.0, 6.5 and 9.0 $dS \cdot m^{-1}$, respectively in Experiment 1; and by 10, 17, 25, and 30% at salinity levels of 1.5, 2.5, 3.5 and 4.5 $dS \cdot m^{-1}$, respectively in Experiment 2 (Table 3.3).

Overall, soil salinity, measured as the electrical conductivity of soil/water 1:5 ratio (w/w) extracts ($EC_{1:5}$), significantly increased with the use of saline water (Table 3.4). Mulching the soil resulted in a less saline soil than that without mulch (bare soil). Soil salinization was greatest in the top layer of soil profile (0-7 cm) compared to the middle and bottom layers (Figure 3.3). Within the top layer, soil salinity values were similar for 4.0, 6.5 and 9.0 $dS \cdot m^{-1}$ treatments and significantly higher than the 1.5 $dS \cdot m^{-1}$ treatment, which in turn was significantly higher than the control. Similarly, soil salinity in the middle and bottom layers (7-14 and 14-21 cm, respectively) increased with increasing saline water, but values were comparable in both layers for each salinity level. The use of either polyethylene mulch decreased soil salinization significantly in the top layer of soil (0-7 cm, Experiment 1) (data not shown) or in the soil profile (0-21 cm, Experiment 2) relative to bare soil (Figure 3.4).

3.4.2 Experiment 1

3.4.2.1 Stomatal conductance, transpiration and photosynthesis

Stomatal conductance increased until flowering ($\leq$ 6.5 $dS \cdot m^{-1}$) or fruit initiation (9.0 $dS \cdot m^{-1}$) then decreased (Figure 3.5). As the level of salinity increased the stomatal conductance decreased. No significant difference was noted in stomatal conductance between plants receiving either 0.2 $dS \cdot m^{-1}$ (control) or 1.5 $dS \cdot m^{-1}$ throughout growth.

After fruit initiation (29 DAT), plants irrigated with 4.0 dS·m^{-1} had significantly lower rates of stomatal conductance than the controls. Higher rates of salinity, 6.5 and 9.0 dS·m^{-1} decreased stomatal conductance by 23, 55, 59, and 46% at 29, 44, 59 and 73 DAT, respectively, compared with the control.

Transpiration rates followed a similar, but time delayed, trend to that of stomatal conductance rates with rates increasing from transplantation until initial fruit set then declining (Figure 3.6). Plants irrigated with 0.2 and 1.5 dS·m^{-1} were similar throughout the experiment. Plants receiving either 1.5 or 4.0 dS·m^{-1} had similar transpiration rates until the start of harvesting (73 DAT) at which plants treated with 4.0 dS·m^{-1} had significant lower transpiration activity. The transpiration rates of plants receiving 6.5 and 9.0 dS·m^{-1} were approximately half those of the control during fruiting.

Photosynthesis peaked at start of flowering and then declined over time (Figure 3.7). No significant differences were found among plants receiving 0.2, 1.5 or 4.0 dS·m^{-1} during the first 59 DAT. Later, plants irrigated with 4.0 dS·m^{-1} had significantly less photosynthetic activity. By 44 DAT, the photosynthetic rate of plants treated with either 6.0 or 9.0 dS·m^{-1} was significantly lower than those of all other treatments.

The stomatal conductance of mulched plants was slightly but not significantly higher than that of plants grown in bare soil from transplanting until flowering. At the start of the fruiting stage (29 DAT), plants grown in bare soil or on IRT mulch had significantly higher rates of stomatal conductance than plants with black mulch (Figure 3.8). However, at 44 DAT plants grown in bare soil had significantly lower rates of stomatal conductance than black mulched plants. These effects were, however, short lived and no significant differences among treatments were noted until final harvest (73 DAT) when the IRT mulched plants had higher stomatal conductance than black mulched plants.

There were no significant differences in transpiration rates between plants grown on IRT or bare soil throughout the growing season (Figure 3.9). However IRT plants showed significantly higher transpiration rates at fruit set and harvest than plants on black mulch.

Photosynthetic rates were similar among mulch treatments with only two exceptions (Figure 3.10). At fruit set (29 DAT) the photosynthetic rate of plants grown on black mulch was significantly lower than those on IRT mulch or bare soil, and mid way through the fruiting period (59 DAT) plants grown in bare soil had significantly higher rates than the ones from the other two treatments.

3.4.2.2 Plant growth

At salinities greater than 1.5 $dS \cdot m^{-1}$ fresh weights of root and shoots significantly decreased with each increase in salinity (Table 3.5). Root weights decreased by 57, 77, and 85% at salinity levels of 4.0, 6.5 and 9.0 $dS \cdot m^{-1}$, respectively, compared with the control. Of the shoot components, fruits were the most susceptible followed by leaves and then stems. The fresh R/S ratio initially reached the lowest value at a salinity of 4.0 $dS \cdot m^{-1}$ then increased. The harvest index decreased with each increase in salinity but the decreases were only significant at levels of 4.0 $dS \cdot m^{-1}$ or greater.

There were no significant differences in root, leaf and fruit weight between plants grown on mulch or bare soil. Mulched plants had stems that were significantly heavier than those of the plants grown in bare soil (Table 3.5). There was no significant difference in fresh root to shoot (R/S) ratio between plants grown under mulch or bare soil condition. Harvest index was higher for plants grown in bare soil than for mulched plants.

Increasing the salinity to 1.5 $dS \cdot m^{-1}$ did not decrease leaf area, number of leaves per plant and leaf size (Table 3.6). As the level of salinity level increased beyond this point leaf area, leaf number and leaf size decreased significantly compared to maximum values. Mulched plants had significantly greater leaf areas than plants grown in bare soil (Table 3.6). There was no significant difference in leaf number and size between plants grown under mulch or bare soil condition (Table 3.6).

Plants irrigated with salinity levels ≥4.0 $dS \cdot m^{-1}$ had significantly lower dry weights than plants receiving either 0.2 or 1.5 $dS \cdot m^{-1}$ (Table 3.6). The reductions increased with increasing salinity. Plants receiving 4.0 $dS \cdot m^{-1}$ had reductions of 53, 28, 41 and 40% for roots, stems, leaves and immature fruits, respectively, compared to 0.2 $S \cdot m^{-1}$. At the highest level of salinity (9.0 $dS \cdot m^{-1}$) dry weights were decreased by 82, 61, 85 and 99% for roots, stems, leaves and immature fruits, respectively.

Mulched plants had lower root dry weights than the plants grown in bare soil. However, only plants mulched with black polyethylene were significantly lighter (31%) than those grown in bare soil (Table 3.6). In contrast, the dry weight of the aerial portion of mulched plants was higher than that of plants grown in bare soil but values were only significant for the IRT mulch.

There was a significant interaction between salinity and mulch for root dry weights at the two lowest levels of salinity (Figure 3.11). Roots of mulched plants were, in average, 43% significantly lighter than roots of plants grown in bare soil. At 1.5 $dS \cdot m^{-1}$, root dry weight of plants grown in bare soil decreased but was significantly heavier than that of plants mulched with black polyethylene. No significant differences were found between the mulched plants over the range of salinity studied. At salinity levels of 4.0 dS·m^{-1} or higher, all root dry weights were similar.

3.4.2.3 Yield quantity and quality

Salinity both delayed early marketable yield and decreased marketable yield (Figure 3.12). Only plants receiving salinity levels ≤4.0 dS·m^{-1} produced any marketable yield during the first 30 days of harvest. Plants irrigated either with 0.2 dS·m^{-1} or 1.5 dS·m^{-1} were similar in terms of marketable fruit production during the first 58 days of harvest (137 DAT). Then, plants irrigated with 1.5 dS·m^{-1} had significantly slower rates of production than the controls (Table 3.7). Plants irrigated with 4.0 dS·m^{-1} produced most of their yield during the first 4 weeks of harvest (107 DAT) but production was significantly lower than those of 0.2 dS·m^{-1} or 1.5 dS·m^{-1} (Figure 3.12). Plants receiving either 6.5 or 9.0 dS·m^{-1} saline irrigation water produced minimal marketable yield.

No clear differences were observed in the production of cumulative marketable yield between mulched plants and the ones grown in bare soil (Figure 3.13). Total yield, number of fruit and quality, were negatively affected by increased salinity (Tables 3.7, 3.8 and 3.9). There was no significant difference in total yield between plants receiving either 0.2 dS·m^{-1} or 1.5 dS·m^{-1}. The latter had 21% less marketable yield than the control but a similar proportion of Grade 1. Plants receiving 4.0, 6.5 or 9.0 dS·m^{-1} had decreases in total yield of 37, 72 and 89%; and marketable yield of 63, 94 and 97% compared with plants receiving 0.2 dS·m^{-1}, respectively. The percentage Grade 1 fruit was significantly lower for plants receiving ≥4.0 dS·m^{-1}. Mean fruit weight was only significantly reduced at 6.5 and 9.0 dS·m^{-1}.

Mulching the soil did not significantly affect total and marketable yield, percentage of Grade 1 fruits and mean fruit weight, relative to bare soil (Table 3.7). However, mulched plants had a significantly greater proportion of grade 1 fruit and number of immature fruits compared with the plants grown in bare soil (Table 3.8).

Among the fruit characteristics evaluated, only length, pericarp thickness and total soluble solids (TSS) were affected by increasing levels of salinity (Table 3.9). As the salinity increased the fruit became shorter and had a thinner pericarp however this was only significant at the highest level of salinity. Interestingly, TSS increased with increasing salinity. The greater the salinity, the sweeter the fruits with plants receiving 4.0 dS·m^{-1} and above having significant higher amounts of TSS that the controls.

Fruit of mulched plants had a thicker pericarp compared with plants grown in bare soil but values were only significant for plants with black mulch (Table 3.9). No other fruit characteristics were affected by the use of mulch. At a salinity level of 4.0 dS·m^{-1}, fruit of plants mulched with green IRT had significantly greater values of TSS compared with the other two treatments (Figure 3.14).

3.4.2.4 Agronomic water use efficiency

Agronomic water use efficiency, WUE_a (yield produced per litre of water) was similar for the control and 1.5 dS·m^{-1} treatments with each producing 10 g of fruit per litre of water (Table 3.10). However, at higher salinity levels there were significant reductions (25, 61 and 80%) in WUE_a for 4.0, 6.5 and 9.0 dS·m^{-1}, respectively, compared to the control. When marketable yield was considered, the WUE_a was similar between the control and plants receiving 1.5 dS·m^{-1}. However, increasing the salinity to 4.0 dS·m^{-1} reduced WUE_a by 54% (3.7 g·L^{-1}) and a greater than 90% reduction was recorded at higher levels.

The use of polyethylene mulch significantly increased WUE_a for total yield (45 and 55%) and marketable yield (17 and 34%) with IRT and black mulch, respectively, compared with bare soil (Table 3.10). No significant differences were found between mulches.

3.4.3 Experiment 2

3.4.3.1 Stomatal conductance, transpiration and photosynthesis

There were no significant differences in the rates of stomatal conductance, transpiration and photosynthesis among plants irrigated with 0.5, 1.5 or 2.5 dS·m^{-1} (Figure 3.15) when sampled 141 DAT. However, the stomatal conductance rates of plant with higher levels of salinity (3.5 and 4.5 dS·m^{-1}) decreased by 42 and 49%, respectively, compared with the control (Figure 3.15A). Similarly, saline water of 3.5 and 4.5 dS·m^{-1} significantly lowered both rates of transpiration (31 and 41%, respectively) and photosynthesis (20 and 30%, respectively) relative to the control (Figure 3.15B, C).

Mulched plants had rates of stomatal conductance, transpiration and photosynthesis 49, 34, and 20% higher, respectively compared with plants grown in bare soil (Figure 3.16). The rate of stomatal conductance was affected by a significant interaction between salinity and mulch (data not shown). Under conditions of no salinity (control), mulched plants had higher stomatal conductance rates than the ones grown in bare soil. At a low level of salinity (1.5 $dS \cdot m^{-1}$), plants grown on black polyethylene mulch had significantly rates of higher stomatal conductance than plants grown on IRT or bare soil. At higher salinity levels, IRT mulched plants slightly increased stomatal conductance compared to the ones grown on black mulch or bare soil being significant at a salinity level of 3.5 $dS \cdot m^{-1}$.

3.4.3.2 Plant growth

Plant fresh weights were reduced by the application of saline water (Table 3.11). Any increase in salinity above the control (0.5 $dS \cdot m^{-1}$) significantly reduced the weights of roots, fruits and shoots by 20-60% depending on the level of salinity. Stems and leaves were more resistant to an increase in salinity with decreases in weight becoming significant only at salinity levels $\geq$3.5 $dS \cdot m^{-1}$. Fresh R/S ratio was not significantly affected by salinity. Harvest index decreased significantly in plants treated with 2.5 $dS \cdot m^{-1}$ and greater, compare with the control.

The type of mulch had no effect on fresh weight (Table 3.11). Mulching reduced root weight but values were only significant for the black (18%) as opposed to the green mulch (8%). There was an interaction between mulching and level of salinity for root fresh weight (data not shown). While all root weights declined with increasing salinity, under non-saline condition (0.2 $dS \cdot m^{-1}$) roots of plants grown on IRT or bare soil were significantly heavier than roots of black mulched plants.

Mulching increased the weight of all aerial parts of the plant (Table 3.11). Increases were significant for stems and shoots. Plants grown in bare soil had greater R/S ratio than either mulched plants. Similar HI was found in plants grown on mulch and bare soil.

Leaf area and number of leaves per plant did not decrease at saline levels of ≤2.5 $dS{\cdot}m^{-1}$, but significant reductions were found at higher salinities relative to the maximum values (Table 3.12). Leaf size was smaller in plants irrigated with saline water ranging from 0.5 to 3.5 $dS{\cdot}m^{-1}$ compared with the leaf size of plants irrigated with 4.5 $dS{\cdot}m^{-1}$ (Table 3.12).

Mulched plants had greater leaf area and individual leaf size than plants grown in bare soil (Table 3.12). There was no difference in leaf number between the mulch and bare soil treatments (Table 3.12).

Increases in salinity consistently decreased plant dry weight (Table 3.12). Roots were most significantly affected by salinity decreasing by 29 to 75% with increasing salinity. On the other hand, dry weights of stems and leaves were only significantly decreased at salinity levels of greater than or equal to 3.5 $dS{\cdot}m^{-1}$. The dry weight of immature fruit was significantly lower (23%) for plants receiving 4.5 $dS{\cdot}m^{-1}$ compared with the control.

Root dry weights of mulched plants were 18% lower than those of plants grown in bare soil (Table 3.12). Conversely, stem and leaves were 25-30% higher, and immature fruits were similar.

3.4.3.3 Yield quantity and quality

Marketable yield was delayed and reduced by salinity during early fruit production (Figure 3.17); the greater the salinity the lower the production (236 and 206 g/plant for plants treated with 3.5 and 4.5 $dS{\cdot}m^{-1}$, respectively). Overall, mulched plants had significantly earlier cumulative and higher cumulative yields over time than plants grown in bare soil (Figure 3.18). During the first four harvests, mulched plants receiving 0.5

$dS{\cdot}m^{-1}$ produced significantly earlier and higher marketable yield than plants grown in bare soil (Figure 3.19). When salinity was increased to 1.5 $dS{\cdot}m^{-1}$, cumulative early marketable yield of the IRT mulched plants was significantly greater at 83, 93 and 105 DAT compared with the plants grown on black mulch or bare soil. Plants mulched with black polyethylene had in turn, higher cumulative marketable yield than plants grown in bare soil at 93 and 105 DAT, although this effect was short-lived (83 and 93 DAT) at 2.5 $dS{\cdot}m^{-1}$. No significant differences were found between plants grown under mulch and bare soil conditions at 3.5 or 4.5 $dS{\cdot}m^{-1}$.

As the level of salinity increased there were significant decreases in total as well as marketable yields (Table 3.13). Compared with the control, each increase in salinity meant that less fruit were Grade 1; however, the decease was only significant (34%) at 4.5 $dS{\cdot}m^{-1}$. Mean fruit weight was similar in plants receiving 0.5 to 2.5 $dS{\cdot}m^{-1}$ but significantly lower 18 and 22% at 3.5 and 4.5 $dS{\cdot}m^{-1}$.

Saline water significantly reduced the number of fruits/plant (Table 3.14). Plants treated with 1.5, 2.5, 3.5 and 4.5 $dS{\cdot}m^{-1}$ produced 3-5 fewer fruits/plant either total or marketable than the controls (0.5 $dS{\cdot}m^{-1}$). The number of fruits/plant of Grade 1 quality decreased significantly (24%) at 4.5 $dS{\cdot}m^{-1}$ compared with the control.

While mulching did not significantly increase total yield or the number of fruit per plant, it did significantly increase marketable yield by more than 30% (Table 3.13). Significantly more fruit on the mulched plants were Grade 1 (Table 3.14) and individual fruits were heavier (Table 3.13).

Although marketable yield decreased with increasingly salinity, using mulch produced higher yields when irrigation water was non-saline (control) or had 1.5 $dS{\cdot}m^{-1}$

(Figure 3.20). Under conditions of high salinity (4.5 dS·m^{-1}), IRT mulched plants produced more marketable yield than with black mulched or plants grown in bare soil.

No significant differences were found in fruit length and number of locules (Table 3.15). Fruit width and pericarp thickness significantly decreased, whereas TSS significantly increased with increasing salinity. Marketable fruit of plants irrigated with 4.5 dS·m^{-1} were narrower with a 30% thinner pericarp, but with 26% higher TSS than the fruit of control plants. Fruits from plants mulched with black polyethylene were similar to those of plants grown in bare soil. However, using an IRT mulch, plants produced significantly wider fruit (5%) with 13% more TSS compared with plants grown in bare soil (Table 3.15).

3.4.3.4 Agronomic water use efficiency

Agronomic water use efficiency decreased with increasing salinity (Table 3.16). Agronomic water use efficiency for marketable yield was more reduced by salinity than WUE_a for total yield. Salinities of 1.5 and 2.5 dS·m^{-1} resulted in significant WUE_a decreases of 23 and 28%, respectively, for total, and of 32 and 46%, respectively, for marketable yield. Maximum reductions in WUE_a were measured at salinities ≥3.5 dS·m^{-1} with average decreases of 45.5 % and 65.5% for total; and marketable yields, respectively.

Regardless of the level of salinity, mulched plants had generally higher WUE_a's than plants grown in bare soil (data not shown). A linear relationship was found to exist between WUE_a and marketable yield indicating that, despite less water was applied to mulched plants relative to plants grown in bare soil, yield was not negatively affected (data not shown).

3.5 DISCUSSION

3.5.1 Soil conditions

The warmest soil temperatures were recorded under the green IRT polyethylene (Figures 3.1 and 3.2), which transmits infrared radiation into the soil (Lamont, 1993; Lamont, 2005). The black polyethylene mulch also warms the soil via shortwave absorptance and conduction (Ham et al., 1993) but to a lesser extent than the IRT. Similar results had been reported by Aziz (1994). The effect of the black mulch on soil warming was slight compared with bare soil in these trials (Figures 3.1 and 3.2). This may be due to the fact that the experiment were carried out in a greenhouse in which radiation could have been limited by the greenhouse structure and shading. In contrast, under field conditions for pepper production with various coloured polyethylene mulches, a slight increased (1.4 °C) of the average soil temperature for the whole growing season with the use of black plastic mulch relative to bare soil was reported (Locher et al., 2005).

Less water was required to maintain soil moisture at a given level under the mulches compared with the bare soil (Table 3.3). Similar improvement in water conservation using polyethylene mulch has been reported for pepper production in a humid area (VanDerwerken and Wilcox-Lee, 1988) and corn in a semiarid area (Fisher, 1995).

As expected, the level of salinity in the water increased soil salinization accordingly, whereas using polyethylene mulch led to a decreased salt concentration in the soil relative to bare soil (Table 3.4). Soil salinity accumulated in the top 7 cm layer more than in deeper layers (Figure 3.3) possibly because soil water in the former layer is most exposed to the evaporation; thus concentrating salts as pure water evaporates (Dasberg and Or, 1999). Since the irrigation was on the soil surface it could be possible that salts had more lateral than vertical displacement. Salts have been shown to move towards the periphery of the wetted area under surface drip irrigation (Hoffman and Shannon, 2007). Mulched soils had a lower salt load since less salt was applied as the amount of irrigation water was reduced. Bare soils accumulated more salts in the top layer of soil as a consequence of the driven effect of evaporation (Wagenet, 1984). Conversely, when evaporation was reduced with mulching, soil salinity was more evenly distributed within the soil profile (Figure 3.4). Regardless of the mulch treatment, salt accumulation in the deeper layers was similar to those of the bare soil control when saline water ranged from 0.2 to 9.0 $dS \cdot m^{-1}$ (data not shown). However, in the second experiment, mulched soils accumulated less salts in the middle and bottom layers of the soil when saline water ranged from 0.5 to 4.5 $dS \cdot m^{-1}$ (Figure 3.4) possibly because of a decreased salt loading by irrigation.

3.5.2 Stomatal conductance, transpiration and photosynthesis

Stomatal conductance, transpiration and photosynthesis were all negatively affected by saline irrigation. Stomatal conductance and transpiration were reduced sooner than photosynthesis (Figures 3.3, 3.6 and 3.7). Salinity affected the stomatal conductance in the first instance, by reducing the size of the stomatal opening, hence limiting gas exchange. This in turn leads to reductions in transpiration and then photosynthesis. Our results are in agreement with those of Chartzoulakis and Klapaki (2000) and De Pascale et al. (2003) working with salinity levels of 12.6 and 17.8 $dS{\cdot}m^{-1}$, and 4.4 and 8.5 $dS{\cdot}m^{-1}$, respectively. Stomatal conductance in bell pepper plants have been reported to be more sensitive to salinity than photosynthesis. Chartzoulakis and Klapaki (2000) reported decreases of 47 and 61% in stomatal conductance, and 34 and 51% in photosynthesis after five weeks of salinity levels of 12.6 and 17.8 $dS{\cdot}m^{-1}$, respectively, compared to plants with no salinity. Applying salinity over the growing season, De Pascale et al. (2003) found overall decreases of 45 and 47% in stomatal conductance, 20 and 54% in photosynthesis, and 15 and 27% in transpiration of plants irrigated with saline water of 4.4 and 8.5 $dS{\cdot}m^{-1}$, respectively, compared to a non-saline control.

Since no significant differences in photosynthesis were found between the control (0.2 $dS{\cdot}m^{-1}$) and 1.5 $dS{\cdot}m^{-1}$ throughout the growing period (Figure 3.7) or between the control (0.5 $dS{\cdot}m^{-1}$) and 2.5 $dS{\cdot}m^{-1}$ until the fruit growth stage (Figure 3.15), it could be possible to use saline water with or less of 2.5 $dS{\cdot}m^{-1}$ to irrigate plants with only limited negative effects in terms of yield.

The reductions noted at higher levels of salinity indicate that the built up of salts in the root zone had reached a critical level. Salt accumulation in the soil is influenced both by salinity (salt concentration) and irrigation volume (salt load) (Assouline et al., 2006). Because salinity in the root zone lowers osmotic potential (Munns, 2002), water uptake decreased (Table 3.3). Consequently, plants irrigated with salinities greater than 3.5 $dS{\cdot}m^{-1}$ might have partially closed their stomata as an adaptive response to water loss (Taiz and Zeiger, 2002); thus decreasing transpiration, and later photosynthesis. Martinez-Ballesta et al. (2004) reported that the reductions in photosynthesis of peppers grown hydroponically for 10 days in saline solution was due to partial stomatal closure.

Additionally, photosynthetic rates might have decreased due to accumulation of sodium and/or chloride in the chloroplasts (Taiz and Zeiger, 2002). A strong negative relationship (R^2= 0.93) was reported between the chloride concentration in leaves and the inhibition of photosynthesis of bell pepper seedlings receiving saline irrigation (Bethke and Drew, 1992). A similar result was found by Chartzoulakis and Klapaki (2000).

The sharp decreases in stomatal conductance, transpiration and photosynthesis for all treatments after reaching a maximum peak could have been worsened by the increasing aphid infestation during those periods which added additional external stress to the plants.

In the first experiment the use of mulch did not affect stomatal conductance, transpiration and photosynthesis due in part to variations in soil moisture during measurements (Figures 3.8, 3.9 and 3.10). At uniform moisture levels, mulched plants had higher rates of stomatal conductance, transpiration and photosynthesis than plants grown in bare soil (Figure 3.16); thus suggesting that the latter were negatively affected by the rate of moisture depletion (Taiz and Zeiger, 2002). Maintaining a constant level of available water by frequent irrigation to minimize abrupt changes in soil moisture was found to stimulate higher rates of transpiration in bell peppers (Bar-Tal et al., 2000). Similarly, a deficit in soil moisture significantly decreased photosynthesis in peppers (Alvino et al., 1994). Another factor that might have contributed to increasing photosynthesis in mulched plants (Experiment 2) is the higher carbon dioxide levels around the planting holes in the mulch (Hopen and Oebker, 1975; Soltani et al., 1995) which would be available to the lower leaves of the crop and to the underside of the leaves where the majority of the stomata are located.

3.5.3 Plant growth

Munns et al. (1995) and Munns and Tester (2008) suggested that salinity inhibits plant growth in two related phases. Firstly, salts at the root zone lower the osmotic potential, reducing the plant's ability to uptake water that eventually leads to water stress and to growth inhibition (Munns, 2002). In our experiment water uptake was limited by salinity and decreased as the level of salinity increased (Table 3.3). Secondly, growth is reduced due to an accumulation of toxic ions (Na^+, Cl^-) within the plant over time (Munns and Tester, 2008; Munns et al., 1995). Peppers which have a limited ability to exclude salts, are expected to accumulate (Na^+, Cl^-) in their roots and shoots under saline conditions (Bethke and Drew, 1992).

Either or both phases negatively affected plants irrigated with saline water of greater than or equal to 2.5 $dS{\cdot}m^{-1}$ (Tables 3.5, 3.6, 3.11 and 3.12). De Pascale et al. (2003) found a significant decrease in root density of field-grown bell peppers irrigated with saline water. Dry weights of pepper roots decreased significantly at levels of 7.2 $dS{\cdot}m^{-1}$ (Kaya and Higgs, 2003; Kaya et al., 2003). Blom-Zandstra et al. (1998) found that roots accumulated more Na^+ than did shoots. Chartzoulakis and Klapaki (2000) reported similar concentrations of Na^+ and Cl^- in roots; these concentrations were higher in the roots than in the leaves of bell pepper plants and rose proportionally with increasing salinity.

The roots of mulched plants weighed less than those of plants grown in bare soil (Tables 3.6, 3.11 and 3.12). No correlation between root growth and root zone temperature was observed in this experiment. A similar response was observed in root development of pepper grown under bare soil and mulch conditions (Gough, 2001). The enhanced dry weight of roots of plants grown in bare soil may be a response to drastic changes of soil moisture as affected by evaporation occurring under bare soil condition. When water uptake is limited by a deficit in soil moisture, roots tend to explore other zones within the soil profile (Hulugalle and Willatt, 1987).

When salinity increased above 1.5 $dS \cdot m^{-1}$ fresh and dry weights of the aerial portion of the plant tended to decrease (Tables 3.5, 3.6, 3.11 and 3.12). However, the decrease was only significant at salinities greater than 2.5 $dS \cdot m^{-1}$ (Tables 3.11 and 3.12). Therefore, it may be speculated that up to 2.5 $dS \cdot m^{-1}$, the effects of the root zone osmotic potential and accumulation of toxic ions (Na^{+}, Cl^{-}) in aboveground parts of the plant did not reach a concentration critical enough to reduce growth. At the lower salinities, cell expansion may have been sufficient to diluted the ion concentration within the plant; thus avoiding toxic accumulation (Munns, 2002). Plants irrigated with salinities of 3.5 $dS \cdot m^{-1}$ and greater may have had a limited water uptake due to high osmotic potential in the root zone. Salt-stressed plants tend to intrinsically save water; thus restricting growth as an adaptation to low water availability (Binzel and Reuveni, 1994). Plants may have higher concentrations of Na^{+} and Cl^{-} in the leaves. Both Bethke and Drew (1992) and Chartzoulakis and Klapaki (2000) reported higher Cl^{-} content than Na^{+} in the leaves of peppers at high salinities, whereas Blom-Zandstra et al. (1998) reported the reverse. Both processes which ultimately limit nutrient uptake, causing nutrient imbalances (Grattan and Grieve, 1999). Based on our results, it could be speculated that Cl^{-} concentration in the leaves might have been more harmful than Na^{+} based on the fact that peppers are incapable of Cl^{-} exclusion (Chartzoulakis and Klapaki, 2000) and that chloride was the most abundant ion in our saline irrigation water (Table 3.1). Our results showing decreases in pepper growth with increasing salinity are consistent with other reports; e.g. leaf area and stem, leaf and shoot dry weights (Chartzoulakis and Klapaki, 2000; De Pascale et al., 2003; Gunes et al., 1996; Kaya and Higgs, 2003; Kaya et al., 2003).

Increases in fresh weight of stems and shoots (Tables 3.5 and 3.11) as well as increases in dry weight of the aerial parts of mulched plants (Tables 3.6 and 3.12) may be due to slower soil water depletion (Table 3.3). Kirnak et al. (2003) found that mulched plants under water stress had significantly greater water content in leaves, shoot dry weight and stem diameters than plants grown in bare soil. Locascio et al. (1985) reported that mulching improved N use efficiency of both applied N and soil N, and shoot dry weight. Under non-saline conditions mulches have been found to significantly increase plant height and stem diameter (Locher et al., 2005), shoot fresh weight (Aziz, 1994) and number of leaves (Siwek et al., 1994).

3.5.4 Yield quantity and quality

Fruit fresh weight was more sensitive to salinity than stem and leaf fresh weights, reflecting in part the distribution of assimilate (Tables 3.5 and 3.11). Approximately 50% of the total dry matter of a pepper plant (Miller et al., 1979) and more than 90% of the daily plant dry weight increase occurred in the fruits during the reproductive phase (Hall, 1977). Water consumption in the salinized plants was reduced, and likely, less water might have been transported to the fruits. Tadesse et al. (1999) found lower water contents in pepper fruit under conditions of high salinity.

Generally, in greenhouse and hydroponics conditions, bell pepper yield is reduced when saline nutrient solutions are above 2.0 $dS \cdot m^{-1}$ with KCl (Tadesse et al., 1999), NaCl (Chartzoulakis and Klapaki, 2000) and/or Na_2SO_4 (Navarro et al., 2002). In field conditions, pepper yield was reported to decreased 14% for each increase of $dS \cdot m^{-1}$ above a threshold of 1.5 $dS \cdot m^{-1}$ of saturated soil paste electrical conductivity, EC_e (Maas, 1990). Soil salinity measured at final harvest (Figure 3.21) confirmed that levels exceeded the threshold in salinity treatments other than the control (0.2 or 0.5 $dS \cdot m^{-1}$ of EC_w). Soil salinity correlated well with marketable yield (Figure 3.22). Mulched soils were less saline (closer to the threshold limit) than bare soil regardless of the level of salinity in the irrigation water, which enhanced early and final marketable yields (Figures 3.19 and 3.20). Yield reductions noted in our experiment were greater than those of De Pascale et al. (2003), reflecting cultivar and climatic differences.

Interestingly, salinity reduced fruit number and weight rather than fruit size suggesting that, under saline conditions, carbohydrate production was used for fruit maintenance (cell expansion) rather than fruit development (cell division) (Binzel and Reuveni, 1994). In contrast, TSS content of the fruit increased with increasing salinity (Tables 3.9 and 3.15). This trend was contrary to those reported by Tadesse et al. (1999) and Navarro et al. (2002) and reflects the differences in composition of the saline solutions $CaCl_2$ + NaCl versus KCl or NaCl or Na_2SO_4, respectively. Rubio et al. (2003) noted that calcium could mitigate the toxic effects of sodium in the fruit. Cabañero et al. (2004) suggested that increasing root zone temperature might enhance water and Ca uptakes in saline conditions, which could explain the positive effect of the IRT mulch which had soil temperatures in the optimal range 24-30 °C for maximum fruit weight

(Gosselin and Trudel, 1986). The IRT increased temperature by 1-2 °C relative to the black mulch or bare soil. Similar results have been reported by Lamont (1993). A further study is needed to find out if the composition of the saline solution and root zone temperature can cause an increase in total soluble solids in the fruit.

The improvement in early and final yields as well as better quality of fruits, e.g. TSS, using polyethylene mulch (Table 3.15) might be due to less drastic changes in the soil moisture (Kirnak et al., 2003; VanDerwerken and Wilcox-Lee, 1988) and to a lesser extend to an increase in soil temperature (Locher et al., 2005). VanDerwerken and Wilcox-Lee (1988) found that pepper yield was slightly higher in black mulched plants without irrigation in a humid area than plants grown in bare soil with irrigation, because under mulch soil moisture was preserved with no drastic variations for about 55 DAT in a relatively dry season. In fact, the use of plastic mulch has been found to mitigate the effect of water stress and improve bell pepper yields (Kirnak et al., 2003). Our better yields with plastic mulches (average across salinity levels) relative to the yield with bare soil are in agreement with the findings reported by several authors (Brown and Channell-Butcher, 2001; Monette and Stewart, 1987; Siwek et al., 1994) for mulched plants grown without salinity stress.

3.5.5 Agronomic water use efficiency

The efficiency of pepper plants to produce yields per unit of water irrigated (WUE_a) decreased with increasing salinity but increased with the use of polyethylene mulches (Tables 3.10 and 3.16). In saline conditions, WUE_a depends on the sensitivity of the crop to salt concentrations in the growth medium (Letey, 1993). Therefore, the higher WUE_a

found for mulched treatments was likely due to lower salt accumulation in mulched soil compare to the bare soil (Figure 3.21). Improvements in the WUE_a by mulching have both agronomic and economic implications. In the case of the former, fruit quality is maintained or enhanced. In the latter case water costs are reduced due both to a reduction in the quantity of water applied and in the quality of that water, although this must be compared with the extra costs associated with mulch purchase, application and removal.

3.6 CONCLUSION

Pepper plants growing on polyethylene mulch can be irrigated with saline water up to 2.5 $dS \cdot m^{-1}$ and produce early marketable yield superior to plants growing in bare soil and irrigated with non-saline water (0.5 $dS \cdot m^{-1}$). If saline water of 3.5 or 4.5 $dS \cdot m^{-1}$ is to be used, the harvest could be terminated after 30 days (105 DAT) as the majority of the marketable yield would have been obtained by this time. Use of mulch decreased the water consumption while maintaining marketable yield, and produced a less saline soil.

Table 3.1 Concentrations of salts or ions calculated by titration for each level of salinity.

Saline water ($dS \cdot m^{-1}$)	Salt concentrations (mM)		Ion concentrations ($mmol \cdot L^{-1}$)		
	NaCl	$CaCl_2$	Na^+	Ca^{2+}	Cl^-
Experiment 1					
0.2	-	-	0.04	0.02	0.07
1.5	7.83	3.92	7.83	3.92	15.65
4.0	22.80	11.42	22.80	11.42	45.61
6.5	37.78	18.93	37.78	18.93	75.57
9.0	52.75	26.43	52.75	26.43	105.53
Experiment 2					
0.5	1.84	0.92	1.84	0.92	3.66
1.5	7.83	3.92	7.83	3.92	15.65
2.5	13.82	2.92	13.82	2.92	27.63
3.5	19.81	9.92	19.81	9.92	39.62
4.5	25.80	12.92	25.80	12.92	51.60

Table 3.2 Fertilization scheduled at different days after transplanting (DAT).

Time	N [z]		P_2O_5 [y]		K_2O [x]	
(DAT)	kg·ha^{-1}	g/plant [v]	kg·ha^{-1}	g/plant	kg·ha^{-1}	g/plant
Preplant	50	2.0	40	1.6	40	1.6
30	10	0.4	-	-	-	-
37 (38) [w]	10	0.4	-	-	-	-
45	10	0.4	-	-	-	-
53 (55)	10	0.4	-	-	-	-
63	10	0.4	-	-	-	-
Total	100	4.0	40	1.6	40	1.6

[z] N = Ammonium nitrate (NH_4NO_3, 34-0-0), monoammonium phosphate ($NH_4H_2PO_4$, 11-48-0), and potassium nitrate (KNO_3, 13.5-0-45)
[y] P_2O_5 = Monoammonium phosphate ($NH_4H_2PO_4$, 11-48-0)
[x] K_2O = Potassium nitrate (KNO_3, 13.5-0-45).
[w] Values in parenthesis correspond to Experiment 2; otherwise the same as Experiment 1.
[v] Based on a population density of 24700 plants/ha

Table 3.3 Effect of varying levels of saline water ($dS \cdot m^{-1}$) and polyethylene mulch on the total irrigation requirement (I) [(z)] and irrigation interval (I_{int}) [(y)].

Experiment 1				Experiment 2			
Salinity ($dS \cdot m^{-1}$)	Mulch	I (L/plant)	I_{int} (day)	Salinity ($dS \cdot m^{-1}$)	Mulch	I (L/plant)	I_{int} (day)
0.2	Black	80.4	2.4	0.5	Black	104.7	1.2
0.2	IRT	85.9	2.2	0.5	IRT	102.3	1.3
0.2	Bare soil	117.6	1.6	0.5	Bare soil	124.9	1.0
1.5	Black	73.3	2.6	1.5	Black	93.5	1.4
1.5	IRT	76.3	2.5	1.5	IRT	96.3	1.3
1.5	Bare soil	103.4	1.8	1.5	Bare soil	110.0	1.2
4.0	Black	65.0	2.9	2.5	Black	86.2	1.5
4.0	IRT	67.6	2.8	2.5	IRT	89.0	1.5
4.0	Bare soil	94.6	2.0	2.5	Bare soil	100.1	1.3
6.5	Black	50.1	3.8	3.5	Black	78.1	1.7
6.5	IRT	49.6	3.8	3.5	IRT	81.1	1.6
6.5	Bare soil	76.7	2.5	3.5	Bare soil	91.1	1.4
9.0	Black	38.1	5.0	4.5	Black	71.0	1.8
9.0	IRT	39.8	4.8	4.5	IRT	73.2	1.8
9.0	Bare soil	57.8	3.3	4.5	Bare soil	87.8	1.5
A) Salinity							
0.2		94.6	2.0	0.5		110.6	1.2
1.5		84.3	2.3	1.5		100.0	1.3
4.0		75.7	2.5	2.5		91.8	1.4
6.5		58.8	3.2	3.5		83.4	1.6
9.0		45.3	4.2	4.5		77.3	1.7
B) Mulch							
Black		61.4	3.1	Black		86.7	1.5
IRT		63.8	3.0	IRT		88.4	1.5
Bare soil		90.0	2.1	Bare soil		102.8	1.3

[(z)] For a period of 183 days (Experiment 1) or 180 days (Experiment 2). The volume of water needed to increased volumetric water content up to field capacity from 40% depletion of the plant available water was 1.04 L/plant (Experiment 1) or from 30% depletion of the plant available water was 0.72 L/plant (Experiment 2).
[(y)] Calculated as [183 days/(I/1.04)] (Experiment 1), or [180 days/(I/0.72)] (Experiment 2)

Table 3.4 Effect of varying levels of saline water ($dS \cdot m^{-1}$) and polyethylene mulch on soil salinity.

Treatment	Experiment 1	$EC_{1:5}$ [(z)] ($dS \cdot m^{-1}$)	Experiment 2	$EC_{1:5}$ ($dS \cdot m^{-1}$)
A) Salinity		**		**
	0.2	0.77 e	0.5	0.96 d
	1.5	2.57 d	1.5	2.26 c
	4.0	3.89 c	2.5	2.33 c
	6.5	5.07 b	3.5	2.75 b
	9.0	6.05 a	4.5	3.56 a
B) Mulch		**		**
	Black	3.16 c	Black	1.42 b
	IRT	3.57 b	IRT	1.41 b
	Bare soil	4.28 a	Bare soil	4.29 a
C) Depth (cm)		**		**
	0-7	4.98 a	0-7	2.69 a
	7-14	2.97 b	7-14	2.27 b
	14-21	3.06 b	14-21	2.14 b
A x B		**		**
A x C		**		NS
B x C		**		**
A x B x C		**		*

[(z)] Electrical conductivity of soil/water extracts 1:5 ratio
*, ** Significant at $P \leq 0.05$ and $P \leq 0.01$, respectively; NS, not significant.
Means not associated with the same letter are significantly different (Tukey P=0.05).

Table 3.5 Effect of varying levels of saline water ($dS \cdot m^{-1}$) and polyethylene mulch on the fresh weights of roots, stems, leaves, fruits and shoots; fresh root to shoot (R/S) ratio; and harvest index (HI) of bell pepper (*Capsicum annuum* L. var. Red Knight X3R).

Treatment	Fresh weight (g/plant)					R/S ratio [y]	HI
	Roots	Shoots	Stems	Leaves	Fruits [z]		
A) Salinity	**	**	**	**	**	*	**
0.2	133.7 a	1183.0 a	85.7 ab	111.5 a	985.8 a	0.11 ab	0.53 a
1.5	105.6 a	1080.1 a	99.7 a	121.1 a	859.2 b	0.10 ab	0.46 ab
4.0	57.4 b	732.0 b	79.5 ab	71.8 b	580.9 c	0.08 b	0.31 b
6.5	31.1 bc	381.0 c	72.9 bc	44.1 c	264.0 d	0.11 ab	0.10 c
9.0	20.3 c	174.4 d	58.2 c	21.0 d	95.2 e	0.14 a	0.11 c
B) Mulch	NS	NS	**	NS	NS	NS	**
Black	62.1	775.3	86.3 a	89.0	600.0	0.09	0.36 b
IRT	70.5	772.1	91.2 a	94.5	586.4	0.10	0.33 b
Bare soil	76.3	729.8	75.4 b	86.7	567.7	0.11	0.41 a
A x B	NS	NS	NS	NS	NS	NS	NS

[z] Mature and immature fruits are included
[y] Calculations were made only with the four plants per treatment sampled for root measurements
*, ** Significant at $P \leq 0.05$ and $P \leq 0.01$, respectively; NS, not significant.
Means not associated with the same letter are significantly different (Tukey P=0.05).

Table 3.6 Effect of varying levels of saline water ($dS \cdot m^{-1}$) and polyethylene mulch on leaf characteristics and dry weight of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) plants.

Treatment	Leaf area (cm^2/plant)	Number of leaves/plant	Leaf size (cm^2)	Dry weight (g/plant)			
				Roots	Stems	Leaves	Immature Fruits [(z)]
A) Salinity	**	**	**	**	**	**	**
0.2	3160 a	138 a	23.5 ab	18.5 a	20.7 a	21.8 a	12.8 a
1.5	3969 a	142 a	28.8 a	16.2 a	22.5 a	22.6 a	11.9 a
4.0	2130 b	110 b	19.6 b	8.6 b	15.0 b	12.9 b	7.7 b
6.5	796 c	99 b	8.1 c	4.5 bc	9.8 c	6.2 c	1.9 c
9.0	586 c	37 c	17.8 b	3.3 c	8.2 c	3.3 c	0.1 c
B) Mulch	*	NS	NS	*	**	**	*
Black	2827 a	126	23.0	8.4 b	15.5 a	13.2 ab	7.6 ab
IRT	3047 a	124	24.2	10.0 ab	16.9 a	15.1 a	7.8 a
Bare soil	2135 b	111	21.2	12.2 a	13.3 b	11.8 b	5.4 b
A x B	NS	NS	NS	*	NS	NS	NS

[(z)] Immature fruits at final harvest
*, ** Significant at P≤0.05 and P≤0.01, respectively; NS, not significant.
Means not associated with the same letter are significantly different (Tukey P=0.05).

Table 3.7 Effect of varying levels of saline water ($dS \cdot m^{-1}$) and polyethylene mulch on total and marketable yield of bell pepper (*Capsicum annuum* L. var. Red Knight X3R).

Treatment	Total yield		Marketable [(z)]		
	Mature fruits (g/plant)	Immature fruits (g/plant)	Yield (g/plant)	% Grade 1 yield	Mean fruit weight (g)
A) Salinity	**	**	**	**	**
0.2	776.8 a	209.0 a	622.5 a	67 a	115.5 a
1.5	717.4 a	141.8 b	492.8 b	74 a	115.7 a
4.0	490.6 b	90.3 b	228.9 c	62 a	101.1 a
6.5	219.8 c	44.2 c	38.1 d	17 b	34.1 b
9.0	87.6 d	7.6 d	19.7 d	0 b	19.6 b
B) Mulch	NS	*	NS	NS	NS
Black	465.0	134.6 a	283.7	33	81.7
IRT	445.8	140.6 a	256.2	28	77.0
Bare soil	464.9	102.8 b	301.3	25	72.9
A x B	NS	NS	NS	NS	NS

[(z)] Marketable fruit = grades 1 and 2.
*, ** Significant at $P \leq 0.05$ and $P \leq 0.01$, respectively; NS, not significant.
Means not associated with the same letter are significantly different (Tukey P=0.05).

Table 3.8 Effect of varying levels of saline water ($dS \cdot m^{-1}$) and polyethylene mulch on the number of total and marketable fruit of bell pepper (*Capsicum annuum* L. var. Red Knight X3R).

Treatment	Total number of fruit/plant		Marketable [z] number of fruit/plant	
	Mature	Immature	Total	% grade 1
A) Salinity	**	**	**	**
0.2	9.0 a	6.0 a	5.5 a	61 a
1.5	8.8 a	5.0 ab	4.3 b	68 a
4.0	7.8 a	4.0 b	2.1 c	57 a
6.5	5.5 b	1.0 c	0.4 d	17 b
9.0	2.2 c	0.2 c	0.2 d	0 c
B) Mulch	NS	*	NS	*
Black	6.6	4.0 a	2.4	45 a
IRT	6.8	4.0 a	2.3	45 a
Bare soil	6.5	2.0 b	2.8	32 b
A x B	NS	NS	NS	NS

[z] Marketable fruit = grades 1 and 2.
*, ** Significant at $P \leq 0.05$ and $P \leq 0.01$, respectively; NS, not significant.
Means not associated with the same letter are significantly different (Tukey P=0.05).

Table 3.9 Effects of varying levels of saline water ($dS \cdot m^{-1}$) and polyethylene mulch on characteristics of marketable [(z)] fruit of bell pepper (*Capsicum annuum* L. var. Red Knight X3R).

	Length (cm)	Width (cm)	Equatorial perimeter (cm)	Locule number/fruit	Pericarp thickness (mm)	Total soluble solids (Brix %)
A) Salinity	**	NS	NS	NS	*	**
0.2	6.22 a	6.81	23.43	3.6	5.7 a	7.54 d
1.5	6.49 a	6.73	23.21	3.7	5.4 ab	8.36 cd
4.0	5.79 a	6.55	26.83	3.7	5.3 ab	8.88 bc
6.5	5.88 a	6.39	22.55	3.7	4.6 b	9.58 ab
9.0	5.04 b	6.50	22.26	4.0	5.1 b	10.36 a
B) Mulch	NS	NS	NS	NS	*	NS
Black	6.15	6.74	23.06	3.7	5.6 a	8.43
IRT	6.07	6.69	23.24	3.7	5.5 ab	8.64
Bare soil	6.02	6.53	26.11	3.6	5.1 b	8.34
A x B	NS	NS	NS	NS	NS	*

[(z)] Marketable fruit = grades 1 and 2.
*, ** Significant at $P \leq 0.05$ and $P \leq 0.01$, respectively; NS, not significant.
Means not associated with the same letter are significantly different (Tukey P=0.05).

Table 3.10 Effect of varying levels of saline water ($dS \cdot m^{-1}$) and polyethylene mulch on the agronomic water use efficiency (WUE_a) to produce total and marketable yield of bell pepper (*Capsicum annuum* L. var. Red Knight X3R).

Treatment	WUE_a ($g \cdot L^{-1}$)	
	Total yield [(z)]	Marketable yield
A) Salinity	**	**
0.2	10.7 a	6.8 a
1.5	10.5 a	5.9 a
4.0	8.0 b	3.1 b
6.5	4.2 c	0.7 c
9.0	2.1 d	0.5 c
B) Mulch	**	*
Black	8.2 a	3.9 a
IRT	7.7 a	3.4 ab
Bare soil	5.3 b	2.9 b
A x B	NS	NS

[(z)] Mature and immature fruits are included.
*, ** Significant at $P \leq 0.05$ and $P \leq 0.01$, respectively; NS, not significant.
Means not associated with the same letter are significantly different (Tukey P=0.05).

Table 3.11 Effect of varying levels of saline water (dS·m^{-1}) and polyethylene mulch on the fresh weight of roots, stems leaves, fruits and shoots; fresh root to shoot (R/S) ratio; and harvest index (HI) of bell pepper (*Capsicum annuum* L. var. Red Knight X3R).

Treatment	Fresh weight (g/plant)					R/S ratio [y]	HI
	Roots	Shoots	Stems	Leaves	Fruits [z]		
A) Salinity	**	**	**	**	**	NS	**
0.5	172.6 a	1478.6 a	127.3 a	135.5 a	1215.8 a	0.12	0.60 a
1.5	120.8 b	1099.1 b	121.7 a	123.5 a	853.9 b	0.12	0.50 ab
2.5	85.0 c	957.7 b	113.1 ab	108.3 ab	736.3 b	0.11	0.41 bc
3.5	73.4 cd	650.1 c	97.9 bc	77.8 bc	474.4 c	0.15	0.36 cd
4.5	55.7 d	641.9 c	86.1 c	63.2 c	492.6 c	0.10	0.32 d
B) Mulch	*	*	**	NS	NS	**	NS
Black	91.1 b	1000.1 a	116.2 a	96.8	787.1	0.10 b	0.48
IRT	102.0 ab	1028.4 a	126.0 a	112.1	790.3	0.11 b	0.50
Bare soil	111.4 a	867.9 b	85.5 b	96.0	686.4	0.15 a	0.43
A x B	*	NS	NS	NS	NS	NS	NS

[z] Mature and immature fruits are included
[y] Calculations were made only with the four plants per treatment sampled for root measurements
*, ** Significant at P≤0.05 and P≤0.01, respectively; NS, not significant.
Means not associated with the same letter are significantly different (Tukey P=0.05).

Table 3.12 Effect of varying levels of saline water ($dS \cdot m^{-1}$) and polyethylene mulch on leaf characteristics and dry weight of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) plants.

Treatment	Leaf area (cm^2/plant)	Number of leaves/plant	Leaf size (cm^2)	Dry weight (g/plant)			
				Roots	Stems	Leaves	Immature Fruits [(z)]
A) Salinity	**	**	**	**	**	**	**
0.5	4574 ab	166 a	27.9 b	26.77 a	26.42 a	30.81 a	4.78 a
1.5	5290 a	171 a	31.8 b	19.05 b	26.50 a	31.94 a	4.71 a
2.5	4983 ab	157 a	32.2 b	13.46 c	24.35 ab	28.14 ab	4.06 ab
3.5	4193 bc	126 b	33.1 b	11.51 c	20.08 bc	23.05 bc	3.91 ab
4.5	3108 c	65 c	49.6 a	6.79 d	19.53 c	18.34 c	3.66 b
B) Mulch	**	*	**	*	**	**	NS
Black	5194 a	142 a	39.6 a	14.27 b	24.57 a	28.43 a	4.23
IRT	4880 a	141 a	37.2 a	14.66 b	25.91 a	28.65 a	4.26
Bare soil	3215 b	129 b	28.1 b	17.61 a	19.64 b	22.28 b	4.17
A x B	NS	NS	NS	NS	NS	NS	NS

[(z)] Immature fruits attached to plants at final harvest of plants
*, ** Significant at $P \leq 0.05$ and $P \leq 0.01$, respectively; NS, not significant.
Means not associated with the same letter are significantly different (Tukey P=0.05).

Table 3.13 Effect of varying levels of saline water ($dS \cdot m^{-1}$) and polyethylene mulch on total and marketable yield of bell pepper (*Capsicum annuum* L. var. Red Knight X3R).

	Total yield		Marketable [z]		
Treatment	Mature fruits (g/plant)	Immature fruits (g/plant)	Yield (g/plant)	% Grade 1 yield	Mean fruit weight (g)
A) Salinity	**	**	**	**	**
0.5	1139.0 a	76.8 a	892.8 a	80 a	120.3 a
1.5	791.0 b	62.9 b	549.0 b	78 a	116.9 a
2.5	692.1 b	44.2 c	395.4 c	71 ab	115.2 a
3.5	433.1 c	41.3 c	236.3 d	61 ab	98.5 b
4.5	459.2 c	33.4 c	206.3 d	53 b	93.7 b
B) Mulch	NS	NS	**	**	**
Black	736.3	50.8	483.6 a	75 a	113.6 a
IRT	737.1	53.2	514.3 a	72 a	114.9 a
Bare soil	635.3	51.1	369.9 b	59 b	98.2 b
A x B	NS	NS	*	NS	NS

[z] Marketable fruit = grades 1 and 2.
*, ** Significant at $P \leq 0.05$ and $P \leq 0.01$, respectively; NS, not significant.
Means not associated with the same letter are significantly different (Tukey P=0.05).

Table 3.14 Effect of varying levels of saline water ($dS \cdot m^{-1}$) and polyethylene mulch on total and marketable [(z)] number of bell pepper (*Capsicum annuum* L. var. Red Knight X3R).

Treatment	Total number of fruits/plant		Marketable number of fruits/plant	
	Mature	Immature	Total	% Grade 1
A) Salinity	**	**	**	*
0.5	12.0 a	1.9 ab	7.5 a	74 a
1.5	9.0 b	2.0 a	4.7 b	71 a
2.5	8.8 b	1.4 bc	3.5 c	65 ab
3.5	5.8 c	1.4 bc	2.3 d	58 ab
4.5	6.6 c	1.3 c	2.0 d	50 b
B) Mulch	NS	NS	**	*
Black	8.7	1.5	4.2 a	69 a
IRT	8.6	1.7	4.4 a	67 a
Bare soil	8.0	1.6	3.5 b	55 b
A x B	NS	NS	NS	NS

[(z)] Marketable fruit = grades 1 and 2.
*, ** Significant at P≤0.05 and P≤0.01, respectively; NS, not significant.
Means not associated with the same letter are significantly different (Tukey P=0.05).

Table 3.15 Effects of varying levels of saline water ($dS \cdot m^{-1}$) and polyethylene mulch on characteristics of marketable [z] fruit of bell pepper (*Capsicum annuum* L. var. Red Knight X3R).

	Length (cm)	Width (cm)	Locule number/fruit	Pericarp thickness (mm)	Total soluble solids (Brix %)
A) Salinity	NS	*	NS	**	**
0.5	6.62	6.38 a	3.7	5.4 a	8.92 b
1.5	6.78	6.10 ab	3.7	4.9 ab	10.47 ab
2.5	6.33	6.29 a	3.6	4.7 ab	10.82 a
3.5	6.24	6.12 ab	4.0	4.5 ab	10.58 ab
4.5	6.31	5.93 b	3.8	3.8 b	11.20 a
B) Mulch	NS	*	NS	NS	*
Black	6.45	6.13 ab	3.8	4.9	10.36 ab
IRT	6.52	6.33 a	3.8	4.8	10.85 a
Bare soil	6.42	6.04 b	3.8	5.0	9.62 b
A x B	NS	NS	NS	NS	NS

[z] Marketable fruit = grades 1 and 2.
*, ** Significant at $P \leq 0.05$ and $P \leq 0.01$, respectively; NS, not significant.
Means not associated with the same letter are significantly different (Tukey P=0.05).

Table 3.16 Effect of varying levels of saline water ($dS{\cdot}m^{-1}$) and polyethylene mulch on the agronomic water use efficiency (WUE_a) to produce total and marketable yield of bell pepper (*Capsicum annuum* L. var. Red Knight X3R).

Treatment	WUE_a ($g{\cdot}L^{-1}$)	
	Total yield [z]	Marketable yield
A) Salinity	**	**
0.5	11.2 a	8.2 a
1.5	8.6 b	5.6 b
2.5	8.1 b	4.4 b
3.5	5.7 c	2.9 c
4.5	6.5 c	2.8 c
B) Mulch	**	*
Black	8.7 a	5.2 a
IRT	8.7 a	5.6 a
Bare soil	6.5 b	3.4 b
A x B	NS	*

[z] Mature and immature fruits are included.
*, ** Significant at P≤0.05 and P≤0.01, respectively; NS, not significant.
Means not associated with the same letter are significantly different (Tukey P=0.05).

Figure 3.1 Soil temperature as affected by black or green infrared-transmitting (IRT) polyethylene mulch and bare soil at different bell pepper growth stages [(z)]. Means ±SEM (n=30) were averaged across salinity levels and depths.

[(z)] A) 7 days after transplanting (DAT) (vegetative growth stage), B) 25 DAT (flowering), C) 45 DAT (fruit development), and D) 105 DAT (fruit harvest).

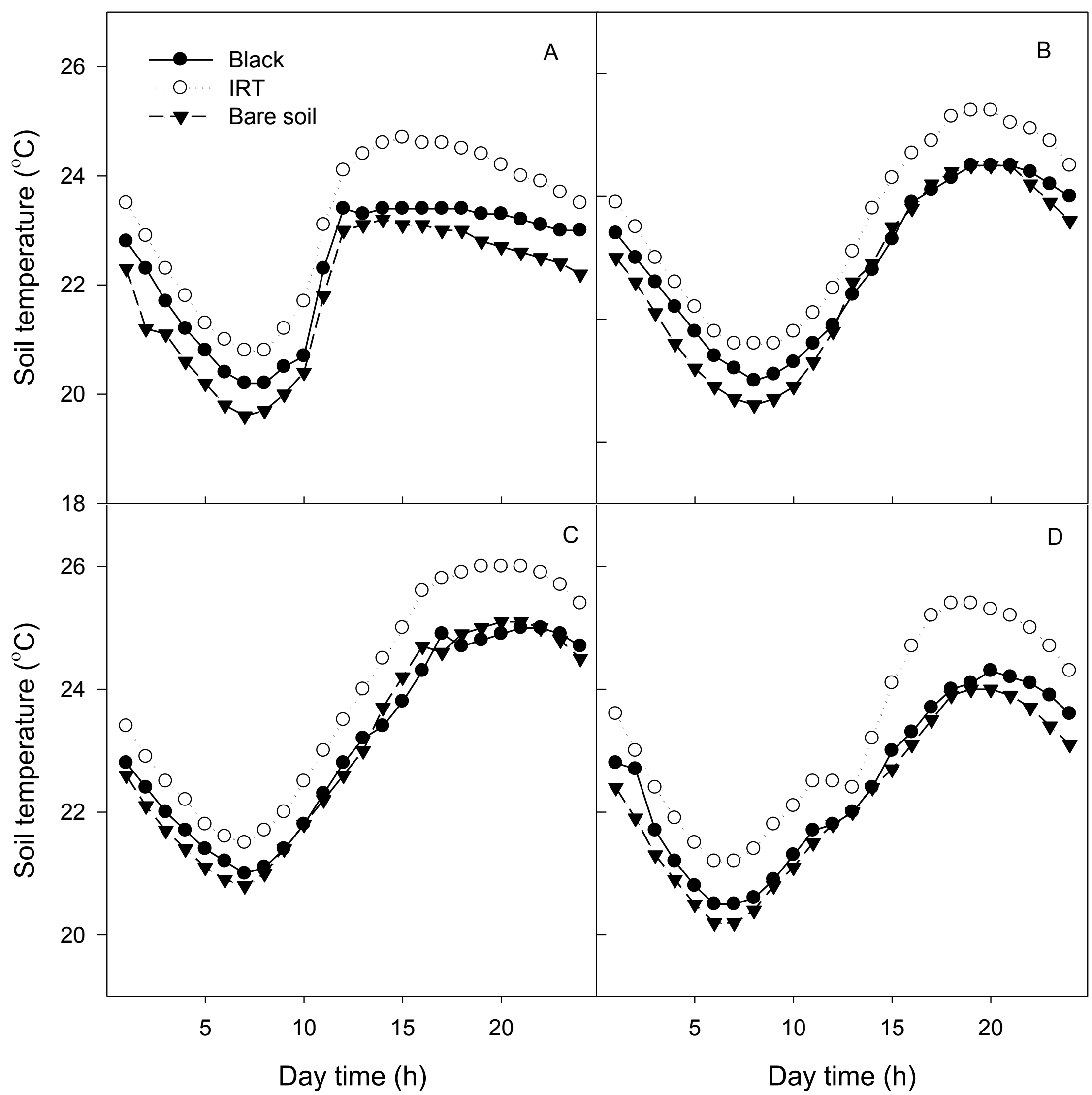


Figure 3.2 Soil temperature as affected by black or green infrared-transmitting (IRT) polyethylene mulch and bare soil. Means ±SEM (n=30) were averaged across salinity levels and depths throughout the season.

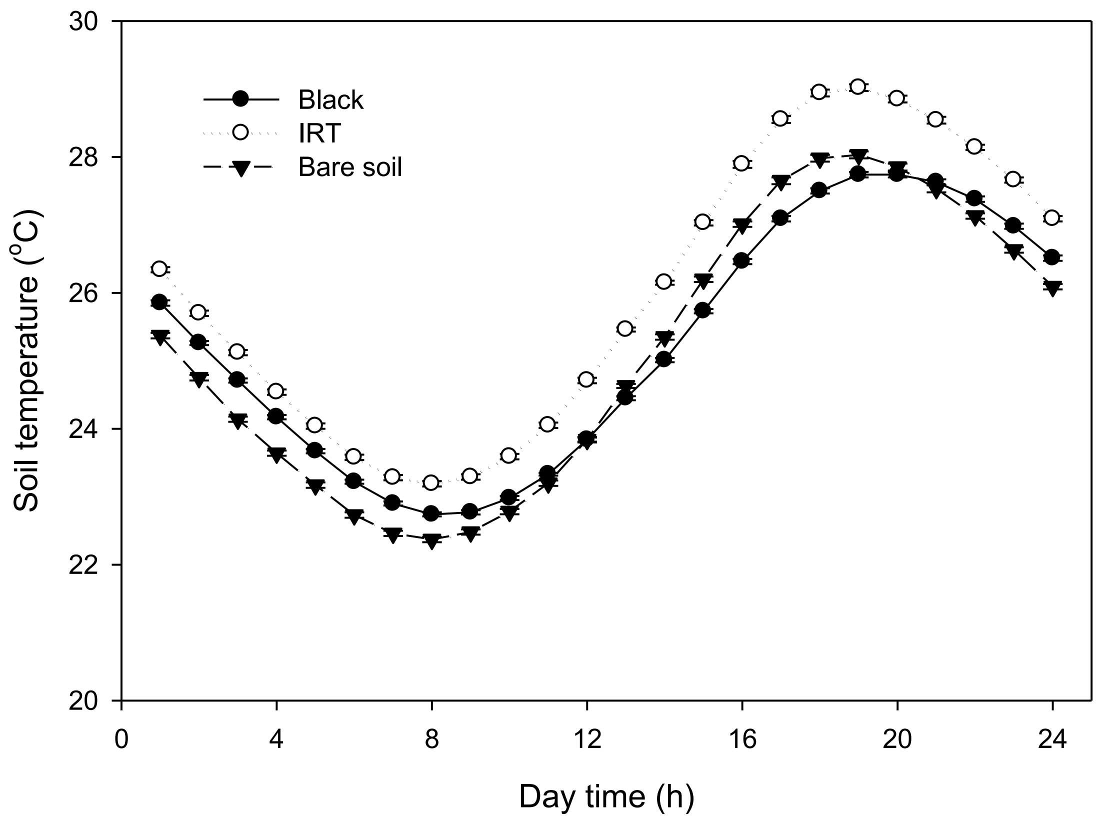


Figure 3.3 Soil salinity (electrical conductivity of soil/water extracts 1:5 ratio, $EC_{1:5}$) as affected by varying levels of saline water ($dS{\cdot}m^{-1}$) at different soil depths. Means ±SEM (n=9) were averaged across mulch levels.

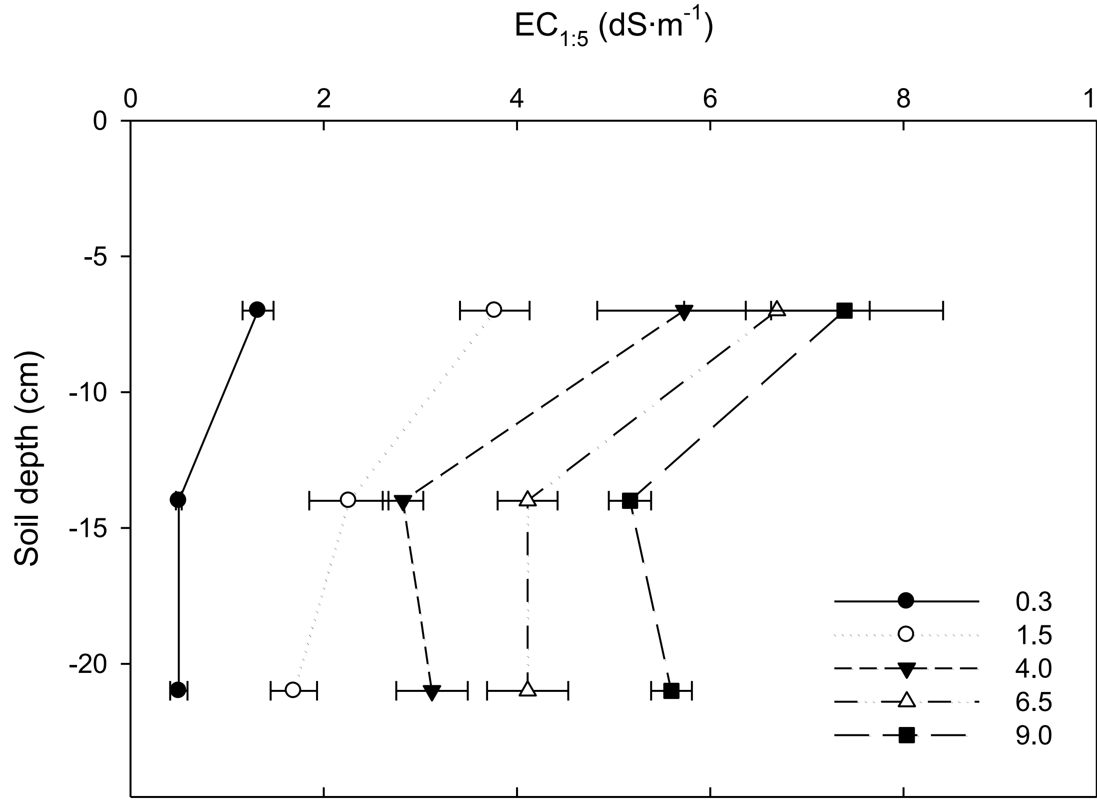


Figure 3.4 Soil salinity (electrical conductivity of soil/water extracts 1:5 ratio, $EC_{1:5}$) as affected by black or green infrared-transmitting (IRT) polyethylene mulch and bare soil at different soil depths. Means ±SEM (n=15) were averaged across saline water levels (0.5-4.5 $dS \cdot m^{-1}$).

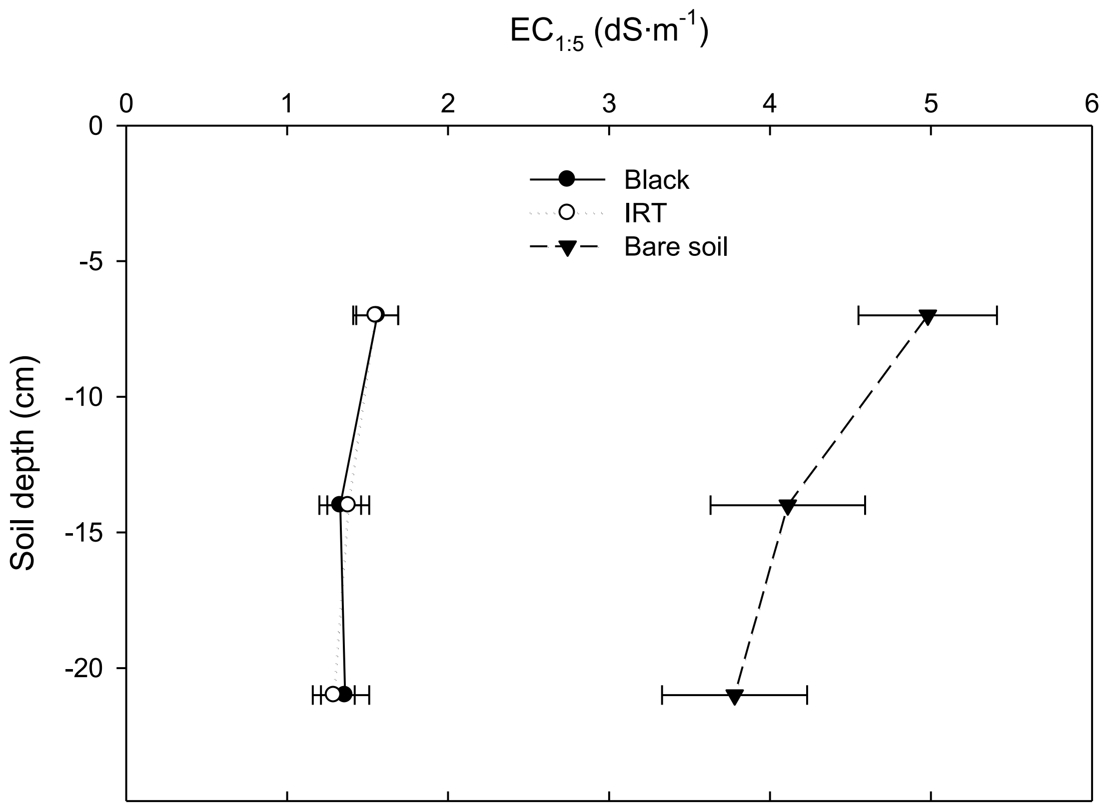


Figure 3.5 Stomatal conductance of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) as affected by varying levels of saline water (dS·m^{-1}). Means ±SEM (n=9) were averaged across mulch levels.

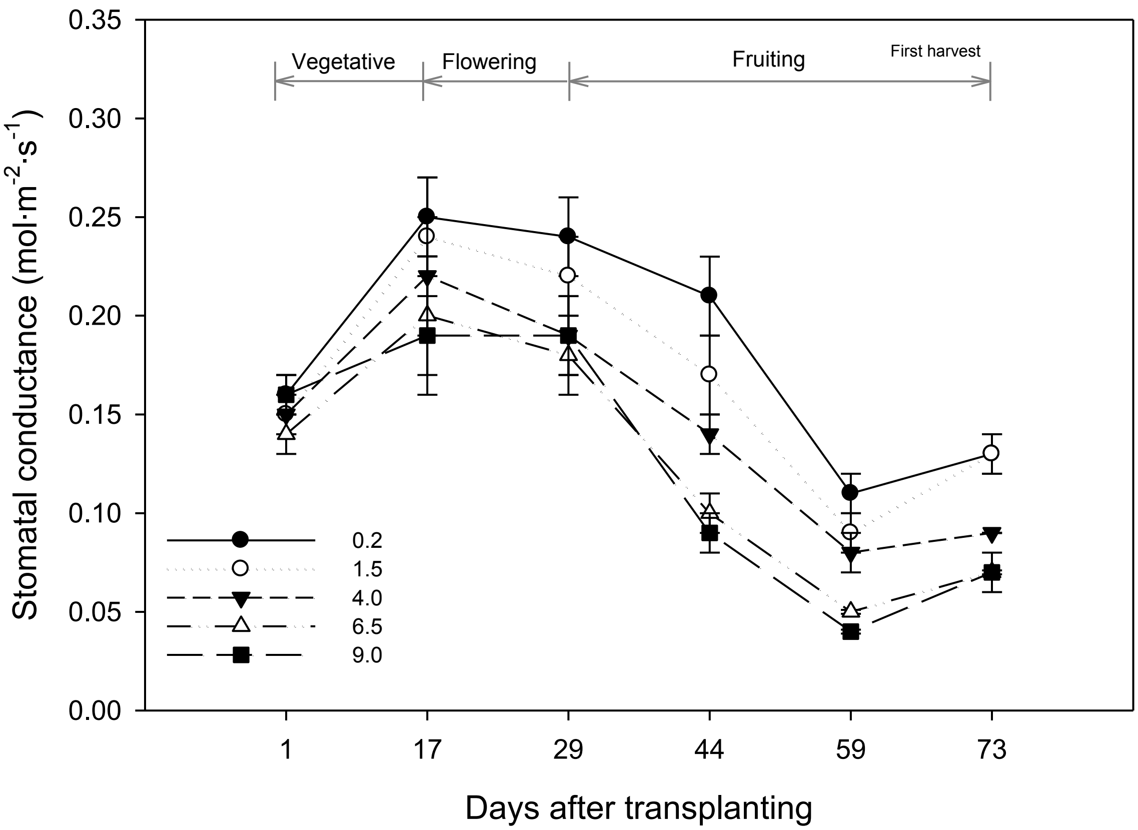


Figure 3.6 Transpiration of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) as affected by varying levels of saline water ($dS{\cdot}m^{-1}$). Means ±SEM (n=9) were averaged across mulch levels.

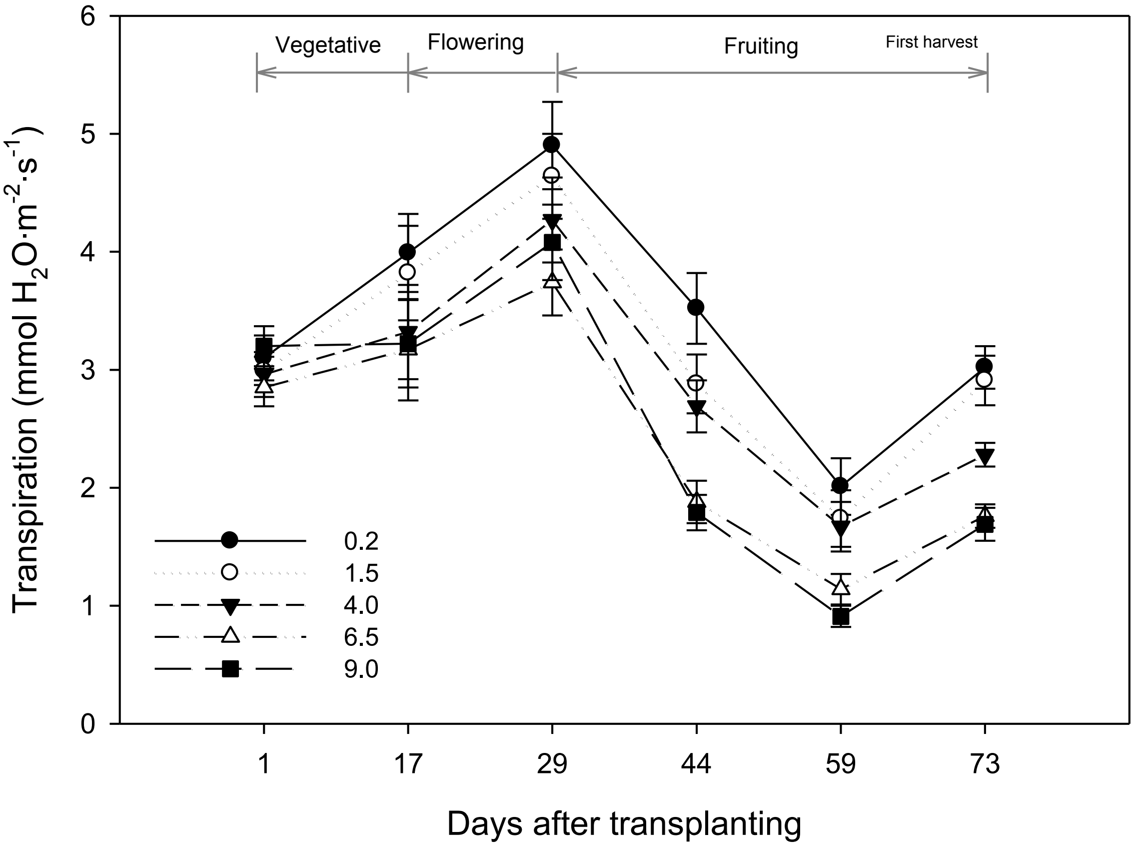


Figure 3.7 Photosynthesis of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) as affected by varying levels of saline water ($dS \cdot m^{-1}$). Means ±SEM (n=9) were averaged across mulch levels.

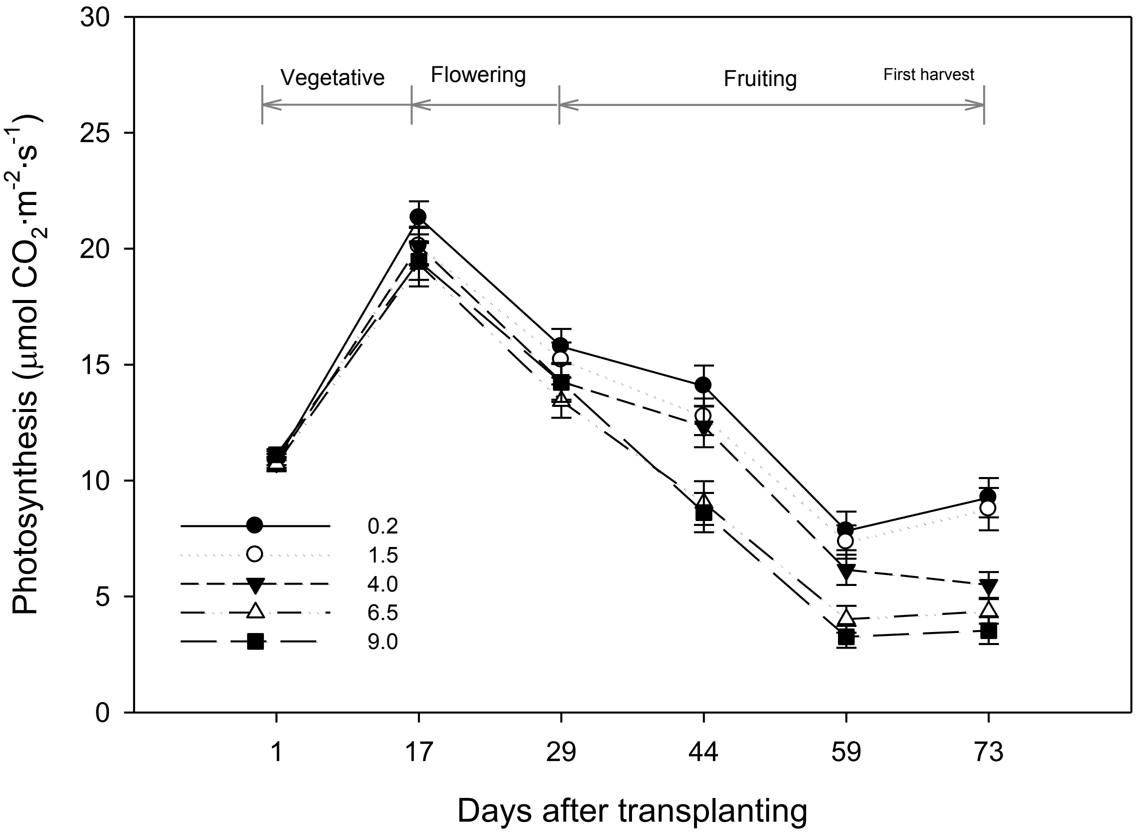


Figure 3.8 Stomatal conductance of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) as affected by black or green infrared-transmitting (IRT) polyethylene mulch and bare soil. Means ±SEM (n=15) were averaged across saline water levels.

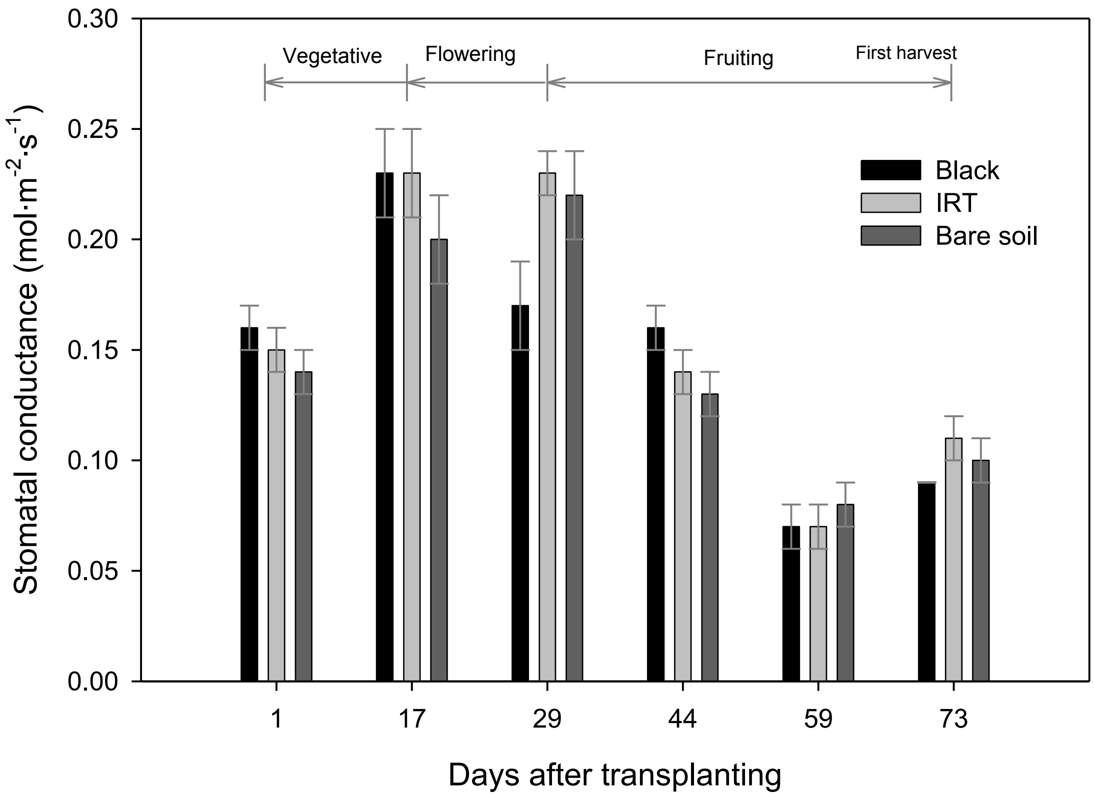


Figure 3.9 Transpiration of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) as affected by black or green infrared-transmitting (IRT) polyethylene mulch and bare soil. Means ±SEM (n=15) were averaged across saline water levels.

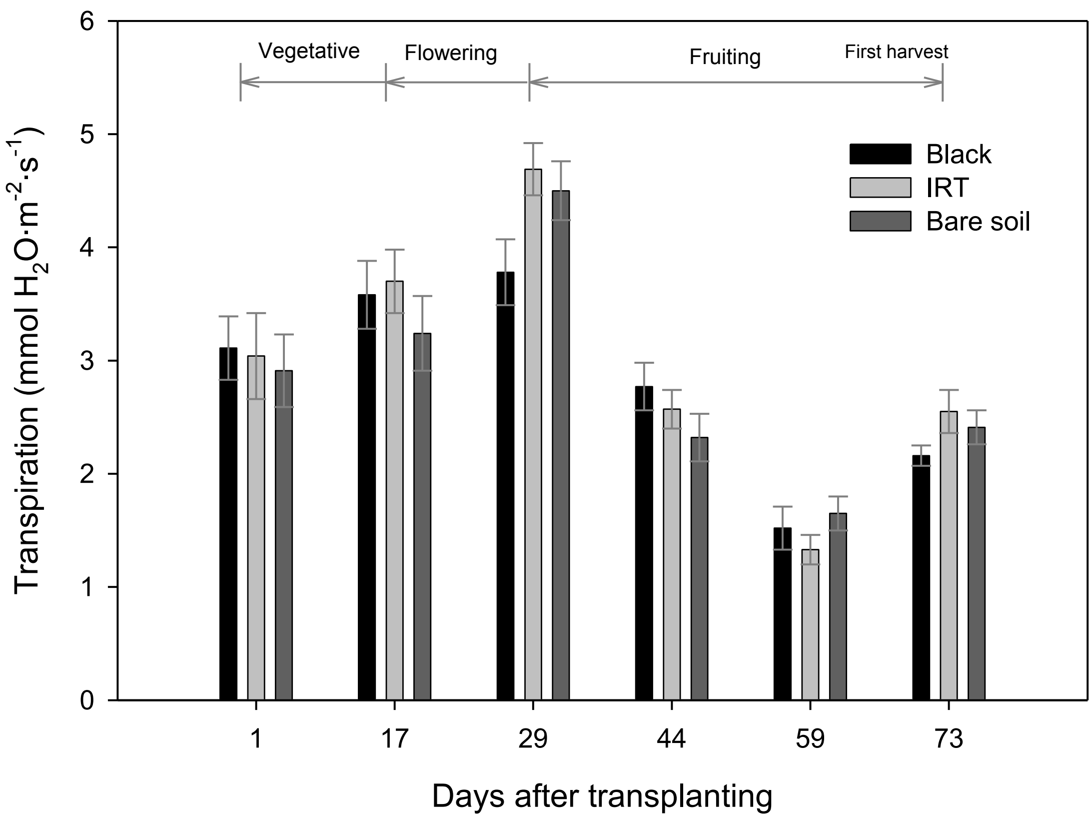


Figure 3.10 Photosynthesis of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) as affected by black or green infrared-transmitting (IRT) polyethylene mulch and bare soil. Means ±SEM (n=15) were averaged across saline water levels.

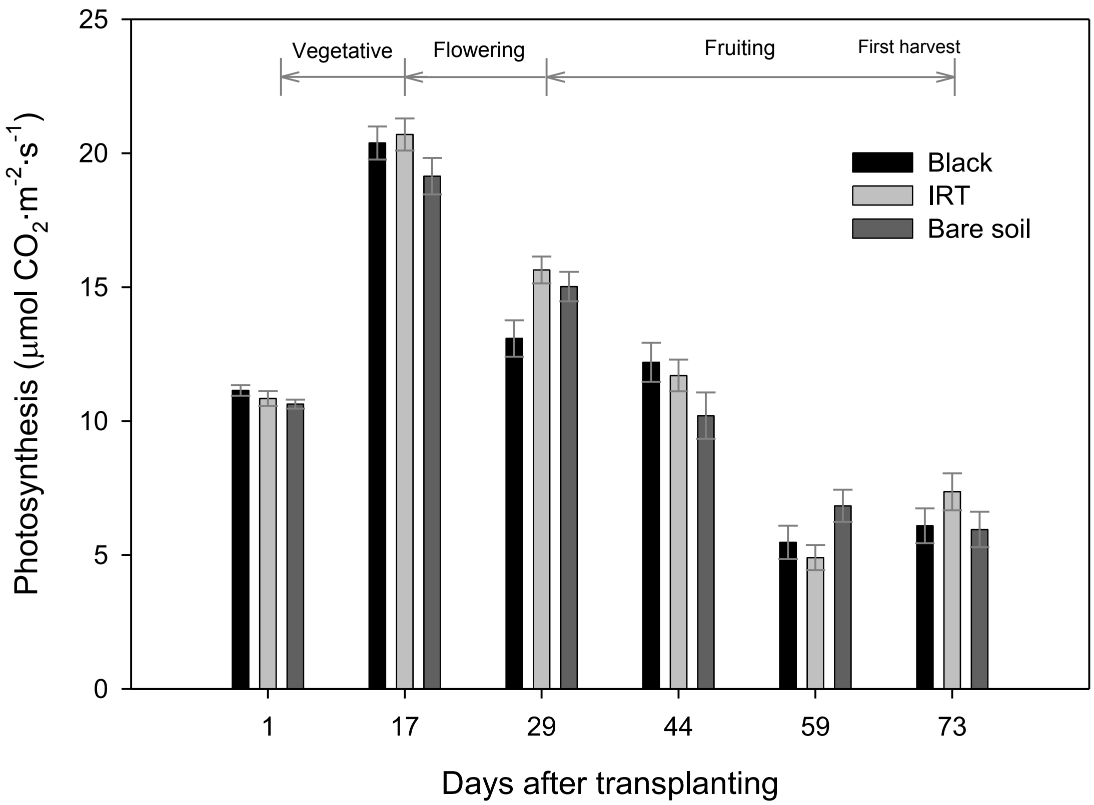


Figure 3.11 Root dry weight of bell pepper (Capsicum annuum L. var. Red Knight X3R) plants as affected by black or green infrared-transmitting (IRT) polyethylene mulch and bare soil over varying levels of saline water. Means ±SEM (n=4).

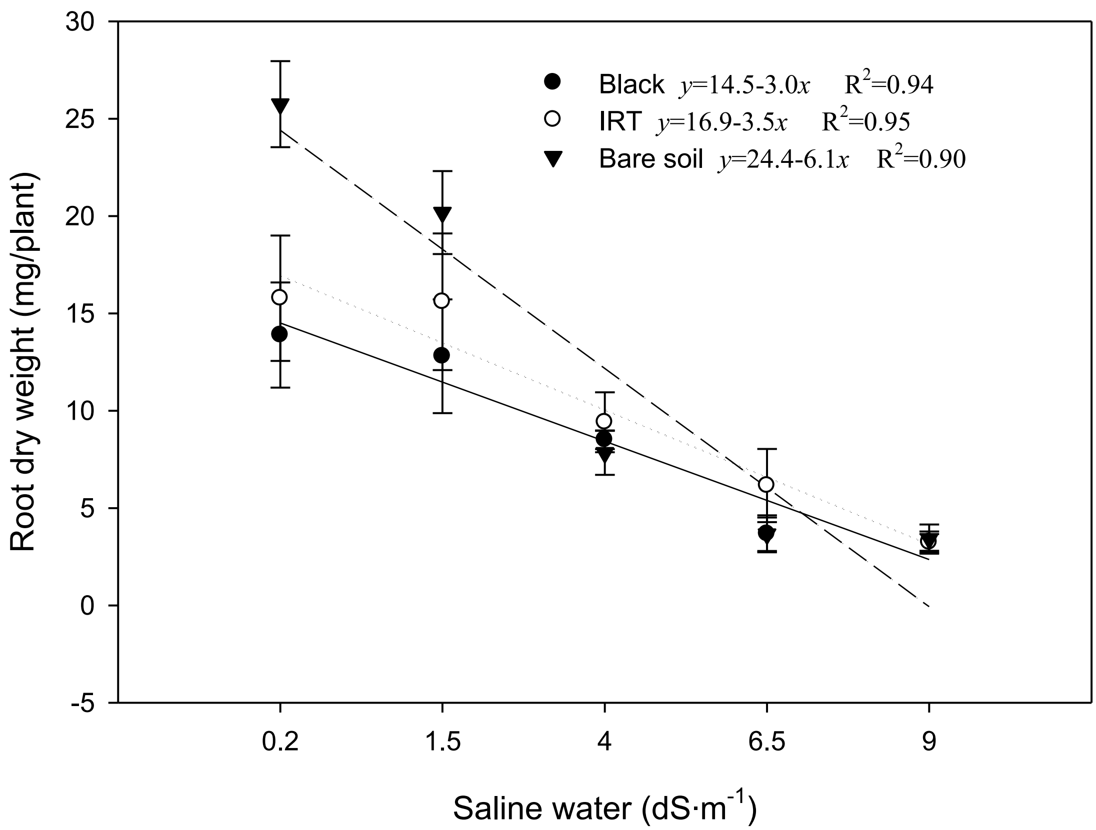


Figure 3.12 Cumulative early marketable yield of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) as affected by varying levels of saline water ($dS \cdot m^{-1}$). Means ±SEM (n=24) were averaged across mulch levels.

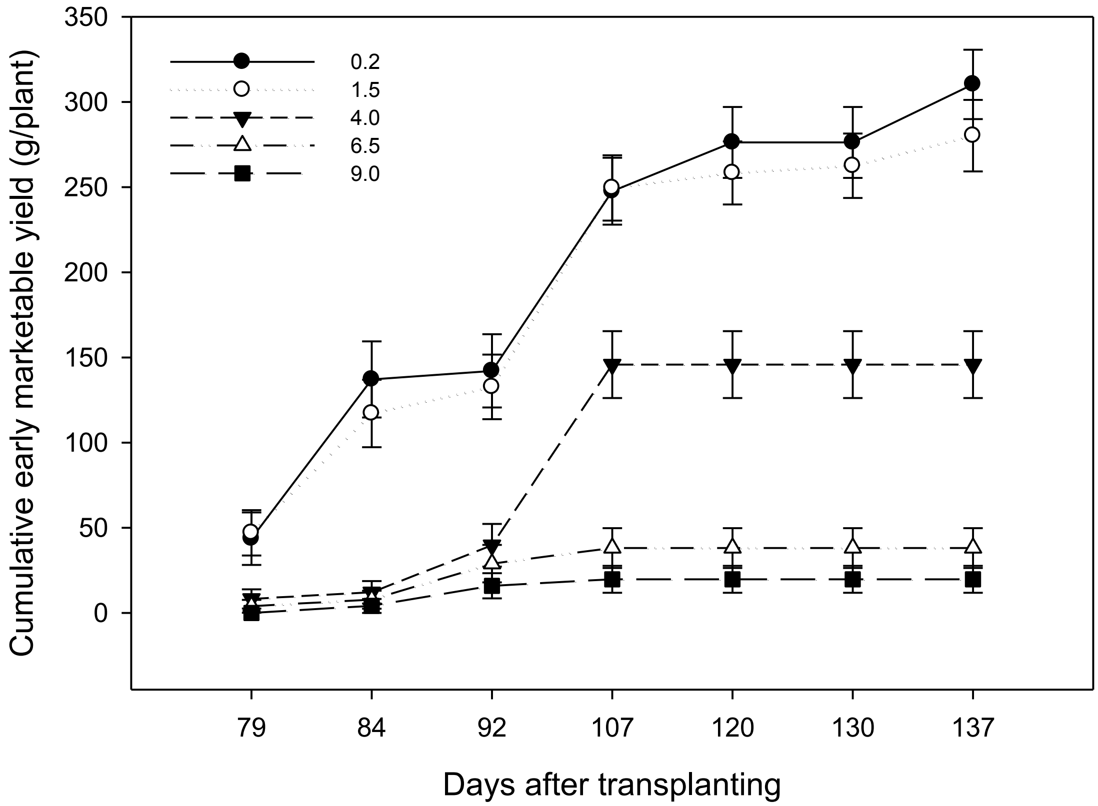


Figure 3.13 Cumulative early marketable yield of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) as affected by black or green infrared-transmitting (IRT) polyethylene mulch and bare soil. Means ±SEM (n=40) were averaged across saline water levels.

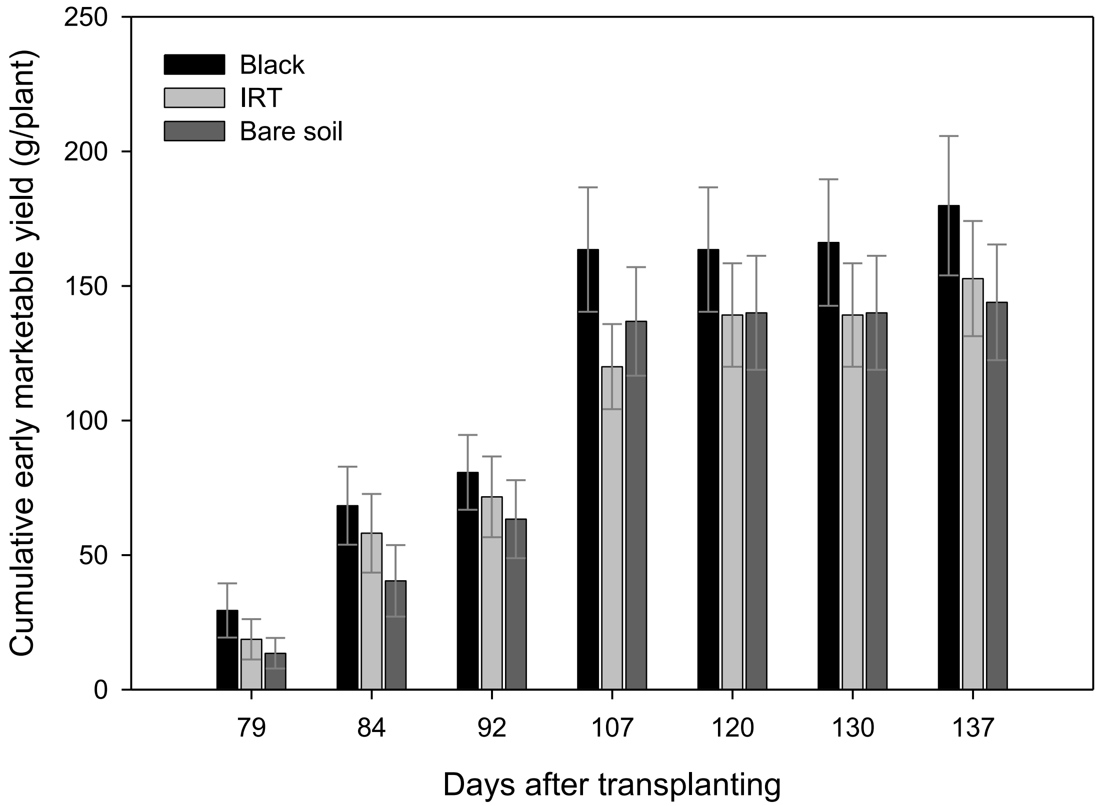


Figure 3.14 Total soluble solids (Brix, %) of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) marketable fruits as affected by black or green infrared-transmitting (IRT) polyethylene mulch and bare soil over varying levels of saline water. Means ±SEM (n=8).

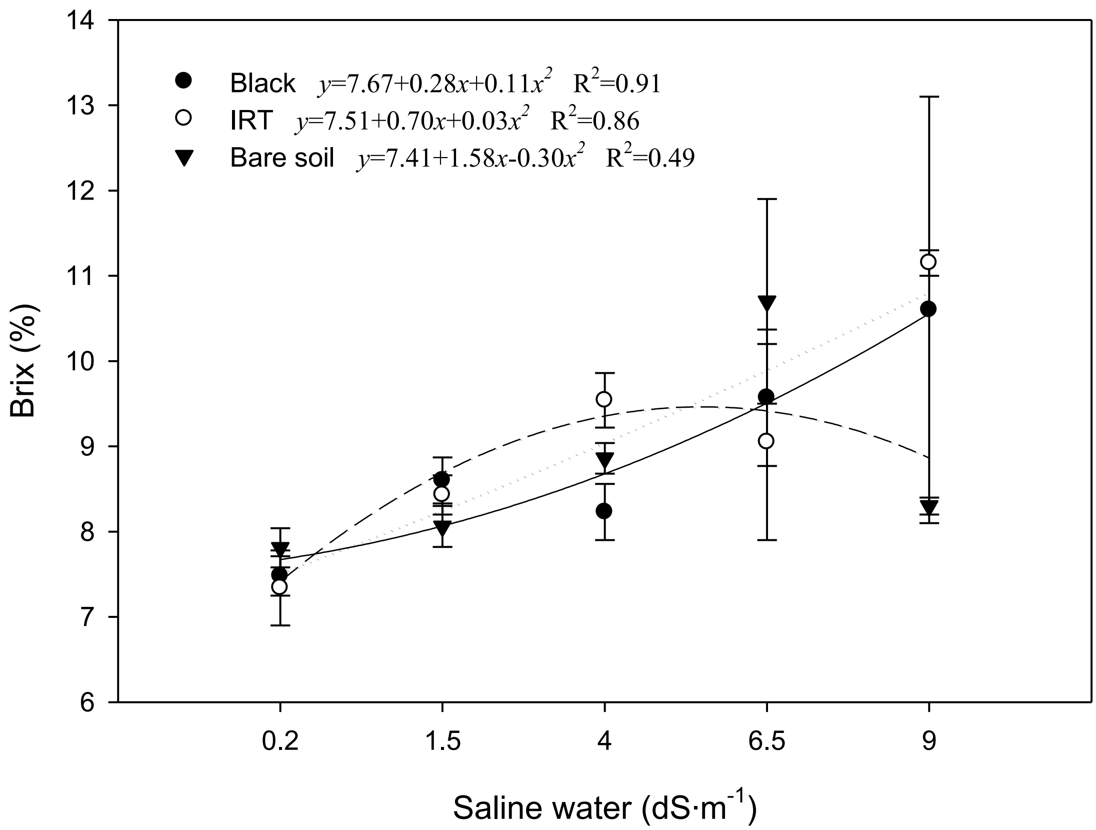


Figure 3.15 A) Stomatal conductance, B) transpiration, and C) photosynthesis of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) at fruiting growth stage as affected by varying levels of saline water. Means ±SEM (n=9) were averaged across mulch levels.

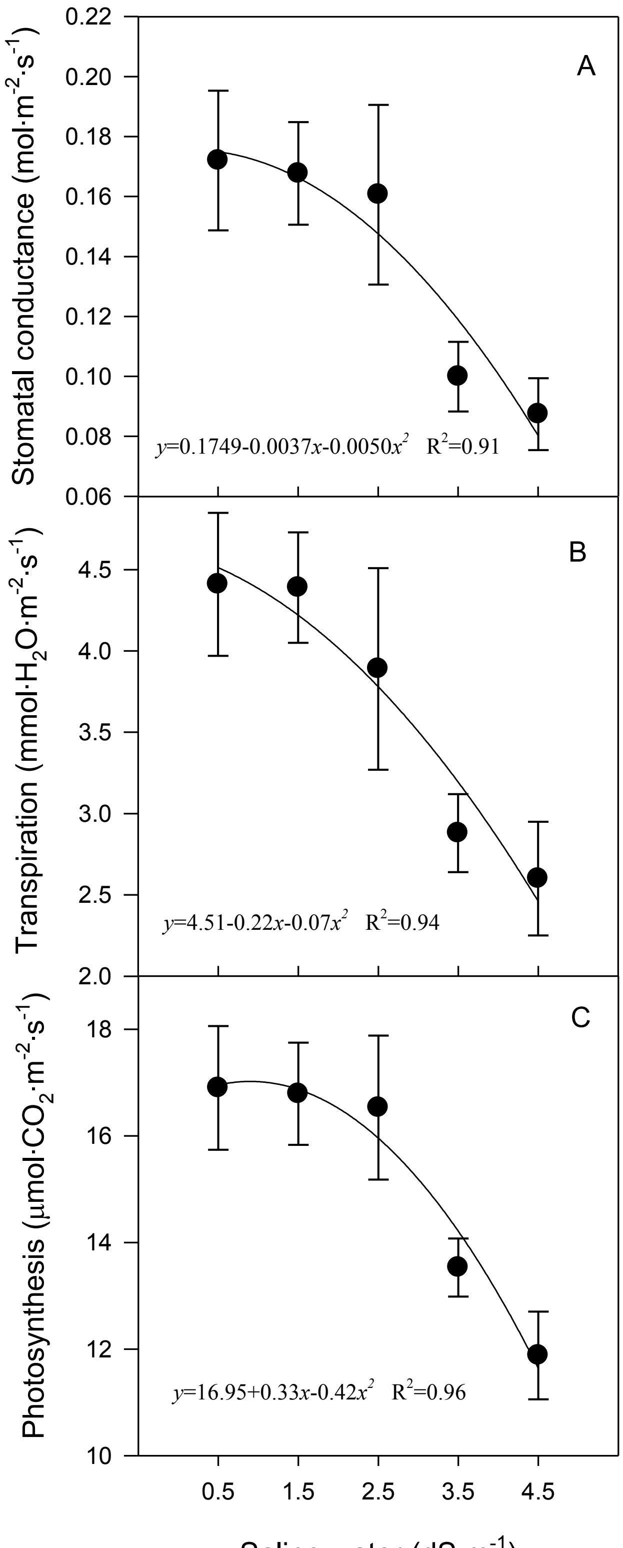
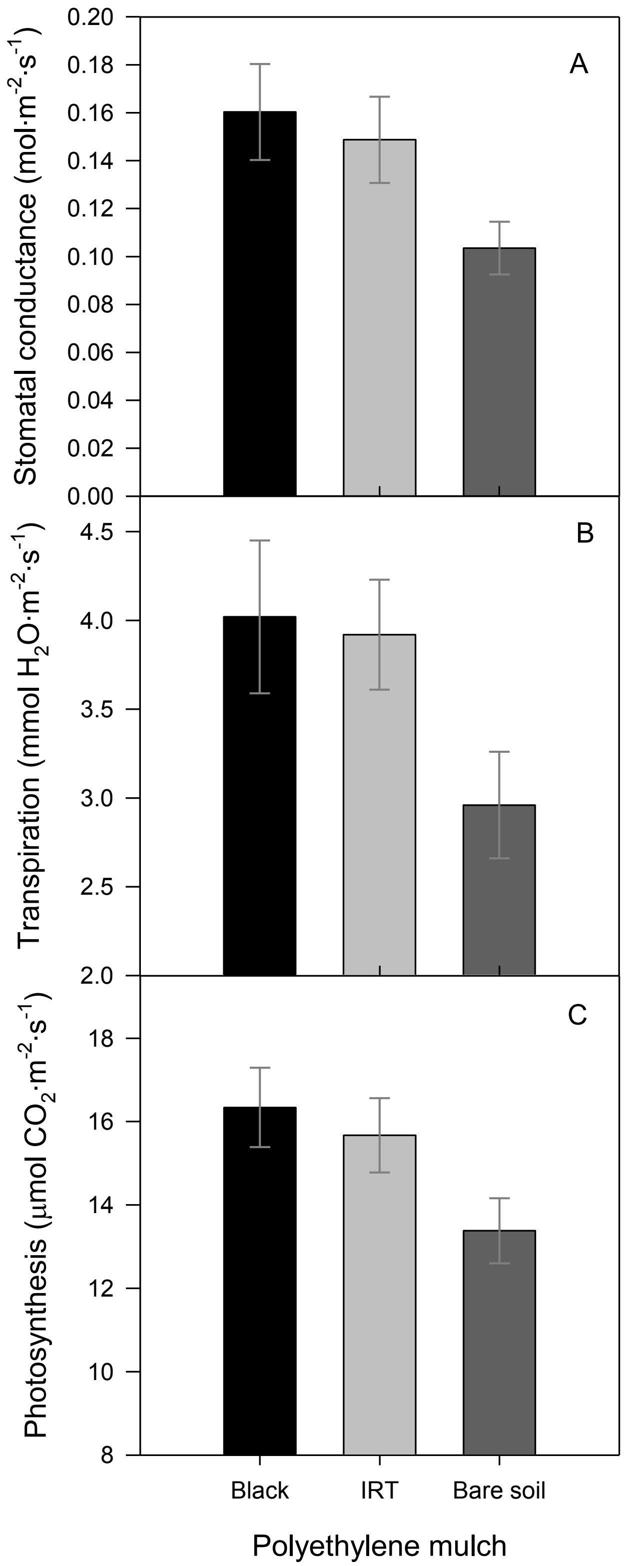

A
B
C
Stomatal conductance (mol·m-2·s-1)
Transpiration (mmol·H2O·m-2·s-1)
Photosynthesis (µmol·CO2·m-2·s-1)
Saline water (dS·m-1)
y=0.1749-0.0037x-0.0050x2 R2=0.91
y=4.51-0.22x-0.07x2 R2=0.94
y=16.95+0.33x-0.42x2 R2=0.96
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
4.5
4.0
3.5
3.0
2.5
2.0
18
16
14
12
10
0.5
1.5
2.5
3.5
4.5

Figure 3.16 A) Stomatal conductance, B) transpiration, and C) photosynthesis of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) as affected by black or green infrared-transmitting (IRT) polyethylene mulch and bare soil. Means ±SEM (n=15) were averaged across saline water levels.



A
B
C
Stomatal conductance (mol·m-2·s-1)
Transpiration (mmol H2O·m-2·s-1)
Photosynthesis (µmol CO2·m-2·s-1)
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
4.5
4.0
3.5
3.0
2.5
2.0
18
16
14
12
10
8
Black
IRT
Bare soil
Polyethylene mulch

Figure 3.17 Cumulative early marketable yield of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) as affected by varying levels of saline water (dS·m^{-1}). Means ±SEM (n=24) were averaged across mulch levels.

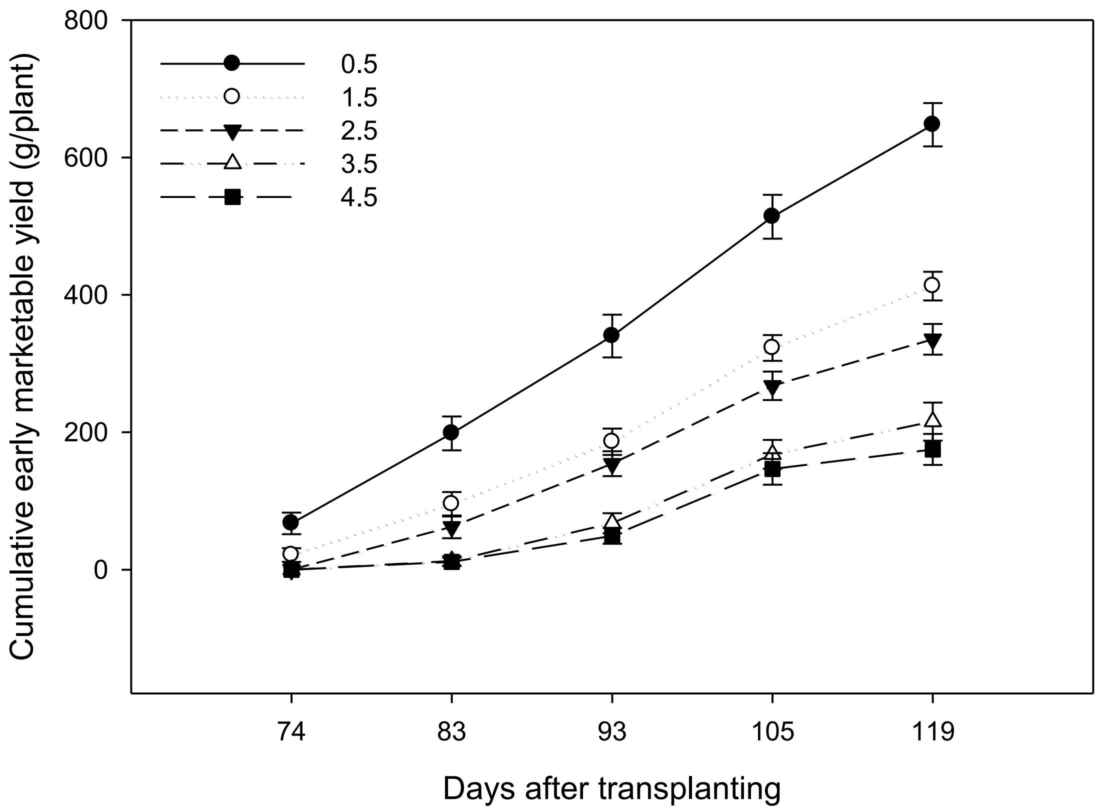


Figure 3.18 Cumulative early marketable yield of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) as affected by black or green infrared-transmitting (IRT) polyethylene mulch and bare soil. Means ±SEM (n=40) were averaged across saline water levels.

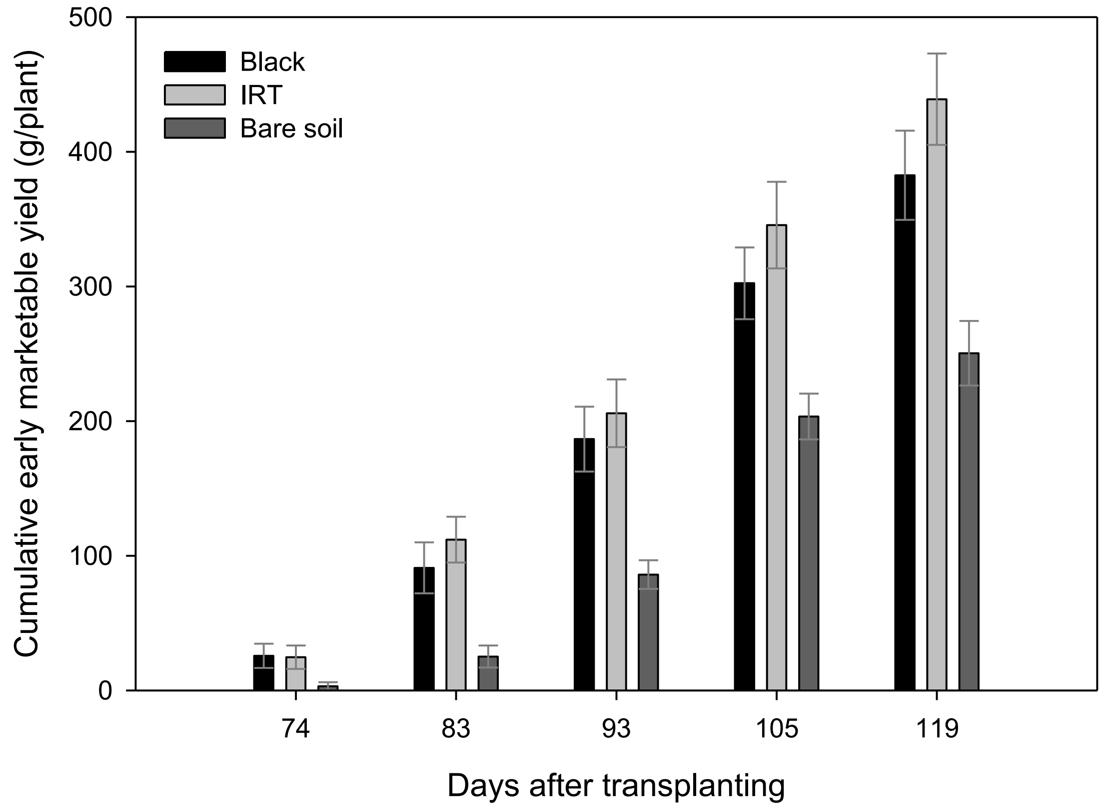


Figure 3.19 Cumulative early marketable yield of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) as affected by black or green infrared-transmitting (IRT) polyethylene mulch and bare soil over varying levels of saline water. A) 74, B) 83, C) 93, and D) 105 days after transplanting. Means ±SEM (n=8).

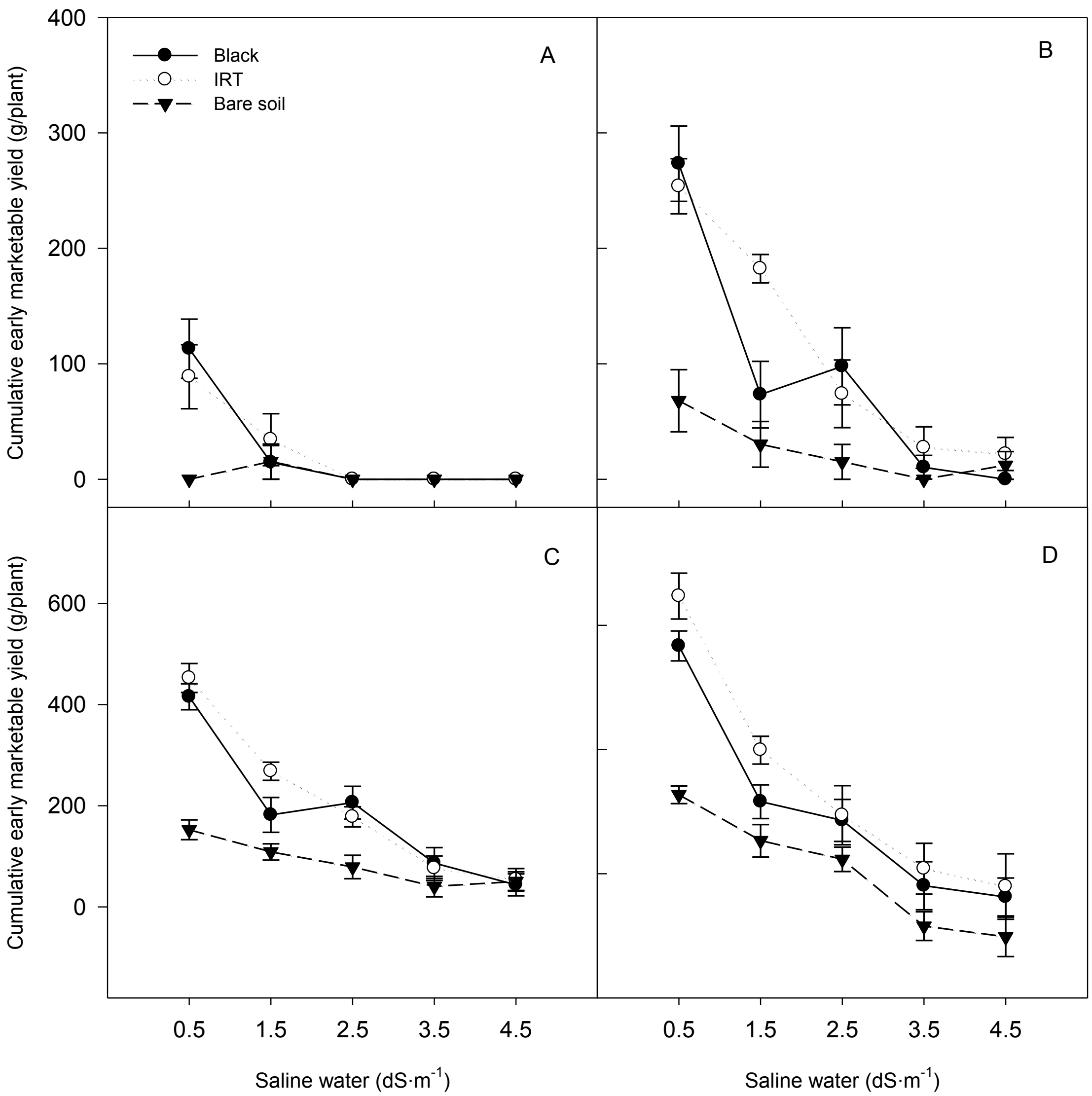


Figure 3.20 Marketable yield of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) as affected by black or green infrared-transmitting (IRT) polyethylene mulch and bare soil over varying levels of saline water. Means ±SEM (n=8).

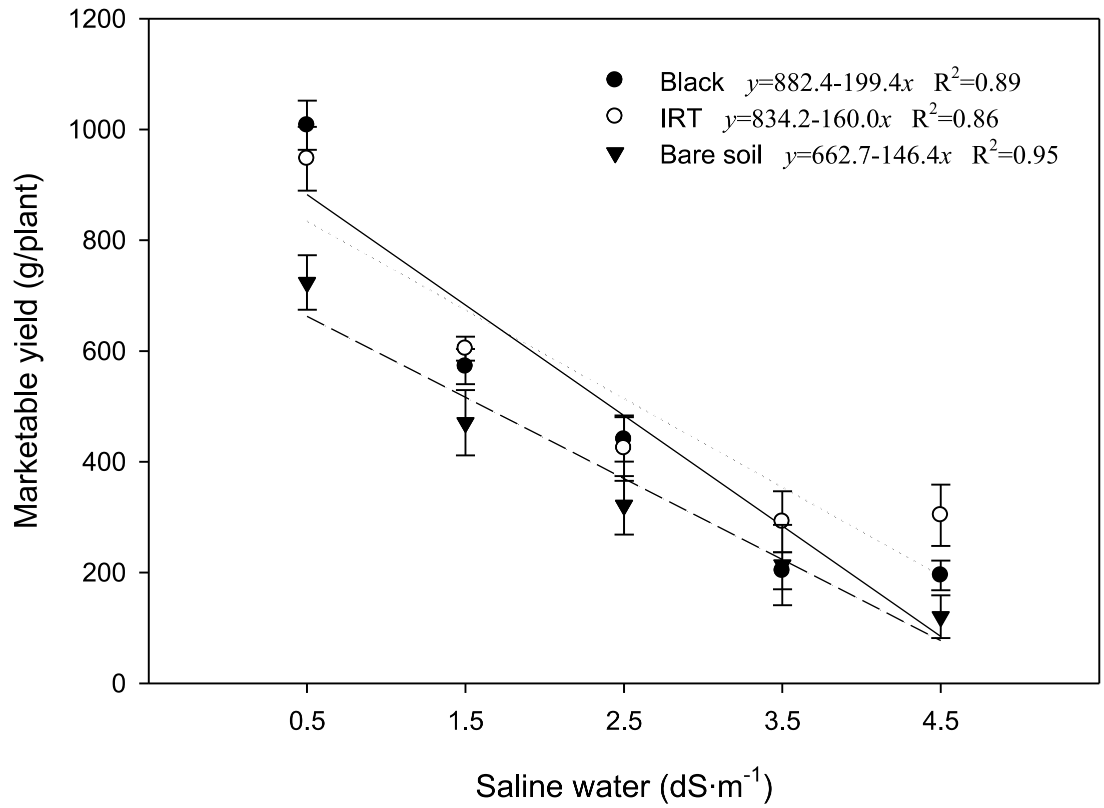


Figure 3.21 Soil salinity (electrical conductivity of the saturation soil paste extract, EC_e) as affected by water salinity (electrical conductivity of the irrigation water, EC_w) and polyethylene mulch or bare soil.

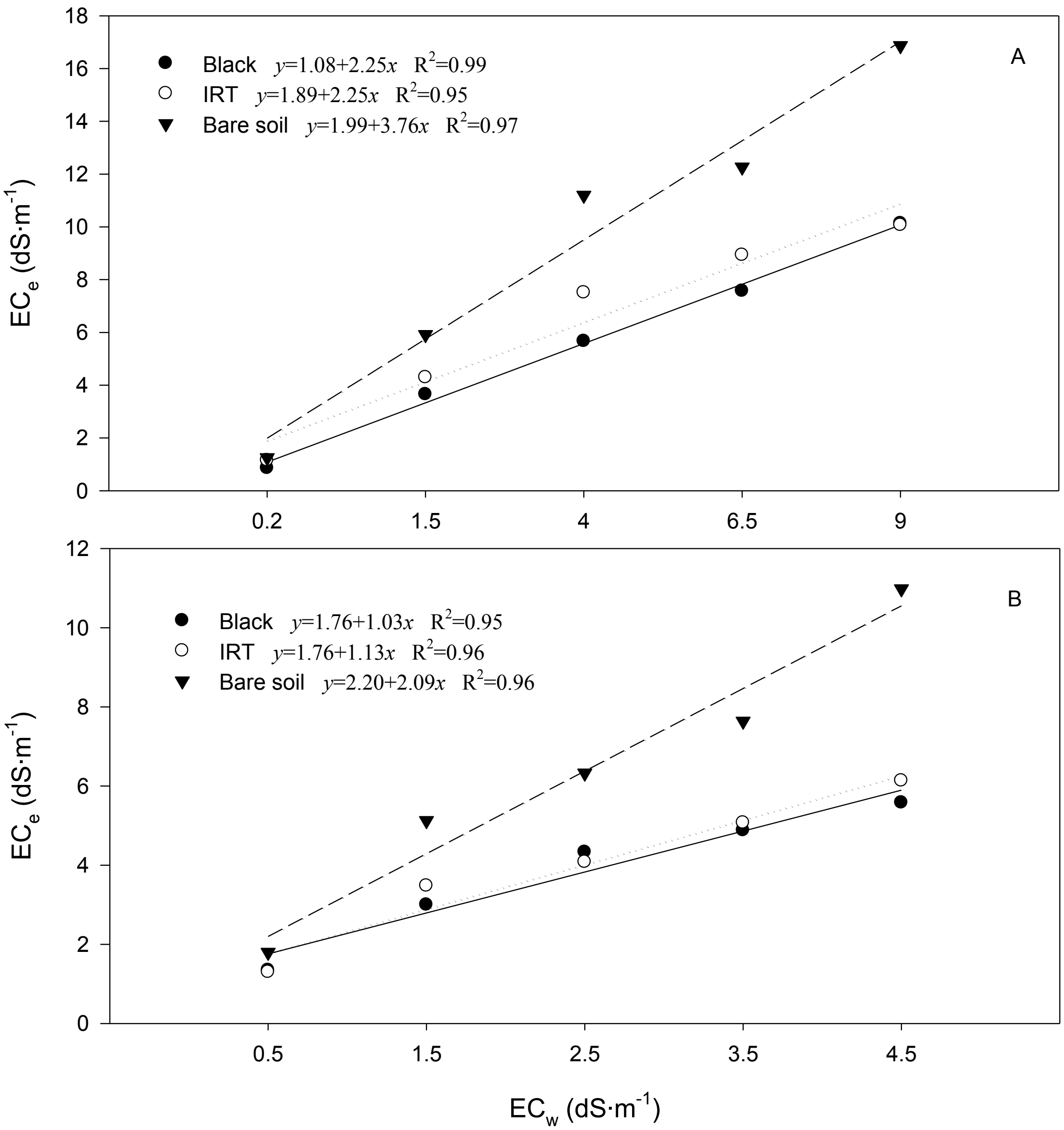
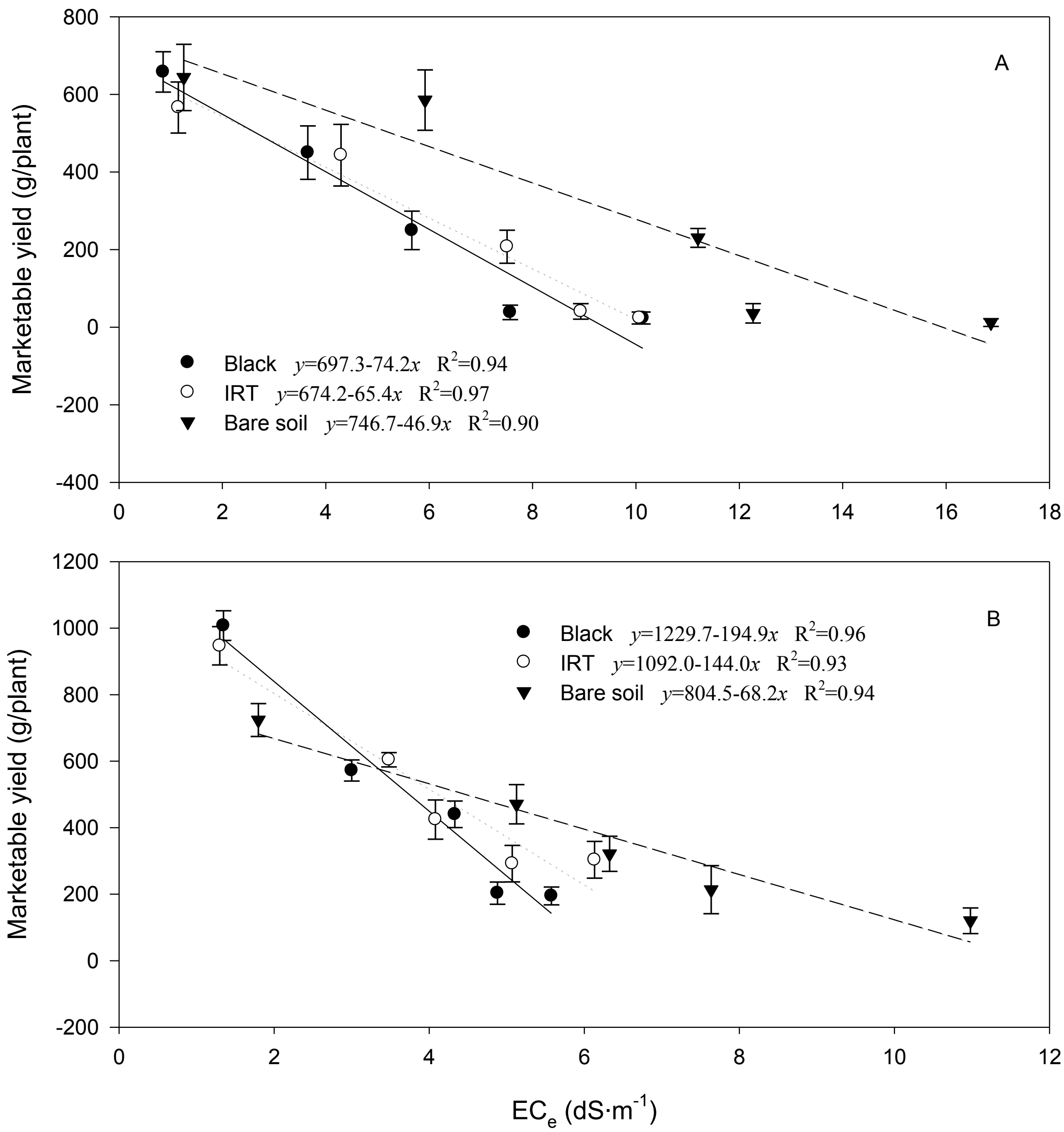


Figure 3.22 Marketable yield of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) as affected by soil salinity (electrical conductivity of the saturation soil paste extract, EC_e) and polyethylene mulch or bare soil. Means ±SEM (n=8).



Preface to Chapter 4

We found in the previous chapter that stomatal conductance, transpiration and photosynthesis of bell pepper were not limited by saline irrigation of 2.5 $dS \cdot m^{-1}$ from transplanting (vegetative stage) until fruit development. Thus, it could be plausible to use this saline water level to irrigate bell pepper plants during vegetative growth. Therefore an experiment was undertaken to determine the effects of saline water on physiology and growth of bell pepper seedlings produced in a containerized system in the greenhouse.

The following chapter is an article published in the *International Journal of Vegetable Science* (http://www.informaworld.com):

Morales-Garcia, D., K. A. Stewart, and P. Seguin. 2008. Effects of saline water on growth and physiology of bell pepper seedlings. *International Journal of Vegetable Science*, 14(2):121-138.

Permission letter to reproduced published data from this article is shown in Appendix B.

Participation of each author is described in the "Contributions of Authors" section. Figures are presented at the end of this chapter and references are listed in Chapter 10. Additional information to this chapter is presented in Appendix A.

Chapter 4

Effects of saline water on growth and physiology of bell pepper seedlings

Dagobiet Morales-Garcia, Katrine A. Stewart and Philippe Seguin

Department of Plant Science, Macdonald Campus of McGill University.

21,111 Lakeshore Road, Ste. Anne de Bellevue, Quebec, H9X 3V9, Canada

4.1 ABSTRACT

Use of saline water to produce pepper (*Capsicum annuum* L.) transplants could have deleterious effects on their growth and physiology because they are moderately sensitive to salinity. Various levels of saline water (0.5, 1.5, 2.5, 3.5, and 4.5 $dS \cdot m^{-1}$) were applied to examine effects on growth and physiology of bell pepper transplants grown in containerized trays under greenhouse conditions. There were no significant differences in growth or physiology of plants receiving 0.5 or 1.5 $dS \cdot m^{-1}$. Final emergence of seedlings was only reduced at salinities ≥3.5 $dS \cdot m^{-1}$ compared with 0.5 $dS \cdot m^{-1}$. Roots were more affected than shoots by increasing salinity. Within shoots, fresh and dry weights of stems were more affected than those of leaves. Relative growth rates were similar at the lowest salinity levels and then declined. Stomatal conductance, transpiration and photosynthesis rates decreased linearly with increasing salinity. The effect of salinity was greater on stomatal conductance and transpiration than on photosynthesis for plants receiving ≥2.5 $dS \cdot m^{-1}$. Depending on the approach, water use efficiency was enhanced (physiological) or lowered (agronomic) as salinity increased.

Keywords: *Capsicum annuum*, pepper, photosynthesis, relative growth rate, salinity, seedling growth, transplants, transpiration, stomatal conductance, water use efficiency.

4.2 INTRODUCTION

Agriculture currently accounts for 71% of the available water used worldwide (FAO, 2000). However, this figure is expected to decline with increasing competition for fresh or high quality water, which will eventually lead to water shortages for agricultural uses (Bouwer, 2002; Parsons, 2000). In this context, the use of saline, or low-quality, water will become an unavoidable and necessary option to irrigate crops, especially in the semiarid, or arid, regions of the world where the scarcity of fresh water is greatest (Oron et al., 1999).

Peppers (*Capsicum annuum* L.), a high value crop with moderate sensitivity to salinity (Maas, 1990; Rhoades et al., 1992), is extensively grown in semiarid and arid regions for domestic and export purposes. Peppers are started as transplants since Leskovar and Cantliffe (1993) demonstrated that transplants established better in the field and gave earlier and higher fruit yields compared with direct seeded plants. Transplant production depends on successful seed germination, emergence and healthy growth of seedlings under greenhouse conditions. Information on the response of bell pepper seedlings to water salinity is scarce (Chartzoulakis and Klapaki, 2000), and what little information there is does not deal with use of saline water in containerized production systems. The objective of this study was to investigate the influence of various levels of saline water on the growth and physiology of bell pepper transplants grown in containers.

4.3 MATERIALS AND METHODS

4.3.1 Plant management and salinization

The experiment was replicated twice and carried out in a greenhouse on the Macdonald campus of McGill University (Sainte-Anne-de-Bellevue, QC, Canada; 45° 24’ 30’’ LN, 73° 56’ 00’’ LW) with air temperatures of 25-27°C and 18°C day and night, respectively. The relative humidity was maintained at 65-75% and carbon dioxide at 365 $\mu L \cdot L^{-1}$. Supplemental high pressure sodium lamps with a photon flux density of 700 $\mu mol \cdot m^{-2} \cdot s^{-1}$ were used to extend daylength to 13 h (400-W Phillips Electronics, Markham, ON, Canada).

Bell pepper, cv. Red Knight X3R (Petoseed, Oxnard, Calif.), was chosen because of its early maturity, bright red uniform color and its adaptability to south and northeast climates in North America (Wehner, 2002). Cell trays (72 semi-pyramidal cells, 4 × 2.5 × 5 cm, volume of ~55 cm^3; ITML Horticultural Products, Brantford, ON, Canada) were filled with a moist peat-based medium (Promix Bx, Premier Horticulture, Rivière-du-Loup, QC, Canada). Seeds were sown (26 February 2004 and 6 January 2006) and covered by a 0.5 cm layer of the media, watered with 1.1 L of treatment solution and covered with a clear polyethylene sheet until seedling emergence. After emergence, additional saline water was added to each tray on a daily basis to leach previously applied salts and maintain the required saline levels in the growing media. Saline water was applied directly on the media surface in order to avoid salinity damage on the foliage and prevent water uptake by leaves. As much as possible, equal volumes of saline water were applied to all treatments.

After appearance of the first true leaves 10 mL of a nutrient solution including (in $mg \cdot L^{-1}$): 100 N, 44 P, 83 K; (in $\mu g \cdot L^{-1}$) 100 B, 250 Cu, 500 Fe, 250 Mn, 2.5 Mo and 250 Zn (Plant Products, Brampton, ON, Canada) was applied/cell weekly for 3 weeks and then (in $mg \cdot L^{-1}$) 200 N, 88 P, 166 K; (in $\mu g \cdot L^{-1}$) 200 B, 500 Cu, 1,000 Fe, 500 Mn, 5.0 Mo and 500 Zn until harvest. The experiment was a randomized complete block design with 3 replicates (72 plants/replicate) of each of the five salinity irrigation treatments (electrical conductivity, EC_w): 0.5, 1.5, 2.5, 3.5 or 4.5 $dS \cdot m^{-1}$. Levels were chosen based on a combination of preliminary trials and work by Maas (1990) and De Pascale et al. (2000; 2003). Saline solutions were prepared using NaCl (Fisher Scientific, Whitby, ON, Canada) and $CaCl_2$ (Anco Chemicals, Maple, ON, Canada) and adjusted to a 2:1 ($NaCl:CaCl_2$) ratio on a molar basis (Dalton et al., 1997). The saline solution was added to tap water (0.2 $dS \cdot m^{-1}$) and adjusted using a portable conductivity-meter with automatic temperature compensation (Model TDSTestr4TM, Oakton, Singapore) until the appropriate level was reached. The ratio of sodium (Na^+) to chloride (Cl^-) was maintained at 0.50 for each level of salinity.

4.3.2 Evaluation of growth and physiology

Seedling emergence, based on fully expanded cotyledons, was counted over an 18 day period. Starting 25 days after seeding (DAS), four seedlings/treatment/block were harvested weekly for six weeks. Sixteen seedlings were used for the final harvest and the remaining 32 plants served as guards (Figure 4.1). To eliminate edge effects at each sampling, the seedlings adjacent to the sampled seedlings were not included as they were considered guard plants. An ending guard row of cells was moved weekly so that it was immediately adjacent to the cells about to be sampled (Figure 4.1).

At each harvest, to prevent desiccation, and losses in fresh weight, sampled seedlings were placed in plastic bags and held in a cold room (5-7°C) for less than 6 h before being separated into roots, stems and leaves and weighed. Samples were oven-dried at 70°C for 48 h and reweighed. Leaf area was determined using images of the fresh leaves compared with a known area using the software Sigma Scan Pro Image Analysis (v. 5.0.0, SPSS, Chicago, IL, USA).

Mean Relative Growth Rate (RGR) of seedling shoots was calculated according to Hunt (1982) for the 67 DAS period:

$$RGR = \frac{\ln W_2 - \ln W_1}{T_2 - T_1} \qquad \text{(Eq. 4.1)}$$

where ln is the natural logarithm; W_2 represents the dry weight of shoots (mg/plant) at 67 DAS (T_2); W_1 represents the dry weight of one seed (9 mg) at seeding (T_1).

Prior to the final harvest at 67 DAS, rates of stomatal conductance, leaf transpiration and net CO_2 assimilation (photosynthesis) were determined on the fourth leaf, which was full expanded, on 3 seedlings/replicate/block. Measurements were taken with a portable photosynthesis meter (Model LI-6400, LI-COR Biosciences, Lincoln, NE, USA) from 1100 to 1230 h in 2004 and from 1400 to 1545 h in 2006.

Water use efficiency (WUE) was calculated according to the physiological WUE_p (Jones, 2004) and agronomic WUE_a (Gregory, 2004) approaches:

$$WUE_p = \frac{A}{E} \qquad \text{(Eq. 4.2)}$$

where WUE_p is the water use physiological efficiency (μmol CO_2·mmol^{-1} H_2O), A is the net CO_2 assimilation (μmol CO_2·m^{-2}·s^{-1}) and E is the leaf transpiration (mmol H_2O·m^{-2}·s^{-1}); and

$$WUE_a = \frac{DW_{Sh}}{I} \qquad \text{(Eq. 4.3)}$$

where WUE_a is the water use agronomic efficiency (g·L^{-1}), DW_{Sh} is the shoot dry weight (g/plant) and I is the amount of water applied by irrigation (L/plant).

4.3.3 Statistical analysis

Data from both experiments were pooled after testing for homogeneity of variances according to the procedure of Gomez and Gomez (1984). Fresh and dry weight data were log-transformed in order to pass the test of homogeneity of variance or to be normally distributed. Data were subjected to analyses of variances (ANOVA) using the procedure GLM of SAS (v. 9.1, SAS Institute, Cary, NC, USA). The ANOVAs followed the structure for combined experiments, in which treatments and experiments (2004, 2006) were considered as fixed effects, and treatment effects were tested against the pooled error (McIntosh, 1983). A Tukey test (P=0.05) was performed to determine statistical differences of the means when indicated by the ANOVA. Linear and quadratic regressions were calculated using SAS. Only results corresponding to final harvest (67 DAS) are presented.

4.4 RESULTS

4.4.1 Seedling growth

Plant emergence: The percentage of seedlings that emerged decreased as salinity increased (Figure 4.2). Significant reductions of 5 and 17% were found at salinity levels of 3.5 and 4.5 $dS{\cdot}m^{-1}$, respectively, compared to 0.5 $dS{\cdot}m^{-1}$. Seedlings treated with 4.5 $dS{\cdot}m^{-1}$ had necrotic lesions on both the radicle and hypocotyl.

Fresh and dry weights: At final harvest, 67 days after seeding, the fresh and dry weights of all plant parts showed negative effects of salinity (Figure 4.3). In general, the effects were significant at salinity levels greater than 2.5 $dS{\cdot}m^{-1}$. Roots were more affected than shoots by salinity resulting in increased shoot/root ratios ranging from 3.1 to 5.9 for 0.5 and 4.5 $dS{\cdot}m^{-1}$, respectively (Figure 4.4).

Leaf area: At final harvest leaf areas were significantly reduced by 19, 26 and 51% for plants receiving 2.5, 3.5 and 4.5 $dS{\cdot}m^{-1}$, respectively, compared to 0.5 $dS{\cdot}m^{-1}$ (99 cm^2/plant) (Figure 4.5).

Growth rate: Mean RGR of shoots treated with 0.5 or 1.5 $dS{\cdot}m^{-1}$ were similar. Thereafter, RGR declined with increasing salinity (Figure 4.6). Decreases of 5, 8 and 16% were found for seedlings treated with 2.5, 3.5 and 4.5 $dS{\cdot}m^{-1}$, respectively, compared with 0.5 $dS{\cdot}m^{-1}$.

4.4.2 Seedling physiology

No significant differences were detected for stomatal conductance, transpiration and photosynthesis in seedlings treated with 0.5 and 1.5 $dS{\cdot}m^{-1}$. Overall, these physiological parameters decreased linearly as salinity increased (Figure 4.7). Relative reductions per unit of salinity ($dS\cdot m^{-1}$) were smaller for photosynthesis (17%) than for transpiration or stomatal conductance (22-23%).

Water use efficiency (WUE) increased, or decreased, depending on whether a physiological or agronomic approach was considered (Figure 4.8). The physiological approach, WUE_p, showed a generally positive quadratic relationship [0.349 μmol $CO_2\cdot mmo^{-1}$ $H_2O/(dS\cdot m^{-1})^2$] with salinity although there was a small decrease with a slope of 0.446 μmol $CO_2\cdot mmol^{-1}$ $H_2O/dS\cdot m^{-1}$ at the two lowest salinity levels (Figure 4.8A). There was a tendency for WUE_a (agronomic approach) to decrease with increasing salinity. The trend was initially linear from 0.5 to 1.5 $dS\cdot m^{-1}$ (0.044 $g\cdot L^{-1}$ $H_2O/dS\cdot m^{-1}$) and producing biomass of 1.33 and 1.34 $g\cdot L^{-1}$ H_2O, respectively (Figure 4.8B). At higher levels of salinity the effect was quadratic [0.031 $g\cdot L^{-1}$ $H_2O/(dS\cdot m^{-1})^2$] with decreasing biomass production to 1.07, 0.97 0.68 $g\cdot L^{-1}$ H_2O for 2.5, 3.5 and 4.5 $dS\cdot m^{-1}$, respectively.

4.5 DISCUSSION

4.5.1 Effects on seedling growth

Emergence reductions for seedlings treated with 4.5 $dS\cdot m^{-1}$ may be due to the sensitivity of the radicle and hypocotyl to high salinity rather than failures in germination. Previous work reported that the practice of imbibing seeds in salt solutions to initiate, but not to complete, germination (halopriming) of pepper seeds with concentrations of NaCl or $NaCl:CaCl_2$ (1:1 on a molar basis) no higher than 100 mM did not inhibit seed germination (Smith and Cobb, 1991). Doubling the concentration of NaCl or $NaCl:CaCl_2$ the percentage germination was reduced by 53 and 17%, respectively, compared to seeds germinated in distilled water (Smith and Cobb, 1991). This observation was later confirmed by Palma et al. (1996) who found that the germinative capacity of pepper seeds was not affected within the range of 0 to 100 mM NaCl (0.11 to 10.03 $dS \cdot m^{-1}$, respectively). Moreover, final germination was not affected by salinity (Na/Ca+Mg ratio of ~2:1 on an equivalent basis) as high as 23 $dS \cdot m^{-1}$ but was completely inhibited at 32 $dS \cdot m^{-1}$ (Miyamoto et al., 1985). In contrast, radicle length was significantly reduced by 52% when pepper seeds were treated with 50 mM NaCl (5.9 $dS \cdot m^{-1}$) in addition to a half-strength Hoagland solution (1.2 $dS \cdot m^{-1}$), a concentration similar to the 4.5 $dS \cdot m^{-1}$ (51.6 $mmol \cdot L^{-1}$ of Cl^{-}) used in our experiment, after successful germination (Chartzoulakis and Klapaki, 2000).

Previous works (Miyamoto et al., 1985; Yildirim and Guvenc, 2006) found that salinity affected seedling emergence more than germination of pepper. Our data indicated that emergence of seedlings decreased with increasing salinity. This observed tendency is in agreement with that found by Miyamoto et al. (1985) for a range of 0.8 to 7.6 $dS \cdot m^{-1}$. Yildirim and Guvenc (2006) reported emergence percentages of 90 and 9% when saline tolerant or sensitive pepper cultivars were treated with 85 mM NaCl. At salinity levels of 170 and 215 mM NaCl no emergence was noted.

According to Munns et al. (1995) the response of plant growth to salinity follows two phases. The first is an exterior effect that decreases root zone osmotic potential. This leads to water stress in plants and growth is probably reduced by inhibitory signals from roots (Munns, 2002).

The second phase of growth reduction is due to salts being concentrated within the plant (Munns et al., 1995). Peppers are moderately sensitive to salinity (Maas, 1990;

Rhoades et al., 1992), and as glycophytes they exhibit little ability to exclude salts (Bethke and Drew, 1992). Consequently, ion-specific (Na^+ and Cl^-) accumulation in the roots and shoots may have occurred as the plants developed. Reductions in fresh and dry weights in pepper seedlings agree with other reports for saline conditions (Chartzoulakis and Klapaki, 2000; Palma et al., 1996; Yildirim and Guvenc, 2006). Dry weight of pepper seedlings significantly decreased in plants treated with either 50 or 100 mM NaCl (5.4 and 10.0 $dS \cdot m^{-1}$, respectively) relative to 0 mM NaCl (Palma et al., 1996). Similarly, fresh and dry weights of seedlings were significantly reduced when salinized with 85 mM NaCl for 30 days after seeding in comparison with non-salinized seedlings (0 mM NaCl) (Yildirim and Guvenc, 2006). The age of the plant and the duration of the exposure to salinity can affect response. In our experiment dry weight was significantly reduced at salinity levels of 2.5 $dS \cdot m^{-1}$ and higher when plants were exposed to these levels for 67 days. However, peppers were able to tolerate up to 7.1 $dS \cdot m^{-1}$ without a decrease in dry weight when 22 day old seedlings were grown under saline conditions for 42 days (Chartzoulakis and Klapaki, 2000). Relative growth rates were negatively affected by salinity levels of 2.5 $dS \cdot m^{-1}$ or higher. The decreases in RGR with increasing salinity agree with findings of Yilmaz et al. (2004) for pepper seedlings treated with 50, 100 and 150 mM NaCl; for tomato (*Lycopersicon esculentum* Mill.) and cucumber (*Cucumis sativus* L.) seedlings treated with NaCl at salinity levels of 2, 4 and 8 $dS \cdot m^{-1}$ (Al-Harbi, 1995), and for eggplant (*Solanum melongena* L) seedlings treated with 50, 100 and 150 mM NaCl (Akinci et al., 2004).

The growth of roots was substantially more affected by salinity than that of shoots, resulting in increases in the shoot/root ratio. This could be a consequence of a higher accumulation of Na^+ in roots than in shoots. Blom-Zandstra et al. (1998) reported higher Na^+ accumulation in roots than shoots of pepper plants grown in a hydroponics system with a 10 mM Na^+ addition to the nutrient solution. Palma et al. (1996) reported significant reductions in root dry weight at 25 mM NaCl (2.99 $dS \cdot m^{-1}$) whereas stem and leaf dry weights had a slight increase. This could also be a consequence of a shorter root length relative to reductions in shoot height of pepper seedlings grown in saline conditions (Yildirim and Guvenc, 2006). Increases in the shoot/root ratio have been reported for tomato and cucumber seedlings (reported as root/shoot ratio) grown under saline conditions of 2, 4 and 8 $dS \cdot m^{-1}$ (Al-Harbi, 1995), and for tomato seedlings treated with 100 mM NaCl as compared with 0 mM NaCl (Rodriguez et al., 1997).

Stems were proportionally more reduced in weight than leaves as salinity increased. Two reasons might account for this result. This response could be a consequence of a differential accumulation of Na^+ and Cl^- in shoots. Bethke and Drew (1992) and Blom-Zandstra et al. (1998) reported Na^+ accumulates more in roots and stems and less in leaves, and Cl^- accumulates more in leaves. It may be that the effect of Na^+ on stem growth was more harmful than that from Cl^- on leaves. Another possible reason that leaves were less damaged by salinity than stems and even roots could be due to the irrigation method. In our study the saline water was applied directly to the growing medium and not the leaves. Shalhevet (1994) noted that one problem of using saline water for sprinkler irrigation was the potential for leaf damage. This would be particularly important since the majority of vegetable transplants grown in greenhouse conditions are sprinkler-irrigated (Leskovar and Heineman, 1994). Reductions in leaf area of pepper seedlings grown under saline conditions are consistent to other reports for peppers (Chartzoulakis and Klapaki, 2000), tomato (Al-Harbi, 1995), and eggplant (Akinci et al., 2004; Chartzoulakis and Loupassaki, 1997).

4.5.2 Effects on physiology

Partial stomatal closure occurred with increasing salinity. This response might have reduced water loss and restricted CO_2 intake by plants for use in photosynthesis. Additionally, accumulation of either Cl^- or Na^+ in leaves indicates a causal relationship which could result in decreases in stomatal conductance, transpiration and photosynthesis. Bethke and Drew (1992) reported that photosynthesis in peppers decreased with increasing accumulation of either Cl^- or Na^+ in leaves, possibly as a consequence of chloroplast damage. Similarly, Chartzoulakis and Klapaki (2000) suggested that reduction in photosynthesis of pepper plants receiving high levels of saline water could be due to increasing Cl^- accumulation in leaves of peppers. It has also been argued that osmotic effects of the salinity outside the roots could cause decreases in photosynthesis (Munns, 2002).

Our data indicated that photosynthesis was less sensitive than transpiration due to increasing salinity which enhanced WUE_p. A similar tendency was observed in peppers grown in hydroponics with increasing saline (NaCl) concentrations (Chartzoulakis and Klapaki, 2000). Under optimal conditions, uptake of CO_2 is less relative to water lost by transpiration based on their diffusion gradients (Chaves et al., 2004). Presumably, reductions in transpiration led to a reduction in water uptake of plants irrigated with 3.5 and 4.5 $dS{\cdot}m^{-1}$ which was reflected in the total amount of water used by plants. In contrast to WUE_p, WUE_a decreased with salinity. This is a clear indication that plants irrigated with more saline solutions failed to use the available water as a result of possible saline mediated osmotic effects (Munns, 2002). Since transpiration was restricted with increasing salinity, plants receiving less saline water took up and transpired more unsalinated water.

4.6 CONCLUSION

Saline water of up to 1.5 $dS{\cdot}m^{-1}$ can be use to start bell pepper transplants without any negative effects. As saline level increases there may be decreases in some physiological parameters, but no effects on seedling emergence, or shoot fresh weight. Levels higher than 2.5 $dS{\cdot}m^{-1}$ are not recommended. Since the water was applied directly to the growing media, it would be interesting to evaluate the effects of saline water applied through different irrigation systems (e.g., overhead or sprinkler, subirrigation or flotation) on pepper seedling growth. Long-term evaluation of transplants produced using saline water under field conditions to determine effects on yield and quality is needed.

Figure 4.1 Representation of a flexible 72-compartment plastic tray indicating the dynamic of its size over seven samplings dates were performed weekly starting at 25 days after seeding (DAS).

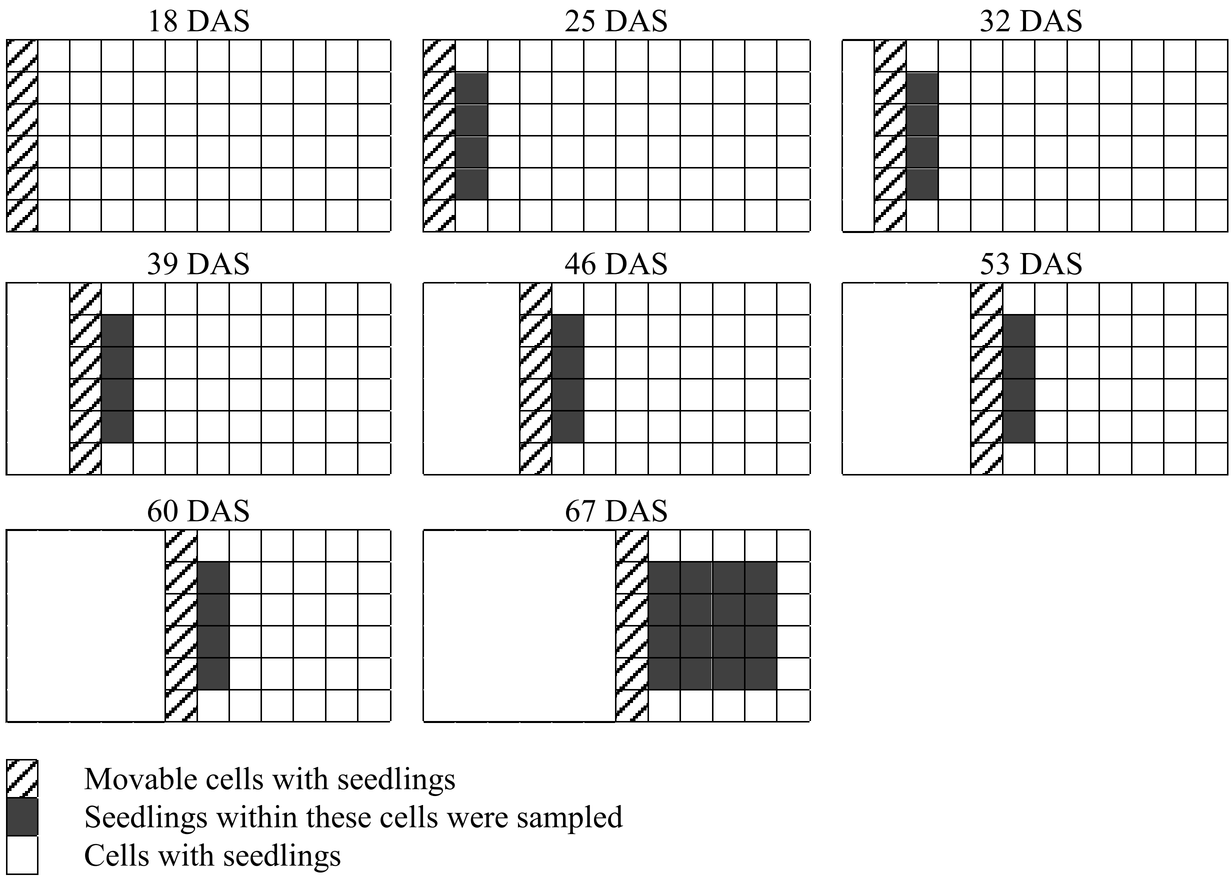


Figure 4.2 Final emergence (18 days after seeding) of bell pepper (*Capsicum annuum* L. cv. Red Knight X3R) seedlings as affected by saline water. Means ±SEM (n=6).

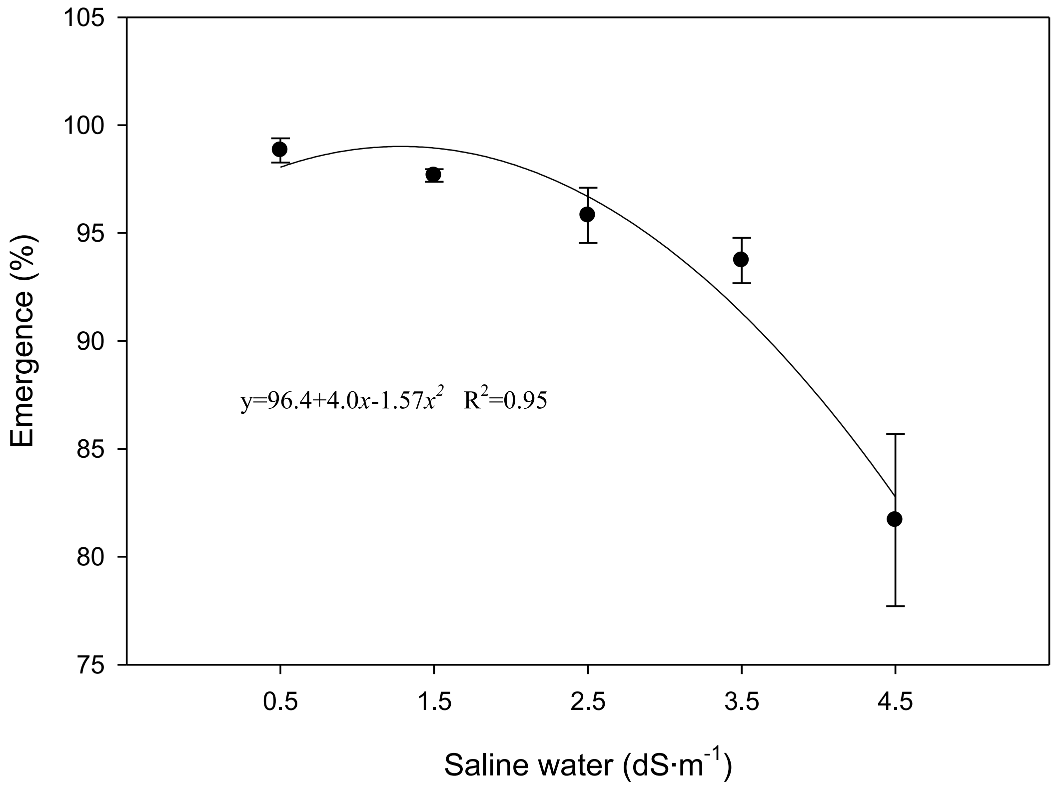


Figure 4.3 A) Fresh, and B) dry weights of bell pepper (*Capsicum annuum* L. cv. Red Knight X3R) seedlings as affected by saline water 67 days after seeding. Means ±SEM (n=6).

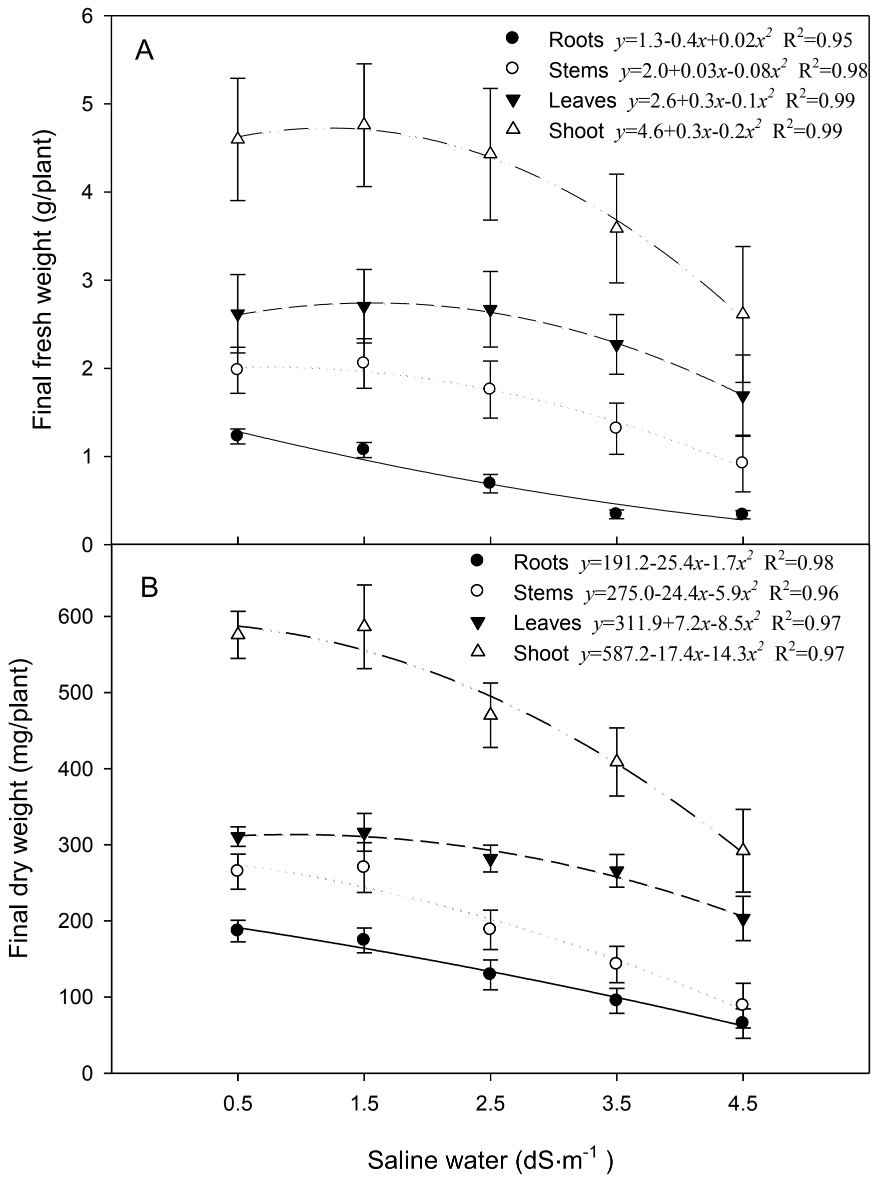


Figure 4.4 Shoot to root ratio (dry weight basis) of bell pepper (*Capsicum annuum* L. cv. Red Knight X3R) seedlings as affected by saline water 67 days after seeding. Means ±SEM (n=6).

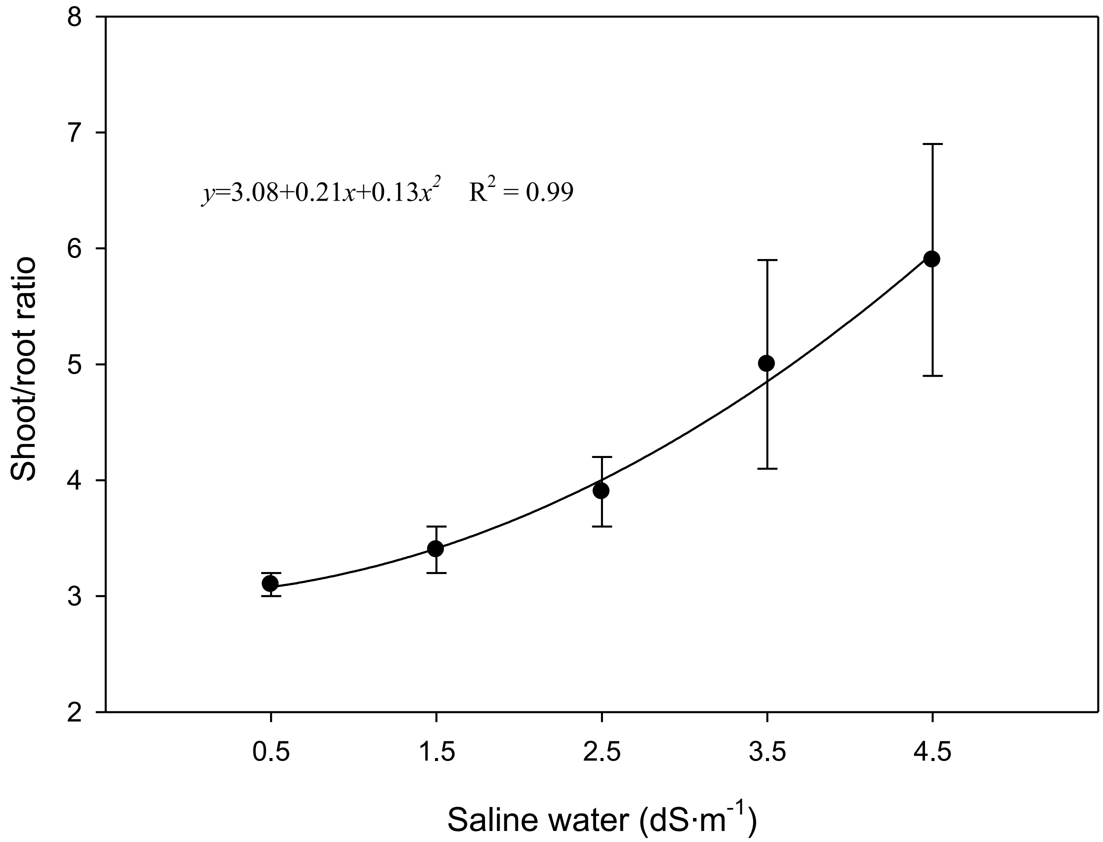


Figure 4.5 Leaf area of bell pepper (*Capsicum annuum* L. cv. Red Knight X3R) seedlings as affected by saline water 67 days after seeding. Means ±SEM (n=6).

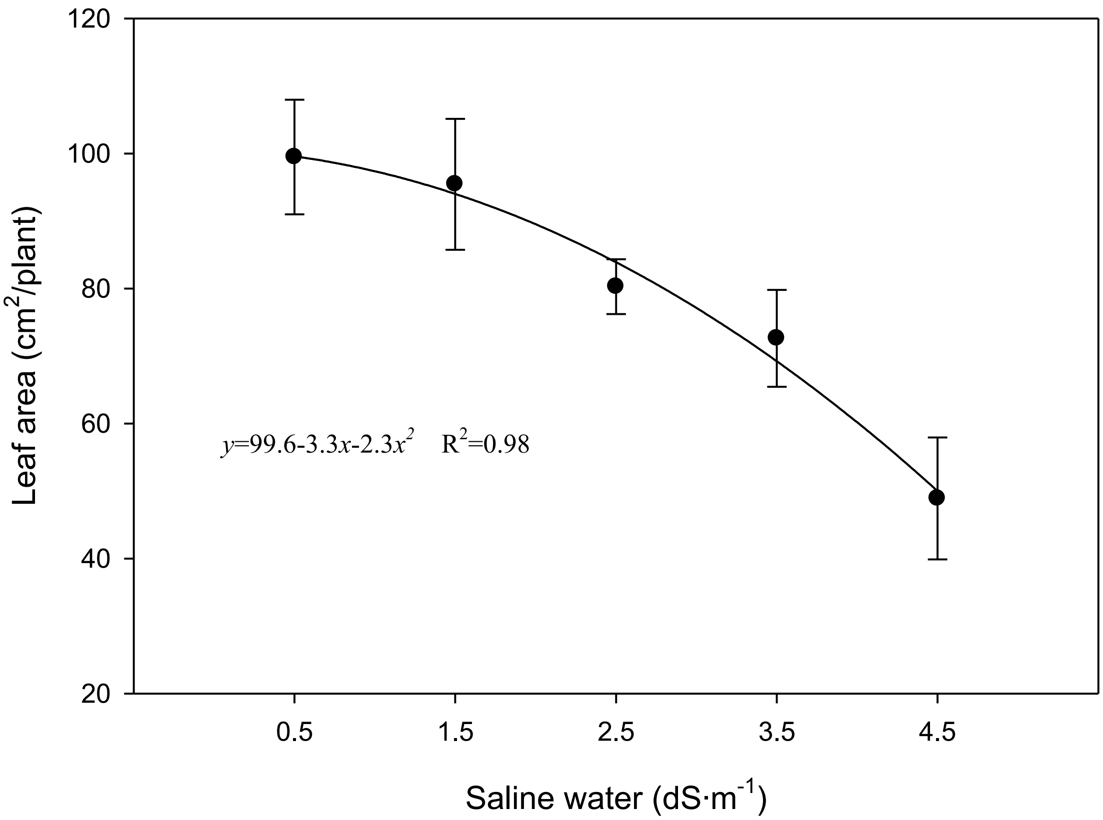


Figure 4.6 Shoot Relative Growth Rate (RGR) of bell pepper (*Capsicum annuum* L. cv. Red Knight X3R) seedlings as affected by saline water over a period of 67 days. Means ±SEM (n=6).

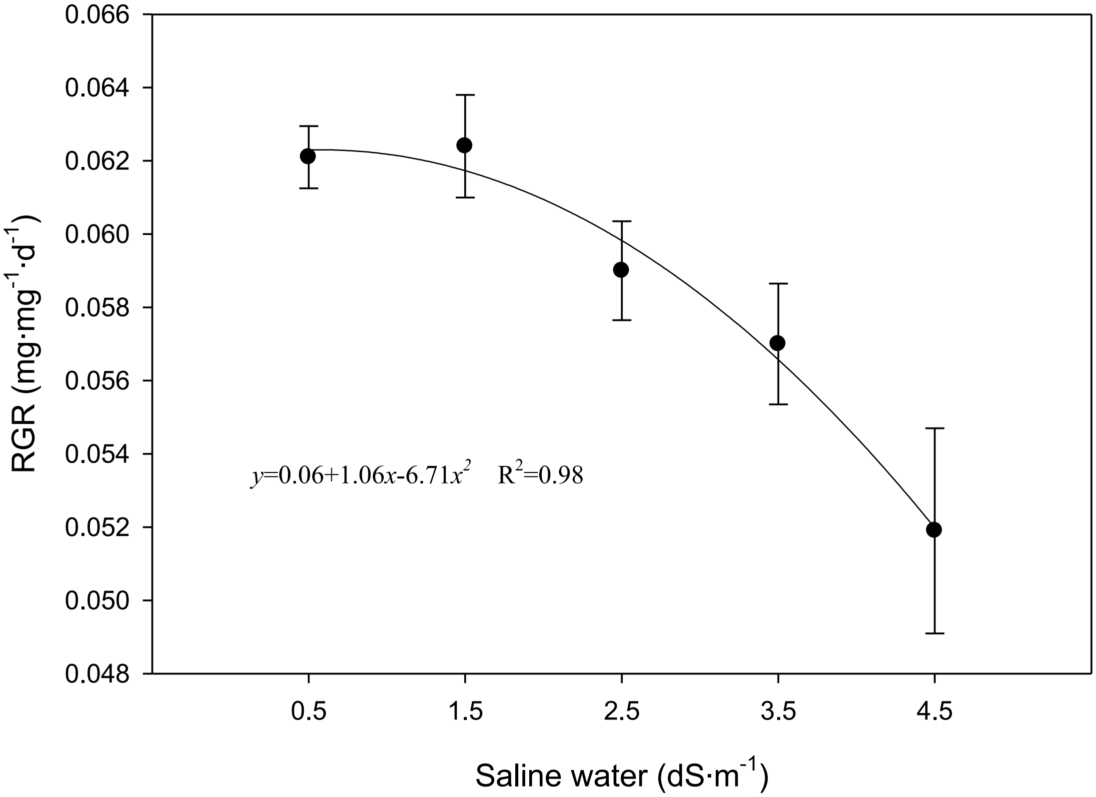


Figure 4.7 Stomatal conductance (g_s), transpiration (E) and photosynthesis (A) of bell pepper (*Capsicum annuum* L. cv. Red Knight X3R) seedlings as affected by saline water 67 days after seeding. Means ±SEM (n=6).

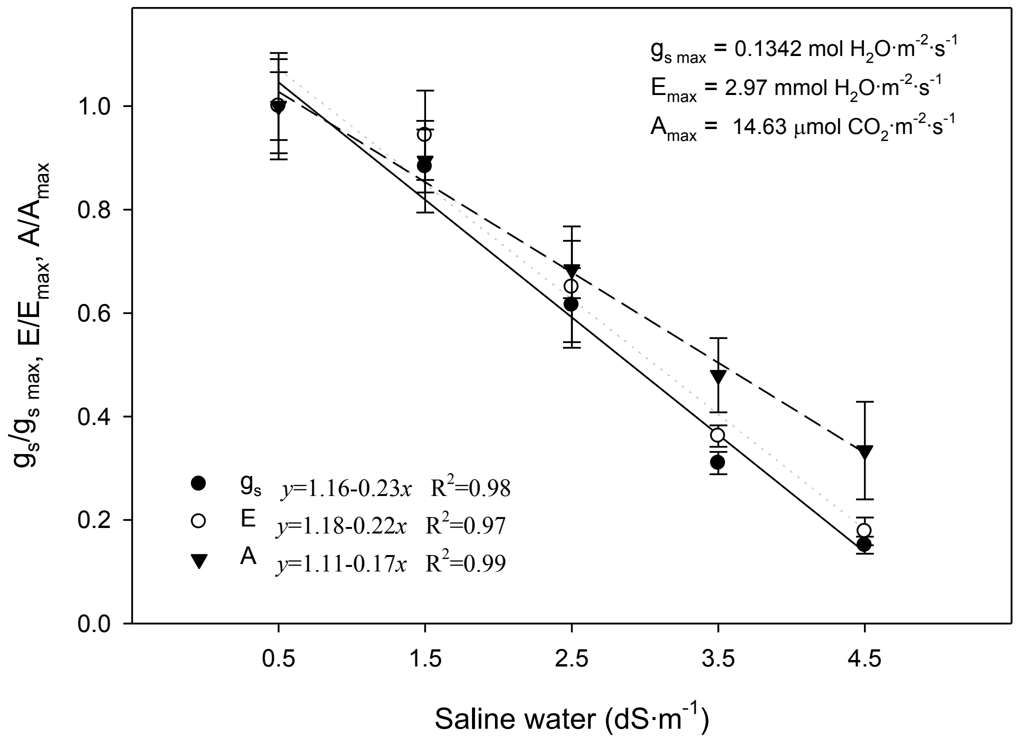
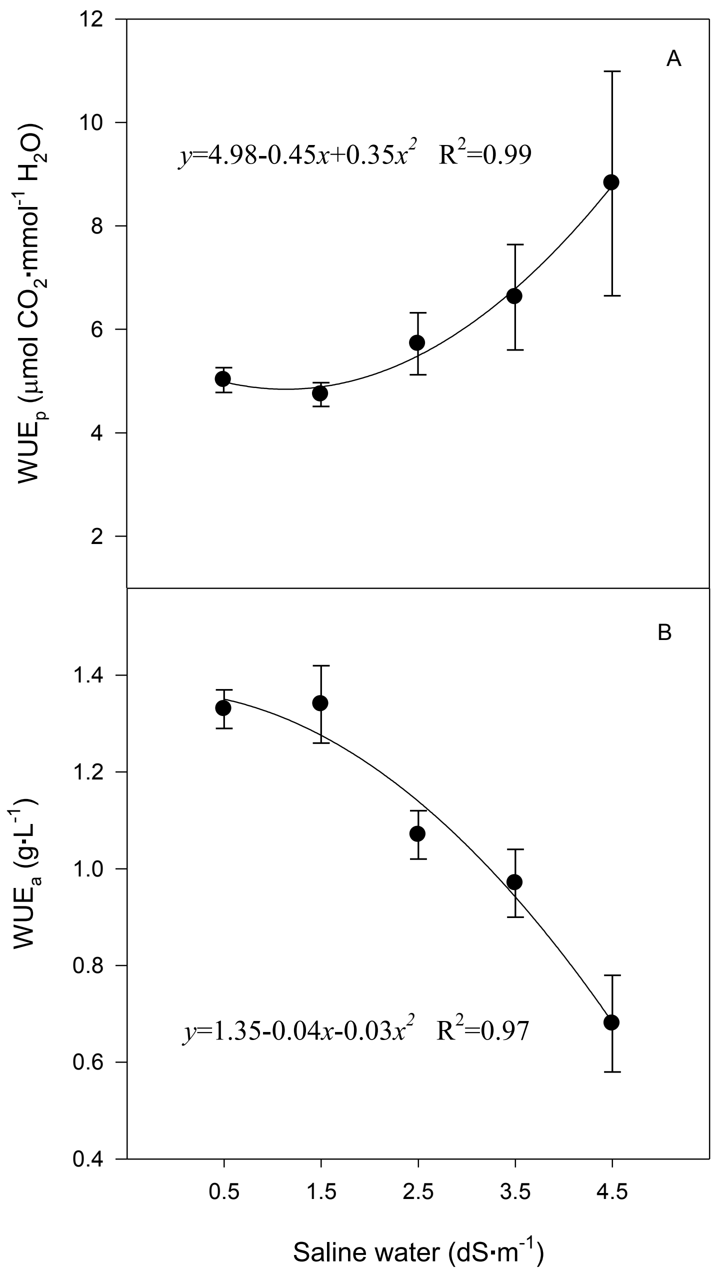


Figure 4.8 A) Water use efficiencies indicated by the physiological approach (WUE_p), and B) agronomic approach (WUE_a) of bell pepper (*Capsicum annuum* L. cv. Red Knight X3R) seedlings as affected by saline water. Means ±SEM (n=6).



Preface to Chapter 5

We had previously determined in Chapter 3 that irrigation with saline water of 2.5 $dS \cdot m^{-1}$ allowed mulched plants to have higher marketable yield than plants grown in bare soil. In Chapter 4, the same level of saline water was reported to not affect shoot fresh weight but did decrease stomatal conductance, transpiration and photosynthesis in seedlings. Thus, physiological, growth and yield responses of bell peppers to the use of saline water during different growth stages remained uncertain and unknown. In this chapter we wanted to determine whether application of saline water during specific growth stages of pepper plants could be accomplished without reducing marketable yield. Physiological, growth and fruit production aspects of mulched plants and plants grown in bare soil were evaluated as well as the effects of saline irrigation on the soil salinity.

The present manuscript is co-authored with Katrine A. Stewart and Philippe Seguin. Participation of each author is described in the "Contributions of Authors" section. Tables and figures are presented at the end of this chapter, and references are listed in Chapter 10. Information from this manuscript will be submitted to the *Agricultural Water Management* journal for peer review. Copyright transfers from co-authors are shown in Appendix B.

Chapter 5

The timing of saline drip irrigation affects growth, physiology and fruit yield of bell pepper grown under mulch or bare soil condition

Dagobiet Morales-Garcia, Katrine A. Stewart and Philippe Seguin

Department of Plant Science, McGill University, Macdonald Campus

21,111 Lakeshore Road, Ste. Anne de Bellevue, Quebec, H9X 3V9, Canada

5.1 ABSTRACT

The effect of applying saline water (2.5 $dS{\cdot}m^{-1}$) via a drip irrigation system at different growth stages of bell peppers (*Capsicum annuum* L. var. Red Knight) grown on mulch or bare soil was investigated under greenhouse conditions. The study included six saline irrigation treatments: i) Non-saline water throughout growth (None); ii) saline irrigation from transplanting until formation of the first fruit set (S1S2); iii) saline irrigation from transplanting until appearance of the first flower and from first harvest to final harvest (S1S4); iv) saline irrigation from appearance of the first flower until first harvest (S2S3); v) saline irrigation from fruit set until final harvest (S3S4); and vi) saline irrigation throughout growth (All). Measurements of stomatal conductance (g_s), transpiration (E), and photosynthesis (A) were taken during vegetative growth, at flowering, at fruit set, and during fruit growth and development. Mulched plants had higher photosynthetic rates than plants grown in bare soil, although values were only significant for treatments S1S2, S2S3 and All. In addition, plants grown in bare soil were slower to recover after periods of saline irrigation than mulched plants. Root growth was significantly reduced with any application of saline water while leaf growth was decreased when saline irrigation was applied at early growth stages. Saline irrigation applied at late growth stages had more deleterious effects on fruit production. Saline irrigation when applied throughout growth (All) or from fruit formation until harvest (S3S4) reduced marketable yields by 38% and 45% compared with the control plants (None). Mulched plants had significantly greater yields than plants grown in bare soil regardless of irrigation treatment as consequence of less soil salinization.

Keywords: Salinity, saline water, *Capsicum annuum* L, bell pepper, stomatal conductance, transpiration, photosynthesis, water use efficiency.

5.2 INTRODUCTION

Agriculture is currently the major water user, accounting for 71% of the total water use worldwide (FAO, 2000). However, availability of water for agriculture is being reduced due to competition among users for better quality water. As populations increase, so does the demand for water for domestic activities, recreational purposes, and industrial use resulting in water shortages for agricultural use (Bouwer, 2002; Parsons, 2000). Consequently, it is reasonable to assume that good quality water in the future might be reserved for human consumption (drinking quality water).

Agricultural water use must, therefore, be optimized regardless of its quality since water is becoming increasingly scarce not only for semiarid or arid zones but also for semi-humid and even, humid areas (Parsons, 2000; Shalhevet, 1994). The use of saline or low-quality water will become a necessary option for irrigation, especially in semiarid or arid zones (Oron et al., 1999). Reductions in crop yield due to exposure to salinity however have been widely reported (Maas, 1990; Rhoades et al., 1992). It is estimated that 0.25 to 0.50 million hectares of agricultural land are abandoned yearly due to salinization (FAO, 2002). Therefore it is critical that improved water management and cultural practices be employed when using saline irrigation water in order to minimize the effects of salinization particularly in semiarid regions where sources for irrigation can be surface water, drainage water or groundwater (Dinar et al., 1986). Among potential sources of irrigation water are the nutrient rich leachates from greenhouse crop production which if recycled could reduce or eliminate a source of groundwater pollution (Bar-Yosef et al., 2001).

In many agricultural areas of the world, both fresh (non-saline) and saline water for irrigation are available in the same agricultural location (Shalhevet, 1994). With two water sources there are a number of possibilities for irrigation use. The waters could be blended until a desirable saline concentration is achieved or they could be alternated (Dinar et al., 1986; Shalhevet, 1994; Shannon and Grieve, 2000). Saline water could be used to irrigate the crop during more salt tolerant growth stages reserving the fresh water for sensitive periods (Shannon and Grieve, 2000). These periods would need to be determined for individual crops.

Microirrigation, particularly drip irrigation, offers the advantage of reducing the surface area exposed to evaporation, thus diminishing water consumption (Dasberg and Or, 1999; Skaggs, 2001). Drip irrigation, also allows for the use of saline water, and the inclusion of soluble fertilizers (Dasberg and Or, 1999). Polyethylene mulch is often combined with drip irrigation; although mulch effects on soil and crops depend on its optical properties (Tarara, 2000). One the advantages attributed to mulch is water saving as soils under the mulch stay wetter longer and hence require less water to maintain soil moisture at a given level (Hartz, 1996). Among high value crops that have been produced under a plasticultural system (drip irrigation and plastic mulch) are sweet peppers (Lamont, 1996).

Peppers (*Capsicum annuum* L.), are moderately sensitive to salinity and can tolerate 1.5 $dS{\cdot}m^{-1}$ of electrical conductivity (EC) in the soil saturated paste extract (EC_e) (Maas,

1990) or 1.0 dS·m^{-1} of the irrigation water (EC_w) (Rhoades et al., 1992). However, research is needed to determine the sensitivity or tolerance of this crop at various phenological growth stages (Bar-Yosef et al., 2001). The objective of this study was to evaluate the effects of polyethylene mulch and saline water applied by drip irrigation on the growth, physiology and fruit yield of pepper plants in order to determine salt sensitivity at each phenological stage.

5.3 MATERIALS AND METHODS

5.3.1 Plant material

The experiment was carried out in a greenhouse with the following conditions. Air temperature was 25-27 °C during the day and 18°C in the night, relative humidity 65-75%, 365 µL·L^{-1} carbon dioxide concentrations and photoperiod 13 h with a light intensity of 700 µmoles·m^{-2}·s^{-1}.

Seeds of pepper (*Capsicum annuum* L. var. Red Knight X3R; Petoseed, Oxnard, CA, USA) were sown on 12 November 2004 in 72-cell trays (semi-pyramidal cells of 4 x 2 x 6 cm; volume of 60 cm^3) containing a peat-based substrate (Promix Bx, Premier Horticulture, Rivière-du-Loup, QC, Canada). The chosen cultivar is well adapted to southeast and northeast regions of North America having early maturity and a bright red uniform colour (Wehner, 2002). After the appearance of the first true leaves, seedlings were watered as required and fertilized (in mg·L^{-1}) for 3 weeks with 200 N, 88 P, and 166 K, 0.2 B, 0.5 Cu, 1.0 Fe, 0.5 Mn, 0.005 Mo, and 0.5 Zn; then for 2 weeks with 400 N, 176 P, 332 K, 0.4 B, 1.0 Cu, 2.0 Fe, 1.0 Mn, 0.01 Mo, and 1.0 Zn (Plant Products, Brampton, ON, Canada).

5.3.2 Experimental design and treatments

The effects of saline (2.5 $dS \cdot m^{-1}$) drip irrigation timing and mulch on bell pepper plants following transplanting were studied under a 6 x 2 factorial experiment in a randomized complete block design in greenhouse conditions. The timing of saline drip irrigation had six levels: i) None (non-saline irrigation), ii) S1S2 (saline irrigation from transplanting to fruit set), iii) S1S4 (saline irrigation from transplanting to flowering, then during harvest), iv) S2S3 (saline irrigation from flowering to first harvest), v) S3S4 (saline irrigation after fruit set), and vi) All (only saline irrigation throughout growth). And the mulch had two levels: black polyethylene mulch (Climagro, Plastitech, St-Remi, QC, Canada) and bare soil. All combination treatments (12) had eight replications. Each plant constituted an experimental unit.

To make the saline solution, NaCl (Fisher Scientific, Whitby, ON, Canada) and $CaCl_2$ (Anco Chemicals, Maple, ON, Canada) in a 2:1 ($NaCl:CaCl_2$) ratio on a molar basis (Dalton et al., 1997) were added to tap water (0.2 $dS \cdot m^{-1}$) and adjusted using a portable conductivity-meter with automatic temperature compensation (Model TDSTestr4TM, Oakton, Singapore). The concentrations of Na^+, Ca^{2+} and Cl^- were 13.8, 6.9 and 27.6 ($mmol \cdot L^{-1}$), respectively. The saline solution had a value of 0.7 as the ratio of $Na^+/(Na^+ + Ca^{2+})$, which is within the range (0.1-0.7) found for most saline waters used to irrigate major horticultural crops around the world (Grattan and Grieve, 1999).

5.3.3 Experimental setup and plant management

A mixture of sandy loam soil (70% sand, 18 % silt and 12% clay) and peat-based growing media (Promix Bx, Premier Horticulture, Rivière-du-Loup, QC, Canada) at a ratio of 2:1 (v/v) was placed into 96 10-L black plastic pots (24 cm inside diameter x 22.5 cm height; Classic 1000, Nursery Supplies, Orange, CA, USA). The soil-mix is henceforth referred to as soil. The pots were set in eight blocks of 12 plants spaced 55 cm between and 45 cm within rows. Pots corresponding to the mulch treatment had the black polyethylene mulch (Climagro, Plastitech, St-Remi, QC, Canada) placed directly on the soil surface, stretched and taped to the rim of the pots, and holes (16 cm^2) cut in the centre of the mulch for the pepper plants. Seedlings with six true leaves were transplanted into the pots on 19 January 2005 to initiate the experiment.

A drip irrigation system consisting of on-line pressure compensating drippers with snout (Netafim, Fresno, CA, USA) and spaghetti tubes was used. Each treatment had a separate irrigation line (rigid polyethylene pipe of 1.24 cm inside diameter) with eight drippers and an independent valve to control the irrigation supply to eight plants. Each plant received water through a single spaghetti tube connected to a dripper (flow rate of 1.1 $L \cdot h^{-1}$) and secured with an angled stake inserted in the soil. Saline or non-saline solutions were stored in six reservoirs (120-L capacity) and pumped (operating pressure of 50 kPa) to the irrigation lines by a submergible pump (Model PE-2H-PW, Little Giant Pump, Oklahoma City, OK, USA).

Time domain reflectometry (TDR) was used to measured soil moisture in order to determine when to irrigate. Three-rod (stainless steel, 21 cm length, 3 mm thickness, and separated 4 cm apart) probes were transversally installed at depths of 5, 10 and 15 cm, respectively, in 3 pots per treatment. The probes were connected to the TDR Tektronix Cable Tester (Model 1502B, Tektronix, OR, USA) using a coaxial cable for determinations of the apparent length (m) of probes embedded in the soil (X_w) as graphically indicated on the TDR screen, which in turn were used for the dielectric constant, ε_b, (electric transmissivity) calculations of a soil matrix (Topp et al., 1980):

$$\varepsilon_b = \left(\frac{X_W}{L}\right)^2 \qquad \text{(Eq. 5.1)}$$

where, L is the actual length of the probes (m) embedded in the soil. Soil moisture was determined according to Topp et al. (1980):

$$\theta_v = -5.3\times10^{-2} + 2.9\times10^{-2}\varepsilon_b - 5.5\times10^{-4}\varepsilon_b^{\,2} + 4.3\times10^{-6}\varepsilon_b^{\,3} \quad \text{(Eq. 5.2)}$$

where, θ_v is the volumetric soil water content ($m^3 \cdot m^{-3}$). Irrigation was applied when 30% of the plant available water (PAW, 0.24 $m^3 \cdot m^{-3}$) was depleted. The amount of water applied was calculated by the following formula:

$$I = (\theta_f - \theta_s)\, V_s \qquad \text{(Eq. 5.3)}$$

where, I is the irrigation requirement (L/plant), θ_f is the soil moisture at field capacity (0.35 $m^3 \cdot m^{-3}$ at −30 kPa of soil matric potential), θ_s is the instantaneous soil moisture ($m^3 \cdot m^{-3}$) at the irrigation time and V_s is the volume of soil to be wetted (L/pot).

Fertilization rates were based on a population density of 24,700 plants/ha. Nitrogen, phosphorus and potassium (NH_4NO_3, $NH_4H_2PO_4$, KNO_3) fertilization was applied at the beginning of each growth stage: transplanting-vegetative stage, appearance of the first flower, first fruit set, and first harvest of fruits at a rate of 25 kg $N \cdot ha^{-1}$, 10 kg $P_2O_5 \cdot ha^{-1}$ and 10 kg $K_2O \cdot ha^{-1}$ each time. At fruit set, plants were staked and tied. A preventative biological insect control program for aphids: parasitic wasps (*Aphidius colemani*) and gall midge (*Aphidoletes aphidimyza*); thrips: predatory mites (*Amblyseius cucumeris*); white flies: parasitic wasps (*Eretmocerus eremicus & Encarsia formosa*); and spider mites: two-spotted spider mite (*Tetranychus urticae*; Koppert Biological Systems, Scarborough, ON, Canada) was used twice during the experiment.

5.3.4 Evaluation of soil temperature

Copper-constantan thermocouples were used to measure root zone temperature (Scott, 2000) in a total of 24 pots (2/treatment). The thermocouples were placed at soil depths of 5 and 15 cm, and connected to a datalogger (CR10, Campbell Scientific, Logan, UT, USA) to store data of soil temperature averaged on an hourly basis.

5.3.5 Evaluation of physiology

Measurements of net CO_2 assimilation (photosynthesis) (A), leaf transpiration rates (E) and stomatal conductance (g_s) were taken four times from transplanting until final harvest. The fourth fully expanded leaf (Chartzoulakis and Klapaki, 2000; De Pascale et al., 2003) from the top of four plants per treatment were used. Measurements were taken between 1100 and 1300 h with a portable photosynthesis meter (Model LI-6400, LICOR Biosciences, Lincoln, NE, USA).

Water use efficiency (WUE) was calculated accordingly to both the physiological (Jones, 2004) and agronomic (Gregory, 2004) approaches:

$$WUE_p = \frac{A}{E} \qquad \text{(Eq. 5.4)}$$

where, WUE_p is the water use physiological efficiency (μmol $CO_2 \cdot mmol^{-1}$ H_2O), A is the net CO_2 assimilation (μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$) and E is the leaf transpiration (mmol $H_2O \cdot m^{-2} \cdot s^{-1}$); and

$$WUE_a = \frac{Y_m}{I} \qquad \text{(Eq. 5.5)}$$

where, WUE_a is the water use agronomic efficiency (g·L^{-1}), Y_m is the marketable fruit yield (g/plant) and I is the amount of water applied by irrigation (L/plant).

5.3.6 Evaluation of growth and quality of fruit yield

At final harvest, plants were divided into roots and shoots to determine fresh weight; then, shoots were separated into stem, leaves, flowers and fruits. Components were oven dried at 70°C for 72 h to determine dry weights. The fresh root to shoot (R/S) ratio was calculated as follow:

$$R/S = \frac{FWR}{FWS} \qquad \text{(Eq. 5.6)}$$

where, *FWR* and *FWS* are the fresh weight (g/plant) of roots and shoots (stems + leaves + fruits), respectively.

Mature fruits were harvested, counted and weighed fresh (g/plant). Fruit were graded based on the following market classifications.

- Marketable grade 1. Fruit weight ≥ 100 g (Aziz, 1994; Rigby, 1988) with uniform shape and less than 3 small scratches (Aziz, 1994).
- Marketable grade 2. Fruit weight ≥ 80 g (Jolliffe and Gaye, 1995) but ≤ 100 with uniform shape and less than 3 small scratches (Aziz, 1994).
- Non-marketable or culls. Fruit weight ≤ 80 g or any fruit weight with injuries (more than 3 small scratches) and/or anomalous shape or characteristics (blossom end rot, sunscald, etc) (Aziz, 1994; Rigby, 1988).

Harvest index, *HI*, was calculated according to the following formula:

$$HI = \frac{Y_m}{FWS} \quad \text{(Eq. 5.7)}$$

Fruit length (cm) and width (cm) were measured using a caliper. Three to five mL of pepper juice at room temperature were placed on a refractometer (0 to 32% Brix grade; ATC-1E, Atago, Japan) to determine total soluble solids (TSS).

5.3.7 Evaluation of soil salinity

Samples of soil were obtained by coring with a cylindrical auger at two different depths: 0-10 and 10-20 cm from four pots per treatment. Further, the soil samples were air-dried for laboratory determinations of the electrical conductivity of soil/water extracts 1:5 ratio ($EC_{1:5}$) following the procedure of Rhoades (1996). Additionally, in order to determine the electrical conductivity of the saturation soil paste extract (EC_e) by the procedure of Rhoades (1996), a composite sample per treatment was formed including soil from the two soil layers. Initial soil salinity level was of 0.73 $dS{\cdot}m^{-1}$ of EC_e.

5.3.8 Statistical analysis

Data were subjected to analyses of variance (ANOVA) using the procedure GLM of SAS (v. 9.1, SAS Institute, Cary, NC, USA). Comparisons among means were made using a Tukey test (P=0.05) when ANOVA indicated model and treatment significances.

5.4 RESULTS

5.4.1 Soil conditions and irrigation

Soil temperatures were significantly higher under mulch compared with bare soil throughout the experiment (data not shown). Differences in soil temperature were greater in the early morning and at night than during midday (Figure 5.1).

Plant received between 68 and 89 L/plant (Table 5.1). Regardless of the type of irrigation supplied, mulched plant used 7% less water than plants grown in bare soil. Water requirements increased as the plants developed and set fruit. The longer the plants were exposed to saline irrigation the lower the water uptake was. Plants irrigated with saline water at all times (ALL), or during fruiting growth stage (S1S4 and S3S4) received more saline water relative to non-saline (>78%).

Soil salinity (measured as electrical conductivity of soil/water extracts 1:5 ratio, $EC_{1:5}$) was significantly higher when saline water was applied during fruiting growth stage compare to other treatments (Table 5.2). Mulched soil had significantly lower (38%) $EC_{1:5}$ than bare soil. The concentration of salts ($EC_{1:5}$) was 56% higher in the top (10-cm) than in deeper (20 cm) soil layer. The significant interaction between saline treatments and soil depth indicated that $EC_{1:5}$ increased at different rates being greater at 0-10 than 10-20 cm (Figure 5.2). The longer the exposure to salinity, the higher the $EC_{1:5}$. The mulch by soil depth interaction for the $EC_{1:5}$ showed that mulched soil significantly concentrated less salts at both soil depths than bare soils (Figure 5.3). Soil pH, measured in the saturation soil paste extract, was slightly decreased with saline irrigation proportionally to the amount of saline irrigation applied (Table 5.2).

5.4.2 Physiology

During vegetative growth there was no effect of saline irrigation or mulch on the rate of stomatal conductance (Figure 5.4). However, at flowering, saline irrigation (S1S2 and All) in mulched plants increased significantly the rates of stomatal conductance compared with plants grown in bare soil (Figure 5.4). Similarly, at fruit set, saline irrigation applied during this period (S2S3) only decreased significantly rates of stomatal conductance in plants grown in bare soil relative to mulched plants. At this growth stage, it was also observed that the deleterious effect of saline irrigation, previously applied during vegetative growth stage (S1S4), was only presented in plants grown in bare soil since they did not recover their rate of stomatal conductance as quickly as mulched plants (Figure 5.4). During fruiting growth stage, use of saline irrigation from fruit set onwards (S3S4) significantly decreased stomatal conductance rates in plants grown in bare soil compared with their mulched counterparts (Figure 5.4). Similarly, irrigation with non-saline water (None) significantly increased stomatal conductance rates in mulched plants relative to plants grown in bare soil.

Saline irrigation applied during vegetative and flowering growth stages (S1S2, All) significantly reduced rates of transpiration in plants grown in bare soil relative to mulched plants (Figure 5.5). At fruit set, saline irrigation applied during flowering and fruit set (S2S3) significantly reduced transpiration rates in mulched plants compared with the ones grown in bare soil (Figure 5.5). Comparable transpiration rates were observed when saline irrigation was initiated at fruit set (S3S4) in both conditions of mulch. At this growth stage, the residual effect of saline water applied at vegetative growth (S1S4) was still decreasing rates of transpiration in plants grown in bare soil relative to their mulched counterparts (Figure 5.5). During fruiting growth stage, irrigation with non-saline water (None) slightly increased transpiration rates in mulched plants compared with plants grown in bare soil (Figure 5.5). It was also observed that saline irrigation during fruiting growth (S1S4, S3S4) in mulched plants had similar effects on transpiration rates to the control irrigation treatment (either mulched or bare soil). However, S1S4 and S3S4 significantly reduced rates of transpiration in plants grown in bare soil compared to mulched plants irrigated with non-saline water (None), and comparable to mulched plants or plants grown in bare soil of the saline (All) treatment (Figure 5.5). When saline irrigation was applied previously to and suspended during fruiting (S1S2, S2S3), comparable rates of transpiration were obtained regardless of mulch (Figure 5.5).

Comparable rates of photosynthesis were observed at vegetative growth between treatments with saline irrigation (S1S2, S1S4, All) or non-saline irrigation at this point (None, S2S3, S3S4). However, there was a significant decreased in photosynthesis in plants grown in bare soil relative to mulched plants as result of treatment S1S2 (Figure 5.6). At first flowering, except for the saline (All) treatment, reductions in photosynthesis rates as affected by saline irrigation (S1S2 and S2S3) were greater in plants grown in bare soil relative to mulched plants mirroring the effects of the non-saline irrigation control (Figure 5.6). At fruit set, the effect of saline irrigation initiated at fruit set (S3S4) on photosynthesis was similar in both mulch and bare soil conditions (Figure 5.6). Similar conditions were found in plants irrigated with saline water during vegetative and flowering (S1S2) or continuously (All). However, when saline irrigation was applied during vegetative (S1S4) or initiated before fruit set (S2S3) decreases in photosynthesis were observed in plants grown in bare soil compared with the mulched plants. Indeed, photosynthesis rate by mulched plants of S1S4 was significantly higher to the control (None).

At fruiting growth stage, saline irrigation during the previous growth stage (fruit set) and continuing during fruiting (S3S4) significantly reduced rates of photosynthesis in plants grown in bare soil compared to the mulched plants (Figure 5.6). A similar situation was found in plants receiving non-saline irrigation (None). Saline irrigation treatments applied during fruiting (S1S4 and S3S4) to plants grown in bare soil had comparable effects on photosynthesis to that of the saline (All) treatment applied to plants grown in bare soil. Comparable photosynthesis rates were observed in plants irrigated with saline water during growth stages previous to fruiting (S1S2, S2S3).

5.4.3 Growth

All treatments involving use of saline water significantly decreased root fresh weight compared to the control (Table 5.3). Across irrigation treatments, the root fresh weights of plants grown on mulch and bare soil were comparable (Table 5.3). However, there was an interaction between salinity and mulch. When only plain water was used, roots of plants grown in bare soil were significantly heavier than the roots of mulched plants (Figure 5.7). Conversely, when plants were irrigated with saline water during early growth stages (S1S2), roots of plants grown in bare soil were lighter than roots of mulched plants; no differences between mulch treatments were observed for other saline irrigation treatments.

Shoot fresh weight decreased 14 and 18% when plants were irrigated with saline water during either early (S1S2) or late growth stages (S3S4), respectively, compared with the control plants (Table 5.3). There was no significant difference in shoot weight among the other salinity treatments and these in turn were not different from the control. Mulched plants had 27% heavier shoots than plants grown in bare soil (Table 5.3). Root to shoot ratios were similar among salinity treatments (Table 5.3). However, this ratio was significantly lower in plants irrigated with saline water during fruit growth and development (S1S4, S2S3 and All) compared with the control. Mulched plants had a significantly lower root to shoot ratio compared with plants grown in bare soil (Table 5.3).

The effect of salinity on shoot was due to the leaf rather than stem component (Table 5.3). While there was no difference in stem weight among the salinity treatments, the stems of mulched plants were 15% heavier than the stems of plants grown in bare soil (Table 5.3). Leaf fresh weight decreased by 26 and 21% when plants were irrigated with saline water at early (S1S2) or intermediate growth stages (S2S3), respectively, compared with control plants (Table 5.3). Mulching significantly increased leaf weight by 13% (Table 5.3). Using saline irrigation at early (S1S2, S1S4) or intermediate growth stages (S2S3) significantly reduced the leaf area compared with the control (Table 5.3). The earlier the salinity was applied the more significant the reduction. For leaf weight and area it was better for plants to receive continuous saline irrigation than irrigation only during vegetative development. Mulched plants averaged 22% larger leaf areas than the plants grown in bare soil (Table 5.3).

5.4.4 Fruit production

Comparable yields among saline irrigation treatments were recorded at the first and second harvest (Figure 5.8). Not surprisingly, applying saline water during the fruit development (S3S4) resulted in the lowest cumulative yields of all the treatments at 114 and 140 DAT (Figure 5.8). Compared with non-saline irrigation, it represented decreases of 23 and 24%, respectively. Mulched plants had significantly higher cumulative early yields (1.6 to 1.8 fold) than plants grown in bare soil (Figure 5.9).

Total fruit yield (mature marketable and non-marketable) decreased by 24 and 16% when plants were irrigated with saline water during fruit growth and development or continuously compared with the control (Table 5.4). A significant difference in total yield was found between plants irrigated during fruit development (S3S4) and at flowering and fruit set (S2S3) or with non-saline control. Mulched plants produced 34% greater yields than plants grown in bare soil (Table 5.4). Salinity had no effect on total fruit number but mulching significantly increased the total number of fruit per plant. Seventy nine percent of the control fruits were marketable compared with, on average, only 64% of the fruit irrigated with saline water. Marketable yield mirrored total yield for both salinity and mulching (Table 5.4). Soil salinity (EC_e), as consequence of saline irrigation and mulch treatments, was an important factor reducing marketable yield (Figure 5.10). Interaction between the saline irrigation and mulch indicated that mulched plants produced significantly higher marketable yields at each saline treatment, except when plants were irrigated with saline water during the vegetative and flowering stages (S1S2) (Figure 5.10). Applying saline irrigation either at early (S1S2) or late (S3S4) was harmful to marketable fruit production in mulched plants than applying it at flowering and fruit set

(S2S3) or continuously (Figure 5.10). Use of saline water at late growth stages (S3S4) of the plants grown in bare soil was more deleterious than using saline water at any other growth stages, and comparable to using saline water continuously (Figure 5.10). Plants irrigated with saline water during fruit development produced the least number of fruit significantly lower than plants that had no saline irrigation and those irrigated between flowering and harvest (S2S3) (Table 5.4). More marketable fruits were significantly produced by mulched plants relative to plants grown in bare soil (Table 5.4). Mean fruit weight was significantly reduced (16, 18 and 24%) when plants were irrigated either at early growth stages (S1S2) or late growth stages (S3S4), or continuously compared with no saline irrigation (Table 5.4). Mulching increased mean fruit weight by 6%. Within marketable fruit, Grade 1 commands the highest prices. The proportion of Grade 1 fruit only declined when saline irrigation was used throughout growth and was not influenced by mulching (Table 5.4). Harvest index (HI) was significantly reduced by 33 and 29% when plants were irrigated with saline water during the late growth stages (S3S4) or throughout growth respectively, compared with control (Table 5.4). Mulching the soil significantly increased the HI by 14% (Table 5.4).

Fruit characteristics, including length, width and total soluble solids (TSS) were unaffected by either salinity or mulching (Table 5.5). However, there was a significant interaction of these factors on the TSS of grade 1 fruit (data not shown). When saline water was applied at early growth stages (S1S2), fruits of mulched plants had significantly higher TSS than the plants grown in bare soil. Under bare soil condition, the lowest TSS values corresponded to plants irrigated with saline water either during vegetative growth or continuously compared with the other saline treatments.

5.4.5 Water use efficiency

Similar physiological water use efficiency (WUE_p) was observed between mulched plants and plants grown in bare soil when no saline irrigation was applied from transplanting (Figure 5.11). When plants were irrigated with saline water at either early growth stages (S1S2), intermediate growth stages (S2S3) or late growth stages (S3S4), comparable WUE_p was observed regardless of mulch or bare soil condition (Figure 5.11). However, applying water during vegetative growth, then interrupting saline irrigation at flowering and fruit set, and reinitiating saline irrigation at fruiting growth stage (S1S4) caused plants grown in bare soil to be more efficient in water use (Figure 5.11). Conversely, when saline irrigation was applied throughout growth, mulched plants were physiologically less efficient in the use of water than plants grown in bare soil at early growth stages (vegetative and flowering) but more efficient at late growth stages (fruit set and fruiting) (Figure 5.11).

Regardless of water quality, mulched plants had significantly higher agronomic water use efficiency (WUE_a) than plants grown in bare soil (Figure 5.12). In average, mulching increased WUE_a by 41% compared with bare soil. Agronomic water use efficiency of mulched plants receiving plain water (control) was similar to those irrigated with saline water from flowering to first harvest (S2S3). All other salinity treatments significantly reduced WUE_a by between 21 and 37% compared with the control. For plants grown under bare soil condition, irrigation with saline water reduced the WUE_a compared with the non-saline control but the reduction was only significant when salinity was applied late in the growing season late in the growing season (S3S4) (Figure 5.12).

5.5 DISCUSSION

5.5.1 Irrigation and soil conditions

Although soil temperature in both mulched and bare soil treatments fell within the optimal range for pepper growth and fruit production, the soil temperature was higher under the mulch (Gosselin and Trudel, 1986). This may have contributed to the greater yields in the mulched treatments (Figure 5.1). Similar findings have been reported by Locher et al. (2005) for peppers, and Diaz-Perez and Batal (2002) for tomato.

Water consumption was lower for the mulched treatments since the mulch reduced evaporation which, in turn, mean that less water was used for irrigation and hence less salts (Hoffman and Shannon, 2007) (Tables 5.1 and 5.2). However, evaporation from the bare soil likely induced an upward flow of soil water accumulating salts within the upper layer of the soil (Yaron et al., 1973).

As the duration of exposure to salinity increased, the water consumption decreased. This decrease was most likely due to reductions in root zone osmotic potential (Munns, 2002). Decline in water consumption by salinity have been reported for pepper (Cabañero et al., 2004), tomato (Reina-Sanchez et al., 2005; Romero-Aranda et al., 2001) and cucumber (Savvas et al., 2005). Salts accumulated in the soil as a consequence of salt loading by saline irrigation may have played a role in lowering soil pH (saturation soil paste extract). Reduction of the soil pH may indicate a higher cation (Na^+, Ca^{2+}) uptake relative to anion (Cl^-) uptake. Cation uptake by the plants may have lowered the soil pH by increasing concentration of H^+ in the rhizosphere by root excretion to stoichiometrically balance the cation uptake (Darrah, 1993; Haynes, 1990).

5.5.2 Physiology

Based on stomatal conductance, transpiration and photosynthesis results, it could be possible to temporarily apply saline irrigation to mulched plants, rather than to plants grown in bare soil, during either early (vegetative and flowering), intermediate (flowering and fruit set) or late (fruit set and onwards) growth stages. No effects were found in stomatal conductance when saline water was applied during vegetative growth stage (Figure 5.4). However, mulched plants had higher transpiration and photosynthesis rates than plants grown in bare soil, although this effect was not consistent for all treatments at this growth stage, even though they received similar amounts of saline water (Figures 5.5 and 5.6). However, it could be argued that the salt concentration in the root zone during vegetative growth was not high enough to lower osmotic potential and, consequently, negatively affect water relations (Munns, 2002; Munns and Tester, 2008). When saline water was applied during the first two growth stages, mulched plants adapted physiologically to saline conditions as opposed to plants grown in bare soil, thus increasing stomatal conductance, transpiration and photosynthesis rates. Similarly, mulched plants achieved higher stomatal conductance, transpiration and photosynthesis values than plants grown in bare soil when saline irrigation was applied during flowering and fruit set or during late growth stages (fruit set and fruiting). This could be due to the lighter salt load by irrigation to the mulched soils compared with the bare soil. The higher salt load of the latter might have lowered the osmotic potential and could have induced partial closure of stomata, ultimately affecting stomatal conductance, photosynthesis, transpiration and water uptake (Munns and Termaat, 1986; Munns et al., 1995). A second phase of plant response to salinity is due to salt accumulation in the plant (Munns and

Tester, 2008; Munns et al., 1995), which could have occurred in the saline treatment during the last two growth stages.

Interestingly, plants grown in bare soil did not recover normal physiological performance as quickly as mulched plants at fruit set after being irrigated with saline water during vegetative growth. Even though salt stress was apparently low at this stage, the increased salt level coupled with rapid changes in soil moisture might have lowered stomatal conductance, and hence, transpiration and photosynthesis (Taiz and Zeiger, 2002). This physiological response is an adapting mechanism to salinity and water stress (Munns, 2002; Taiz and Zeiger, 2002). Pepper plants have been reported to be susceptible to both moderate and long-term water stress which declined stomatal conductance, thus decreasing photosynthesis (Delfine et al., 2001; Delfine et al., 2002).

5.5.3 Growth

Growth, particularly that of the roots, was negatively affected by salinity (Table 5.3, Figure 5.7). The effects on roots may be greater due to their proximity with the soil salt concentration, and the salt accumulation in the plant due to its restricted ability to exclude salts (Bethke and Drew, 1992). Peppers roots were reported to concentrate higher levels of Na^+ and Cl^- in the roots than in the shoots when grown in saline conditions (Blom-Zandstra et al., 1998; Chartzoulakis and Klapaki, 2000). It was more deleterious for leaf production to apply saline water on a temporal basis rather than continuously. Shoot growth was reduced when saline water was applied at either early growth (S1S2) because of leaf growth reduction, or at late growth (S3S4) because of decreases in fruit production. Prior to fruiting, leaf growth was susceptible to salinity than stems possibly because osmotic potential may have reduced water uptake during these growth periods, thus reducing plant growth (Munns, 2002). Additionally, salt accumulation within the plant could have occurred. It has been found that Cl^- concentrated more than Na^+ in the leaves (Chartzoulakis and Klapaki, 2000). Since Cl^- was the most abundant ion in our irrigation water, it is possible that its accumulation in the leaves could have occurred at levels that reduced or retarded leaf growth. Therefore, when fruit competed with other organs of the plants, leaf growth could have been inhibited by fruit growth even when irrigated with fresh water during fruiting.

Shoot growth was enhanced by the use of mulch (Tables 5.3). Growth increases may be due to slight but consistently higher soil temperature in mulched soils throughout the growing period. Similar results for these and other growth parameters have been reported by other authors for bell peppers grown in mulch and non-saline conditions (Aziz, 1994; Locher et al., 2005; Siwek et al., 1994). Mulching reduced the rate of soil water depletion and maintained more uniform soil moisture within the root zone. The improved soil moisture condition stimulated growth and increase fresh and dry weight of the aerial parts of the plant relative to bare soil (Kirnak et al., 2003).

5.5.4 Fruit production

Reductions found in growth of the vegetative parts of the plants as result of saline irrigation during growth stages prior to fruiting did not ultimately affect fruit production across mulch treatments (Table 5.4). Conversely, applying saline water during fruiting or throughout growth significantly reduced early (Figure 5.8), total and marketable yields (Table 5.4). Under saline condition with no leaching or minimized leaching of salts, as in our case, saline irrigation applied during fruit growth (S3S4) loaded and concentrated more salts and, likely, lowered the root zone osmotic potential soon. Since fruit growth represents about 50% of the total growth and, therefore, is dominant over other parts of the plant at this stage (Miller et al., 1979), it was expected that fruit production declined because of salt stress caused by deleterious effects on water uptake (osmotic phase) and possibly induction of high salt concentration within the plant (ionic phase) (Munns, 2002; Munns and Tester, 2008). This observation was further supported by the harvest index values which indicated saline water applied during fruiting growth stage (S3S4) or throughout the experiment suppressed marketable fruit production rather than the other aerial parts of the plant.

Under the premise of saving water regardless of its quality, it would be advisable to not irrigate with saline water during fruiting in those areas where rainfall does not occur during this growth stage to leach salts away from the root zone (e.g. semiarid or arid zones). Otherwise, it could be recommendable to use 25% more water than the required rate (e.g. ET_c) such as to leach salts (Assouline et al., 2006). However, this figure may depends on the water quality; the higher the level of water salinity the greater the amount of irrigation water required (Ben-Gal et al., 2008). Since all saline treatments had electrical conductivity of the saturation soil paste extract (EC_e) values above threshold (1.5 $dS{\cdot}m^{-1}$) preventing yield reduction (Maas, 1990), the use of mulch should be another factor to consider in marketable fruit production (Figure 5.10). Saline irrigation applied to mulched plants at flowering and fruit set (S2S3) or during vegetative and later fruiting stages (S1S4) produced significantly higher marketable yield than their counterpart plants grown in bare soil (S2S3, S1S4). Better soil conditions (soil moisture and temperature) under mulch, relative to bare soil, might have favored water and nutrient uptake. Therefore, it would be possible that salts concentrated within the plant could have been diluted with growth increase from fruit set to fruiting in the case of S2S3, or the plants would have been able to dilute the salts concentrated within the plant and maintain a dilution rate as uptake of salts occurring simultaneously with growth increase at fruiting.

In general, the longer the exposure to salinity the lower the marketable yield. Interestingly, salinity reduced fruit weight and number but not size suggesting that in the fruit the carbohydrates were used for cell expansion rather than division (Binzel and Reuveni, 1994). Similar to our results, yields of tomato decreased when saline water was applied during fruit development (del Amor et al., 2001; Mizrahi et al., 1988) or at early (first true leaf) growth stage (Mizrahi et al., 1988).

Unexpectedly, there was a significant increase in TSS in fruits of mulched plants when plants received saline irrigation during vegetative and flowering growth stages (S1S2). Better soil condition for mulched plants during the experiment could have favored uptake of Na^+ or Cl^-. These ions concentrated within the plants could have been further translocated to fruits causing decreases in cell water content of fruits by cell osmotic potential effects and, thus, increasing TSS. Similar results have been reported for tomato (Mizrahi et al., 1988). In melons fruits of plants grown on sandy soil in field conditions, compared with the control ($1.2\ dS{\cdot}m^{-1}$), TSS increased significantly when saline irrigation ($7\ dS{\cdot}m^{-1}$) was started 14 d after emergence (DAE) as opposed to starting at 25 and 40 DAE (Bustan et al., 2005). This increase might be associated with increases in total sugar concentration in the leaves especially when saline water is applied during vegetative growth (Carvajal et al., 1998).

Comparisons among the various growth stages to determined sensitivity to salt stress without taking into consideration salt load cannot be easily accomplished. One of the reasons is that the duration of each stage differs and so does irrigation requirement. In the future, one possible strategy might be splitting all growth stages, particularly the set fruit and fruiting, into smaller periods of approximately two weeks or 20 days so that comparisons could be more feasible. Hydroponic conditions may be appropriate to have homogeneous salt concentration in the root zone during the periods of saline irrigation.

Mulching increased fruit weight and number of fruits produced. Our findings are in agreement with those reported for bell peppers grown in non-saline conditions (Brown and Channell-Butcher, 2001; Monette and Stewart, 1987; Siwek et al., 1994). The improvements are likely due to enhanced preservation of soil moisture (Kirnak et al., 2003; VanDerwerken and Wilcox-Lee, 1988), and slightly but consistent higher soil temperature over the growing period (Locher et al., 2005).

5.5.5 Water use efficiency

Physiological water use efficiency (WUE_p) between mulched plants and the ones grown in bare soil was only significantly different when saline irrigation was applied either continuously (All) or during vegetative growth, interrupted during flowering and fruit set, and resumed at fruiting (S1S4) (Figure 5.11). Plants grown on bare soil increased their efficiency in terms of gas exchanges at late growth stages. Photosynthesis was more restricted than transpiration in mulched plants than plants grown in bare soil. In contrast, plants irrigated continuously with saline water showed that mulching increased the rate of CO_2 uptake relative to that of water loss at late growth stages. Under normal conditions, it is expected that the diffusion gradient of CO_2 uptake be smaller than that of transpiration (Chaves et al., 2004). However, in saline conditions WUE_p is improved when leaf stomata limits the gas exchange, although the tradeoff is a reduction in growth because intake and fixation of CO_2 by plants is decreased (Hoffman and Shannon, 2007).

Enhanced agronomic water use efficiency (WUE_a) in mulched plants was the result of more marketable fruit production and less water used, relative to plants grown in bare soil (Figure 5.12). In lights of water conservation and fruit production, use of mulch seemed a feasible technology to implement when using saline irrigation water without leaching requirement. Since efficiency in water use depends on the plant sensitivity to soil salinity (Letey, 1993), it would be recommendable to discontinue saline irrigation before fruiting to avoid heavy salt load into the soil by irrigation, and therefore, to achieve successful fruit production with less water applied (Figure 5.12) and less soil salinization (Figure 5.10) as by treatment S2S3 regardless of growing system. Furthermore, fruit development is characterized by an intense demand for water and nutrients (Miller et al., 1979), which may be altered by the effects of the root zone osmotic potential and salt accumulation within the plant (Grattan and Grieve, 1999; Munns, 2002), ultimately causing reductions in fruit production.

5.6 CONCLUSION

Under conditions of minimal salt leaching, use of black polyethylene mulch increased fruit production and water use efficiency when saline irrigation was applied at flowering and fruit set. The use of saline water at late growth stages, particularly fruiting growth stage, was more deleterious than at any other growth stages.

Table 5.1 Amount of saline (2.5 dS·m^{-1}) and non-saline (0.2 dS·m^{-1}) drip irrigation water (L/plant) applied to bell pepper (*Capsicum annuum* L. var. Red Knight X3R) grown under mulch or bare soil condition.

Timing of saline irrigation (days) [z]	Mulch	Vegetative (22 days)	Flowering (15 days)	Fruit set (40 days)	Fruiting (95 days)	Non-saline	Saline	Total	% saline water
None (0)	Black	6.4	3.6	13.4	55.0	78.4	0	78.4	0
	Bare soil	6.9	3.8	15.8	62.1	88.7	0	88.7	0
S1S2 (37)	Black	**6.5**	**3.5**	12.4	51.7	64.1	10.0	74.1	13.5
	Bare soil	**6.7**	**3.5**	13.3	56.1	69.4	10.2	79.6	12.8
S1S4 (117)	Black	**6.4**	3.5	12.7	**51.8**	16.1	58.3	74.4	78.3
	Bare soil	**6.7**	3.6	13.9	**54.7**	17.5	61.4	78.9	77.9
S2S3 (55)	Black	6.5	**3.6**	**12.1**	54.6	61.1	15.7	76.8	20.4
	Bare soil	6.7	**3.6**	**13.4**	55.6	62.2	17.0	79.2	21.5
S3S4 (135)	Black	6.4	3.5	**10.5**	**49.0**	9.8	59.5	69.3	85.8
	Bare soil	6.8	3.8	**12.1**	**52.4**	10.5	64.5	75.0	86.0
All (172)	Black	**6.3**	**3.3**	**10.7**	**47.5**	0	67.8	67.8	100
	Bare soil	**6.6**	**3.5**	**12.0**	**50.0**	0	72.1	72.1	100

[z] None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering, then during harvest, S2S3 (saline irrigation from flowering to first harvest), S3S4 (saline irrigation after fruit set), and All (only saline irrigation). Note: Values in bold are saline water.

Table 5.2 Effect of saline (2.5 $dS \cdot m^{-1}$) drip irrigation timing and black polyethylene mulch or bare soil on the electrical conductivity of soil/water extracts 1:5 ratio ($EC_{1:5}$) or saturation soil paste extract (EC_e) and pH.

Treatment	$EC_{1:5}$ ($dS \cdot m^{-1}$)	EC_e ($dS \cdot m^{-1}$)	pH [(y)]
A) Timing of saline irrigation [(z)]	**		
None	0.50 b	1.21	7.25
S1S2	1.02 b	2.73	7.05
S1S4	2.57 a	5.37	6.50
S2S3	0.93 b	2.30	6.90
S3S4	2.28 a	5.16	6.75
All	1.99 a	5.56	6.45
B) Mulch	**		
Black	1.18 b	3.00	6.78
Bare soil	1.92 a	4.44	6.85
C) Depth (cm)	**	-	-
0-10	2.16 a		
10-20	0.94 b		
		-	-
A x B	NS	-	-
A x C	*	-	-
B x C	*	-	-
A x B x C	NS	-	-

[(z)] None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering, then during harvest, S2S3 (saline irrigation from flowering to first harvest), S3S4 (saline irrigation after fruit set), and All (only saline irrigation).
[(y)] Measured in the saturation soil paste extract.
*, ** Significant at $P \leq 0.05$ and $P \leq 0.01$, respectively; NS, not significant.
Means with the same letter are not significantly different (Tukey P=0.05).

Table 5.3 Effect of saline (2.5 dS·m^{-1}) drip irrigation timing and black polyethylene mulch or bare soil on fresh weights of roots, shoots, root shoot ratio, stems and leaves, and plant leaf area of bell pepper (*Capsicum annuum* L. var. Red Knight X3R).

Treatment	Fresh weight					Plant leaf area (cm^2)
	Roots [y] (g/plant)	Shoots (g/plant)	R/S ratio [y]	Stems (g/plant)	Leaves (g/plant)	
A) Timing of saline irrigation [z]	**	**	**	NS	**	**
None	143 a	1593 a	0.090 a	92	107 a	4684 a
S1S2	95 b	1368 bc	0.074 ab	90	80 c	2960 c
S1S4	90 b	1406 abc	0.067 b	85	98 ab	3516 bc
S2S3	86 b	1497 ab	0.059 b	83	84 bc	3422 bc
S3S4	95 b	1298 c	0.079 ab	76	99 a	3926 abc
All	78 b	1399 abc	0.057 b	83	94 abc	4043 ab
B) Mulch	NS	**	**	**	**	**
Black	96	1650 a	0.060 b	92 a	100 a	4222 a
Bare soil	100	1204 b	0.082 a	78 b	87 b	3295 b
A x B	**	NS	NS	NS	NS	NS

[z] None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering, then during harvest, S2S3 (saline irrigation from flowering to first harvest), S3S4 (saline irrigation after fruit set), and All (only saline irrigation).
[y] Mean of 4 plants per treatment
*, ** Significant at $P \leq 0.05$ and $P \leq 0.01$, respectively; NS, not significant.
Means with the same letter are not significantly different (Tukey P=0.05).

Table 5.4 Effect of saline (2.5 $dS \cdot m^{-1}$) drip irrigation timing and black polyethylene mulch or bare soil on total and marketable yield of bell pepper (*Capsicum annuum* L. var. Red Knight X3R).

Treatment	Total yield (y) (g/plant)	Total yield (y) (Fruit/plant)	Marketable Yield: Yield (g/plant)	Marketable Yield: (Fruit/plant)	Marketable Yield: Mean fruit weight (g)	Marketable Yield: % grade 1 (x)	HI (w)
A) Timing of saline irrigation (z)	**	NS	**	*	**	*	**
None	1141 a	11.4	900 a	6.9 a	130 a	83 a	0.55 a
S1S2	1002 abc	12.1	646 abc	5.9 ab	109 bc	70 ab	0.47 ab
S1S4	988 abc	11.4	657 abc	5.6 ab	117 ab	78 ab	0.46 ab
S2S3	1053 ab	12.2	767 ab	6.9 a	111 abc	81 ab	0.50 ab
S3S4	862 c	11.6	491 c	4.6 b	107 bc	73 ab	0.37 b
All	960 bc	13.4	555 bc	5.6 ab	99 c	64 b	0.39 b
B) Mulch	**	**	**	**	*	NS	*
Black	1206 a	14.3 a	818 a	7.0 a	117 a	76	0.49 a
Bare soil	796 b	9.8 b	521 b	4.8 b	109 b	73	0.43 b
A x B	NS	NS	*	NS	NS	NS	NS

(z) None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering, then during harvest, S2S3 (saline irrigation from flowering to first harvest), S3S4 (saline irrigation after fruit set), and All (only saline irrigation).

(y) Mature fruits

(x) Percentage of grade 1 with respect to the total marketable yield.

(w) HI is based on marketable yield.

*, ** Significant at P≤0.05 and P≤0.01, respectively; NS, not significant.

Means with the same letter are not significantly different (Tukey P=0.05).

Table 5.5 Effect of saline (2.5 dS·m^{-1}) drip irrigation timing and black polyethylene mulch or bare soil on length, width and total soluble solids (TSS) of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) fruits.

Treatments	Grade 1 (y)			Marketable (x)		
	Length (cm)	Width (cm)	TSS (Brix, %)	Length (cm)	Width (cm)	TSS (Brix, %)
A) Timing of saline irrigation (z)	NS	NS	NS	NS	NS	NS
None	7.59	6.94	8.73	8.03	6.68	8.38
S1S2	7.40	6.87	8.23	12.14	6.58	7.78
S1S4	8.01	7.06	8.05	10.89	6.88	8.06
S2S3	7.28	6.81	8.32	7.01	6.66	8.04
S3S4	7.69	7.03	8.22	9.98	6.74	8.28
All	7.23	6.98	8.12	6.89	6.71	7.99
B) Mulch	NS	NS	NS	NS	NS	NS
Black	7.53	6.99	8.30	9.49	6.75	8.14
Bare soil	7.54	6.90	8.25	8.83	6.67	8.04
A x B	NS	NS	*	NS	NS	NS

(z) None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering, then during harvest, S2S3 (saline irrigation from flowering to first harvest), S3S4 (saline irrigation after fruit set), and All (only saline irrigation).
(y) Percentage of grade 1 with respect to the total marketable yield.
(x) Marketable fruit = grades 1 and 2.
*, ** Significant at P≤0.05 and P≤0.01, respectively; NS, not significant.
Means with the same letter are not significantly different (Tukey P=0.05).

Figure 5.1 A daily representation of the soil temperature in black polyethylene mulched soil and bare soil treatments. Means ±SEM (n=24) were averaged across saline irrigation timing and two soil depths (5 and 15 cm) throughout the growing season.

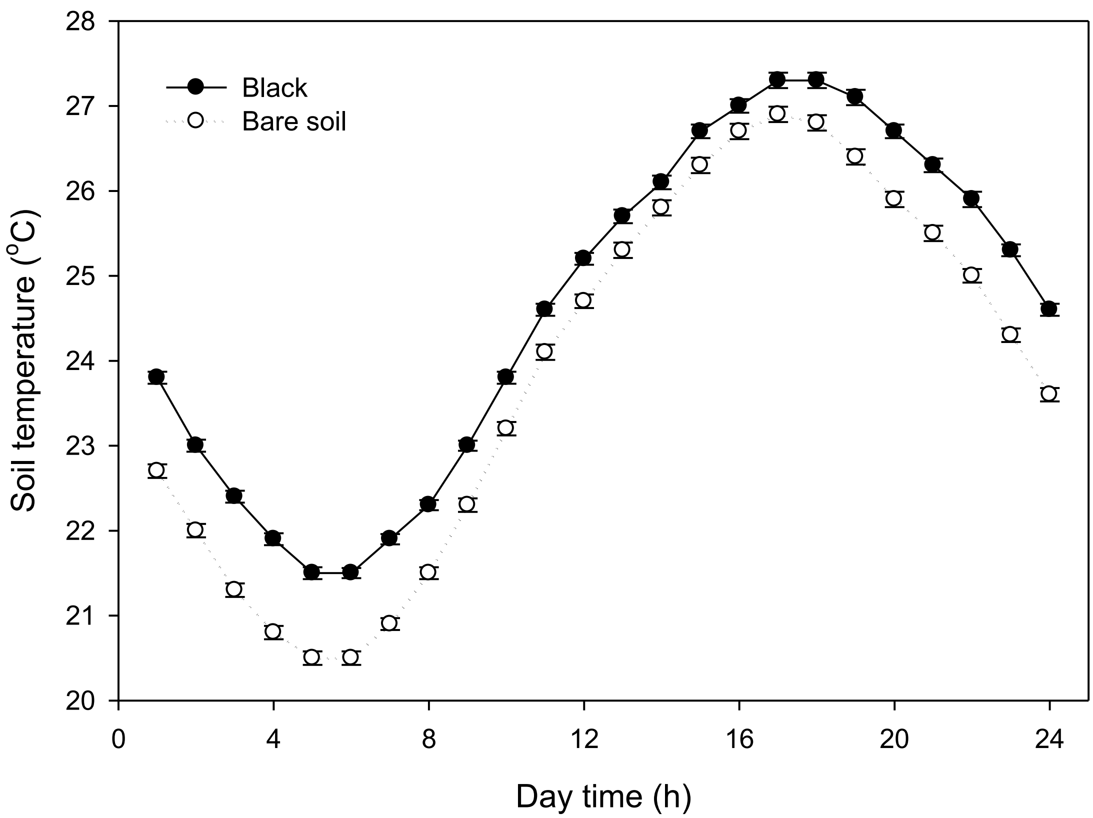


Figure 5.2 Soil salinity (electrical conductivity of soil/water extracts 1:5 ratio, $EC_{1:5}$) as affected by saline (2.5 $dS \cdot m^{-1}$) drip irrigation timing [(z)]. Means ±SEM (n=6) were averaged across mulch levels.

[(z)] None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering, then during harvest), S2S3 (saline irrigation from flowering to first harvest), S3S4 (saline irrigation after fruit set); and All (only saline irrigation).

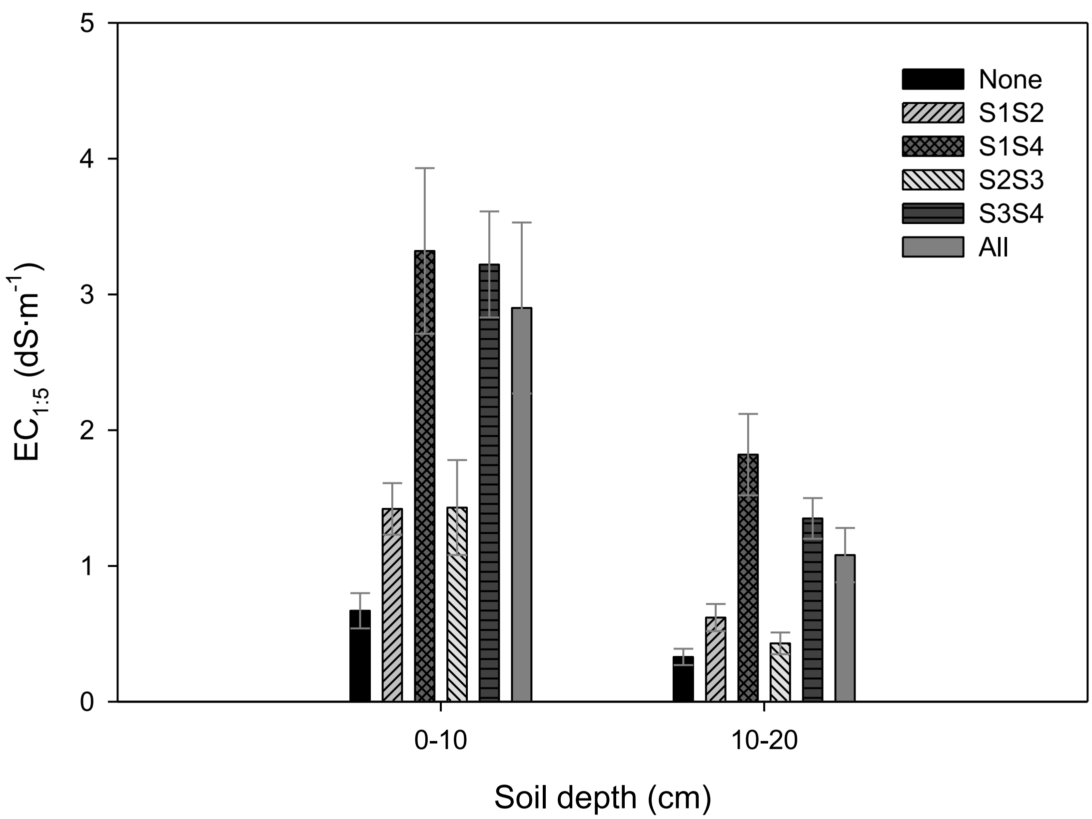


Figure 5.3 Soil salinity (electrical conductivity of soil/water extracts 1:5 ratio, $EC_{1:5}$) as affected by black polyethylene mulch or bare soil at two soil depths (0-10 and 10-20 cm). Means ±SEM (n=18) were averaged across levels of saline irrigation timing.

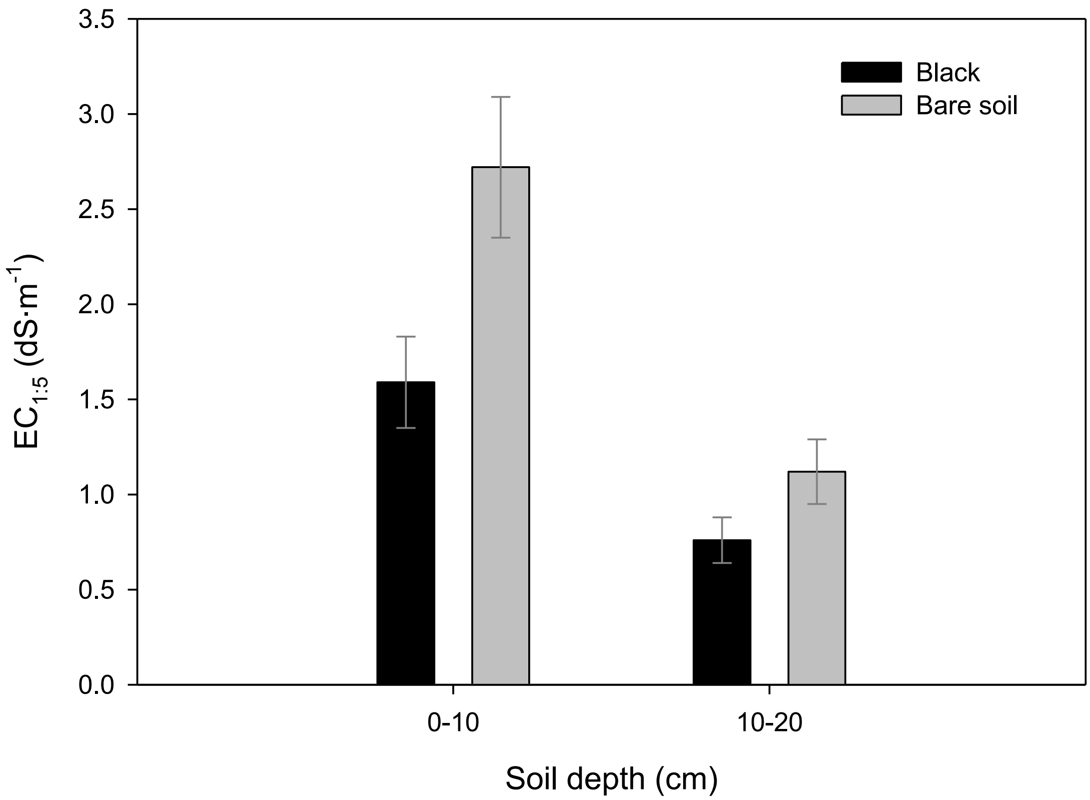
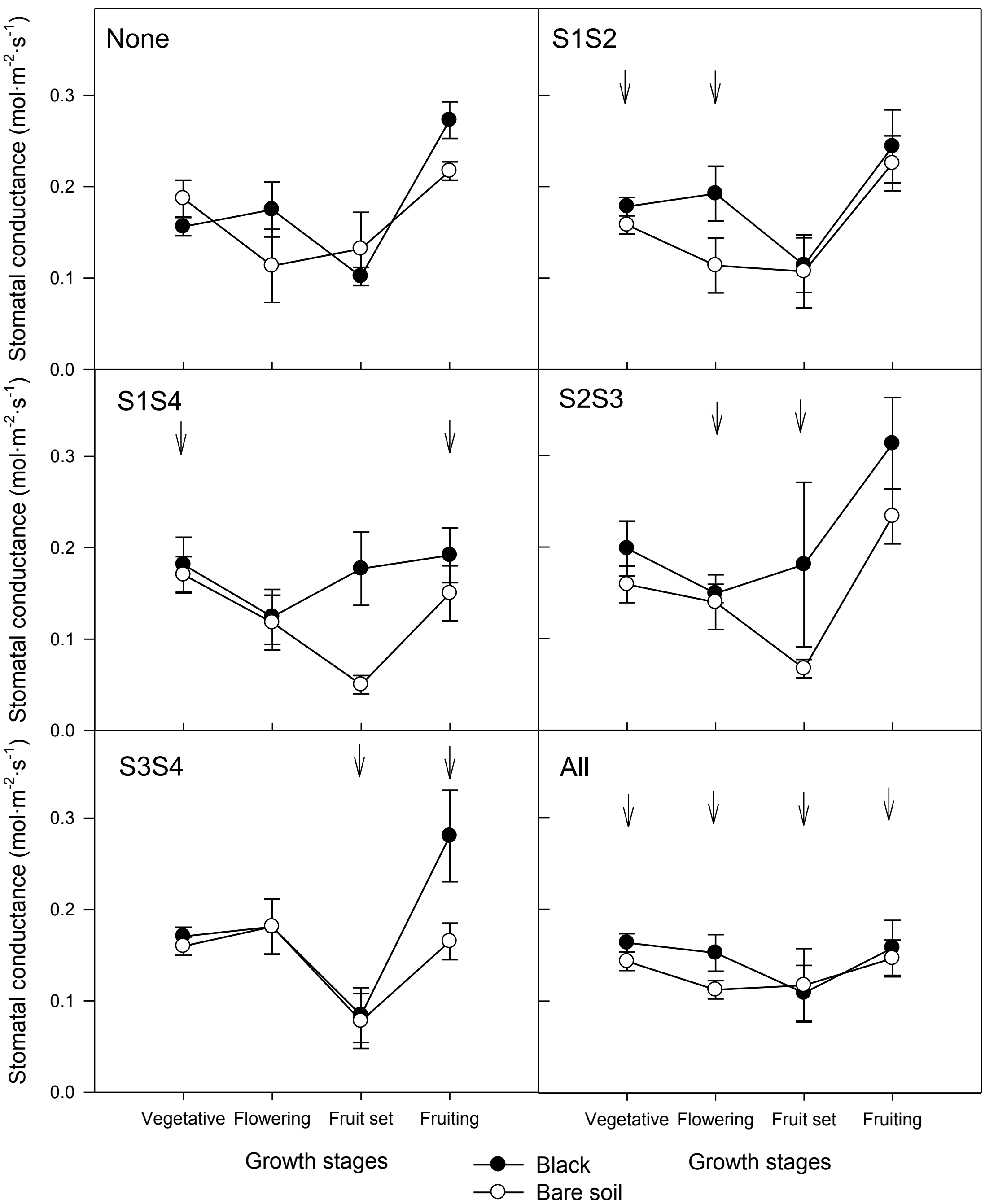


Figure 5.4 Stomatal conductance of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) as affected by black polyethylene mulch or bare soil and saline (2.5 $dS \cdot m^{-1}$) drip irrigation timing [(z)]. Means ±SEM (n=4).

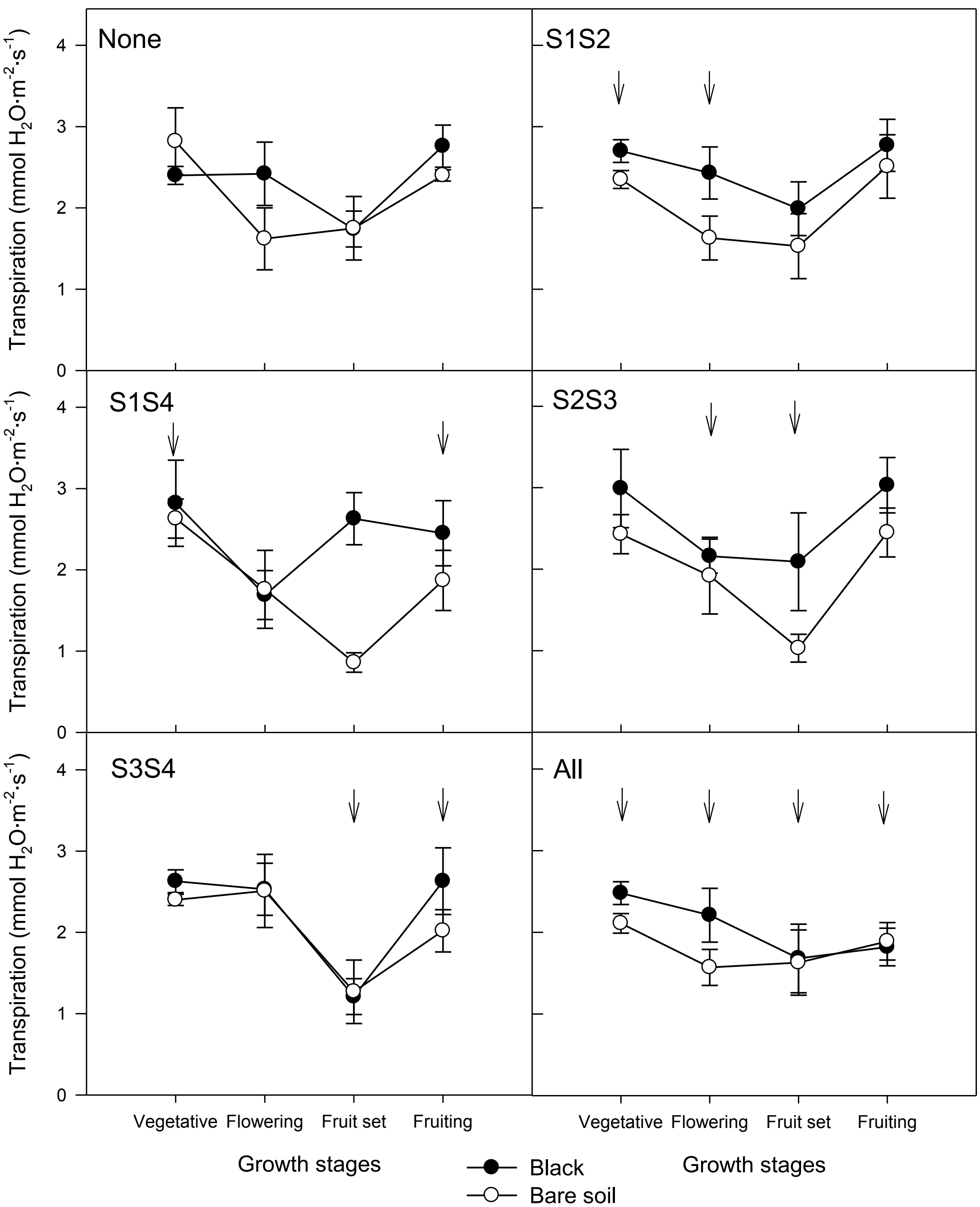
[(z)] None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering, then during harvest), S2S3 (saline irrigation from flowering to first harvest), S3S4 (saline irrigation after fruit set); and All (only saline irrigation). Arrows indicate timing of saline irrigation.



None
S1S2
S1S4
S2S3
S3S4
All
Stomatal conductance (mol·m^{-2}·s^{-1})
0.0
0.1
0.2
0.3
Vegetative
Flowering
Fruit set
Fruiting
Growth stages
Black
Bare soil

Figure 5.5 Transpiration of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) as affected by black polyethylene mulch or bare soil and saline (2.5 $dS{\cdot}m^{-1}$) drip irrigation timing [(z)]. Means ±SEM (n=4).

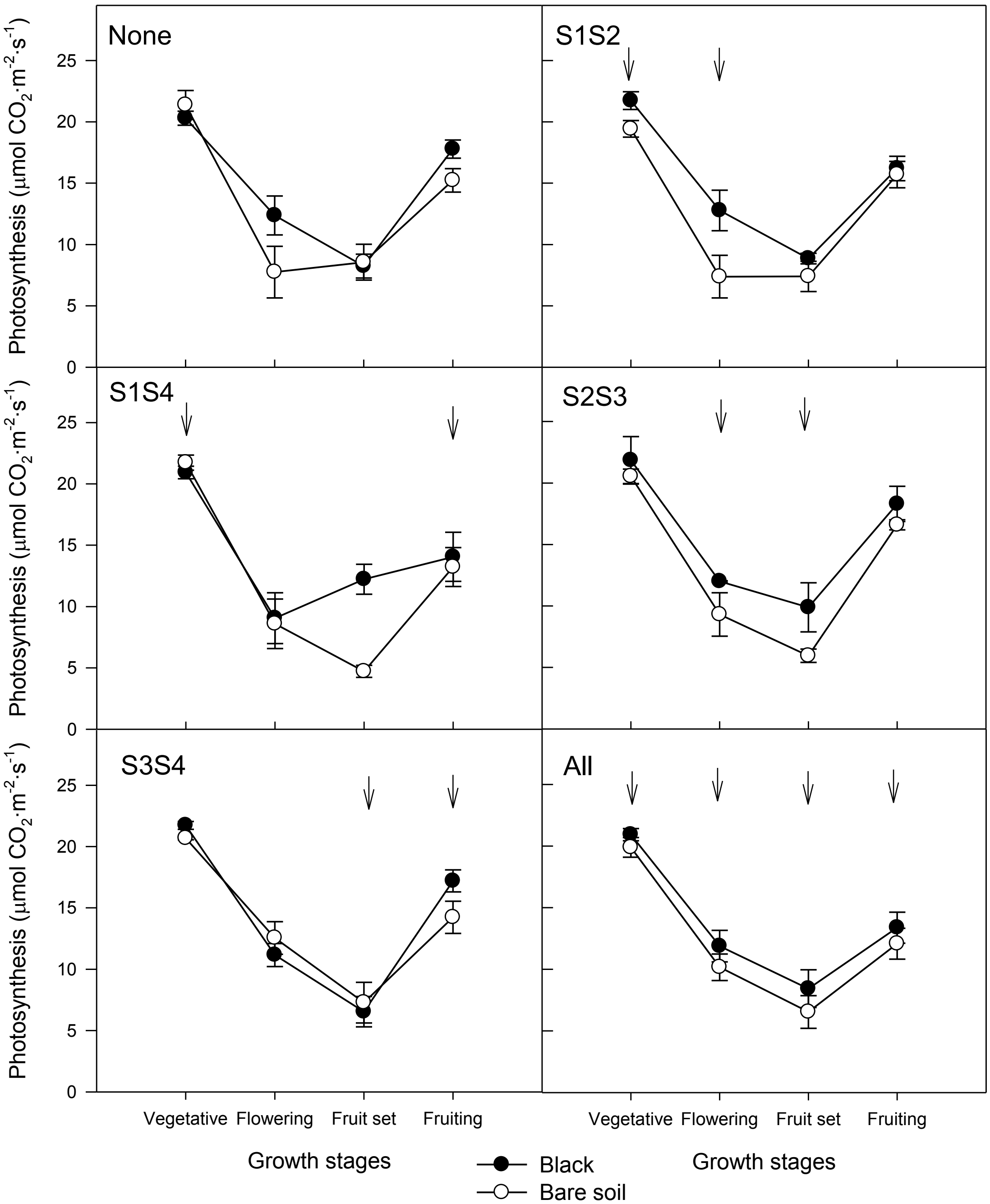
[(z)] None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering, then during harvest), S2S3 (saline irrigation from flowering to first harvest), S3S4 (saline irrigation after fruit set); and All (only saline irrigation). Arrows indicate timing of saline irrigation.



None
S1S2
S1S4
S2S3
S3S4
All
Transpiration (mmol $H_2O \cdot m^{-2} \cdot s^{-1}$)
0
1
2
3
4
Vegetative
Flowering
Fruit set
Fruiting
Growth stages
Black
Bare soil

Figure 5.6 Photosynthesis of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) as affected by black polyethylene mulch or bare soil and saline (2.5 $dS \cdot m^{-1}$) drip irrigation timing [(z)]. Means ±SEM (n=4).

[(z)] None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering, then during harvest), S2S3 (saline irrigation from flowering to first harvest), S3S4 (saline irrigation after fruit set); and All (only saline irrigation). Arrows indicate timing of saline irrigation.



None
S1S2
S1S4
S2S3
S3S4
All
Photosynthesis (μmol CO2·m-2·s-1)
0
5
10
15
20
25
Vegetative
Flowering
Fruit set
Fruiting
Growth stages
Black
Bare soil

Figure 5.7 Root fresh weight of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) as affected by black polyethylene mulch or bare soil and saline drip irrigation timing [(z)]. Means ±SEM (n=4).

[(z)] None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering, then during harvest), S2S3 (saline irrigation from flowering to first harvest), S3S4 (saline irrigation after fruit set); and All (only saline irrigation).

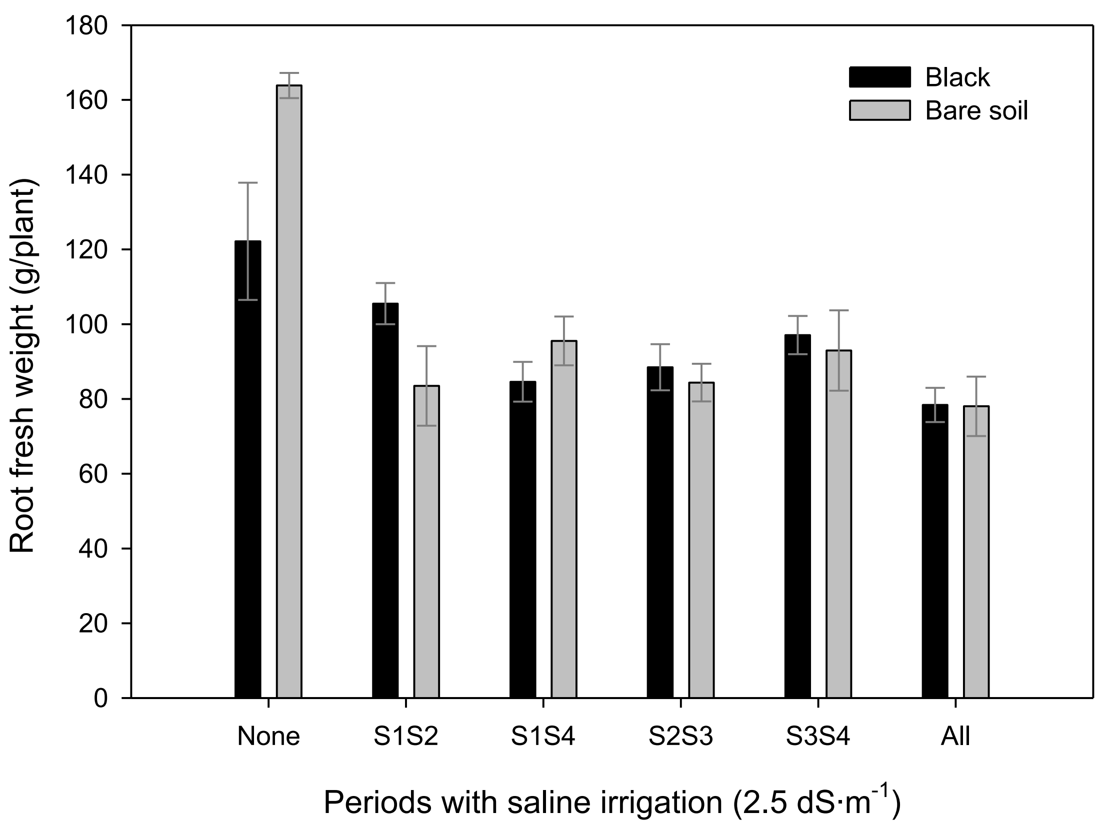


Figure 5.8 Cumulative early total yield of bell peppers (*Capsicum annuum* L. var. Red Knight X3R) as affected by saline (2.5 $dS \cdot m^{-1}$) drip irrigation timing [(z)]. Means ±SEM (n=16) were averaged across mulch levels.

[(z)] None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering, then during harvest), S2S3 (saline irrigation from flowering to first harvest), S3S4 (saline irrigation after fruit set); and All (only saline irrigation).

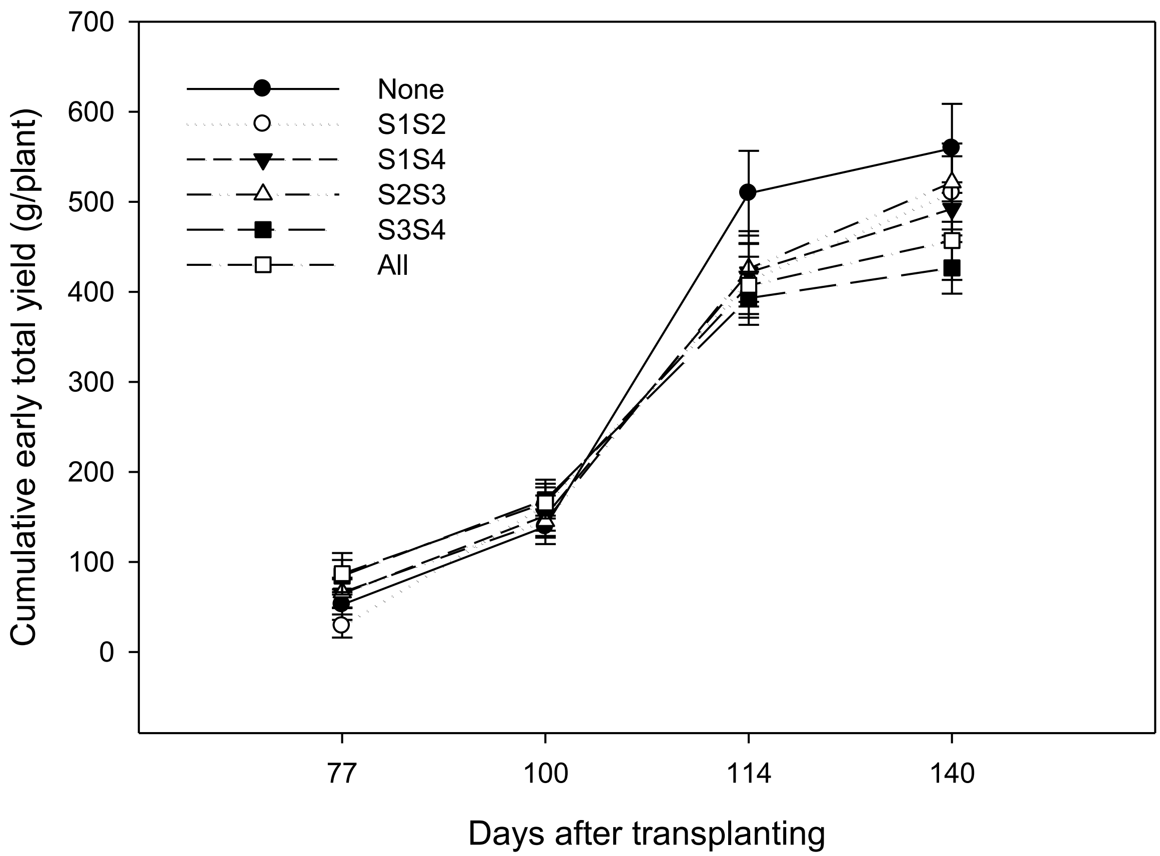


Figure 5.9 Cumulative total marketable yield of bell peppers (*Capsicum annuum* L. var. Red Knight X3R) as affected by black polyethylene mulch or bare soil. Means ±SEM (n=48) were averaged across levels of saline irrigation timing.

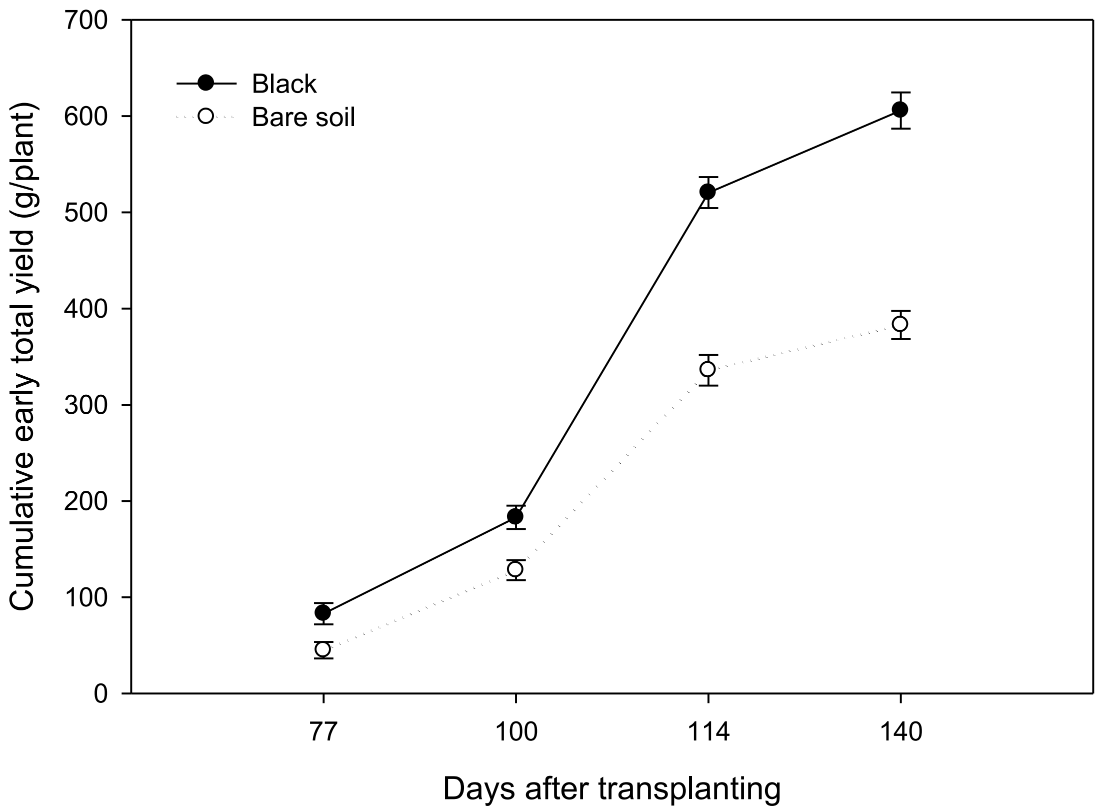


Figure 5.10 Relationship between marketable yield of bell peppers (*Capsicum annuum* L. var. Red Knight X3R) and the electrical conductivity of the saturation soil paste extract (EC_e) as affected by black polyethylene mulch or bare soil and saline (2.5 $dS{\cdot}m^{-1}$) drip irrigation timing [(z)]. Means ±SEM (n=8).

[(z)] None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering, then during harvest), S2S3 (saline irrigation from flowering to first harvest), S3S4 (saline irrigation after fruit set); and All (only saline irrigation).

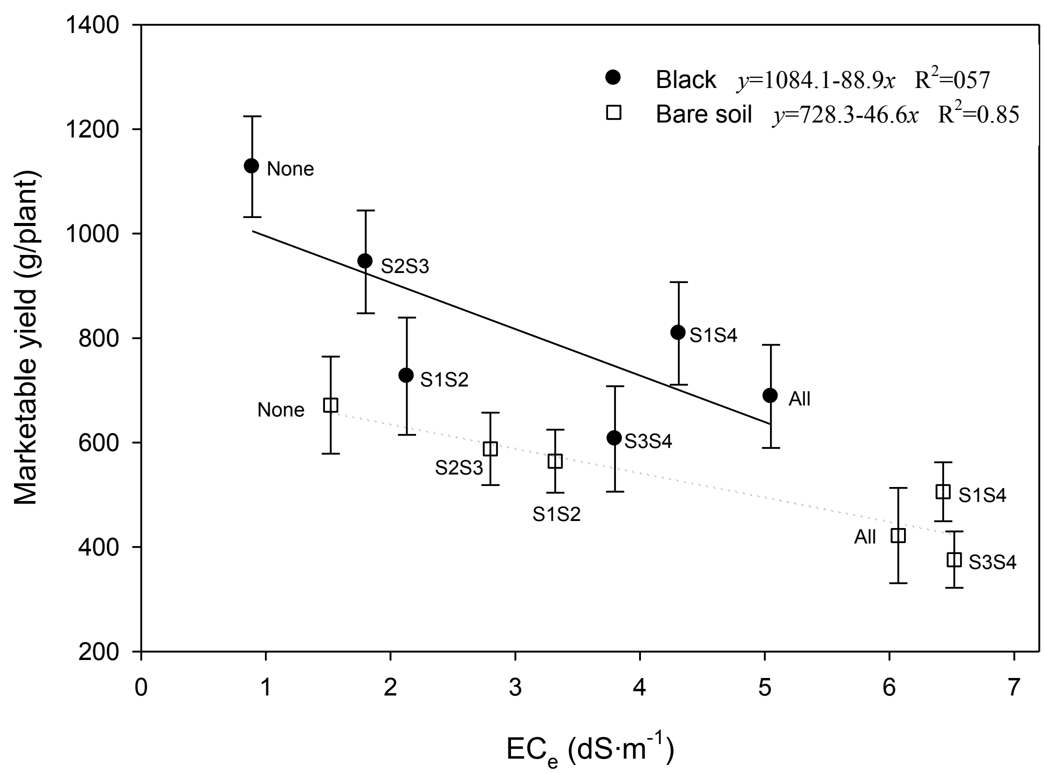
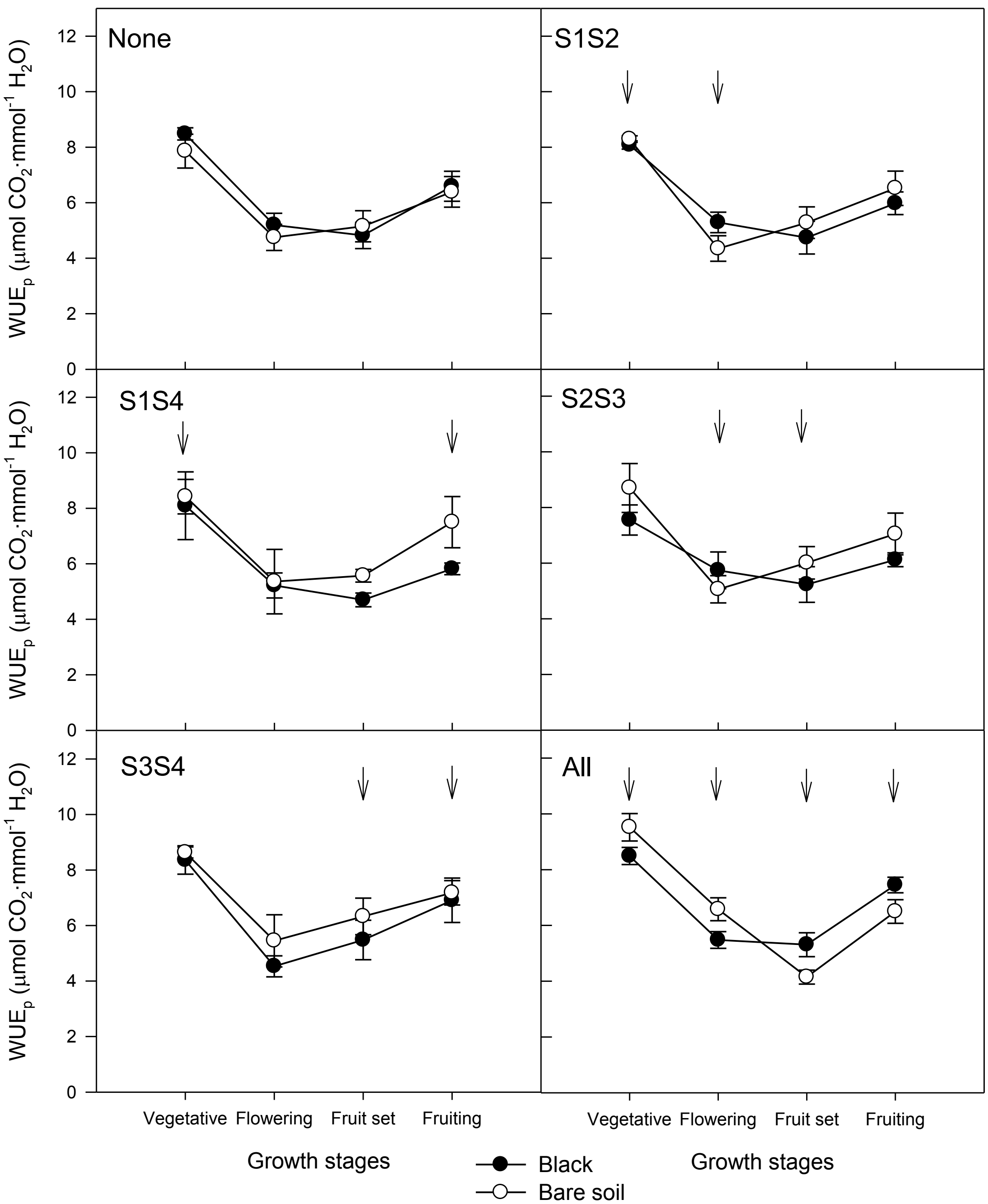


Figure 5.11 Physiological water use efficiency (WUE_p) of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) as affected by black polyethylene mulch or bare soil and saline (2.5 $dS \cdot m^{-1}$) drip irrigation timing [(z)]. Means ±SEM (n=4).

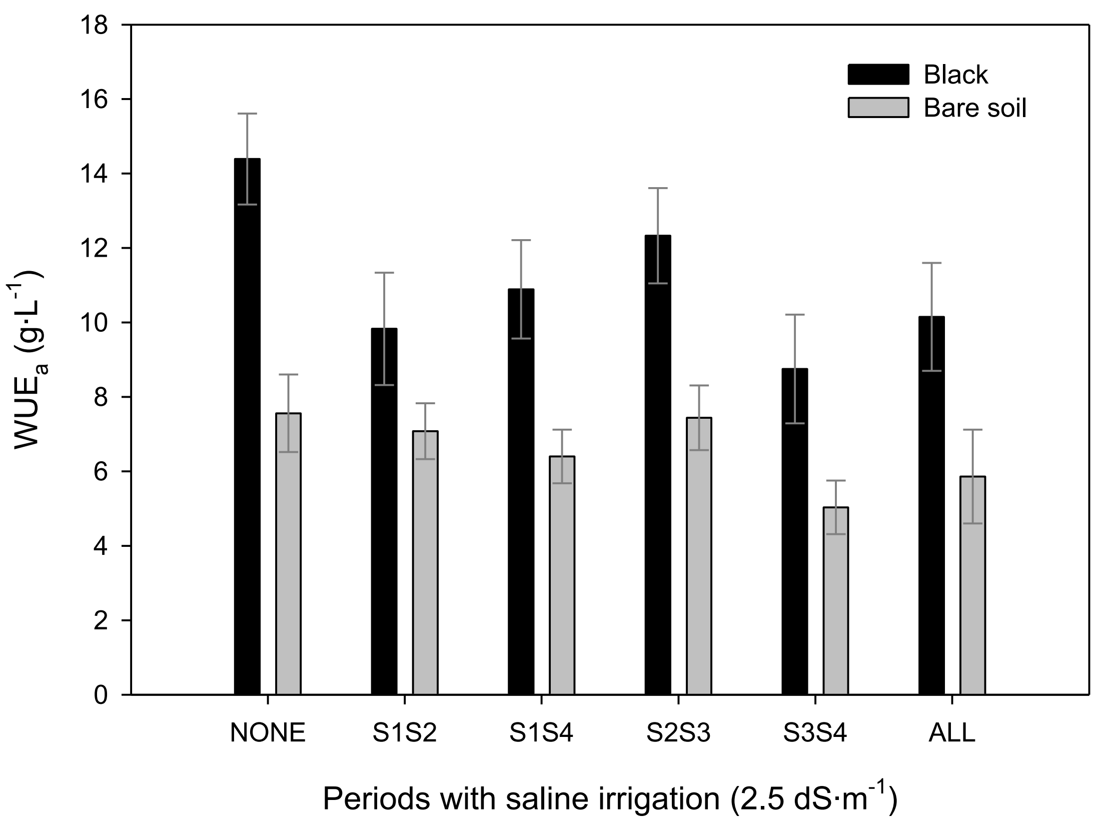
[(z)] None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering, then during harvest), S2S3 (saline irrigation from flowering to first harvest), S3S4 (saline irrigation after fruit set); and All (only saline irrigation). Arrows indicate timing of saline irrigation.



None
S1S2
S1S4
S2S3
S3S4
All
WUE$_p$ (μmol CO_2·mmol^{-1} H_2O)
Vegetative Flowering Fruit set Fruiting
Growth stages
Black
Bare soil

Figure 5.12 Agronomic water use efficiency (WUE_a) of pepper plants (*Capsicum annuum* L. var. Red Knight X3R) as affected by black polyethylene mulch or bare soil and saline drip irrigation timing [z]. Means ±SEM (n=8).

[z] None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering, then during harvest), S2S3 (saline irrigation from flowering to first harvest), S3S4 (saline irrigation after fruit set); and All (only saline irrigation).



Preface to Chapter 6

In Chapter 5, results showed that, under condition of limited or minimal salt leaching, mulched plants irrigated with non-saline water throughout growth or with saline water (2.5 $dS \cdot m^{-1}$) during flowering and fruit set growth stages produced higher marketable yield than plants grown in bare soil and irrigated with non-saline water or saline water at any growth stage. It was also found that the longer the periods with saline irrigation, the greater the soil salinity. However, it remained unanswered as to whether the same results could be obtained under field conditions where frequent salt leaching may occur. Therefore, research was carried out to investigate the effects of saline irrigation timing on two bell pepper cultivars grown on mulch or bare soil, and soil salinity under field conditions.

The present manuscript is co-authored with Katrine A. Stewart and Philippe Seguin. Participation of each author is described in the "Contributions of Authors" section. Tables and figures are presented at the end of this chapter, and references are listed in Chapter 10. Information from this manuscript will be submitted to the *International Journal of Vegetable Science* for peer review. Copyright transfers from co-authors are shown in Appendix B.

Chapter 6

Saline drip irrigation applied at different growth stages of two bell pepper cultivars grown with or without mulch in non-saline soil

Dagobiet Morales-Garcia, Katrine A. Stewart and Philippe Seguin

Department of Plant Science, McGill University, Macdonald Campus

21,111 Lakeshore Road, Ste. Anne de Bellevue, Quebec, H9X 3V9, Canada

6.1 ABSTRACT

The effect of saline (2.5 $dS\cdot m^{-1}$) drip irrigation timing and black polyethylene mulch on two cultivars of bell peppers (*Capsicum annuum* L.) was investigated under field conditions. The research included six irrigation treatments: i) Non-saline irrigation control applied throughout growth (None); ii) saline irrigation from transplanting until formation of the first fruit set (S1S2); iii) saline irrigation from transplanting until appearance of the first flower and from first harvest to final harvest (S1S4); iv) saline irrigation from appearance of the first flower until first harvest (S2S3); v) saline irrigation from fruit set until final harvest (S3S4); and vi) saline irrigation throughout growth (All); two mulch treatments: i) black mulch, and ii) bare soil; and two bell pepper cultivars: i) Early Sunsation, and ii) Red Knight. Stomatal conductance (g_s), transpiration (E) and photosynthesis (A) slightly decreased when saline irrigation was applied at flowering or later (S2S3, S3S4 and All) rather than at a vegetative stage (S1S4). Mulched plants had higher rates of g_s, E and A than plants grown in bare soil. Generally, saline irrigation timing did not affect fresh or dry weight of plants. However, mulched plants had heavier fresh and dry plant weights than the ones grown in bare soil. Similarly, Early Sunsation cultivar had heavier fresh and dry stem and leaf weights than Red Knight. Production of fully ripened fruits was higher in mulched plants regardless of the saline irrigation treatment. Efficiency of physiological water use (WUE_p) was enhanced by saline irrigation applied at flowering or fruit set (S2S3, S3S4 and All) whereas agronomic water use efficiency (WUE_a) was not affected by saline irrigation timing. Mulching improved

WUE_a. In humid areas with non-saline soil, saline drip irrigation could be used with black polyethylene mulch to save water while maintaining fruit production.

Keywords: Salinity, saline water, *Capsicum annuum* L, bell pepper, growth, stomatal conductance, transpiration, photosynthesis, water use efficiency.

6.2 INTRODUCTION

Use of water to irrigate crops will be limited as demand for water for domestic, industrial and recreational activities increase (Bouwer, 2002; Parsons, 2000). Consequently, use of good quality water could be reserved for human consumption. Worldwide, agriculture is the most important user of water (70%) regardless of quality (FAO, 2000). However, this figure could decline in the future due to not only competition among water users for better water quality (Bouwer, 2002) but also decreased availability of water. This is particularly a problem in semiarid or arid regions, but could also extend to semihumid or humid areas (Parsons, 2000; Shalhevet, 1994).

Use of saline water for irrigation may become an unavoidable alternative, particularly in regions where water is scarce (Oron et al., 1999). Therefore, appropriate water management and cultural practices must be included in production systems to reduce soil salinization and maintain crop productivity. Use of both saline and non-saline water could be one approach to water management in many areas around the world (Shalhevet, 1994). In this context, ideally, saline water should only be used during the most salt tolerant growth stages of any crop (Shannon and Grieve, 2000). Alternatively, blending water from both sources until a saline level tolerable to each specific crop is reached could also be another option (Dinar et al., 1986).

Drip irrigation improves water management because it allows for the use of saline water and nutrient solution (fertigation); and also, reduces the irrigated area exposed to evaporation, thus diminishing water consumption (Dasberg and Or, 1999; Skaggs, 2001). Another strategy to reduce the amount of water to irrigate crops with high demand of water (e.g. horticultural crops) is black polyethylene mulch, which preserve soil moisture by minimizing evaporation (Hartz, 1996), and increases soil temperature (Tarara, 2000).

Bell pepper (*Capsicum annuum* L.) is a high value crop generally produced using a plasticultural system that includes drip irrigation and polyethylene mulch (Lamont, 1996). However, this crop should be carefully managed under saline condition because fruit marketable yield could decrease if electrical conductivities of the irrigation water (EC_w) and soil saturated paste extract (EC_e) are higher than 1.0 and 1.5 $dS{\cdot}m^{-1}$, respectively (Maas, 1990; Rhoades et al., 1992). Selection of an appropriate cultivar also plays an important role in pepper production as they may differ in their response to saline condition (Aktas et al., 2006). However, there is a general lack of knowledge regarding the sensitivity or tolerance to saline irrigation of bell peppers at various growth stages (Bar-Yosef et al., 2001); particularly when drip irrigation and mulch are incorporated into the saline water management. Therefore, the objective of this research was to evaluate the effect of saline drip irrigation timing on the growth, physiology and marketable fruit production of two bell pepper cultivars grown on black polyethylene mulch or bare soil.

6.3 MATERIALS AND METHODS

6.3.1 Plant material and site conditions

Bell pepper seedlings (*Capsicum annuum* L.) vars. Red Knight (Petoseed, Oxnard, CA, USA) and Early Sunsation (Norseco, Laval, QC, Canada) were grown in a greenhouse with day temperature ranging from 16 to 30 °C and night temperature ranging from 12 to 15 °C. Peppers were seeded into 72-cell plastic trays containing peat-based growing substrate (Promix Bx, Premier Horticulture, Rivière-du-Loup, QC, Canada) on 19 April 2005. After appearance of the first true leaves, seedlings were watered as required and fertilized (in $mg \cdot L^{-1}$) weekly with 200 N, 88 P, and 166 K, 0.2 B, 0.5 Cu, 1.0 Fe, 0.5 Mn, 0.005 Mo, and 0.5 Zn (Plant Products, Brampton, ON, Canada). The seedlings were grown in greenhouse conditions until they had eight fully expanded leaves.

The experiment was established in 2005 at the Horticulture Research Centre, Macdonald Campus, McGill University, Ste-Anne-de-Bellevue, QC, Canada (latitude 45º 26' N, longitude 73º 56' W, elevation 39 m), the soil being a clay loam (31% sand, 37% silt, 32% clay) with an electrical conductivity in the soil saturated paste extract (EC_e) of 0.67 $dS \cdot m^{-1}$, pH of 7.9 and 7.4 (soil saturated paste extract and 2:1 soil/water, respectively) and 6.6% organic matter, field capacity at 0.3 at −30 kPa of soil matric potential (0.32 $cm^3 \cdot cm^{-3}$) and permanent wilting point at −1500 kPa of soil matric potential (0.18 $cm^3 \cdot cm^{-3}$). The field was ploughed in the fall of 2004 and harrowed in the spring of 2005.

Raised beds (6 m length x 1.1 m width and 0.3 m high) were made using a plastic mulch layer and bed raiser (Model 2550, Rain-Flo Irrigation, East Earl, PA, USA) on 1 June 2005. The machine laid a drip irrigation tape (T-Tape TSX-508-12-340, T-Systems

International, San Diego, CA, USA) in the centre of the bed and covered the bed with black polyethylene mulch. For treatments on bare soil the mulch was then removed. Beds were of 2.5 m centre to centre and there was 1 m between blocks.

Seedlings with eight true leaves were mechanically transplanted (Rain-Flo Transplanter Model 1600, Rain-Flo Irrigation, East Earl, PA, USA) on 10 June 2005 in staggered rows (0.3 m apart) with 0.45 m between plants. Each transplant received 150 mL of a starter nutrient solution (in $mg{\cdot}L^{-1}$) with 500 N, 115 P, 42 K, 1.0 B, 2.5 Cu, 5.0 Fe, 2.5 Mn, 0.025 Mo, and 2.5 Zn (Plant Products, Brampton, ON, Canada).

6.3.2 Treatments and experimental design

The experimental design was a randomized complete block design with split-split plot restriction and three replicates. Saline or non-saline irrigation timing factor was randomly assigned to the main plots. This factor consisted of six levels: i) None (non-saline irrigation control), ii) S1S2 (saline irrigation from transplanting to fruit set), iii) S1S4 (saline irrigation from transplanting to flowering, then during harvest), iv) S2S3 (saline irrigation from flowering to first harvest), v) S3S4 (saline irrigation after fruit set), and vi) All (only saline irrigation throughout growth). The subplot was either black polyethylene mulch (Climagro, Plastitech, St-Remi, QC, Canada) or bare soil, and the sub-subplot assigned to bell pepper cultivar, Red Knight (red) and Early Sunsation (yellow). At the level sub-subplot, 13 plants of each cultivar were transplanted with the six central plants used for experimental measurements and the remainder serving as guards (Figure 6.1).

6.3.3 Irrigation and crop management

The saline water (2.5 $dS \cdot m^{-1}$) had a 2:1 ratio of $NaCl:CaCl_2$ on a molar basis (Dalton et al., 1997) to reflect a value of 0.7 as the $Na^+/(Na^+ + Ca^{2+})$ ratio found for most saline waters used to irrigate major horticultural crops around the world (Grattan and Grieve, 1999). Salinity was measured with a portable conductivity meter that compensates for temperature within a range of 0 to 19 $dS \cdot m^{-1}$ (Model TDSTestr4TM, Oakton, Singapore). Tap water (0.2 $dS \cdot m^{-1}$) was used as the non-saline water treatment.

Six independent containers were used to store saline or non-saline water for the irrigation treatments. Water in each container was pumped (operating pressure of 57 kPa) by an electric submersible pump (Mastercraft Model 62-3515-0) through polyethylene pipes [19 mm inside diameter (ID), main line] to the corresponding main plot. At the main plot, this main line was split into two sub-lines (19 mm ID, pipes) with independent in-line valves installed prior to the subplots to control irrigation flow at the subplot levels in the closest block. To irrigate plants in each subplot, a drip irrigation tape with emitter discharge rates of 0.75 $L \cdot h^{-1}$ (wall thickness 0.2 mm, 16 mm ID, emitter separation 30 cm) was connected to the sub-line. At the end of the subplot, the drip irrigation tape was reconnected to the sub-line and directed to its corresponding subplot in the next blocks.

Following transplanting of seedlings in the experimental field, a total of 34 mm of non-saline water was applied to all plants regardless of saline or non-saline irrigation treatments to allow the establishment of the plants.

Irrigation requirement varied according to the treatments, it was determined on a daily basis considering evapotranspiration and precipitation data (Madramootoo et al., 1993):

$$I_r = I_{r(i-1)} + ET_{c\,(i-1)} - P_{i-1} - I_{i-1} \quad \text{(Eq. 6.1)}$$

where I_r is the irrigation requirement on the i^{th} day (mm), $I_{r(i-1)}$ is the irrigation requirement on the previous day (mm), $ET_{c(i-1)}$ is the crop evapotranspiration on the previous day (mm), P_{i-1} is the precipitation (rainfall) on the previous day (mm), I_{i-1} is the irrigation applied on the previous day (mm).

Crop evapotranspiration, ET_c (mm), was determined daily based on the use of a reference evapotranspiration, ET_0 (mm), and adjusted by the crop coefficient, K_c (dimensionless) (Allen et al., 1998):

$$ET_c = ET_0\, K_c \quad \text{(Eq. 6.2)}$$

Data of wind speed, solar radiation, air temperature, and relative humidity were required to derive the parameters for daily ET_0 calculation following procedures outline by Allen et al. (1998). Wind speed data was obtained from the closest weather station located less than 1 km from the field experiment. Solar radiation was measured by using a pyranometer (Model LI-200, LI-COR Biosciences, Lincoln, NE, USA), and air temperature and relative humidity were measured by using a HMP45C-L probe (Campbell Scientific, Logan, UT, USA) installed on site at a height of 2 m. Both sensors were connected to a datalogger (CR10, Campbell Scientific, Logan, UT, USA) to collect data. After all parameters were derived, ET_0 was computed according to the FAO Penman-Monteith formula (Allen et al., 1998):

$$ET_0 = \frac{0.408\,\Delta\,(R_n - G) + \gamma\,\dfrac{900}{T+273}\,u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34\,u_2)} \quad \text{(Eq. 6.3)}$$

where, R_n is the net radiation at the crop surface (MJ·m^{-2}·day^{-1}), G is the soil heat flux density (MJ·m^{-2}·day^{-1}), T is the mean daily air temperature at 2 m height (°C), u_2 is the wind speed at 2 m height ($m \cdot s^{-1}$), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), e_s-e_a is the saturation vapour pressure deficit (kPa), Δ is the slope vapour pressure curve ($kPa \cdot °C^{-1}$), and γ is the psychrometric constant ($kPa \cdot °C^{-1}$).

The single crop coefficient approach (Allen et al., 1998) was used to determine the K_c. The basic K_c values were 0.60, 1.05 and 0.90 for the initial, middle and end of the pepper growth, respectively. From these basic values, other intermediate values were later estimated and defined for periods of 10 days as follow: 0.60, 0.60, 0.65, 0.75, 0.85, 0.95, 1.05, 1.05, 1.05, 1.05, 0.98 and 0.94. Originally the K_c values corresponded to the values for standard conditions (K_{cs}); this is for treatments receiving temporally or permanently non-saline irrigation under bare soil condition, so that:

$$K_c = K_{cs} \qquad \text{(Eq. 6.4)}$$

However, the K_c values were further modified in the remaining treatments with salinity and/or plastic mulch to obtain their corresponding K_c values. Thus, three additional particular cases (Equations 6.5, 6.6 and 6.8) were considered for the K_c calculations.

For treatments receiving temporally or permanently non-saline irrigation under mulch condition, the previous equation was adjusted by a mulch coefficient, k_m, which is a multiplier factor of 0.70 suggested by Allen et al. (1998) when drip irrigation is being used:

$$K_c = k_m \, K_{cs} \qquad \text{(Eq. 6.5)}$$

A different modification for the K_c calculation was introduced for treatments receiving temporally or permanently saline irrigation under bare soil condition according to Allen et al. (1998):

$$K_c = k_s\ K_{cs} \qquad \text{(Eq. 6.6)}$$

where, k_s is the saline stress coefficient without water stress (dimensionless). The value of k_s was previously estimated as 0.75 according to the following equation (Allen et al., 1998):

$$K_s = \left(1 - \frac{b}{k_y 100}\left(EC_e - EC_{et}\right)\right) \qquad \text{(Eq. 6.7)}$$

where, b is the percentile reduction (12 % dS·m^{-1} for the case of peppers) in yield per increase in salinity as electrical conductivity of the saturated paste extract (Rhoades et al., 1992), K_y is the yield response function coefficient (dimensionless, 1.1 for peppers) (Doorenbos et al., 1979), EC_e is the electrical conductivity of the soil saturated paste extract (established at 3.75 dS·m^{-1}, $EC_e = 1.5 \times EC_w$) (Rhoades et al., 1992), EC_{et} is the electrical conductivity threshold (1.5 dS·m^{-1} for the case of peppers) value as measured in the soil saturated paste extract from which yield is expected to be reduced (Rhoades et al., 1992).

Finally, for treatments receiving temporally or permanently saline irrigation under mulch condition, the following formula was used:

$$K_c = k_s\ k_m\ K_{cs} \qquad \text{(Eq. 6.8)}$$

Nitrogen, phosphorus and potassium (NH_4NO_3, $NH_4H_2PO_4$, KNO_3) fertilization was applied by fertigation at the beginning of each growth stage: vegetative stage (transplanting), appearance of the first flower, first fruit set, and first harvest of fruits at a rate of 25 kg·ha^{-1} of N, and 10 kg·ha^{-1} of P_2O_5 and K_2O each time.

Weeding was done manually within plots and mechanically (mini-tractor and weeder) in the space between beds as needed. Plant staking was performed on 9 August, 2005 to support fruit load. Pests were controlled by the use of the insecticide Orthene® (Acephate 75%) applied twice at a rate of 1.1 $kg \cdot ha^{-1}$ during the experiment.

6.3.4 Soil temperature

The soil temperature was measured by using a pair of copper-constantan thermocouples (Scott, 2000) at soil depths of 10 and 20 cm, respectively, within each sub-subplot. The thermocouples were connected to a datalogger (CR10, Campbell Scientific, Logan, UT, USA) to store information. Readings of averaged temperature were registered every hour.

6.3.5 Physiological measurements

Measurements of net CO_2 assimilation (A), leaf transpiration rates (E), stomatal conductance (g_s) were carried out on 18 August, 2005 (69 DAT) at fruit set growth stage by using a portable photosynthesis meter (Model LI-6400, LICOR Biosciences, Lincoln, NE, USA). The fourth youngest fully expanded leaf (Chartzoulakis and Klapaki, 2000; De Pascale et al., 2003) from one plant per sub-subplot was selected for the measurements performed from 1100 to 1500 h.

Water use efficiency (WUE) was calculated accordingly to the physiological (Jones, 2004) and agronomic (Gregory, 2004) approaches:

$$WUE_p = \frac{A}{E} \qquad \text{(Eq. 6.9)}$$

where, WUE_p is the water use physiological efficiency ($\mu mol\ CO_2 \cdot mmol^{-1}\ H_2O$), A is the net CO_2 assimilation ($\mu mol\ CO_2 \cdot m^{-2} \cdot s^{-1}$) and E is the leaf transpiration ($mmol\ H_2O \cdot m^{-2} \cdot s^{-1}$); and

$$WUE_a = \frac{Y_m}{I} \qquad \text{(Eq. 6.10)}$$

where, WUE_a is the water use agronomic efficiency (kg·mm^{-1}), Y_m is the marketable fruit (fully ripened + green) yield (kg·ha^{-1}) and I is the amount of water applied by irrigation + rain (mm).

6.3.6 Evaluation of growth and fruit yield quality

Mature fruits of the center six plants per sub-subplot were harvested, graded, counted and weighed (Model PB800, Mettler Toledo, Switzerland). Marketable fruits were sorted based on size as follows: jumbo (≥ 10 cm diameter and length), extra-large (9 cm diameter, 9.5 cm length), large (7.5 cm diameter, 9 cm length) and medium (6 cm diameter and length); smaller or damaged fruits were considered non-marketable.

Length and width of three marketable fruit per sub-subplot were measured at each harvest. Fruits were then cut and 5 mL of pepper juice were used to determine total soluble solids (TSS, Brix %) (hand refractometer, ATC-1E, Atago, Japan).

At the final harvest 2 plants in each sub-subplot were sampled. Shoots were harvested, placed into plastic bags and kept in a cold room (6 °C) for a maximum of 24 h, immature fruits were separated from shoots and fresh weight was determined. Plants were later oven-dried to a constant weigh at 70 ºC for 48 h, leaves were separated from stems and dry weight was determined.

Harvest index, *HI*, was calculated according to the following formula:

$$HI = \frac{Y_m}{FWS} \qquad \text{(Eq. 6.11)}$$

where, *FWS* is the fresh weight of shoots (fruits included).

6.3.7 Evaluation of salt distribution in the soil

In order to evaluate the lateral and vertical displacement of salts as consequence of saline drip irrigation and mulch treatments, soil samples for soil electrical conductivity (EC) measurements were taken from the 24 treatment combinations (sub-subplot level) in all blocks. A semi-cylindrical auger was used to take samples from two soil layers (0-15 and 15-30 cm) at two perpendicular distances (0 and 15 cm) to the direction of the drip irrigation tape. The lateral and vertical samplings (4) for all treatment combinations (24) recorded a total of 96 samples for determinations of the electrical conductivity of the soil/water extracts 1:5 ratio ($EC_{1:5}$). Later, one third of each lateral and vertical samples (four) was used to have one composite sample (Petersen and Calvin, 1996) for each treatment combination (sub-subplot). Hence, a total of 24 composite samples for determinations of the electrical conductivity of the saturation soil paste extract (EC_e) were obtained. Samples were then air-dried and determinations of $EC_{1:5}$ and EC_e were further carried out following the procedures of Rhoades (1996).

6.3.8 Statistical analysis

Data were subjected to analyses of variances (ANOVA) using the procedure GLM of SAS (v. 9.1, SAS Institute, Cary, NC, USA). A Tukey test (P=0.05) was performed to determine statistical differences of the means when indicated by ANOVA. No statistical analysis was performed on EC_e; however, values were averaged to present this information for saline irrigation timing (across mulch and cultivars), mulch (across saline irrigation treatments and cultivars) and cultivars (across saline irrigation treatments and mulch). Data of $EC_{1:5}$ were subjected to ANOVA, in which the effects of distance and depth were included, in addition to the saline irrigation timing, mulch and cultivars. Only significant interactions are presented.

6.4 RESULTS

6.4.1 Soil conditions and irrigation

Soil temperature was significantly higher under mulch than bare soil at 10 and 20 cm deep (Figure 6.2). Clearly, mulched soil retained more heat; thus increasing the differences in morning and night temperatures at 10 cm.

There was 554.2 mm of rain during the experimental period. Additional water required by the plants was applied as saline or non-saline irrigation (Table 6.1). More water was applied to the non-saline control than all other treatments. For each level of salinity the mulched plant required less water (69-70%) than the plant grown in bare soil. The pH measured in saturation soil paste extracts was similar among saline irrigation treatments (Table 6.2). However, the electrical conductivity of the saturation soil paste extract (EC_e) showed a tendency to increase when saline irrigation was applied during fruiting growth stage (Table 6.2). Furthermore, a more detailed analysis of the soil salinity measured as the electrical conductivity of the soil/water extracts 1:5 ratio ($EC_{1:5}$) indicated that, when saline irrigation was applied either during fruit growth and development or throughout growth, the $EC_{1:5}$ values were significantly higher than those of the other treatments. Even though plants grown in bare soil received more saline water, $EC_{1:5}$ was significantly higher (43%) in mulched than bare soil because of occurrence of salt leaching by rainfall (Table 6.2). Cultivar did not influence soil salinity as $EC_{1:5}$. Salt concentration was evenly distributed both horizontally and vertically with respect to the point of application (Table 6.2).

There was a significant interaction between salinity and mulching (Figure 6.3). Mulched soil contained significantly more salts than bare soil with the exception of plants that had received saline irrigation from transplanting to fruit set where there was no difference. Irrigating with saline at early then at late growth stages (S1S4) had a similar effect on soil salinity to using saline water at intermediate growth stages (S2S3) in mulched soil. In mulched soils, use of saline water during late growth stages (S3S4) or continuously (All) concentrated more salts into the soil than applying saline water at any other growth stages. Conversely, irrigating with saline water at early growth stages (S1S2) concentrated less salts than the non-saline control (None). For bare soil, the salt concentration was significantly higher for plants receiving saline water transplanting to flowering and then during harvest (S1S4) and those receiving only saline irrigation (All) than other treatments.

Lateral displacement of salts was significantly affected by saline irrigation timing (Figure 6.4). At the drip irrigation line, soil salinity was highest when saline water was always used (All) or applied at late growth stages (S3S4). However, the salt concentration S1S4 was comparable to that of S3S4. Soil salinity by S2S3 was similar to the control but significantly higher than that of S1S2. The effect of distance from the drip irrigation line on the salt concentration was variable. It remained similar for plants receiving no saline water or salinity in early growth, declined for all treatments having saline water in later growth stages (S1S4, S3S4, All), and increased slightly when saline irrigation was applied from flowering to first harvest (S2S3).

Soil salinity increased significantly with depth under bare soil condition. Conversely, in mulched soil salt concentrations significantly decreased with depth (data not shown).

6.4.2 Physiology

Since plants had not reached fruiting growth stage when physiology data was taken (fruit set growth stage), treatments involving saline irrigation at fruiting growth stage (S1S4, S3S4 and All) are in this section referred to as saline irrigation applied at vegetative (S1S4), fruit set (S3S4) or throughout growth (All) from vegetative to fruit set.

There was no difference in stomatal conductance (g_s) among plants irrigated with saline water at early growth stages (S1S2) or at vegetative only (S1S4) and the non-saline control (Table 6.3). Plants irrigated with saline water at vegetative (S1S4) having the highest rate of stomatal conductance. Conversely, applying saline irrigation during flowering and fruit set (S2S3), fruit set (S3S4) or throughout growth (All) significantly reduced stomatal conductance by 30, 28 and 38%, respectively, compared with the maximum value of g_s (Table 6.3). Mulched plants had an 11% increased in g_s compared with plants grown in bare soil (Table 6.3).

Similarly, plants irrigated with saline water at vegetative (S1S4), vegetative and flowering (S1S2) or never (None) had similar rates of transpiration (Table 6.3). Plants irrigated with saline water at flowering and fruit set (S2S3), fruit set (S3S4) and continuously (All), transpired significantly less water (26%) than those of the non-saline control. On average, plants grown in bare soil had 7% less transpiration compared with mulched plants (Table 6.3).

The photosynthesis rate of plants irrigated with saline water during vegetative growth (S1S4) was comparable to that of plants that did not receive saline irrigation (Table 6.3). However, extending application of saline irrigation from vegetative to flowering (S1S2) or to fruit set (All), or applying saline irrigation at flowering and fruit set (S2S3 and S3S4) significantly reduced photosynthesis rates by an average of 11% compared to that of S1S4 plants. On average, photosynthesis rate was slightly greater (4%) in mulched than plants grown in bare soil (Table 6.3). Red Knight photosynthesized more than Early Sunsation (Table 6.3). Early Sunsation plants grown in bare soil had a 7 % lower rate of photosynthesis than the two mulched cultivars or Red Knight plants grown in bare soil (data not shown).

6.4.3 Growth

Fresh weight (FW) of shoots composed of leaves, stems, and fruits, were not affected by the use of saline irrigation or mulching. However, Red Knight had significantly lighter (15%) shoot FW compared with Early Sunsation (Table 6.4). Plants irrigated with saline water throughout growth (All) had heavier FW of stems and leaves than those irrigated with saline water only at early growth stages (S1S2) (Table 6.4). Mulched plants had 11% heavier stems and leaves than plants grown in bare soil, and those of Early Sunsation were 25% heavier than those of Red Knight (Table 6.4). Mulching speeded up growth and hence accelerated maturity of fruits (Table 6.4). Therefore, fruit FW in mulched plants increased significantly (13%) while decreasing FW of immature fruits compared with plants grown in bare soil. Since Early Sunsation is an early cultivar and Red Knight is mid season, there was a 27% reduction in FW of immature fruits produced by the later cultivar compared to Early Sunsation (Table 6.4).

Fresh weight of immature fruits was greater in Early Sunsation than in Red Knight when plants received saline irrigation during fruit growth (S1S4 and S3S4) (Figure 6.5A). There was no difference among saline treatments for the Red Knight. However, in the case of Early Sunsation, the lowest FW of immature fruits was found in plants receiving saline irrigation at S1S2 with values comparable to plants of the control but significantly lower than those of any other saline treatment.

Overall, the number of immature fruits per plant was greater in Early Sunsation than in Red Knight (Table 6.4). Number of immature fruits produced per plant was significantly greater in Early Sunsation relative to Red Knight when saline irrigation was applied at fruiting (S1S4, S3S4) (Figure 6.5B). It was more deleterious for number of immature fruits in Early Sunsation plants when saline irrigation was applied at vegetative and flowering (S1S2) rather than at vegetative (S1S4), fruit set and fruiting (S3S4). Within Early Sunsation plants, those of S1S4 and S3S4 treatments had comparable values to those of non-saline control or continuously saline irrigation (All). No differences were found among saline irrigation treatments within Red Knight plants.

6.4.4 Fruit production

Since fruits were harvested when they reached maturity (90% of color developed), marketable yield information is presented into two forms: fully ripened fruit production (Table 6.5) and final harvest of fruits (green) (Table 6.6). Saline irrigation did not influence the yield of fully ripened fruits in any of the four marketable categories nor the total (Table 6.5). Mulched plants produced significantly higher total yield of ripened fruit (45%) than plants grown in bare soil (Table 6.5). Most of the fruit produced by mulched plants were classified as extra-large (50%) and large (24%) compared with 43% and 18%, respectively, for the fruit of plants grown in bare soil (Table 6.5). Relative to total yield, Early Sunsation fruit of the extra-large category comprised 53% compared with 41% of Red Knight fruit (Table 6.5).

In all irrigation treatments, mulched plants produced significantly more marketable yield than plants grown in bare soil (Figure 6.6A). In mulch condition, the use of non-saline irrigation produced similar total marketable yield to saline treatments. Applying saline water during fruit growth (S1S4 and S3S4) significantly increased marketable yield compared with applying saline water at early growth stage (S1S2). Marketable yield from mulched S3S4 plants was significantly higher than that of the saline treatment (All); whereas the effect was reversed for plants grown in bare soil. Except for S1S2, any other temporal application of saline water significantly decreased total marketable yields for plants grown in bare soil. Additionally, saline irrigation at late growth stages (S3S4) significantly decreased marketable yield relative to early growth stages (S1S2). Mulched plants had higher weights of large fruit compared with plants grown in bare soil (Figure 6.6B). Among mulched plants, the use of saline irrigation at S1S4 produced higher yield of large fruits than All and S2S3 treatments. In contrast, among plants grown under bare soil condition, the S1S4 and S3S4 had the lowest large category yields, significantly lower than both the non-saline control and saline treatment (All). Irrigating with saline water at intermediate growth stages (S2S3) produced higher yield of large fruits than irrigating at late growth stages (S3S4).

The marketable yield of green fruits was not influenced by salinity (Table 6.6). However, the significant interaction of saline irrigation with mulch indicated that higher green yield of extra-large category was found in plants grown in bare soil that received saline irrigation from flowering onwards (S2S3, S3S4) or continuously (All) as opposed to their mulched counterparts irrigated with saline water at vegetative (S1S2, S1S4) or with non-saline water (data not shown). Plants grown in bare soil produced significantly higher green yield than mulched plants in all categories except jumbo size (Table 6.6). Cultivars did not affected total marketable green yield. However, in Early Sunsation plants, 33% of the total green yield was of large category compared with 23% of Red Knight plants (Table 6.6).

Regardless of salinity treatment, plants produced on average 7 fruits per plant of which 4 were fully ripened (Table 6.7). However, mean weight of ripened fruit of plants irrigated at early then late growth stages (S1S4) was 11% less compared with those plants irrigated at late growth stages (S3S4). Mean fruit weight was heavier in fully developed fruits than in green ones (Table 6.7). Mulch significantly increased number of fully ripened or green fruits but did not increase their mean fruit weight (Table 6.7). Mean fruit weight was greater in Early Sunsation than in Red Knight only when fruits reached fully ripeness (Table 6.7).

Mulched plants had more fully ripened fruits than plants grown in bare soil at each saline irrigation treatment (Figure 6.7). Use of saline water at fruiting growth stage (S1S4 and S3S4) produced significantly more marketable fruits than using saline water throughout growth for mulched plants. However, the opposite was observed in plants grown in bare soil.

Salinity did not affect length, width and total soluble solids (TSS) of ripen marketable fruits (Table 6.8). Slight but significant increases in fruit width were found in mulched plants and Red Knight cultivar relative to plants grown in bare soil and Early Sunsation cultivar, respectively (Table 6.8). It was observed that fruit width of Early Sunsation was reduced when plants were grown in bare soil (data not shown).

Salinity did not affect harvest index (HI) (Table 6.9). Mulched plants and Red Knight significantly improved HI (8-9%) compared with plants grown in bare soil and Early Sunsation, respectively (Table 6.9). When saline irrigation was applied at fruiting growth stage (S1S4, S3S4), the HI was significantly higher for Red Knight relative to Early Sunsation (Figure 6.8). In fact, Early Sunsation treated with saline water at fruiting (S1S4 and S3S4) had lower HI than when treated at earlier growth stages (S1S2) or with non-saline irrigation. Red Knight, on the other hand, had significantly lower HI only when plants were treated with saline water at intermediate growth stages (S2S3) compared with early growth stages (S1S2). Mulching increased significantly HI in Red Knight compared with Red Knight grown in bare soil or Early Sunsation with or without mulch (data not shown).

6.4.5 Water use efficiency

Physiological water use efficiency (WUE_p) was highest in plants irrigated with saline water throughout growth (Table 6.9). Applying saline irrigation at early growth stages (S1S2, S1S4) or using non-saline water significantly decreased WUE_p by 14, 21 and

14%, respectively, compared with the saline treatment (All). However, the application of saline irrigation at flowering and later growth stages (S2S3, S3S4) resulted in comparable WUE_p to that of the saline treatment. Mulching did not influence WUE_p. Cultivars showed a small but significant difference in WUE_p, being higher (4%) in Red Knight than in Early Sunsation. Conversely to WUE_p, saline irrigation timing did not influence agronomic water use efficiency (WUE_a) (Table 6.9). However, mulched plants had a 25% greater WUE_a relative to plants grown in bare soil.

6.5 DISCUSSION

6.5.1 Soil conditions and irrigation

Due to its optical properties, such as high absorptance of radiation, the black polyethylene mulch retains more heat (Ham et al., 1993; Lamont, 2005; Tarara, 2000) and thus soil temperatures were higher under a mulch than under bare soil (Figure 6.2). This result agrees with others who also reported increased soil temperature when black mulch was used to grow peppers under field condition (Locher et al., 2005; Roberts and Anderson, 1994; Siwek et al., 1994).

Mulched plants needed less irrigation water as suggested by Allen et al. (1998). Mulching decreased by 30% the value of the crop coefficient, k_c, for mulch treatments (Eq. 6.5, 6.8); which in turn reduced both crop evapotranspiration, ET_c (Eq. 6.2) and irrigation requirement, I_r (Eq 6.1) accordingly. The reduction in irrigation requirement by mulching as suggested by Allen et al. (1998) is in agreement with our previous findings (Chapters 3 and 5). Since salinity decreases irrigation requirement, predetermined adjustments (25% decrease) in the value of *kc* were applied according to Allen et al.

(1998) (Eqs. 6.6 and 6.8). Therefore, decreases in water consumption were higher during saline irrigation periods (Table 6.1). Reduction in water consumption appears when salts concentrate in the soil, thus lowering root zone osmotic potential (Munns, 2002). This effect on pepper plants has been observed in our previous studies (Chapters 3 and 5) and reported by Cabañero et al (2004).

Increases in soil salinity when saline water was applied during late growth stages (S3S4) or continuously (All) could have been the consequence of salt load by irrigation (Hoffman and Shannon, 2007). Values from these two treatments were higher than the threshold value (EC_e of 1.5 $dS \cdot m^{-1}$) for peppers to prevent yield reduction (Maas, 1990). Salt accumulation in the soil could have been higher with saline irrigation applied during late growth (S3S4) or continuously (All) had there not been a significant amount of precipitation (Table 6.1). The rain caused salts, which had accumulated in the bare soil, to leach deeper into the soil profile whereas they accumulated in the root zone in the mulch protected soil (Table 6.2, Figure. 6.3). When saline irrigation was applied before fruiting (e.g. S1S2, S2S3), soil salinity remained lower (S1S2) or comparable (S2S3) than the use of non-saline water (Figure 6.4). This result suggest that salts applied during these growth stages could have been taken up by the plants in greater concentrations than plants which received saline irrigation during fruiting (S1S4, S3S4) or continuously (All).

6.5.2 Physiology

Plants irrigated with non-saline water or with saline water before fruit set (e.g. S1S2 and S1S4) did not reduce rates of both stomatal conductance and transpiration as much as the remaining treatments (Table 6.3). Since measurement of these physiological parameters was carried out at fruit set, it would be possible that plants undergoing saline treatments at this growth stage (e.g. S2S3, S3S4 and All) would have suffered the effects of lowered root zone osmotic potential (Munns, 2002; Munns and Tester, 2008) and therefore have a slight partial closure of stomata to reduce water loss by transpiration (Munns, 2002; Taiz and Zeiger, 2002). It is possible that saline irrigation applied only at the vegetative growth (e.g. S1S4) slightly benefited stomatal conductance, and hence, transpiration and photosynthesis. Photosynthesis rates (at fruit set) were comparable between non-salinized plants and those irrigated with saline water during vegetative growth (S1S4) but higher than the remaining saline irrigation treatments. Hence, reductions in photosynthesis in the latter treatments were possibly due to higher Na^+, Cl^- or both concentrations within the plant to a such extend as to slightly decrease photosynthesis (Bethke and Drew, 1992).

Higher rates of stomatal conductance, transpiration and photosynthesis in mulched plants (Table 6.3) could have been the result of higher soil temperatures (Figure 6.2) relative to plants grown in bare soil. Adding Ca^{2+} (10 mM) to NaCl (50 mM) saline solution was found to ameliorate the negative effects of salinity on stomatal conductance of pepper plants, this effect being greater with increase of root zone temperature from 25 °C to 35 °C (Cabañero et al., 2004). Similarly, adding Ca^{2+} (0.8-8 mM) to NaCl (10 mM) was found to restrict Na^+ uptake in pepper plants (Rubio et al., 2003). Therefore, photosynthesis could be normally maintained as Na^+ concentration within the plant remained low (Bethke and Drew, 1992).

Across saline irrigation and mulch treatments, Red Knight had higher rate of photosynthesis than Early Sunsation (Table 6.3). This may be a consequence of differences in genotype by environment interaction which ultimately did not affect fruit production.

6.5.3 Growth

Growth was not reduced by salinity (Table 6.4). However, it would be detrimental to irrigate with saline water during the two early growth stages (S1S2, vegetative and flowering) for stem and leaf fresh weights as opposed to irrigate continuously with saline water (All). Furthermore, indications of slight increases in stem and leaf fresh weight with longer periods of saline irrigation (Table 6.4) would suggest that root zone osmotic potential had only a minimal negative effect on primarily plant physiology. Since the experimental soil was not saline, it could also be possible that accumulation of Ca^{2+} in the soil and within the plant benefited stem and leaf fresh weight by inhibiting Na^{+} uptake which limits plant growth (Rubio et al., 2003). According to the final measurement of soil salinity, a similar situation could have occurred with plants grown under mulch because higher concentration of salts (Ca^{2+}, Na^{+}, and Cl^{-}) were observed under mulch compared with bare soil. Additionally, higher soil temperature under mulch could have improved plant fresh and dry weights, and have accelerated maturity of fruits as compared with bare soil condition. Similar growth enhancement by mulch has been reported for bell pepper grown in non-saline condition (Aziz, 1994; Locher et al., 2005; Siwek et al., 1994).

Differences in plant growth between the two cultivars could have been the result of genotype by environment interaction. Across saline irrigation and mulch treatments, Early Sunsation had heavier plant weights than Red Knight. Hence, selection of the former cultivar must be preferred in order to prevent reductions in growth or production of fully ripened fruits (e.g. Extra-large quality).

6.5.4 Fruit production

On average, application of saline irrigation at different growth stages did not reduce or increase production of fully ripened fruits (Table 6.5). Mulched plants had more total and large fully ripened fruits when irrigated for long periods with saline water (e.g. S1S4, S3S4) compared with their bare soil counterparts (Figure 6.6). This finding suggested that reductions in stomatal conductance, and hence transpiration and photosynthesis might have also occurred during fruit development in plants irrigated with saline water under bare soil condition. A measurement of these physiological parameters during fruit set indicated some reductions in plants grown under bare soil condition (Table 6.3). Since the soil in the experimental site was not saline (EC_e of 0.67 $dS{\cdot}m^{-1}$), irrigation with saline water at 2.5 $dS{\cdot}m^{-1}$ was achieved without marketable yield reduction. Additionally, rainfall could have leached salts out of root zone. These may be the main reasons for which our results disagreed with other studies reporting reductions in fruit production of tomato plants when saline water was used during fruit development (del Amor et al., 2001; Mizrahi et al., 1988). Conversely, a combination of increased soil temperature and higher Ca^{2+} concentration in the soil under mulch could have been the reasons for not having reductions in fully ripened fruit production (Figure 6.6). Improvement of fruit production in plants grown under mulch condition was likely due to increased soil temperature (Locher et al., 2005). Furthermore, higher soil temperature could have enhanced Ca^{2+} uptake by plants in saline condition (Cabañero et al., 2004). This ion has been reported to alleviate effects from deleterious (toxicity) Na^+ uptake (Rengel, 1992) by maintaining or improving the selective K^+ uptake by plants (Epstein, 1998). It was noticed that there was a delay in fruit maturity in plants grown under bare soil condition (Tables 6.5, 6.6 and 6.7), possible induced by lower soil temperature than under mulch condition (Locher et al., 2005). Additionally, it could be speculated that under mulch condition, salt concentration in the soil and possibly within the plants did not reach critical concentrations such as to cause deleterious effects on fruit production or fruit maturity. Therefore, in humid areas with non-saline soils, use of saline water may be feasible to drip irrigate peppers in combination with polyethylene mulch to save water while maintaining high fruit production. Increases in fruit production (weight and number) of bell peppers grown in mulch and non-saline conditions have been previously reported by several authors (Brown and Channell-Butcher, 2001; Monette and Stewart, 1987; Siwek et al., 1994).

6.5.5 Water use efficiency

Although the effect of saline irrigation on stomatal conductance at fruit set was limited (Table 6.3), the consequent partial closure of stomata in plants irrigated with saline water at flowering (S2S3) or fruit set (S3S4) or especially throughout growth (All), restricted more the diffusion of water loss by transpiration than the diffusion of CO_2 uptake (photosynthesis), thus improving physiological water use efficiency (Table 6.9). The opposite trend occurs in normal or non-saline conditions at which a diffusion gradient of CO_2 uptake occurs to a lesser extend than that of transpiration (Chaves et al., 2004). Increase of the physiological water use efficiency in saline conditions has been previously reported for peppers (Chartzoulakis and Klapaki, 2000). While WUE_p is enhanced where salinity is a limiting factor, growth reduction is expected to follow as a consequence of limited gas exchanges (Hoffman and Shannon, 2007). However, neither growth reductions nor marketable yield decreases were observed as effects of salinity (across mulch and cultivars treatments), suggesting that soil salinity did not reach or exceed the critical threshold (EC_e of 1.5 $dS \cdot m^{-1}$) reported by Maas (1990) at fruit set growth stage.

Agronomic water use efficiency was not affected by saline irrigation (Table 6.9). However, mulching the soil did enhance WUE_a as the combined result of improved total marketable yield and reductions in water consumption by mulched plants relative to plants grown in bare soil. Enhancement of WUE_a could be due to the positive effects of mulch on soil temperature increase and soil moisture conservation by minimizing evaporation, which in turn improved fruit production. Similar improvement of WUE_a was found by Kirnak et al. (2003) when bell peppers were grown under mulch condition relative to bare soil condition.

6.6 CONCLUSION

In humid areas with non-saline soils where saline irrigation could be use alternatively, application of saline water to mulched bell pepper plants could be done during fruiting while avoiding yield reductions. However, if bare soil condition is to prevail, saline irrigation should be applied at vegetative and flowering growth stages instead.

Table 6.1 Amount of saline (2.5 $dS \cdot m^{-1}$) and non-saline (0.2 $dS \cdot m^{-1}$) irrigation water (mm) applied to bell peppers (*Capsicum annuum* L.) grown under mulch or bare soil condition.

Timing of saline drip irrigation (days)[z]	Mulch	Vegetative (23 days)	Flowering (14 days)	Fruit set (37 days)	Fruiting (44 days)	Non-saline	Saline	Total	% saline water
None (0)	Black	63.7	20.6	62.9	57.3	204.5	0	204.5	0
	Bare soil	78.8	30.2	96.6	86.0	291.6	0	291.6	0
S1S2 (37)	Black	34 + **21.1**	**15.2**	62.9	57.3	154.2	36.3	190.5	19
	Bare soil	34 + **32.3**	**22.3**	96.6	86	216.6	54.6	271.2	20
S1S4 (67)	Black	34 + **21.1**	20.6	62.9	**41.0**	117.5	62.1	179.6	35
	Bare soil	34 + **32.3**	30.2	96.6	**65.5**	160.8	97.8	258.6	38
S2S3 (51)	Black	63.7	**15.2**	**42.5**	54.8	118.5	57.7	176.2	33
	Bare soil	78.8	**22.3**	**68.6**	82.5	161.3	90.9	252.2	36
S3S4 (81)	Black	63.7	20.6	**42.5**	**38.6**	84.3	81.1	165.4	49
	Bare soil	78.8	30.2	**68.6**	**62.0**	109.0	130.6	239.6	55
All (118)	Black	34 + **21.1**	**15.2**	**42.5**	**38.6**	34.0	117.4	151.4	78
	Bare soil	34 + **32.3**	**22.3**	**68.6**	**62.0**	34.0	185.2	219.2	84
Rainfall (mm)		173.2	101.5	67.5	212.0	-	-	554.2	-

[z] None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering, then during harvest), S2S3 (saline irrigation from flowering to first harvest), S3S4 (saline irrigation after fruit set), and All (only saline irrigation). Note: A volume of 34 mm of non-saline water was applied during one week following transplanting. Values in bold represents saline irrigation.

Table 6.2 Effect of saline (2.5 dS·m^{-1}) drip irrigation timing, black polyethylene mulch or bare soil, and cultivars on soil salinity [electrical conductivity of soil/water extracts 1:5 ratio ($EC_{1:5}$) and saturation soil paste extract (EC_e)] and soil pH.

Treatment	pH [(y)]	EC_e (dS·m^{-1})	$EC_{1:5}$ (dS·m^{-1})
A) Timing of saline irrigation [(z)]			**
None	8.28	0.96	0.13 c
S1S2	7.98	0.75	0.10 c
S1S4	8.11	1.46	0.19 b
S2S3	8.15	1.12	0.14 c
S3S4	7.97	1.79	0.23 ab
All	7.96	1.94	0.26 a
B) Mulch			**
Black	8.05	1.84	0.23 a
Bare soil	8.10	0.84	0.13 b
C) Cultivar			NS
Early Sunsation	8.07	1.28	0.17
Red Knight	8.08	1.40	0.18
D) Distance (cm)	-	-	NS
0			0.18
10			0.17
E) Depth (cm)	-	-	NS
0-15			0.18
15-30			0.17
A x B	-	-	**
A x D	-	-	*
B x E	-	-	**

[(z)] None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering, then during harvest), S2S3 (saline irrigation from flowering to first harvest), S3S4 (saline irrigation after fruit set), and All (only saline irrigation).
[(y)] Measured in the saturation soil paste extract.
*, ** Significant at $P \leq 0.05$ and $P \leq 0.01$, respectively; NS, not significant.
Means with the same letter are not significantly different (Tukey P=0.05).

Table 6.3 Effect of saline (2.5 $dS \cdot m^{-1}$) drip irrigation timing, black polyethylene mulch or bare soil, and cultivars on stomatal conductance, transpiration and photosynthesis of bell peppers (*Capsicum annuum* L.).

Treatment	Stomatal conductance [(y)] ($mol \cdot m^{-2} \cdot s^{-1}$)	Transpiration [(y)] ($mmol\ H_2O \cdot m^{-2} \cdot s^{-1}$)	Photosynthesis [(y)] ($\mu mol\ CO_2 \cdot m^{-2} \cdot s^{-1}$)
A) Timing of saline irrigation [(z)]	**	**	**
None	0.2845 ab	3.29 ab	15.28 ab
S1S2	0.2784 ab	3.15 ab	14.77 b
S1S4	0.3354 a	3.79 a	16.55 a
S2S3	0.2356 b	2.89 b	14.74 b
S3S4	0.2425 b	2.91 b	14.89 b
All	0.2067 b	2.66 b	14.66 b
B) Mulch	*	*	*
Black	0.2788 a	3.22 a	15.42 a
Bare soil	0.2489 b	3.01 b	14.88 b
C) Cultivar	NS	NS	**
Early Sunsation	0.2668	3.13	14.86 b
Red Knight	0.2609	3.10	15.44 a
A x B	NS	NS	NS
A x C	NS	NS	NS
B x C	NS	NS	*
A x B x C	NS	NS	NS

[(z)] None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering), S2S3 (saline irrigation at flowering and fruit set), S3S4 (saline irrigation at fruit set), and All (only saline irrigation).
[(y)] Measurements taken at 69 days after transplanting (Fruit set growth stage).
*, ** Significant at $P \leq 0.05$ and $P \leq 0.01$, respectively; NS, not significant.
Means with the same letter are not significantly different (Tukey P=0.05).

Table 6.4 Effect of saline (2.5 $dS \cdot m^{-1}$) drip irrigation timing, black polyethylene mulch or bare soil, and cultivars on the fresh weight and number of immature fruits of bell pepper plants (*Capsicum annuum* L.).

Treatment	Fresh weight (g/plant)				Number of immature fruits/plant
	Stems and Leaves	Immature fruits	Mature fruits	Shoots [y]	
A) Timing of saline irrigation [z]	*	NS	NS	NS	NS
None	483 ab	241	1498	2222	7.6
S1S2	465 b	169	1343	1977	5.5
S1S4	509 ab	313	1365	2187	8.8
S2S3	659 ab	263	1539	2461	7.5
S3S4	676 ab	281	1471	2428	8.9
All	713 a	268	1601	2582	7.9
B) Mulch	*	**	*	NS	NS
Black	618 a	188 b	1567 a	2373	6.7
Bare soil	550 b	324 a	1371 b	2245	8.7
C) Cultivar	**	**	NS	**	**
Early Sunsation	668 a	295 a	1539	2502 a	8.9 a
Red Knight	500 b	216 b	1399	2115 b	6.4 b
A x B	NS	NS	NS	NS	NS
A x C	NS	*	NS	NS	*
B x C	NS	NS	NS	NS	NS
A x B x C	NS	NS	NS	NS	NS

[z] None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering, then during harvest), S2S3 (saline irrigation from flowering to first harvest), S3S4 (saline irrigation after fruit set), and All (only saline irrigation).
[y] Immature fruits at final harvest.
*, ** Significant at $P \leq 0.05$ and $P \leq 0.01$, respectively; NS, not significant.
Means with the same letter are not significantly different (Tukey P=0.05).

Table 6.5 Effect of saline (2.5 dS·m^{-1}) drip irrigation timing, black polyethylene mulch or bare soil, and cultivars on fully ripened marketable yield of bell pepper plants (*Capsicum annuum* L.).

Treatment	Fully ripened marketable yield (t·ha^{-1}) [(y)]				
	Total	Jumbo	Extra-large	Large	Medium
A) Timing of saline irrigation [(z)]	NS	NS	NS	NS	NS
None	18.15	4.82	8.36	3.75	1.22
S1S2	16.66	3.00	7.83	4.02	1.81
S1S4	17.40	4.09	7.93	4.48	0.90
S2S3	15.78	3.89	7.11	3.66	1.12
S3S4	17.24	4.41	8.89	3.07	0.87
All	17.10	3.97	8.37	3.41	1.35
B) Mulch	**	NS	**	**	NS
Black	22.05 a	4.47	10.93 a	5.29 a	1.36
Bare soil	12.08 b	3.59	5.24 b	2.18 b	1.07
C) Cultivar	NS	NS	*	NS	NS
Early Sunsation	17.17	3.56	9.13 a	3.39	1.09
Red Knight	16.94	4.50	7.03 b	4.07	1.34
A x B	*	NS	NS	*	NS
A x C	NS	NS	NS	NS	NS
B x C	NS	NS	NS	NS	NS
A x B x C	NS	NS	NS	NS	NS

[(z)] None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering, then during harvest), S2S3 (saline irrigation from flowering to first harvest), S3S4 (saline irrigation after fruit set), and All (only saline irrigation).
[(y)] Early Sunsation (yellow), Red knight (red).
*, ** Significant at P≤0.05 and P≤0.01, respectively; NS, not significant.
Means with the same letter are not significantly different (Tukey P=0.05).

Table 6.6 Effect of saline (2.5 dS·m^{-1}) drip irrigation timing, black polyethylene mulch or bare soil, and cultivars on final fruit harvest (green marketable) of bell pepper plants (*Capsicum annuum* L.).

Treatment	Marketable yield of green fruits (t·ha^{-1}) [y]				
	Total	Jumbo	Extra-large	Large	Medium
A) Timing of saline irrigation [z]	NS	NS	NS	NS	NS
None	8.38	0.62	2.72	2.41	2.63
S1S2	7.13	0.43	3.30	1.57	1.83
S1S4	6.66	0.23	1.57	2.92	1.94
S2S3	11.30	0.42	4.12	2.86	3.90
S3S4	8.84	0.22	3.35	2.04	3.23
All	11.28	0.48	4.08	3.41	3.31
B) Mulch	**	NS	**	**	**
Black	5.57 b	0.65	1.90 b	1.42 b	1.60 b
Bare soil	12.29 a	0.15	4.48 a	3.65 a	4.01 a
C) Cultivar	NS	NS	NS	*	NS
Early Sunsation	9.94	0.37	3.08	3.28 a	3.21
Red Knight	7.93	0.42	3.31	1.79 b	2.41
A x B	NS	NS	**	NS	NS
A x C	NS	NS	NS	NS	NS
B x C	NS	NS	NS	NS	NS
A x B x C	NS	NS	NS	NS	NS

[z] None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering, then during harvest), S2S3 (saline irrigation from flowering to first harvest), S3S4 (saline irrigation after fruit set), and All (only saline irrigation).
[y] green fruits did not reach fully ripeness.
*, ** Significant at P≤0.05 and P≤0.01, respectively; NS, not significant.
Means with the same letter are not significantly different (Tukey P=0.05).

Table 6.7 Effect of saline (2.5 $dS \cdot m^{-1}$) drip irrigation timing, black polyethylene mulch or bare soil, and cultivars on number of fruits per plant and mean fruit weight of bell pepper plants (*Capsicum annuum* L.).

Treatment	Fully ripened marketable fruits [y]		Green marketable fruits [x]	
	Number of fruits per plant	Mean fruit weight (g)	Number of fruits per plant	Mean fruit weight (g)
A) Timing of saline irrigation [z]	NS	*	NS	NS
None	4.4	232.9 ab	2.6	143.6
S1S2	4.4	209.9 b	2.2	151.3
S1S4	4.3	228.5 ab	2.2	126.5
S2S3	4.0	215.8 ab	3.7	155.5
S3S4	4.1	236.8 a	3.0	149.6
All	4.2	224.6 ab	3.6	161.2
B) Mulch	**	NS	**	NS
Black	5.5 a	224.6	4.0 a	131.9
Bare soil	3.0 b	224.9	1.7 b	164.0
C) Cultivar	NS	**	NS	NS
Early Sunsation	4.2	231.0 a	3.2	147.5
Red Knight	4.3	218.5 b	2.6	148.3
A x B	*	NS	NS	NS
A x C	NS	NS	NS	NS
B x C	NS	NS	NS	NS
A x B x C	NS	NS	NS	NS

[z] None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering, then during harvest), S2S3 (saline irrigation from flowering to first harvest), S3S4 (saline irrigation after fruit set), and All (only saline irrigation).
[y] Fully ripened fruits: Early Sunsation (yellow), Red knight (red).
[x] Fruits did not reach fully ripeness
*, ** Significant at P≤0.05 and P≤0.01, respectively; NS, not significant.
Means with the same letter are not significantly different (Tukey P=0.05).

Table 6.8 Effect of saline (2.5 $dS{\cdot}m^{-1}$) drip irrigation timing, black polyethylene mulch or bare soil, and cultivars on length, width and total soluble solids (TSS) of fully ripened marketable fruits of bell pepper plants (*Capsicum annuum* L.).

Treatment	Fruit characteristics		
	Length (cm)	Width (cm)	TSS (Brix, %)
A) Timing of saline irrigation [(z)]	NS	NS	NS
None	9.85	9.10	6.55
S1S2	9.30	8.94	6.74
S1S4	11.03	9.26	6.87
S2S3	9.61	9.04	6.89
S3S4	9.73	9.34	6.95
All	9.59	9.15	6.71
B) Mulch	NS	*	NS
Black	10.22	9.25 a	6.84
Bare soil	9.48	9.03 b	6.73
C) Cultivar	NS	**	NS
Early Sunsation	9.65	9.04 b	6.76
Red Knight	10.06	9.24 a	6.81
A x B	NS	NS	NS
A x C	NS	NS	NS
B x C	NS	*	NS
A x B x C	NS	NS	NS

[(z)] None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering, then during harvest), S2S3 (saline irrigation from flowering to first harvest), S3S4 (saline irrigation after fruit set), and All (only saline irrigation).
*, ** Significant at P≤0.05 and P≤0.01, respectively; NS, not significant.
Means with the same letter are not significantly different (Tukey P=0.05).

Table 6.9 Effect of saline (2.5 dS·m^{-1}) drip irrigation timing, black polyethylene mulch or bare soil, and cultivars on harvest index, and physiological (WUE_p) and agronomic (WUE_a) water use efficiencies of bell pepper plants (*Capsicum annuum* L.).

Treatment	Harvest Index	Water use efficiency	
		WUE_p (μmol CO_2·mmol^{-1} H_2O)	WUE_a (kg·ha^{-1}·mm^{-1})
A) Timing of saline irrigation [z]	NS	**	NS
None	0.66	4.81 b	33.33
S1S2	0.67	4.82 b	30.47
S1S4	0.62	4.44 b	31.41
S2S3	0.61	5.14 ab	35.46
S3S4	0.60	5.21 ab	34.77
All	0.60	5.61 a	38.32
B) Mulch	*	NS	*
Black	0.65 a	4.95	37.73 a
Bare soil	0.60 b	5.06	30.18 b
C) Cultivar	**	*	NS
Early Sunsation	0.60 b	4.90 b	35.35
Red Knight	0.66 a	5.11 a	32.56
A x B	NS	NS	NS
A x C	*	NS	NS
B x C	*	NS	NS
A x B x C	NS	NS	NS

[z] None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering, then during harvest), S2S3 (saline irrigation from flowering to first harvest), S3S4 (saline irrigation after fruit set), and All (only saline irrigation).

*, ** Significant at $P \leq 0.05$ and $P \leq 0.01$, respectively; NS, not significant.

Means with the same letter are not significantly different (Tukey P=0.05).

Figure 6.1 A schematic representation of main plots for saline irrigation treatments, subplots for mulch treatments, and sub-subplots for cultivar treatments; and location of plants within sub-subplots used for measurements of physiology, growth and fruit production. Layout not to scale.

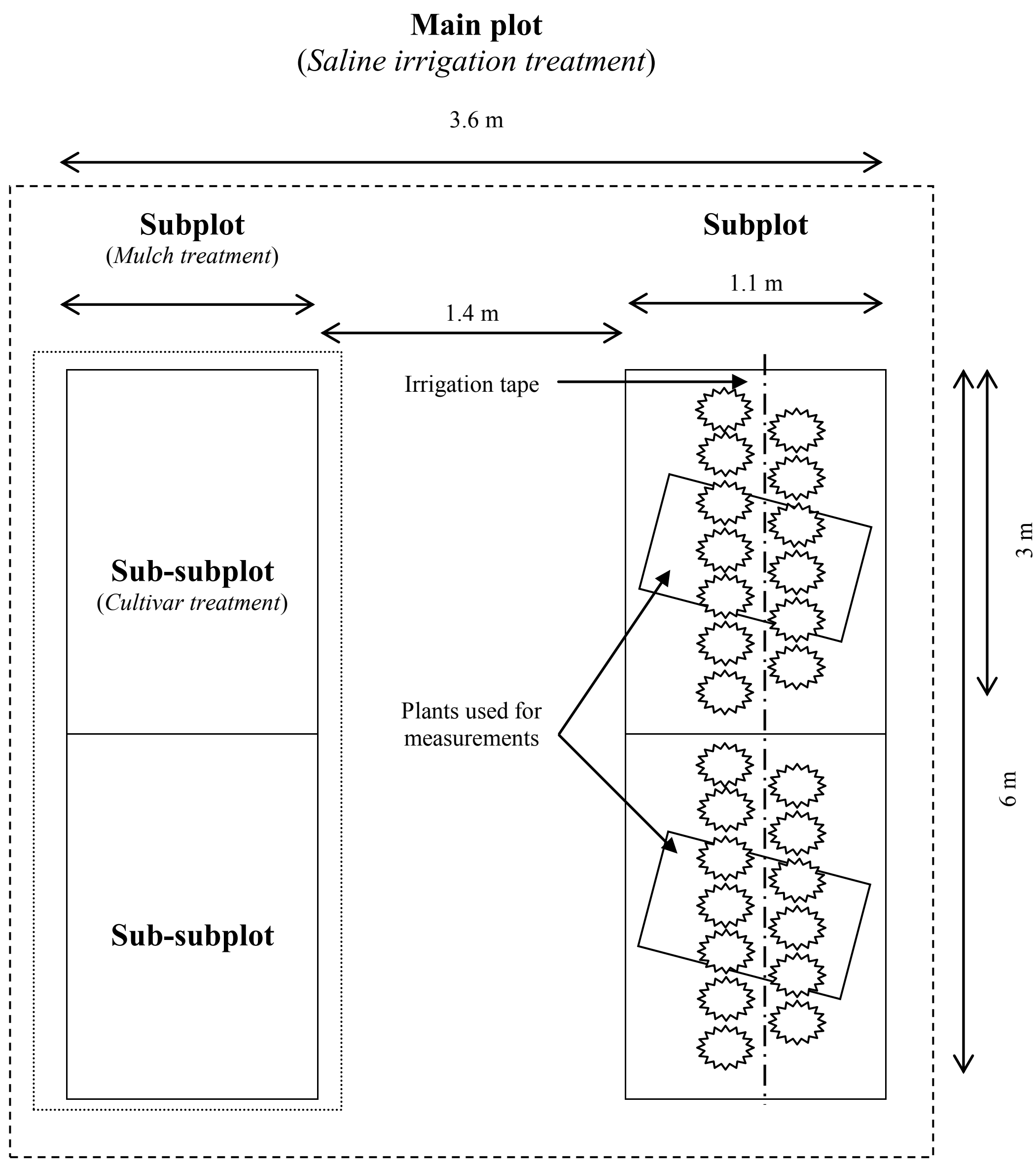


Figure 6.2 A daily representation throughout the growing season of soil temperature at two depths (10 and 20 cm) under black polyethylene mulch and bare soil treatments. Means ±SEM (n=48) were averaged across levels of saline irrigation timing.

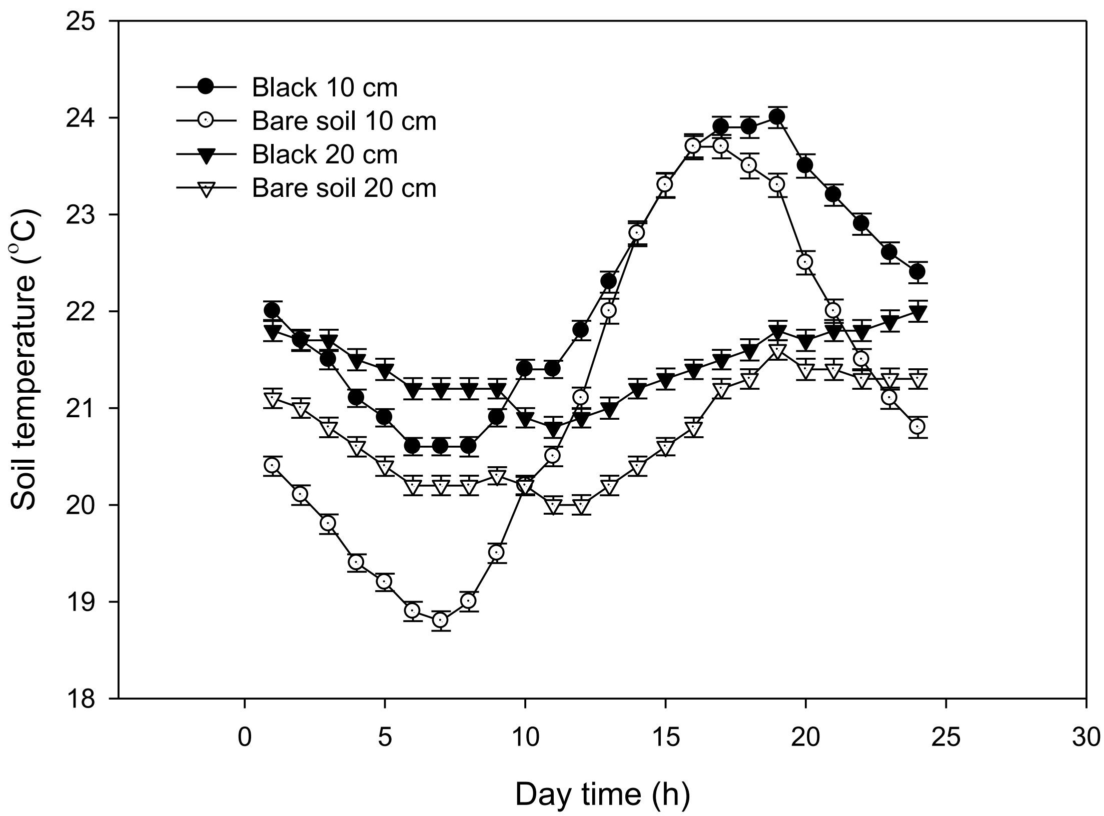


Figure 6.3 Soil salinity (electrical conductivity of soil/water extracts 1:5 ratio, $EC_{1:5}$) as affected by black polyethylene mulch or bare soil, and saline drip irrigation timing $^{(z)}$. Means, ±SEM (n=8) were averaged across cultivar levels.

$^{(z)}$ None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering, then during harvest), S2S3 (saline irrigation from flowering to first harvest), S3S4 (saline irrigation after fruit set); and All (only saline irrigation).

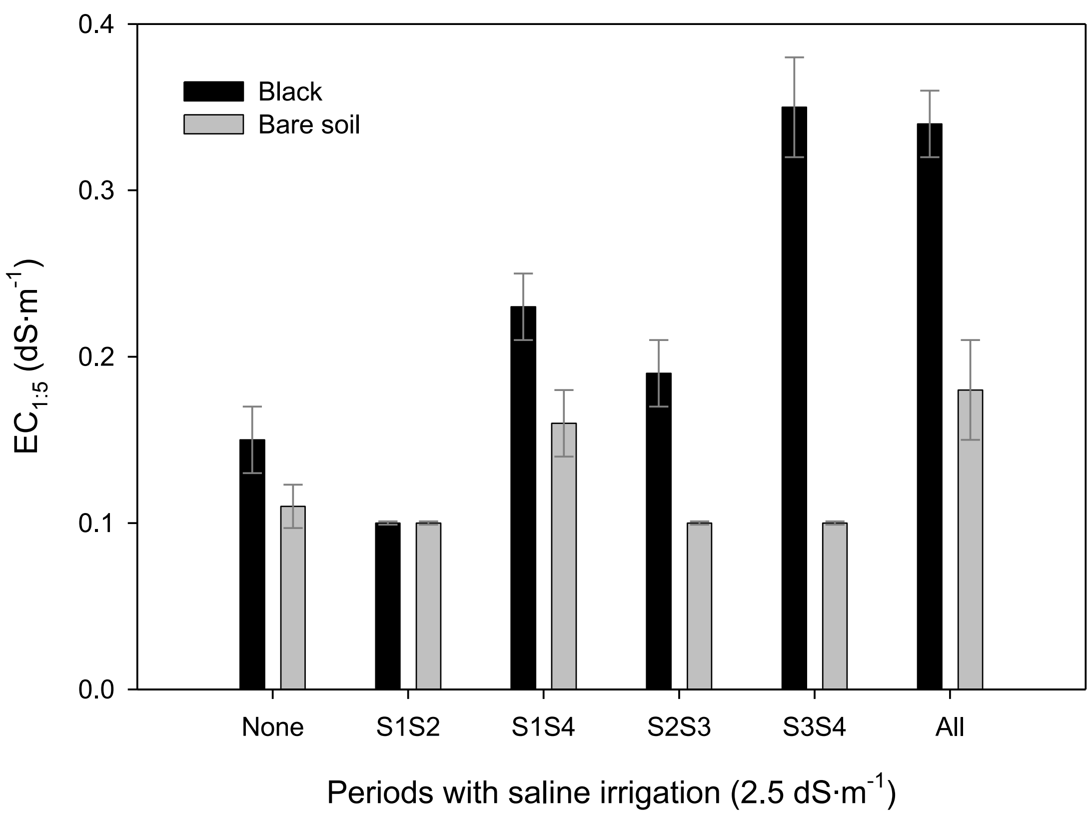


Figure 6.4 Soil salinity (electrical conductivity of soil/water extracts 1:5 ratio, $EC_{1:5}$) as affected by the distance from drip irrigation line and saline (2.5 $dS \cdot m^{-1}$) drip irrigation timing [(z)]. Means ±SEM (n=8) were averaged across mulch and cultivar levels.

[(z)] None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering, then during harvest), S2S3 (saline irrigation from flowering to first harvest), S3S4 (saline irrigation after fruit set); and All (only saline irrigation).

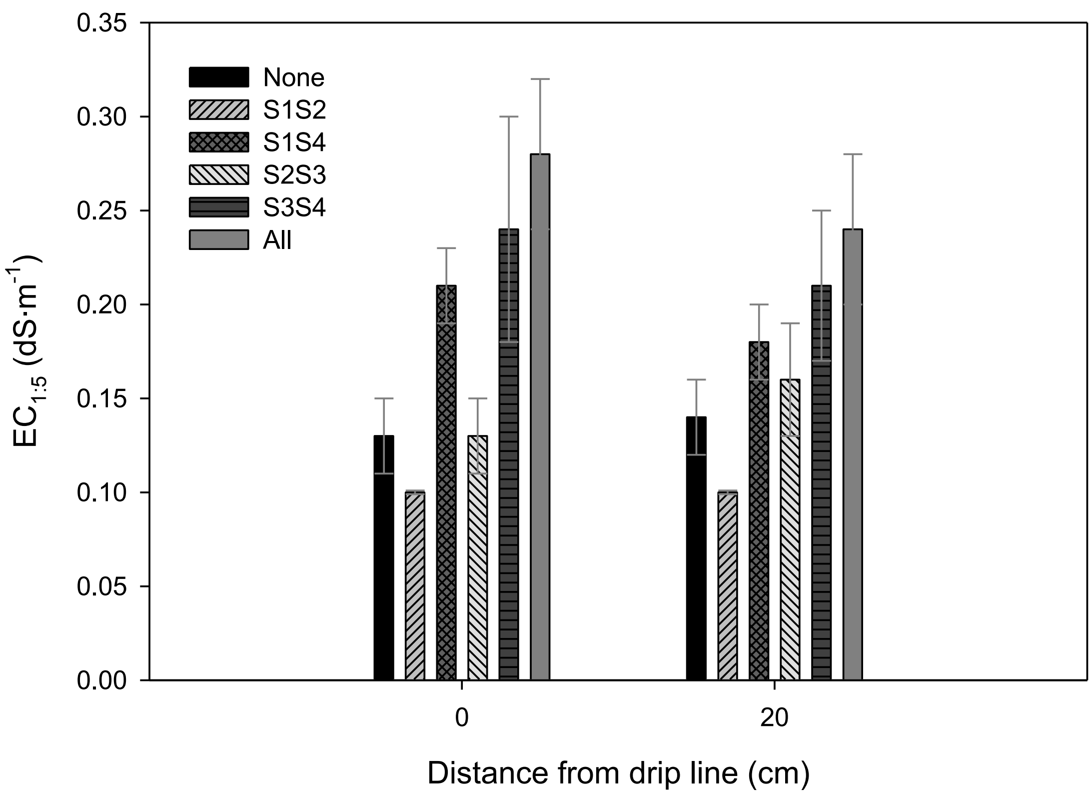
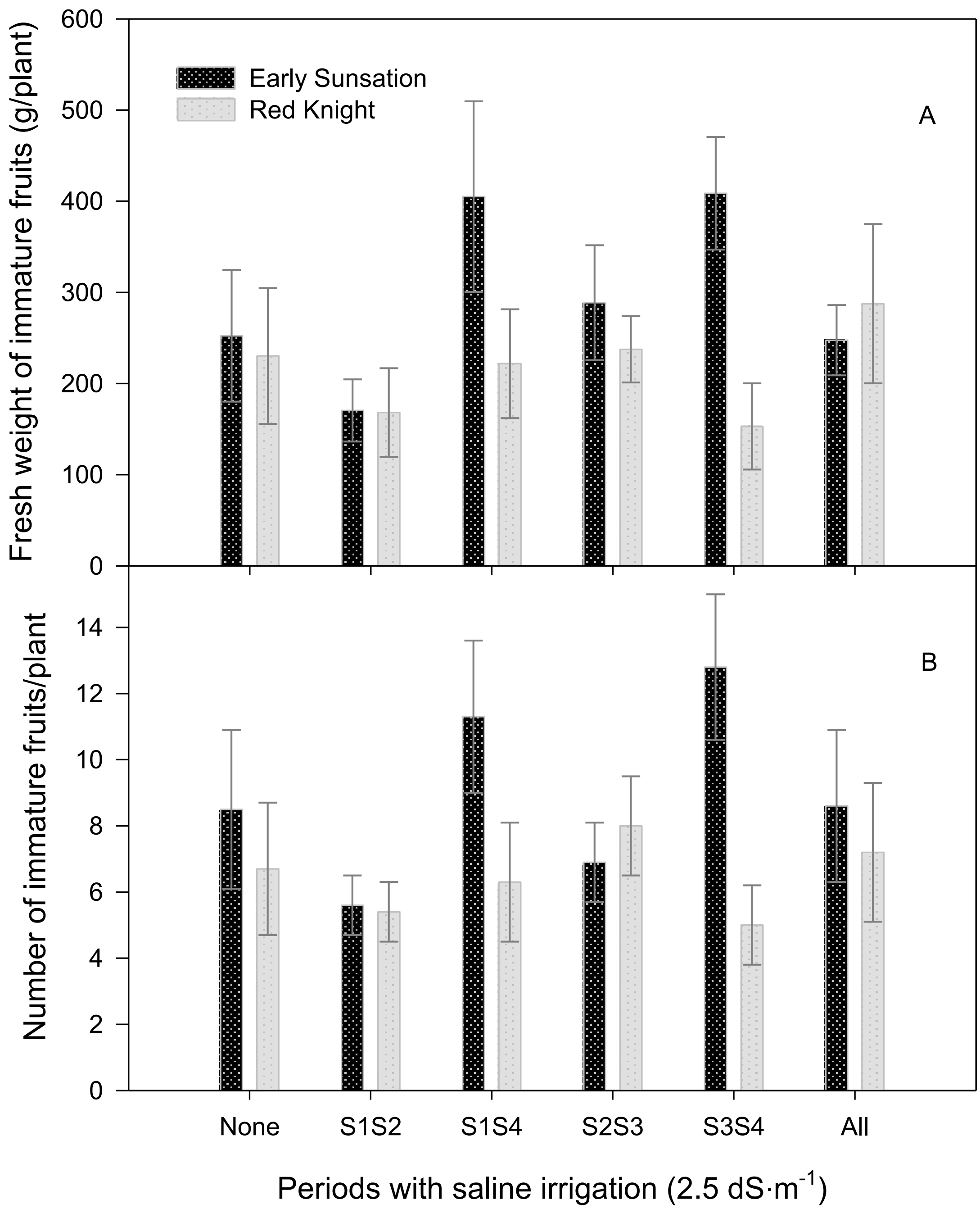


Figure 6.5 A) Fresh weight, and B) number of immature fruits of bell pepper (*Capsicum annuum* L.) cultivars: Early Sunsation and Red Knight as affected by saline drip irrigation timing [(z)]. Means ±SEM (n=6) were averaged across mulch levels.

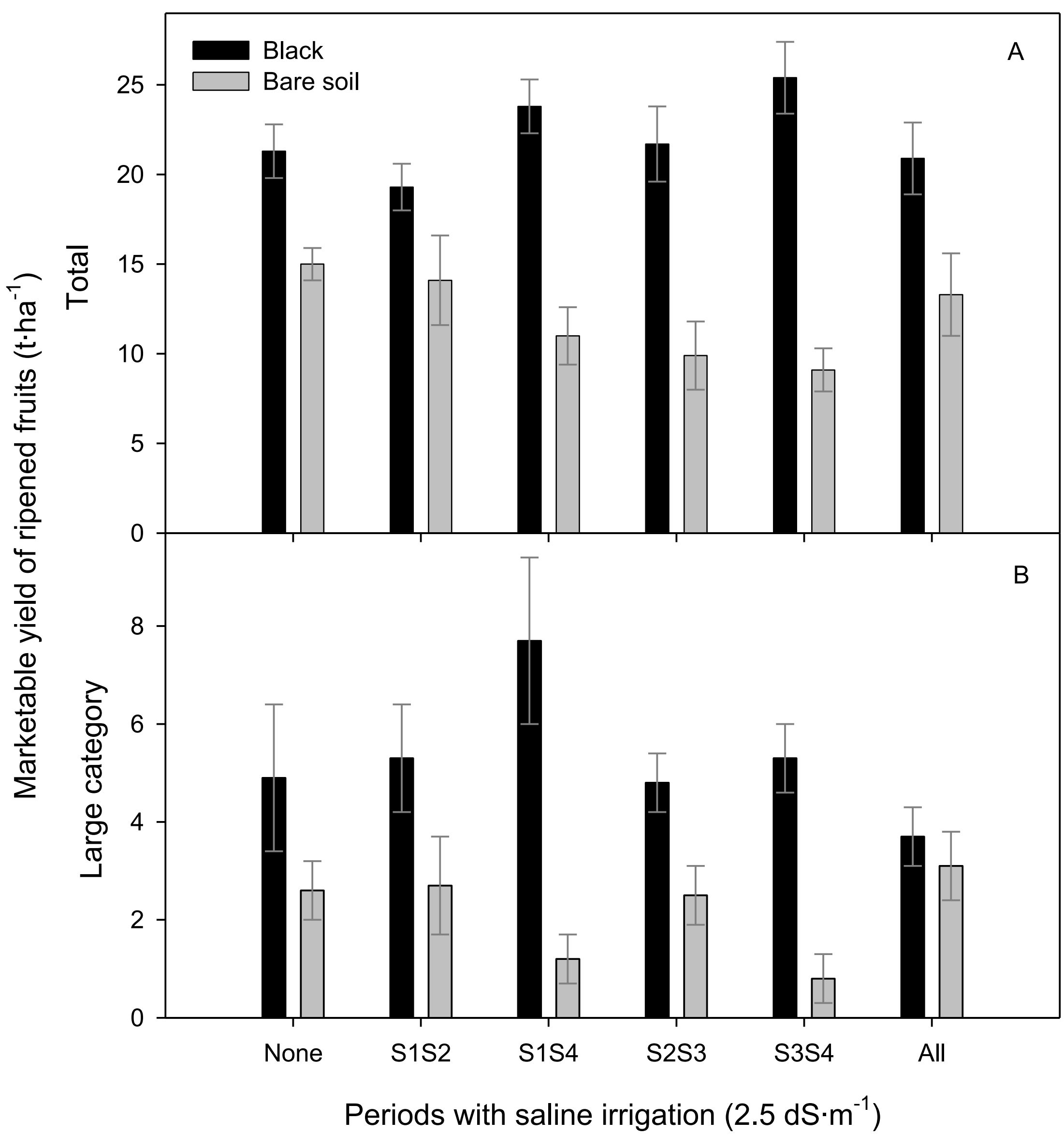
[(z)] None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering, then during harvest), S2S3 (saline irrigation from flowering to first harvest), S3S4 (saline irrigation after fruit set); and All (only saline irrigation).



Fresh weight of immature fruits (g/plant)
0
100
200
300
400
500
600
Early Sunsation
Red Knight
A
Number of immature fruits/plant
0
2
4
6
8
10
12
14
B
None
S1S2
S1S4
S2S3
S3S4
All
Periods with saline irrigation (2.5 dS·m-1)

Figure 6.6 A) Total, and B) large category marketable yield of fully ripened fruits of bell pepper (*Capsicum annuum* L. vars. Early Sunsation and Red Knight) as affected by black polyethylene mulch or bare soil, and saline drip irrigation timing [(z)]. Means ±SEM (n=6) were averaged across cultivar levels.

[(z)] None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering, then during harvest), S2S3 (saline irrigation from flowering to first harvest), S3S4 (saline irrigation after fruit set); and All (only saline irrigation).



Black
Bare soil
A
B
Marketable yield of ripened fruits (t·ha-1)
Total
Large category
0
5
10
15
20
25
0
2
4
6
8
None
S1S2
S1S4
S2S3
S3S4
All
Periods with saline irrigation (2.5 dS·m-1)

Figure 6.7 Number of fully ripened marketable fruits of bell pepper (*Capsicum annuum* L. vars. Early Sunsation and Red Knight) as affected by black polyethylene mulch or bare soil, and saline drip irrigation timing [(z)]. Means ±SEM (n=6) were averaged across cultivar levels.

[(z)] None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering, then during harvest), S2S3 (saline irrigation from flowering to first harvest), S3S4 (saline irrigation after fruit set); and All (only saline irrigation).

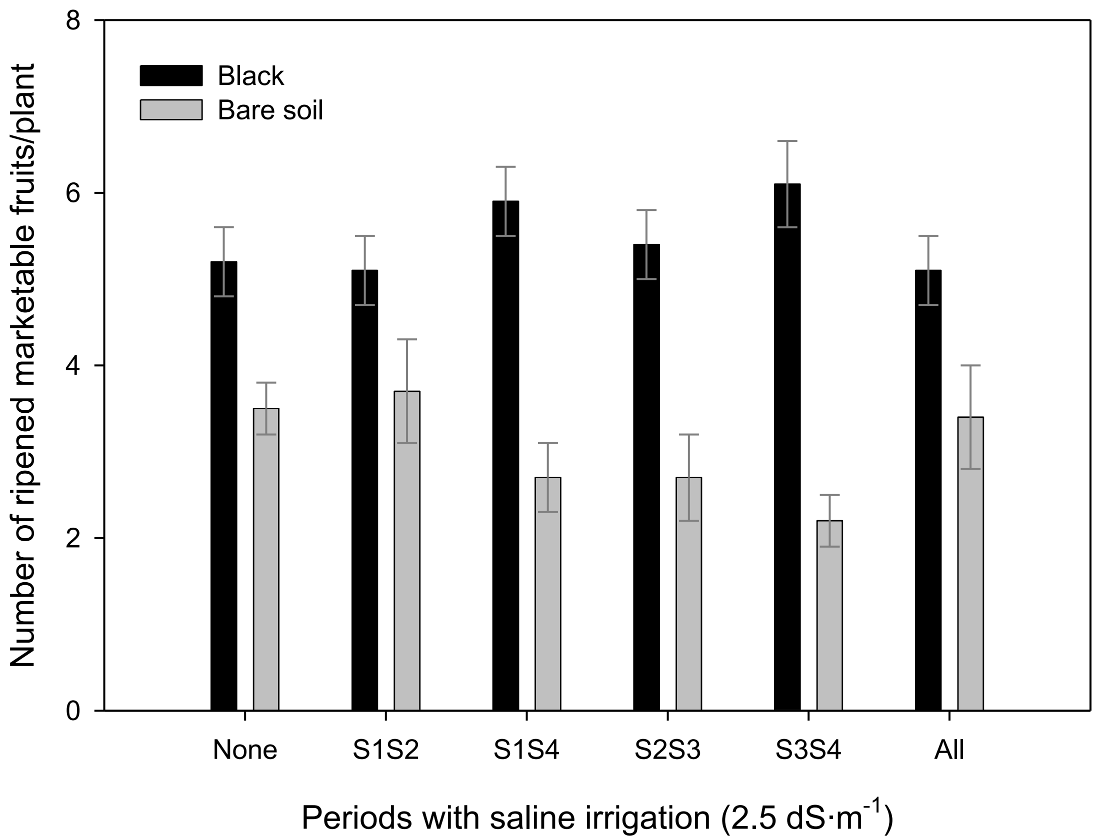
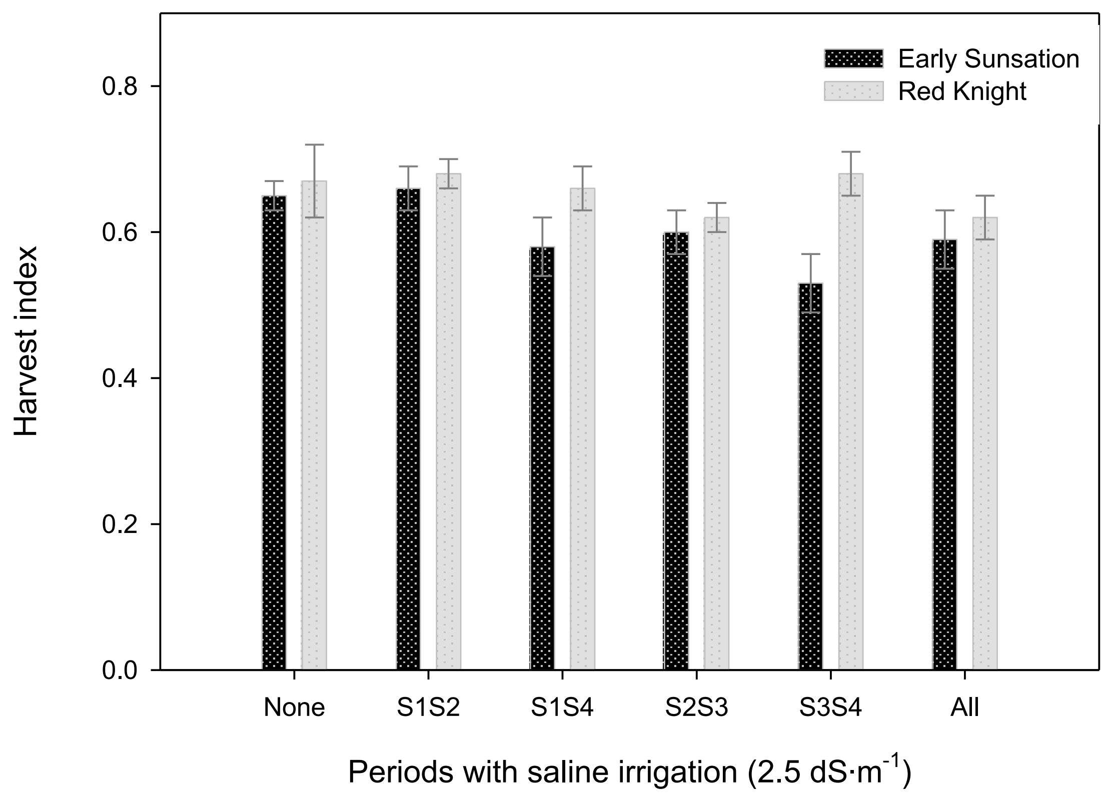


Figure 6.8 Harvest index of bell pepper (*Capsicum annuum* L.) cultivars: Early Sunsation and Red Knight as affected by saline drip irrigation timing [(z)]. Means ±SEM (n=6) were averaged across mulch levels.

[(z)] None (no saline irrigation), S1S2 (saline irrigation from transplanting to fruit set), S1S4 (saline irrigation from transplanting to flowering, then during harvest), S2S3 (saline irrigation from flowering to first harvest), S3S4 (saline irrigation after fruit set); and All (only saline irrigation).



Chapter 7

General discussion

The studies included in this thesis focused on the physiological, growth and fruit production responses of bell pepper plants grown on mulch or bare soil to saline water applied via an on-surface drip irrigation system. At the start of this study I made a number of hypotheses. The first was that saline drip irrigation is more deleterious when pepper plants are grown under bare soil condition rather than under mulch condition, based on the physiology, growth and fruit production. In the study reported in Chapter 3, I found that stomatal conductance (g_s), transpiration (E) and photosynthesis (A) were all negatively affected by saline irrigation. Photosynthesis was not significantly reduced by saline water of 2.5 $dS{\cdot}m^{-1}$ until the fruit growth stage. The greater sensitivity to salinity of stomatal conductance than photosynthesis in bell pepper plants have been previously reported (Chartzoulakis and Klapaki, 2000; De Pascale et al., 2003). Mulched plants had higher rates of g_s, E and A than plants grown in bare soil, mostly likely due to the reduction in abrupt changes in soil moisture (Bar-Tal et al., 2000). I was not able to prove the physiological part of the hypothesis since statistical analysis indicated no significant interaction of saline water with mulch. Partial closure of stomata occurred at salinities of 2.5 $dS{\cdot}m^{-1}$ or higher; thus reducing water loss and restricting CO_2 intake by plants. Osmotic effects by salinity outside the roots may have caused reductions in stomatal conductance, and hence affecting transpiration and photosynthesis (Munns, 2002; Munns and Tester, 2008). Additionally, accumulation of either Cl^- or Na^+ in leaves could cause damage in chloroplasts and decrease these physiological parameters (Bethke and Drew, 1992; Chartzoulakis and Klapaki, 2000).

Salinity limits plant growth in two related phases: osmotic and ionic (Munns and Tester, 2008; Munns et al., 1995). These two phases may have decreased growth in plants irrigated with saline water of 2.5 $dS \cdot m^{-1}$ or greater. This finding is consistent with other reports for bell pepper grown under saline condition (Chartzoulakis and Klapaki, 2000; De Pascale et al., 2003; Gunes et al., 1996; Kaya and Higgs, 2003; Kaya et al., 2003). Across saline irrigation treatments, plants grown in bare soil were smaller compared to mulched ones, possibly as a consequence of slower soil water depletion (Kirnak et al., 2003) and improved soil temperature (Locher et al., 2005) under the mulch.

Of the aerial parts of the plants, fruits were most sensitive to salinity. Mulched plants produced higher early marketable yield than plants grown in bare soil when using saline water of 2.5 $dS \cdot m^{-1}$ or lower. A similar trend was found with saline water of 1.5 $dS \cdot m^{-1}$ to produce total marketable yield. This finding supports the benefits of using polyethylene mulch under saline condition with minimized salt leaching.

In order to investigate my second hypothesis whether the use of polyethylene mulch reduces water needs, regardless of the water quality, while maintaining fruit production, I determined WUE_a. I was able to prove this hypothesis as I found that although less water was applied to mulched plants, the marketable yield was similar to or higher than that of plants grown in bare soil. The WUE_a was higher in mulched plants compared with plants grown in bare soil when the level of salinity was 2.5 $dS \cdot m^{-1}$ or lower. This is an important finding for pepper production in semiarid areas where there is little salt leaching.

I had hypothesised that under condition of minimal salt leaching, use of polyethylene mulch decreases soil salinization and concentrates salts evenly in the root zone compared to bare soil. In fact, mulched soils were less saline than bare soils regardless of saline water levels, which enhanced early and final marketable yields. This was a consequence of a decreased salt loading by irrigation under mulch condition (Assouline et al., 2006). I was able to prove this hypothesis.

I questioned whether bell pepper seedlings could tolerate saline water levels of ≤2.5 $dS \cdot m^{-1}$ without significant growth reductions and physiological disturbances. In Chapter 4, I reported that, indeed, this was the case with the final emergence of seedlings under salinized peat-based growth media which was only reduced at salinities ≥3.5 $dS \cdot m^{-1}$. The reduction in emergence may be due to the sensitivity of the radicle and hypocotyl to high salinity (≥3.5 $dS \cdot m^{-1}$) rather than failures in germination. This finding is in agreement with other works reporting that salinity affected seedling emergence more than germination of pepper (Miyamoto et al., 1985; Yildirim and Guvenc, 2006). The growth of roots was substantially more affected by salinity than that of shoots, whereas within shoots, stems were proportionally more reduced in weight than leaves as salinity increased. This may be caused by higher Na^+ concentration in roots than in shoots (Blom-Zandstra et al., 1998), and higher Na^+ concentration in stems than in leaves (Bethke and Drew, 1992; Blom-Zandstra et al., 1998). Reductions in fresh and dry weights in pepper seedlings agree with other reports for saline conditions (Chartzoulakis and Klapaki, 2000; Palma et al., 1996; Yildirim and Guvenc, 2006). Relative growth rates were negatively affected by salinity levels of 2.5 $dS \cdot m^{-1}$ or higher. The decreases in RGR with increasing salinity agree with findings of Yilmaz et al. (2004) for pepper seedlings.

Having determined that saline water of 2.5 $dS \cdot m^{-1}$ can be used to grow bell peppers, a study was carried out to evaluate whether the phenological stage of development of bell peppers influences its response to saline irrigation (Chapter 5). Mulched plants, which received a lighter salt load by irrigation, recovered or maintained normal physiological activity during or after being exposed to the same level of salinity as plants grown in bare soil. A greater salt load in bare soils might have lowered the osmotic potential and induced partial closure of stomata, ultimately affecting stomatal conductance, transpiration and photosynthesis.

Across mulch treatments, roots were more negatively affected by the timing of the saline irrigation. In non-saline conditions, greater root weights were found in plants grown in bare soil compared with mulched plants. However, the opposite occurred when saline water was applied during early growth (vegetative and flowering stages), at which the young roots of plants grown in bare soil might have been exposed to a higher concentration of salts in the soil than the roots of mulched plants. Shoot growth was reduced when saline water was applied at either early growth (vegetative and flowering stages) because of reductions of leaf growth, or at late growth (fruit set and fruiting stages) because of a reduction in fruit production. Across saline irrigation treatments, mulch enhanced shoot growth probably due to higher soil temperatures in mulched soils (Aziz, 1994; Locher et al., 2005; Siwek et al., 1994) and a more uniform soil moisture within the root zone (Kirnak et al., 2003).

Interestingly, under saline condition with no leaching or minimized leaching of salts, applying saline water during late growth stages (fruit set and fruiting) negatively affected marketable fruit production by loading more salts into the soil; thus, it may be expected that fruit production declined because of salt stress caused by deleterious effects on water uptake (osmotic phase) and possibly induction of high salt concentrations within the plant (ionic phase) (Munns, 2002; Munns and Tester, 2008). The use of mulch decreased soil salinity, and hence, increased marketable fruit production. Saline irrigation applied to mulched plants at flowering and fruit set, or during vegetative and fruiting increased marketable fruit production relative to plants grown in bare soil.

In the same study (Chapter 5), I also tested whether steady saline irrigation concentrates more salts in the soil than temporal saline irrigation. It was observed that, in general, the longer the periods with saline irrigation, the higher the soil salinity. Therefore, use of saline water during vegetative and flowering growth or flowering and fruit set growth resulted in comparable soil salinity to irrigating with non-saline water. All of these treatments gave produce lower soil salinities than using saline water steadily throughout growth. In order to prevent excessive soil salinization, it would be worth while to discontinue saline irrigation before fruiting. Mulching limited evaporation, therefore less water was applied by irrigation and hence less salts (Hoffman and Shannon, 2007). Evaporation from bare soil condition likely induced an upward flow of soil water accumulating salts within the upper layer of the soil of the (Yaron et al., 1973).

The last two hypotheses were also tested in the field in a humid area with a non-saline soil (Chapter 6). It was observed that plants irrigated with non-saline water or temporarily with saline water during early growth (vegetative and flowering) did not have reduced stomatal conductance and transpiration. Since physiological measurements were performed at fruit set, plants undergoing saline treatments at this growth stage would have suffered the effects of lowered root zone osmotic potential (Munns, 2002; Munns and Tester, 2008) and have reduced transpiration due to a slight partial closure of stomata (Munns, 2002; Taiz and Zeiger, 2002). Plants irrigated with saline water during vegetative growth, had photosynthesis rates similar to the non-saline control and higher than other salinity treatments. Reductions in photosynthesis of plants irrigated with saline water beyond the vegetative stage were possibly due to osmotic (Munns and Tester, 2008) or ionic effects (e.g. higher Na^+, Cl^- or both concentrations within the plant). Mulched plants had higher stomatal conductance, transpiration and photosynthesis than plants grown in bare soil, which could be related to higher soil temperature, which in turn might have favored Ca^{2+} uptake and reduced Na^+ uptake in pepper plants (Cabañero et al., 2004; Rubio et al., 2003).

Contrary to the findings in Chapter 5, salinity had only a limited affect on growth. Leaf and stem fresh weights were lower when saline water was applied during vegetative and flowering growth rather than continuously. Mulching the soil improved growth and accelerated the maturity of fruits. Enhancing growth by using mulch has been reported for bell pepper grown in non-saline condition (Aziz, 1994; Locher et al., 2005; Siwek et al., 1994).

In a humid area with non-saline soil, applying saline water ($2.5\ dS \cdot m^{-1}$) for long periods did not reduce marketable yields of ripe fruits in mulched plants. The increase in yield of mulched plants irrigated with saline water during fruit growth likely due to increased soil temperature (Locher et al., 2005); which in turn may have enhanced Ca^{2+} uptake by plants in saline condition (Cabañero et al., 2004) and may have lessened toxic Na^+ uptake (Rengel, 1992) by maintaining or improving the selective K^+ uptake by plants (Epstein, 1998). If the plants are not mulched, then saline water should be used to irrigate the crop only during the vegetative and flowering to avoid yield reductions.

Soil salinity increased when saline water was applied during fruit set and fruiting, or continuously. This finding is in agreement with those found in Chapter 5, confirming that soil salinization is related to the amount of salts applied in the irrigation water (Hoffman and Shannon, 2007). Therefore, saline irrigation applied before fruiting set consequently induced less soil salinization than continuous saline irrigation. Rainfall also played an important role in salt leaching; thus preventing high salt accumulation in bare soil relative to mulched soil.

Under conditions of limited salt leaching, mulched plants receiving saline drip irrigation of 2.5 $dS{\cdot}m^{-1}$ or less were able to ameliorate negative effects of salinity compared with plants grown on bare soil.

Chapter 8

Future directions

Various suggestions for future research could be arise from the studies reported in this thesis:

1. Research involving saline drip irrigation and mulch could be expanded to different types of soils, position of drippers (surface vs subsurface), and mulch materials to examine their effects on peppers or other crops, and soil salinity.
2. A further study is needed to explore the effects of the composition of saline solutions and root zone temperature on fruit quality (e.g. size, total soluble solids) of peppers.
3. The use of saline water through different irrigation systems (e.g., overhead or sprinkler, subirrigation or flotation) to produce pepper seedlings (transplants) could be studied to determined appropriateness.
4. Long-term evaluations under field conditions of transplants produced using saline water to determine effects on yield and fruit quality needs research.
5. To study the effect of saline water at different growth stages of pepper, one possible strategy could be splitting all growth stages, particularly the set fruit and fruiting, into smaller periods of approximately two weeks or 20 days so that comparisons of saline irrigation periods could be more feasible. Hydroponic conditions may be appropriate to have homogeneous salt concentration in the root zone during the periods of saline irrigation.

6. Studies involving long-term use of saline water applied via drip irrigation, and soil mulch under field conditions with both minimal and frequent salt leaching could be done to evaluate impacts on plants and soil salinity.

Chapter 9

Contributions to knowledge

9.1 From Chapter 3

1. Results reported in Chapter 3 constitute the first study focused on the response of bell pepper plants (physiology, growth, yield and water use) and soil salinity to different levels of saline drip irrigation and use of polyethylene mulch.
2. This study showed that marketable yield of bell peppers is not affected by saline water levels of $\leq 2.5\ dS \cdot m^{-1}$ if grown under polyethylene mulch condition compared to bare soil condition.
3. It is the first report on water use efficiency (WUE) involving saline water and polyethylene mulch. This study showed that agronomic WUE was higher in mulched plants, relative to plants grown in bare soil, when saline water level was $\leq 2.5\ dS \cdot m^{-1}$.
4. The study provided evidences that soil mulching contributed to less soil salinization, relative to bare soil, under minimal salt leaching.

9.2 From Chapter 4

5. This is the first study reporting effects of saline water on growth and physiology of bell pepper seedlings grown under a containerized production system (trays and peat-based growing medium) in greenhouse conditions.

6. This study showed that saline water of up to 1.5 $dS \cdot m^{-1}$ can be use to start bell pepper seedlings (transplants) without any negative effects on growth and physiology (stomatal conductance, transpiration and photosynthesis).

9.3 From Chapter 5

7. This is the first study exploring the effects of saline water, applied through drip irrigation at different growth stages of bell pepper grown under mulch or bare soil condition, on plant physiology, growth and yield, and soil salinity, under condition of minimal salt leaching.
8. This study showed that mulched plants recover normal physiology more quickly than plants grown in bare soil during or after being irrigated with saline water (2.5 $dS \cdot m^{-1}$); and that saline water could be applied at flowering and fruit under mulch condition.
9. This research showed that agronomic water use efficiency was higher for mulched plants than for plants grown in bare soil, regardless of saline irrigation timing.

9.4 From Chapter 6

10. This study determined bell pepper crop evapotranspiration under conditions of saline drip irrigation (2.5 $dS \cdot m^{-1}$) and mulching as outlined by Allen et al. (1998).
11. This is the first research on the application of saline water via drip irrigation at different growth stages bell peppers grown with or without black polyethylene mulch under field conditions.

12. This study showed that, in humid areas with non-saline soil, the use of polyethylene mulch should be taken into consideration to determine when to irrigate with saline water. While avoiding yield reductions, irrigating with saline water may be accomplished at fruit set and fruiting stages for mulched plants, or at vegetative and flowering growth stages for plants grown in bare soil.

Chapter 10

References

Akinci, I. E., S. Akinci, K. Yilmaz, and H. Dikici. 2004. Response of eggplant varieties (*Solanum melongena*) to salinity in germination and seedling stages. New Zealand Journal of Crop and Horticultural Science 32:193-200.

Aktas, H., K. Abak, and I. Cakmak. 2006. Genotypic variation in the response of pepper to salinity. Scientia Horticulturae 110:260-266.

Ali, A.M., and W.C. Kelly. 1992. The effects of interfruit competition on the size of sweet pepper (*Capsicum annuum* L.) fruits. Scientia Horticulturae 52:69-76.

Al-Harbi, A. R. 1995. Growth and nutrient composition of tomato and cucumber seedlings as affected by sodium chloride salinity and supplemental calcium. Journal of Plant Nutrition 18:1403-1416.

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration. FAO, Rome. 300 pp.

Alvino, A., M. Centritto, and F. Delorenzi. 1994. Photosynthesis response of sunlit and shade pepper (*Capsicum annuum*) leaves at different positions in the canopy under two water regimes. Australian Journal of Plant Physiology 21:377-391.

Assouline, S., M. Moller, S. Cohen, M. Ben-Hur, A. Grava, K. Narkis, and A. Silber. 2006. Soil-plant system response to pulsed drip irrigation and salinity: Bell pepper case study. Soil Science Society of America Journal 70:1556-1568.

Ayars, J.E., C.J. Phene, R.B. Hutmacher, K.R. Davis, R.A. Schoneman, S.S. Vail, and R.M. Mead. 1999. Subsurface drip irrigation of row crops: a review of 15 years of research at the Water Management Research Laboratory. Agricultural Water Management 42:1-27.

Ayers, R.S., and D.W. Westcot. 1985. Water quality for agriculture. FAO, Rome. 174 pp.

Aziz, F. 1994. Effect of mulch on the soil microenvironment, yield of pepper (*Capsicum annuum* L.), and aphid population. Thesis (M.Sc.), McGill University, Montreal. 67 pp.

Bakker, J.C. 1989. The effects of temperature on flowering, fruit set and fruit development of glasshouse sweet pepper (*Capsicum annuum* L.). Journal of Horticultural Science 64:313-320.

Bar-Tal, A., M. Keinan, B. Aloni, L. Karni, Y. Oserovitz, S. Gantz, A. Hazan, M. Itach, N. Tartakovski, A. Avidan, and I. Posalski. 2000. Relationships between blossom-end rot and water availability and Ca fertilization in bell pepper fruit production. Acta Horticulturae 554:97-104.

Bar-Yosef, B. 1999. Advances in fertigation. Advances in Agronomy 65:1-77.

Bar-Yosef, B., T. Markovich, and I. Levkovich. 2001. Pepper response to leachate recycling in a greenhouse in Israel. Acta Horticulturae 548:357-364.

Beese, F., R. Horton, and P.J. Wierenga. 1982. Growth and yield response of chile pepper to trickle irrigation. Agronomy Journal 74:556-561.

Ben-Gal, A., E. Ityel, L. Dudley, S. Cohen, U. Yermiyahu, E. Presnov, L. Zigmond, and U. Shani. 2008. Effect of irrigation water salinity on transpiration and on leaching requirements: A case study for bell peppers. Agricultural Water Management 95:587-597.

Bethke, P.C., and M.C. Drew. 1992. Stomatal and nonstomatal components to inhibition of photosynthesis in leaves of *Capsicum annuum* during progressive exposure to NaCl salinity. Plant Physiology 99:219-226.

Binzel, M.L., and M. Reuveni. 1994. Cellular mechanisms of salt tolerance in plant cells. Horticultural Reviews 16:33-69.

Blom-Zandstra, M., S.A. Vogelzang, and B.W. Veen. 1998. Sodium fluxes in sweet pepper exposed to varying sodium concentrations. Journal of Experimental Botany 49:1863-1868.

Borsani, O., V. Valpuesta, and M.A. Botella. 2003. Developing salt tolerant plants in a new century: a molecular biology approach. Plant Cell Tissue and Organ Culture 73:101-115.

Bosland, P.W., and E.J. Votava. 2000. Peppers: vegetable and spice Capsicums. CABI, New York, NY. 204 pp.

Bouwer, H. 1994. Irrigation and global water outlook. Agricultural Water Management. 25: 221-231.

Bouwer, H. 2002. Integrated water management for the 21st century: Problems and solutions. Journal of Irrigation and Drainage Engineering 128:193-202.

Brouwer, C., and M. Heibloem. 1986. Irrigation water needs. Irrigation Water Management, Training Manual no. 3, FAO, Rome. 60 pp.

Brown, J.E., and C. Channell-Butcher. 2001. Black plastic mulch and drip irrigation affect growth and performance of bell pepper. Journal of Vegetable Crop Production 7:109-112.

Bustan, A., S. Cohen, Y. De Malach, P. Zimmermann, R. Golan, M. Sagi, and D. Pasternak. 2005. Effects of timing and duration of brackish irrigation water on fruit yield and quality of late summer melons. Agricultural Water Management 74:123-134.

Cabañero, F.J., V. Martínez, and M. Carvajal. 2004. Does calcium determine water uptake under saline conditions in pepper plants, or is it water flux which determines calcium uptake?. Plant Science 166:443-450.

Carvajal, M., F.M. del Amor, G. Fernandez-Ballester, V. Martinez, and A. Cerda. 1998. Time course of solute accumulation and water relations in muskmelon plants exposed to salt during different growth stages. Plant Science 138:103-112.

Chartzoulakis, K.S. and M.H. Loupassaki. 1997. Effects of NaCl salinity on germination. Growth, gas exchange and yield of greenhouse eggplant. Agricultural Water Management 32:215-225.

Chartzoulakis, K., and G. Klapaki. 2000. Response of two greenhouse pepper hybrids to NaCl salinity during different growth stages. Scientia Horticulturae 86:247-260.

Chaves, M.M., J. Osório, and J.S. Pereira. 2004. Water use efficiency and photosynthesis. *In*: M. A. Bacon (ed.), Water use efficiency in plant biology. Blackwell Publishing Ltd, Oxford. pp. 42-74.

Chhabra, R. 1996. Soil salinity and water quality. A.A. Balkema publishers, VT, USA. 284 pp.

Colla, G., Y. Rouphael, C. Fallovo, M. Cardarelli, and A. Graifenberg. 2006. Use of *Salsola soda* as a companion plant to improve greenhouse pepper (*Capsicum* *annuum*) performance under saline conditions. New Zealand Journal of Crop and Horticultural Science 34:283-290.

Dalton, F.N., A. Maggio, and G. Piccinni. 1997. Effect of root temperature on plant response functions for tomato: comparison of static and dynamic salinity stress indices. Plant and Soil 192:307-319.

Dalton, F.N., A. Maggio, and G. Piccinni. 2001. Assessing the effect of solar radiation on plant salt tolerance as defined by the static and dynamic indices. Plant and Soil 229:189-195.

Darrah, P.R. 1993. The rhizosphere and plant nutrition - A quantitative approach. Plant and Soil 156:1-20.

Dasberg, S., and D. Or. 1999. Drip irrigation. Springer, Berlin; New York. 162 pp.

De Pascale, S., C. Ruggiero, and G. Barbieri. 2000. Effects of irrigating pepper (*Capsicum annuum* L.) plants with saline water on plant growth, water use efficiency, and marketable yield. Acta Horticulturae 537:687-695.

De Pascale, S., C. Ruggiero, G. Barbieri, and A. Maggio. 2003. Physiological responses of pepper to salinity and drought. Journal of the American Society for Horticultural Science 128:48-54.

Decoteau, D.R. 2000. Vegetable crops. Prentice Hall, Upper Saddle River, NJ. 464 pp.

Decoteau, D.R., M.J. Kasperbauer, and P.G. Hunt. 1990. Bell pepper plant development over mulches of diverse colors. HortScience 25:460-462.

Dehghanisanij, H., M. Agassi, H. Anyoji, T. Yamamoto, M. Inoue, and A.E. Eneji. 2006. Improvement of saline water use under drip irrigation system. Agricultural Water Management 85:233-242.

del Amor, F.M., V. Martinez, and A. Cerda. 2001. Salt tolerance of tomato plants as affected by stage of plant development. HortScience 36:1260-1263.

Delfine, S., F. Loreto, and A. Alvino. 2001. Drought-stress effects on physiology, growth and biomass production of rainfed and irrigated bell pepper plants in the Mediterranean region. Journal of the American Society for Horticultural Science 126:297-304.

Delfine, S., R. Tognetti, F. Loreto, and A. Alvino. 2002. Physiological and growth responses to water stress in field-grown bell pepper (*Capsicum annuum* L.). Journal of Horticultural Science and Biotechnology 77:697-704.

Diaz-Perez, J.C., and K.D. Batal. 2002. Colored plastic film mulches affect tomato growth and yield via changes in root-zone temperature. Journal of the American Society for Horticultural Science 127:127-135.

Dinar, A., J. Letey, and H.J. Vaux. 1986. Optimal ratios of saline and nonsaline irrigation waters for crop production. Soil Science Society of America Journal 50:440-443.

Doorenbos, J., A.H. Kassam, and C.L.M. Bentvelsen. 1979. Yield response to water. FAO, Rome. 193 pp.

Epstein, E. 1998. How calcium enhances plant salt tolerance. Science 280:1906-1907.

FAO-AGL. 2000. Global network on integrated soil management for sustainable use of salt-affected soils [Online]. Land and Plant Nutrition Management Services, FAO, Rome. Available from http://www.fao.org/ag/AGL/agll/spush/intro.htm (cited July 23, 2008).

FAO. 2000. Irrigation in Latin America and The Caribbean in figures. Water Reports 20. FAO, Rome. 348 pp.

FAO. 2002. Crops and drops: Making the best use of water for agriculture. FAO, Rome. 22 pp.

Fisher, P.D. 1995. An alternative plastic mulching system for improved water management in dryland maize production. Agricultural Water Management 27:155-166.

Flowers, T.J., and S.A. Flowers. 2005. Why does salinity pose such a difficult problem for plant breeders? Agricultural Water Management 78:15-24.

Gomez, K.A. and A.A. Gomez. 1984. Statistical procedures for agricultural research. Wiley, New York, NY. 680 pp.

Gosselin, A., and M.J. Trudel. 1986. Root-zone temperature effects on pepper. Journal of the American Society for Horticultural Science 111:220-224.

Gough, R.E. 2001. Color of plastic mulch affects lateral root development but not root system architecture in pepper. HortScience 36:66-68.

Grattan, S.R., and C.M. Grieve. 1999. Salinity mineral nutrient relations in horticultural crops. Scientia Horticulturae 78:127-157.

Gregory, P.J. 2004. Agronomic approaches to increasing water use efficiency. *In*: M. A. Bacon (ed.), Water use efficiency in plant biology. Blackwell Publishing Ltd, Oxford. pp. 142-170.

Gunes, A., A. Inal, and M. Alpaslan. 1996. Effect of salinity on stomatal resistance, proline, and mineral composition of pepper. Journal of Plant Nutrition 19:389-396.

Hall, A.J. 1977. Assimilate source-sink relationships in *Capsicum annuum* L. I. The dinamics of growth in fruiting and deflorated plants. Australian Journal of Plant Physiology 4:623-636.

Ham, J.M., G.J. Kluitenberg, and W.J. Lamont. 1993. Optical-properties of plastic mulches affect the field temperature regime. Journal of the American Society for Horticultural Science 118:188-193.

Hanson, B., and D. May. 2004. Effect of subsurface drip irrigation on processing tomato yield, water table depth, soil salinity, and profitability. Agricultural Water Management 68:1-17.

Hartz, T.K. 1996. Water management in drip-irrigated vegetable production. HortTechnology 6:165-167.

Hasegawa, P.M., R.A. Bressan, J.K. Zhu, and H.J. Bohnert. 2000. Plant cellular and molecular responses to high salinity. Annual Review of Plant Physiology and Plant Molecular Biology 51:463-499.

Haynes, R.J. 1990. Active ion uptake and maintenance of cation-anion balance: A critical examination of their role in regulating rhizosphere pH. Plant and Soil 126:247-264.

Hoffman, G.J., and M.C. Shannon. 2007. Salinity. *In*: F. R. Lamm, J.E. Ayars, and F.S. Nakayama (eds.), Microirrigation for crop production: Design, operation, and management. Elsevier, New York, NY. pp. 131-160.

Hopen, H.J., and N.F. Oebker. 1975. Mulch effects on ambient carbon dioxide levels and growth of several vegetables. HortScience 10:159-161.

Horton, R., F. Beese, and P.J. Wierenga. 1982. Physiological response of chile pepper to trickle irrigation. Agronomy Journal 74:551-555.

Howard, L.R., S.T. Talcott, C.H. Brenes, and B. Villalon. 2000. Changes in phytochemical and antioxidant activity of selected pepper cultivars (*Capsicum* species) as influenced by maturity. Journal of Agricultural and Food Chemistry 48:1713-1720.

Hulugalle, N.R., and S.T. Willatt. 1987. Patterns of water uptake and root distribution of chilli peppers grown in soil columns. Canadian Journal of Plant Science 67:531-535.

Hunt, R. 1982. Plant growth curves: the functional approach to plant growth analysis. Edward Arnold, London. 248 pp.

Jolliffe, P.A., and M.M. Gaye. 1995. Dynamics of growth and yield component responses of bell peppers (*Capsicum Annuum* L.) to row covers and population-density. Scientia Horticulturae 62:153-164.

Jones, H. 2004. What is water use efficiency?. *In*: M.A. Bacon (ed.), Water use efficiency in plant biology. Blackwell Publishing Ltd, Oxford. pp. 27-41.

Kang, S.Z., L. Zhang, X.T. Hu, Z.J. Li, and P. Jerie. 2001. An improved water use efficiency for hot pepper grown under controlled alternate drip irrigation on partial roots. Scientia Horticulturae 89:257-267.

Kaur, C., and H.C. Kapoor. 2001. Antioxidants in fruits and vegetables - the millennium's health. International Journal of Food Science and Technology 36:703-725.

Kaya, C., and D. Higgs. 2003. Relationship between water use and urea application in salt-stressed pepper plants. Journal of Plant Nutrition 26:19-30.

Kaya, C., D. Higgs, F. Ince, B.M. Amador, A. Cakir, and E. Sakar. 2003. Ameliorative effects of potassium phosphate on salt-stressed pepper and cucumber. Journal of Plant Nutrition 26:807-820.

Kirnak, H., C. Kaya, D. Higgs, and I. Tas. 2003. Responses of drip irrigated bell pepper to water stress and different nitrogen levels with or without mulch cover. Journal of Plant Nutrition 26:263-277.

Lamont, W.J. 1993. Plastic mulches for the production of vegetable crops. HortTechnology 3:35-39.

Lamont, W.J. 1996. What are the components of a plasticulture vegetable system?. HortTechnology 6:150-154.

Lamont, W.J. 2005. Plastics: Modifying the microclimate for the production of vegetable crops. HortTechnology 15:477-481.

Läuchli, A. 1990. Plant responses to saline and sodic conditions. *In*: K. K. Tanji (ed.), Agricultural salinity assessment and management. ASCE Manual and Reports on Engineering Practice No. 71, American Society of Civil Engineers, New York, NY. pp. 113-137.

Leskovar, D. I. and D. J. Cantliffe. 1993. Comparison of plant establishment method, transplant, or direct seeding on growth and yield of bell pepper. Journal of the American Society for Horticultural Science 118:17-22.

Leskovar, D. I., and R. R. Heineman. 1994. Greenhouse irrigation systems affect growth of 'Tam-Mild jalapeño-1' pepper seedlings. HortScience 29:1470-1474.

Letey, J. 1993. Relationship between salinity and efficient water-use. Irrigation Science 14:75-84.

Locascio, S.J. 2005. Management of irrigation for vegetables: Past, present, and future. HortTechnology 15:482-485.

Locascio, S.J., J.G.A. Fiskell, D.A. Graetz, and R.D. Hauck. 1985. Nitrogen accumulation by pepper as influenced by mulch and time of fertilizer application. Journal of the American Society for Horticultural Science 110:325-328.

Locher, J., A. Ombodi, T. Kassai, and J. Dimeny. 2005. Influence of coloured mulches on soil temperature and yield of sweet pepper. European Journal of Horticultural Science 70:135-141.

Maas, E.V. 1990. Crop salt tolerance. *In*: K. K. Tanji (ed.), Agricultural salinity assessment and management. ASCE Manual and Reports on Engineering Practice No. 71, American Society of Civil Engineers, New York, NY. pp. 262-304.

Madramootoo, C.A., M. Rigby, A.F. MacKenzie, and K.A. Stewart. 1993. Yield response of bell pepper to four irrigation levels and three nitrogen fertilizers rates in a humid climate. ICID Bulletin, Vol. 42, No. 1, International Commission on Irrigation and Drainage.

Marcelis, L.F.M., and L.R.B. Hofman-Eijer. 1995. Growth analysis of sweet pepper fruits (*Capsicum annuum* L.). Acta Horticulturae 412:470-478.

Marin, A., F. Ferreres, F.A. Tomas-Barberan, and M.I. Gil. 2004. Characterization and quantitation of antioxidant constituents of sweet pepper (*Capsicum annuum* L.). Journal of Agricultural and Food Chemistry 52:3861-3869.

Martinez-Ballesta, M.C., V. Martinez, and M. Carvajal. 2004. Osmotic adjustment, water relations and gas exchange in pepper plants grown under NaCl or KCl. Environmental and Experimental Botany 52:161-174.

Martínez Beltrán, J. 1999. Irrigation with saline water: benefits and environmental impact. Agricultural Water Management 40:183-194.

McIntosh, M. S. 1983. Analysis of combined experiments. Agronomy Journal 75:153-155.

McMahon, M.J., A.M. Kofranek, and V.E. Rubatzky. 2002. Hartmann's plant science: growth, development, and utilization of cultivated plants. Prentice Hall, Upper Saddle River, NJ. 573 pp.

Miller, C.H., R.E. McCollum, and S. Claimon. 1979. Relationships between growth of bell peppers (*Capsicum annuum* L.) and nutrient accumulation during ontogeny in field environments. Journal of the American Society for Horticultural Science 104:852-857.

Miyamoto, S., K. Piela, and J. Petticrew. 1985. Salt effects on germination and seedling emergence of several vegetable crops and guayule. Irrigation Science 6:159-170.

Mizrahi, Y., E. Taleisnik, V. Kaganzur, Y. Zohar, R. Offenbach, E. Matan, and R. Golan. 1988. A saline irrigation regime for improving tomato fruit quality without reducing yield. Journal of the American Society for Horticultural Science 113:202-205.

Mmolawa, K., and D. Or. 2000. Root zone solute dynamics under drip irrigation: A review. Plant and Soil 222:163-190.

Monette, S., and K.A. Stewart. 1987. The effect of a windbreak and mulch on the growth and yield of pepper (*Capsicum annuum* L.). Canadian Journal of Plant Science 67:315-320.

Munns, R. 2002. Comparative physiology of salt and water stress. Plant Cell and Environment 25:239-250.

Munns, R., and A. Termaat. 1986. Whole-plant responses to salinity. Australian Journal of Plant Physiology 13:143-160.

Munns, R., and M. Tester. 2008. Mechanisms of salinity tolerance. Annual Review of Plant Biology 59:651-681.

Munns, R., D.P. Schachtman, and A.G. Condon. 1995. The significance of a two-phase growth response to salinity in wheat and barley. Australian Journal of Plant Physiology 22:561-569.

Navarro, J.M., C. Garrido, M. Carvajal, and V. Martinez. 2002. Yield and fruit quality of pepper plants under sulphate and chloride salinity. Journal of Horticultural Science and Biotechnology 77: 52-57.

Navarro, J.M., C. Garrido, V. Martinez, and M. Carvajal. 2003. Water relations and xylem transport of nutrients in pepper plants grown under two different salts stress regimes. Plant Growth Regulation 41:237-245.

Navarro, J.M., P. Flores, C. Garrido, and V. Martinez. 2006. Changes in the contents of antioxidant compounds in pepper fruits at different ripening stages, as affected by salinity. Food Chemistry 96:66-73.

Oron, G., Y. DeMalach, L. Gillerman, I. David, and V.P. Rao. 1999. Improved saline-water use under subsurface drip irrigation. Agricultural Water Management 39:19-33.

Palma, B., P. Peñaloza, C. Galleguillos, and C. Trujillo. 1996. Germinación de semillas y desarrollo de plántulas de pimiento (*Capsicum annuum* L.) en un ambiente salino constante. Phyton International Journal of Experimental Botany 59:177-186.

Papadopoulos, I., and Y. Stylianou. 1991. Trickle irrigation of sunflower with municipal wastewater. Agricultural Water Management 19:67-75.

Parida, A.K., and A.B. Das. 2005. Salt tolerance and salinity effects on plants: a review. Ecotoxicology and Environmental Safety 60:324-349.

Parsons, L.R. 2000. Water management and water relations of horticultural crops: Introduction to the colloquium. HortScience 35:1035-1036.

Patel, R.M., S.O. Prasher, and R.B. Bonnell. 2000. Effects of watertable depth, irrigation water salinity, and fertilizer application on root zone salt buildup. Canadian Agricultural Engineering 42:111-115.

Petersen, R.G., and L.D. Calvin. 1996. Sampling. *In*: D. L. Sparks, A. Klute, R.W. Weaver, S.H. Mickelson, D.L. Sparks, and J.M. Bartels (eds.), Methods of soil analysis. Part 3: Chemical methods. Soil Science Society of American, Inc., American Society of Agronomy, Inc., Madison, WI. pp. 1-17.

Polowick, P.L., and V.K. Sawhney. 1985. Temperature effects on male fertility and flower and fruit development in *Capsicum annuum* L. Scientia Horticulturae 25:117-127.

Porter, W.C., and W.W. Etzel. 1982. Effects of aluminum-painted and black polyethylene mulches on bell pepper, *Capsicum annuum* L. HortScience 17:942-943.

Pratt, P.F., and D.L. Suarez. 1990. Irrigation water quality assessments. *In*: K. K. Tanji (ed.), Agricultural salinity assessment and management. ASCE Manual and Reports on Engineering Practice No. 71, American Society of Civil Engineers, New York, NY. pp. 161-185.

Reina-Sanchez, A., R. Romero-Aranda, and J. Cuartero. 2005. Plant water uptake and water use efficiency of greenhouse tomato cultivars irrigated with saline water. Agricultural Water Management 78:54-66.

Rengel, Z. 1992. The role of calcium in salt toxicity. Plant Cell and Environment 15:625-632.

Rhoades, J.D. 1996. Salinity: electrical conductivity and total dissolved solids. *In*: D. L. Sparks, A. Klute, R.W. Weaver, S.H. Mickelson, D.L. Sparks, and J.M. Bartels (eds.), Methods of soil analysis. Part 3: Chemical methods. Soil Science Society of American, Inc., American Society of Agronomy, Inc., Madison, WI. pp. 417-435.

Rhoades, J.D., A. Kandiah, and A.M. Mashali. 1992. The use of saline waters for crop production. Irrigation and Drainage Paper 48, FAO, Rome. 133 pp.

Rhoades, J.D., F. Chanduvi, and S. Lesch. 1999. Soil salinity assessment: methods and interpretation of electrical conductivity measurements. FAO, Rome. 150 pp.

Rigby, M. 1988. Trickle fertigation of bell peppers in Southern Quebec. Thesis (M.Sc.), McGill University, Montreal. 106 pp.

Roberts, B.W., and J.A. Anderson. 1994. Canopy shade and soil mulch affect yield and solar injury of bell pepper. HortScience 29:258-260.

Rodriguez, P., J. Dell'Amico, D. Morales, M. J. Sánchez Blanco, and J.J. Alarcón. 1997. Effects of salinity on growth, shoot water relations and root hydraulic conductivity in tomato plants. Journal of Agricultural Science 128:439-444.

Romero-Aranda, R., T. Soria, and J. Cuartero. 2001. Tomato plant-water uptake and plant-water relationships under saline growth conditions. Plant Science 160:265-272.

Romero-Aranda, R., T. Soria, and J. Cuartero. 2002. Greenhouse mist improves yield of tomato plants grown under saline conditions. Journal of the American Society for Horticultural Science 127:644-648.

Romic, D., M. Romic, J. Borosic, and M. Poljak. 2003. Mulching decreases nitrate leaching in bell pepper (*Capsicum annuum* L.) cultivation. Agricultural Water Management 60:87-97.

Rubatzky, V.E.and M. Yamaguchi. 1997. World vegetables: principles, production, and nutritive values. Chapman and Hall, New York, NY. 704 pp.

Rubio, F., P. Flores, J.M. Navarro, and V. Martinez. 2003. Effects of Ca^{2+}, K^{+} and cGMP on Na^{+} uptake in pepper plants. Plant Science 165:1043-1049.

Sairam, R.K., and A. Tyagi. 2004. Physiology and molecular biology of salinity stress tolerance in plants. Current Science 86:407-421.

Sairam, R.K., A. Tyagi, and V. Chinnusamy. 2006. Salinity tolerance: Cellular mechanisms and gene regulation. *In*: B. Huang (ed.), Plant-Environment interactions. CRC Press Taylor and Francis Group, Boca Raton, FL. pp. 121-175.

Savvas, D., G. Meletiou, S. Margariti, I. Tsirogiannis, and A. Kotsiras. 2005. Modeling the relationship between water uptake by cucumber and NaCl accumulation in a closed hydroponic system. HortScience 40:802-807.

Savvas, D., E. Stamati, I.L. Tsirogiannis, N. Mantzos, P.E. Barouchas, N. Katsoulas, and C. Kittas. 2007. Interactions between salinity and irrigation frequency in greenhouse pepper grown in closed-cycle hydroponic systems. Agricultural Water Management 91:102-111.

Schleiff, U. 2008. Analysis of water supply of plants under saline soil conditions and conclusions for research on crop salt tolerance. Journal of Agronomy and Crop Science 194:1-8.

Scott, H.D. 2000. Soil physics: agricultural and environmental applications. Iowa State University Press, Ames, IA. 421 pp.

Sezen, S.M., A. Yazar, and S. Eker. 2006. Effect of drip irrigation regimes on yield and quality of field grown bell pepper. Agricultural Water Management 81:115-131.

Shalhevet, J. 1994. Using water of marginal quality for crop production - Major Issues. Agricultural Water Management 25:233-269.

Shannon, M.A., P.W. Bohn, M. Elimelech, J.G. Georgiadis, B.J. Marinas, and A.M. Mayes. 2008. Science and technology for water purification in the coming decades. Nature 452:301-310.

Shannon, M.C. 1997. Adaptation of plants to salinity. Advances in Agronomy 60:75-120.

Shannon, M.C., and C.M. Grieve. 1999. Tolerance of vegetable crops to salinity. Scientia Horticulturae 78:5-38.

Shannon, M.C., and C.M. Grieve. 2000. Options for using low-quality water for vegetable crops. HortScience 35:1058-1062.

Shannon, M.C., C.M. Grieve, and L.E. Francois. 1994. Whole-plant response to salinity. *In*: R.E. Wilkinson (ed.), Plant-Environment interactions. Marcel Dekker, Inc., New York, NY. pp. 199-244.

Shannon, M.C., V. Cervinka, and D.A. Daniel. 1997. Drainage water re-use. *In*: C.A. Madramootoo, W.R. Johnston, and L.S. Willardson (eds.), Management of agricultural drainage water quality. FAO, Rome. pp. 29-40.

Siwek, P., S. Cebula, A. Libik, and J. Mydlarz. 1994. The effect of mulching on changes in microclimate and on the growth of yield of sweet pepper grown in plastic tunnels. Acta Horticulturae 366:161-167.

Skaggs, R.K. 2001. Predicting drip irrigation use and adoption in a desert region. Agricultural Water Management 51:125-142.

Smedema, L.K., and K. Shiati. 2002. Irrigation and salinity: a perspective review of the salinity hazards of irrigation development in the arid zone. Irrigation and Drainage Systems 16:161-174.

Smith, P. T. and B. G. Cobb. 1991. Accelerated germination of pepper seed by priming with salt-solutions and water. HortScience 26:417-419.

Soltani, N., J.L. Anderson, and A.R. Hamson. 1995. Growth analysis of watermelon plants grown with mulches and rowcovers. Journal of the American Society for Horticultural Science 120:1001-1009.

Tadesse, T., M.A. Nichols, and K.J. Fisher. 1999. Nutrient conductivity effects on sweet pepper plants grown using a nutrient film technique 1. Yield and fruit quality. New Zealand Journal of Crop and Horticultural Science 27:229-237.

Taiz, L., and E. Zeiger. 2002. Plant physiology. Sinauer Associates, Inc., Publishers, Sunderland, Mass. 690 pp.

Tarara, J.M. 2000. Microclimate modification with plastic mulch. HortScience 35:169-180.

Topp, G.C., J.L. Davis, and A.P. Annan. 1980. Electromagnetic determination of soil-water content −Measurements in coaxial transmission-lines. Water Resources Research 16:574-582.

Trout, T.J. 2000. Environmental effects of irrigated agriculture. Acta Horticulturae 537:605-610.

VanDerwerken, J.E., and D. Wilcox-Lee. 1988. Influence of plastic mulch and type and frequency of irrigation on growth and yield of bell pepper. HortScience 23:985-988.

Villa-Castorena, M., A.L. Ulery, E.A. Catalan-Valencia, and M.D. Remmenga. 2003. Salinity and nitrogen rate effects on the growth and yield of chile pepper plants. Soil Science Society of America Journal 67:1781-1789.

Wagenet, R.J. 1984. Salt and water movement in the soil profile. *In*: I. Shainberg and J. Shalhevet (eds.), Soil salinity under irrigation: Processes and management. Springer-Verlag, New York, NY. pp. 100-114.

Wehner, T.C. 2002. Vegetable cultivar descriptions for North America: List 26. HortScience 37:15-78.

Wien, H.C. 1997. Peppers. *In*: H. C. Wien (ed.), The physiology of vegetable crops. CAB International, New York, NY. pp. 259-293.

Wierenga, P.J., and J.M.H. Hendrickx. 1985. Yield and quality of trickle-irrigated chile peppers. Agricultural Water Management 9:339-356.

Yaron, B., J. Shalhevet, and D. Shimshi. 1973. Patterns of salt distribution under trickle irrigation. *In*: A. Hadas, D. Swartzendruber, P.E. Rijtema, M. Fuchs, and B. Yaron (eds.), Physical aspects of soil water and salts ecosystems. Springler-Verlag, New York, NY. pp. 389-394.

Yildirim, E. and I. Guvenc. 2006. Salt tolerance of pepper cultivars during germination and seedling growth. Turkish Journal of Agriculture and Forestry 30:347-353.

Yilmaz, K., I. E. Akinci, and S. Akinci. 2004. Effect of salt stress on growth and Na, K contents of pepper (*Capsicum annuum* L.) in germination and seedling stages. Pakistan Journal of Biological Sciences 7:606-610.

Appendix A

Time course growth evaluation of bell pepper seedlings in response to saline water

This section comprises complementary information to Chapter 4 “Effects of saline water on growth and physiology of bell pepper seedlings”. Tables and figures are presented at the end of the section.

A.1 Methodology for seedling growth evaluation

Evaluation methods for seedling emergence and seedling growth are described in Chapter 4. The amount of water used for irrigating the plants is reported in Table A1. Due to the limited number of seedlings (four per replication) sampled weekly before the final harvest, the functional was chosen over the classical approach to calculate instantaneous absolute growth rate (AGR) and relative growth rate (RGR) of seedlings. The logistic model was used to fit the plant grow data (Hunt, 1982):

$$W = \frac{a}{(1 + be^{-cT})} \qquad \text{(Eq. A.1)}$$

where W represents the fresh or dry weight of the plant or part of the plant (i.e. roots, stems, leaves or shoots) (mg/plant); T is the time (days after seeding, DAS); e is the base of natural logarithms; and a, b and c are constants of the model. Actual values of fresh and dry weight for the different organs were used separately to calculate the parameters a, b and c of the model for each treatment using the NLIN procedure of the SAS software v. 9.1 (SAS Institute, Cary, NC, USA). With all the parameters calculated, fresh and dry weights were predicted to fit the growth curves, plotted and regressed against the actual values. Additionally, the parameters were used to calculate the AGR (mg·d^{-1}) and RGR (mg·mg^{-1}·d^{-1}) of shoots following the equations of Hunt (1982):

$$AGR = \frac{dW}{dT} = \frac{abce^{-cT}}{(1+be^{-cT})^2} \qquad \text{(Eq A.2)}$$

and,

$$RGR = \frac{1}{w} \cdot \frac{dW}{dT} = \frac{bce^{-cT}}{1+be^{-cT}} \qquad \text{(Eq. A.3)}$$

A. 2 Results for growth of seedlings

The percentage of seedlings that emerged decreased and the time taken for emergence increased with increasing salinity (Figure A.1). There was no difference in seedling emergence between plants receiving 0.5 dS·m^{-1} and 1.5 dS·m^{-1}. By 12 DAS, more than 50% of the pepper seedlings had emerged in treatments receiving 2.5 dS·m^{-1} or less. Germination of plants receiving 2.5 and 3.5 dS·m^{-1} was initially slower than those of the 0.5 dS·m^{-1} and 1.5 dS·m^{-1} plants but reached similar values by the 18th day. However plants receiving 4.5 dS·m^{-1} were significantly slower to germinate and the final germination percentage was significantly lower than that of the other treatments being 97 and 82%, respectively. The differences in number of seedlings that emerged at the 0.5 dS·m^{-1} and the 1.5, 2.5 and 3.5 dS·m^{-1} treatments became smaller over time.

Seedlings treated with 0.5 and 1.5 dS·m^{-1} had similar fresh root weight throughout the experiment (Figure A.2A). At the final harvest (67 DAS), roots of plants that received 2.5 dS·m^{-1} weighed 43% less than those of 0.5 dS·m^{-1}. At the highest rates of salinity

(3.5 and 4.5 dS·m^{-1}) roots grew very slowly and root weight remained relatively constant after 50 DAS. At the end of the experiment the roots of these plants weighed only 0.34 g/plant, which was significantly less than those of the other treatments, being 1.23, 1.07 and 0.69 g/plant for 0.5, 1.5 and 2.5 dS·m^{-1}, respectively. Similarly, root dry weights did not differ between plants receiving either 0.5 or 1.5 dS·m^{-1} (Figure A.2B). Root dry weight was less for plants irrigated with saline water at 2.5, 3.5 or 4.5 dS·m^{-1} which by the final harvest (67 DAS) had reduced root weight by 31, 49 and 65%, respectively, compared with 0.5 dS·m^{-1}.

There were no differences in shoot fresh weights of plants receiving 0.5, 1.5 or 2.5 dS·m^{-1} (Figure A.3A), these treatments having an average final weight of 4.60 g/plant. However, applying water with a higher EC_w reduced final shoot weights by 22 and 43% for 3.5 and 4.5 dS·m^{-1} compared with plants receiving 0.5 dS·m^{-1}. Only saline water with 4.5 dS·m^{-1} significantly reduced shoot dry weight compared with 0.5 dS·m^{-1} throughout the growing period (Figure A.3B). Initially, lower levels of salinity (1.5, 2.5 and 3.5 dS·m^{-1}) did not reduce significantly shoot dry weight. However, after 53 DAS 2.5 or 3.5 dS·m^{-1} significantly reduced shoot dry weight. At the final harvest there was no difference between 0.5 and 1.5 dS·m^{-1}, while 2.5, 3.5, and 4.5 dS·m^{-1} reduced shoot dry weight by 18, 29 and 49%, respectively.

Shoot changes were more a function of the stems than the leaves. Plants irrigated with 1.5 dS·m^{-1} had slightly heavier and those with 2.5 dS·m^{-1} lighter stems than those of 0.5 dS·m^{-1} although the differences were not significant over time (Figure A4.A). At the final harvest stem fresh weight of these treatments were comparable averaging 1.93 g/plant. Applying irrigation water with levels of salinity of 3.5 and 4.5 dS·m^{-1} significantly reduced final stem fresh weight by 33 and 53%, respectively, compared with 0.5 dS·m^{-1}. The use of saline water up to 1.5 dS·m^{-1} did not affect the dry weight of stems during the evaluation period (Figure A.4B). In fact, only small differences were found among treatments from 0.5 up to 3.5 dS·m^{-1} for the first 46 DAS. Thereafter, saline water with 2.5 dS·m^{-1} or higher significantly decreased stem dry weights compared with either 0.5 or 1.5 dS·m^{-1}. At the final harvest stem weight decreased by 30, 47 and 67% for plants receiving 2.5, 3.5 or 4.5 dS·m^{-1}, respectively, compared with 0.5 dS·m^{-1} (264.8 mg/plant).

Leaf fresh weight showed a similar trend to that of the stems. Plants were able to tolerate up 2.5 dS·m^{-1} with minimal effects (Figure A.5A). Higher salinities (3.5 and 4.5 dS·m^{-1}) significantly reduced final leaf fresh weights by an average of 15 and 36%, respectively compared to all other treatments. The greatest leaf dry weights were recorded for plants receiving 0.5 and 1.5 dS·m^{-1} averaging 314 mg/plant (Figure A.5B). Plants irrigated with 2.5 dS·m^{-1} initially had leaf dry weights similar to those of the two lower levels of salinity, but by final harvest, were 9% less than that of 0.5 dS·m^{-1}. Salinity levels of 3.5 or 4.5 dS·m^{-1} routinely had lower leaf dry weights than the other treatments and by 67 DAS were significantly lower 15% and 35%, respectively, than 0.5 dS·m^{-1}. The ratio of stem to leaf fresh weight decreased from 43/57 for those receiving 0.5 or 1.5 dS·m^{-1} to 40/60, 37/63 and finally 35/65 for plants receiving 2.5, 3.5 and 4.5 dS·m^{-1}, respectively. Reductions in the ratios of stem to leaves were greater in dry than fresh weight changing from 46/54 for seedlings receiving either 0.5 or 1.5 dS·m^{-1} to 40/60, 35/65 and 30/70 with increasing salinity levels of 2.5, 3.5 and 4.5 dS·m^{-1}, respectively.

For the first 25 DAS leaf areas were similar regardless of salinity treatment (Figure A.6). No differences were found between the leaf areas of 0.5 and 1.5 $dS{\cdot}m^{-1}$ throughout the experiment. Leaf area of plants irrigated with 2.5 $dS{\cdot}m^{-1}$ was similar to those of the lower salinities for the first 53 and then was significantly lower. When the salinity increased to 3.5 $dS{\cdot}m^{-1}$ leaf areas were similar to 0.5 and 1.5 $dS{\cdot}m^{-1}$ for 46 DAS and then significantly lower. Plants irrigated with 4.5 $dS{\cdot}m^{-1}$ had significantly smaller leaf areas than those receiving either 0.5 or 1.5 $dS{\cdot}m^{-1}$ throughout the study and were also significant smaller compared than those irrigated with either 2.5 or 3.5 $dS{\cdot}m^{-1}$ from 46 DAS onwards.

The instantaneous absolute growth rates (AGR) of the 0.5 and 1.5 $dS{\cdot}m^{-1}$ shoots were similar until 53 DAS, thereafter that rate of plants receiving 1.5 $dS{\cdot}m^{-1}$ was faster than that of 0.5 $dS{\cdot}m^{-1}$ reaching a difference of 3.4 $mg{\cdot}d^{-1}$ at harvest (Figure A.7A). Plants receiving 2.5 $dS{\cdot}m^{-1}$ and higher had increasing slower AGR over time compared with those of either 0.5 or 1.5 $dS{\cdot}m^{-1}$. At the final harvest the AGR of these treatments was 23, 34 and 58% lower for 2.5, 3.5 and 4.5 $dS{\cdot}m^{-1}$, respectively, compared with that of plants receiving 0.5 $dS{\cdot}m^{-1}$ (30.9 $mg{\cdot}d^{-1}$). Conversely, instantaneous relative growth rates (RGR) of shoots decline over time (Figure A.7B). Initially, the RGR of plants receiving 0.5 $dS{\cdot}m^{-1}$ was greater than those of all other salinity treatments. However, by 53 DAS the maximum RGR values were recorded for plants irrigated with 1.5 $dS{\cdot}m^{-1}$. The RGR of plants receiving 2.5 and 3.5 $dS{\cdot}m^{-1}$ were similar throughout growth whereas plants irrigated with 4.5 $dS{\cdot}m^{-1}$ had a consistently lower RGR over time. The decreases in RGR at harvest were 5% for 2.5 and 3.5 $dS{\cdot}m^{-1}$; and 16% for 4.5 $dS{\cdot}m^{-1}$ compared with the RGR of 0.5 $dS{\cdot}m^{-1}$ (0.0541 $mg{\cdot}mg^{-1}{\cdot}d^{-1}$).

Table A.1 Total volume of water applied by irrigation and concentrations of salts or ions calculated by titration for each level of salinity.

Saline water ($dS \cdot m^{-1}$)	Total volume of irrigation water (L/plant)		Salt concentrations (mM)		Ion concentrations ($mmol \cdot L^{-1}$)		
	2004	2006	NaCl	$CaCl_2$	Na^+	Ca^{2+}	Cl^-
0.5	0.480	0.430	1.84	0.92	1.84	0.92	3.66
1.5	0.480	0.430	7.83	3.92	7.83	3.92	15.65
2.5	0.480	0.430	13.82	2.92	13.82	2.92	27.63
3.5	0.465	0.410	19.81	9.92	19.81	9.92	39.62
4.5	0.465	0.410	25.80	12.92	25.80	12.92	51.60

Figure A.1 Emergence of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) seedlings as affected by various levels of saline water ($dS{\cdot}m^{-1}$) over time. Means ±SEM (n=6).

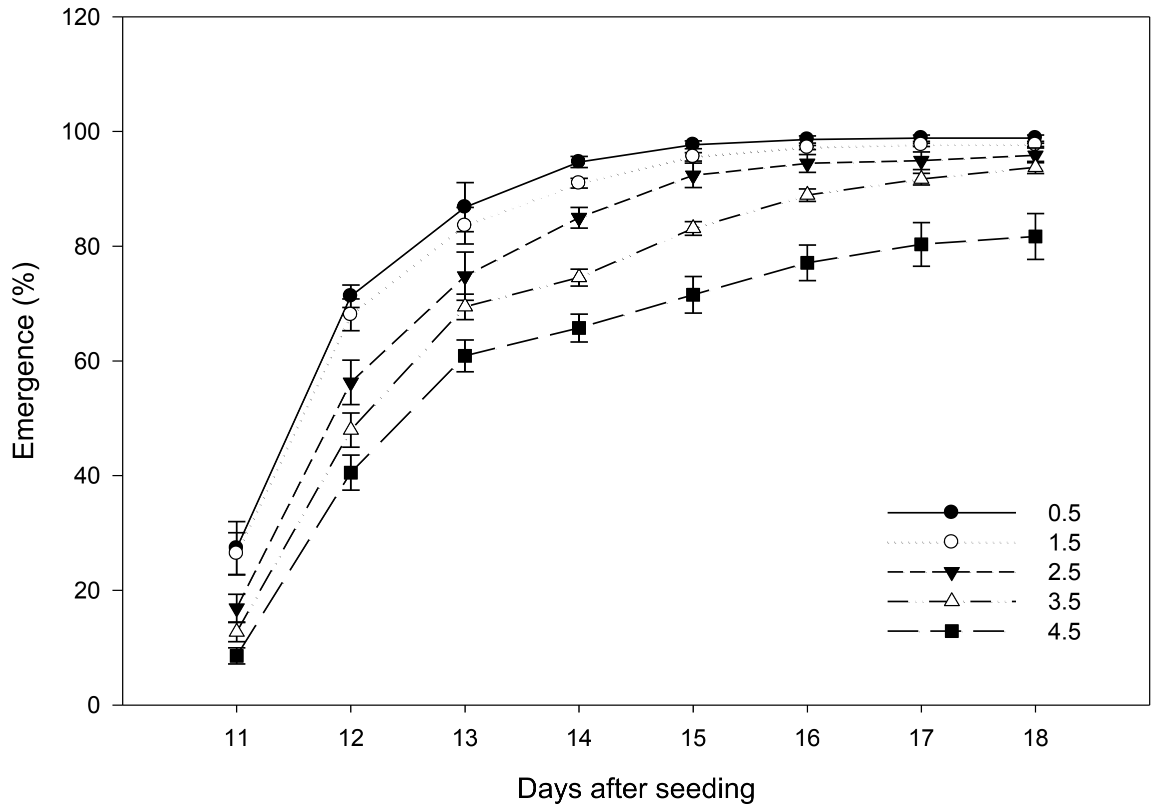


Figure A.2 A) Fresh, and B) dry weights of roots of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) seedlings as affected by various levels of saline water (dS·m^{-1}) over time and their predicted trends based on the logistic plant growth model. Means ±SEM (n=6).

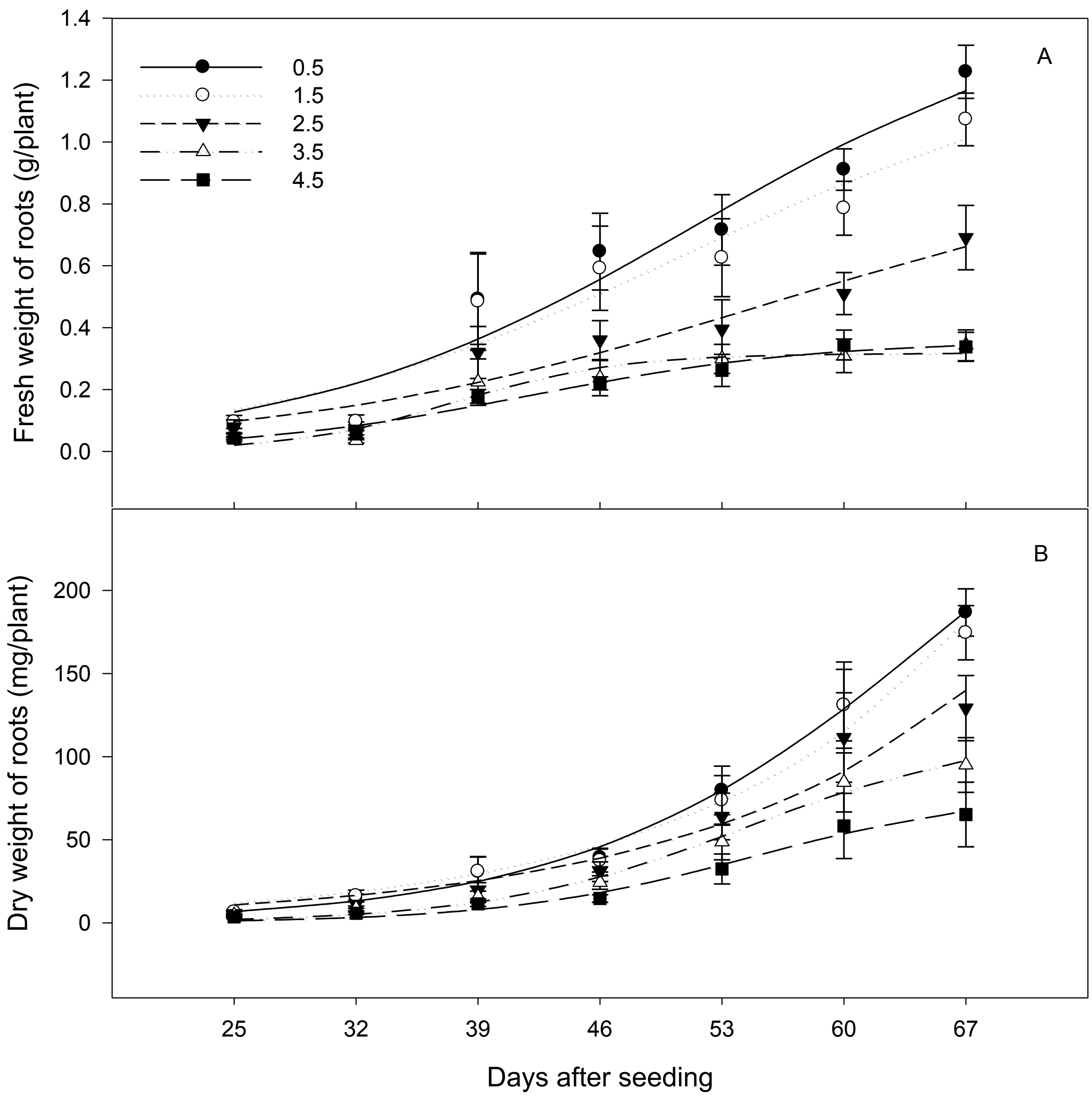


Figure A.3 A) Fresh, and B) dry weights of shoots of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) seedlings as affected by various levels of saline water ($dS{\cdot}m^{-1}$) over time and their predicted trends based on the logistic plant growth model. Means ±SEM (n=6).

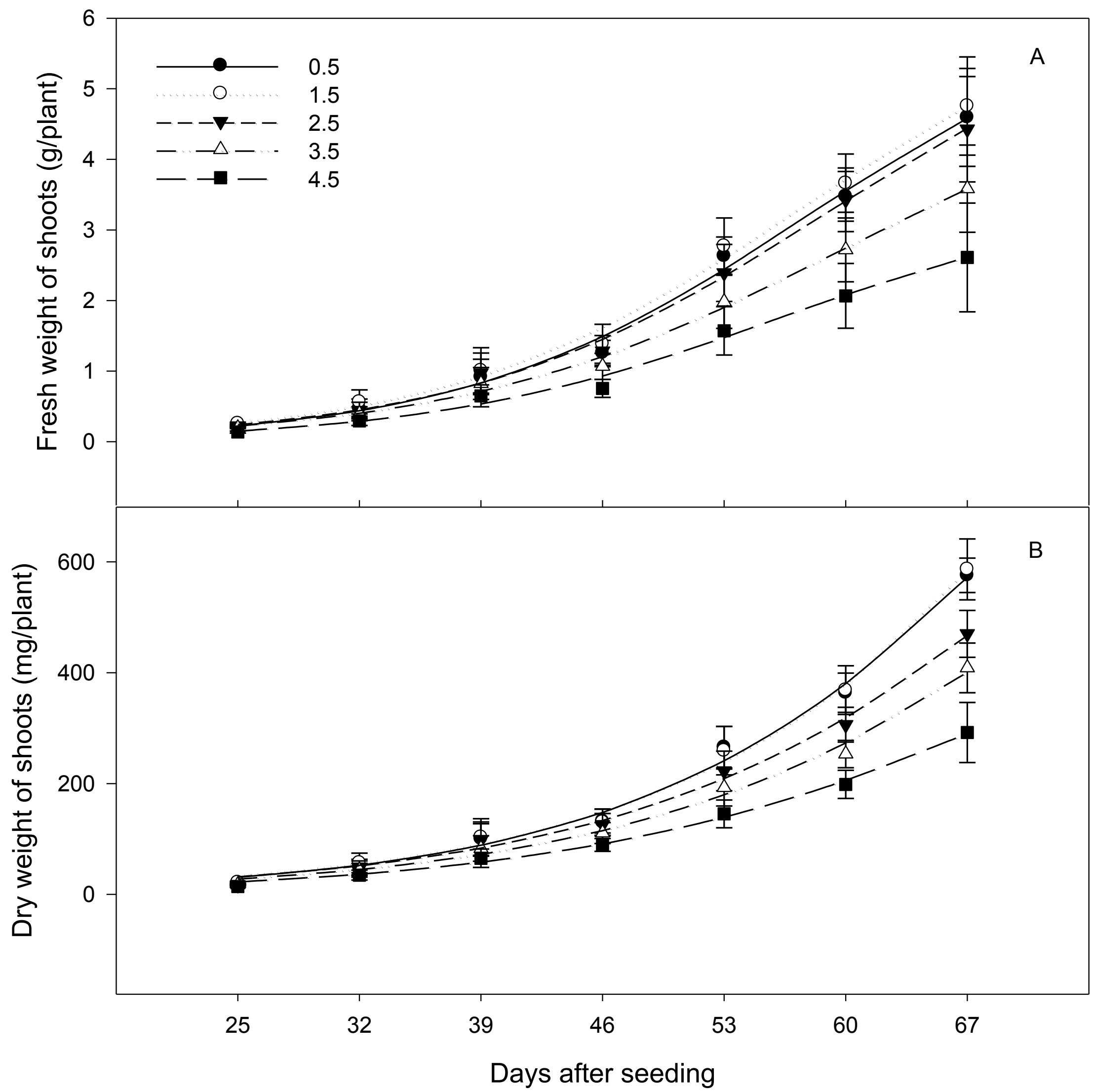


Figure A.4 A) Fresh, and B) dry weights of stems of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) seedlings as affected by various levels of saline water ($dS{\cdot}m^{-1}$) over time and their predicted trends based on the logistic plant growth model. Means ±SEM (n=6).

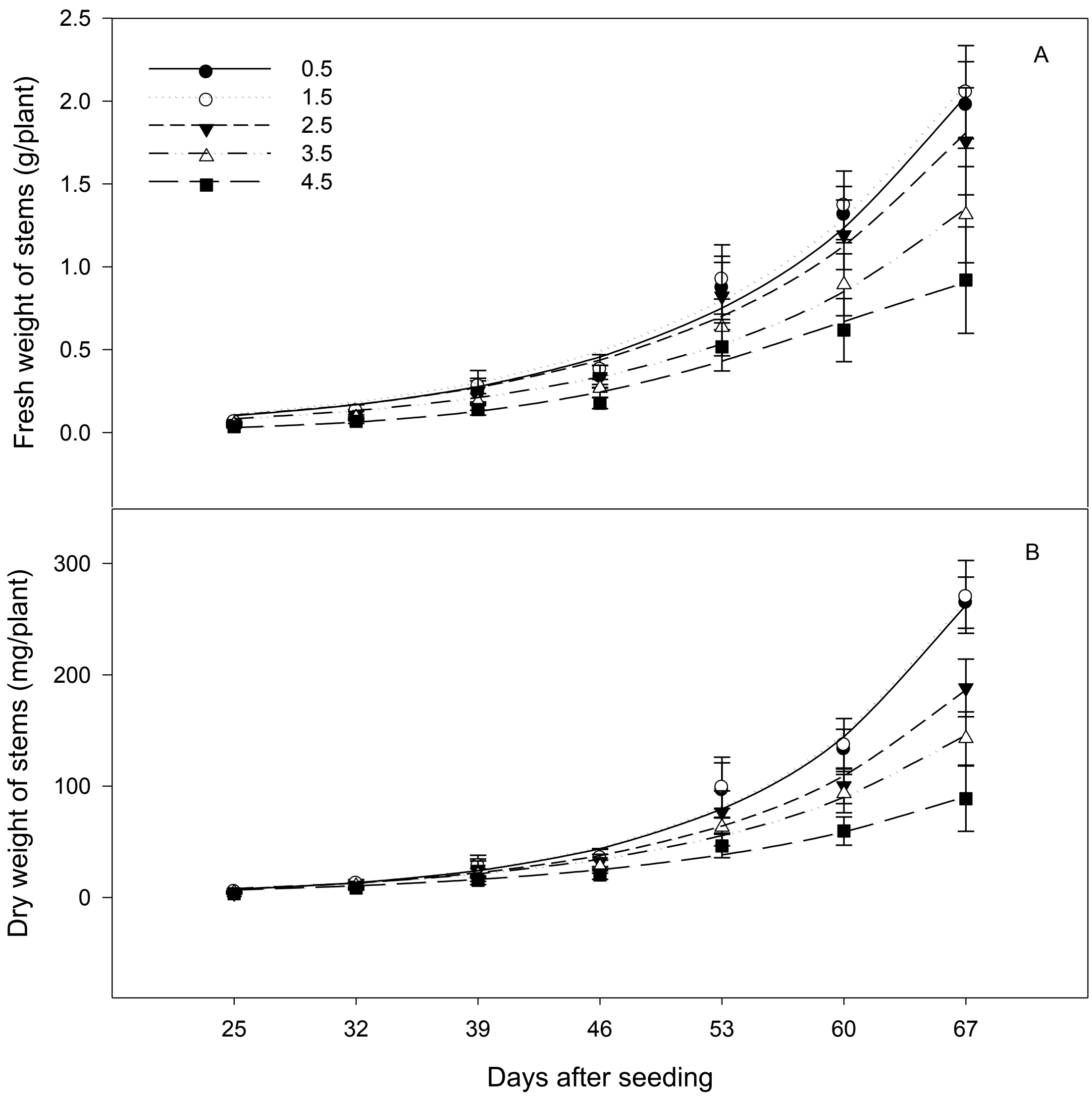


Figure A.5 A) Fresh, and B) dry weights of leaves of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) seedlings as affected by various levels of saline water ($dS \cdot m^{-1}$) over time and their predicted trends based on the logistic plant growth model. Means ±SEM (n=6).

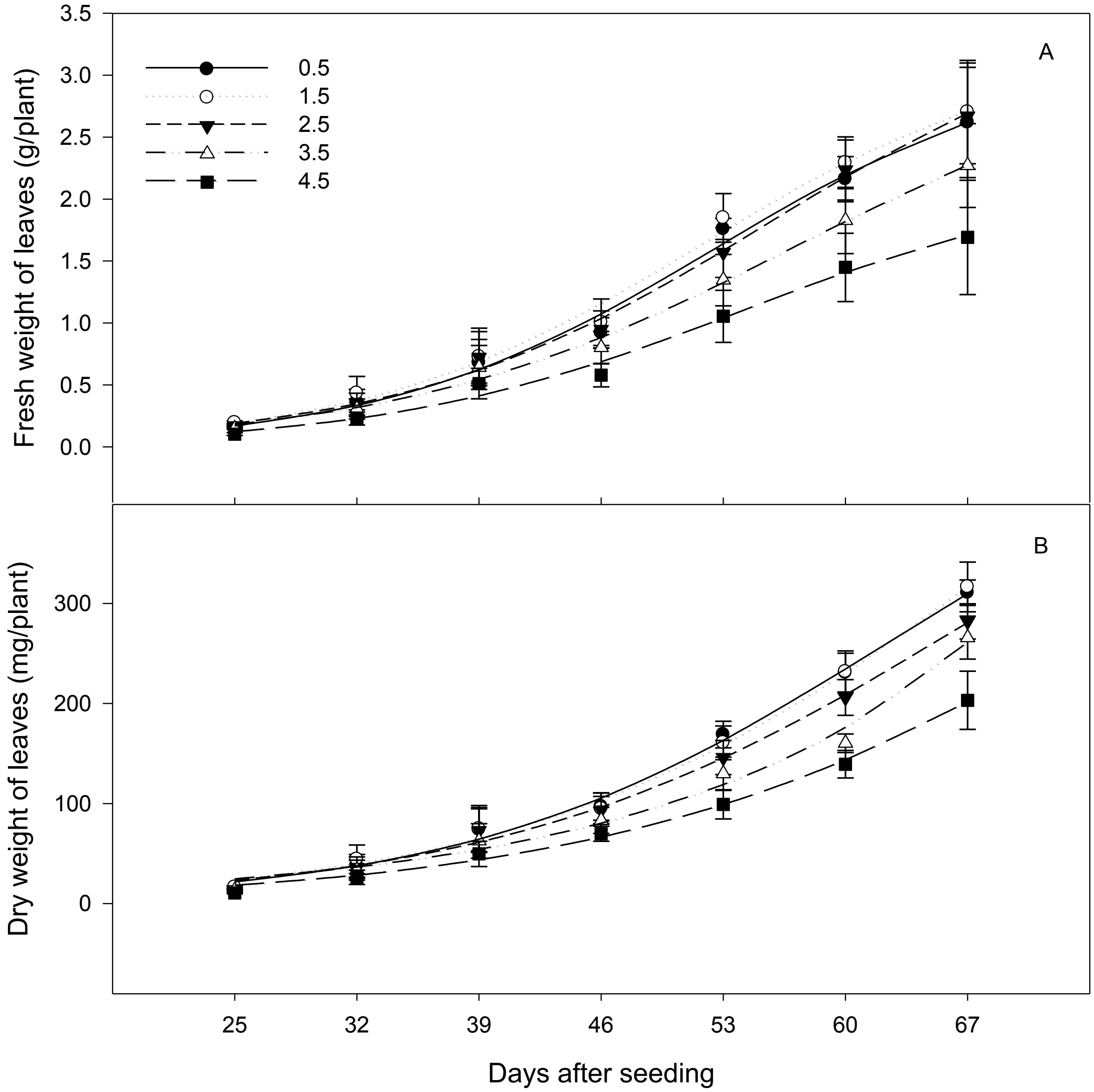


Figure A.6 Leaf area of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) seedlings as affected by various levels of saline water (dS·m^{-1}) over time and their predicted trends based on the logistic plant growth model. Means ±SEM (n=6).

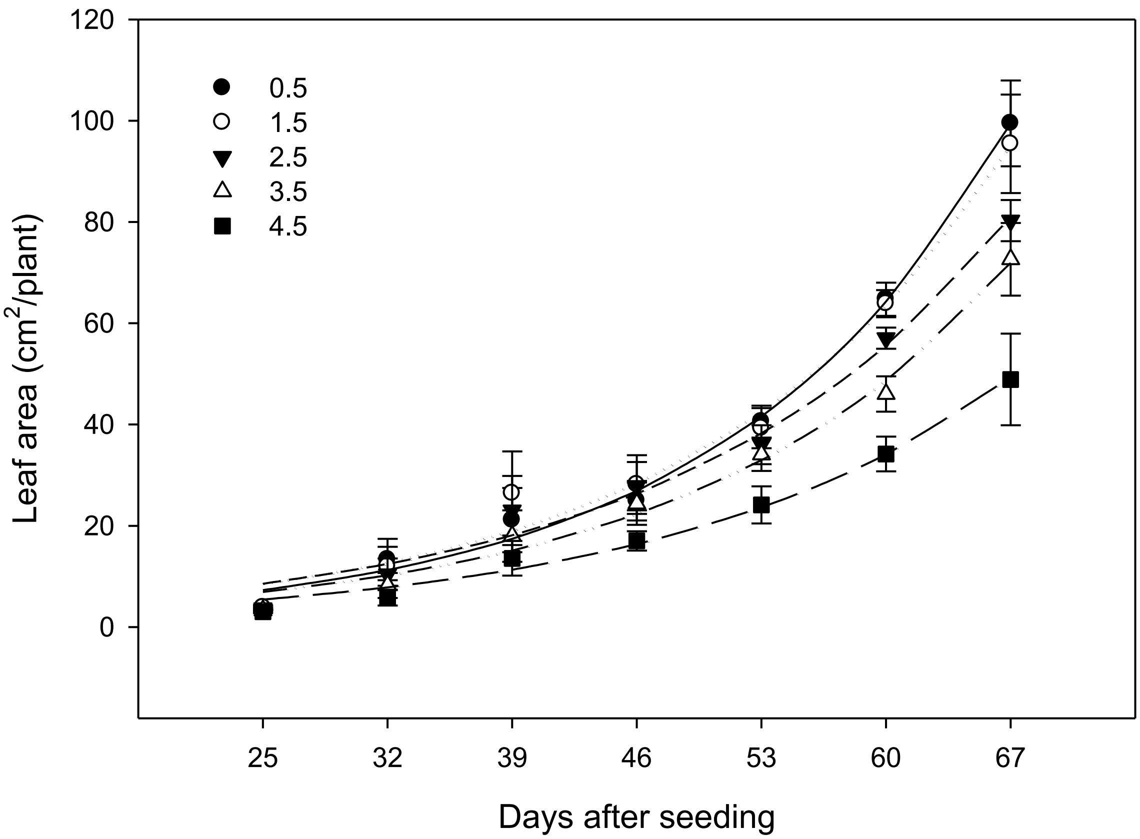
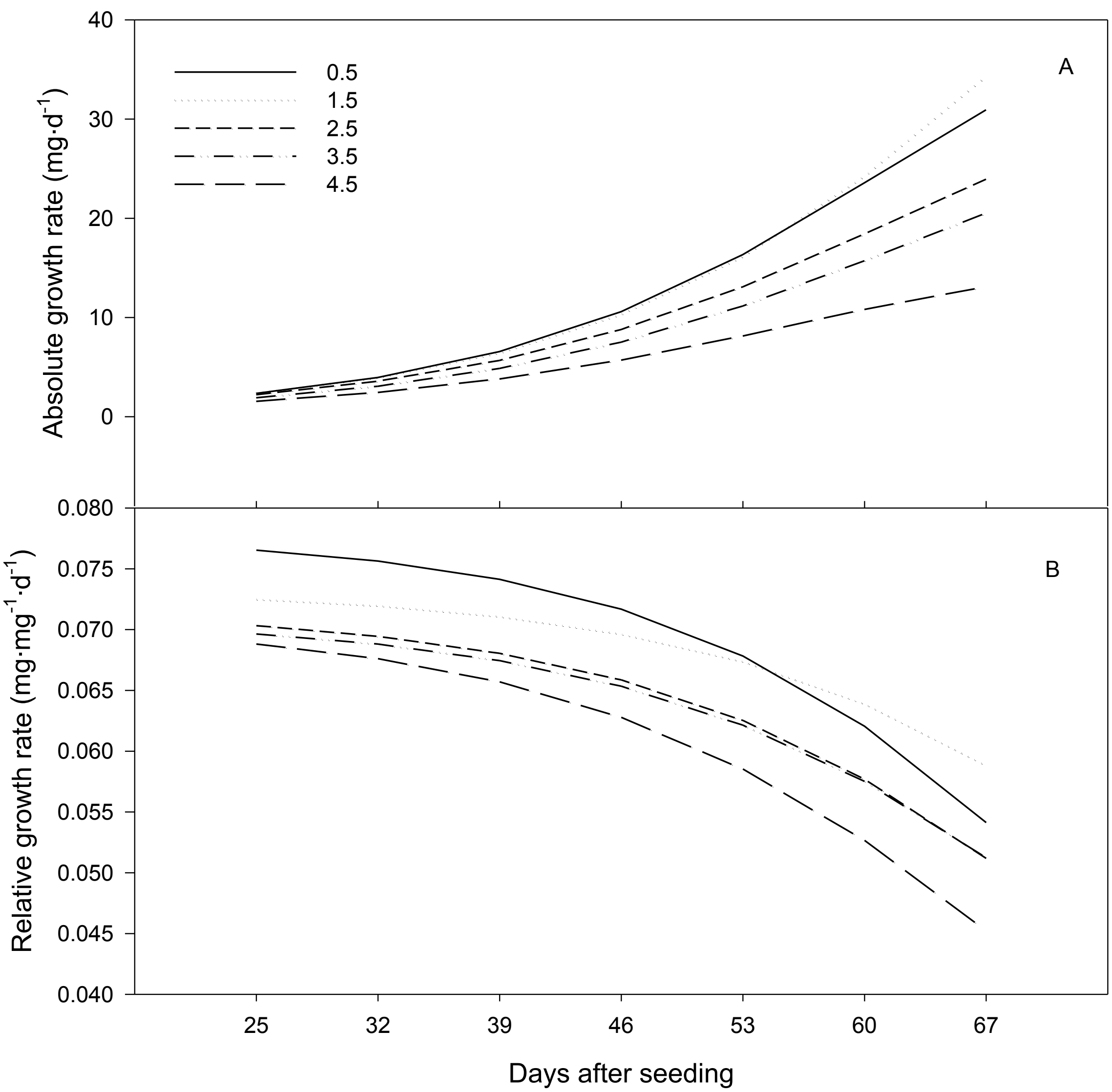


Figure A.7 A) Instantaneous absolute growth rate, and B) instantaneous relative growth rate of bell pepper (*Capsicum annuum* L. var. Red Knight X3R) seedlings as affected by various levels of saline water ($dS{\cdot}m^{-1}$) over time. Calculations were made using the logistic plant growth model.



Appendix B

Copyright transfers

McGill

Faculty of Agricultural and Environmental Sciences
McGill University
Macdonald Campus
Department of Plant Science

Faculté des sciences de l'agriculture et de l'environnement
Université McGill
Campus Macdonald
Département de sciences végétales

Tel.: (514) 398-7851
Fax: (514) 398-7897
www.mcgill.ca/plant
21,111 Lakeshore
Ste-Anne-de-Bellevue
Québec, Canada H9X 3V9

Graduate and Postdoctoral Studies Office
James Administration Building
McGill University
845 Sherbrooke Street West
Room 400
Montreal Quebec H3A 2T5

August 26th 2008

To Whom It May Concern;

I hereby grant Dagobiet Morales – Garcia permission to include the following 3 unpublished manuscripts on which I am a co-author as part of his Ph.D thesis" The effects of saline irrigation water on the growth and development of bell pepper (*Capsicum annuum* L.) grown using a plasticulture system."

Manuscript 1 – "The timing of saline drip irrigation affects growth, physiology and fruit yield of bell pepper growing in mulched and unmulched conditions"
Dagobiet Morales-Garcia, **Katrine A. Stewart** and Philippe Seguin

Manuscript 2- "Saline drip irrigation applied at different growth stages of two bell peppers cultivars grown under mulch or unmulched conditions in nonsaline soil"
Dagobiet Morales-Garcia, **Katrine A. Stewart** and Philippe Seguin

Manuscript – "Effects of saline drip irrigation and polyethylene mulch on physiology, growth and yield of bell peppers"
Dagobiet Morales-Garcia, **Katrine A. Stewart**, and Chandra A. Madramootoo

Sincerely
KAStewart
Katrine Stewart
Associate Professor
Department of Plant Science
Macdonald Campus of McGill University.
21,111 Lakeshore Road,
Ste. Anne de Bellevue, Quebec, H9X 3V9, Canada

McGill

Faculty of Agricultural and Environmental Sciences
Faculté des sciences de l'agriculture et de l'environnement

McGill University
Macdonald Campus
Université McGill
Campus Macdonald

Department of Plant Science
Département de sciences végétales

Tel.: (514) 398-7851
Fax: (514) 398-7897
www.mcgill.ca/plant
21,111 Lakeshore
Ste-Anne-de-Bellevue
Québec, Canada H9X 3V9

Graduate and Postdoctoral Studies office
James Administration Building
McGill University
845 Sherbrooke Street West
Room 400
Montreal Quebec H3A 2T5

August 26th 2008

To Whom It May Concern;

I hereby grant Dagobiet Morales – Garcia permission to include the following unpublished manuscript on which I am a co-author as part of his Ph.D thesis" The effects of saline irrigation water on the growth and development of bell pepper (*Capsicum annuum* L.) grown using a plasticulture system."

Manuscript – "Effects of saline drip irrigation and polyethylene mulch on physiology, growth and yield of bell peppers"

Dagobiet Morales-Garcia, Katrine A. Stewart, and **Chandra A. Madramootoo**

Sincerely

Chandra A. Madramootoo

Chandra Madramootoo
Dean Faculty of Agricultural and Environmental Sciences
James McGill Professor
Department of Bioresource Engineering
Macdonald Campus of McGill University.
21,111 Lakeshore Road,
Ste. Anne de Bellevue, Quebec, H9X 3V9, Canada

McGill

Faculty of Agricultural and Environmental Sciences
McGill University
Macdonald Campus
Department of Plant Science

Faculté des sciences de l'agriculture et de l'environnement
Université McGill
Campus Macdonald
Département de sciences végétales

Tel.: (514) 398-7851
Fax: (514) 398-7897
www.mcgill.ca/plant
21,111 Lakeshore
Ste-Anne-de-Bellevue
Québec, Canada H9X 3V9

Graduate and Postdoctoral Studies office
James Administration Building
McGill University
845 Sherbrooke Street West
Room 400
Montreal Quebec H3A 2T5

August 26th 2008

To Whom It May Concern;

I hereby grant Dagobiet Morales – Garcia permission to include the following 2 unpublished manuscripts on which I am a co-author as part of his Ph.D thesis" The effects of saline irrigation water on the growth and development of bell pepper (*Capsicum annuum* L.) grown using a plasticulture system."

Manuscript 1 – "The timing of saline drip irrigation affects growth, physiology and fruit yield of bell pepper growing in mulched and unmulched conditions"

Dagobiet Morales-Garcia, Katrine A. Stewart and **Philippe Seguin**

Manuscript 2- "Saline drip irrigation applied at different growth stages of two bell peppers cultivars grown under mulch or unmulched conditions in nonsaline soil"

Dagobiet Morales-Garcia, Katrine A. Stewart and **Philippe Seguin**

Sincerely,

Philippe Seguin
Associate professor
Department of Plant Science
Macdonald Campus of McGill University.
21,111 Lakeshore Road,
Ste. Anne de Bellevue, Quebec, H9X 3V9, Canada

Taylor & Francis
Taylor & Francis Group

US Ref No.: P082708-02
August 27, 2008

Dagobiet Morales-Garcia
Department of Plant Science
McGill University
845 Sherbrooke St. W.
Montreal, QC H3A 2T5
Canada

Dear Dagobiet:

Morales-Garcia, D., K.A. Stewart, and P. Seguin. "Effects of saline water on growth and physiology of bell pepper seedlings" *International Journal of Vegetable Science* 14 (2): 121-138.

Thank you for your letter requesting permission to reproduce the above material in your dissertation

As you are the author of the above article, we will be pleased to grant permission without charge on the condition that you include a full acknowledgement to the original source of publication and insert a reference to the Journal's web site:

http://www.informaworld.com

You will also need to obtain permission from any co-authors of this article.

Thank you for your interest in our Journal.

Sincerely,

John R. Banionis
Supervisor of Journal Sales Administration
Permissions Coordinator

325 Chestnut Street, Suite 800, Philadelphia, PA 19106 • Phone: 215-625-8900 • Fax: 215-625-2940
Web: www.informaworld.com