PRESSURE AND SPACING EFFECT OF SPRINKLER IRRIGATION FOR COLD PROTECTION IN STRAWBERRIES

By

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To God
And to my parents Ricardo Zamora and Claudia Re

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LIST OF ABBREVIATIONS

AC	Automated treatment. Treatment with an automatic irrigation system control for cold protection based on average air temperature and dew point temperature measured by wireless sensors
AR	Application rate
DP	Dew point Temperature
DU_{LQ}	Low Quarter Distribution Uniformity
GROW	GROW Treatment replicates strawberry grower's practices for cold protection using a 345 kPa at the irrigation system pressure, 14.6 m sprinkler spacing and a thermostat/thermocouple to turn on/off the irrigation system for cold protection
LOW	LOW treatment. Treatment that consists of reducing the pressure in the irrigation system supply to 207 kPa and following the other strawberry generally used conditions for cold protection (14.6 m sprinkler spacing and the use of a thermostat/thermocouple to turn on/off the irrigation system)
NO	NO treatment. Treatment without sprinkler irrigation for cold protection (non-irrigated plots) which constituted the control treatment for comparison
SPC	SPC treatment. Treatment which consisted on reducing the sprinkler spacing to 12.2 m and following the other strawberry generally used conditions for cold protection (345 kPa irrigation system pressure and the use of a thermostat/thermocouple to turn on/off the irrigation system)
TC	Critical damage temperature. Temperature at which plant damages can occur if reached

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The United States is the largest strawberry producing country in the world and Florida ranks as the second largest producing state. To achieve high profits, strawberries are planted during the winter and protection from cold damage is needed.

Irrigation is the primary means for cold protection. During extreme cold events recently experienced in the Dover/Plant City area of Florida, high volumes of irrigation used to protect the plants caused the aquifer level to drop 18.3 meters, about 750 residential wells were impacted and over 140 sinkholes were reported. Although sprinkler irrigation for cold protection has been effective for the past several decades, the recommended application rate (AR) of 6.35 mm hr^{-1} has not been revised neither the effectiveness of alternative rates for satisfactory protection.

The objectives for this project were to: (i) investigate cold protection practices in Florida's strawberry industry and optimize current strawberry irrigation cold protection ARs (ii) assess the effect of sprinkler type, spacing, irrigation system pressure variations and varied wind conditions over irrigation distribution uniformity (DU_{lq}) and AR, and (iii) evaluate the effect of varying sprinkler spacing and pressure on strawberry yield quality and quantity under cold conditions. Four sprinkler types: Wade Rain WR-32 impact

sprinklers and three Nelson rotators: R33 R33LP and R2000WF were evaluated at three pressures (345, 276 and 207 kPa), two spacings (14.6 and 12.2 m) and varied wind conditions. The interactions sprinkler type- pressure, sprinkler type-spacing and pressure-spacing had a significant effect on DU_{lq} and AR, as well as the presence of high wind conditions. Significantly higher DU_{lq} values were obtained by R2000WF and WR-32 at 345 kPa and 12.2 m spacing, by contrast uniformity was significantly reduced at 207 kPa and 14.6 m spacing. Higher wind speed reduced significantly the uniformity. Nelson R33 and R33LP obtained significantly higher AR at all pressure levels and 12.2 m spacing. By contrast, the lowest AR were obtained by WR-32 and R2000WF at 207 kPa and 14.6 m spacing.

Under cold conditions five treatments were evaluated: AC (automatic control system), GROW (345 kPa at 14.6 m spacing), LOW (207 kPa at 14.6 m spacing), SPC (345 kPa at 12.2 m spacing), and NO (non-irrigated). Thermocouples controlled the irrigation system for GROW, LOW and SPC treatments. Results showed significant yield differences between the irrigated treatments and the control. Recovery capability from the cold events among the irrigated treatments did not differ significantly showing a linear increase in the yield after cold events. Water savings of 5% and up to 23% were obtained by using an automated irrigation system (AC treat.) during the 2011-12 and 2012-13 seasons correspondingly. Reducing the irrigation system pressure resulted in lower DU_{lq} but without yield differences and achieving water savings of 19.3 billion liters of water per harvest season on average considering the strawberries planted in Florida in 2010.

CHAPTER 1
LITERATURE REVIEW: SPRINKLER IRRIGATION COLD PROTECTION

Introduction

Irrigation is the primary method used for fruit, vegetable and nursery cold protection. Low-growing crops, such as strawberries, and deciduous fruit trees can be protected from cold damage by using overhead sprinkler irrigation (Snyder and de Melo Abreu 2005a). If the application rates and uniformity are adequate, this method of protection can be effective under windy conditions and temperature as low as -7°C (Snyder and de Melo Abreu 2005a).

Sprinkler irrigation for cold protection has been used to protect strawberries for several decades (Locascio et al. 1967). Two sprinkler application rates of 3.3 and 6.6 mm hr^{-1} were evaluated under various weather conditions. Both resulted equally effective under low wind conditions (0-0.9 m s^{-1}) and relatively higher temperatures (>4.4°C). When air and dew point temperatures reached as low as -8.9°C and -17.8°C, respectively, only the 6.6 mm hr^{-1} application rate was effective to protect the crop (Locascio et al. 1967).

A table of application rates based on sprinkler irrigation model for cold protection of citrus developed by Gerber and Harrison (1964) was published by Gerber and Martsolf (1965a). This table provides the precipitation rate according to a range of wind conditions and minimum leaf temperature, e.g. for a minimum leaf temperature of -5.6°C and wind speed ranging from 0.9 to 1.8 m s^{-1}, an application rate of 6.1 mm hr^{-1} was recommended (Table 1-1). Even when this recommended table of application rates has been generally accepted, it has been overestimated (Perry 1979) and recent investigation on lower application rates which may achieve adequate cold protection has not been thoroughly tested.

The U.S. is the largest strawberry producer in the world, and Florida represents the second largest harvesting state (FAOSTAT 2013a). In Florida, strawberries are planted using raised beds with drip irrigation under plastic mulch. Sprinkler irrigation is used for plant establishment and also to protect the crop from cold damage during the winter (Albregts and Howard 1984).

In recent years, severe cold conditions were experienced in the Dover/Plant City area, which resulted in several resource problems believed to be caused by irrigation used for crop protection. Associated problems such as resource depletion, nutrient leaching, and increased plant diseases may be consequence of overwatering plants.

In spite of reducing the volume of water applied through irrigation and optimizing the best management practices followed by the growers, this project found an opportunity to investigate current irrigation cold protection practices with the intent to identify ways to enhance and optimize irrigation for crop cold protection. This included current application rates and possible changes to system uniformity under varying conditions. This first chapter consists of a literature review on cold protection used in Florida agriculture focusing on strawberry production.

Strawberry Description

Strawberry belongs to the *Rosaceae* family and it is a cross between *Fragaria x ananassa*. Although other crops such as apples, pears, cherries and plums are included in this family, it is the only vegetable crop in this family (Peres et al. 2010).

Even when other wild *Fragaria* species had been spread in the Americas, Europe and Asia, as the main zones in the world, *F. x ananassa* is the species more commercially recognized around the world due to its economic significance (Davis 2008). Some of the varieties grown in Florida are: Camarosa (developed by UC- Davis), Carmine (UF), Camino Real (UC- Davis), Gaviota (UF), Strawberry Festival (UF), Sweet Charlie (UF), Treasure (JP Research), Ventana (UC- Davis) and Winter Dawn (UF) (Peres et al. 2010).

The common transplant types used in Florida for planting are bare-root green-top plants and containerized transplants (plugs), generally coming from Canada or places where lower temperatures are predominant and can provide beneficial conditions for transplant adaptation. The former is the most broadly available type of transplant; however, it presents more difficulties to be established in the field and requires higher overhead irrigation during the first seven to twelve days. The latter requires less overhead irrigation for establishment. Recommended planting dates range from 15 September to 15 October for North Florida, 15 September to 25 October for Central Florida and 1 October to 1 December for South Florida (Peres et al. 2010).

In Florida the two row bed system is used with a distance of 1.2-1.5 m between beds, 30.5-40.6 cm between plants and 30.5-35.6 cm between rows. The first ripe fruit can be harvested 40-100 days from transplanting. Typical plant populations range, 39,500-54,300 plants per hectare (Peres et al. 2010).

Strawberry Production and Importance

The United States of America has been the largest strawberry producing country in the world, followed by Spain, Turkey, Republic of Korea and Japan on average during the last decade (FAOSTAT 2013a). Even when some of these countries still have had a high production, their growth is relatively stable or negative in some cases during the ten years. However, in the same period Turkey, Egypt and Mexico had experienced high growth in production that positioned them also between the top five producers (FAOSTAT 2013b).

In 2011, the total U.S. strawberry production was 1,312,960 Mg harvested in 23,260 hectares (FAOSTAT 2013a) and the total value of strawberry production (fresh and processed) in the United States was estimated as $2.4 billion (USDA 2012) in the same year. Mexico was the fifth top producer for the period 2004-11 (FAOSTAT 2013b); it plays an important role in the strawberry exportation market to the U.S., which increased dramatically since 2010. Mexico exported around 178,800 Mg of fresh and frozen strawberries in 2011 (U.S. Department of Commerce and U.S. Census Bureau 2012).

Strawberries represent an important crop to the state of Florida, where around 17% of the total U.S. crop is harvested, second only to California (USDA, Economics, Statistics and Market Information System 2012). The production value in 2011 was estimated to be $366 million from about 4,000 ha harvested in open field systems (USDA 2013). The west central counties, Hillsborough and Manatee, represent approximately 95% of Florida's commercial strawberry production areas, where most of the strawberry fields are located in the Plant-City Dover production area in Hillsborough County. Other southwestern counties represent the remainder (USDA, Economics, Statistics and Market Information System 2012).

However, strawberry growers have faced big challenges in recent years due to the high production and marketing costs, which average over $67,126 per hectare (VanSickle et al. 2009) but more importantly, the dramatic increase in U.S. imports from

Mexico, which caused an oversupply in the market and a staggering pressure in the strawberry industry (Wu et al. 2012).

Strawberry Irrigation Systems

Florida strawberries are produced in annual hills using bare-root transplants under open field conditions with a two component irrigation system that includes drip and sprinkler.

Drip Irrigation

Typically, strawberries in Florida are grown in polyethylene mulch beds which are irrigated and fertilized through a single drip line per bed. Drip irrigation is used to produce strawberries improving water and nutrient management; hence reducing crop production costs (Hochmuth et al. 2011). Drip irrigation may contribute to keep the moisture and compaction in the soil, storing more heat during the day, than a loose dry soil. Therefore, during a freeze/frost night, more heat can be transferred from the soil to the crop, reducing the incidence microclimate (cold spots formed by cold air drainage) in the field and keeping the temperature from falling below critical damage (Perry 1998).

Sprinkler Irrigation

Sprinkler irrigation is typically used by Florida strawberry growers for crop establishment and frost protection (Albregts and Howard 1984). Bare root strawberry transplants may require 10 to 14 days of frequent intermittent overhead irrigation after transplanting for 12 and 14 hours per day giving an approximately of 406-610 mm just for plant establishment prior the irrigation with the drip system (Santos et al. 2010).

The effectiveness of sprinkler irrigation for cold protection in strawberries has been proven for several decades (Locascio et al. 1967). The heat loss from the plant to its immediate environment is substituted by the sensible heat and the heat of fusion associated with the water from the sprinkler irrigation, protecting the plants from frost or freeze damage (Harrison et al. 1987).

Microsprinklers

Microirrigation systems have been evaluated for frost protection. The goal of this type of irrigation system is to reduce the volume of water used compared to sprinklers. Therefore, only the ground under the plants is kept near 0°C with the intention of concentrating and enhancing radiation and sensible heat transmitted upwards into the plants (Snyder and de Melo Abreu 2005a).

Protection from cold damage in strawberries was evaluated using microsprinklers as well as using an automated pulsed irrigation system developed for frost protection intended to reduce the amount of water used without compromising crop protection (Stombaugh et al. 1992). The effectiveness of using this type of irrigation showed less than 3% blossoms killed from frost when constant sprinkling was applied compared to 52% blossoms killed for the control treatment without cold protection under a minimum air temperature at 1.5 m above the soil surface of -2.16°C and -4°C measured at the lowest unsprinkled bud. Furthermore, an 89% of water savings was achieved by using the automated irrigation system when mild frost conditions occurred (Stombaugh et al. 1992).

Historical Data Temperatures

In Florida, strawberry growers use sprinkler irrigation as a common method to protect their crop from cold damage during the winter. However, variations in temperature and duration of cold events have resulted in an increase of irrigation pumping, endangering the water supplies, affecting the groundwater and resulting in sinkholes in many cases, which have affected the surrounding areas and communities.

An example of this situation occurred in the winter of 2010 as a result of cold protection pumping, when the aquifer level dropped nearly 18.3 meters in some locations, around 750 residential wells were impacted and more than 140 sinkholes were reported (SWFWMD 2012).

During the last 34 strawberry seasons the amount of hours where the temperature has dropped below freezing point (0°C) and the temperature at which normally the growers turn on the irrigation system (1.1°C) has varied dramatically (1-1; NOAA 2013a; NOAA 2013b). The average number of hours below 0°C is 69.5 hours and below 1.1°C is 107.5 hours. The seasons with the most hours below freezing were 2008-09, 2009-10 and 2010-11 with a total amount of hours below 0°C of 129, 145 and 147 hours respectively for each season. However, the last two seasons 2011-12 and 2012-13, only 50 and 30 hours were below freezing, respectively, and both seasons were below the average number of hours compared to the last 34 years (1-1).

Energy Balance

It is important to understand the energy balance occurring in the atmosphere in order to provide enough energy for the plant to be protected from cold damage. During daytime, radiation from the sun and sky adds energy to the surface (Snyder and de Melo Abreu 2005a), through direct rays to all objects remaining with lower temperatures. However at nighttime, particularly during clear nights, no heat through radiation is coming from the sky and more energy is lost through radiant cooling (Braud and Hawthorne 1965). Although, when clouds are present, some radiant energy is retained and reflected back to the earth reducing the rapid cooling that may produce cold damage (Snyder and de Melo Abreu 2005a).

Four main weather conditions influence the occurrence of cold damage in plants: air temperature, relative humidity, wind speed and net radiation. When water vapor in the atmosphere changes phase to liquid through condensation, it results in dew formation on cold surfaces. However, if air temperature drops, this moisture can be transformed into ice crystals leading to the formation of frost over solid objects such as flowers, buds or berries. These solid surfaces can reduce their temperature to freezing point or lower as a result of a high radiant cooling rate and no wind conditions (Braud and Hawthorne 1965).

During a clear night, high radiant cooling rate from solid objects occur when low wind conditions are present; therefore the surface at the ground cools forming a cold layer, which gets heavier and clings near the surface forming “a coat” as long as the temperature continues dropping and little or no wind is present (Braud and Hawthorne 1965).

The process describe above refers to “inversion” which corresponds to the term from atmospheric conditions being inversed to the normal daytime condition at which air temperature is reduced according to the height (Haman 2006). By the contrast, if wind is present the inversion process is dissipated when wind blows the cold layer and combines it with the warmer upper air without resulting in frost occurrence due to the equalization of air and surface temperatures when warmer air exchanges heat to the solid surfaces (Braud and Hawthorne 1965). Although energy fluxes from the soil and air moderately balances the energy losses, the temperature falls due to a decrease in the sensible heat of the air: therefore, a net loss of radiation is present during a radiation frost night (Snyder and de Melo Abreu 2005a).

Hence, the purpose of the cold protection methods is to intentionally modify the energy balance components in order to decrease the magnitude of energy changes stored in the crop. Therefore, by cooling or freezing water, it converts latent to sensible heat, raises the surface temperature and decreases the rate of temperature drop at the plant surface (Snyder and de Melo Abreu 2005a).

Latent Heat Transfer

The chemical energy stored in the bonds that join water molecules together is called latent heat, whereas the sensible heat is the heat measured with a thermometer. Latent heat is released to the atmosphere and is converted to sensible heat when water condenses, cools or freezes, increasing the temperature of the surrounding environment. Vice versa, when water changes phase and melts, warms or evaporates sensible heat is changed to latent heat decreasing the air temperature (Snyder 2000).

The heat released through fusion is 80 calories per gram and the temperature when water is freezing will be close to 0°C, even though the surroundings may be colder. Therefore, an equilibrium temperature state will be established as long as the mixture of water and ice is present and the temperature remains close to 0°C. This equilibrium between vapor, liquid and ice is known as triple point temperature (Harrison et al. 1987).

Evaporative Cooling

Evaporative cooling occurs when a gas flows over a liquid. Evaporation takes place when liquid molecules near the surface collision increasing their energy above that needed to overcome the surface binding energy. The latent heat of vaporization of the liquid is the energy relative with the phase change. The internal energy of the liquid will maintain the evaporation, which will experience then the cooling effect when a reduction in the temperature occurs. However, the latent energy lost by the liquid due to evaporation has to be replenished by energy transfer to the liquid from its surroundings, if steady-state conditions are to be constant.

Psychrometrics

The study of physical and thermodynamic properties of air water mixtures is called psychrometrics, which can be useful to predict freezing and frost conditions to apply cold protection methods (Bucklin and Haman 2009).

An estimation of the potential for frost and the determination of the best time to start and stop the sprinklers for frost protection can be done by using the dew point temperature and the wet-bulb temperature. Generally, the nighttime low temperature is determined by the heat lost to the sky and the dew point temperature. As heat radiates to the sky at night, the dry-bulb temperature decreases, and if enough heat is lost it will reach the dew point temperature and stabilizes as moisture starts condensing from the air as dew or frost. Therefore, with this information, the lowest possible night time low air temperature can be estimated. However, on clear nights with low humidity, the radiation losses from plant surfaces can provoke lower temperatures than air temperature (Bucklin and Haman 2009).

Sprinklers can be used to avoid cold damage by evaporative cooling when they are turned on at the correct time. At the moment of turning the sprinklers on, the air around them will reach the wet-bulb temperature. Damage can result from the sprinkler system if the wet bulb temperature is below 0°C. Hence, in order to avoid plant damages it should be started when the wet-bulb temperature is 1.1°C or higher (Bucklin and Haman 2009).

Frost Damage

Many crops such as apples, peaches, grapes and strawberries are susceptible to frost damage. When the freezing temperatures threaten the plants, flowers and fruits, heat must be applied by an effective frost protection management strategy. Consequently, crop loss and susceptibility to diseases will be reduced, and profitability will be increased. However, frost protection management requires timely and accurate monitoring of environmental variables and proper frost protection measures (Heinemann et al. 1992).

Cell Injury

Essentially, the main cause of plant injury is not the cold temperature. Direct damage in the plants is due to the intracellular freezing, when ice crystals form inside the protoplasm of cells. However, when the ice crystals form inside the plants but outside of the cells (i.e. extracellular freezing), indirect damage can occur (Westwood 1978).

Intracellular ice formation produces “mechanical disruption of the protoplasmic structure” and the damage will extend due to two main factors: temperature speed to drop and the super cool level before freezing (Levitt 1980).

As a consequence of the extracellular ice mass growth, cells will gradually be killed due to the evaporation of the liquid water (vapor pressure gradient) inside the cells and the increased solute concentration which reduces the freezing possibilities, but increases the cell’s dehydration (Levitt 1980). In injured plants, normally the desiccation provokes dead cells in the surrounding of the ice crystal. Hence, frost damage is mainly caused by extracellular ice formation that produces secondary water stress to the surrounding cells (Snyder and de Melo Abreu 2005a).

Plant Sensitivity

Frost damage varies within varieties and species at the same temperature and phenological stage. “Hardening”, the adaptation to cold temperatures prior to a frost night, is developed in the plants against freeze injury after the cold periods due to an increase in solute content of the plant tissue, or a decrease in ice-nucleation active (INA) bacteria concentrations, or a combination of both during those periods. Therefore, the freezing temperature can vary noticeably according to the hardening level of the plants (Snyder and de Melo Abreu 2005a).

Avoidance and tolerance are the two different forms used by the plants to support low temperatures and both are involved in hardening. The freezing temperature of tissues (e.g. in olive and citrus tree leaves) gets lower due to the accumulation of sugars or sugar alcohols and supercooling increases in many deciduous and evergreen fruit trees in response to low air temperature. Also, an increase of fatty acids of plasma membrane lipids may harden some cells and so, it would increase membrane stability in desiccation. However, hardening will be reduced whenever the assimilate level in the tissues is depleted or if exposed to warm temperatures (Snyder and de Melo Abreu 2005a).

“Freeze” and “Frost” Definitions

In general, the words “freeze” and “frost” are used interchangeably with an indistinct definition being “*an air temperature less than or equal to 0°C”*. Those terms have been used to express a meteorological event, which causes crops and plant freezing injury (Snyder and de Melo Abreu 2005a). However, as a technical term, “frost” refers to the formation of ice crystals on surfaces either by freezing of dew or a phase change from vapor to ice (Blanc et al. 1963; Cuhna 1982).

According to Snyder and de Melo-Abreu (2005*) "A "frost" is the occurrence of an air temperature of 0°C or lower, measured at a height of between 1.25 and 2.0 m above soil level, inside an appropriate weather shelter"*. Some avoidance factors (e.g. supercooling and concentration of ice nucleating bacteria) might provoke a freezing of the water within plants. *"A "freeze" occurs when extracellular water within the plant freezes (i.e. changes from liquid to ice)".* Damage to the plant tissue depends on some tolerance factors (e.g. solute content of the cells).

When extracellular ice forms inside of the plants, the frost event is converted into a freeze event. However, freeze injury is present when an irreversible physiological condition occurs causing death or malfunction of the plant cells after falling below a critical value (Snyder and de Melo Abreu 2005a).

Crop Sensitivity and Critical Temperatures

The air "critical temperatures" are correlated with the damaging plant tissue temperature. Subzero air temperatures are the consequence of the reduction in sensible heat content of air near the surface, due to the following main factors: (i) net radiation loss from the surface to the sky (i.e. radiation frost), (ii) or warmer air replaced by wind blowing in subzero air temperature (i.e. advection frost), or (iii) a combination of both.

Commonly, frost damage occurs to crops from extracellular ice formation inside plant tissue, consequently damages to the cells are present due to water withdrawing and dehydration. As a protective response to cold events, the plants tend to harden against freeze injury. This is one of the factors which determine the temperature at which ice forms within the plant tissue and when damage occurs. Therefore, frost injury increases when the temperature decreases. The "critical damage temperature" (TC) is the temperature related to a specific level of damage (Snyder and de Melo Abreu 2005a).

The critical temperature is defined as the temperature below which, a percent of the plant part will be killed when hold for 30 minutes or more, i.e. if for blossoms T_{90} = -2.2°C thus, 90% of the blossoms will be killed if blossoms are exposed below -2.2°C during 30 minutes or more (Perry 1979; Perry 1986). The critical temperature is determined according to the plant variety and stage of development. In general, the critical temperature is below 0°C considering that the water within a plant is at a water potential lower than that of free water, thus intracellular freezing, which causes damages in the plant, does not occur (Perry 1979). Some approximate values based on observations and opinions of leading small extension personnel, not on controlled research, showed critical temperature of the blossoms, and young fruits of strawberries (Table 1-2; Phillips et al. 1962).

A critical temperature of -3.11°C was observed for two stages of blossom development: open blossom and buds with visible petals of four strawberry cultivars. The minimum air and blossom/bud temperature recorded was -3.7°C and -3.8°C, correspondingly, and the minimum wind speed was 1 m s^{-1}, occurring damage during that night of frost protection on strawberries (Table 1-3; Perry and Poling 1986).

Perry and Poling (1986) suggested a critical temperature within all this criteria and it was supported by Boyce and Strater (1984), demonstrating that popcorn and open blossoms damage increased from 0% to 7% and from 0% to 20%, respectively, when the freezing temperature changed from -3.0 to -4.0°C for eight cultivars. Usually, the critical temperature increases with time after the developing of the buds until the fruit stage, since this crop stage the most sensitive to freezing.

The definition of “frost” has two categories: “Advective” and “Radiative” (Kalma et al. 1992; Snyder et al. 1992) Nevertheless, in some cases a combination of both conditions will occur.

Advective Frosts

These frosts occur when cold air blows into an area to replace warmer air present before the weather changes. Large-scale incursions of cold air with a well-mixed, windy atmosphere, no temperature inversion, low humidity and a subzero temperature generally present even during daytime; are conditions associated to advective frosts (Snyder et al. 1992). In these frosts the lowest temperatures are usually observed on the middle and higher portions of hillsides that are open and exposed to the wind. Higher night-time temperatures are observed on the down-wind sides of hills and in low spots that are sheltered from the wind (Snyder and de Melo Abreu 2005a).

Radiative Frosts

In general, the radiative frosts are present on a clear and calm night, as the result of the cooling attributable to the energy loss through radiant exchange, with temperature inversions (i.e. temperature increases with height), low dew-point temperatures and air temperatures that usually fall below 0°C during the night but above 0°C during the day (Snyder et al. 1992). Cold air accumulates in depressions, where the air becomes vertically stratified with temperature increasing with height; therefore, higher night-time temperatures are observed on hilltops and on upper middle sections of hillsides that are free from obstacles to block cold air drainage (Snyder and de Melo Abreu 2005a).

Economic Importance of Cold Protection

In strawberries market the prices usually determine the length of the strawberry season; however, most Florida growers concur that early yields provide the highest profits per unit, with prices generally declining at the end of February.

Sprinkler Irrigation Cold Protection

Increases or decreases in water temperature are dependent on changes in the sensible heat content. Three processes cause a reduction on water temperature: (i) sensible heat in the water is transferred to its surroundings; (ii) evaporation, when sensible heat consumption occurs to break the hydrogen bonds between water molecules; or (iii) when there is net radiation loss. Part of sensible heat is lost by radiation as water droplets fly from a sprinkler head to a plant and soil surfaces, some will transfer from the warmer water to the cooler air and some will be lost to latent heat as water evaporates from the droplets (Snyder and de Melo Abreu 2005b).

Sprinkler irrigation is used for frost or freeze protection under the principle of latent heat transfer. The heat loss from the plant to its surrounding environment is replaced by the sensible heat and the heat of fusion associated with the water. Cold protection is supplied due to the release of the latent heat of fusion when water changes phase from liquid to solid (water to ice) (Harrison et al. 1987). The amount of heat released expressed as BTU's and calories is explained in Table 1-4.

The water freezing point is at 0°C and the heat released as the water freezes keeps this temperature approximately constant although the surroundings may be colder. Therefore, cold protection will be provided as long as the mixture of water and ice is present and the temperature continues close to 0°C. However, greater damage can occur than experienced by an unprotected crop when windy conditions are present or when temperature falls so low that the application rate is inadequate to provide greater heat than it is lost to evaporation (Snyder and de Melo Abreu 2005b).

Momentarily plant temperature rises when water droplets strike a flower, bud or small fruit, due to latent heat release when water freezes; however, energy is lost as latent heat when water vaporizes from the ice-coated plant tissue. These two processes and radiation losses, cause the temperature to drop until the sprinklers rotate and strike the plant again. Therefore, to prevent the plant temperature from falling too low between pulses, it is necessary to re-apply water frequently at a sufficient application rate (Snyder and de Melo Abreu 2005b). A frequency of application no longer than 60 s (Wheaton and Kidder 1965) and a variable application rate according to minimum temperature and wind speed are recommended (Gerber and Martsolf 1965a).

A wet leaf may be colder than a dry leaf due to cooling by evaporation. The heat consumption during evaporation is approximately 7.5 times more than is liberated by freezing, hence at least 7.5 times as much water must be frozen as is evaporated. Therefore, the temperature on a sprinkled leaf will be lower than a non-sprinkled leaf if less heat is released by freezing than is used for evaporation of water and ice from the leaf (Gerber and Martsolf 1965b). Thus, it is important when irrigation is used for freeze protection that an application rate can be maintained over the entire irrigated area during a cold event based on minimum temperature and wind speed conditions (Gerber and Martsolf 1965a; Gerber and Harrison 1964).

The leaf temperature may be 1.6 to 2.2°C below air temperature under no wind and clear conditions due to the process of inversion; in which temperature drops faster as a result of radiation cooling. When a light wind is present, the leaf temperature will be only slightly below air temperature (Gerber and Martsolf 1965b); as a result of breaking the inversion process and increasing the exchange of heat among air and surface temperatures (Braud and Hawthorne 1965).

Sprinkler application rates of 3.3 mm h^{-1} and 6.6 mm h^{-1} were evaluated for cold protection in strawberries during four severe freeze events (Locascio et al. 1967). These evaluations recorded a minimum air temperature of -8.8°C, variations in wind speed ranging from 0 to 5.4 m s^{-1} and 0°C as the lowest dew point temperature. Under low wind conditions (0-0.9 m s^{-1}) and minimum temperature of -4.4°C, both 3.3 mm h^{-1} and 6.6 mm h^{-1} application rates were equally effective. However, no protection was provided using 3.3 mm h^{-1} under air temperatures lower than -4.4°C, and wind speeds greater than 0.9 m s^{-1}. The injury reported with a no irrigation treatment was 87% of the flowers, 98% of the immature fruit and 100% of the mature fruit. As a comparison, the corresponding results for injury of flowers, immature fruit and mature fruit were 41, 59 and 50% in plots receiving the 3.3 mm h^{-1} rate and 13, 19 and 6% in plots receiving the 6.6 mm h^{-1} rate.

In another study strawberry conducted during the winter of 1985-1986 using overhead sprinkler irrigation showed satisfactory protection of early fruits with 15% fruit losses to freezing. Using a 6.4 mm h^{-1} application rate, 889 mm of water were applied to the uncovered sprinkler irrigated plants. This amount represented approximately 50% of the total water used by many commercial strawberry growers at that time (Hochmuth 1993).

Sprinkler Uniformity

Since uniform coverage must be accomplished for effective plant protection from cold damage; sprinkler irrigation uniformity must be achieved accordingly. Irrigation efficiency is defined as a ratio between the total volume of irrigation water beneficially used over the total water applied minus the outflow (the total volume of irrigation water that leaves the boundaries). This term is defined as a performance indicator and is generally expressed as a percentage (Burt et al. 1997a).

Distribution Uniformity (DU_{lq}) measures the variation of the irrigation water applied to different areas in a field. In general, DU_{lq} is defined as a ratio of the smallest accumulated depths of water in the distribution, to the average depth accumulated. Although high DU_{lq} values can be obtained, irrigation efficiency may not be achieved due to under or over-irrigation. Nevertheless, irrigation cannot be non-uniform and efficient. Therefore, DU irrigation system performance is a tool which can provide information of the potential irrigation efficiency (Burt et al. 1997a).

The average low-quarter depth, $\overline{D_{lq}}$, is the average of the depths accumulated in the quarter of the field area receiving the smallest depths (ASAE 2001). An emphasis on the areas receiving the least irrigation is given by focusing on a minimum value range (the lowest quarter) instead of using the absolute minimum value (zero) (Burt et al. 1997a).

The low-quarter distribution uniformity, DU_{lq}, is a ratio defined by the following formula (Merriam and Keller 1978):

$$DU_{lq} = \frac{\overline{D_{lq}}}{\overline{D_{tot}}} \tag{1-1}$$

Where $\overline{D_{lq}}$ is the average of lowest quarter of catch can measurements (mL) and $\overline{D_{tot}}$ is the average depth of application over all catch cans measurements (mL).

The Coefficient of Uniformity (CU) is another indicator which can assist in system design and/or selection, and can be used to quantify certain aspects of system performance in the field. However, the entire irrigation system performance can be affected by multiple factors such as: wind, application rates, water applied, runoff, pump performance and overall system management (ASAE 2001).

The Christiansen Uniformity Coefficient (Christiansen 1942); (ASAE 2001) is defined by the following formula:

$$CU = 100 * \left[1 - \frac{\sum_{i=1}^{n}|V_i - \overline{V}|}{\sum_{i=1}^{n} V_i}\right] \tag{1-2}$$

Where V_i is the individual catch can measurement (mL) and $\overline{V}$ is the average volume of application over all the catch can measurements (mL).

Frequency of Application

The system design and operation; e.g. the frequency of application or sprinkler rotational speed, also influence the effectiveness of cold protection (Wheaton and Kidder 1965). The temperature of a wet plant rises as water freezes, but it falls as water vaporizes and radiative losses occur; therefore frequent rotation rate is required to reduce the interval when the plant temperature falls below 0°C (1-2).

Three scenarios may result from the frequency in which water is applied to the plants: (i) a fast frequency of application in which the plant remains wet at the next sprinkler rotation, (ii) a rotation rate in which the duration allows the water applied just to turn into ice, and (iii) the sprinkler could revolve too slow so that the water is frozen and the temperature of the ice falls below freezing temperature (0°C) (Niemann 1957-1958). Ideally, the second condition should be accomplished, in which a good coverage is provided during enough time to keep the temperature near 0°C to avoid damage to the plant.

The greater the wind speed, the greater the evaporation rate, which causes a temperature decrease to near the wet-bulb temperature before another pulse of water hits the plant. As well, the lower the dew point temperature, the greater the evaporation rate (Snyder 2000). Hence, higher sensible heat losses from the plant surfaces and more water needs to be frozen to compensate for these losses. When the unprotected minimum temperature is lower, more energy is needed from the freezing process to make up for the sensible heat deficit; hence, a higher application rate is needed (Snyder and de Melo Abreu 2005b). Consequently, a frequent interval of time for a rotation rate no longer than 60 seconds is required in order to shorten the period the temperature is below the critical damage temperature (Wheaton and Kidder 1965).

Experiments conducted by Wheaton and Kidder (1965) were performed in order to determine the effect of repeat frequency of application under windborne freeze conditions in the absence of radiation cooling. The tests were conducted with rotation speeds of 20 s, 60 s and 120 s for application rates of 2.8 mm h^{-1} and 5.1 mm h^{-1}.

Under low wind conditions (0.4 m s^{-1}) the 2.8 mm h^{-1} application rate gave protection to about -1.1°C using 20 s repeat frequency; while the 60 s frequency protected to a minimum temperature around -3.6°C. Hence, changing the frequency from 120 s to 60 s allowed to decrease the secure temperature in more than 2.2 degrees. When tests were performed under higher wind conditions (1.3 m s^{-1}) using the same application rate, protection was provided nearly -2.8°C using the 20 s frequency and only down to -1.1°C when 60 s frequency was tested (Wheaton and Kidder 1965).

Leaf cold protection to a temperature of -2.2°C was provided using 60 s frequency and 5.1 mm h^{-1} application rate under wind speed of 1.3 m s^{-1}; whereas the

20 s frequency protected down to -3.6°C under the same wind conditions (Wheaton and Kidder 1965). It was determined that the safe temperature level was lowered from 0.8 to 2.2 degrees by increasing the rotational speed from 120 s to 60 s or from 60 s to 20 s (and other factors remaining constant) under windborne freeze conditions. Furthermore, fewer temperature variations at the leaf surface resulted from shorter frequencies of repeat application without ice mass formation (Fig 1-2; Wheaton and Kidder 1965). Results may vary if ice layer is formed at the leaf.

Application Rate (AR)

The requirement rate for cold protection is defined as the amount of water needed to be applied to provide enough heat by freezing in order to compensate for the heat loss by other means, i.e. radiation, convection and evaporation (Braud and Hawthorne 1965; Businger 1965; Gerber and Martsolf 1965a; Gerber and Harrison 1964; Perry 1979; Perry et al. 1980; Perry and Poling 1986; Snyder and de Melo Abreu 2005a; Wheaton and Kidder 1965).

AR Models. The application rate for over-plant irrigation with conventional sprinklers depends on the rotation rate, wind speed, dew point temperature and unprotected minimum temperature (Snyder 2000; Snyder and de Melo Abreu 2005b). The following section presents previous models which were developed in order to determine the amount of water needed to provide enough heat release and freezing of ice-water film on the plant to be protected.

Businger Model and Gerber and Harrison Model. Application rates had been developed for different crops. In order to determine a sprinkling application rate (AR), two main models were established initially by Businger (1965) and then by Gerber and Harrison (1964) based on previous Businger’s studies presented in 1963 (Perry 1979).

These models are based on theoretical computations and were developed from given set of atmospheric conditions (i.e. plant part temperature, minimum tolerable or critical temperature, wind speed and plant part size). The AR requirement was calculated taking into consideration the heat balance of a single horizontal leaf. Also, the minimum “off” period of a pulsing cycle was calculated in the models.

The results from the models of Businger (1965) and Gerber and Harrison (1964) for sprinkler irrigation for cold protection of citrus showed an extreme low temperature of -9.4°C under wind speed ranges between 2.2-4.5 m s^{-1}. The application rates were strongly dependent on wind speed. However, due to rapid ice formation, ice with a milky white appearance was observed and with inclusion of air bubbles; hence, a deficient sprinkling and a temperature depression were more likely. The variability of exposure, water distribution and height above the surface (affected by the wind) produced variability in temperatures.

The results of using this general theory of irrigation, to estimate the amount of water required based on the lowest anticipated temperature and wind speed, showed that the drop size used was too small for most efficient water use of heat in the water (Gerber and Harrison 1964). As a consequence of the deficient sprinkling, more damage occurred by increasing the killing temperature of citrus leaf and decreasing the temperature below ambient (Gerber and Harrison 1964).

Gerber and Martsolf Application Rate Table. Based on the Gerber and Harrison (1964) model, Gerber and Martsolf (1965a) developed a suggested application rate table for expected minimum temperatures and wind conditions during a freeze/frost night (Table 1-1). Successful protection using this AR table had been achieved; however, it has been shown that is generally overestimated (Perry 1979).

Gerber and Martsolf (1979) showed a sprinkler application rate theoretical model of a 20 mm diameter tree leaf. This model used the following simple empirical equation for the application rate (R_A):

$$R_A = (0.0538\, u^2 - 0.5404\, u - 0.4732)T_l \tag{1-3}$$

Where, u is the wind speed (m s^{-1}), and T_l is the temperature of a dry unprotected leaf (°C). To estimate the temperature difference between air and a leaf of 20 mm diameter on a typical frost night, where a high stomatal resistance is present, the approach outlined by Campbell and Norman (1998) can be used as follows:

$$T_a - T_l = 1.4458\, u^{-0.4568}\ ^{\circ}\mathrm{C} \tag{1-4}$$

For $0.1 \le u \le 5$ m s^{-1}. If these two equations are combined, a new simple equation is developed for the AR in terms of wind speed (u) and air temperature T_a (°C) described as follows:

$$R_A = (T_a - 1.4458\, u^{-0.4568})(0.0538\, u^2 - 0.5404\, u - 0.4732)\ mm\ h^{-1} \tag{1-5}$$

This equation is valid for wind speeds in the range of 0.5 and 5.0 m s^{-1}. It is recommended an additional application amount ranging from 0 mm h^{-1} for sprinkler systems with a uniform coverage over a thin crop canopy, to 2 mm h^{-1} for canopies with dense foliage or for sprinkler systems with less uniform coverage.

The ARs generated in Equation 5 are recommended for tall crops such as grapevines; however, lower ARs are needed for smaller crops such as strawberries due to the less surface area to cover, less evaporation and better uniformity reached when shorter vegetation is wetted. An AR comparison between short and tall crops is described in Table 1-6 and 1-3 shows the application rates for short crops such as strawberries.

Barfield (et al.1981) Model. The sprinkler AR model described by Gerber and Harrison (1964), assumes no humidity effect in the calculation. Consequently, , Barfield et al. (1981) showed through their model that ignoring humidity can cause an underestimation of the required AR, hence, a larger error which may result in subsequent damage to valuable horticultural crops. Therefore, this parameter has to be taken into account. An example given by Barfield et al. (1981), for air temperature -5 ºC, wind speed 2 m s^{-1} and relative humidity 50%, estimated an application rate of 6.9 mm h^{-1}. By ignoring the relative humidity term, a large error would have been made resulting in 1.97 mm h^{-1} lower AR, equivalent to an underestimation of 28% of the requirement (Barfield et al. 1981).

Perry K.B. Model. Further analyses of these models were performed by Perry (1979) who incorporated humidity and ice accumulation into amended versions of former models creating a new refined model to predict variable sprinkler AR in time and space.

The results from Gerber and Harrison (1964) model were published in a table of AR for various wind speed and minimum temperature of a dry leaf by Gerber and Martsolf (1965a) (Table 1-1). Furthermore, Perry (1979) made a detailed comparison among the published values in the AR table by Gerber and Martsolf (1965a) and these values reprogrammed in FORTRAN (program used by Businger 1965 in initial model). Even when the AR table had been used successfully, an overestimation was determined throughout this comparison (Table 1-7). In the AR table, a lower limit of 2.5

mm hr^{-1} was established and rounding was applied. The reprogrammed values were supposed to be equal to the AR table by Gerber and Martsolf (1965a) (GM) if they were (i) < 2.5 mm hr^{-1} when GM used 2.5 mm hr^{-1} (ii) within 10% of GM value, and (iii) rounded off to the nearest tenth of a cm. However, only 21% of their values were verified (Table 1-7 values with asterisk (*)). Although the AR table has been successful, its usage is limited due to overestimations for wind speeds over 5 m s^{-1}, which are very extreme and unusual frost/freeze conditions. Only 33% of the values were validated for lower wind conditions (Perry 1979).

Turning irrigation systems on and off can achieve water conservation and greater efficiency by an adjustment of the sprinkling AR according to the atmospheric conditions (Perry et al. 1980). In order to conserve water Perry et al. (1980) added intermittent sprinkling as another component to the model.

A calculation of the maximum off period can be made through the sum of time required to freeze the applied water plus the time in which the ice coated plant parts cool to the critical temperature. This off period has to be long enough to conserve water, but not excessive that the plant parts cools below the critical temperature (Perry et al. 1980). Experimental results conducted by Perry et al. (1980) indicated that the optimum off time is between 1.5 and 4.0 min, concluding that water consumption for frost protection can be reduced by intermittent sprinkling.

The initial model developed by Perry (1979) was SPAR79 (Sprinkling Application Rate model developed in 1979), then it was transformed into SPAR81 and furthermore it enhance into FROSTPRO (Perry 1986). This microcomputer program calculated irrigation rates for frost/freeze protection of orchards based on given atmospheric and crop parameters, including the relative humidity parameter suggested by Barfield et al. (1981). The rate of heats lost by the plant was determined using an energy budget approach at the actual plant part temperature and at the critical temperature. Therefore, the difference of these two rates of heat loss is the rate at which heat must be applied by the latent heat of fusion liberated as the applied water freezes (Perry 1986).

Martsolf J.D. (Minimum diameter of pattern). Under different meteorological conditions, models have been used for decades to predict the minimum precipitation rate that will provide protection. However, it is necessary to determine whether the specific sprinkler system can be expected to deliver enough water. Therefore, the minimum diameter of pattern that will provide the minimum precipitation rate was defined by Martsolf (1993) as follows:

$$d = 1.43\sqrt{\frac{R}{P}} \tag{1-6}$$

Where *d* is the minimum diameter of the cylinder of protection (ft.), R is flow rate through the nozzle (gph), P is the minimum precipitation rate given by the sprinkler model (in hr^{-1}).

Stombaugh et al. (1990) Automated pulsing system. As a consequence of the development of mathematical models to predict the application rate to provide effective protection from frost damage (Perry 1986) and due to the achievement of a desired application rate by an intermittent irrigation (Perry et al. 1980); an automated pulsing irrigation system for frost protection of strawberries was developed by Stombaugh et al. (1990). This automated system determines, based on three models, when to start the irrigation, (according to the atmospheric conditions and before dropping below critical temperature, but it won’t turn on under high wind conditions), how much to applied (AR based on FROSTPRO) and when to stop the system (ice layer on the plant is melting).Tests were performed under actual frost conditions and it was concluded that a microcomputer can effectively control a pulsed irrigation system for frost protection for strawberries (Stombaugh et al. 1990).

Start and Stop Sprinklers

According to the literature the temperature to start and stop the sprinklers for frost protection is based on the dew-point and wet-bulb temperatures (Table 1-8). To use Table 1-8, first, find in the top row the wet-bulb temperature, which is greater than or equal to the critical damage temperature, for the crop. Second, locate the dew-point temperature in the left-hand column and match the air temperature that corresponds. The sprinklers should be operating before the air temperature measured upwind from the crop falls to the selected air temperature. When frost alarms are used, it is recommended to set it about 0.4 ºC higher than the starting air temperature identified in Table 1-8 to safeguard sufficient time to start the sprinklers and when the irrigation is started using a thermostat, it should be set 0.4-2 ºC, according to its accuracy (Snyder and de Melo Abreu 2005b). Table 1-9 can be used in order to determine dew-point temperature (°C) when air temperature and relative humidity are known.

To estimate the start and stop temperature, the vapor pressure (e_d in kPa) at the dew point temperature (T_d in ºC) is estimated from the wet-bulb temperature (T_w in ºC) as:

$$e_d = e_w - 0.000660\ (1 + 0.000115T_w)(T_a - T_w)P_b\ kPa \tag{1-7}$$

Where the saturation vapor pressure at the wet-bulb temperature (e_w) is:

$$e_w = 0.6108 \exp\left(\frac{12.27T_w}{T_w + 237.3}\right)\ kPa \tag{1-8}$$

And the barometric pressure (P_b) as a function of the elevation (E_L in meters) is:

$$P_b = 101.3 \left[\frac{293 - 0.0065\, E_L}{293}\right]^{5.26} \; kPa \tag{1-9}$$

Therefore the corresponding air temperature (T_a) can be calculated as:

$$T_a = T_w + \frac{e_w - e_d}{0.00066(1 + 0.00115\, T_w)P_b} \; ℃ \tag{1-10}$$

Where the saturation vapor pressure at the dew point temperature (e_d) is

$$e_d = 0.6108 \exp\left(\frac{17.27 T_d}{T_d + 237.3}\right) \; kPa \tag{1-11}$$

The variation in exposed leaf temperature can be higher than air temperature due to exposure to the sky and should be used to determine the moment to start the system. It is less risky when the irrigation system is started when the wet-bulb temperature reaches 0 ºC (Snyder and de Melo Abreu 2005a).

A freezing ice/water mixture remains near 0° C, as equal as a melting ice/water mixture; therefore, the irrigation is typically stopped when ice is melting from the crop. The longest time the plant can support being without rewetting is the time required to freeze a film of water adhering to the leaf (Harrison et al. 1987).

However, the sprinklers should not be turned off if the air temperature is above 0° C and the sun is shining unless the wet-bulb temperature measured upwind from the crop is above the critical damage temperature. Therefore, the highest freezing temperature for strawberries is -0.8 ºC. A psychrometer can be used to directly measure wet-bulb temperature or it can be estimated from the dew-point and air temperatures (Snyder and de Melo Abreu 2005a).

Over the past years, higher interest in irrigation management throughout the application of better practices and technology has risen in response to the occurrence of unusual cold events in the Dover Plant/City area, which caused hydric resource problems believed to be caused by irrigation for cold protection. Therefore, this research found as a main goal to optimize irrigation management practices for cold protection in strawberries that could conserve water. The objectives for this project were to: (i) investigate cold protection practices in Florida's strawberry industry and optimize current strawberry irrigation cold protection application rates (ii) assess the effect of sprinkler type, sprinkler spacing, irrigation system pressure variations and varied climatic wind conditions over irrigation distribution uniformity (DU_{lq}) and application rate (AR), and (iii) evaluate the effect of varying sprinkler spacing and pressure on strawberry yield quality and quantity under cold conditions.

Table 1-1. Citrus cold protection application rate (mm hr^{-1}) recommendation according to minimum temperature expected and wind speed conditions (Gerber and Martsolf 1965a; Gerber and Harrison 1964).

Min. Temp. Expected (°C)	Wind Speed (m s^{-1}) 0 - 0.4	0.9 - 1.8	2.2 - 3.6	4.5 - 6.3	8.0 - 9.8	13.4
	Application Rate (mm hr^{-1})					
-2.8	2.5	2.5	2.5	2.5	5.1	7.6
-3.3	2.5	2.5	3.6	5.1	10.2	15.2
-4.4	2.5	4.1	7.6	10.2	20.3	40.6
-5.6	3.0	6.1	12.7	15.2	30.5	45.7
-6.7	4.1	7.6	15.2	20.3	40.6	61.0
-7.8	5.1	10.2	17.8	25.4	50.8	76.2
-9.4	6.6	12.7	22.9	33.0	66.0	101.6
-11.7	8.6	17.8	30.5	43.2	86.4	127.0

Table 1-2. Critical temperature (°C) of the blossoms, and young fruits of strawberries for four stages (Phillips et al. 1962).

Crop	Tight Bud	Balloon Bud	Full Bloom	Green Fruit
Strawberries	-5.6	-2.2	-0.56	-2.2

Table 1-3. Assessment of survival and minimum temperature (°C) reached for exposed and covered blossoms in open and popcorn stages for four strawberry cultivars (Perry and Poling 1986).

Cultivar	Open				Popcorn			
	Exposed		Covered		Exposed		Covered	
	Assess.	Min temp.	Assess.	Min temp.	Assess.	Min temp.	Assess.	Min temp.
Atlas	0	-3.7	0	-3.8	0	-3.3	0	-3.4
Apollo	+	-3.1	0	-3.2	+	-1.7	+	-2.2
Chandler	0	-3.6	+	-1.9	+	-2.7	0	-3.6
Douglas	+	-2.6	+	-3.1	0	-3.7	+	-0.9

0=Dead
+ Alive

Table 1-4. Comparison of heat consumed through evaporation (heat of vaporization) with heat released (heat of fusion) through freezing (Gerber and Martsolf 1965b).

Unit of water	Heat of vaporization (at 0°C)	Heat of fusion
1 gram	596 Calories or 2.4 BTU	80 Calories or 0.32 BTU
1 Pound	1072 BTU	144 BTU
1 Gallon	8100 BTU	1200 BTU

Table 1-5. Results obtained at the Archer Road Unit with irrigation for citrus cold protection (Gerber and Harrison 1964).

Date	Min temp (°C)	Wind (m s^{-1})	Application rate (mm h^{-1})	Results
Dec 6-7	-3.1	0.0-0.5	2.54	Good
Dec 10-11	-2.4	0.0-0.5	2.54	Good
Dec 12-13	-9.2	2.2-4.5	2.54	Trees killed
Dec-13-14	-5.6	0.0-0.5	2.54	Trees killed
Dec 14-15	-5.1	0.0-0.5	2.54	Trees killed
Jan 24-25	-4.2	1.8-2.7	2.79	Variable

Note: The operating pressure for the system was 413.7 kPa at the nozzle of the sprinkler. The nozzle size was 3.2 mm, except for January 24 and 25 when 3.97 mm. nozzles were used.

Table 1-6. Application rates (mm h^{-1}) for overhead sprinkler protection of tall (orchard and vine) and short (field and row) crops depending on the minimum temperature and rotation rate, for wind speeds between 0 and 2.5 m s^{-1}.

Minimum temperature (°C)	Tall crops		Short crops	
	30 s rotation	60 s rotation	30 s rotation	60 s rotation
-2.0	2.5	3.2	1.8	2.3
-4.0	3.8	4.5	3.0	3.5
-6.0	5.1	5.8	4.2	4.7

Note: Application rates are about 0.02 mm hr^{-1} lower for no wind and about 0.02 mm hr^{-1} higher for wind speeds near 2.5 m s^{-1}. The “short crop” rates cover field and row crops with canopies similar in size to strawberries. Taller field and row crops (e.g. potatoes and tomatoes) require intermediate application rates (Snyder and de Melo Abreu 2005c).

Table 1-7. Application rates (mm hr^{-1}) comparison between composite table of AR from the computer model (GH) (Gerber and Harrison 1964) and AR from Table 1-6 of Gerber and Martsolf (1965a) (GM) at different wind conditions (m s^{-1}).

	Application Rate Comparison (mm hr^{-1})											
Wind Speed (m s^{-1})	0 to 5		1 to 2		2.5 to 4		5 to 7		9 to 11		15	
Temp of Dry Leaf (°C)	GM	GH	GM	GH	GM	GH	GM	GH	GM	GH	GM	GH
-2.8	2.5 *	1.8	2.5	3.9	2.5	5.6	2.5	7.5	5.0	9.6	7.5	11.7
-3.3	2.5 *	2.1	2.5	4.6	3.6	6.7	5.1	8.9	10.1	11.5	15.3 *	14
-4.4	2.5 *	2.8	4.1	6.1	7.6	8.8	10.2	11.8	20.4	15.1	40.6	18.4
-5.6	3.0 *	3.4	6.1	7.6	12.7	10.9	15.2 *	14.6	30.4	18.7	45.6	22.7
-6.7	4.1 *	4.1	7.6	9.0	15.2	12.9	20.3	17.3	40.6	22.2	60.9	27.0
-7.8	5.1 *	4.7	10.2 *	10.4	17.8	14.9	25.4	20.0	50.8	25.6	76.2	31.2
-9.4	6.6	5.6	12.7 *	12.5	22.9	17.9	33.0	24.0	66.0	30.7	99.0	37.4
-11.7	8.6	6.9	17.8	15.2	30.5	21.8	43.2	29.2	86.4	37.3	129.6	45.4

Table comparison established by Perry (1979)
(*) Designates that the pair comparison (AR from the computer model (GH) and Table 1-6 (GM)) is considered equal (Perry 1979).

Table 1-8. Minimum starting and stopping air temperatures (°C) for frost protection with sprinklers as a function of wet-bulb and dew-point temperature (°C) at mean sea level (Snyder and de Melo Abreu 2005b)

Dew-point temperature	Wet bulb-temperature °C					
°C	-3.0	-2.5	-2.0	-1.5	-1.0	-0.5	0.0
0.0							0.0
-0.5						-0.5	0.3
-1.0					-1.0	-0.2	0.6
-1.5				-1.5	-0.7	0.1	1.0
-2.0			-2.0	-1.2	-0.4	0.4	1.2
-2.5		-2.5	-1.7	-0.9	-0.1	0.7	1.5
-3.0	-3.0	-2.2	-1.4	-0.6	0.2	1.0	1.8
-3.5	-2.7	-2.0	-1.2	-0.4	0.4	1.3	2.1
-4.0	-2.5	-1.7	-0.9	-0.1	0.7	1.5	2.3
-4.5	-2.2	-1.4	-0.7	0.1	1.0	1.8	2.6
-5.0	-2.0	-1.2	-0.4	0.4	1.2	2.0	2.8
-5.5	-1.7	-1.0	-0.2	0.6	1.4	2.2	3.1
-6.0	-1.5	-0.7	0.1	0.9	1.7	2.5	3.3
-6.5	-1.3	-0.5	0.3	1.1	1.9	2.7	3.5
-7.0	-1.1	-0.3	0.5	1.3	2.1	2.9	3.7
-7.5	-0.9	-0.1	0.7	1.5	2.3	3.1	3.9
-8.0	-0.7	0.1	0.9	1.7	2.5	3.	4.1
-8.5	-0.5	0.3	1.1	1.9	2.7	3.5	4.3
-9.0	-0.3	0.5	1.3	2.1	2.9	3.7	4.5
-9.5	-0.1	0.7	1.5	2.2	3.1	3.9	4.7
-10.0	0.1	0.8	1.6	2.4	3.2	4.0	4.9

Note**:** Select a wet-bulb temperature that is above the critical damage temperature for your crop and locate the appropriate column. Then choose the row with the correct dew-point temperature and read the corresponding air temperature, from the table to turn your sprinklers on or off. This table is for the mean sea level, which should be reasonable accurate up to about 500 m elevation.

Table 1-9. Dew-point temperature (°C) corresponding to air temperature and relative humidity (Snyder and de Melo Abreu 2005b).

Dew-point Temp. °C	Wet bulb-temp. °C -2.0	0.0	2.0	4.0	6.0	8.0	10.0	12.0
100	-2.0	0.0	2.0	4.0	6.0	8.0	10.0	12.0
90	-3.4	-1.4	0.5	2.5	4.5	6.5	8.4	10.4
80	-5.0	-3.0	-1.1	0.9	2.8	4.8	6.7	8.7
70	-6.7	-4.8	-2.9	-1.0	1.0	2.9	4.8	6.7
60	-8.7	-6.8	-4.9	-3.0	-1.2	0.7	2.6	4.5
50	-11.0	-9.2	-7.3	-5.5	-3.6	-1.8	0.1	1.9
40	-13.8	-12.0	-10.2	-8.4	-6.6	-4.8	-3.0	-1.2
30	-17.2	-15.5	-13.7	-12.0	-10.2	-8.5	-6.8	-5.0
20	-21.9	-20.2	-18.6	-16.9	-15.2	-13.6	-11.9	-10.2
10	-29.5	-27.9	-26.4	-24.8	-23.3	-21.7	-20.2	-18.6

Note: Select a relative humidity in the left column and an air temperature from the top row. Then find the corresponding dew-point temperature in the table.

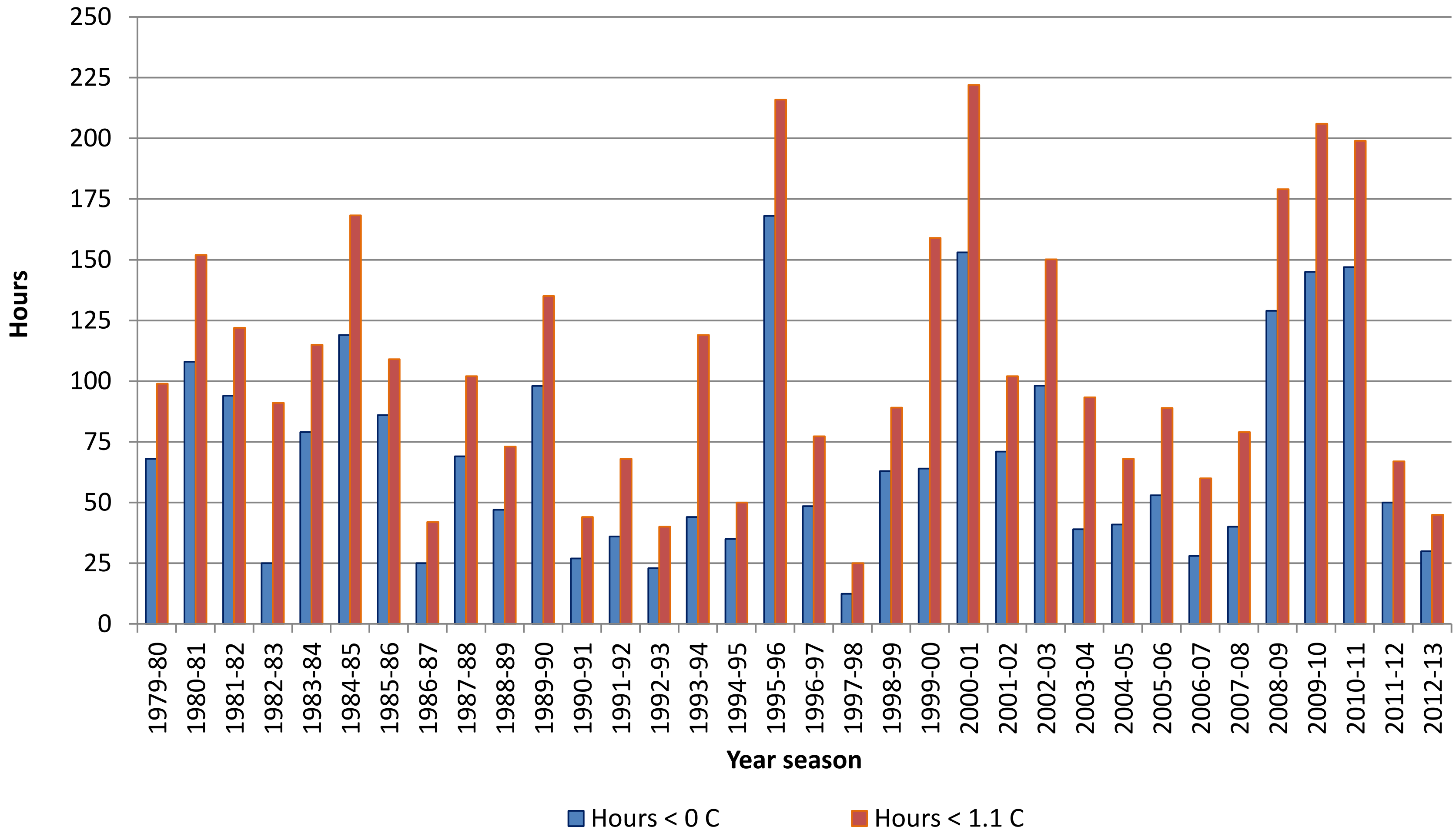

Figure 1-1. Amount of hours below freezing point (0°C) and below irrigation system turn ON temperature (1.1°C). Historical Seasonal Years from 1979 to 2013 for Gainesville (1982-1991; (Florida Climate Center 2012a) and Citra, FL (1992-2000; Florida Climate Center 2012b; 2000-13(FAWN 2013; Florida Climate Center 2012b)).

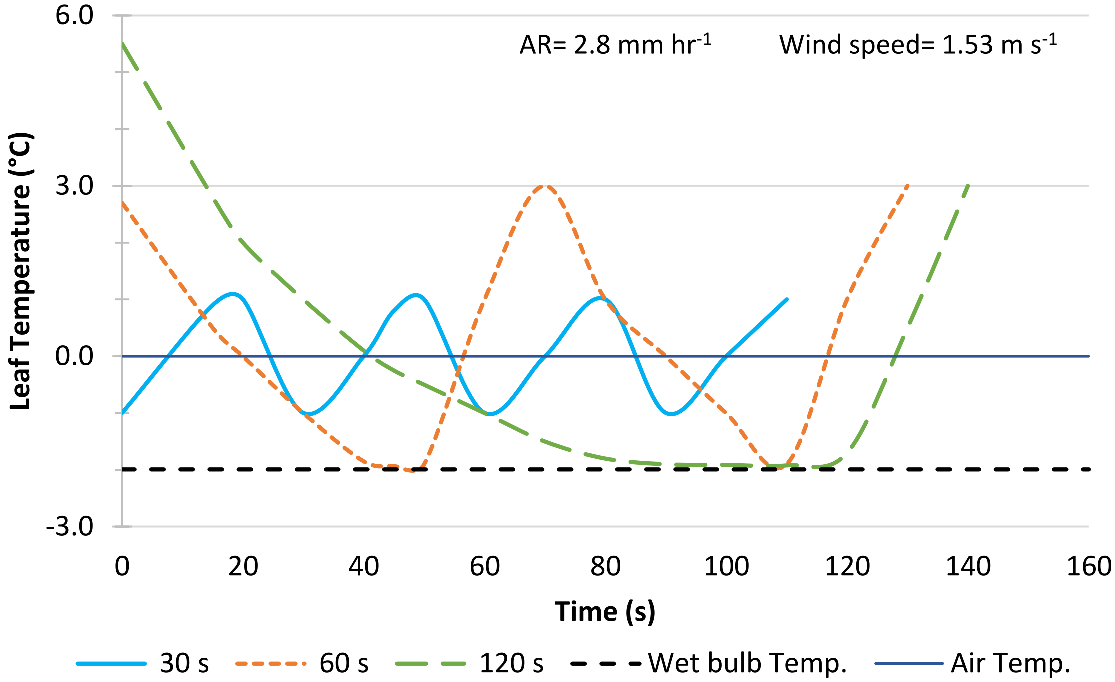

Figure 1-2. Effect of three frequencies of application (120 s, 60 s and 30 s) over leaf temperature using a sprinkler application rate of 2.8 mm hr^{-1} under 1.53 m s^{-1} wind conditions, a wet bulb and air temperatures near -2.0°C and 0°C (Wheaton and Kidder 1965).

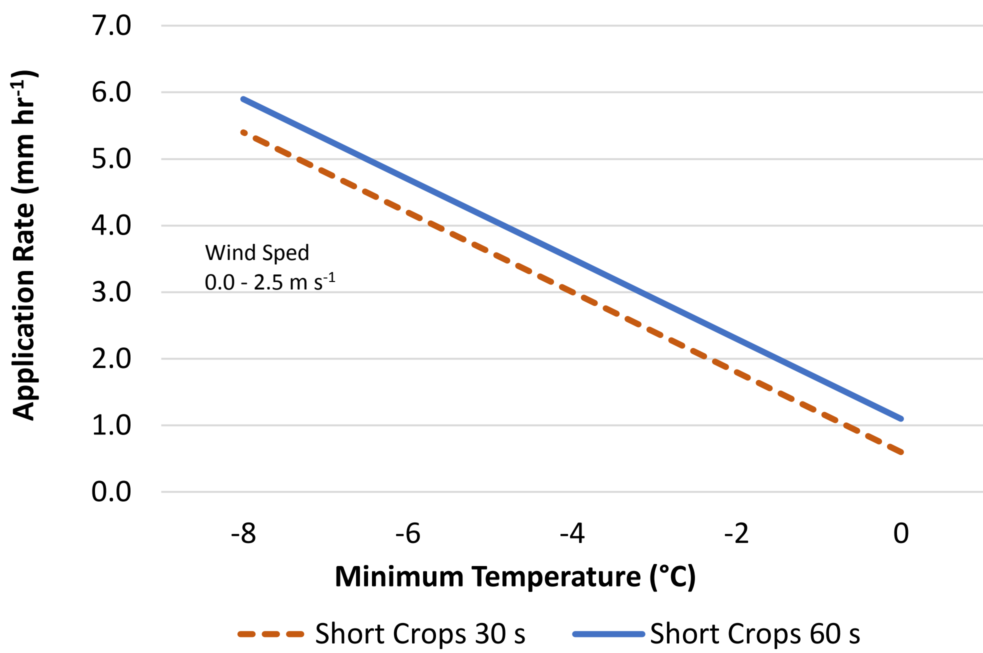

Figure 1-3. Short crops application rates. Over-plant conventional sprinkler application rate requirements for frost protection of short crops with head rotation rates of 30 s and 60 s. Wind speed ranges from 0.0 m s^{-1} at the bottom to 2.5 m s^{-1} at the top (Schultz and Lider 1968; Snyder and de Melo Abreu 2005b).

CHAPTER 2
EFFECT OF SPRINKLER TYPE AND PRESSURE ON IRRIGATION UNIFORMITY

Introduction

Agricultural irrigation has been used since ancient times to meet the crop water needs for evapotranspiration (ET) (Ali 2010a). However, when calculating the amount of water required, other parameters must be considered, e.g. soil and plant type, plant stage of growth and climatic conditions, in order to optimize the irrigation management (Ali 2010a). Irrigation management also depends on the irrigation system characterization, management practices and soil characteristics of the area irrigated.

In Florida, during the strawberry season, water is required for successful establishment; growth and development, system maintenance, chemical delivery (fertigation), and cold protection among others (Albregts and Howard 1984).

When water is applied through irrigation, there are two main issues: how well is the applied water used? And how uniformly is the water distributed to the plants? (Burt et al. 1997b). Therefore, an irrigation system can be evaluated based on two metrics: (i) uniformity and (ii) efficiency (Irrigation Association 2011).

Uniformity. Irrigation distribution uniformity (DU) is a parameter to measure the evenness of water application to a crop over an area, and it is negatively affected when variation increases (Ali 2010b). Generally it is expressed as a decimal; therefore a value of 1.00 would represent an ideal and perfect uniformity, meaning an equal amount of water received at any point within the irrigated area, which is unlikely to occur in reality (Ali 2010b; Irrigation Association 2011). One of the conventional methods to describe irrigation uniformity is the lower quarter distribution uniformity (DU_{lq}), which compares the driest 25% of an irrigated area to the total area. This method is preferred since it is easily measured in the field (Irrigation Association 2011). A table of expected DU_{lq} values according to the sprinkler type used is shown in Table 2-1.Three main components are required in order to achieve high sprinkler uniformity: nozzle type, pressure level according to the selected nozzle, and spacing, based on the two previous components. Uniformity will decrease proportionally if one or more of the elements changes or reduces its optimal performance (Irrigation Association 2011). The distribution of water will depend on the sprinkler nozzle distribution to the soil or crop, and afterward its distribution in the soil profile from the soil surface (Pair 1968).

Therefore, non-uniform sprinkler water applications may result from different sprinkler rotation speeds, diameter changes due to wear, asymmetrical trajectory angle due to non-vertical risers and wind influence over the aerial water distribution (Irrigation Association 2011).

Efficiency. Even when efficiency is related to uniformity, and sometimes both terms are used interchangeably, but are different concepts. When water is applied to crops, the percent of the water applied beneficially used by the plants, is referred as efficiency. Lower efficiency values will be obtained as a result of water unavailability (lack of water at the root zone) or not used (plant water needs satisfied) after its application (Irrigation Association 2011).

Uniformity and efficiency can be affected by different factors, which can be categorized as: irrigation system components (installation, maintenance and repair) and water management human factors (scheduling and timing). Uniformity is associated with the former components, while efficiency is associated with both factors. More factors and the combination influence the efficiency and distribution of water use (e.g. soil, water, plants, irrigation system and scheduling which also are related to the design, installation, maintenance and adequate management of the crop and the irrigation) (Irrigation Association 2011).

Therefore, a combination of these factors: the distribution patterns from adjacent sprinklers, the pressure in the system as well as the nozzle size variation throughout the field influence the sprinkler irrigation DU (Burt et al. 1997b). Some studies have determined wind effects over irrigation distribution uniformity when it exceeds 1.8 – 2 m s^{-1} (Mateos 1998). A non-uniform distribution may result in yield damage due to lack of water, or on the other hand, over-irrigation can occur causing plant injury, water-logging, salinization and chemical transport leading to groundwater pollution (Solomon 1983).

Although high uniformity can be achieved; water applied can be excessive and may cause runoff and deep percolation, resulting in low application efficiency (AE). However, high AE (with minimal under-irrigation) only can be accomplished when (DU) is high (Burt et al. 1997b), reducing consequently, over and underwater areas (Irrigation Association 2011). Hence, maximum efficiency can be achieved when using irrigation systems with adequate design and maintenance that can apply uniform irrigation application (Ali 2010b).

Space Pro for Simulation

Irrigation simulation models had been developed aiming to achieve irrigation system uniformity. This means to minimize the difference among maximum and minimum wetted areas, without irrigating the dry zones, thus, avoiding over-irrigation of the rest areas (Zoldoske 2007).

Irrigation system uniformity is derived from single leg profile tests. These tests consist of an evaluation of the radius of single sprinklers. The application volume or depth values from the sprinkler's radius of throw are measured using equidistant open containers (catch cans) placed one touching each other) starting from the nearest sprinkler head and extending through the sprinkler wetted radius. When these tests are performed, only one sprinkler head is operated during a time enough to collect an average of 12.7 ml of water in the catch cans (Zoldoske 2007).

Sprinkler Profile And Coverage Evaluation (SPACE PRO) is a computer program developed by the Center of Irrigation Technology (CIT) to support irrigation designers in the process of sprinkler and spacing selection (Oliphant 2005).

Using single leg profile tests data, SPACE Pro can "model" sprinklers and spacing design to generate a matrix, simulating a field test developed in a grid pattern (2-1). The catchment spacing of the test and the sprinkler spacing in the irrigation system design will determine the matrix size (Oliphant 2005). This program allows testing the uniformity of irrigation system designs by assessing different spacing designs, sprinkler nozzles and pressure combinations which can be compared in order to define the best efficient design, coverage and lower cost (Oliphant 2005).

SPACE Pro can be an useful tool for growers to implement, in order to select optimum sprinkler type, spacing and pressure, thus achieving higher irrigation uniformity application and potentially reduce yield damage due to over or under irrigation, or deficient sprinkler coverage when used for cold protection.

Over-Head Sprinkler Irrigation for Cold Protection

Low growing crops, such as strawberries, have been effectively protected from cold damage by over-head sprinkler irrigation when a sufficient and uniform application rate (AR) is used. Nevertheless, under high wind conditions or very low temperatures that water application is not enough to provide greater heat than what is lost due to evaporation, and in that case less damage may occur on non- irrigated plants (Snyder and de Melo Abreu 2005c).

Conventional impact sprinklers have been used for cold protection in strawberries; however, these sprinklers are most effective when plants are coated uniformly (Snyder and de Melo Abreu 2005c). A frequency of application no longer than 60 s (Wheaton and Kidder 1965) and a variable application rate according to minimum temperature and wind speed are recommended (Gerber and Martsolf 1965a). Higher application rates (AR) are needed for longer rotation intervals, lower minimum temperatures and higher wind speeds.

AR requirements will depend on variability on conventional rotating, variable rate, or low-volume targeted sprinklers. However, protection will be provided if plants are coated with a liquid-ice mixture and water dripping off the icicles. Cold damage can occur due to insufficient AR or slow rotation rates, so the water may freeze and the temperature from ice-coated plants can get lower than the non-irrigated plants (Snyder and de Melo Abreu 2005c).

The efficiency of sprinkler irrigation is reduced by non-uniform water application. Therefore, in conjunction with uniformity, sprinkler types and irrigation system pressure play an important role in providing high AE which might be reached through lower application rates (Burt et al. 1997b).

Even when pressure, discharge and wetted diameter are the most important parameters to select a specific sprinkler type, some other parameters such as nozzle size, wind, sprinkler overlap and sprinkler rotation speed should be taken in consideration when this decision is made in order to determine the AR, the spacing between sprinklers and the size of water droplets (Parker 2009). Sprinkler overlapping is a parameter to be achieved; therefore, spacing usually is designed in a matter that around 50-60% of the wetted areas overlap (Parker 2009).

In Florida, two main purposes are accomplished by using sprinkler irrigation in strawberry production fields: establishment and cold protection (Albregts and Howard 1984). Strawberry transplant establishment may require 10 to 14 consecutive days of frequent intermittent overhead irrigation, totaling approximately 165 to 247 ha-mm (1 ha-mm~ 10,000 L) (Santos et al. 2010). During both establishment and cold protection, growers generally use impact sprinklers spaced at 14.6 m and a pressure of 345 kPa. However, other impact sprinklers are being used recently by strawberry growers: Nelson F32 at 14.6 m spacing and Rain Bird L20 at 12.2 m spacing. As well as two sprinkler rotators: Nelson R33 and Nelson R2000WF with 14.6 m and 12.2 m sprinkler spacing, respectively, are being used lately for the same purposes in strawberries (Whidden 2013).

The optimum recommendations for highest survival rate and lowest amount of water were determined by evaluating controlled irrigation settings to protect crops under cold conditions. A two-phased approach was implemented for the whole study and this chapter corresponds to the first phase accomplished.

DU_{lq} tests were performed in order to potentially maximize crop yield and efficiently use the available water supplies. The objective of this experiment was to evaluate the effect of sprinkler type, sprinkler spacing, pressure variation in the water supply line and varied wind conditions on irrigation distribution uniformity and application rate.

Materials and Methods

In order to replicate Florida grower irrigation practices for cold protection in strawberries, one conventional impact sprinkler (WR-32) and three rotator types (Nelson R33, Nelson R33LP, Nelson R2000WF) were tested using two sprinkler spacings (14.6m and 12.2 m) and three irrigation pressure levels (345, 276 and 207 kPa) under variable wind conditions. The most likely sprinkler used by the strawberry growers (WR-32) under the conditions generally performed (345 kPa and 14.6 m sprinkler spacing) was evaluated at two locations (Citra and Hastings); and the results were analyzed for the specific location separately. Details are described as follows:

Uniformity Testing Analysis

The measure of how uniform irrigation water is distributed to different areas in the field is defined as DU This term is generally defined as a ratio of the average of the smallest accumulated depths in the distribution (DU_{lq}), to the average depth accumulated in all the elements ($DU_{total\ avg}$) (Burt et al. 1997b). The fraction defined for the formula could vary; however, the lowest quarter (1/4) depth (DU_{lq}) has been used by the USDA NRCS since 1940's and had shown practical results when used in agriculture irrigation (ASCE 1978).

DU_{lq}, is a ratio defined by the following formula (Merriam and Keller 1978):

$$DU_{lq} = \frac{\overline{D_{lq}}}{\overline{D_{tot}}} \qquad (2\text{-}1)$$

Where:
$\overline{D_{lq}}$: Average of the lowest quarter of catch can measurements (mL).

$\overline{D_{tot}}$: Average depth of application over all catch cans measurements (mL).

DU_{lq} tests were performed at two University of Florida, Institute of Food and Agricultural Sciences (UF-IFAS) facilities. Initial tests were performed from March 10 until May 26, 2011 at Cowpen Branch Facility located near Hastings, Florida; however, most tests were completed within the period June 2011 until May 2013 at the Plant Science Research and Education Unit (PSREU) near Citra, Florida. Two overhead sprinkler systems were setup at 14.6 and 12.2 m sprinkler spacing and discharge was measured for uniformity under three different operating pressures and variable wind conditions.

Sprinklers

A visit to strawberry farmers at Hillsborough, FL. was done in April 2011 with the aim to investigate the types of sprinklers, spacing and pressure used to protect their crops. In accordance with this visit, it was concluded to evaluate four types of sprinklers in order to replicate the most common grower irrigation practices for cold protection in strawberries. Among them the sprinkler traditionally used by growers was evaluated: Wade Rain WR-32 brass impact sprinkler aluminum arm with 3.6 mm nozzles for low volume applications (Wade Rain Inc. 2007), and also three Nelson rotators: R33 and R33LP (low pressure model) both using 3.6 mm nozzles (Nelson Irrigation Corporation 2003) and Nelson R2000WF(Nelson Irrigation Corporation 2009) with 3.18 mm nozzle and a purple diffuser. At the Cowpen Branch Facility located near Hastings, only the WR-32 impact sprinklers were tested, while at PSREU, near Citra, all sprinklers were evaluated (Table 2-2).

Collectors and Spacing

The distribution uniformity of the sprinkler irrigation system was tested using plastic collectors, usually referred as “catch-cans”, to measure the depth of water applied after an irrigation event (2-2). The sprinkler types were evaluated under two different spacings: 14.6 m by 14.6 m, being this the more used spacing by strawberry growers and 12.2 m by 12.2 m (2-3), being close to the manufacturer recommended spacing in order to achieve optimum overlapping. Two uniformity testing areas were established which consisted of seven lines of plastic collectors, seven collectors per line, totaling 49 collectors per test. The catch cans of approximately 20 cm diameter, and 16 cm tall were spaced uniformly along the straight lines forming an equally spaced grid. The collector spacing along each line was 1.8 m when the 14.6 m sprinkler spacing was tested, and 1.5 m collector spacing when the 12.2 m sprinkler spacing was evaluated (2-3).

Irrigation System Supply Pressure

In order to test the recommended cold protection application rate of 6.35 mm hr^{-1}, tests were performed under different pressures during one hour irrigation event, time enough to collect the minimum volume of water recommended for cold protection. A control valve was manually operated and a pressure regulator series 25AUB-Z3 and LF25AUB-Z3 ½” -2” (Watts Regulator Co. 2009) was used to keep the pressure under steady conditions (2-4). This pressure regulator was adjusted according to the pressure to be assessed (345, 276 or 207 kPa).

Prior the test, the pressure desired was specified as 345, 276 or 207 kPa. According to the pressure under evaluation, Senninger pressure regulators (Senninger Irrigation Inc. 2010) and pressure gauges were placed at the bottom of each sprinkler head, in order to keep the pressure stable and monitor it at the beginning and at the end of the test (2-5). Graduated cylinders (250 ml) were used to measure catch-can volumes.

Irrigation Simulation Using SPACE Pro

Single leg profile tests. These tests consist of the evaluation of a single sprinkler application volume values, which can be measured using catch cans, in order to obtain water application profiles along one or more radial leg. Therefore, for this experiment, the catch cans were placed next to each other, starting from the sprinkler head and extending beyond the sprinkler wetted radius of throw. During a one hour test duration, only one sprinkler was operated in order to capture the volume of water applied. Generally, the sprinkler water application rate defines the duration of the test; however, a minimum reading of 3 mm in the driest catch can is recommended (ASAE 1985). Once the profile tests were finished, the data was input into SPACE Pro to perform the simulations and obtain the uniformity profiles. The tests were executed in order to simulate the sprinkler type performance at three different pressures (345, 276 and 207 kPa), two nozzle types (3.6 and 3.18 mm) and two sprinkler spacings (12.2 m and 14.6 m).

Using the data from the single leg profile tests, the program measures the distance from the sprinkler head to each catch can and look up in the profile the application rate (AR) at that distance, filling a grid using the ‘Pythagoras theorem’. This theorem relates the three sides of a right triangle and states that the square of the hypotenuse (the side opposite to the right angle) is equal to the sum of squares of the two other sides. Therefore, using this theorem, SPACE Pro squares and sums the looked up volume values (from the single leg profile tests) at the distances where the catch cans are from the sprinkler head, and finally takes the square root of them to obtain the AR for that specific catch can (i.e. the hypotenuse). These calculations are performed in the program filling a grid for the total area irrigated, which can be shown as a densogram.

Calculations. SPACE Pro calculates: Christiansen's coefficient of uniformity (CU), DU_{lq}, AR, and scheduling coefficient, which normally is based on 1% of the covered area (Oliphant 2005).

Densograms. A densogram is a pattern of dots showing the irrigation coverage resulting from the combination of sprinklers, nozzles, pressure and spacing (Solomon 1988). The densograms and scheduling coefficient are SPACE Pro tools provided with the aim of testing sprinklers systems designs and solving potential problems before being installed. These tools provide a preview of irrigation using specific sprinkler types and spacing combinations (Solomon 1988).

For this study, an experiment was conducted in order to simulate full-field sprinkler irrigation uniformity obtaining water distribution profiles at three pressure levels and two sprinkler spacings of two different sprinkler types: WR-32 impact sprinklers and Nelson R33 rotator sprinklers. Single leg sprinkler profile tests were performed at PSREU, near Citra under near no –wind conditions to avoid measurement distortions. SPACE Pro was used to simulate the DU_{lq} and AR using the data from single leg sprinkler profile tests described previously.

Data Analysis

At two different UF-IFAS facilities, two main response variables were analyzed:

- Low quarter distribution uniformity (DU_{lq})
- Application rate (AR)

These response variables were analyzed in a three factorial experiment with different sprinkler types, pressures and spacings. Data recording for the different treatments resulted in unequal sample sizes. The GLM procedure of Minitab® was used to compute the ANOVA for unequal sample sizes, the adjusted least square means and their corresponding standard error (SE) (Minitab Inc. 2013). In most cases, the H_0 was rejected for the first order interaction, so the specific treatment means had to be compared using the Bonferroni simultaneous multiple comparison procedure. Also to test the differences between treatment main effects the LSD according to Bonferroni (LSD_{Bon}) was applied. This comparison was performed using the 95% CI based on their specific SE. In order to reduce the error variation (MS-Error) the wind speed (m s^{-1}) as a co-variable was recorded. This co-variable was always highly significant and contributed so to significant shorter CI's i.e. higher detection rate of significant differences between means. DU_{lq} and AR results are presented in this document.

Results and Discussion

A total of 339 catch can tests were conducted under a variety of wind conditions at the two locations. Due to the variability present at the test locations, separate analyses were performed for PSREU and Cowpen Branch UF-IFAS facilities, respectively. The former shows the comparison between four sprinkler types, two sprinkler spacings, and three irrigation system pressures tested at Citra, FL; while the latter analysis evaluated only the WR-32 impact sprinklers 14.6 m spaced, (sprinkler type and spacing conditions more likely used by strawberry growers in Florida) evaluated at the three different irrigation system pressures (345, 276 and 207 kPa) at Hastings, FL. The procedure of LSD_{Bon} was applied for main treatment mean comparisons.

Wind Conditions

With the aim of replicate strawberry producer's cold protection practices, in which wind conditions are unpredictable, DU_{lq} tests were conducted under different wind conditions from nearly no wind (min avg. 0.2 m s^{-1}) to high wind speed conditions (max. avg. 7.2 m s^{-1}) in a few tests. However, the overall average wind speed during the tests was 2.7 m s^{-1}. A FAWN weather station located on site was used to monitor wind speed at 10 m height, giving an output average every 15 minutes. Wind conditions were categorized as low < 1.73 m s^{-1}, medium 1.74 to 3.53 m s^{-1} and high > 3.53 m s^{-1}. However, quantitative wind measurements (m s^{-1}) were included in the ANOVA analysis as a covariate.

Sprinkler Irrigation Uniformity Testing (DU_{lq})

Citra

A total of 297 catch can tests were evaluated at PSREU, near Citra, FL from Jun. 2011 to May 2013. During the catch can tests performed, the average wind speed ranged between 1.74 to 3.53 m s^{-1} being categorized as medium wind speed conditions (Table 2-3, Table 2-4). Among the four sprinklers when 14.6 m sprinkler spacing was used over the three pressure levels, maximum and minimum DU_{lq} was 0.89 and 0.49, respectively (Table 2-3), while 12.2 m sprinkler spacing yielded respective maximum and minimum DU_{lq} of 0.90 and 0.43 under medium wind speed conditions (Table 2-4). Overall average DU_{lq} was 0.73 and 0.76 for 14.6 m and 12.2 m sprinkler spacing; respectively under medium wind speed conditions (1.74 to 3.53 m s^{-1}) (Table 2-3, Table 2-4).

Irrigation low quarter distribution uniformity tests (DU_{lq}) were significantly influenced by wind speed (Table 2-5). Furthermore, the interactions among factors:

sprinkler-pressure, sprinkler-spacing, and pressure-spacing resulted in a statistically significant effect on uniformity (Table 2-5) and are explained as follows:

Sprinkler type-pressure interaction. The interaction among sprinkler and pressure resulted in a significant effect on DU_{lq} (2-7). The four sprinklers tested under three irrigation supply pressures resulted in five different statistical groups. The two highest DU_{lq} values were achieved by Nelson R2000WF at 345 kPa and at 276 kPa under low wind conditions (DU_{lq}= 0.81 for both conditions), followed by WR-32 at the same pressures under medium wind conditions (DU_{lq}= 0.80 and 0.79, accordingly). High DU_{lq} values were achieved by Nelson R33LP (DU_{lq}= 0.79) and R33 (DU_{lq}= 0.77) only at the 345 kPa pressure. No significant differences were present among any of these sprinkler-pressure interactions and neither between those sprinkler types and pressures. However, significantly lower distribution uniformity resulted when using WR-32 and Nelson R2000WF at 207 kPa irrigation system pressure versus the same sprinklers evaluated under higher pressures. Nelson R33 at 276 kPa resulted in significantly lower uniformity (DU_{lq}= 0.70) than the sprinklers previously described, but significantly higher than Nelson R33LP and R33 when used at the lowest pressure (DU_{lq}= 0.66 and 0.61, respectively). The lowest Du_{lq} was obtained by the Nelson R33 when a 207 kPa irrigation system pressure was tested, which is not surprising, since this sprinkler should be used under higher pressures according to manufacturer recommendations (Table 2-2).

Comparing the sprinkler types separately under each pressure, all the sprinkler types achieved the highest low quarter distribution uniformity (DU_{lq}) values when using the highest pressure (345 kPa), and vice versa, also obtained the lowest DU_{lq} values when tested under the lowest pressure (207 kPa) (2-6). Highest pressures (345 and 276 kPa) were significantly different versus the lowest pressure (207 kPa) within each sprinkler type. However, no significant differences were found when the two highest pressures were compared among them for all the sprinkler types, with the exception of the R33 sprinkler rotator. The effect of the sprinkler Nelson R33 and variable pressures resulted in significantly different DU_{lq} values at each pressure level, obtaining the lowest DU_{lq} among the sprinklers at 207 kPa pressure.

Sprinkler type-sprinkler spacing interaction. The sprinkler type -spacing interaction resulted in a significant effect on distribution uniformity (2-7). The highest DU_{lq} was achieved by the impact sprinkler WR-32 at 12.2 m sprinkler spacing, followed by the rotator Nelson R2000WF using the same spacing (DUl_q= 0.81 for both). Likewise, the effect of spacing over uniformity was not significant when using the R2000WF, which reached a similar irrigation uniformity at the two sprinkler spacings (DUl_q= 0.76 and 0.81, respectively). This same pattern was followed by the Nelson rotator sprinklers, which did not differ significantly when tested under different sprinkler spacing. Nevertheless, this was not the case of the WR-32 impact sprinkler, which resulted in significantly higher DU_{lq} at 12.2 m versus 14.6 m spacing (DUl_q= 0.81 versus 0.74) (2-7).

However, when a comparison among the sprinkler types at each spacing is performed, significant differences among them are present in some cases (2-7). At the 12.2 m spacing, WR-32 and R2000WF (DU_{lq}= 0.81 and 0.81) were significantly higher on uniformity than the Nelsons R33LP and R33 (DU_{lq}= 0.74 and 0.68), the latter representing the lowest overall uniformity value. When the sprinkler types were performed under 14.6 m spacing, a similar uniformity pattern was more likely to occur, where the R2000WF and the WR-32 obtained the highest DUlq values (DU_{lq}= 0.76 and 0.74), but only the former obtained a significantly higher uniformity than the rest of the sprinklers (DUl_q R33LP= 0.72 and R33= 0.70) (2-7).

Irrigation system pressure-sprinkler spacing interaction. Significant effect over distribution uniformity resulted from the irrigation system pressure and sprinkler spacing interaction (2-8). When the irrigation system pressure was 345 kPa, the highest uniformity values were obtained at either sprinkler spacing (DU_{lq} 0.80 and 0.80). However, when the irrigation system pressure was reduced to 276 kPa and at a sprinkler spacing of 12.2 m DU_{lq} of 0.78 was not statistically different. In contrast, when the sprinkler spacing was increased to 14.6 m, DU_{lq} was significantly lower (0.74). The same trend occurred at the lowest irrigation system pressure (207 kPa), which differs statistically when the sprinkler spacing is increased to 14.6 m (DU_{lq} at 12.2 m= 0.71 versus 14.6 m= 0.66), these being the lowest overall uniformity values (2-8).

Hastings

At the Cowpen Branch UF/IFAS facility, near Hastings, at total of 50 DU_{lq} tests were performed within the period of March- May 2011. These tests only evaluated the impact sprinklers WR-32 at 14.6 m sprinkler spacing under three irrigation supply pressures (345, 276 and 207 kPa). Generally, wind conditions predominant during the tests performed at Hastings were high (> 3.53 m s^{-1}). The sprinkler type and sprinkler spacing were chosen intended to mimic strawberry grower’s practices in open fields where high wind conditions are common.

A comparison among DU_{lq} values obtained at Hastings was performed versus the results acquired at PSREU, near Citra by using the same sprinkler type, pressure levels and spacing settings (Table 2-6).

Irrigation system pressure-location interaction. The results from the interaction among the pressure and location caused a significant effect on distribution uniformity (2-9). The highest mean uniformity value (DU_{lq}= 0.75) was achieved when 345 kPa was used as irrigation pressure supply at the PSREU, Citra, presenting significantly higher differences when compared to 207 kPa at Hastings and Citra (DU_{lq}= 0.66 and 0.63, accordingly). Higher DU_{lq} values were obtained under higher pressure levels. However, when using the highest pressure (345 kPa) at Hastings, distribution uniformity was lower than the DU_{lq} value obtained when decreasing the irrigation pressure to 276 kPa at Hastings (DU_{lq}= 0.68 and 0.71, correspondingly). Nevertheless, differences were not significant when this interaction was compared to the three pressure levels at Hastings (DU_{lq} at 345 kPa= 0.68, 276 kPa= 0.71 and 207 kPa= 0.66), or when it was compared to 276 kPa at Citra (DU_{lq}= 0.69) (2-9). A similar pattern was followed when the pressure was set on 276 and 207 kPa at the two locations, where none of those interactions resulted in significant effects on uniformity.

Wind Speed. During the catch can tests performed at Hastings, the average wind speed ranged between 5.15 and 4.59 m s^{-1} being categorized as “high” wind speed conditions, while in Citra the wind conditions prevailed into the “medium” category which presented speed conditions lower than 2.31 m s^{-1} on average (Table 2-6). The maximum DU_{lq} value was obtained when using the highest pressure (345 kPa) under medium wind conditions at Citra; while the lowest DU_{lq} value was obtained when using the same pressure under high wind speed conditions at Hastings (Table 2-6). Wind speed, which was included as a co-variable, resulted in high significant effect on distribution uniformity (Table 2-7; 2-10).

Application Rate (AR)

Water application rates (AR) were evaluated at the two different locations (Citra and Hastings), using three irrigation supply system pressures (345, 276 and 207 kPa) and two sprinkler spacings (14.6 m and 12.2 m). Results from the two locations are explained in the following section.

Citra

Overall average application rates using four sprinklers types and three pressure levels were 2.9 mm hr^{-1} for the 14.6 m sprinkler spacing and 4.5 mm hr^{-1} when 12.2 m spacing was evaluated (Table 2-3, Table 2-4). Therefore, a 55.2% overall increase in the application rate resulted as an effect of shortening the sprinkler spacing. It was determined through an ANOVA that the wind speed (as co-variable) and the interactions among factors: sprinkler-pressure, sprinkler-spacing and pressure-spacing resulted in a statistically significant effect over application rate when evaluated at the PSREU, near Citra, FL (Table 2-8). Each interaction is described as follows:

Sprinkler type-irrigation system pressure interaction. The mean application rates, as a result of the pressure levels and sprinkler types interactions, varied almost 50% in some of the cases. The AR means ranged between a minimum of 2.3 mm hr^{-1} when using the rotator sprinkler R2000WF at 276 kPa, to a maximum of 4.7 mm hr^{-1} applied by R33LP at a 345 kPa system pressure. The rotators R33 and R33LP produced the highest water application rates at a pressure of 345 kPa and then at 276 kPa (AR= 4.6, 4.5, 4.2 and 4.1 mm hr^{-1}, respectively), without significant differences among them (2-11). Both sprinkler types applied lower water rates when using the higher pressures than the recommended by the manufacturer (Table 2-2).

The impact sprinkler WR-32 using the highest pressure did not differ significantly on water application rate (AR= 4.0 mm hr^{-1}) from the previous rotators when both were performed at 276 kPa (2-11). However, it was lower than the recommendation at 345 kPa (i.e. 5.5 mm hr^{-1} at 13.0 sprinkler spacing; Table 2-2). A similar pattern occurred comparing the WR-32 application rate of 3.5 mm hr^{-1} at 276 kPa system pressure, and the 3.2 and 3.0 mm hr^{-1} AR of the rotators R33LP and R33 at 207 kPa pressure, without statistical differences between them (2-11). All these AR were lower than the recommended AR (when applicable). The AR values by using R33 at 207 kPa pressure might be as a result of not recommendations applicable for this sprinkler at low pressure levels (Table 2-2).

The lowest mean application rate was obtained by the R2000WF sprinkler performed under the three pressure levels (345 kPa= 2.9, 276 kPa= 2.3 and 207 kPa= 2.5 mm hr^{-1}). The R2000WF evaluated at 276 and 207 kPa obtained statistically lower water AR than the rest of the sprinkler types at the three pressure levels (Fig 2-11). The results at 207 kPa are not surprising since not recommendations have been developed for this sprinkler at the lowest pressure level evaluated at the experiment (Table 2-2).

Sprinkler type-sprinkler spacing interaction. Variations on sprinkler type and spacing leaded to statistical differences in application rate. A value of 5.1 mm hr^{-1} was the highest mean AR acquired by R33LP sprinkler at 12.2 m spacing, which resulted significantly different from the other sprinkler-spacing interactions. However, this AR value is close to the lower limit for low pressure applications range recommended by the manufacturer; this meaning that higher application rates could be reached if it is used on higher pressures (e.g. 5.6 mm hr^{-1} at 345 kPa 12.8 m spacing; Table 2-2).

Similar mean water application rate values were obtained by the Nelsons R33 and R33LP performed at 14.6 m spacing (AR= 3.3 mm hr^{-1} for both sprinklers); however, statistically different AR were obtained when 12.2 m spacing was used (AR= 4.7 and 5.1 mm $hr^{-1}$for R33 and R33LP, respectively; 2-12). Thus, application rates were more likely to follow the manufacture recommendations achieving similar ARs when using the lower spacing for these two sprinkler types.

The impact sprinkler WR-32 mean application rates were 2.6 and 4.4 mm hr^{-1} using 14.6 m and 12.2 m spacing (2-12). These results showed lower AR than the manufacturer recommendations; however, when using the 12.2 m sprinkler spacing similar results could be obtained at the lowest pressure level (e.g. 4.7 mm hr^{-1} at 207 kPa, 12.3 m spacing; Table 2-2).

Thus, the Nelson R33, R33LP and impact WR-32 sprinklers obtained 30%, 33% and 40% increase in mean application rate when the sprinkler spacing was reduced from 14.6 m to 12.2 m. All of them were statistically different within and among sprinkler types. However, this was not the case for the R2000WF rotator, which obtained AR of 2.4 and 2.7 mm hr^{-1} (at 14.6 m and 12.2 m spacings, accordingly); not presenting statistical differences between them. The rotator R2000WF obtained an AR of 2.4 mm hr^{-1} at 14.6 m spacing representing the lowest AR versus the rest of the sprinkler-spacing interactions (2-12). Also, it is important to note that AR values at 14.6 m may be as a consequence that there are not recommendations applicable for this sprinkler at large spacing (Table 2-2).

Irrigation system pressure-sprinkler spacing interaction. Significantly higher water application rates were obtained when the 12.2 m sprinkler spacing was used compared to the 14.6 m spacing among all pressure levels. Reducing the sprinkler spacing to 12.2 m, resulted in an AR increase of 30%, 30% and 33% when evaluated at the three irrigation pressure levels 207, 276 and 345 kPa, correspondingly (2-13).

The highest application rate was obtained using the highest pressure level at the shortest sprinkler spacing, this being an AR of 4.8 mm hr^{-1} using 345 kPa at 12.2 m spacing, which was statistically different from the rest of interactions. The succeeding highest ARs were obtained using the reduced sprinkler spacing of 12.2 m at 276 kPa followed by 207 kPa (AR= 4.1 and 3.7 mm hr^{-1}). Lower application rates were achieved when a large distance among sprinklers was used. Mean application rates of 3.2, 3.0 and 2.6 mm hr^{-1} were obtained at 345, 276 and 207 kPa (2-13).

All the irrigation system pressure-sprinkler spacing interactions were significantly different from each other, with the exception of the 345 and 276 kPa pressures at 14.6 m sprinkler spacing, which did not differ significantly. The lowest application rate was obtained by using the lowest irrigation system pressure at the larger spacing among sprinklers (2-13).

Hastings

At the Cowpen Branch facility, near Hastings only the impact sprinklers WR-32 spaced 14.6 m at three pressure levels (345, 276 and 207 kPa) were evaluated. A comparison was performed with the results achieved at the PSREU, near Citra with the same irrigation settings.

The highest mean water application rate was obtained using 345 kPa system pressure (AR= 3.1 mm hr^{-1}) at Hastings. However, this AR differed from the mean rate obtained from using the same sprinkler type and pressure level at Citra (AR= 2.9 mm hr^{-1}). A significantly lower AR was obtained at Citra when the highest pressure was performed. Nevertheless, only this application rate was significantly different using the same settings when evaluated at the two locations (2-14).

Evaluating the 276 kPa pressure level at both facilities resulted in a mean AR of 2.9 mm hr^{-1} at Hastings and 2.7 mm hr^{-1} at Citra, and when the lowest pressure level was tested, mean AR of 2.2 mm hr^{-1} for both locations were obtained. Thus, equal pressure levels (276 and 207 kPa) evaluated at both locations did not differ significantly. Statistical differences were only found only when pressure levels were compared within them (2-14).

Space Pro Results

Uniformity profiles were simulated using SPACE Pro for two sprinkler types: WR-32 impact sprinklers and Nelson R33 rotator sprinklers. A comparison among sprinkler types was performed at the three pressure levels and two sprinkler spacings (Table 2-9, 2-15). Data from sprinkler single leg profile tests was input into the program previously described in order to develop distribution profile simulations for both sprinkler types. In order to describe the results from this section, a comparison was performed among individual sets of data, which are called treatments for this results section. The treatments evaluated consisted of: (i) Field data evaluated at PSREU, Citra and (ii) simulated data using SPACE Pro. The relationships between distribution uniformity and application rate at different sprinkler types, pressures, spacings and pressure variations were evaluated at Citra and simulated using SPACE Pro and are described as follows:

Distribution Uniformity (DU_{lq})

WR-32 sprinklers. The interaction spacing- treatment caused a significant effect on WR-32 distribution uniformity, as well as the irrigation system pressure on uniformity.

WR-32 sprinklers SPACE Pro simulations vs. field data. Significantly higher DU_{lq} values were obtained at 345 kPa using a 14.6 m spacing and at 276 kPa using 12.2 m spacing both evaluated at Citra (DU_{lq}= 0.87 and 0.85, respectively). As well, significantly higher DU_{lq} values were obtained when WR-32 sprinkler's uniformity was simulated using SPACE Pro at 345 kPa and 12.2 m spacing (DU_{lq}= 0.84) in comparison to the two lowest pressures (276 and 207 kPa) performed in both treatments at 14.6 m sprinkler spacing. No statistically differences were present between the treatments when WR-32 was compared at 12.2 m spacing and the same pressure level (DU_{lq} = 0.84, 0.83, 0.77 at 345, 276 and 207 kPa for SPACE Pro and DU_{lq}= 0.83, 0.85 and 0.75 for the same pressure levels evaluated at Citra). However, WR-32 SPACE Pro simulations at 14.6 m sprinkler spacing resulted in significantly lower DU_{lq} values of 0.66, 0.64 and 0.58 when evaluated at 345, 276 and 207 kPa, accordingly. In comparison, the field data resulted in DU_{lq} values of 0.87, 084 and 0.77 evaluated at the same spacing and pressure levels respectively. By instance, the simulations at 14.6 m in SPACE Pro were the lowest DU_{lq} values obtained across all the spacings settings and pressure levels at the two treatments (modeled and observed data) (Table 2-9, 2-15).

WR-32 distribution uniformity was statistically influenced by the irrigation system pressure supply. The results showed significantly higher DU_{lq} values as the pressure level increased, following the same pattern as the field data results (Table 2-9, 2-15). No significant differences were present between the SPACE Pro data and the field data among the two highest pressures and at the two sprinkler spacings, except for the data simulated at 14.6 m spacing which presented very low DU_{lq} at the three pressure levels. However, significantly lower DU_{lq} values were obtained when the lowest pressure was evaluated throughout the simulations and field assessments. The overall significantly lowest uniformity values were obtained throughout simulations in SPACE Pro using the 276 and 207 kPa pressure levels and 14.6 m spacing (Fig. 2-15).

SPACE Pro simulations using WR-32 sprinklers at varied factors. WR-32 distribution uniformity increased on average 30% at all the three pressure levels when the spacing among sprinklers was reduced to 12.2 m. Average DU_{lq} values were 0.84, 0.83 and 0.77 at the pressures 345, 276 and 207 kPa; respectively (Table 2-9; 2-15). These results also showed that very similar distribution uniformity values can be achieved when the highest pressure levels are used, but uniformity may be reduced by 8% if the lowest pressure (207 kPa) is used.

Higher DU_{lq} values achieved at 12.2 m sprinkler spacing might be attributable because a better overlapping among the sprinklers is achieved since the shorter sprinkler spacing is close to the manufacturer recommendations, in which a sprinkler spacing within 13.0 m and 12.3 m should be used at the highest and the lowest pressures under evaluation; respectively (Table 2-2). A comparison of WR-32 sprinklers evaluated at the three pressure levels at the two spacings was performed and is shown in 2-16.

WR-32 impact sprinklers simulated at 14.6 m spacing (2-16 A, C, E) showed the lowest water application values in the center area between the sprinklers (2-16 red square), demonstrating a possible lack of sprinkler overlapping even when the highest pressure was performed (2-16 A). Low DU_{lq} values might resulted since the sprinkler spacing recommendation ranges from 13.0 m to 12.3 m for high and low pressure; respectively, both values being below the 14.6 m sprinkler spacing tested.

However, when the sprinkler spacing was lowered to 12.2 m (2-16 B, D, F), which is closer to the manufacturer recommendations, distribution uniformity values increased and sprinkler overlapping occurred. The only exception was when the lowest pressure was performed, which presented the highest water values concentrated in the center area (green square) resulting in overall lower uniformity (DU_{lq}= 0.77) compared to the highest pressures (DU_{lq}= 0.84, 83 for 345 and 276 kPa, respectively) (2-16 F). Nevertheless, no significant differences in uniformity were present between any of those pressure levels when using the 12.2 m sprinkler spacing.

Nelson R33 sprinklers. Using R33 sprinkler significant differences on DU_{lq} were present between the treatments (SPACE Pro and field data) and also among the pressure levels (Table 2-10; 2-15).

Nelson R33 SPACE Pro simulations vs. field data. Field data resulted in significantly higher uniformity values in comparison to SPACE Pro simulations only when evaluated at 207 kPa pressure level at both spacings. The highest overall DU_{lq} value was obtained at the highest pressure and larger spacing evaluated at Citra (DU_{lq} =0.80 at 345 kPa and 14.6 m spacing). However, no significant differences were found when it was compared to the two highest pressures at both spacings evaluated at Citra (DU_{lq}= 0.75 at 345 kPa 12.2 m spacing, DU_{lq}= 0.72, 0.70 at 276 kPa evaluated at 12.2 m and 14.6 m spacings evaluated at Citra), neither compared to SPACE Pro simulations at 345 kPa for both spacing (DU_{lq}= 0.70 and 0.68 at 14.6 m and 12.2 m spacing, respectively) (Fig. 2-15).

Irrigation system pressure influenced uniformity, as significantly lower uniformity values were obtained under lower pressure levels evaluated. The DU_{lq} values obtained at 207 kPa pressure were significantly lower (DU_{lq}= 0.64, 0.63, at 12.2m and 14.6m performed at Citra, and DU_{lq}= 0.50 and 0.47 SPACE Pro simulations at the same spacings) than the uniformity values obtained at any higher pressures performed in the field (Table 2-10; 2-15).

R33 uniformity tested at Citra at the two highest pressures and two spacings (DU_{lq}= 0.80, 0.75 at 345 kPa 14.6 m and 12.2 m, DU_{lq}= 0.72, 0.70, at 276 kPa at 12.2 m and 14.6 m spacings) did not differ from the simulated data input using the same pressure levels and spacing settings (DU_{lq}= 0.70, 0.68 at 345 at 14.6 m and 12.2 m, accordingly; and DU_{lq}= 0.64 SPACE Pro at 276 kPa at 12.2 m spacing). The only exception was the SPACE Pro simulation using 276 kPa at 14.6 m sprinkler spacing, which presented significantly lower DU_{lq} values (DU_{lq}= 0.57) than the field assessments. Nevertheless, when the lowest pressure was tested, significantly lower DU_{lq} values were obtained throughout SPACE Pro at 14.6 m and 12.2 m spacings (DU_{lq}= 0.47 and 0.50, respectively) versus the field data measured at the two sprinkler spacings (DU_{lq}= 0.63 and 0.64, accordingly). These simulated outcomes were the lowest DU_{lq} values obtained across the three pressure levels and two sprinkler spacings for Nelson R33 sprinkler (Table 2-10; 2-15).

SPACE Pro simulations using Nelson R33 sprinklers at varied factors. Distribution uniformity values obtained by Nelson R33 spaced 14.6 m with a pressure level of 345 kPa resulted 6% higher than WR-32 DU_{lq} values at the same spacing and pressure settings (DU_{lq} R33= 0.70 and WR-32= 0.66). By contrast, when R33 was simulated using 276 and 207 kPa pressure levels, the uniformity was reduced in 11.3% and 19.0% (DU_{lq} = 0.58 and 0.47), accordingly, compared to the impact sprinklers. The lowest uniformity (DU_{lq}= 0.47) was obtained when the lowest pressure was simulated, not surprising results since no manufacturer recommendations exist for this sprinkler at pressures below 276 kPa (Table 2-2).

When Nelson R33 sprinklers were simulated at 12.2 m spacing, overall DU_{lq} values were 0.68, 0.64 and 0.50 at the 345, 276 and 207 kPa pressure levels (Table 2-10). Higher uniformity values were obtained at higher pressure levels. Alike DU_{lq} values were achieved when the simulations were performed at the two highest pressures without significant differences among them, and by contrast, and significantly lower DU_{lq} values resulted under the lowest pressure. Also, R33 at 12.2 m spacing showed similar values to the WR-32 performed at 14.6 m spacing. It is important to note that when reducing the sprinkler spacing, the R33 simulated DU_{lq} increased about 12.3% and 6.3% only at 276 and 207 kPa pressures, and by contrast, reduction of 2.9% in uniformity was obtained when 345 kPa pressure level was used. These outcomes possibly resulted since the sprinkler spacing recommended for the Nelson R33 is 13.1 m; thus, low uniformity values are expected if spacings below this value are used (Table 2-2).

Nelson R33 densograms simulations performed at three pressure levels and two sprinkler spacings using SPACE Pro are shown in 2-16. The results from this sprinkler simulated at 345 kPa pressure level and spaced 14.6 m, showed that the region receiving the lowest water applications was located in the center area between the sprinklers (2-17 A red square). While as lower irrigation system pressures were simulated, the distribution uniformity values were reduced, showing more color diversification among the densograms (2-17 A, C, E). When shorter sprinkler spacing was simulated, similar overall uniformity values were obtained at the two highest pressure levels (DU_{lq}= 0.68 and 0.64 at 345 and 276 kPa, 2-16 B, D). However, this was not the case when the lowest pressure level was simulated, which obtained on average 24.2% lower DU_{lq} values than the two higher pressures (Table 2-9, 2-17 F).

Thus, these outcomes might be the result from exceeding or not reaching the recommendations, since the spacings under evaluation were higher or lower (14.6 m and 12.2 m) than the range recommended by the manufacturer (13.4 m and 13.1 m for 345 and 276 kPa), showing very low uniformity values and a lot of water application variations.

As seen in densograms for the Nelson R33, when the sprinkler pressure is significantly below the recommended range, the water distribution profile presents high color diversification in which water falls within an annular ring around the sprinkler, resulting in a relatively poor overlap pattern. As the sprinkler spacing increases, higher DU_{lq} overall values were obtained and slightly less color variation is shown in the densograms (2-17 E, F). As the sprinkler pressure increases, the magnitude of water application color lessens and more water is distributed in the field along the radial leg. Therefore, the higher the sprinkler pressure, the larger the wetted radius using values within the manufacturer-recommended range (2-17 A, B, C, D). Using a shorter spacing among the sprinklers showed the area within the radius near the sprinkler as the region receiving the lowest water application values, while the higher water application values were located in the center area (2-17 B, D, F). More uniformity variability was displayed under low pressures (2-17 D, F), which exceeded the pressure recommendations from the manufacturer (Table 2-2).

Application Rate (AR)

WR-32 sprinklers. The interaction spacing –pressure as well as the interaction spacing-treatment resulted in significant effect on water application rates.

AR values were significantly higher when the sprinkler spacing was reduced to 12.2 m and higher pressures were evaluated in comparison to the larger sprinkler spacing at the three pressure levels. Significantly higher AR resulted from the combination of the overall highest pressure and the lowest spacing (345 kPa and 12.2 m spacing). By contrast, the lowest AR was obtained by the lowest pressures at the largest sprinkler spacings (207 kPa and 14.6 m spacing).

Therefore, the highest mean AR resulted from the evaluation of R33 at Citra using 345 kPa at 12.2 m sprinkler spacing (AR= 5.3 mm hr^{-1}). The following two highest ARs, but significantly lower than the previously described were obtained at 207 and 276 kPa both at 12.2 m spacing tested at Citra (AR= 4.4 and 4.2 mm hr^{-1}, respectively). Significantly lower ARs were obtained throughout SPACE Pro simulations at the two highest pressures and the shorter spacing (AR= 3.4 and 3.2 mm hr^{-1} for 345 and 276 kPa, accordingly). However, none of them differed from the field data evaluated at 345 and 276 kPa at 14.6 m spacing (AR= 3.0 mm hr^{-1} for both pressures) neither from the SPACE Pro simulations at 207 kPa and 12.2m spacing (AR= 2.9 mm hr^{-1}). The lowest AR were obtained by SPACE Pro simulations at 14.6 m spacing and 345, 276 and 207 kPa (AR= 2.4, 2.2 and 2.0 mm hr^{-1}, accordingly), without significant differences among them.

The spacing-treatment interaction resulted in a significant effect on water application rate, in which the simulated and the evaluated in the field both significantly increased when shorter sprinkler spacing was performed, and vice-versa (Table 2-9, Fig. 2-15).Field data using 12.2 m spacing produced statistically the highest water applications rates compared to SPACE Pro simulations at 12.2 m spacing and compared to field data and simulations at 14.6 m spacing. At each sprinkler spacing (12.2 m and 14.6 m), the observed AR field data resulted significantly higher than the AR simulated in SPACE Pro.

Simulations of WR-32 impact sprinklers spaced 14.6 m resulted in AR of 2.4, 2.2 and 2.0 mm hr^{-1} when performed at 345, 276 and 207 kPa irrigation pressure levels. Alike AR were obtained at the two highest pressures; however, reductions of 16.6% on AR were achieved when pressure was decreased from 345 to 207 kPa. In comparison, the field data showed 3.0, 3.0 and 2.5 mm hr^{-1}, which did not differ significantly from the simulations only at the highest pressure, but significant differences were present under lower pressure levels (Table 2-9, Fig. 2-15).

SPACE Pro simulations reducing the sprinkler spacing to 12.2 m resulted in ARs of 3.4, 3.2 and 2.9 mm hr^{-1} at 345, 276 and 207 kPa pressure levels evaluated. Therefore, by decreasing the spacing among the sprinklers led to an overall application rate increase of 42%, 45% and 45% at 345, 276 and 207 kPa pressures, compared to the larger spacing (Table 2-9). Also, the AR was reduced in 1% when the irrigation system pressure was lowered from 345 kPa to 207 kPa.

Nelson R33 sprinklers. Significantly higher ARs resulted from higher pressures and significant differences were present at each pressure level. As well, the spacing-treatment interaction resulted in a significant effect on water application rates. Therefore, statistically higher AR were applied at 12.2 m sprinkler spacing performed at Citra, followed by the AR obtained at 14.6 m spacing evaluated also in the field without significant differences compared to the AR resulted from SPACE Pro simulations at 12.2 m spacing. The statistically lowest AR was produced by SPACE Pro simulated at 14.6 m sprinkler spacing. Also, the AR simulations and field data were significantly different from each other. Nelson R33 rotator sprinklers simulated at 14.6 m sprinkler spacing, obtained an overall AR of 2.8, 2.1 and 1.9 mm hr^{-1} performed at 345, 276 and 207 kPa irrigation pressures. Decreasing the pressure from the highest to the lowest achieved 32% less water application rates at this sprinkler spacing simulation. In comparison, the field data results were 3.7, 3.4 and 2.9 mm hr^{-1} performed at the same pressure levels, accordingly (Table 2-10, Fig. 2-15).

By shortening the spacing among the sprinklers resulted in about 43%, 48% and 42% increase in the application rate (AR= 4.0, 3.1 and 2.7 mm hr^{-1}) significantly higher compare to the AR obtained at 14.6 m sprinkler spacing. Reductions in about 33% were reached by Nelson R33 when the irrigation system pressure was reduced from 345 to 207 kPa. Similar pattern was followed by the observed values when the sprinklers were tested in the field at the three pressure levels, however they presented significantly higher water application rates (AR= 5.4, 5.0 and 3.8 mm hr^{-1}) (Table 2-10; Fig. 2-15).

Application rates achieved by both sprinklers had in common an increase on AR at smaller spacings and a decrease in water application when the pressure was reduced from the highest to the lowest level.

Uniformity and efficiency (i.e. how evenly is the water applied to an area and how efficiently that water is used), are two main factors to be considered when irrigation is applied to the crops to meet their ET demand, as well as when used to protect them from cold damage. However, these two terms are affected by many factors (e.g. soil and plant type, water quality, pressure available, wind, irrigation system and scheduling, among many others) that also should be taken in consideration in order to reduce the risks of under or over-irrigations, which lead to low application efficiencies and very likely to waste water.

The interactions sprinkler type- pressure, sprinkler type-spacing and pressure-spacing had a significant effect on distribution uniformity and application rate. Furthermore, including the wind speed as a co-variable in the analyses, resulted in significant lower distribution uniformities when high wind speed conditions were present.

Significantly lower application rates can be obtained as a result of larger sprinkler spacings. However, not in all the cases optimum distribution uniformity was acquired when 14.6 m sprinkler spacing was used, since very poor overlap pattern occurred among the sprinklers.

Generally, the lowest DU_{lq} values were obtained under the lowest irrigation system pressure across all the sprinkler types. In some sprinkler types (e.g. WR-32 and R2000WF), no differences in uniformity were present when using the two highest pressure levels (345 kPa or 276 kPa); however, other sprinkler types (e.g. Nelson R33), obtained significantly lower DU_{lq} values at each pressure level. In some instances, increased pressure improves distribution uniformity.

It was determined that the interaction among the pressure variation and sprinkler spacing caused different DU_{lq} values mainly for the 276 and 207 kPa pressure levels. The highest pressure at the two spacings did not differ significantly at the two sprinkler spacings. It was found that the effect of spacing on uniformity was higher than the effect of pressure on uniformity and on application rate.

Impact sprinklers evaluated under high wind conditions resulted in distortions on uniformity very observable when evaluated at open fields located at Hastings.

Simulating sprinkler distribution patterns, throughout the use of programs, i.e. SPACE Pro, may contribute in making decisions over the selection of sprinkler types, pressures, spacings, and other factors which impact the uniformity and efficiency of the irrigation systems before their installation or improve the systems if already installed. However, for this particular study, SPACE Pro results showed that the simulation data did not correspond with real uniformity and water application rate values. SPACE Pro densograms can contribute to visually interpret uniformity profiles and track over and under irrigated areas and find possible solutions; however, more preciseness may be required to be able to compare simulated values with real field values.

Even when the application rate recommended for cold protection of 6.35 mm hr^{-1} has been used largely and successfully, the results of this research found that lower application rates can be achieved by using any of the sprinklers simulated and tested at the field, which on average, overall sprinklers applied lower than 5.63 mm hr^{-1}. Therefore, more opportunities to reduce the amount of water applied through irrigation using lower pressures in the system, but achieving adequate irrigation uniformity can be accomplished.

Table 2-1. Expected DU_{lq} values according to the sprinkler type (Irrigation Association 2011).

Sprinkler type	DU_{lq} Achievable	Target	Historical *
Rotary	0.75-0.85	0.65-0.75	0.55-0.65
Spray	0.65-0.75	0.55-0.65	0.45-0.55

(*)= Asterisk denotes that if DU_{lq} values obtained are lower than historical, then it should be consider improving layout or changing components.

Table 2-2. Manufacturer recommendations for sprinklers tested (WR32, R33, R33LP and R2000WF) at Citra and Hastings, FL. (Nelson Irrigation Corporation 2003; Nelson Irrigation Corporation 2009; Wade Rain Inc. 2007).

Sprinkler type	Description	Plate	Nozzle (mm)	Flow rate, Radius of throw and App. Rate	at different pressures (kPa) 345	276	207
WR-32	Brass impact	Aluminum arm	3.6	(L h^{-1})	924	827	715
				RAD (m)	13	13	12
				*AR (mm hr^{-1})	6	5	5
Nelson R33	Rotator	Gold 18		LPH	924	827	715
				RAD	13	13	-
				*AR	5	5	-
Nelson R33LP	Rotator (Low Press. Model)	Gold 18		LPH	924	827	715
				RAD	13	13	12
				*AR	6	5	5
Nelson 2000WF	Rotator (w/purple diffuser)	Red WF16	3.2	LPH	734	656	-
				RAD	12	12	-
				*AR	5	5	-

RAD= radius of throw.

*AR= Application rate calculated from flow rate and radius of flow recommended by the manufacturer.

(-)= Not available manufacturer recommendations for that specific pressure.

Table 2-3. Uniformity (DU_{lq}) and application rate (AR: mm hr^{-1}) averages for four sprinkler types measured over three irrigation system supply pressures at 14.6 m sprinkler spacing and variable wind conditions. PSREU, Citra, FL.

Sprinkler Type	Spacing Pressure (kPa)	14.6 m DUlq Max	Min	Avg	*n*	Avg AR (mm h^{-1})	Avg wind Speed (m s^{-1})	Category
WR-32	345	0.89	0.64	0.79	31	2.96	2.31	med
	276	0.87	0.53	0.74	21	2.70	1.95	med
	207	0.82	0.49	0.68	21	2.24	1.91	med
R33	345	0.83	0.50	0.76	5	3.68	3.27	med
	276	0.73	0.63	0.71	5	3.36	3.17	med
	207	0.66	0.61	0.64	5	2.85	2.45	med
R33LP	345	0.86	0.74	0.79	5	3.70	2.43	med
	276	0.77	0.65	0.73	5	3.39	3.10	med
	207	0.67	0.57	0.65	5	2.95	0.28	low
2000WF	345	0.85	0.74	0.80	5	2.66	1.67	low
	276	0.88	0.70	0.80	5	2.38	1.58	low
	207	0.72	0.67	0.69	5	2.19	1.58	low
Overall		0.89	0.49	0.73		2.92	2.14	

Table 2-4. Uniformity (DU_{lq}) and application rate (AR: mm hr^{-1}) averages for four sprinkler types measured over three irrigation system supply pressures at 12.2 m sprinkler spacing and variable wind conditions. PSREU, Citra, FL.

Sprinkler Type	Spacing Pressure (kPa)	12.2 m DUlq Max	Min	Avg	*n*	Avg AR (mm h^{-1})	Avg wind Speed (m s^{-1})	Category
WR-32	345	0.90	0.68	0.81	24	5.07	2.91	med
	276	0.90	0.74	0.84	26	4.28	2.67	med
	207	0.85	0.69	0.79	22	3.82	2.76	med
R33	345	0.85	0.68	0.75	30	5.36	2.94	med
	276	0.78	0.63	0.70	21	4.97	2.77	med
	207	0.77	0.43	0.61	20	3.80	2.60	med
R33LP	345	0.85	0.74	0.79	5	5.63	2.46	med
	276	0.83	0.69	0.76	5	5.02	2.32	med
	207	0.74	0.63	0.68	5	4.53	2.31	med
R2000WF	345	0.84	0.79	0.83	5	3.12	2.23	med
	276	0.86	0.80	0.83	5	2.20	2.11	med
	207	0.77	0.72	0.75	5	2.74	2.13	med
Overall		0.90	0.43	0.76		4.21	2.52	

Table 2-5. The p-values of the F-test statistic for interactions from the ANOVA for distribution uniformity (DU_{lq}) obtained from catch can tests performed near Citra, FL.

Source	DU_{lq}
Wind speed m s^{-1} (Co-variable)	**
Sprinkler*Pressure	**
Sprinkler*Spacing	**
Pressure*Spacing	**
Sprinkler*Pressure*Spacing	ns

ns= not significant, *=p<0.05 and **=p<0.005

Table 2-6. Uniformity (DU_{lq}) and application rate (AR: mm hr^{-1}) for WR-32 impact sprinkler measured over three pressures (345, 276, 207 kPa), one sprinkler spacing (14.6 m) and variable wind conditions near Hastings, FL.

Location	Press. (kPa)	DU_{lq} Max	Min	Avg		Tests (n)	Avg AR (mm h^{-1})		Avg wind Speed (m s^{-1})	Categ.
Hastings	345	0.79	0.44	0.68	AB	19	3.13	A	5.15	high
	276	0.87	0.53	0.71	AB	16	2.89	BC	4.97	high
	207	0.82	0.47	0.66	B	15	2.19	D	4.59	high
Citra	345	0.89	0.64	0.75	A	31	2.90	B	2.31	med
	276	0.87	0.53	0.69	AB	21	2.66	C	1.95	med
	207	0.82	0.49	0.63	B	21	2.19	D	1.91	med

Different letters within a column indicate significantly different means (LSD_{Bon} 95%CI).

Table 2-7. The p-values of the F-test statistic for interactions from the ANOVA for irrigation uniformity (DU_{lq}) and application rate (AR: mm hr^{-1}), near Citra and Hastings, FL.

Source	DU_{lq}	AR (mm hr^{-1})
Wind speed m s^{-1} (Co-variable)	**	**
Pressure*Location	*	*

ns= not significant, *=p<0.05 and **=p<0.005

Table 2-8. The p-values of the F-test statistic for interactions from the ANOVA for application rate (AR: mm hr^{-1}) obtained from catch can tests performed near Citra, FL.

Source	AR (mm hr^{-1})
Wind speed m s^{-1} (Co-variable)	**
Sprinkler*Pressure	**
Sprinkler*Spacing	**
Pressure*Spacing	**
Sprinkler*Pressure*Spacing	*

ns= not significant, *=p<0.05 and **=p<0.005

Table 2-9. WR-32 sprinkler distribution uniformity (DU_{lq}) and application rate (AR) means comparison among values resulted from the SPACE Pro sprinklers simulations and field data evaluated near Citra, FL at three pressure levels and two sprinkler spacings.

Sprinkler	Spacing (m)	Pressure (kPa)	DU_{lq} SPACE Pro		DU_{lq} Citra	.	AR (mm hr^{-1}) SPACE Pro	.	AR (mm hr^{-1}) Citra	
WR-32	12.2	207	0.77	ABC	0.75	CD	2.9	CDE	4.4	B
		276	0.83	ABC	0.85	A	3.2	C	4.2	B
		345	0.84	ABC	0.83	ABC	3.4	C	5.3	A
	14.6	207	0.58	E	0.77	BC	2.0	G	2.5	EF
		276	0.64	E	0.84	AB	2.2	FG	3.0	C
		345	0.66	DE	0.87	A	2.4	DEFG	3.0	CDE

Different letters within a column indicate significantly different means (LSD_{Bon} 95%CI).

Table 2-10. Nelson R33 sprinkler distribution uniformity (DU_{lq}) and application rate (AR) means comparison among SPACE Pro simulations and field data evaluated near Citra, FL at three pressure levels and two sprinkler spacings.

Sprinkler	Spacing (m)	Pressure (kPa)	DU_{lq} SPACE Pro	·	DU_{lq} Citra		AR (mm hr^{-1}) SPACE Pro		AR (mm hr^{-1}) Citra	
R33	12.2	207	0.50	DE	0.64	BC	2.7	DEF	3.8	B
		276	0.64	BC	0.72	AB	3.1	DE	5.0	A
		345	0.68	ABC	0.75	AB	4.0	BC	5.4	A
	14.6	207	0.47	E	0.63	CD	1.9	F	2.9	DEF
		276	0.57	CDE	0.70	ABC	2.1	EF	3.4	BCD
		345	0.70	ABC	0.80	A	2.8	CDE	3.7	BCD

Different letters within a column indicate significantly different means (LSD_{Bon} 95%CI).

Figure 2-1. Single leg profile tests performed using WR-32 and Nelson R33 sprinklers at three pressure levels in order to develop uniformity profiles throughout simulations performed into SPACE Pro program. Photo courtesy of María Zamora.

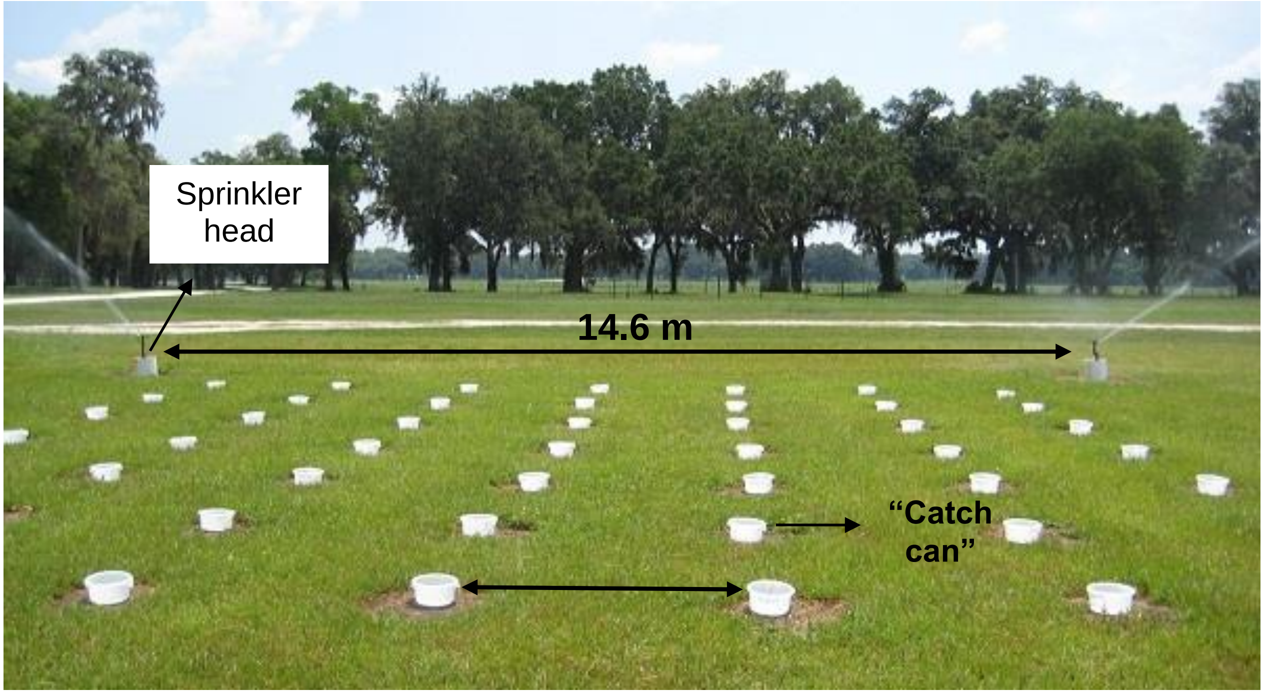

Figure 2-2. Collector layout for testing area using 14.6 m sprinkler spacing and 1.8 m collector spacing. Second testing area follows the same pattern but with 12.2m sprinkler spacing and 1.5 m collector spacing. Experimental fields located near Citra and Hastings, FL. Photo courtesy of María Zamora.

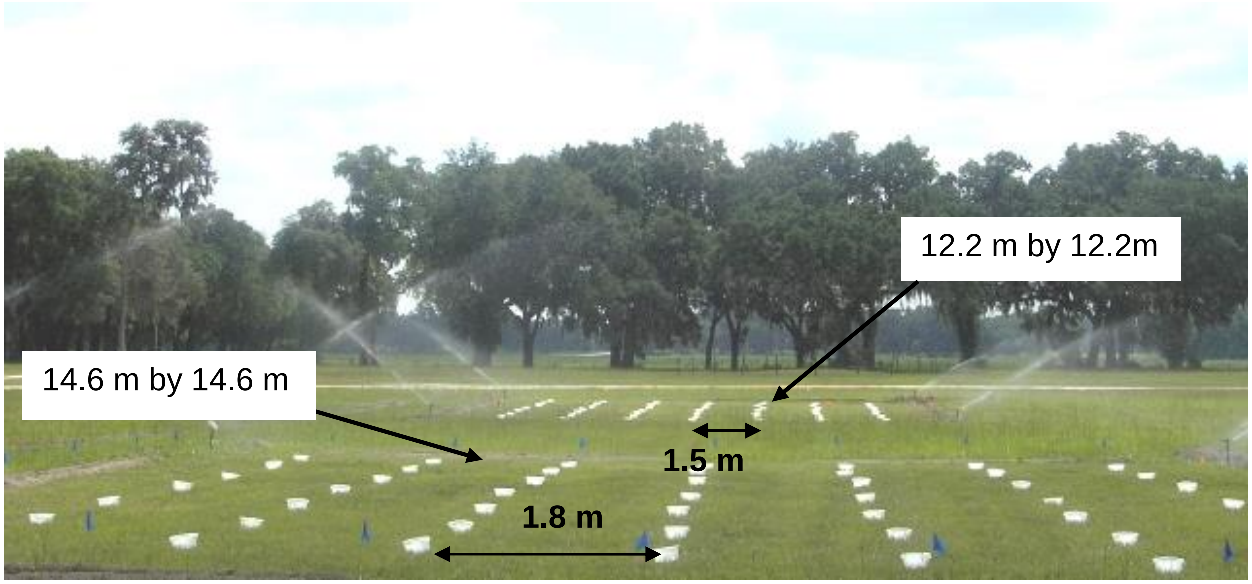

Figure 2-3. Testing areas at different sprinkler spacing (14.6 and 12.2 m) and collector spacing (1.8 m and 1.5 m). Set up used at the experimental fields located near Citra and Hastings, FL. Photo courtesy of María Zamora.

Figure 2-4. Pressure regulator series 25AUB-Z3 and LF25AUB-Z3 ½" -2" placed after the control valve in order to keep steady pressure conditions during the performance of DU_{lq} tests. Uniformity experimental field, PSREU near Citra. Photo courtesy of María Zamora.

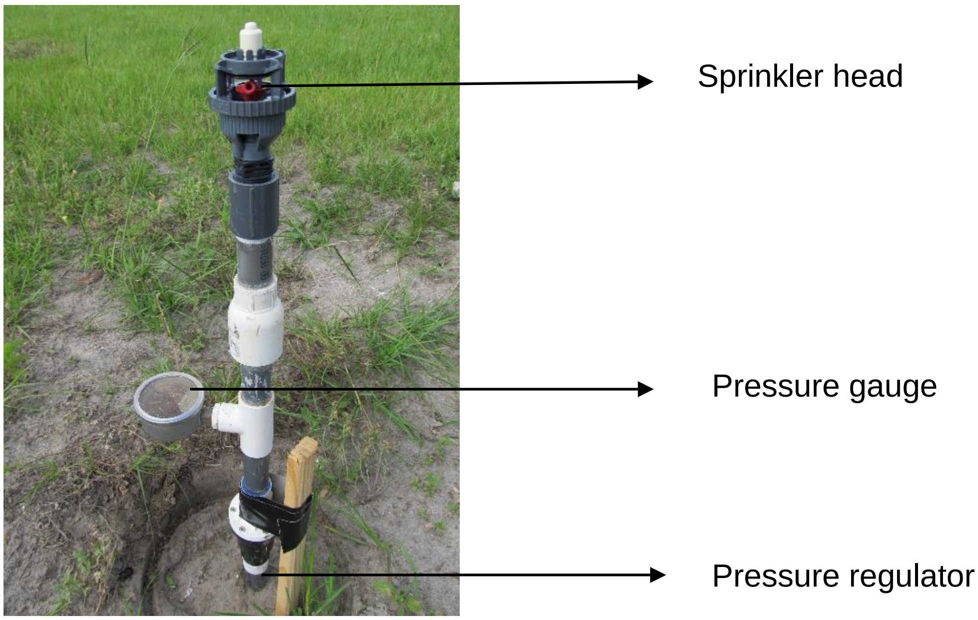

Figure 2-5. Sprinkler pressure monitoring using pressure gauges and regulators placed at the bottom of the sprinkler heads. Experimental fields near Citra and Hastings, FL. Photo courtesy of Michael Gutierrez.

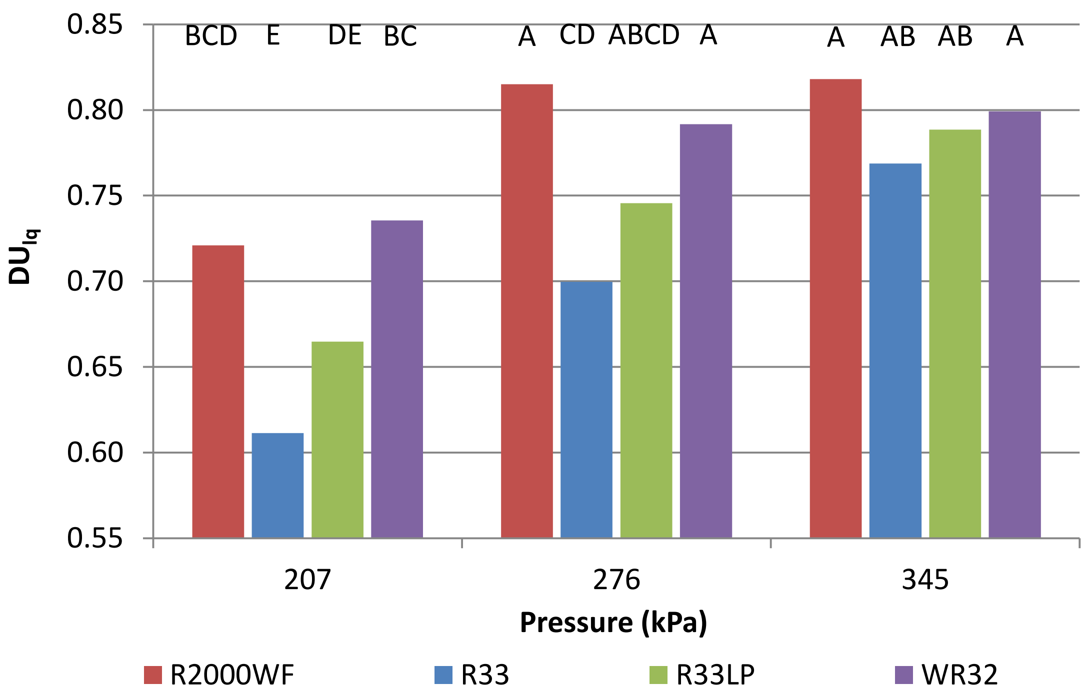

Figure 2-6. Low quarter distribution uniformity (DU_{lq}) as a function of sprinkler and pressure interaction, near Citra, FL. Means that do not share a letter are significantly different LSD_{Bon} CI 95%.

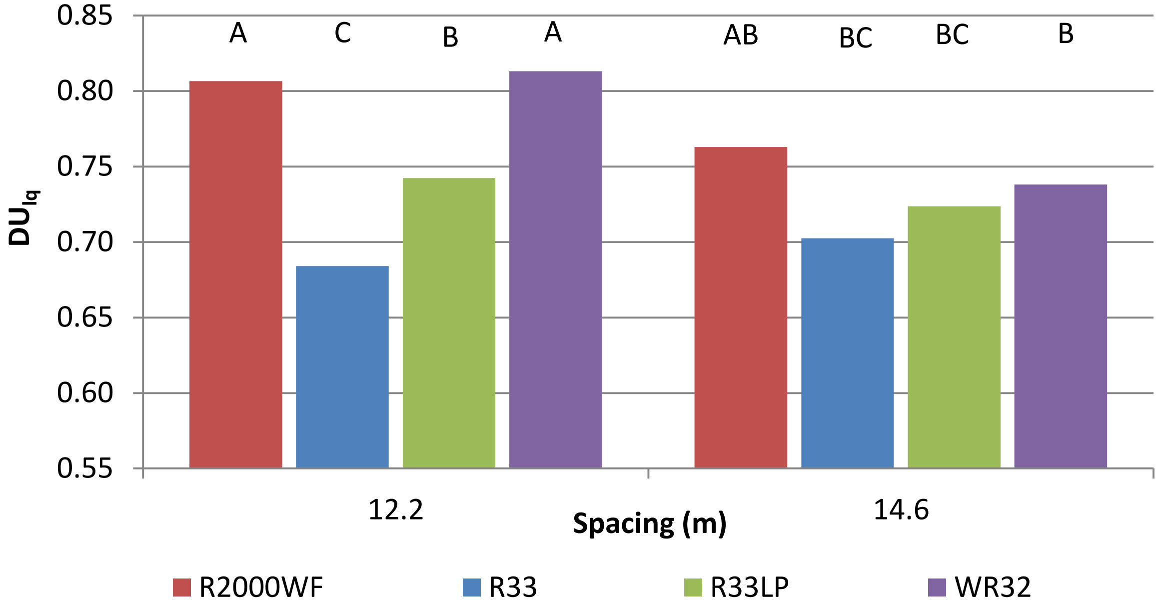

Figure 2-7. Effect of sprinkler type and sprinkler spacing on low quarter distribution uniformity (DU_{lq}), near Citra, FL. Means that do not share a letter are significantly different LSD_{Bon} CI 95%.

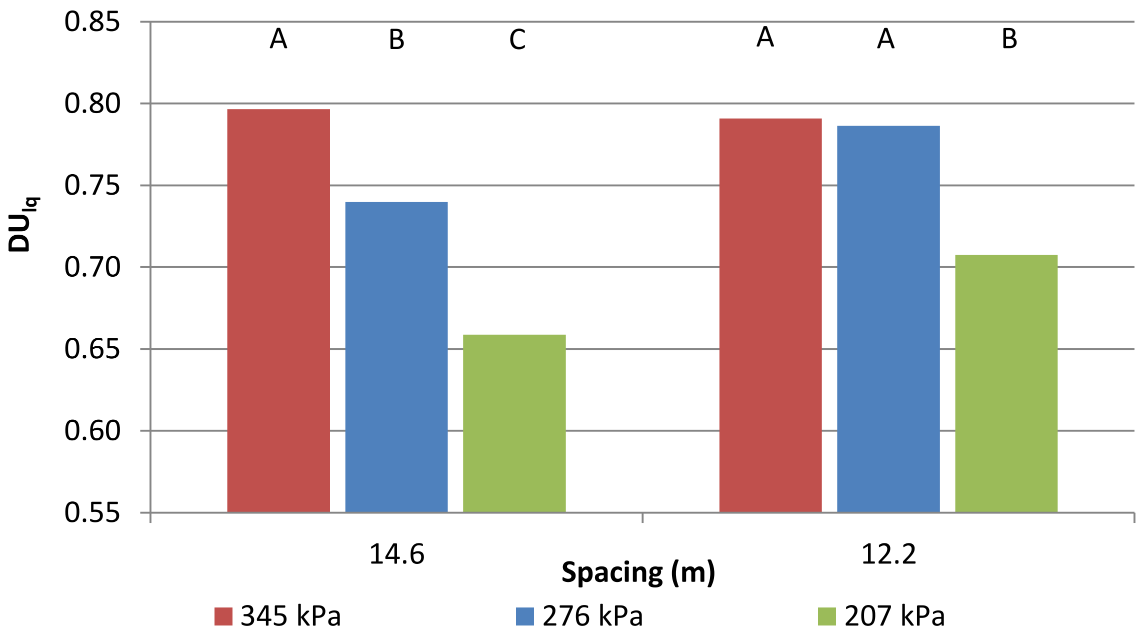

Figure 2-8. Effect of irrigation pressure and sprinkler spacing over low quarter distribution uniformity (DU_{lq}), near Citra, FL. Means that do not share a letter are significantly different LSD_{Bon} CI 95%.

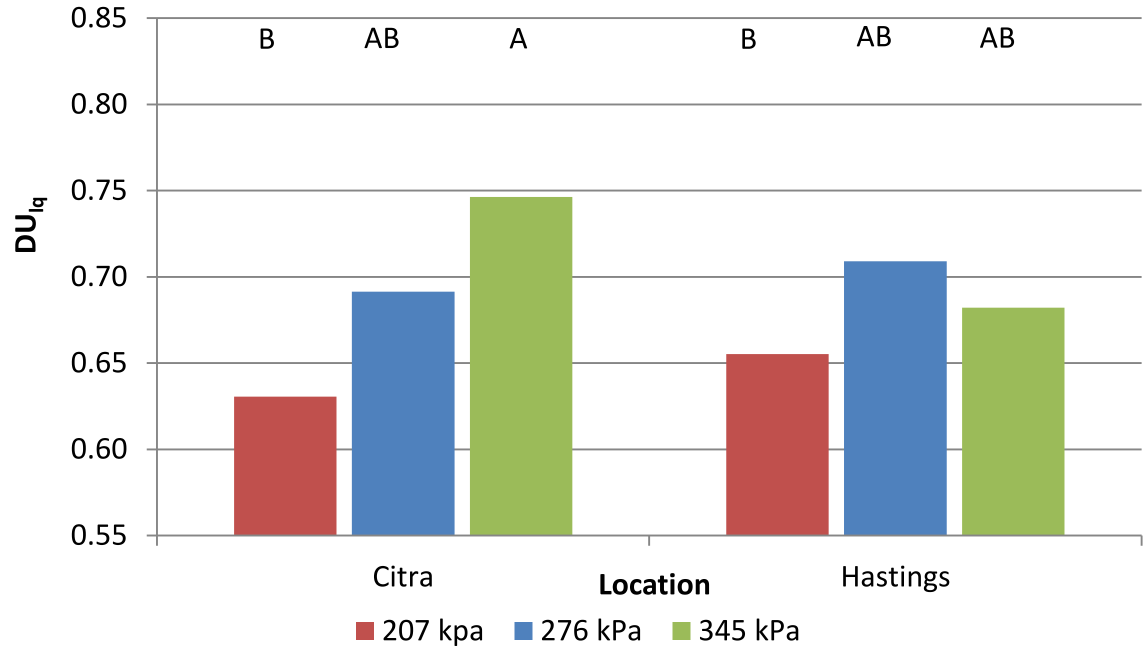

Figure 2-9. Low quarter distribution uniformity (DU_{lq}) as a function of pressure-location interaction tested near Citra, and Hastings FL. Means that do not share a letter are significantly different LSD_{Bon} CI 95%.

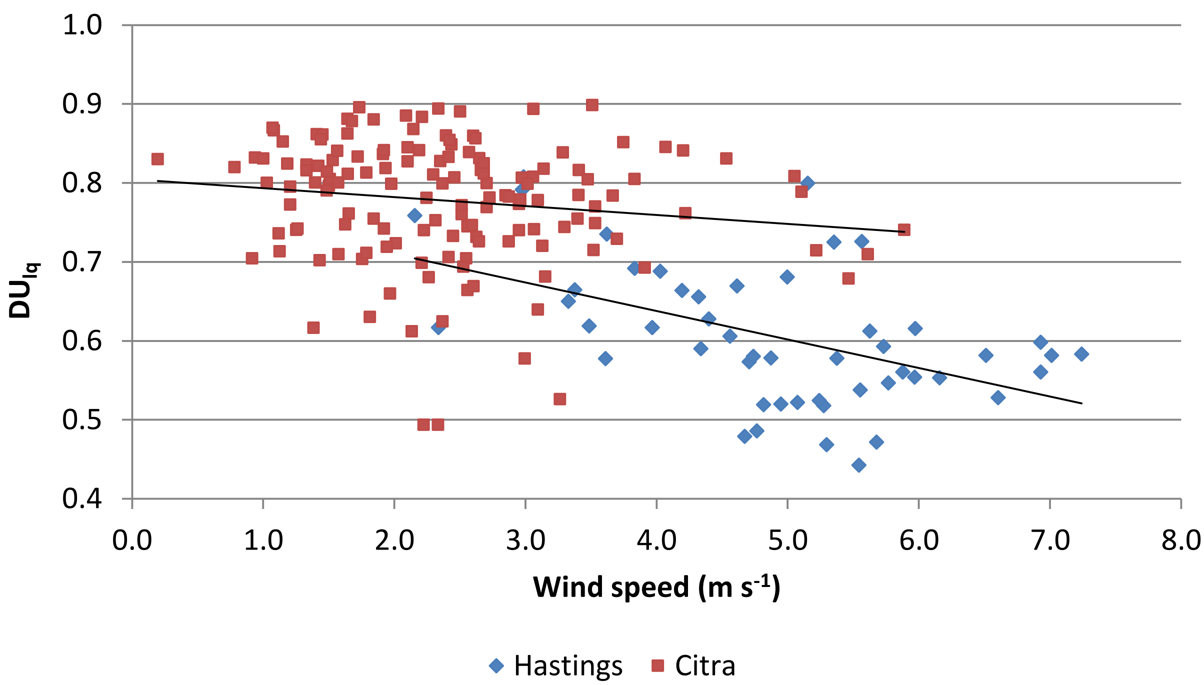

Figure 2-10. Effect of wind speed (m s^{-1}) over low quarter distribution uniformity (DU_{lq}) of the WR-32 impact sprinkler evaluated near Citra and Hastings FL.

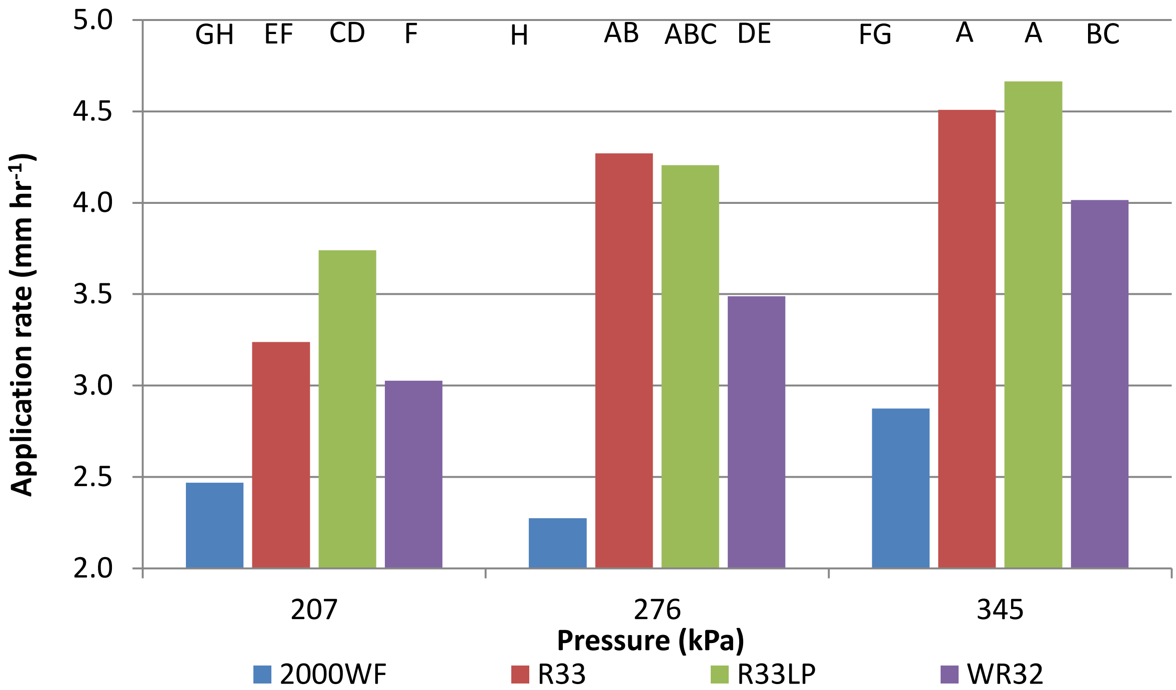

Figure 2-11. Application rates (AR) as a function of the sprinkler type-pressure interaction, near Citra, FL. Means that do not share a letter are significantly different LSD_{Bon} CI 95%.

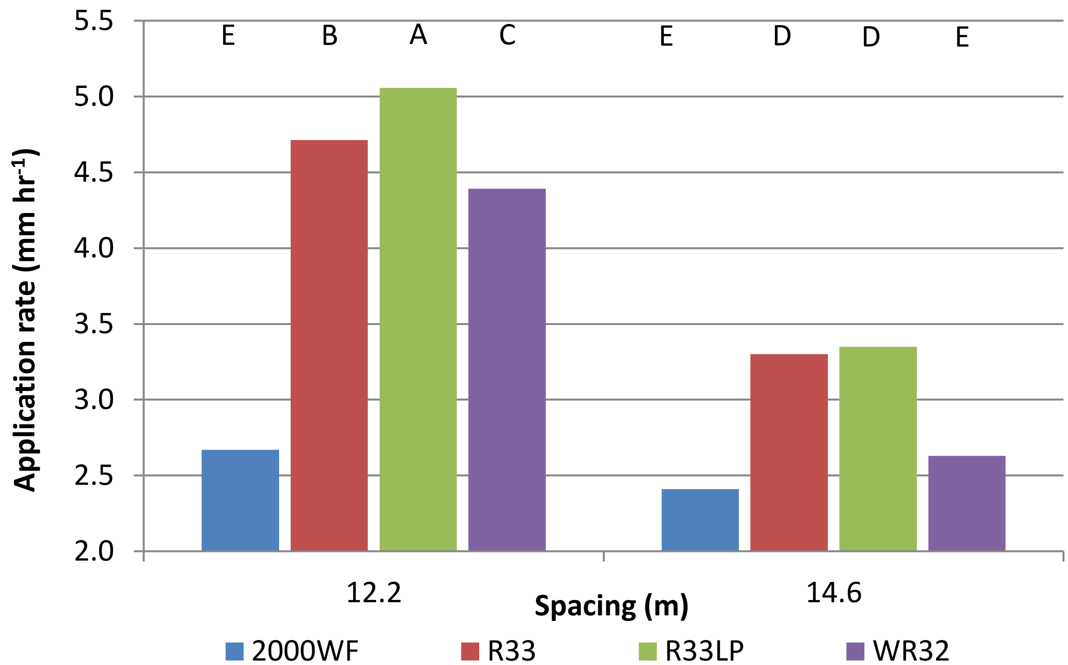

Figure 2-12. Effect of sprinkler type-spacing interaction over application rate (AR), near Citra, FL. Means that do not share a letter are significantly different LSD_{Bon} CI 95%.

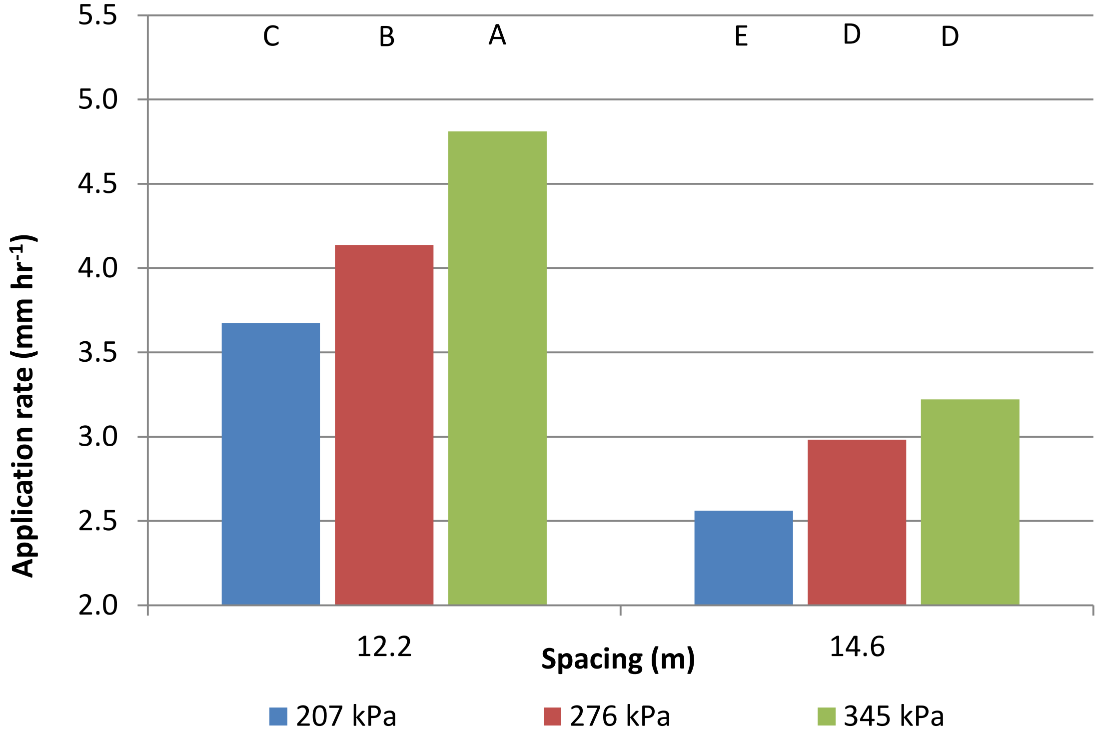

Figure 2-13. Application rate (AR) as a function of the sprinkler pressure-spacing interaction evaluated near Citra, FL. Means that do not share a letter are significantly different LSD_{Bon} CI 95%.

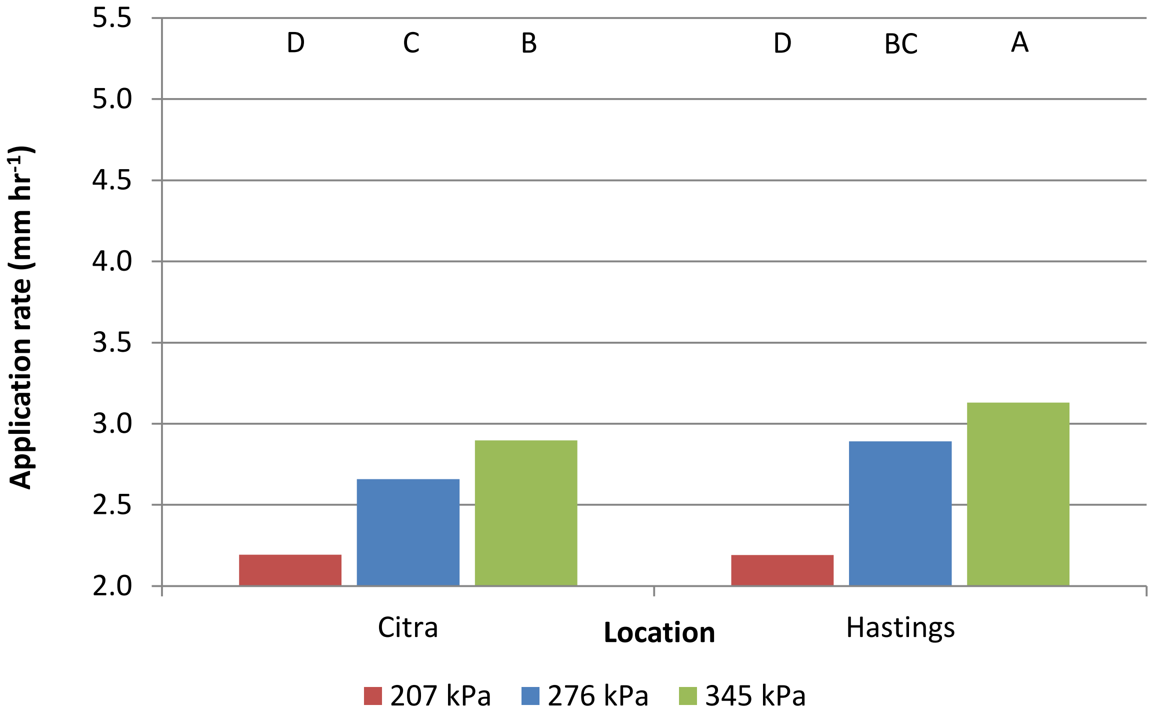

Figure 2-14. Application rate (AR) obtained from using WR-32 impact sprinklers at 14.6 m spacing at three pressure levels evaluated near Citra, and Hastings FL. Means that do not share a letter are significantly different LSD_{Bon} CI 95%.

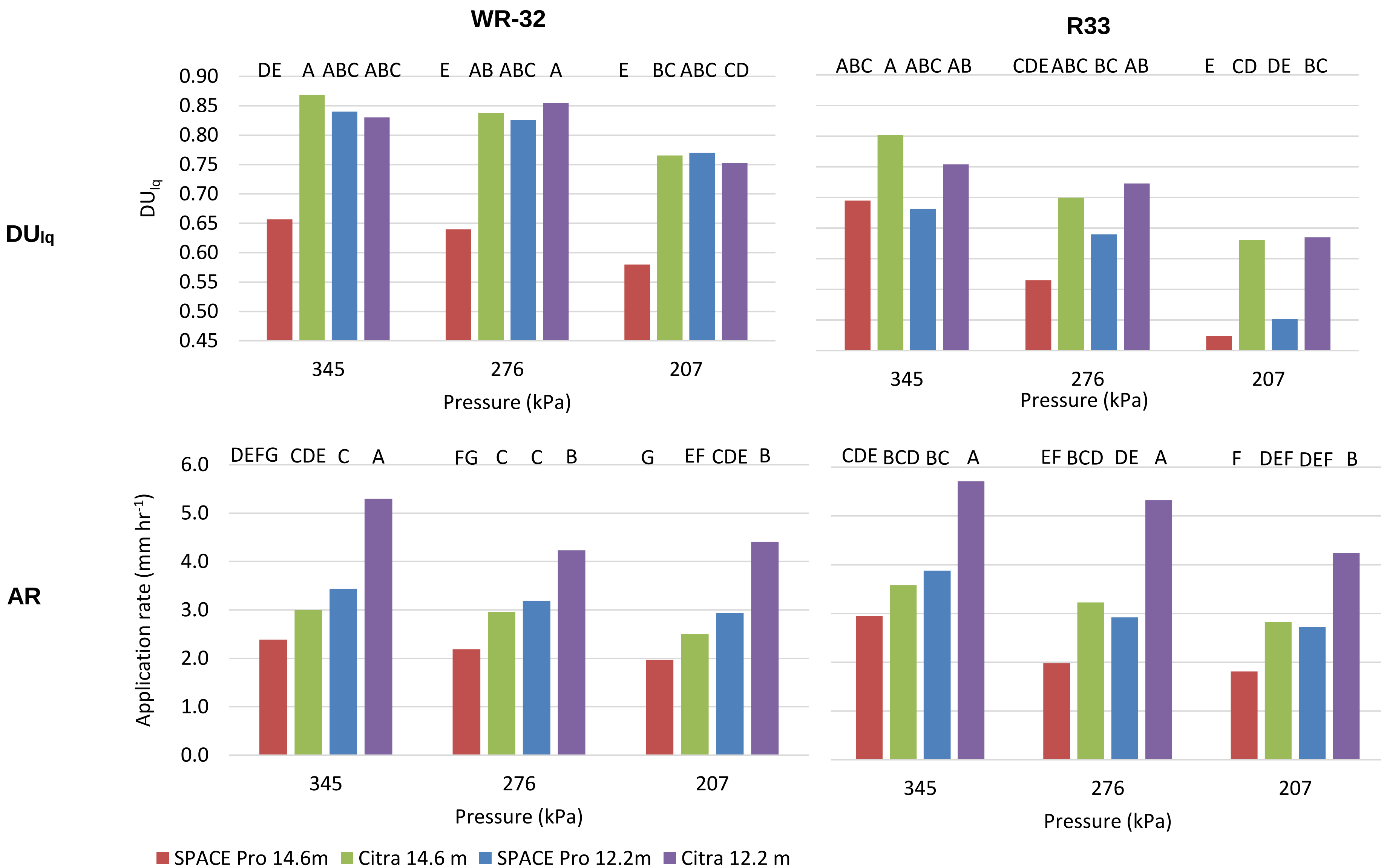

Figure 2-15. Distribution uniformity (DU_{lq}) and application rate (AR) comparisons among SPACE Pro simulations and field data evaluated near Citra using WR-32 and R33 sprinklers at three pressure levels and two sprinkler spacings.

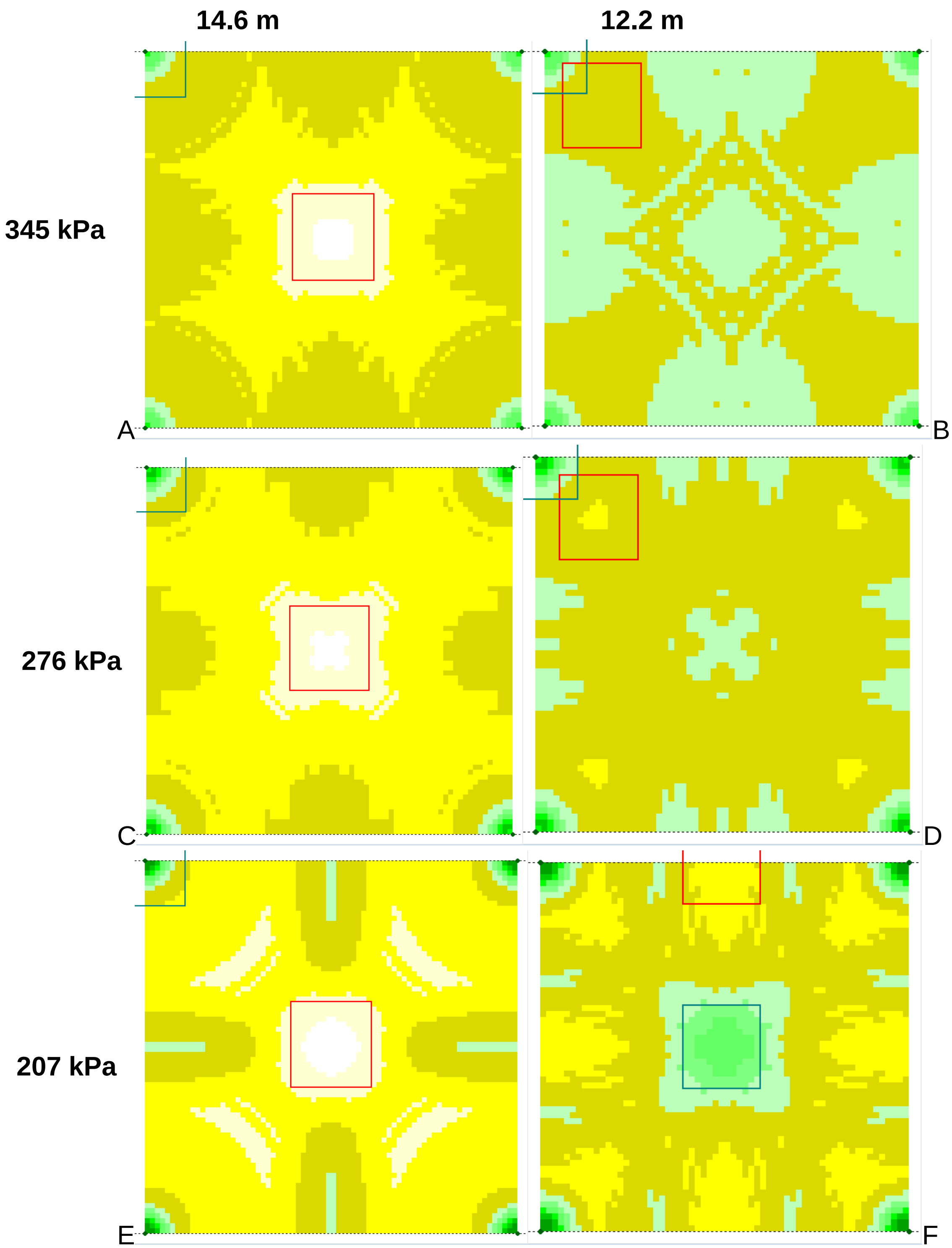

Figure 2-16. WR-32 sprinklers distribution uniformity (DU_{lq}) densograms from the SPACE Pro sprinklers simulations at three pressure levels and two sprinkler spacings. Red and green squares mean the lowest and the highest water application values, respectively.

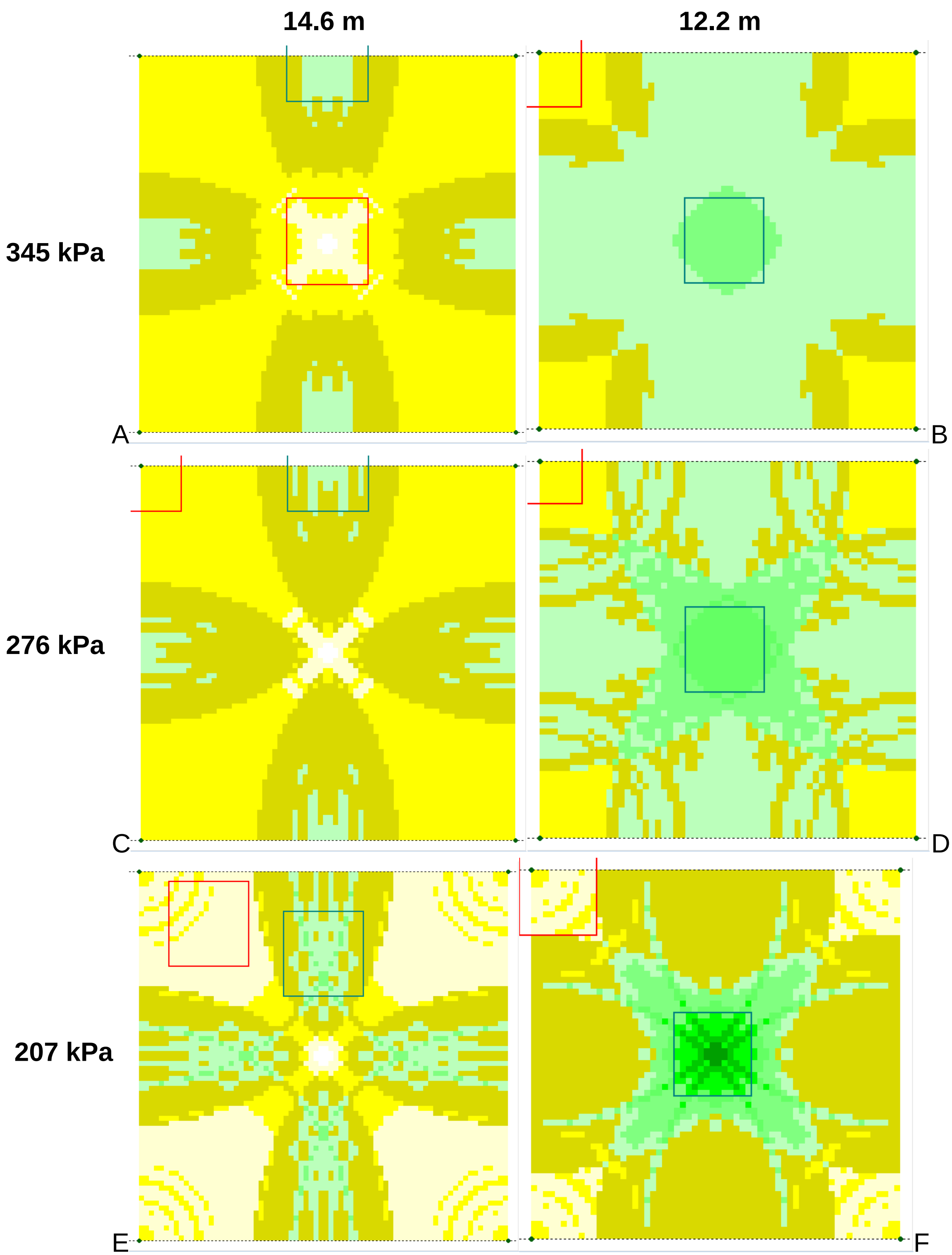

Figure 2-17. Nelson R33 sprinklers distribution uniformity (DU_{lq}) densograms resulted from the SPACE Pro sprinklers simulations at three pressure levels and two sprinkler spacings. Red and green squares mean the lowest and the highest water application values, respectively.

CHAPTER 3
EFFECT OF SPRINKLER PRESSURE AND SPACING ON STRAWBERRY YIELD DURING COLD PROTECTION

Introduction

The total value for strawberries accounted for $366.3 and $200.97 million in Florida during the 2011-12 and 2012-13 seasons, respectively (USDA 2013a). After tomatoes, strawberries are the second ranked crop (vegetable and berry crops) in agricultural revenue in the state (NASS and FDACS 2012).

The strawberry industry in Florida is mainly concentrated in the Dover/Plant City area in Hillsborough County. A normal season generally develops from mid-October until mid-March or April; however, early yields occurring in November, December and January represent the most important part of the season due to higher prices in the market ($16.7- $26.6 per 5.4 kg flat in 2012; USDA 2012).

The strawberry industry has to face many challenges in this short production window in addition to the intense competition and weather conditions. The biggest competitor for Florida is California, which ranks first in U.S. strawberry production (USDA, Economics, Statistics and Market Information System 2012); however, Mexico is playing an important role more recently due to its rapid increase in production, which makes it among the top five producers in the world (FAOSTAT 2013). Weather conditions may represent another threat for the production of this crop in Florida, considering that extreme weather conditions might result in significant damage to strawberries, Florida growers have used sprinkler irrigation for many years to protect their crops from frost/freeze damage during the winter.

The effectiveness of sprinkler irrigation on strawberries has been reported decades ago. According to Locascio et al. (1967), two sprinkler application rates (3.3

and 6.6 mm hr^{-1}) provided successful cold damage protection under low wind conditions (0 to 0.4 m s^{-1}) and air temperature as low as -4°C. The 3.3 mm hr^{-1} application rate resulted in 46, 39 and 50% less mortality on flowers, immature fruits and mature fruits versus the unprotected plots. The 6.6 mm hr^{-1} application rate resulted in 74, 79 and 94% lower injury on the same parts of the plant compared to the non-irrigated plants. Nevertheless, under higher wind conditions and lower air temperatures, the 3.3 mm hr^{-1} application rate did not provide equivalent protection to the higher rate.

Another study developed during the 1962 season, evaluated three sprinkler application rates for cold protection in Louisiana strawberries at two locations (Braud and Hawthorne 1965). At the first site, an application rate of 2.8 mm hr^{-1} was tested during nearly 1.5 h of clear sky and no wind. This rate successfully protected the irrigated plants keeping the temperature at berry plant height about 1.1°C above freezing.

With the aim of proving effectiveness for cold protection using a lower application rate, Braud and Hawthorne (1965) evaluated a 2.3 mm hr^{-1} rate; however, results showed insufficient coverage mainly in the center of the sprinklers, when this application rate was used; hence, they recommended a greater application rate to achieve coverage and uniformity. Furthermore, an application rate of 3.3 mm hr^{-1} proved effective protection for blossoms and fruits, keeping the sprinkled areas most of the time near 0.5°C when air temperature reached -4.4°C (Braud and Hawthorne 1965).

At the second site, during the 1963 season, three sprinkler application rates: 1.3, 2.5 and 5.1 mm hr^{-1} were evaluated under mild cold conditions, in which temperature did not fall to critical damage level. The three application rates resulted equally effective to protect strawberries in Louisiana under those conditions (Braud and Hawthorne 1965).

Other studies had shown effective protection from frost damage on strawberries by using microsprinklers controlled by an automated system during mild frost conditions. The average application rates of 3.8 and 5.8 mm hr^{-1} provided protection under -2.2°C and -4°C air and bud temperatures, respectively. Results showed less than 3% blossom damage when microsprinklers were used, versus 52% blossom damage in the non-irrigated plots (Stombaugh et al. 1992).

A specific protection rate during a normal frost has been found more through empiricism than though mathematical modeling (Bagdonas et al. 1978). The sprinkler application rate will vary according to the weather conditions, mainly on minimum air temperature and wind speed (Locascio et al. 1967). As a result of evaporative cooling, the wind condition represents an important parameter to consider for application rates (Perry and Poling 1986).

The application rate recommended for citrus increases as air temperature is lower and wind speed is higher. When air temperature is about -5.6°C and low wind conditions (0.9-1.8 m s^{-1}) are present, an application rate of 6.1 mm hr^{-1} is recommended in order to avoid cold damage in citrus (Table 3-1, Gerber and Martsolf 1965). Furthermore, according to the same parameters: minimum air temperature and wind speed conditions; these application rates has been adapted and used in the strawberry industry for many years to protect this crop from cold damage (O'Dell and Williams 2009). Although this table of application rates has been used largely and successfully for cold protection, the values are generally overestimated (Perry 1979), Critical temperature according to the stage of the strawberries and suggested temperatures to start the irrigation are described in Table 3-2.

Critical Temperatures and Cold Damage

The damage that occurs in plants due to cold temperatures is attributed to the extracellular ice formation inside the plant tissue; however, injury to the cells occurs due to dehydration when water is drained out once the crystals of the ice are formed (Snyder and de Melo Abreu 2005).

“Critical temperature” or the “critical damage temperature” (TC) is the temperature at which some injury is expected, it is associated with air temperatures (measured in standard instrument shelters) and varies among crops depending on their tolerance factors (Snyder and de Melo Abreu 2005). The temperature difference among the plant tissue and its immediate environment plus the radiation balance, will determine the rate at which the plant tissue will cool (Snyder and de Melo Abreu 2005).

Some standard recommendations have evolved from tree fruit (i.e. citrus) and low growing crops (i.e. strawberries) literature with the aim of avoiding damage on the plants based on the critical temperature. Some of these general recommendations are: start irrigation at a temperature of 1.1°C, stop irrigation when ice is melted, avoid irrigation under windy conditions (more than 4.5 m s^{-1}) and critical temperatures for strawberries varies among cultivars and stage of development (Perry and Poling 1986).

Research on strawberry’s critical temperature is limited; however, some studies have defined it as the temperature at which a blossom will be damaged after 30 min exposure. Phillips et al. (1962) showed variations in the critical temperature based on the stage of the crop: tight bud -5.5°C, balloon bud -2.2°C, full bloom -0.5°C and green fruit -2.2°C based on observations and opinions of leading small fruits research and extension personnel.

Due to the uncertainties, years later Perry and Poling (1986) developed another study in order to assess critical temperatures on two blossom stages. Four different strawberry cultivars were tested using the standard recommendations and also, testing a microcomputer program to determine application rates. The results showed different critical temperatures on each cultivar; however, no differences occurred on critical temperature around -3.1°C for blossoms in open and popcorn stages. Also, application rates calculated throughout the program ranged from 2.0 to 5.1 mm hr^{-1} during the night according to minimum temperatures and weather conditions present (Perry and Poling 1986).

The critical temperature of a plant part at a certain stage of development differs from air temperature and as critical temperature is approached, the risk increases. In order to achieve energy conservation through irrigation for cold protection, it should be applied as critical temperature is reached and should be kept just above it during the whole cold event; however, if the temperature monitoring system is not accurate or reliable, very high risk results, in which the economic damage may be unrecoverable for the growers. Therefore, many times, irrigation is used for cold protection even when the need is questionable (Martsolf 1992).

As a result, enhanced systems are needed to monitor temperature and determine the best time to turn on/off the irrigation systems for cold protection, hence reduce damage on strawberries and potentially increase water conservation by decreasing the irrigation requirements (Zotarelli et al. 2012).

Pollination and successive fertilization of all the pistils in strawberry flowers is the key to obtain maximum fruit size later in the season (Peres et al. 2010). Premium prices for strawberries are available for early yields, making this period the most important for grower's profitability (Santos et al. 2007). Therefore, irrigation for cold protection is critical during the blooming period to safeguard the pistils to be pollinated, thus enhancing early production and profitability.

Sprinkler Irrigation for Cold Protection

Sufficient water is needed when irrigation is applied for cold protection, but without resulting in excess water that can cause root rot, or other disease problems (e.g. Botrytis fruit rot) affecting the yields (Perry and Poling 1986).

In Florida, sprinkler irrigation has been used as a best management practice (BMP) in agriculture (i.e. citrus, strawberries, blueberries, nurseries and aquaculture). However, when the crops are exposed to temperatures where damage can occur, irrigation is turned on for protection, generally when air temperature is 1.1°C. Thus, this BMP allows the growers to protect their crops, but can strain the aquifer and lower its level, impacting residential wells and causing sinkholes to form (SWFWMD 2012).

An unusual 11 days of severe freezes occurred in the Dover/Plant City area in January 2010 causing water source problems thought to be caused by irrigation for crop protection. The amount of water during one night of freeze/frost protection is estimated to be among 508 and 762 m^3 ha^{-1} when high volume sprinklers are used (Santos et al. 2011), which may be converted into an estimate of 1.8 and 2.7 million m^3 needed to protect the 3,561 ha planted in Florida in 2010 (USDA 2013b). Thus, during those 11 unusual freezes nights an estimated 19.9 to 29.9 million m^3 of water was applied through irrigation to protect the strawberries in Florida. Around 750 residential wells were impacted and more than 140 sinkholes were reported due to the reductions in groundwater level (SWFWMD 2012).

Further investigation is needed on the strawberry sprinkler application rate recommendation and on alternate rates under lower volume of water which may provide adequate protection.

In order to develop strategies to decrease the groundwater impacts and therefore, provide an opportunity to conserve water through irrigation for cold protection, the objective of this chapter was to evaluate the effect of varying sprinkler spacing and pressure on strawberry yield quality and quantity under cold conditions.

In addition, it has been hypothesized that an operational system which integrates air temperature, relative humidity, wind speed and blossom temperature, may provide a better control on when to start the irrigation for cold protection (Perry and Poling 1986). Hence, an alternate objective was to assess new technologies based on temperature and relative humidity in order to control irrigation for freeze/frost protection, potentially reduce water requirements and assure yield.

Materials and Methods

Treatments

This experiment evaluated WR-32 brass impact sprinklers (Wade Rain Inc. 2007) with varying irrigation system pressures and sprinkler spacings. Five different treatments were developed in order to replicate strawberry grower practices but with the aim to conserve water through irrigation. Therefore, the treatments consisted of (i) GROW treatment, which used 345 kPa as irrigation system pressure controlled by a thermostat or thermocouple at 14.6 m sprinkler spacing. This treatment mimicked the irrigation practices used by strawberry growers for cold protection, therefore, it is also referred as “grower practice” it was used as a benchmark for treatment comparison, (ii) AC treatment, followed the same pressure and spacing settings as GROW treatment; however the irrigation was controlled automatically though wireless temperature and relative humidity sensors, (iii) LOW treatment had a reduced irrigation system pressure of 207 kPa and 14.6 m sprinkler spacing, (iv) SPC had 345 kPa irrigation system pressure and reduced the sprinkler spacing of 12.2 m, this being the manufacturer recommended spacing for WR-32 impact sprinklers to achieve optimum sprinkler overlapping, (v) the NO treatment consisted on a non-irrigated plots which were used as a comparison against the irrigated ones. The GROW, LOW and SPC treatments were controlled by a thermostat in the 2011-12 season, and by thermocouples during the 2012-13 season (Table 3-3).

Strawberry Field Experiment

A field study was conducted from September to April in two seasons: 2011-12 and 2012-13. The experimental area was located in the University of Florida, Institute of Food and Agricultural Sciences (UF/IFAS) Plant Science Research and Education Unit (PSREU), near Citra, Florida. During early October the varieties ‘Strawberry Festival’ and ‘Treasure’ bare-root transplants were planted for the 2011-12 season and only ‘Strawberry Festival’ transplants for the 2012-13 season. After planting, sprinkler irrigation was applied to the plants during 10 hours per day approximately 10 days in both seasons to reduce transplant shock. The experiment was established on an Arredondo Sand soil with 0.5% organic matter and pH of 6.2 (USDAc, 2013). A Kennco Super Bedder was used to pre-form the planting beds, which were approximately 66 cm wide at the base, 61 cm wide on the top, and 10-13 cm high. The soil was fumigated with methyl bromide and chloropicrin (50/50, v/v) and immediately covered with black high-density polyethylene mulch, 1.25 mm thickness. Pre-plant fertilizer 10-10-10 at 448.3 kg ha^{-1} was incorporated into the bed before fumigation and mulching. Fertilization and pest control was done according to existing recommendations (Peres et al. 2010). A tractor mounted hole puncher was used to make approximately 4.8 cm wide openings at 40.6 cm intervals in twin staggered rows with each 20.3 cm from the bed center. Fertigation was applied through a 15.9 mm drip tape line 0.25 mm thickness with 30.5 cm emitter spacing with a flow rate of 113.6 L hr^{-1} per 30.5 m of tape buried 2.5 cm deep. Overhead irrigation was used for frost protection and crop establishment (Albregts and Howard 1984). Variations in the irrigation system pressure and in the sprinkler spacing were assessed using Wade Rain WR-32 impact sprinklers with 3.6 mm nozzles for low volume applications (Wade Rain Inc. 2007). In addition, 345 kPa or 207 kPa Senninger pressure regulators (Senninger Irrigation Inc. 2010) were placed at the bottom of the sprinkler to maintain the irrigation system pressure at the corresponding treatment. Shields were set on determined sprinklers to control water direction and avoid plot overlapping.

Plot Description and Harvest Protocol

The strawberry field experiment consisted of 15 plots 15.2 m by 15.2 m. Strawberry bare root transplants from nurseries in Canada were planted in five rows. A set of five treatments with three replications each were tested. Strawberries were harvested twice per week following a protocol consistently during the strawberry season. The center of the three middle rows was used as harvest areas. The ends of the rows and outside rows were established to eliminate border effects (3-1).

Yield data from the harvest area was weighed at the field, separated and classified as: “marketable” fruit weight and “culls” weight. The “marketable” fruit weight was defined as “*strawberries firm, not overripe or undeveloped, and which are free of mold or decay and free from damage caused by dirt, moisture, foreign matter, disease, insects or mechanical or other means*. *Each strawberry has not less than three fourths of its surface showing a pink or a red color*” (USDA 2006). The minimum diameter required was 1.9 cm (USDA 2006). The strawberries not following the standards previously mentioned were weighted separately and categorized as “culls”.

Temperature

During the two years of experiment, temperature within each plot was monitored using two different temperature devices: thermocouples and wireless temperature sensors (only placed at the automated control treatments).

Thermocouples

Air temperature was recorded below, within and above the plant canopy (at 3.6, 16 and 30 cm above ground) using cooper-constantan thermocouples placed within each plot and connected to six Campbell Scientific dataloggers (Campbell Scientific 2013), also called “temperature stations”. Due to the variation in temperature data recorded, the “cold events” were defined using the data from the temperature station that usually showed the most extreme cold effect below the temperature at which growers turn on the irrigation for cold protection in general (i.e. temperatures below 1.1°C for the longest periods of time).

Cold events are defined as periods when air temperatures were consistently below 1.1°C for more than 2 hours according to the station showing the most extreme cold effect. A detailed explanation of the cold events with temperatures below the "physiological critical temperature" for strawberries (-0.56°C) is shown in the appendix.

This temperature is lower than where damage occurs in the "open blossom" stage of the crop (Table 3-2).

The irrigation for cold protection on irrigated treatments (GROW, LOW and SPC) was controlled by two thermocouples directly connected to the solenoid valve. These were programmed to turn on the irrigation when any of them reached an air temperature of 1.1°C, mimicking a grower turning on the system at this temperature; thus it is called “grower irrigation” through the document. The irrigation was programmed to turn off when both thermocouples reach a temperature above 1.7°C.

Other climatic data (e.g. minimum air temperature, minimum dew point temperature, precipitation and average wind speed) was monitored and obtained from the Florida Automated Weather Network (FAWN) archived weather data from the station located at the PSREU.

Wireless sensors

The implementation of new technologies to control the irrigation valves to turn on/off during freezing nights was evaluated using wireless sensors nodes (Praxsoft, Orlando, FL) that integrated canopy level temperature and relative humidity. This technology was evaluated using the AC treatment, which irrigation was automatically activated based on the dew point temperature from the sensors and the strawberry stage critical temperature (Table 3-2).

On site temperature and RH monitoring through the wireless sensors was used to calculate an average dew point (DP) and therefore, determine the safest time to turn on/off the irrigation system automatically avoiding damage in the plant tissues and potentially saving water. Using Table 3-2, the wet bulb temperature corresponded to the strawberry open blossom critical temperature, the dew point temperature was measured and selected in the matching row, and then the corresponding air temperature to trigger the irrigation for cold protection was read from the table. Using this method, the irrigation system was programmed to shut off when temperature exceeded 2.2°C. This type of irrigation is called “AC irrigation” throughout the document.

A complete weather station was installed at the strawberry experimental field in order to monitor temperature, relative humidity (RH), solar radiation and wind speed. Data access from the wireless sensors and the weather station was available online at www.agnetlive.com.

Experimental Design

The experimental design was a split-plot design in which different harvest times were treated as subplots, whereas the different irrigation systems were the main plots. This design with three repetitions (three blocks) was implemented during both crop seasons. In every block WR-32 impact sprinklers were used (Wade Rain Inc. 2007). Yield data were analyzed by an analysis of variance (ANOVA) and a regression analysis in order to investigate and model the relationship between yields and treatments. The Bonferroni procedure was used for the comparison of treatment means. Yield recovery development after freeze events was analyzed using linear and quadratic polynomial contrasts.

Results

Cold protection field experiment results from two seasons, 2011-12 and 2012-13, are presented. Minimum leaf temperatures, air temperature, and other climatic data in the strawberry field were recorded from December through March in both seasons. Cold events occurring prior to December are not shown because temperature did not reach blossom critical damage that could affect the harvest season. The “Grower practice”

(GROW treatment) was used for treatment comparison on yield and volume of water applied through irrigation during cold events on both year seasons (Table 3-4).

In the first season, yield did not vary between the two cultivars; therefore, no distinction was made in yield from the harvest areas. In order to analyze the data, cold events (temperature below 1.1°C for more than two hours) were grouped into “cold recovery periods” these being the periods of yield recuperation per treatment after the occurrence of cold events. A total of five and four cold recovery periods were present during the 2011-12 and 2012-13 seasons, respectively.

Data from twice weekly harvests was weighted in order to have equal number of days between harvests. Mean yields were analyzed using ANOVA and Least Square Difference method of Bonferroni (LSD_{Bon}) (Table 3-5 and Table 3-8 for 2011-12 and 2012-13 seasons, correspondingly). Treatment contrasts were performed using the coefficient of orthogonal polynomials for equally spaced intervals to analyze the treatment yield recovery after the incident of cold events.

2011-2012 Season

Yields

Initial cold events started 11 November 2011, but consecutive cold events until the harvest season were above strawberry bloom critical temperature. A total of 23 harvests were performed 21 December 2011 to 15 March 2012. Early yields were affected by continuous cold events starting 2 January until 5 January 2012, where minimum air and dew point temperatures of -8.5°C and -12.8°C were reached. A total of 29.2 hours “grower practice” irrigation and 33.8 hours AC irrigation were needed to protect the crop during those consecutive nights in which 27 hours of both irrigation types occurred on temperatures below strawberry blossom critical temperature (A-1).

These cold events drastically impacted the control treatment (non-irrigated), resulting in very low average marketable weight (0.80 Mg ha^{-1}) during the harvesting period. Even when the irrigated treatments were affected and produced lower yields after the cold events, succeeding production recovery increased significantly (3-2). Non-irrigated plots had 70% lower marketable yield (0.80 Mg ha^{-1}) than the grower practice (2.66 Mg ha^{-1}; 3-3). However, average yield among irrigated treatments did not differ significantly over the season (Table 3-5).

The freeze events from December 2011 thru March 2012 were grouped into five recovery periods. Mean comparison results showed high significant yield differences between the irrigated treatments and the control (Table 3-5). The control was affected by the initial severe cold events and on average mean yield was 84% lower (0.12 Mg ha^{-1}) during the 5 recovery periods (LSD_{Bon} NO > critical LSD_{Bon} for each period). P-values of the ANOVA F test statistic for treatment means showed no significant differences between the irrigated treatments (Table 3-6), except during the second and fifth cold recovery periods, when some irrigated treatments presented slightly significant differences (Table 3-7).

Prior the second cold recovery period, cold events occurred from 14 January until 16 January 2012 with minimum air and dew point temperatures of -4.9°C and -3.8°C correspondingly, and an average of 27.4 hours of irrigation in which 26 hours were applied when temperatures reached the critical for strawberry blossoms. The yield recovery after these cold events presented significant differences between certain irrigated treatments (Table 3-6). LOW (1.20 Mg ha^{-1}) was 16.7% higher in yield versus AC (1.00 Mg ha^{-1}), (Table 3-7). For this recovery period, the GROW (1.25 Mg ha^{-1}) was

4%, 14% and 20% significantly higher than the LOW (1.20 Mg ha^{-1}), SPC (1.08 Mg ha^{-1}) and AC (1.00 Mg ha^{-1}) treatments respectively. The comparison between the "grower practice" against the control (0.06 Mg ha^{-1}) showed a high significant difference ($p<0.005$) by a 95% higher yield when irrigation was used to protect the crops (Table 3-7).

During the 3rd and 4th cold periods, no significant effect on yield was present when using different irrigation systems. However, significant differences were found when compared to the control (Irr./NO in Table 3-6). Previous the 3rd cold recovery period, only an average of 2.4 hours were irrigated when temperatures got below critical temperature on January 30, while the majority cold events occurred above critical temperatures (A-1). However, consecutive cold events previous the 4th cold recovery period reached-6.5°C and -10.6°C as the lowest air and dew point temperatures. For these cold events occurred on 12 and 13 February 2012, irrigation systems were activated under critical temperatures during 18.8 and 21.7 hours for the grower practice and AC irrigation, correspondingly.

During the fifth cold recovery period, significant differences between the irrigated treatments were found when using the LOW (0.86 Mg ha^{-1}) treatment, which obtained 40%, 58% and 14% greater yields than SPC (0.52 Mg ha^{-1}), GROW (0.36 Mg ha^{-1}) and AC treatments (0.74 Mg ha^{-1}) correspondingly, and 83% higher in yield when compared to the non-irrigated (0.14 Mg ha^{-1}; Table 3-7). During the same recovery period, the comparison between the "grower practice" (0.36 Mg ha^{-1}) against the AC treatment (0.74 Mg ha^{-1}) resulted in 51% significantly lower yield (Table 3-7).

Volume of water applied for cold protection

From the 2011-12 season, AC irrigation was activated during ten cold events for a total of 93.8 hours, while the "grower practice" irrigation (the rest of the treatments) was triggered for 16 cold events totaling 98.4 hours. From the total hours of irrigation, only 77 and 78 hours of "grower practice" and AC irrigation were applied when temperatures fell below strawberry blossom critical temperature (A-1). Table 3-8 shows the amount of water applied per treatment during the cold events for the first season. The GROW treatment used a total of 18,324 m^3 $ha^{-1,}$ while AC used 17,473 m^3 ha^{-1}, LOW applied 14,209 m^3 ha^{-1} and the SPC treatment applied 26,390 m^3 ha^{-1}. Water savings of 5% was achieved by AC and 22% when using LOW as the irrigation system pressure. However, by decreasing the sprinkler spacing, 44% extra water application was obtained.

Cold events according to the crop stage critical temperature (-0.56°C)

During the 2011-12 season, minimum air and dew point temperatures of -8.5°C and -12.9°C were reached. However, thru the season only eleven cold events presented temperatures below the blossom critical temperature (A-1). All of them were freeze protected by irrigation, with the exception of the critical hours occurred on 2 January 2012 (AC and "grower practice"). Irrigation hours for cold events where temperatures got below the blossom critical accounted for 77 and 78 hours for the GROW and the AC treatments, respectively. Both types of irrigation were activated during the same critical hours, however, an excess of 2% irrigation was applied thru AC irrigation. The amount of water applied during the critical temperature events was very similar across all the treatments. A treatment comparison against the "grower practice" for strawberry critical temperature is presented in Appendix-1 (A-1). AC used 222 m^3 ha^-

^{1} extra water, this being a 2% more than the “grower practice”. Reducing the pressure to LOW resulted in 22% water savings (3,221 m^3 ha^{-1}), while reducing the sprinkler spacing to SPC treatment increased the water use by 44% applying 6,314 m^3 ha^{-1} more than GROW treatment.

2012-2013 Season

Yields

A total of 22 harvests were measured at the strawberry field from 3 January. 2012 thru 18 March 2013. The “grower practice” irrigation was triggered 16 cold events, while AC irrigation was triggered only 12 cold events throughout the strawberry harvest season. According to the cold episodes occurred between December 2012 and April 2013 four cold recovery periods were defined during the strawberry harvest season in order to evaluate the recovery in yield of the treatments after cold events.

The NO treatment was strongly affected by certain cold events and thus produced lower average marketable weights (1.27 Mg ha^{-1}) at the end of the harvest period. The AC (2.71 Mg ha^{-1}) and SPC (2.63 Mg ha^{-1}) treatments both showed only slight differences in yield compared to GROW treatment (2.59 Mg ha^{-1}). However, the LOW treatment achieved water savings of 22% without an effect on yield throughout the harvest period, and presented a slightly higher yield at the middle-end of the period (3-4). Irrigation showed a significant effect on cumulative yield against the control treatment (3-5); however, no significant differences between irrigated treatments on average yield were present (Table 3-9).

According to the LSD Bonferroni procedure, AC (0.87 Mg ha^{-1}) and SPC (0.91 Mg ha^{-1}) treatments showed slight differences in yield means compared to the “grower practice” (0.89 Mg ha^{-1}; Table 3-9). Nevertheless, the average yield of the non-irrigated treatment (0.43 Mg ha^{-1}) was significantly lower than the other treatments for all pairwise comparisons (AC: 0.87 Mg ha^{-1}, GROW: 0.89 Mg ha^{-1}, LOW: 0.92 Mg ha^{-1} and SPC: 0.91 Mg ha^{-1}). No significant differences in average yield were found between irrigated treatments (Table 3-9).

Table 3-10 shows the p values of the ANOVA F test statistic for treatment mean comparison according to the yield recovery from cold occurrence during the strawberry 2012-13 harvesting season. Only during the second cold period the NO treatment followed the trend of the irrigated treatments due to prevailing overall mild temperatures. However for the cold periods 1, 3 and 4, significant effect of irrigation was found when compared to the non-irrigated treatment ($p<0.005$). Recover capability from freeze events among the irrigated treatments differ significantly only during the third recovery cold period (Table 3-10).

Among the irrigated treatments, differences in the irrigations systems were significant only during the third recovery cold period in which the LOW treatment showed higher yields (2.83 Mg ha^{-1}) at the end of the season. In contrast, the GROW treatment (2.20 Mg ha^{-1}) obtained 74% and 63% significantly lower yields than LOW (2.83 Mg ha^{-1}) and SPC (2.09 Mg ha^{-1}) respectively. Only irrigated treatments showed a linear increase in the yield after each freeze event.

Cold events and yield recovery periods during the 2012-13 season is described as follows. However, a detailed explanation can be found in the Appendix section. Cold events initiated since 19 December 2012; however, the predominant temperatures were above critical blossom temperature. Nevertheless, subsequent six cold events occurred in late December (22 through 31 December 2012) previous to the harvest season in which air temperature of -4.4˚C and dew point temperature of -2.7˚C were reached respectively. During this entire period “grower practice” irrigation applied 37.3 cumulative hours and AC irrigation 33.9 cumulative hours to protect the plants in the different nights of cold occurrence, however, only 13.3 hours of irrigation were applied when temperature was below critical (A-2). As a result, initial yields (1-10 January 2013) were impacted by freeze and rainfall events occurred in mid-December previous to the harvesting season, affecting more considerably the control treatment (3-4). Consequently, this leaded to the appearance and impact of *Botrytis cinerea,* to the crop. *Botrytis* is a fungus known as Botrytis fruit root or gray mold that affects fruits in the field, occasioning severe pre-harvest losses (Peres 2011). A combination of pesticides and cultural practices (i.e. removing decaying and infected plants and fruits) reduced the damage and successfully controlled the disease in the strawberry field.

After the cold events occurred pre-harvest, mild temperatures predominated until cold events occurred in late-January (22, 23 and 24 January 2013). The sum of 15.3 hours of grower irrigation and 5.7 hours of AC irrigation were needed to protect the crop from low air and dew point temperatures of -2.2˚C and -0.7˚C, respectively. Nevertheless, only one hour of irrigation was triggered to protect the crops from physiological damage. The irrigation effect on the treatments during this first recovery cold period was high significantly different compared to the non-irrigated treatment (Table 3-10).

Five following cold events occurred from 31 January until 5 February 2013. The lowest air temperature reached was -2.3˚C taking place during the first event of the cold period occurred on 31 January until 1 February. The following four cold events were above -1.9˚C. During the five cold events, grower practice irrigation accounted for 39.8 hours for a total of 1,175 m^3 ha^{-1}, and 28.8 hours AC irrigation, which applied 851 m^3 ha^{-1}. Nevertheless, only 6.8 and 3.8 hours of grower practice and AC irrigation occurred when cold periods reached critical temperatures for the strawberry blossom stage; however, no significant differences on yield recovery between the irrigated treatments and the control were present (Table 3-10).

Severe cold events occurred from 17 February until 18 February 2013 reaching the lowest air and dew point temperatures: -6.0˚C and -8.3˚C during the strawberry harvesting season 2012-13. Total hours of irrigation were 19.1 and 22 for the grower practice and AC, correspondingly, and 18.8 and 18.3 hours applied when temperatures fell below critical damage for strawberries. Yields were impacted by these two severe events, showing high significant differences during the third cold recovery period between the irrigated treatments and the control (Table 3-10). The non-irrigated treatment presented the poorest yield recovery (0.95 Mg ha^{-1}) when compared to the irrigated treatments, obtaining 66% 55%, 57% and 57% lower yield than LOW (2.83 Mg ha^{-1}), SPC (2.09 Mg ha^{-1}), GROW (2.20 Mg ha^{-1}) and AC (2.21 Mg ha^{-1}) treatments respectively (Table 3-11). However, the irrigation effect among irrigated treatments was significant as well. The LOW treatment presented significant difference in yield recovery in contrast to the irrigated treatments (Table 3-11). The total weighted yield (2.83 Mg ha^{-1}) achieved was 26%, 22% and 22% higher than SPC, GROW and AC treatments accordingly during that cold period recovery (Table 3-11).

The fourth period of cold events affecting treatment yields initiated on 2 March until 8 March 2013. Minimum air and dew point temperatures fell down to -4.2˚C and -

3.3˚C. During this period grower practice irrigation applied 909, m^3 hr^-1 for a cumulative of 38.7 hours, while the AC irrigation was turned on only 26.4 hours, applying 778 m^3 hr^{-1}. For critical temperature protection, irrigation run during 16.5 and 13.3 hours of grower practice and AC irrigation, correspondingly.

Cumulative marketable weight (kg) per treatment shows slightly differences among irrigated treatments, but almost twice difference total cumulative yield when compared to the non-irrigated treatment (3-5), which obtained 49.1% lower yield than the “grower practice”.

Volume of water applied for cold protection

A total of 23 cold events occurred which received “grower practice” irrigation, while only 17 were irrigated by the AC irrigation (A-2). However, during the harvest season, AC sprinkler irrigation was activated for the duration of 12 cold events, while the “grower practice” irrigation, which activated also the rest of the treatments, was triggered for a total of 16 cold events (3-4). The amount of water applied per treatment during the cold events is shown in Table 3-12. The GROW treatment applied 1,931 m^3 ha^{-1}, while AC used 23,202 m^3 ha^{-1}, LOW applied 22,313 m^3 ha^{-1} and the SPC treatment applied 43,298 m^3 ha^{-1}. Water savings of 22% were achieved using LOW in the irrigation system pressure, followed by 23% water savings when AC technology was used. However, 44% extra water application was obtained by decreasing the sprinkler spacing to 12.2 m.

Cold events according to the crop stage critical temperature (-0.56°C)

During the 2012-13 season, a total of 15 cold events were identified to occur below the critical temperature (-0.56°C) (A-2). All of them were freeze protected by irrigation totaling 56.3 and 51.9 hours applied by the “grower practice” and AC treatment, correspondingly. A comparison between the amount of water applied per treatment showed that AC used 823 m^3 ha^{-1} less water, this being 8% of water savings in comparison to the “grower practice”. Reducing the pressure to LOW resulted in 22% (2,353 m^3 ha^{-1}) water savings. The SPC treatment increased the water use by 44% applying 4,613 m^3 ha^{-1} more than the “grower practice” (A-2).

Low Quarter Distribution Uniformity (DU_{lq}) and Application Rate (AR) Scenarios for the SPC, AC, GROW and LOW Treatments

Scenarios for the SPC, AC, GROW and LOW treatments were performed for DU_{lq} and AR (3-6 and 3-7).

Uniformity (DU_{lq})

Very high uniformity values without significant differences were obtained between SPC (DU_{lq}= 0.80) AC and GROW treatments (DU_{lq} = 0.79 for both), which all were performed using an irrigation system pressure of 345 kPa and 14.6 m spacing, with the exception of SPC treatment which used 12.2 m spacing (3-6). By the contrast, when the irrigation system pressure was reduced to 207 kPa (LOW treatment), uniformity was significantly lower (DU_{lq} =0.68) (3-6).

Application rate (AR)

When application rates were assessed for the different treatments, significantly higher mean AR was obtained by the SPC (AR= 5.1 mm hr^{-1}) in comparison to the AC, GROW (AR= 2.9 mm hr^{-1} for both) and LOW (AR= 2.2 mm hr^{-1}) treatments (3-7). LOW treatment obtained significant lower mean AR in comparison to all other treatments (AR= 2.2 mm hr^{-1}), resulting in 57%, 24% and 24% lower AR compared to SPC, AC and GROW treatments (3-7).

Consequently, if the distribution uniformity values, application rates and yield data are compared, it can be shown that almost 70% uniformity and reductions in the AR up to 57% can be achieved using a lower irrigation system pressure (207 kPa) and 14.6 m spacing and resulting in no significant differences in yield (LOW treatment) compared to the SPC, GROW and AC treatments. By contrast, using a shorter spacing among the sprinklers and high irrigation system pressure (12.2 m spacing and 345 kPa) achieved up to 80% of irrigation uniformity and no significant differences in yield; however, increased the AR by 2.3 times in comparison to the LOW treatment's AR.

Conclusions

During the two winter seasons of 2011-12 and 2012-13, both seasons were about 28% and 57% respectively, below the average number of freezing hours compared to the last 34 years of historical data. The results during these seasons affirmed the effectiveness of sprinkler irrigation for cold protection on strawberries since unprotected strawberries resulted in significantly lower yield. However, during non-severe cold events, the unprotected plants followed the trend of the irrigated treatments. Recovery capability from the cold events among the irrigated treatments differed randomly. Even when the irrigated treatments had a linear increase in yield recovery from cold events, there were no differences between them. Although there were similar total yields among irrigated treatments, there were differences in irrigation volume. Using an automated system based on dew point and air temperature reduced irrigation by 5% during the 2011-12 season and up to 23% during the 2012-13 season. However, increasing the application rate by reducing sprinkler spacing resulted in 44% extra water applied. Reducing the pressure in the irrigation supply to LOW resulted in 22% water savings. Reducing the pressure resulted in 4,115 m^3 ha^{-1} less irrigation during the first season and 6,751 m^3 ha^{-1} in the second season without affecting yield under weather conditions below normal freeze years, in which this study was performed. Therefore, an estimated average of 19.3 billion liters of water per harvest season could be saved considering the 3,561 ha of strawberries planted in Florida in 2010 (USDA 2013b). Number that will proportionally increase with the area planted per season.

Table 3-1. Citrus cold protection application rate (mm hr^{-1}) recommendation according to minimum temperature expected and wind speed conditions (Gerber and Martsolf 1965).

Min. Temp. Expected (°C)	0 - 0.4	0.9 - 1.8	2.2 - 3.6	4.5 - 6.3	8.0 - 9.8	13.4
	Wind Speed (m s^{-1})					
	Application Rate (mm hr^{-1})					
-2.8	2.5	2.5	2.5	2.5	5.1	7.6
-3.3	2.5	2.5	3.6	5.1	10.2	15.2
-4.4	2.5	4.1	7.6	10.2	20.3	40.6
-5.6	3.0	6.1	12.7	15.2	30.5	45.7
-6.7	4.1	7.6	15.2	20.3	40.6	61.0
-7.8	5.1	10.2	17.8	25.4	50.8	76.2
-9.4	6.6	12.7	22.9	33.0	66.0	101.6
-11.7	8.6	17.8	30.5	43.2	86.4	127.0

Table 3-2. Strawberry critical temperatures at different crop stages calculated using dew point and wet bulb temperatures (°C) *. Note: Table used to determine turn-on and turn-off times for the AC treatment irrigation system.

Crop Stage	Tight bud	Popcorn	Fruit	Open Blossom	Suggest Starting (Air) Temperatures
	Strawberry Critical Temp. at				
	Critical Temperature or Wet Bulb Temperature (°C)				
Dew Point (°C)	-5.0	-2.2	-1.7	-0.6	(°C)**
0.0	-	-	-	-	1.1
-0.6	-	-	-	-0.6	1.6
-1.1	-	-	-	-0.2	
-1.7	-	-	-1.7	0.2	2.2
-2.2	-	-2.2	-1.3	0.5	2.8
-2.8	-	-1.9	-1.0	0.8	
-3.3	-	-1.6	-0.7	1.1	3.3
-3.9	-	-1.3	-0.4	1.4	
-4.4	-	-1.0	-0.1	1.7	4.4
-5.0	-5.0	-0.7	0.2	2.0	
-5.6	-4.7	-0.4	0.4	2.3	5.0
-6.1	-4.4	-0.2	0.7	2.6	
-6.7	-4.2	0.1	0.9	2.8	5.6
-7.2	-3.9	0.3	1.2	3.1	
-7.8	-3.7	0.6	1.4	3.3	6.1

* Adapted from Snyder (2000)
**Adapted from O'Dell and Williams (2009)

Table 3-3. Treatments evaluated in the experimental field at PSREU, near Citra, FL 2011-2013.

Treatment	Sprinkler	Pressure (kPa)	Sprinkler spacing (m)	Control
GROW	WR-32	345	14.6	Thermocouple
LOW	WR-32	207	14.6	Thermocouple
AC	WR-32	345	14.6	Wireless sensors
NO	No sprinklers	Non frost protected	NA	NA
SPC	WR-32	345	12.2	Thermocouple

NA: Not Applicable

Table 3-4. Summary water applied and water savings per treatment during two years of field results. PSREU, Citra, FL.

Treat.	Pressure (kPa)	Irrigation $m^3\ ha^{-1}$		Mean yield ($Mg\ ha^{-1}$)		Water Savings (%)	
		Yr. 1	Yr. 2	Yr. 1	Yr. 2	Yr. 1	Yr. 2
AC	345	17,473	23,202	3.11 a	2.71 a	5	23
GROW	345	18,324	30,06	2.66 a	2.59 a	0	-
LOW	207	14,209	23,313	2.99 a	2.76 a	22	22
NO	-	-	-	0.80 b	1.27 b	100	100
SPC	345	26,390	43,298	2.68 a	2.63 a	-44	-44

Yr. 1 and Yr. 2 correspond to the 2011-12 and the 2012-13 seasons, correspondingly. Different letters correspond to significant differences between treatments.

Table 3-5. Treatment means ($Mg\ ha^{-1}$) and pairwise comparison tests according to Bonferroni LSD during 2011-12 season.

Treatment	Yield means ($Mg\ ha^{1}$)	Pairwise comparison of yield means LOW	SPC	GROW	AC	NO
LOW	2.99	0.00	-0.31	-0.33	0.12	-2.19**
SPC	2.68		0.00	-0.02	0.43	-1.88**
GROW	2.66			0.00	0.45	-1.86**
AC	3.11				0.00	-2.31**
NO	0.80					0.00

ns: Not significant.
(*) Denotes significant differences between treatments at each cold period ($p< 0.05$).
(**) Denotes high significant differences between treatments at each cold period ($p<0.005$).

Table 3-6. P-values of the ANOVA F-test statistic for treatment means through recovery cold periods during 2011-2012 season.

		2011-12				
	Cold Period	1	2	3	4	5
Block		ns	ns	ns	ns	ns
Treat		**	**	**	**	**
	Irr. /NO	**	**	**	**	*
	Betw. Irrig.Treat.	ns	*	ns	ns	*
		ns	*	ns	ns	*
Interaction						
Time		**	**	**	**	ns
	Irr./NO lin.	**	**	ns	ns	ns
	Irr./NO sq.	ns	ns	ns	ns	ns
Error 2		ns	ns	ns	ns	ns

ns: Not significant.
(*) Denotes significant differences between treatments at each cold period (p< 0.05).
(**) Denotes high significant differences between treatments at each cold period (p<0.005).
Irr. /NO: Comparison among irrigated treatments (Irr) versus non-irrigated treatment (NO).
Irr. /NO lin. or Irr/NO sq.: Linear (lin.) or square (sq.) interaction among Irrigated versus non-irrigated treatment.

Table 3-7. Mean Comparison on recovery cold periods with significant differences between irrigated treatments during the 2011-12 season.

	Cold Period			
Treat	2		5	
LOW	/AC	*	/other	*
SPC		ns		ns
GROW	/other	*	/AC	*
AC		ns		ns
NO	/Irr.	**	/Irr.	**

ns: Not significant.
(*) Denotes significant differences between treatments at each cold period (p< 0.05).
(**) Denotes high significant differences between treatments at each cold period (p<0.005).
/other: other irrigated treatments (AC, GROW and SPC) comparison.
/Irr.: all irrigated treatments (AC, GROW, LOW and SPC) comparison.

Table 3-8. Amount of water applied during the cold events and percent water savings per treatment (compared to GROW treatment). Citra, FL. 2011- 12 season.

Treatment	Pressure (kPa)	Irrigation (m^3 applied)*	$m^3 ha^{-1}$	Water savings ($m^3 ha^{-1}$)	Water Savings (%)
AC	345	1,122	17,473	851	5
GROW	345	1,177	18,324	-	-
LOW	207	913	14,209	4,115	22
NO	-	-	-	18,324	100
SPC	345	1,177	26,390	-8,066	-44

* Total irrigation (m^3) applied on the three repetition plots of the treatment, over all cold events.

Table 3-9. Treatment yield means ($Mg\ ha^{-1}$) and pairwise comparison tests according to Bonferroni LSD during 2012-13 season.

Treatment	Avg. yield ($Mg\ ha^{-1}$)	LOW	SPC	GROW	AC	NO
		Pairwise comparison of yield means				
LOW	2.76	0.00	-0.13	-0.17	-0.05	-1.49**
SPC	2.63		0.00	-0.04	0.08	-1.36**
GROW	2.59			0.00	0.12	-1.32**
AC	2.71				0.00	-1.44**
NO	1.27					0.00

ns: Not significant.
(*) Denotes significant differences between treatments at each cold period ($p< 0.05$).
(**) Denotes high significant differences between treatments at each cold period ($p<0.005$).

Table 3-10. P-values of the ANOVA F-test statistic for treatment means through recovery cold periods during 2012-2013 season.

		2012-13			
	Cold Period	1	2	3	4
Block		*	ns	*	ns
Treat		**	ns	**	**
	Irr./NO	**	ns	**	**
	Betw. Irrig.Treat	ns	ns	*	ns
Interaction					
Time		**	**	**	**
	Irr./NO lin.	ns	ns	**	ns
	Irr./NO sq.	ns	ns	ns	ns
Error 2		ns	ns	ns	*

ns: Not significant.
(*) Denotes significant differences between treatments at each cold period ($p< 0.05$).
(**) Denotes high significant differences between treatments at each cold period ($p<0.005$).
Irr/NO: Comparison among irrigated treatments (Irr) versus non-irrigated treatment (NO).
Irr/NO lin. or Irr/NO sq.: Linear (lin.) or square (sq.) interaction among Irrigated versus non-irrigated treatment.

Table 3-11. Mean Comparison on recovery cold periods with significant differences between irrigated treatments during the 2012-13 season.

	2012-13	
Treat		Cold period
		3
LOW	/other	*
SPC		ns
GROW		ns
AC		ns
NO	/Irr	**

ns: Not significant.
(*) Denotes significant differences between treatments at each cold period ($p< 0.05$).
(**) Denotes high significant differences between treatments at each cold period ($p<0.005$).
/other: other irrigated treatments (AC, GROW and SPC) comparison.
/Irr: all irrigated treatments (AC, GROW, LOW and SPC) comparison.

Table 3-12. Amount of water applied during the cold events and percent water savings per treatment (compared to GROW treatment). Citra, FL. 2012- 13 season.

Treatment	Pressure	Irrigation		Water savings	Water Savings
	(kPa)	(m^3 applied)*	$m^3\ ha^{-1}$	($m^3\ ha^{-1}$)	(%)
AC	345	1,490	23,202	6,862	23
GROW	345	1,931	30,06	-	-
LOW	207	1,497	23,313	6,751	22
NO	-	-	-	30,064	100
SPC	345	1,931	43,298	-13,234	-44

(*)=Total irrigation (m^3) applied on the three repetition plots of the treatment, over all cold events.

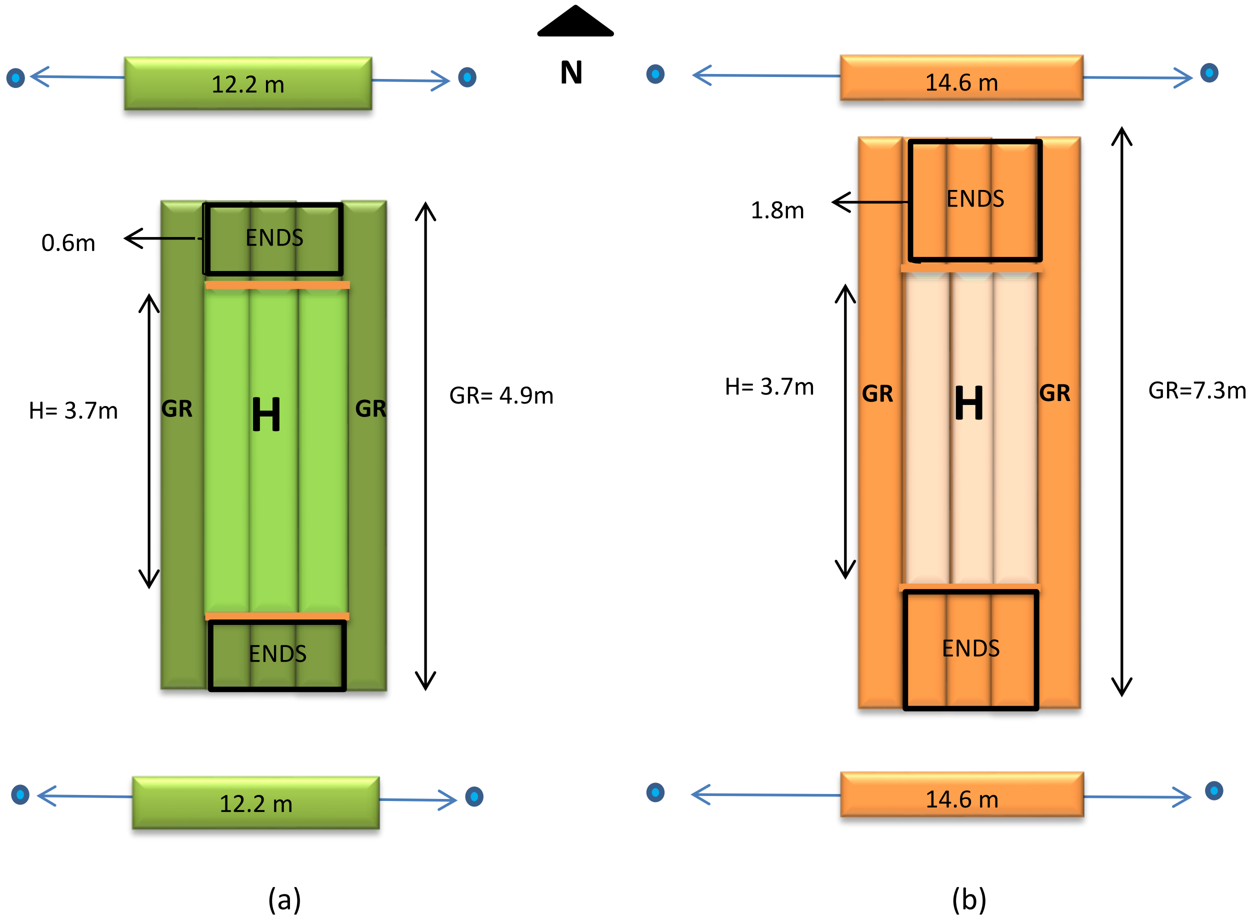

Figure 3-1. Strawberry harvesting layout. Subplots designed for (a) SPC at12.2 m. sprinkler spacing and (b) for AC, GROW and LOW treatments at 14.6 m sprinkler spacing. H= harvest areas for data analysis, GR= guard rows and ENDS= ends of the rows, both established to eliminate border effect. Blue dots represent the sprinkler heads at the two sprinkler spacings.

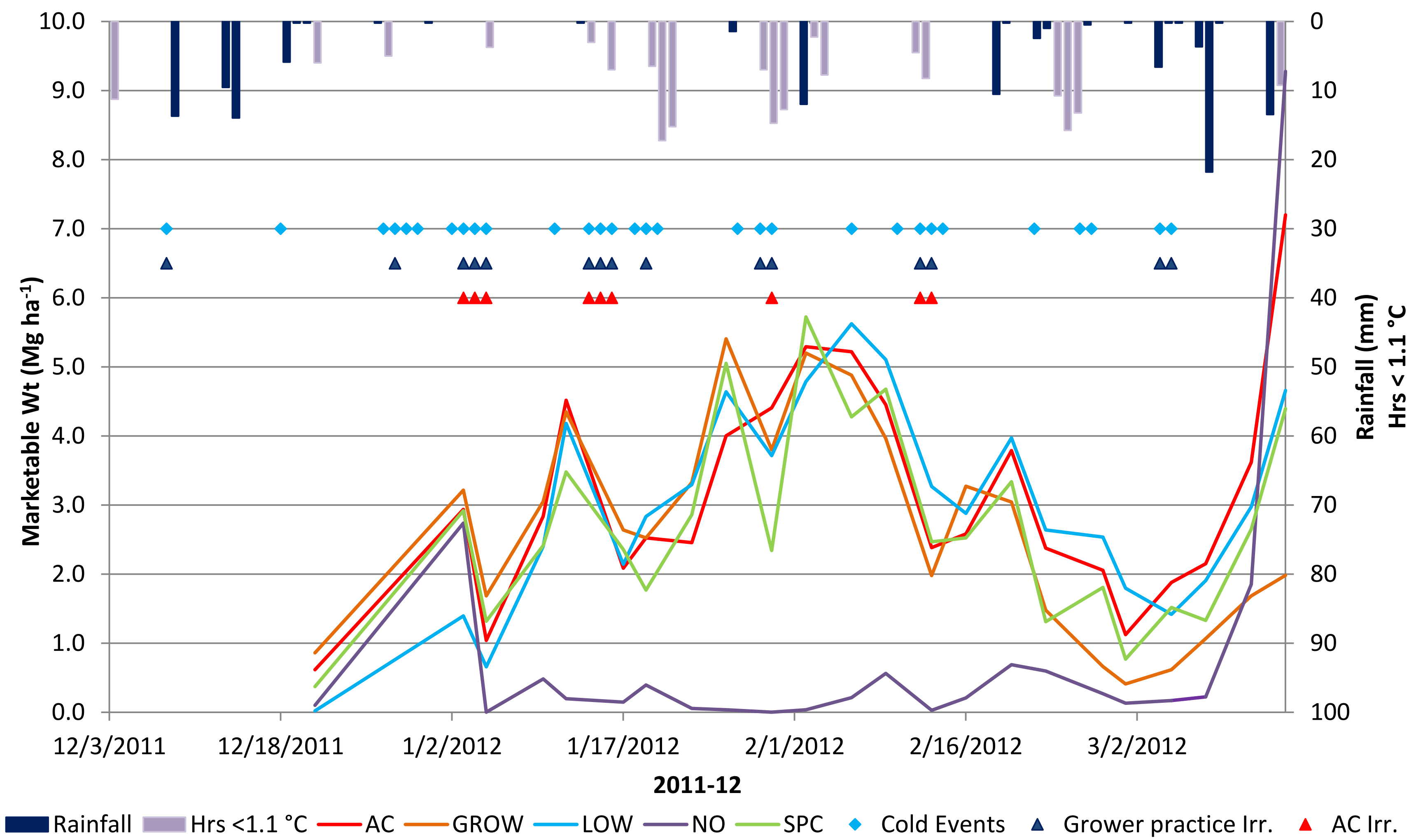

Figure 3-2. Weighted marketable weight (Mg ha^{-1}) per treatment (lines). Irrigation cold protection events during harvest season 2011-12. PSREU, Citra, FL. Note: irrigation or cold events data points might be jointed through overnight and continued days cold events; therefore, only one data point is shown in 3-2, 3-3, 3-4 and 3-5.

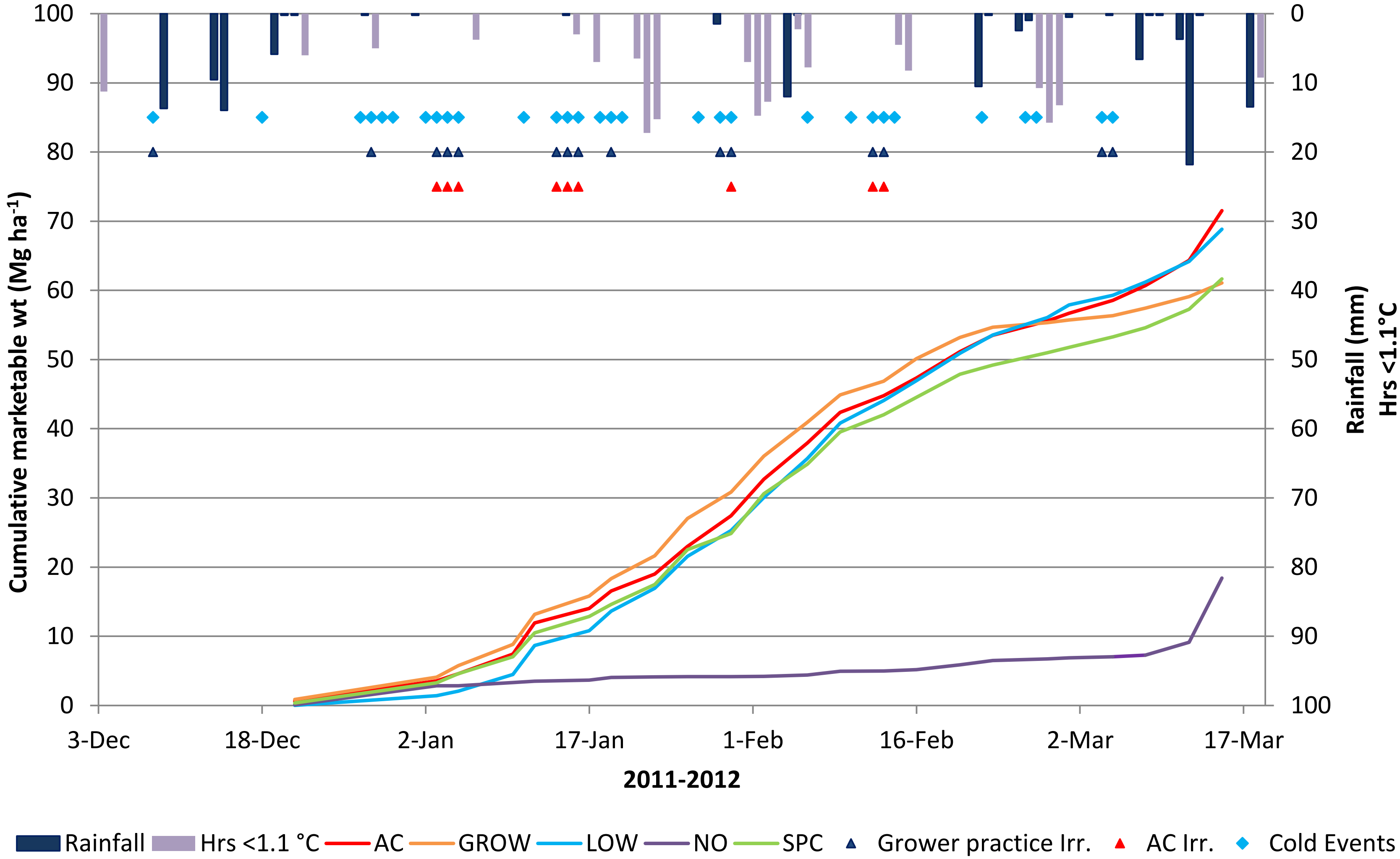

Figure 3-3. Cumulative marketable weight (Mg ha^{-1}) per treatment (lines). Irrigation cold protection events during harvest season 2011-12. PSREU, Citra, FL.

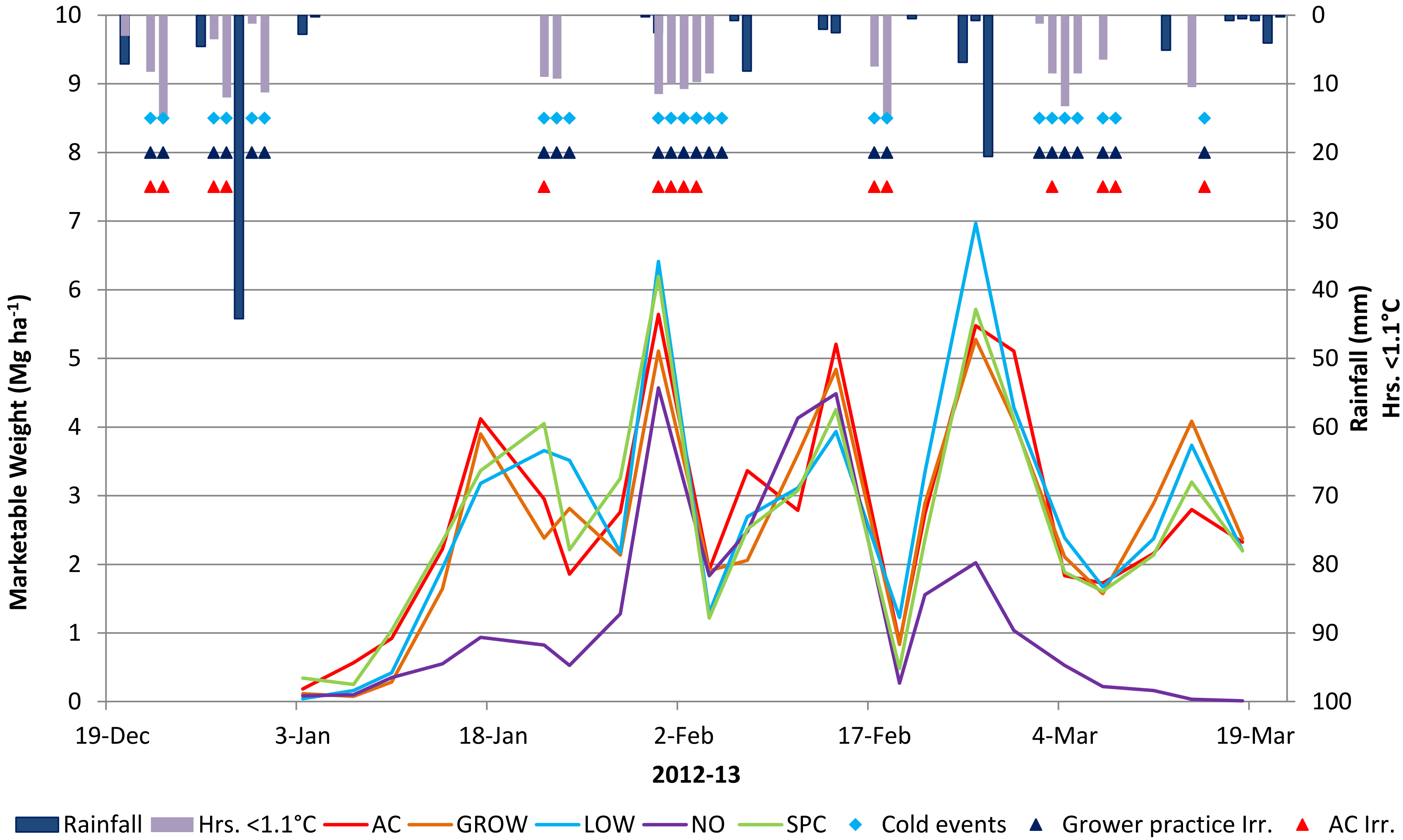

Figure 3-4. Weighted marketable weight (Mg ha^{-1}) per treatment (lines). Irrigation cold protection events during harvest season 2012-13. PSREU, Citra, FL.

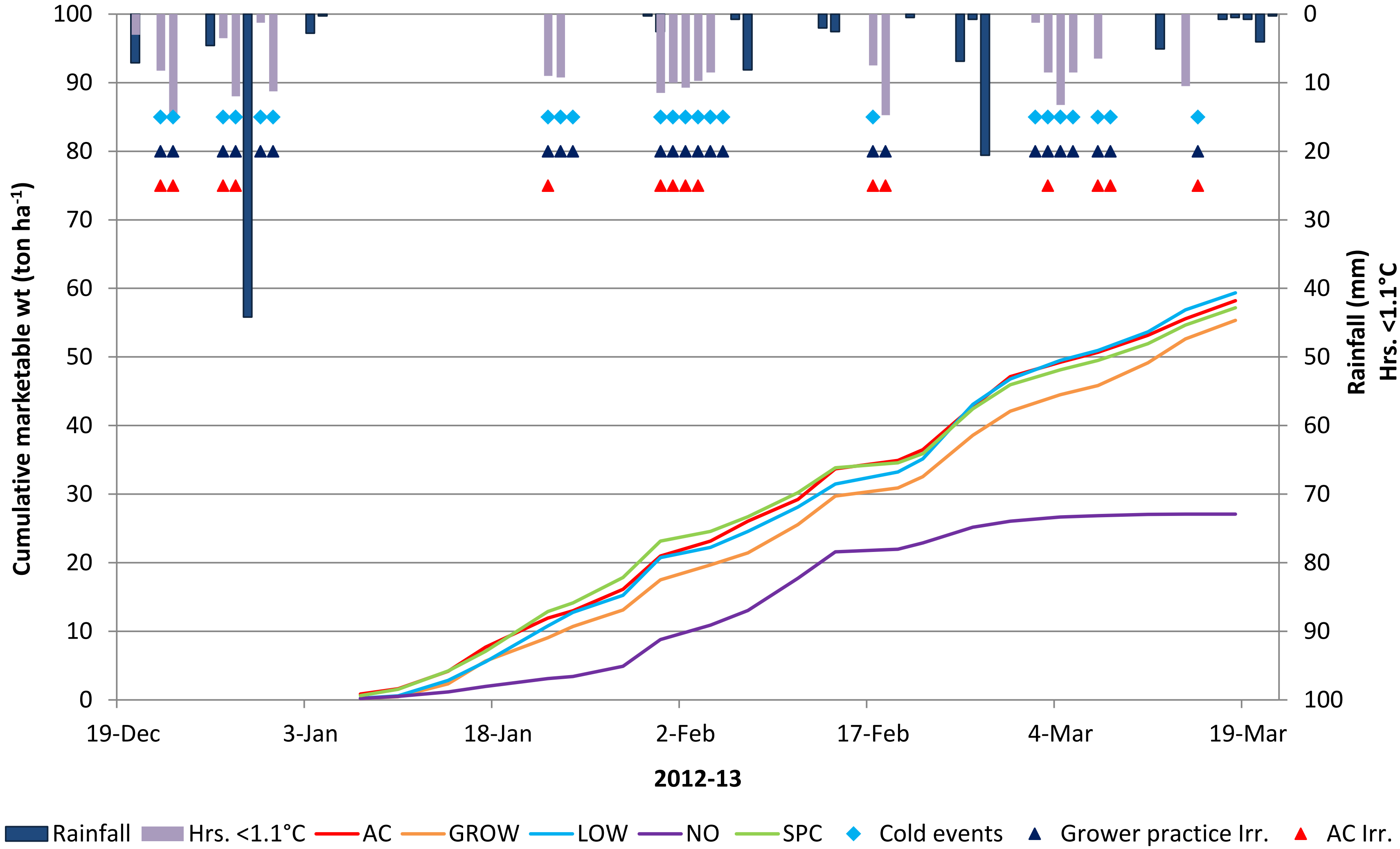

Figure 3-5. Cumulative marketable weight (Mg ha^{-1}) per treatment (lines). Irrigation cold protection events during harvest season 2012-13. PSREU, Citra, FL.

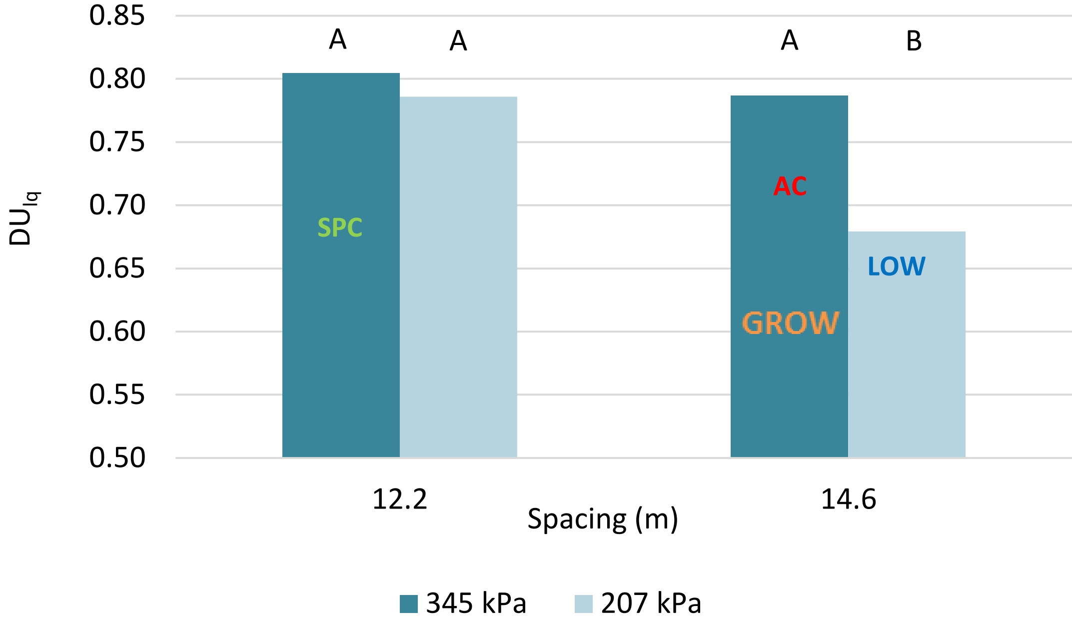

Figure 3-6. Low quarter distribution uniformity values (DU_{lq}) for WR-32 impact sprinklers evaluated at two irrigation system pressures (345 and 207 kPa) and two sprinkler spacings (14.6 and 12.2 m) corresponding to the SPC AC, GROW and LOW treatments evaluated under cold conditions at the different pressures and spacings at Citra, FL. Different letters indicate significantly different means (LSD_{Bon} 95%CI).

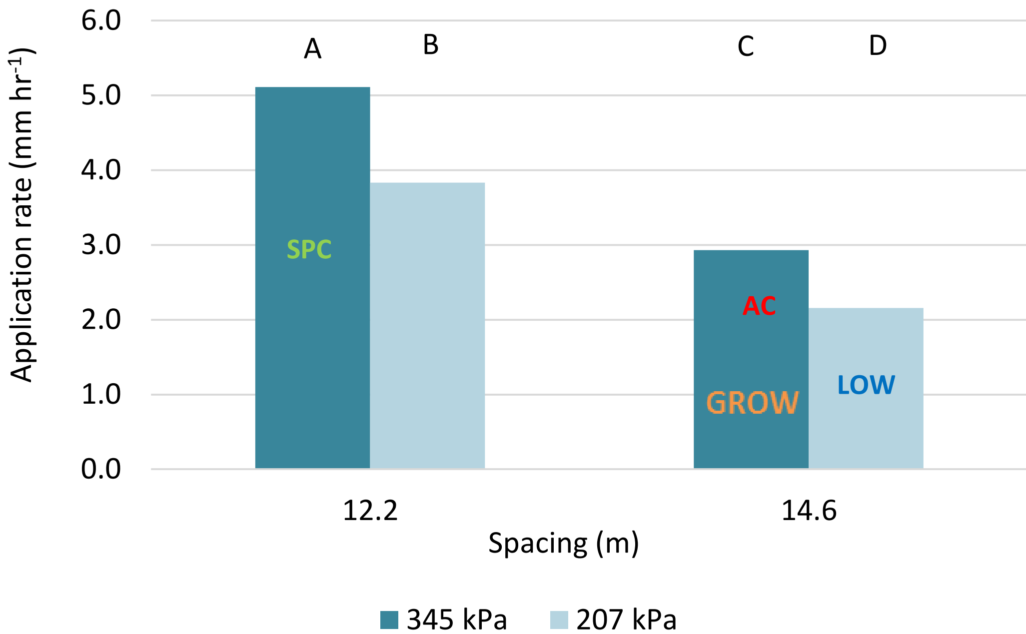

Figure 3-7. Application rates resulted from the evaluation of WR-32 impact sprinklers at two irrigation system pressures (345 and 207 kPa) and two sprinkler spacings (14.6 and 12.2 m) corresponding to the SPC, AC, GROW and LOW treatments evaluated under cold conditions at the different pressures and spacings at Citra, FL. Different letters indicate significantly different means (LSD_{Bon} 95%CI).

CHAPTER 4
CONCLUSIONS AND FUTURE WORK

Conclusions

The main goal for this research was to optimize irrigation management practices for cold protection in strawberries that could conserve water. The primary objectives for this project were to: (i) investigate cold protection practices in Florida's strawberry industry and optimize current strawberry irrigation cold protection application rates (ii) assess the effect of sprinkler type, sprinkler spacing, irrigation system pressure variations and varied climatic wind conditions over irrigation distribution uniformity (DU_{lq}) and application rate (AR), and (iii) evaluate the effect of varying sprinkler spacing and pressure on strawberry yield quality and quantity under cold conditions.

Sprinkler irrigation is a current practice widely used in Florida applied as an effort to reduce cold (freeze/frost) damage on strawberries during the winter. Two main parameters should be taken into consideration when water is applied for a successful protection: uniformity and application rate.

A variety of sprinkler types are used for cold protection; however impact sprinklers are most commonly used in Florida strawberry fields. Four sprinkler types were tested as follows: Wade Rain impact sprinklers WR-32, and three Nelson rotators R33, R33LP and R2000WF. The evaluation of the sprinkler types previously described, showed that all sprinklers achieved higher uniformity under higher pressure levels, and vice versa, the lower the pressure level, the lower the distribution uniformity for all sprinkler types. However, if the irrigation system pressure was reduced to 276 kPa and 207 kPa, the WR-32 impact sprinklers and R2000WF rotator sprinklers resulted in significantly higher DU_{lq} in comparison to the Nelson R33 and R33LP sprinklers evaluated at the same pressure levels. By contrast, WR-32 and R2000WF water application rates (AR) were significantly lower than the R33 and R33LP performed at each pressure level and across all the irrigation pressure levels. Therefore, the former ones can achieved higher uniformity profiles under lower application rates in comparison to the latter ones.

In the same manner, WR-32 and R2000WF obtained significantly higher DU_{lq} at a 12.2 m sprinkler spacing than the R33 and R33LP, but significant differences were not found in uniformity when all the sprinkler types were evaluated at 14.6 m sprinkler spacing. Nevertheless, significantly lower AR were applied by WR-32 and R2000WF in comparison to the two other Nelson rotators at both sprinkler spacings. All sprinkler types applied significantly higher AR at a 12.2 m spacing, except R2000WF which applied statistically the same AR as WR-32 and R2000WF when evaluated at 14.6 m spacing.

Significant differences in low quarter distribution uniformity (DU_{lq}) were not found when the sprinklers were tested at the two highest pressures and shorter spacing (345 and 276 kPa at 12.2 m spacing) neither when evaluated at the highest pressure and largest spacing (345 kPa at 14.6 m sprinkler spacing). However, significantly lower DU_{lq} values were obtained at 207 kPa system pressure in comparison to the higher pressures.

Significantly higher AR were obtained at the 12.2 m spacing in comparison to the 14.6 m spacing at all pressure levels, and overall significantly lower ARs were obtained as a result of using the 207 kPa when compared to the other pressure levels at the same spacing.

High wind speed resulted in significantly lower uniformity for the impact sprinklers. Therefore, sprinkler irrigation non-uniform coverage may result during cold nights under high wind conditions, impacting the yields.

Distribution profiles simulations can be performed by using programs e.g. SPACE Pro, which can be used to determine some irrigation system design components (i.e. sprinkler nozzle, pressure, spacing, sprinkler type) which may impact uniformity and efficiency of the irrigation systems. For this particular study, SPACE Pro results showed that the simulation data differed from real uniformity and water application rate values.

The AR recommended for cold protection of 6.35 mm hr^{-1} has been used largely and successfully; though, the results of this research found that lower application rates can be achieved by using any of the sprinklers simulated and tested at the field, which on average, overall sprinklers applied AR lower than 5.63 mm hr^{-1}. The commonly used WR-32 impact sprinklers had average reductions in water application rates up to 37%, 45% and 52% using 345, 276 and 207 kPa compared to the 6.35 mm hr^{-1} recommended AR for cold protection and 57% and 31% when these impact sprinklers are spaced at 14.6 m and 12.2m, respectively.

Therefore, more opportunities to reduce the amount of water applied through irrigation using lower pressures in the system, but achieving adequate irrigation uniformity can be accomplished.

Even though the weather conditions for the 2011-12 and 2012-13 winter seasons, in which this research was performed, were 28% and 57% respectively below the average number of freezing hours in comparison to the last 34 years of historical data, the results affirmed the effectiveness of sprinkler irrigation for cold protection on strawberries since unprotected strawberries resulted in significantly lower yield and a reduced recovery from the occurrence of cold events. By the contrast, irrigated treatments presented a linear increase in yield as a recovery from the cold events, without differences among them.

Although no differences in yield were observed between the irrigated treatments, significant differences in irrigation volume occurred. Simply reducing the irrigation system supply pressure to 207 kPa (LOW treatment) consistently produced 22% water savings during both year seasons even under lower distribution uniformity profiles. Using an automated irrigation system (AC treatment) based on dew point and air temperature with an AR of 2.9 mm hr^{-1} achieved 5% and up to 23% water savings during 2011-12 and 2012-13 year seasons in comparison to the GROW treatment, which had the same AR (2.9 mm hr^{-1}). However, reductions in AC water savings can result if low dew point temperatures are reached in shorter periods of time, more likely to occur during severe cold events for longer periods. By contrast, reducing sprinkler spacing from 14.6 m to 12.2 m (SPC treatment) higher uniformity (DU_{lq}= 0.80) and application rate (AR= 5.1 mm hr^{-1}) were achieved; however it resulted in 44% excess of water applied in both seasons in comparison to grower practices. This treatment may be effective under severe cold events since more water is applied, thus more heat could be released in order to keep the temperature around 0°C, higher uniformity can be achieved reducing possible damages in yield due to non-uniformity applications. Under weather conditions below normal cold years, in which this study was performed, a total of 4,115 m^3 ha^{-1} less irrigation was applied by the LOW treatment during the first season and 6,751 m^3 ha^{-1} in the second season without affecting yield. Therefore, substantial irrigation savings up to 19.3 billion liters of water per harvest season on average could be saved by reducing the pressure in the irrigation system, considering only 3,561 ha of strawberries planted in Florida in 2010 (USDA 2013b). Proportionally higher water savings can be achieved if larger strawberry areas are planted per season.

Future Work

Higher uniformity was achieved by using shorter sprinkler spacings, however, under cold conditions only the irrigation treatment combination of a shorter spacing and higher pressure was evaluated (SPC treatment: 12.2 m spacing at 345 kPa). Therefore, testing uniformity distribution and yield results under cold conditions using a shorter spacing and a lower pressure may result in substantial irrigation savings that may result in good yield quality and quantity.

These irrigation treatments were evaluated under weather conditions below average normal cold years and were shown to save water under those conditions. However, severe cold conditions will prevail in normal cold years; therefore these treatments should be tested under normal and excessive cold year conditions in order to prove water savings without impacting yields.

APPENDIX

IRRIGATION COMPARISON DURING CRITICAL TEMPERATURES FOR STRAWBERRIES

A-1. Comparison of volume applied by AC and other treatments during the physiological critical temp. events 2011-12.

							"Grower practice"				AC treatment			
Cold event		Treat	Min Temp (˚C)			Wind Speed	Irr. Time	Irr. H	Flow rate	Vol. applied	Irr. Time	Irr. H	Flow rate	Vol. applied
Date	Time		Air	Leaf	DP	(m s^{-1})		(h)	(m^3 h^{-1})	(m^3)		(h)	(m^3 h^{-1})	(m^3)
1/2/2012		AC	4.8	-1.5	-2.9	0.9	-	0			-	0	1.0	0.0
Start time	19:30	GROW		-1.0					1.0	-				
End Time	20:45	LOW		1.7					0.8	-				
		NO		3.6					-	-				
		SPC		4.3					1.0	-				
Sum										-				0.0
1/3/2012		AC	-0.8	-3.1	-12.9	3.4		2				2	1.0	23.9
Start time	5:15	GROW		-3.6			5:45		1.0	23.9	5:45			
End Time	10:30	LOW		-3.4			7:45		0.8	18.5	7:45			
		NO		-2.9					-	-				
		SPC		-2.9					1.0	23.9				
Sum										66.4				23.9
1/3-4/12		AC		-3.2				13.75				13.75	1.0	164.5
Start time	18:00	GROW	-7.2	-4.4	-8.9	0.7	18:30		1.0	164.4	18:30			
End Time	8:30	LOW		-7.1			8:15		0.8	127.5	8:15			
		NO		-8.5					-	-				
		SPC		-3.9					1.0	164.4				
Sum										456.3				164.5
01/04-5/12		AC	-3.3	-2.1	-7.5	0.5		11.25				11.25	1.0	134.6
Start time	18:15	GROW		-2.6			20:45		1.0	134.5	20:45			
End Time	8:00	LOW		-3.9			8:00		0.8	104.3	8:00			
		NO		-5.1					-	-				
		SPC		-2.3					1.0	134.5				
Sum										373.3				134.6

A-1. Continued

Cold event		Treat	Min Temp (˚C)			Wind Speed	"Grower practice" Irr. Time	Irr. H	Flow rate	Vol. applied	AC treatment Irr. Time	Irr. H	Flow rate	Vol. applied
Date	Time		Air	Leaf	DP	(m s^{-1})		(h)	(m^3 h^{-1})	(m^3)		(h)	(m^3 h^{-1})	(m^3)
1/14/2012		AC	-2.4	-2.1	-1.2	0.9		4.5				4.5	1.0	53.8
Start time	3:45	GROW		-1.8			3:45		1.0	53.8	3:45			
End Time	8:15	LOW		-2.7			8:15		0.8	41.7	8:15			
		NO		-4.9					-	-				
		SPC		-2.4					1.0	53.8				
Sum										149.3				53.8
01/14-15/12		AC	-3.3	-2.2	-3.8	0.4		12.25				12	1.0	146.5
Start time	18:45	GROW		-2.1			19:45		1.0	146.5	19:45			
End Time	8:00	LOW		-3.4			8:00		0.8	113.6	8:00			
		NO		-3.4					-	-				
		SPC		-2.6					1.0	146.5				
Sum										406.5				146.5
01/15-16/12		AC	-2.2	-1.7	-2.2	0.1		10				8.5	1.0	101.7
Start time	20:45	GROW		-1.6			21:45		1.0	119.6	23:17			
End Time	7:45	LOW		-1.8			7:45		0.8	92.7	7:45			
		NO		-3.3					-	-				
		SPC		-1.8					1.0	119.6				
Sum										331.8				101.7
1/30/2012		AC	0.1	-1.5	0.5	0.3		2.5				2.3	1.0	26.9
Start time	4:30	GROW		-0.5			4:30		1.0	29.9	4:45			
End Time	7:00	LOW		-0.6			7:00		0.8	23.2	7:00			
		NO		-2.2					-	-				
		SPC		0.2					1.0	29.9				
Sum										83.0				26.9

A-1. Continued

Cold event		Treat	Min Temp (˚C)			Wind Speed	"Grower practice" Irr. Time	Irr. H	Flow rate	Vol. applied	AC treatment Irr. Time	Irr. H	Flow rate	Vol. applied
Date	Time		Air	Leaf	DP	(m s^{-1})		(h)	(m^3 h^{-1})	(m^3)		(h)	(m^3 h^{-1})	(m^3)
2/12/2012		AC	-3.6	-4.2	-10.6	3.3		6.8				9.7	1.0	116.0
Start time	1:00	GROW		-4.9			2:01		1.0	81.3	2:00			
End Time	9:45	LOW		-4.0			8:45		0.8	63.0	8:45			
		NO		-4.0					-	-				
		SPC		-4.0					1.0	81.3				
Sum										225.6				116.0
2/12-13/2012		AC	-6.3	-3.0	-7.3	0.5		12				12	1.0	143.5
Start time	19:15	GROW		-3.7			19:45		1.0	143.5	19:45			
End Time	8:30	LOW		-6.2			7:45		0.8	111.3	7:45			
		NO		-6.5					-	-				
		SPC		-3.1					1.0	143.5				
Sum										398.2				143.5
3/5/2012		AC	1.1	-0.9	1.5	0.3		2				2	1.0	23.9
Start time	1:30	GROW		-0.3			2:30		1.0	23.9	2:30			
End Time	6:15	LOW		0.9			4:15		0.8	18.5	4:15			
		NO		-0.8					-	-				
		SPC		1.4					1.0	23.9				
Sum										66.4				23.9
Total (L) applied in the experiment. (All treat running at the same time)								77		2,556.7		78		935.4
									GROW	921.2				
									LOW	714.3				
									NO	-				
									SPC	921.2				
Difference (GROW-AC)										(14.3)				
% AC Savings										-(1.5)				

A-2. Irrigation comparison between grower practice and other irrigated treatments vs.AC irrigation during the strawberry physiological critical temp. events 2012-13.

Cold event		Treat	Min Temp (˚C)			Wind Speed	"Grower practice"				AC treatment			
Date	Time		Air	Leaf	DP	(m s⁻¹)	Irr. Time	Irr. H (h)	Flow rate ($m^3 h^{-1}$)	Vol. applied (m^3)	Irr. Time	Irr. H (h)	Flow rate ($m^3 h^{-1}$)	Vol. applied (m^3)
12/22/2012		AC	1.6	-1.7	1.8	2.2	5:15	2.5				2.5	1.0	29.9
Start time	3:30	GROW		-2.1			7:45		1.0	29.9	3:30			
End Time	7:45	LOW		-0.9					0.8	23.2	7:45			
		NO		-2.1					-	-				
		SPC		-0.9					1.0	29.9				
Sum							Sum			83.0				29.9
12/22-23/12		AC	-2.8	-2.2	-2.7	0.4		9.8				9.8	1.0	117.2
Start time	19:15	GROW		-3.2			19:45		1.0	117.2	20:00			
End Time	8:00	LOW		-3.4			21:00		0.8	90.9	8:00			
		NO		-4.4			23:30		-	-				
		SPC		-2.1			8:00		1.0	117.2				
Sum							Sum			325.2				117.2
12/27/2012		AC	0.6	-1.7	0.0	1.2		0.5				0.5	1.0	6.0
Start time	6:30	GROW		-0.6			6:30		1.0	6.0	6:30			
	7:30	LOW		-0.4			7:30		0.8	4.6	7:30			
		NO		-0.6					-	-				
		SPC		0.8					1.0	6.0				
Sum							Sum			16.6				6.0
12/27-28/12		AC	0.0	-1.7	0.2	0.3		0.25				0.25	1.0	3.0
Start time	21:45	GROW		-1.0			7:00		1.0	3.0				
End Time	3:00	LOW		-0.7			7:15		0.8	2.3	3:00			
	7:00	NO		-1.3					-	-	7:00			
	7:15	SPC		0.1					1.0	3.0	7:15			
Sum							Sum			8.3				3.0

A-2. Continued

Cold event: Date	Cold event: Time	Treat	Min Temp (˚C): Air	Min Temp (˚C): Leaf	Min Temp (˚C): DP	Wind Speed ($m\ s^{-1}$)	"Grower practice": Irr. Time	"Grower practice": Irr. H (h)	"Grower practice": Flow rate ($m^3\ h^{-1}$)	"Grower practice": Vol. applied (m^3)	AC treatment: Irr. Time	AC treatment: Irr. H (h)	AC treatment: Flow rate ($m^3\ h^{-1}$)	AC treatment: Vol. applied (m^3)
12/30/2012		AC	1.7	-1.1	-1.2	2.3		0.25				0.25	1.0	3.0
Start time	7:15	GROW		-0.3			7:15		1.0	3.0	7:15			
End Time	7:30	LOW		-0.4			7:30		0.8	2.3	7:30			
		NO		-0.3					-	-				
		SPC		0.5					1.0	3.0				
Sum							Sum			8.3				3.0
1/23/2013		AC	-0.7	-1.7	-0.7	0.4		1				1	1.0	12.0
Start time	1:00	GROW		-1.0			2:00-2:30		1.0	12.0	2:40			
End Time	7:45	LOW		-1.7			5:30-5:45		0.8	9.3	7:45			
		NO		-2.2			7:15-7:30		-	-				
		SPC		-0.6					1.0	12.0				
Sum							Sum			33.2				12.0
2/1-2/13	23:30	AC	4.1	-1.1	0.6	0.6	23:30	0.25			23:45	0.25	1.0	3.0
	23:45	GROW	-0.7	-0.3	-1.6	0.4	23:45	2.25	1.0	29.9	4:30-	2.25		26.9
2/2/2013	4:30-	LOW		-1.2					0.8	23.2	6:45			
	6:45	NO		-1.9					-	-				
		SPC		-0.3					1.0	29.9				
Sum							Sum			83.0				29.9
2/3/2013	1:45-	AC	1.4	-1.1	0.1	0.2	1:45-	3			1:45-	0.25	1.0	3.0
	2:00-	GROW	0.0	-1.3	-0.1	0.4	2:00-		1.0	35.9	2:00-	2.75		32.9
	4:15	LOW		-1.6			4:15		0.8	27.8	4:15			
	7:00	NO		-1.6			7:00		-	-	7:00			
		SPC		-1.0			1:45-		1.0	35.9				
										99.5				35.9

A-2. Continued

Cold event		Treat	Min Temp (˚C)			Wind Speed	"Grower practice" Irr. Time	Irr. H	Flow rate	Vol. applied	AC treatment Irr. Time	Irr. H	Flow rate	Vol. applied
Date	Time		Air	Leaf	DP	(m s^{-1})		(h)	(m^3 h^{-1})	(m^3)		(h)	(m^3 h^{-1})	(m^3)
2/4/2013	0:15	AC	1.0	-1.1	1.3	0.4	0:15	1.25			6:15	0.5	1.0	3.0
	1:00	GROW		-0.2			1:00		1.0	14.9	7:00			3.0
	2:00	LOW		-1.2			2:00		0.8	11.6				
	6:15	NO		-1.4			6:15		-	-				
	7:00	SPC		-0.1			7:00		1.0	14.9				
Sum							Sum			41.5				6.0
2/17/2013		AC	-2.2	-2.2	-5.9	1.5		5.75				5.8	1.0	69.4
Start time	1:30	GROW		-2.2			1:45		1.0	68.7	1:15			
End Time	7:30	LOW		-2.6			7:30		0.8	53.3	7:30			
		NO		-2.0					-	-				
		SPC		-0.8					1.0	68.7				
Sum							Sum			190.8				69.4
2/17-18/13		AC	-5.5	-2.2	-8.3	0.3		13				12.5	1.0	149.5
Start time	19:00	GROW		-4.1			19:00		1.0	155.4	19:30			
End Time	8:00	LOW		-6.0			8:00		0.8	120.5	8:00			
		NO		-6.0					-	-				
		SPC		-3.1					1.0	155.4				
Sum							Sum			431.4				149.5
3/2/2013	23:45-	AC	1.0	-1.1	-1.6	0.6		0.75				0.5	1.0	6.0
3/2-3/2013	0:15	GROW	-0.2	-0.2	-2.3	1.5	23:45-	0:15	1.0	9.0	0:15			
	3:30	LOW		-0.2			3:30-	3:45	0.8	7.0	3:30			
	3:45	NO		-0.4					-	-	3:45			
		SPC		0.1					1.0	9.0				
Sum							Sum			24.9				6.0

A-2. Continued

Cold event		Treat	Min Temp(˚C)			Wind Speed	"Grower practice"				AC treatment			
							Irr. Time	Irr. H	Flow rate	Vol. applied	Irr. Time	Irr. H	Flow rate	Vol. applied
Date	Time		Air	Leaf	DP	(ms^{-1})		(h)	(m^{3}h^{-1})	(m^3)		(h)	(m^3 h^{-1})	(m^3)
03/3-4/13		AC	-3.1	-1.7	-3.3	0.7		11.8			20:15	11	1.0	131.6
Start time	19:15	GROW		-2.8			19:30		1.0	140.5	7:15			
End Time	7:15	LOW		-4.2			7:15		0.8	108.9				
		NO		-4.2					-	-				
		SPC		-1.6					1.0	140.5				
Sum										389.9				131.6
3/7/2013		AC	0.0	-0.7	-1.1	0.9	1.75	3.25			5:54	1	1.0	12.0
Start time	5:00-	GROW		-1.1			1.5		1.0	38.9	6:45			
End Time	6:45	LOW		-1.1					0.8	30.1				
		NO		-2.2					-	-				
		SPC		-0.6					1.0	38.9				
Sum							Sum			107.8				12.0
3/8/2013		AC	0.9	-0.1	1.2	0.4	1:00	0.75				0.75	1.0	9.0
Start time	1:00,	GROW		0.6			2:00		1.0	9.0	3:00			
End Time	2:00,	LOW		-0.1			3:00		0.8	7.0	3:15			
	3:00	NO		-0.7			3:15		-	-	3:45			
	3:15,	SPC		0.8			3:45		1.0	9.0				
	3:45						4:45							
										24.9				9.0
Total (gal) applied per treatment during cold events (Assuming start irrigation time at critical temperature)								56.3	GROW	673.1		51.9		
									LOW	522.0				
									NO	-				
									SPC	673.1				
								Total UF plots		1,868.2		Total AC plots		620.2
Total (gal) applied by "grower practice" irrigation(all treat)and AC irrigation										2,488.4				620.2
Difference (GROW–AC)=										52.9				
% AC Savings										7.9				

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BIOGRAPHICAL SKETCH

Costa Rica, the small Central American country great in biodiversity, surrounded by beaches and mountains, gave birth to Maria Isabel Zamora Re. Her younger educational stages, started at different schools, since her parents always were looking for higher education standards. Therefore, after switching from various elementary schools, she got accepted at the Marista High School, a small catholic school in which she learned: to “live simple”, to “do the best” on whatever she did, but specially “to love” what she was doing. Therefore, she was recognized during her 5 years of high school for her academic excellence and participation in multicultural activities.

Furthermore, Ms. Zamora chose to attend EARTH University to start her career, due to their learning process generated through experience and participation. During her third year, she performed an exchange program working on water efficiency and conservation by using soil moisture sensors at the Agricultural and Biological Engineering Department of the University of Florida. The experience acquired throughout this program let her apply into her senior project before finishing her career. After four intense years of knowledge and hard work, she received with honors her Bachelor of Science in Agricultural Engineering at EARTH University, Costa Rica. At this University she instilled values as leadership, sustainable development and management of agriculture and natural resources, managerial and entrepreneurial capacity and high sense of environmental conservation working together with the society.

Soon after her graduation, she was hired by a golf course company in Costa Rica as the turfgrass project manager in order to establish nine holes at the golf course. After accomplishing this goal, she decided to pursue a higher degree education, therefore, she accepted an assistantship for a master's degree offered back in the Agricultural and Biological Engineering Department at the University of Florida. Her main research project was focused on optimizing sprinkler irrigation for cold protection in strawberries; however she led other research projects i.e. rain sensor testing and distribution uniformity. She enjoyed her stay at the Department and appreciated all the collaboration and support from different ABE faculty members and staff, friends and family. She will continue doing what she loves building her life path, contributing to the society and preserving the environment.