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Agronomic and physiological basis for automating regulated deficit irrigation in sweet cherry trees

PhD Program in Advanced Techniques for Research and Development in Food and Agriculture

PhD THESIS

2019

Author: Víctor Blanco Montoya

Directors: Rafael Domingo Miguel
Alejandro Pérez Pastor

AGRONOMIC AND PHYSIOLOGICAL BASIS FOR AUTOMATING REGULATED DEFICIT IRRIGATION IN SWEET CHERRY TREES

A Thesis submitted to

Universidad Politécnica de Cartagena

For the degree of

Doctor of Philosophy

In the International Doctoral School

2019

Víctor Blanco Montoya

La parte experimental de la tesis presentada se ha desarrollado en el marco de los proyectos *“Diseño de protocolos agronómicos y tecnológicos para el manejo del riego deficitario controlado en frutales a partir de redes inalámbricas de sensores”* (AGL2013-49047-C2-1-R) y *"Gestión automatizada del riego de precisión en frutales. Diseño de sensores y estudio de sensibilidad de indicadores de estrés hídrico"* (AGL2016-77282-C3-3-R), del Ministerio de Economía y Competitividad.

El trabajo de tesis doctoral que se presenta se acoge a la modalidad de tesis por compendio de publicaciones del Programa de Doctorado "Técnicas Avanzadas en Investigación y Desarrollo Agrario y Alimentario" de la Escuela Internacional de Doctorado de la Universidad Politécnica de Cartagena.

Consta de cuatro artículos, de los cuales dos de ellos han sido publicados en la revista "Agricultural Water Management" con un factor de impacto de 3,182 y otros dos en la revista "Scientia Horticulturae" con un factor de impacto de 1,76.

El nexo común de estos trabajos es el de promover el avance del conocimiento científico del funcionamiento hídrico del cerezo a partir del empleo de diferentes estrategias de riego y técnicas de cultivo. Para ello, se evaluaron las respuestas agronómica y fisiológica del cultivo y se estudiaron y compararon diferentes indicadores del estado hídrico del continuo suelo, planta, atmósfera con el fin último de aumentar la productividad del uso de agua.

Artículo I. **Blanco, V.,** Domingo, R., Pérez-Pastor, A., Blaya-Ros, P.J., Torres-Sánchez, R., 2018. *Soil and plant water indicators for deficit irrigation management of field-grown sweet cherry trees.* Agricultural Water Management, 208:83-94. DOI: 10.1016/j.agwat.2018.05.021

Artículo II. **Blanco, V.,** Martínez-Hernández, G.B., Artés-Hernández, F., Blaya-Ros, P.J., Torres-Sánchez, R., Domingo R., 2019. *Water relations and quality changes throughout fruit development and shelf life of sweet cherry grown under regulated deficit irrigation.* Agricultural Water Management, 217:243-254. DOI: 10.1016/j.agwat.2019.02.028

Artículo III. **Blanco, V.,** Torres-Sánchez, R., Blaya-Ros, P.J., Pérez-Pastor, A., Domingo, R., 2019. *Vegetative and reproductive response of 'Prime Giant' sweet cherry trees to regulated deficit irrigation.* Scientia Horticulturae, 249:478-489. DOI: 10.1016/j.scienta.2019.02.016

Artículo IV. **Blanco, V.,** Zoffoli, J.P., Ayala, M., 2019. *High tunnel cultivation of sweet cherry (Prunus avium L.): physiological and production variables.* Scientia Horticulturae, 251:108-117. DOI: 10.1016/j.scienta.2019.02.023

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Visto el informe favorable del Director de Tesis y el Vº Bº de la Comisión Académica del Programa de Doctorado "Técnicas Avanzadas en Investigación y Desarrollo Agrario y Alimentario" para la presentación de la Tesis Doctoral titulada: **"Agronomic and physiological basis for automating regulated deficit irrigation in sweet cherry trees"** solicitada por D. Víctor Blanco Montoya, el Comité de Dirección de la Escuela Internacional de Doctorado de la Universidad Politécnica de Cartagena, en reunión celebrada el 25 de marzo de 2019, considerando lo dispuesto en el artículo 23 del Reglamento de Estudios Oficiales de Doctorado de la UPCT, aprobado en Consejo de Gobierno el 17 de diciembre de 2015,

ACUERDA

Autorizar la presentación de la Tesis Doctoral a D. Víctor Blanco Montoya en la modalidad de "compendio de publicaciones".

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INFORMAN:

Que la referida Tesis Doctoral, ha sido realizada por D. VÍCTOR BLANCO MONTOYA, dentro del Programa de Doctorado Técnicas Avanzadas en Investigación y Desarrollo Agrario y Alimentario, dando nuestra conformidad para que sea presentada ante el Comité de Dirección de la Escuela Internacional de Doctorado para ser autorizado su depósito.

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INFORMA:

Que la Tesis Doctoral titulada, "AGRONOMIC AND PHYSIOLOGICAL BASIS FOR AUTOMATING REGULATED DEFICIT IRRIGATION IN SWEET CHERRY TREES", ha sido realizada, dentro del mencionado Programa de Doctorado, por D. Víctor Blanco Montoya, bajo la dirección y supervisión del Dr. Rafael Domingo Miguel y del Dr. Alejandro Pérez Pastor.

En reunión de la Comisión Académica, visto que en la misma se acreditan los indicios de calidad correspondientes y la autorización del Director de la misma, se acordó dar la conformidad, con la finalidad de que sea autorizado su depósito por el Comité de Dirección de la Escuela Internacional de Doctorado.

La Rama de conocimiento por la que esta tesis ha sido desarrollada es:

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LIST OF ABBREVIATIONS

- AGR: Absolute growth rate
- ANOVA: Analysis of variance
- BCSA: Branch cross sectional area
- BCSGR: Branch cross section relative growth rate
- BGR: Branch growth rate
- Ca: CO_2 concentration
- CI: Cracking index
- CIHEAM: International Center for Advanced Mediterranean Agronomic Studies
- CTL: Control treatment-full irrigation
- cv.: Cultivar
- CV: Coefficient of variation
- CWSI: Crop water stress index
- DAFB: Days after full bloom
- DOY: Day of year
- $EC_{25ºC}$: Electrical conductivity at 25ºC
- ET: Evapotranspiration
- ET_0: Crop reference evapotranspiration
- ET_c: Crop evapotranspiration
- FAO: Food and Agriculture Organization of the United Nations
- FAOSTAT: Food and Agriculture Organization of the United Nations. Statistics division
- FDR: Frequency domain reflectometry
- FE: Fruit efficiency
- FRM: Farm treatment
- FTI: Number of fruit per trunk increment
- GR: Growth rate
- gs: Stomatal conductance
- IWUE: Intrinsic water use efficiency
- Kc: crop coefficient
- Kr: localization factor

- L*: Lightness
- LA: Leaf area
- LA/F: Leaf area to fruit ratio
- LDVT: Linear variable differential transformer
- MDS: Maximum daily shrinkage
- MI: Maturity index
- N: North
- ns: No significance
- P: Significant level
- PFR: Photosynthetic photon flux rate
- Pn: Net photosynthesis
- PPFD: Photosynthetic photon flux density
- P-value: Significant level
- r: Correlation coefficient value
- RD: Regulated deficit irrigation treatments
- RDI: Regulated deficit irrigation
- RDM: Regulated deficit irrigation treatment which applied a mild water stress during preharvest and a medium stress during postharvest
- RDS: Regulated deficit irrigation treatment which applied a severe water stress during postharvest
- RH: Relative humidity
- RH_{Max}: Maximum relative humidity
- RH_{mean}: Mean relative humidity
- RH_{min}: Minimum relative humidity
- S: Sensitivity according to Goldhamer and Fereres (2001)
- S*: Sensitivity according to de la Rosa et al. (2014)
- SDI: Sustained deficit irrigation
- SI: Signal intensity
- SI_{MDS}: Maximum daily branch shrinkage signal intensity
- SIAR: Servicio Integral de Asesoramiento al Regante

- SL64: Saint Lucie 64 (*Prunus mahaleb* L.)
- SSC: Soluble solids concentration
- TA: Titratable acidity
- TCSA: Trunk cross-sectional area
- TD: Trunk diameter
- Ta: Temperature of the air
- Tc: Temperature of the canopy
- Tleaf: Leaf temperature
- T_{Max}: Maximum temperature
- T_{mean}: Mean temperature
- T_{min}: Minimum temperature
- tri: Irrigation treatment
- UNESCO: United Nations Educational, Scientific and Cultural Organization
- VPD: Vapour pressure deficit
- W: West
- WP: Water productivity
- $WSI_{\Psi stem}$: Water stress integral
- YE: Yield efficiency

LIST OF SYMBOLS

- $\Psi_{\pi fruit}$: Fruit osmotic water potential
- $\Psi_{\rho fruit}$: Fruit turgor potential
- Ψ_{fruit} : Fruit water potential
- Ψ_{m} :Soil water matric potential
- Ψ_{stem} : Midday stem water potential
- θv: Soil volumetric water content
- θv_{FC}: Soil volumetric water content referenced to field capacity

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CHAPTER 1

SCOPE AND OBJECTIVES

The global sweet cherry production has sharply increased in the last decades. As consumer interest in this seasonal fruit keeps growing, growers from areas where cherries have not been traditionally cultivated exhibit interest, and consider its cultivation due to a demand exceeding the offer.

These new areas are interested in extending sweet cherry season and providing high quality fruit when there is a low supply on the market. To achieve these goals, it has been necessary to adopt new orchard systems, new cultivar/rootstock combinations adapted to different edaphoclimatic conditions, and drip irrigation systems.

Rain-induced fruit cracking is the major limiting factor for cherry production. However, regarding defect-free fruit, small size fruit is a big problem that can compromise cherry profitability and pose an obstacle in its exportation, and this is where irrigation plays a main role. Hence the importance of researching sweet cherry response to irrigation; particularly in trees grown in areas with great potential for their cultivation, but highly vulnerable to climate change and water scarcity such as the Region of Murcia (Spain) and the Region of Maule (Chile).

To cope with the current situation exposed above and with the purpose of overcoming future challenges, the main objective of this thesis dissertation is to generate and transfer technical and scientific knowledge which could help sweet cherry automatic irrigation scheduling in Mediterranean climate areas where water is a limiting factor. This requires the characterisation of sweet cherry tree water status, water relations, soil water availability and climatic demand, and the evaluation of its physiological and agronomical response. Thus, the overall aim was achieved by meeting the following secondary objectives:

- Identify which of the commonly used soil and plant water status indicators are more useful for irrigation scheduling of sweet cherry trees (Article I).

- Estimate plant water status from meteorological and soil water indicators that can be easily integrated in automated systems (Article I).

- Assess the effects of deficit irrigation and different environments on cherry growth, quality and cracking susceptibility at harvest and during postharvest life (Articles II and IV).

- Study the long-term effect (2015-2018) of different deficit irrigation strategies on adult sweet cherry trees water status and their vegetative and reproductive response in order to ascertain the most recommendable irrigation strategy in warm areas with scarce water resources (Articles II and III).

- Make progress in the investigation of the effects of crop protection strategies on sweet cherry vegetative and reproductive response and the applied irrigation water (Article IV).

CHAPTER 2

STATE OF THE ART

1. Sweet cherry cultivation

1.1. Origin and characteristics

Sweet cherry (*Prunus avium* L.) is the most important species from the subgenus Cerasus, which belongs to the genus Prunus of the Rosaceae family. This genus includes 400 species and among them, some examples such as almond, apricot, cherry, peach and plum represent some of the most important tree crops in temperate areas. The origin of sweet cherries is thought to be related to the Near East, the regions around the Black and Caspian Seas (Vavilov, 1951). Its cultivation was expanded throughout the Mediterranean Basin with the ancient Greek civilisation. In Spain, there are documents that report the presence of sweet cherry trees in the 14th century (Flores del Manzano, 1985).

Sweet cherry is a deciduous tree fruit crop which has shown high tree vigour and moderate to high chilling requirements (Samish, 1954). Sweet cherry trees are traditionally large (10 m) with an upright growth, although in commercial orchards trees are pruned and canopies are shaped (Spanish bush, Y-shaped hedges, spindle, etc.) in order to increase tree densities—which can vary from 667 to 1250 trees ha^{-1}—and consequently precocity and productivity (Picture 1A and 1B). This fleshy non-climacteric fruit is highly appreciated by consumers because it is one of the first temperate stone fruits to ripen in spring-summer, due to its balanced flavour (sweet-acid), and its streaking appearance with a small size, round to heart shape and a vibrant red to mahogany colour (Crisosto et al., 2003). It is also appreciated by growers mainly because it is a highly valuable tree crop and, moreover, because of its short period of fruit development which leads to lower water requirements compared to other fruit trees, and because it potentially promotes to be managed with other tree crops in the same orchard (García-Montiel et al., 2010).

Picture 1. Traditional sweet cherry tree (A) and intensive sweet cherry orchard system (B).

1.2. Crop physiology

1.2.1. Tree growth cycle

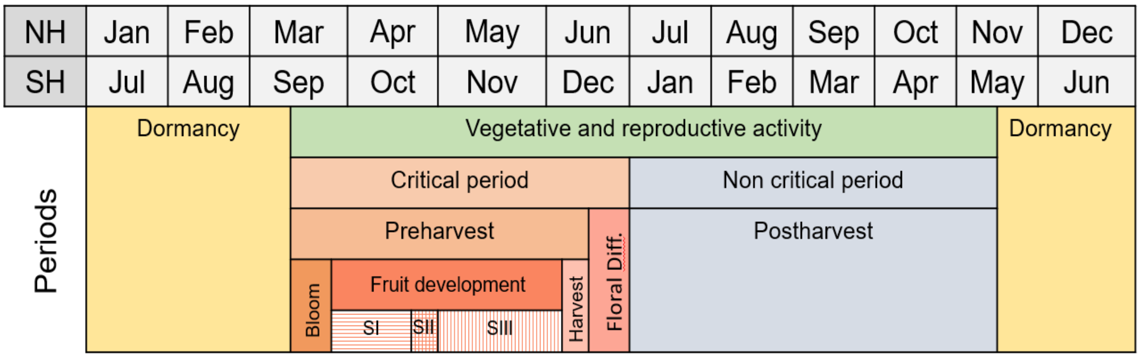
Sweet cherry trees annual growth cycle is clearly influenced in temperate climates by temperature (Agustí, 2004). Thus, two periods can be distinguished according to tree physiology response to seasonal evolution: (i) one of dormancy (from late autumn until the spring of the following year with the budding) and (ii) one of vegetative and reproductive activity which approximately corresponds to an eight-month duration: spring, summer and early autumn (Table 1).

The dormancy is the annual period required in the deciduous species when tree activity is negligible. The latency stage is developed by the trees as a response to cold winter (Kaufmann and Blanke, 2017). It begins in autumn when daytime becomes shorter and sunlight intensity and crop exposition time to sunlight declines, as well as temperature. As a consequence, trees slow down their production of chlorophyll and begin a progressive accumulation of growing-inhibitor compounds, such as abscisic acid while the plant continues to absorb nutrients (Agustí, 2004). Eventually, leaves which after all season often end up damaged by weather conditions (sunburn), diseases or insects, shrivel. During the dormancy period, sweet cherry must accomplish its chilling requirements (Atkinson et al., 2013). Sweet cherry trends to lack of chilling, and chilling accumulations under 50 % of its necessities might produce erratic and long blooms which will penalise crop yield (Cortés and Gratacós, 2008).

Within the vegetative activity two periods, preharvest and postharvest, are easily distinguishable. However, another period, floral differentiation, which temporarily matches with late preharvest and early postharvest is also considered. Vegetative activity was thereby divided into three periods: (i) preharvest, which starts with the swollen buds and finishes with the harvest, and includes sprout, bloom, fruit complete development and most vegetative development, (ii) floral differentiation, which includes the first part of flower induction and first flower bud differentiation, 15-20 days after the first harvest and (iii) postharvest, the largest period within the vegetative cycle, which starts after harvest and flower differentiation.

Vegetative and reproductive activity division into three periods was undertaken in accordance with sweet cherry sensitivity to water stress (Table 1). Thus, preharvest is a short period in which bloom and fruit development matches sprout and principal leaf area development and current season shoot extension. This period is defined as a stage susceptible to water deficit (critical period) and due to its short duration water savings in this period might not be as important as in postharvest (Marsal et al., 2010). Floral differentiation was considered an individual period of vegetative activity. It has been reported in *Prunus* trees as a stage sensitive to water deficit (critical period) which could affect next season floral development. Yield decreases from slight in almond (Esparza et al., 2001) to severe in apricot (Brown, 1953) have been reported as a result of deficit irrigation during the floral differentiation of the previous year. In sweet cherry, flower differentiation has been described to overlap pre and postharvest (Engin and Ünal, 2007). It begins earlier than in other fruit crops, during the final part of the fruit ripening in preharvest (Koutinas et al., 2010). However, this can last for 20 to 56 days depending on the cultivar, rootstock or climate conditions, so consequently it finishes in postharvest (Guimond et al., 1998; Li et al., 2010; Watanabe, 1982). Postharvest is the period when there is no fruit in the tree. In sweet cherry during this period final primary vegetative growth and secondary vegetative growth take place. It is described as a suitable period to apply deficit irrigation in different prunus crops (Torrecillas et al., 2018), such as apricot (Laajimi et al., 2009; Pérez-Pastor et al., 2014), nectarine (de la Rosa et al., 2016; Thakur and Singh, 2013), peach (Gelly et al., 2004), plum (Intrigliolo and Castel, 2006) and sweet cherry (Blanco et al., 2018; Morandi et al., 2018).

Table 1. Sweet cherry annual calendar in the northern (NH) and southern (SH) hemispheres.



NH	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SH	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun

1.2.2. Fruit growth cycle

Sweet cherry fruit follows a double sigmoid growth pattern which consists of three stages (Coombe, 1976). Stage I is the period of cell division, which supposes an exponential fruit growth. During stage II the growth rate drastically decreases until values are close to zero, the pit hardens and the embryo develops. Once the stone's endocarp lignifies and the embryo in the seed is completely developed, stage III begins. Stage III is characterised by cell enlargement and increase in growth rates, with, again, an exponential growth pattern. In this stage trees show a high demand of water and carbohydrates. Fruit size is, therefore, conditioned by the number of cells reached in cell division during stage I and their enlargement during stage III (Yamaguchi et al., 2004), and only stage II could be considered as a non-critical stage according to fruit growth.

Although the fruit development of sweet cherry always has got these three stages, the double sigmoid pattern is based on the growth of mid- and late ripening cultivars such as 'Bing', 'Sweetheart' and 'Regina' (Fig. 1A). In extra-early and early cultivars, such as 'Royal Dawn', 'Brooks' and 'Prime Giant' the stage II is shorter and is overlapped by stage I and stage III (Fig. 1B). In those cultivars, as fruit development is fast, it is not evident a sharply decrease of growth rates to values close to zero as it is noticeable in late cultivars.

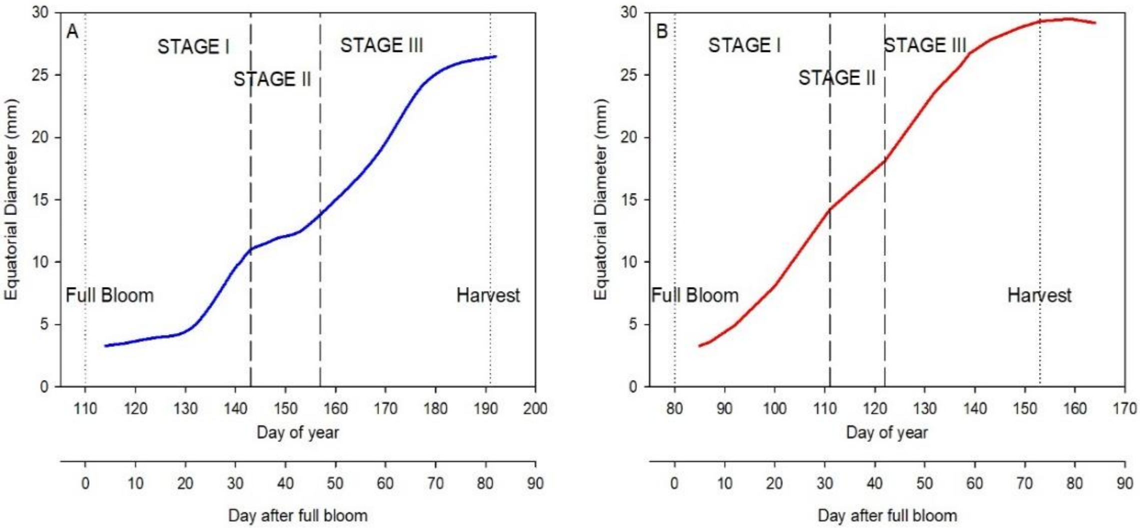


Fig. 1. Sweet cherry fruit growth pattern of a late cultivar 'Bing' (A) and an early cultivar 'Prime Giant' (B). (Source: (A) Zhang and Whiting, 2013; (B) prepared by the author).

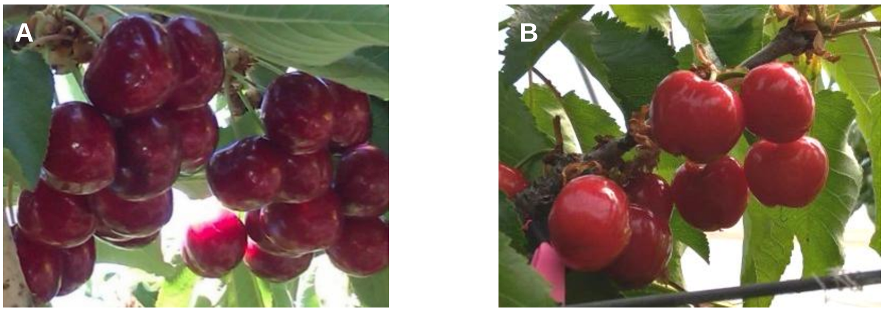
1.3. Cultivars and rootstocks

Of all existing possibilities among sweet cherry cultivar/rootstock combinations, this thesis dissertation studies the behaviour of two combinations: ‘Prime Giant’/‘SL64’ and ‘Royal Dawn’/‘MaxMa14’. Both combinations, which were chosen to perform the trials shown below, are commonly used in commercial orchards.

1.3.1. Cultivar

‘Prime Giant’ is an early sweet cherry cultivar with high productivity which was selected by Marvin Nies in California (USA) from hybrid parental (‘Lody’ x ‘Ruby’) and open pollination. Tree growth is semi-upright with medium to strong vigour. It blooms at the same time as ‘Brooks’ and ‘Burlat’ at early spring and ripens 7 days after them. It is self-sterile and its compatible pollinators are those cultivars from group II (S-alleles S_1S_3), ‘Brooks’ and ‘Lapins’ are commonly used. Their fruits are large (equatorial diameter higher than 27 mm) with a shape similar to a spheroid oblate (sphere whose equatorial diameter is longer than the polar diameter), with a dark red-mahogany skin colour, a red pulp colour and high firmness (Picture 2A). Its flavour is intense with a balanced sweet acid ratio, presenting a soluble solids concentration of 18 ºBrix. It is susceptible to cracking and double fruits and sensitive to bacterial canker. However, it is a cultivar recommended in warm regions with mild winters due to its low chilling requirements.

‘Royal Dawn’ is an extra-early sweet cherry cultivar obtained by Zaiger Genetics in California (USA) from the cultivar ‘32G500’ x open pollination. It is self-sterile, and ‘Tulare’ and ‘Lapins’ are compatible pollinators. The tree has a vigorous growth, high upright branching and a good productivity; however, yield above 12 t ha^{-1} delay the harvest. Blooming and ripening times are earlier than ‘Prime Giant’. Their fruits are roundish of medium-large size (equatorial diameter between 26 and 30 mm), with a bright red skin colour, high firmness, good taste and a soluble solids concentration higher than 16 ºBrix (Picture 2B). It is highly susceptible to stylar cracking and bacterial canker.



Picture 2. Details of ‘Prime Giant’ (A) and ‘Royal Dawn’ (B) sweet cherry fruit.

1.3.2. Rootstock

‘SL64’ is a *P. mahaleb* L. clonal rootstock selected by INRA (Picture 3A) in France. It is compatible with most sweet cherry cultivars and induces high productivity. ‘SL64’ is well adapted to calcareous and stony soil but is highly susceptible to root asphyxia, so it is only recommendable in well-drained soil. It has got high vigour and is low explorative. Cultivars grafted on ‘SL64’ rootstock grow about 20-30 % more vigorously than the same cultivars on ‘MaxMa14’.

‘MaxMa14’ is a rootstock hybrid of *P. mahaleb* × *P. avium*, obtained by Brooks Nurseries (Picture 3B) in Oregon (USA) and well adapted to lime soil. It induces more precocity than ‘SL64’, moderate vigour and it is resistant to *Phytophthora cambivora* and *megasperma* and tolerant to bacterial canker. However, it is susceptible to severe droughts, but low susceptible to cherry leaf spot.

Picture 3. Details of ‘SL64’ (A) and ‘MaxMa14’ (B) rootstocks.

1.4. Advances in cultivation

Currently trends in sweet cherry cultivation are based on the combination of two factors, new conduction systems that promote higher tree densities (fruiting walls) and covers (nets, tents and high tunnels) that protect the crop from adverse weather, rain and hail avoiding fruit cracking losses. High tunnels have emerged as the best cover method in highly valuable fruit crops such as sweet cherry (Picture 4). Apart from the fruit protection, the modification of the environment extends the harvest period, modifies the phenological response of the crop and increases the water use efficiency as soil evaporation decreases.

High tunnels protect fruit and bring forward the harvest, which significantly increases the fruit economic return. Their installation is justified only when fruit yield has a potential market willing to pay the added expense of this cultivation and its management costs (Lang, 2009).

Picture 4. Sweet cherry trees inside high tunnel.

1.5. Production

Sweet cherries are commercially produced in 68 countries, mainly in the temperate countries from the northern hemisphere, where Europe and Asia account for more than the 80 % of world production. Turkey is the largest producer according to FAOSTAT (2019) and during the period 2011-2017 the top six producing nations also included in the rank were United States of America, Islamic Republic of Iran, Italy, Spain and Chile (Fig. 2).

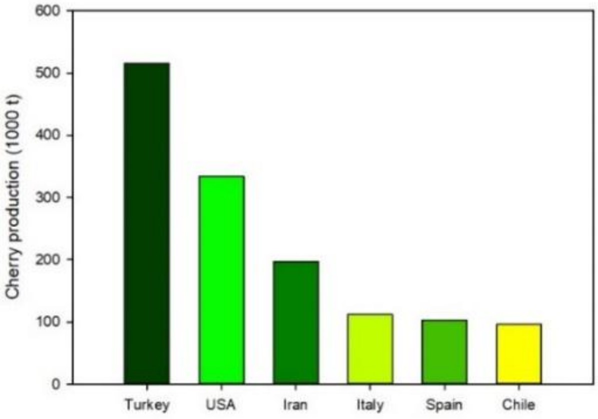


Fig. 2. Top 6 sweet cherry producer countries in the world for the 2011-2017 period. (Source: FAOSTAT, 2019).

World production and the harvested area have continued to increase until today since the late 1980s, early 1990s, when intensive orchard systems where imposed and new cultivar/rootstock combinations were developed to increase tree density, control tree size and extent picking season (Bujdosó and Hrotkó, 2017). From 2004 to 2017 sweet cherry world production and area increased 44 and 20 % respectively up to values of 2.4 million t and 416,000 ha (Fig. 3) with a matching increase in demand, particularly by China (Bravo, 2014), and production in countries such as Chile. Chile was a minor producer in 2001, but it increased its production by 363 % in 2016, reaching 23,000 ha and becoming the first country in volume and value of sweet cherry exports.

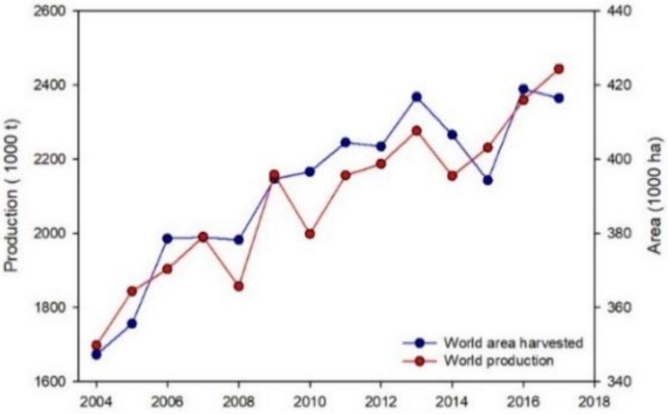


Fig. 3. Sweet cherry world area harvested and world yield for the 2004-2017 period.
(Source: FAOSTAT, 2019).

In Spain in 2017, there were 27,600 ha that produced 114,400 t, which represented 6.6 and 4.7 % of the world's sweet cherry area and production (FAOSTAT, 2019). The production is mainly intended for domestic consumption or export to European markets. Sweet cherry tree is the third non-citric fruit tree with larger area in Spain after almond and peach trees. The most common sweet cherry cultivars are, for early season, 'Burlat', 'Prime Giant' and 'Frisco', for mid-season 'Santina', 'Summit' and 'New Star' and for late season 'Ambrunes', 'Sweetheart' and 'Lapins'; and the most common rootstock is 'SL64'. However, other rootstocks such as 'MaxMa14' or 'Marilan' are increasing their presence (Negueroles Pérez, 2005). Within Spain, Extremadura (Valle del Jerte) is the traditionally most important sweet-cherry-grower region, which in 2017 produced one third of the Spanish production (MAPA, 2018). Aragon (Valle del Ebro) was the second producer in Spain, 28 % of the total production. Both regions constitute more than 60 % of the Spanish sweet cherry production and are followed by Catalonia, Andalusia and the Valencian Community (Iglesias et al., 2016).

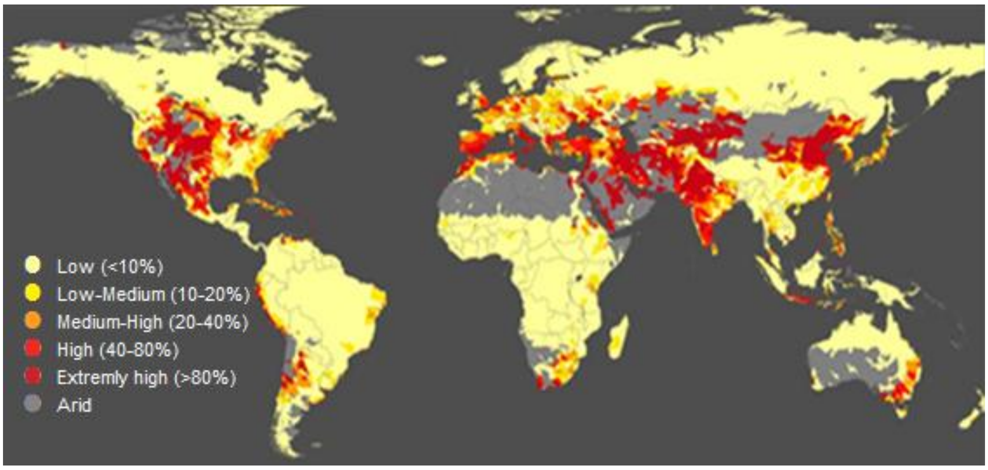
Although the Region of Murcia is not a traditional area to grow sweet cherry trees, its cultivation has got current and future possibilities due to the weather conditions there, which could promote early fruit development, move up the harvest time and get higher economic return to the grower (Guirao López, 2018). Thus, the area dedicated to this crop keeps on growing there; it has already increased from 184 ha producing 1,584 t year^{-1} in 2014 to 332 ha producing 2,925 t year^{-1} in 2017, all of them under irrigation, reaching the early cultivars (harvested in May–early June) prices between 4 and 3.6 € kg^{-1} in 2016 and 2017 (CARM, 2017).

1.6. Current perspectives and future challenges

Sweet cherry production could continue to increase in accordance with consumer demand, so its cultivation would expand to areas where it has not been previously grown, with more extreme weather conditions and lower water supply, as well as new conditions in areas where it is already, due to the climate change (Wenden and Mariadassou, 2017). This is the reason why field research will play a key factor in sweet cherry in the near future. Thus, new cultivars with lower chilling requirements, new rootstocks that promote narrow tree architectures which facilitate operations such as harvesting, studying tree response to covering technologies that protect the crop from hail and rain, improving irrigation management, optimising leaf area fruit ratio, etc. would achieve good yields of high quality fruit not just at harvest but during cold storage and will ensure crop profitability (Ayala and Lang, 2017).

2. Climate change and agriculture

The areas under Mediterranean climate conditions such as the Mediterranean basin, California, Australia, South Africa and Chile, where agriculture is highly productive, are described as extremely vulnerable to climatic change (Giorgi and Lionello, 2008). These regions are already facing temperature increases, irregular rainfall patterns (storms) and severe water scarcity (Cosgrove and Loucks, 2015). Thus, there is an increasing concern between water resources and its efficient use (Picture 5). We are already in a water crisis and the agriculture as first water consumer is adapting to these conditions by improving water distribution channels and incorporating new technologies and sensors to crop management (Perry, 2018). However, it is not enough to the future perspective, which foresees in 2050 that water stress in these areas would increase due to a water resources drop between 30 and 50 % (Milano et al., 2013).



Picture 5. Baseline water stress calculated as the ratio between water demand and water supply. (Source: WRI, 2013)

Agricultural research should focus not only on increasing crop yields, but also on increasing the productivity of limiting and irreplaceable factors such as water. The agricultural adaptation to this complex scenario is causing the need for further research in plant water relations within the soil–plant–atmosphere continuum in order to know and understand plant response to climate change. Thus, irrigation and crop management strategies which maintain yield and fruit quality without compromising food security and increasing water efficiency should be adopted (Fan et al., 2017).

3. Irrigation and water management

The advances in irrigation science and the application of adequate irrigation strategies and water management have involved (and involve) major improvements in agriculture's development. First, by increasing crop yield and consequently contributing to the development of rural areas, and now by helping the agricultural sector to adapt to new challenges such as the climate change, migrations and a rapidly growing world population with dwindling resources (Sauer et al., 2010). FAO (2018a) has highlighted how arid and semiarid regions that have kept traditional and intensive irrigation without implementing irrigation strategies to obtain a sustainable development have resulted in yield degradation, the collapse of the groundwater levels and finally the desertification of rural areas.

That is why irrigation scheduling should contemplate an efficient water use and must be based on scientific and technical knowledge. Irrigation has to be based on the crop water requirements according to its phenology and plant water status, but also on soil water availability and atmospheric demand. In order to increase irrigation water efficiency, irrigation should be, therefore, studied within the soil-plant-atmosphere continuum.

3.1. Soil-Plant-Atmosphere continuum

The soil-plant-atmosphere continuum (SPAC) analyses the flow of water throughout the plant which is driven by energy gradients from the soil to the atmosphere. This gradient is the result of the difference between water potentials, from high potential (less negative) in the soil, to a gradually lower potential in the root, stem and leaf, and finally to the lowest potential in the atmosphere.

With the objective of clarifying this pathway, van den Honert (1948) proposed a model similar to the Ohm's law. The model explains in steady state conditions that the water flux is proportional to the gradients of water potential and inversely proportional to the flow resistances. In the analogy, electrical current is replaced by water flow (transpiration rate, $\mathrm{J_v}$), voltage by water potential difference between two parts of the continuum ($\Delta\Psi$) and electrical resistance by water resistance to the flow mass, osmosis and diffusion (Rn), as shown in equations 1 and 2.

Equation 1
$$\mathrm{J_v} = \frac{(\Psi_{\mathrm{soil}} - \Psi_{\mathrm{root}})}{\mathrm{R_1}} = \frac{(\Psi_{\mathrm{root}} - \Psi_{\mathrm{stem}})}{\mathrm{R_2}} = \frac{(\Psi_{\mathrm{stem}} - \Psi_{\mathrm{leaf}})}{\mathrm{R_3}} = \frac{(\Psi_{\mathrm{leaf}} - \Psi_{\mathrm{air}})}{\mathrm{R_4}}$$

Equation 2
$$\mathrm{J_v} = \frac{\Delta\Psi}{\sum \mathrm{R}} = \frac{(\Psi_{\mathrm{soil}} - \Psi_{\mathrm{air}})}{\mathrm{R_1} + \mathrm{R_2} + \mathrm{R_3} + \mathrm{R_4}}$$

The SPAC considers the soil physics as soil water available to the plant (tension), the physiology of the plant as water transported throughout the plant from the roots to the stem and leaves to finally be transpired to the atmosphere (root, stem and leaf water potentials) and the atmospheric physics as water demanded by the atmosphere (vapour pressure deficit). Water energetic status ought to be measured, therefore, throughout the SPAC to validate irrigation strategies used, and according to the results obtained, crop water requirements can be assessed, and irrigation doses and scheduling can be improved, what consequently will avoid water losses and will improve irrigation water productivity.

3.2. Irrigation strategies

Water is indispensable for crop production and satisfying crop water requirements achieve yields close to maximum crop potential. When rainfall does not meet crop demand, irrigation water has to supplement it. As a result, water scarcity is the main factor limiting production in agriculture (Steduto et al., 2012). In this context, there is a widespread agreement on the fact that uncontrolled water stress affects crop production and development.

Sweet cherries are grown both under irrigation and rain-fed conditions. However, in warm areas with hot dry seasons vegetative growth, fruit yield and fruit size are negatively affected in trees under no irrigation (Proebsting et al., 1981). In Valle del Ebro in Navarra (Spain) where annual precipitation exceeded 750 mm, the uneven rain distribution causes that during summer the monthly accumulated precipitation was 35 mm; consequently, it was reported that rain-fed trees produced less than half of the fruit compared to trees under irrigation, 12.5 t ha^{-1} (GEN, 1990).

However, in areas where water is scarce and its demand increases, irrigated agriculture must do an intelligent use of this resource, and sustainable management and utilisation of natural resources should be a main objective. Irrigation strategies such as regulated deficit irrigation (RDI) that increases water efficiency without decreasing crop yield, can be proposed in arid or semiarid regions susceptible to water deficit as an adaptation to water availability that improves water efficiency.

3.2.1. Regulated Deficit Irrigation

RDI is an irrigation strategy based on reducing the amount of water supplied to the crop depending on its phenology and sensitivity to water stress. Thus, in periods when the crop is highly sensitive to water stress (critical periods), and water restrictions can affect its yield or/and quality, full irrigation is applied in order to ensure that plant water necessities are satisfied. Nevertheless, during the drought-tolerant phenological stages (non-critical periods) irrigation is limited. Consequently, the amount of water applied in RDI is lower than the amount calculated as optimal, so water productivity increases, vegetative growth decreases and yield or fruit quality is not negatively affected (Chalmers et al., 1981; Mitchell and Chalmers, 1982; Mitchell et al., 1986).

The effective implementation of this irrigation strategy requires a complete and deep knowledge of the crop physiology and the crop water requirements at each period of development in order to identify the crop critical phenological stages and foresee the effects of its application. RDI has achieved in numerous crops—especially fruit tree crops and vines—positive results. In horticultural and extensive crops, irrigation doses below crop necessities during their development are associated with decreases in yield, which consequently diminish crop profitability (Comas et al., 2019; Coyago-Cruz et al., 2019). Such yield reduction does not happen or are lower than those reported in vegetables and extensive crops in fruit trees under RDI due to the accurate period and intensity when deficit irrigation is applied. Thus, RDI is proposed as an irrigation strategy for fruit tree crops in regions sensitive to water scarcity, what might maximise grower's profit as well (García et al., 2004; Hargreaves et al., 1984). This reduces the investment in factors with high and rising prices, such as irrigation water and energy and, as it decreases excessive vegetative vigour, enhances tree aeration and solar interception, what diminishes fungal diseases, improves fruit development and also reduces agricultural costs associated to tree growth like pruning. Furthermore, not only does this strategy not affect tree yield, but it can positively affect fruit quality, increasing sweetness (soluble solids concentration), the colour (anthocyanins), etc,

However, RDI results vary depending on the crop, and in order to recommend RDI as an effective irrigation strategy in fruit trees, especially in drought-resistant species (or cultivars), the non-critical periods when water deficit is going to be applied must be stated, as well as the intensity of stress because the plant must be able to rapidly recover from the water stress once the non-critical period has finished (Pérez-López et al., 2018). It is necessary to know, therefore, which water stress indicator is the best option for each fruit tree crop and the threshold values that should not be exceeded.

3.2.2. Regulated deficit irrigation in sweet cherry

In sweet cherry, deficit irrigation is generally applied during postharvest, once the fruit has been harvested but the vegetative growth is still growing, which matches with summer, the season of maximum crop evapotranspiration. This is due to the sweet cherry growth pattern, where stage II overlaps stage I and III. Stage II is generally described as the stage when fruit growth stops and the stone hardens—while vegetative growth keeps on growing. In sweet cherry, during preharvest vegetative and fruit growth occur simultaneously so, to avoid water stress during fruit growth, all preharvest is considered a critical period.

RDI experiments previously reported in sweet cherry have achieved water savings of 1,451 m^3 ha^{-1}, 23 % of the water applied to the control treatment (6,279 m^3 ha^{-1}) without reducing fruit yield (18-34 t ha^{-1}) in The Dalles (Oregon, USA) for the combination ‘Lapins’/‘Mazzard’ (Einhorn, 2012) and 1,617 m^3 ha^{-1}, 33 % of the water applied to the full irrigated treatment (4,900 m^3 ha^{-1}) with a fruit yield of 19 t ha^{-1} in Torrente de Cinca (Aragon, Spain) with the combination ‘New Star’/‘SL64’ (Marsal et al., 2009). Dehghanisanij et al. (2007) applied sustained deficit irrigation in sweet cherry trees in the Moghan region (Iran) reaching water savings of 50 % and 75 % of the water applied to the control treatment (8,765 m^3 ha^{-1}); however, both deficit treatments resulted in 10 to 30 % lower fruit yield than the control treatment.

As a main effect of deficit irrigation in sweet cherry trees different authors described a significant lower vegetative growth, measured as current season shoot extension (Dehghanisanij et al., 2007; Podestá et al., 2011) and trunk cross sectional area (Nieto et al., 2017). Regarding fruit quality, Marsal et al. (2009; 2010) reported a higher soluble solids concentration in fruit from RDI trees in the combination ‘Summit’/‘SL64’ but contrary values in the combination ‘New Star’/‘SL64’.

3.3. Water status indicators

RDI application requires, in addition to an accurate irrigation scheduling, high knowledge of the plant water status, which can be assessed by physiological and physical indicators (Table 2). Physiological indicators such as stem water potential, gas exchange, trunk diameter variations, sap flow and leaf temperature quantify plant water status directly or indirectly from the changes that it experiments. Physical indicators such as meteorological variables, soil water potential and soil water content measure changes in the environment that affect plant water status (Padilla-Díaz et al., 2018; Remorini and Massai, 2003).

Table 2. Classification and threshold values of common use soil and plant water status indicators.

	Water status indicator	Crop	Threshold values		References
			Critical period	**Non critical period**	
Physiological indicators	Stem water potential	*P. avium L.* 'Summit'/'SL64'	-0.7 - -0.8 MPa	-1.5 MPa	Marsal et al., 2009
	Stomatal conductance	*P. avium L.* 'Bing'/Mazzard 'Skeena'/'Gisela6'	150 - 200 mmol m^{2} s^{-1}	100 mmol m^{2} s^{-1}	Antunez-Barria, 2006 Neilsen et al., 2016
	Net photosynthesis	*P. avium L.* 'Burlat'/'MaxMa14' 'Van'/'MaxMa14'	13 - 20 µmol m^{2} s^{-1}	10 - 15 µmol m^{2} s^{-1}	Gonçalves et al., 2005
	MDS	*P. avium L.*	200 µm d^{-1}	350-450 µm d^{-1}	Biel et al., 2012
	SI$_{MDS}$	*P. persicae Batsch.* 'Flanoba'/'GF677'	1.1	1.4	de la Rosa et al., 2015
	BGR	*P. salicina Lindl.* Black Gold'/'Mariana'	25 - 30 µm d^{-1}	5 - 10 µm d^{-1}	Intrigliolo and Castel, 2006
	TGR	*P. avium L.* 'Brooks'/'MaxMa14'	50 µm d^{-1}	5 µm d^{-1}	Livellara et al., 2011
	Sap flow	*P. avium L.*	0.4 L m^{-2} leaf area d^{-1}	0.2 L m^{-2} leaf area d^{-1}	Abdelfatah et al., 2013
	CWSI	*P. avium L.* 'Z900'/'Gisela5'	0.15	0.4 – 0.5	Köksal et al., 2010
Physical indicators	Soil water content related to field capacity	*P. avium L.* 'Cristalina'/'Gisela6' 'Skeena'/'Gisela6'	85 %	60 – 55 %	Neilsen et al., 2014
	Soil water potential	*P. dulcis (Mill.)D.A.Webb* 'Guara'/'GF677'	-30 kPa	-200 – -400 kPa	Puerto et al., 2013

It is always better to count on multiple water stress indicators to manage irrigation scheduling. Thus, advantages and disadvantages of water indicators should be known in order to choose among them, those which adapt better to your specific circumstances. The election of the best water status indicators to sweet cherry irrigation management will be determined by the indicator's response, its sensitivity to rapidly detect and quantify water stress providing stable and representative measures with little variation. Moreover, other characteristics such as the capability of being automated, providing continuous measures, low cost and low work associated with the obtaining of the measures should be considered.

3.3.1. Midday stem water potential

Midday stem water potential has been reported as the most straightforward water stress indicator of plant water status in fruit tree crops (Abrisqueta et al., 2015; Gonçalves et al., 2003; McCutchan and Shackel, 1992; Naor and Peres, 2001). Its measures are consistent and sensitive to irrigation regime as it integrates soil and environmental effects on whole tree water status. In addtion, it is less dependent on weather conditions than leaf water potential (McCutchan and Shackel, 1992) and it has shown to be a reliable indicator of tree status even in the dormant period (Milliron et al., 2018). Its low variability, compared to other water status indicators, enables it to clearly distinguish between irrigation treatments despite other indicators are unable to differentiate between them (Abrisqueta et al., 2015; García-Orellana et al., 2013). Hence, it is proposed as a reference indicator (Naor and Peres, 2001).

In sweet cherry, Marsal et al. (2009) and Podestá et al. (2011) assessed midday stem water potential as a good tree water status indicator in irrigation management (Fig. 4). Neilsen et al. (2014) reported threshold values to identify detrimental stress in sweet cherry, although it has been reported that factors such as rootstock and cultivar combination affect significantly midday stem water potential (Gonçalves et al., 2003).

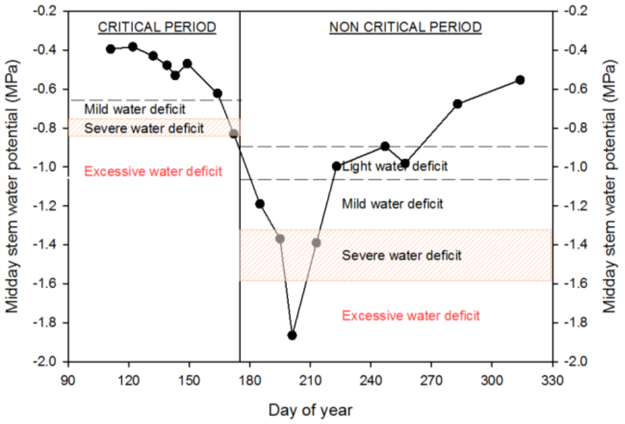


Fig. 4. Seasonal evolution of sweet cherry trees midday stem water potential irrigated according to grower's irrigation in a warm area under Mediterranean climate (Jumilla, R. Murcia, Spain).

On the other hand, midday stem water potential presents limitations; it is a one-off, labour-intensive measure that cannot be automated (Picture 6 A and B) (Esteves et al., 2015; Puerto et al., 2013).

Picture 6. Scholander pressure chamber (A) and covered leaf ready to be measured (B).

3.3.2. Gas exchange: Stomatal conductance and net photosynthesis

Stomatal conductance measures the degree of openness of leaf stomata. It is influenced among others by light intensity, vapour pressure deficit, temperature and relative humidity differentials between leaf and environment and water availability. In sweet cherry, as a consequence of water deficit, stomatal conductance decreases (Fig. 5). Stomatal aperture adjustment is an effective mechanism of the plant to deal with water deficit in order to regulate water flux throughout the plant and avoid water-loss dehydration. It is a consequence of leaf turgor loss and concentration increase of phytohormone abscisic acid (Blanco-Cipollone, 2017; Chater et al., 2014). Stomata reaction to plant water stress has been reported as a reliable indicator; however, it also shows high variability (Intrigliolo and Castel, 2006).

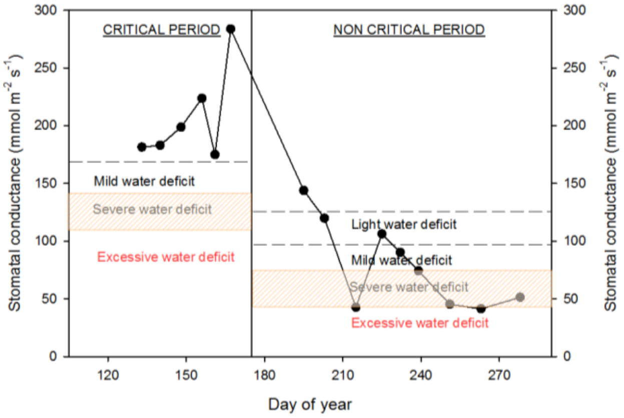


Fig. 5. Seasonal evolution of sweet cherry stomatal conductance irrigated according to grower's irrigation in a warm area under Mediterranean climate (Jumilla, R. Murcia, Spain).

Net photosynthesis is also affected by plant water stress. Stomatal closure is followed by a reduction of CO_2 availability to the chloroplast which triggers a decrease in net photosynthesis and slows plant growth and development (Antúnez-Barria, 2006). Concerning plant gas exchange analysis, its measurement is complex and it is not yet widespread amongst commercial orchards (Picture 7).

Picture 7. CIRAS-2 portable photosynthesis system.

3.3.3. Branch diameter variations

Branch diameter variation follows a circadian pattern. In the late afternoon, and mainly at night, as leaves' stomata close, plants can rehydrate their vascular tissues from the water available in the soil. Thus, their trunk and branch diameters grow during the night until dawn when they reach the maximum. Once the sun rises, stomata open, transpiration starts and plant water reserves in the vascular tissues decline as the vapour pressure deficit increases, consequently decreasing branch diameter, which reach its daily minimum in the early afternoon. From continuous measures of branch diameter, two indicators are obtained: maximum daily shrinkage (MDS) and branch growth rate (BGR). MDS is the resultant value of the difference between the maximum and the minimum daily branch diameter, and BGR is the difference between the maximum daily branch diameter of two consecutive days (Goldhamer and Fereres, 2001). Among the indicators obtained from diameter variations, MDS is the most used and the one that has showed better results in water stress detection in fruit trees and irrigation scheduling (de la Rosa et al., 2014; Ghrab et al., 2013; Intrigliolo and Castel, 2006; Ortuño et al., 2010; Puerto et al., 2013). In sweet cherry, MDS has been described as better water stress indicator than BGR (Livellara et al., 2011), and has been reported as a reliable water stress indicator (Fig. 6), particularly sensitive in early detection of water stress (Abdelfatah et al., 2013).

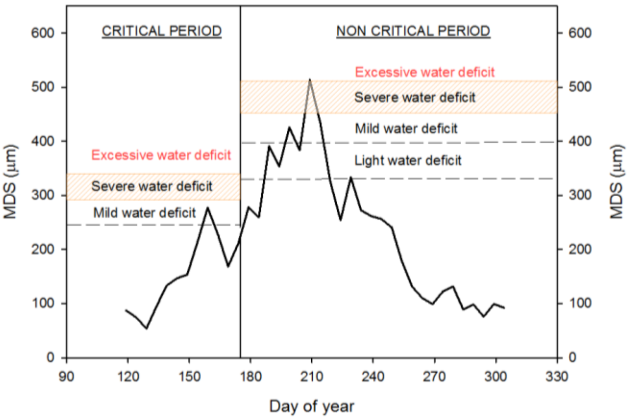


Fig. 6. Seasonal evolution of sweet cherry branch maximum daily shrinkage according to grower's irrigation in a warm area under Mediterranean climate (Jumilla, R. Murcia, Spain).

Furthermore, branch diameter variations can be automatable, which is very interesting in irrigation management (Picture 8). On the other hand, its measurement does not provide information by itself, since it needs to be compared to the measures obtained by a complete irrigated tree. MDS values are highly dependent of external parameters such as tree size, crop load, weather, etc. so consequently values obtained from research trials are difficult to interpret and extrapolate to commercial orchards in order to schedule irrigation. Goldhamer and Fereres (2001) proposed, therefore, instead of using MDS absolute values, using the signal intensity (SI_{MDS}) which is calculated as shown in equation 3.

Equation 3
$$SI_{MDS} = \frac{MDS_{measured\ tree}}{MDS_{complete\ irrigated\ tree}}$$

This situation, despite the good results obtained in fruit crops, early water stress detection restricts its use in commercial orchards.

Picture 8. LVDT sensor installed in a tree branch measuring its diameter variations.

3.3.4. Sap flow

Sap flow is a sensitive water stress plant indicator that can be measured automatically. This indicator identifies the water availability in the plant in order to not restrict transpiration, as it compares sap flow with the transpiration and estimates water use. It is reported as a sensitive plant water stress indicator by several authors in woody plants (Alarcón et al., 2000; Bhusal et al., 2019; Nicolás et al., 2005). The most common and successful method to measure sap flow in fruit trees is the compensation heat pulse method, which measures the velocity of a heat pulse between two points down- and up-stream by measuring the temperature in those points. The lower the velocity, the higher the plant water stress. This has been successfully used in sweet cherry to estimate tree water consumption (Juhász et al., 2013). In spite of the positive results achieved, its current implementation beyond research trials is limited.

3.3.5. Leaf temperature

Leaf (or canopy) temperature is an indirect indicator of plant water status that has been used for tree water stress detection. Water stress induces stomatal closure which consequently increases canopy temperature. Water release by plants over its surface (mainly leaf surface) is the temperature-controlling mechanism that crops have got for temperature regulation. The water evaporated by a vegetable surface regulates crop temperature depending on the environmental conditions (temperature, relative humidity, vapour pressure deficit, evapotranspirative demand). Crops whose water requirements are satisfied show lower canopy temperature than air temperature (ranging between 1 or 2ºC below). However, when transpiration decreases canopy temperature increases and exceeds air temperature, generally values close to 2-4ºC above air temperature, although differentials of 15ºC have been recorded (Akkuzu et al., 2013).

In order to quantify crop water stress from this indicator, the crop water stress index was proposed (CWSI, Idso et al., 1978; Jackson et al., 1981):

Equation 4
$$CWSI = \frac{[(T_c - T_a)_n - (T_c - T_a)_{wet}]}{[(T_c - T_a)_{dry} - (T_c - T_a)_{wet}]}$$

In equation 4, Tc is the temperature of the canopy and Ta the temperature of the air, in three different situations: n for the case under study, wet is the temperature differential when the crop is transpiring at the maximum potential rate under the same conditions of n and dry is the temperature differential when the crop is not transpiring. According to this situation, CWSI can vary from 0 to 1. CWSI is 0 in non-water deficit conditions when stomata are completely open and the canopy is transpiring at its maximum potential rate, and CWSI is 1 when the plant is under the most extreme water deficit conditions and stomata are completely closed.

Considering that this indicator is automatable, the good results obtained in crop water stress detection and the latest advances of thermal imaging, its use in crop water status monitoring has drawn attention of researchers and producers and provides an interesting and promising stream of research (García-Tejero et al., 2018).

3.3.6. Meteorological variables

Traditional irrigation based on applying fixed amounts of water at specific time periods dramatically changed when irrigation scheduling incorporated into its calculation weather variables; mainly crop evapotranspiration (ETc), as it is defined as the amount of water both evaporated by the soil and transpired by the crop (Allen et al., 1998). And although the areas with remote and open access to climate networks and historical and real-time weather data are increasing, the cost of installation and maintenance of a complete weather station is so high that this implies a low density of stations and consequently a high number of growers that cannot access to representative climatic data (Collins, 2011). However, the advances in climate monitoring systems have developed low scale meteorological devices which are able to record and store specific weather data from growers' orchards, what improves irrigation management and water use (Lorite et al., 2015).

Among all weather parameters evapotranspiration (ET_0) and vapour pressure deficit (VPD), which in turn integrate different climate variables, have shown to affect tree water status the most (Abrisqueta et al., 2015; Corell et al., 2016). In sweet cherry, a strong relationship has been reported between VPD and plant water stress indicators such as stem water potential (Blanco et al., 2018) and sap flow (Juhász et al., 2013), and between ET_0 and branch diameter fluctuations (Abdelfatah et al., 2013).

3.3.7. Soil water content

To know soil water content at root zone provides useful information of the amount of water present in the soil and available to the plant. It can be measured as the volumetric water content, the ratio of water in a specific volume of soil. As soil water content can be continuously measured, soil moisture sensors can be used to automate irrigation scheduling and activate irrigation when soil water content is below the desired values (Datta et al., 2017).

In order to use soil moisture sensors to manage irrigation, it is necessary to know soil water content at field capacity to adapt threshold values to each soil. Soil water content variations will determinate when and how much water to apply to the plant in each situation. The range of values where soil water content can be considered optimal highly depends on the soil texture and depth. Moreover, the results measured sometimes are difficult to replicate due to the high variability of the soil.

3.3.8. Soil water matric potential

Among all soil water deficit indicators, soil water matric potential has been described as the most useful indicator, since it contemplates not only soil water content but also soil properties and texture (number and size of pores) and surface properties and tension. Soil water matric potential is the potential derived from the necessary force exerted by the roots of the plants to extract water from the soil.

Monitoring soil water matric potential has been reported as a successfully method to improve irrigation scheduling (Shock and Wang, 2011). It is able to be automated and provides continuous measures of soil water availability to the plant (Fig. 7). This has made this technology to be already implemented in commercial orchards. Thus, advances in automated measures of soil water matric potential such as autocalibrated sensors, low cost and resistant devices would help to increase the measuring points and consequently diminish the high variability of the soil, which could suppose a great step.

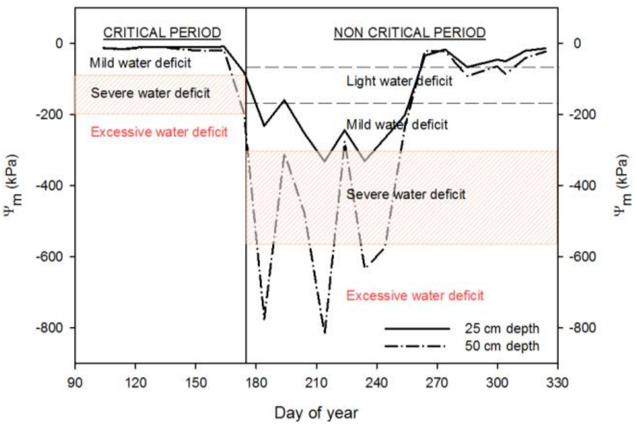


Fig. 7. Seasonal evolution of soil matric potential measured by MPS6 sensors (METER Group, Inc. USA) in a sweet cherry orchard according to grower’s irrigation in a warm area under Mediterranean climate (Jumilla, R. Murcia, Spain).

3.3.9. Future perspectives

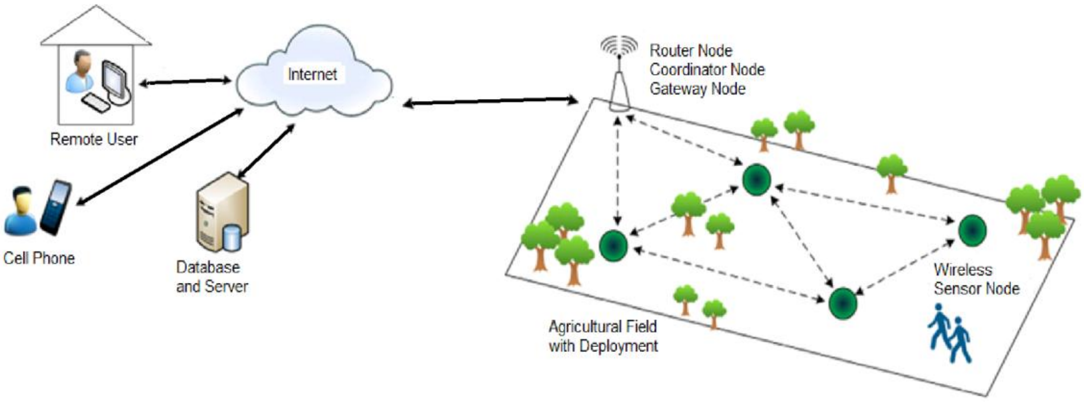
Nowadays, in commercial orchards meteorological and soil water status sensors are already a tool in irrigation management, while plant indicators such as sap flow or branch diameter fluctuations—although they also provide continuous measures—have not been as widely implemented. Stem water potential is considered the best plant water stress indicator, and in commercial orchards is commonly used; however, it is a one-off, destructive measure. Although there is already an automated sensor on the market capable of estimating stem water potential from the temperature gradient between tree sapwood surface and air “PSY1 Stem Psycrhrometers” (ICT International Pty Ltd, Armidale, Australia) and it has been successfully used in research trials (Wang et al., 2016), its commercial use is limited. As in the soil-plant-atmosphere continuum the plant hence responds to soil water availability and environmental conditions. To improve the use of those popular and continuous measuring sensors would entail a large step in knowing plant water status and would immediately help growers in the irrigation management decision-making.

4. Information and communication technologies in agriculture

FAO (2018b) projects that the global population will reach 9,700 million people in 2050, 2,400 million more than current population, making an increase of food production necessary. Resources are being more and more reduced and the increasing environmental concern demands agriculture to be more productive and sustainable, ensuring crop yields and environmental protection. This huge challenge requires global, efficient and smart solutions.

Information and communication technologies (ICTs) have led to a rapid change in all the principal development fields, and agriculture has not been left behind, adopting new technologies and changing progressively. Thus, precision irrigation incorporates ICTs (sensor networks, geographic information systems, satellite imaging, Internet of Things) to control crop, enhance the decision-making and optimise the use of water and inputs, pesticides, fertilisers, etc (López et al., 2015). Regarding the irrigation management, the amount of water and timing to apply it to the crop is based on knowing crop water requirements in accordance with the water status of soil, plant, and atmosphere, minimising water losses and avoiding soil salinity. ICTs such as remote sensing, wireless sensor networks, and mobile devices provide specific and real-time information to growers to maximise production efficiency, increasing water efficiency and decreasing carbon footprint and energy use (Bilali and Allahyari, 2018).

In this regard, and particularly in irrigation scheduling of RDI strategies which need a deep control of plant water status, soil water availability and atmospheric demand, the use of sensors and automatable water indicators are key factors to monitor and optimise crop and water management. Wired sensor networks are reliable and stable; however, compared to wireless sensor networks (WSN), wired networks show disadvantages in installation and maintenance, such as higher cost (mainly due to labour and cable costs) and location, sensor location distance is wired-limited (Ruiz-García et al., 2009). Moreover, WSN count on interesting characteristics, such as autonomy, low energy consumption and heterogeneity, and they are prepared to be connected to several sensors with different interfaces. Furthermore, its scalable architecture allows them to add new nodes to the network or easily change the configuration of the nodes. WSN are composed of several devices, commonly called nodes, which are connected wirelessly (Picture 9). In order to carry out a common objective, the different types of nodes can communicate with each other. The sensor nodes are the devices where the sensors are connected. Sensor nodes need router nodes to transmit the information to the coordinator node. The coordinator node collects the data and manages the network of sensor nodes. The coordinator node also acts as the gateway node, which is the node that sends data. The user from its computer or cell phone can connect to the gateway node and access the stored data (Banđur et al., 2019).



Picture 9. WSN connection scheme (Source: Navarro-Hellín, 2016).

WSN are prepared to work under hostile meteorological conditions and tolerate electronic and communication failures. Regarding its appearance, nodes are small and do not hinder farmer's work. Due to the problems of wired sensor networks and the attractive characteristics of WSN— although in research trials with high sensor density wired networks have provided good results— in commercial orchards the trend is to install WSN (Navarro-Hellín, 2016).

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CHAPTER 3

ABSTRACTS OF THE SCIENTIFIC ARTICLES

ARTICLE I:

Soil and plant water indicators for deficit irrigation management of field-grown sweet cherry trees

Objective

The main objective of this article was to identify which of the commonly used soil and plant water status indicators is the most useful for deficit irrigation scheduling of ‘Prime Giant’ sweet cherry trees. Another purpose was to estimate midday stem water potential from meteorological and soil and plant water status variables that can be easily integrated in automated systems.

Materials and methods

The study was performed during the 2015 and 2016 growing seasons in a commercial orchard located in Jumilla (Murcia, Spain, 38° 8' N; 1° 22' W). The trial was carried out on fifteen year-old mature 'Prime Giant' sweet cherry trees (*P. avium* L.) grafted on SL64 rootstock in a tree spacing of 5 m x 3 m. Three irrigation treatments were imposed: (i) a control treatment (CTL) irrigated at 110 % ETc; (ii) a regulated deficit irrigation treatment (RDI), irrigated at 100 % ETc during pre-harvest and flower differentiation and 55 % ETc during post-harvest; (iii) farmer treatment (FRM), irrigated according to the farmer’s practices. Treatments were distributed according to a completely randomised block design with four replicates per treatment.

The plant water status was monitored approximately every ten days at noon by measuring midday stem water potential (Ψ_{stem}) and stomatal conductance (gs). Continuous measurements of branch diameter fluctuations (BDF) were recorded by two dendrometers per replicate. From BDF, the maximum daily branch shrinkage (MDS) was calculated. Soil water status was measured from daily minimum soil volumetric water content (θv_{FC}) and soil water matric potential (Ψm). Daily agrometeorological parameters were provided by a weather station near the experimental orchard owned by SIAR. From these meteorological data vapour pressure deficit (VPD) was calculated. The sensitivity (S) of the studied water stress indicators was calculated according to Goldhamer and Fereres (2001). S is the result of the division of the Signal Intensity (SI) by the coefficient of variation (CV). Corrected sensitivity (S*) proposed by De la Rosa et al. (2014) is calculated by the ratio between SI−1 and CV.

Results and discussion

According to Girona et al. (2006), Naor and Peres (2001), Shackel et al. (2000), Ψ_{stem} can be considered as a reference water stress indicator in fruit trees. Consequently, water deficit indicators were ranked according to the goodness of fit of the calculated relations between these different indicators and Ψ_{stem}, MDS = θv_{FC} > Ψm > gs. Moreover, MDS was the indicator that first detected water stress. However, the relationship between MDS and Ψ_{stem} achieved a maximum value of -1.3 MPa beyond which MDS and Ψ_{stem} were not linearly related. Thus, MDS as water stress indicator only has got a limited range in which it can be used to manage RDI. The evaluation analysis showed gs to be the plant indicator with the highest SI followed by MDS and Ψ_{stem}. Although Ψ_{stem} had a lower SI than gs and similar to that of MDS, S and S* were much higher due to the low CV obtained. Soil water deficit indicators showed high SI values. However, they also had the highest CV.

The major drawback with Ψ_{stem} is that the measurement process cannot be automated and it provides one-off measurements. As the plant responds to soil water availability, as well as atmospheric demand, Ψm and VPD were related to estimate Ψ_{stem}. This relation describes two different situations to obtain an estimated Ψ_{stem} value, which depends on soil water availability and evaporative demand. If Ψm is lower than -30 kPa, there is a limiting soil water condition and the reference line is derived from Ψm and VPD, whereas if Ψm is higher than -30 kPa, Ψ_{stem} is mainly influenced by VPD.

If $\Psi m<-30$ kPa $\Psi_{stem\ estimated} = -0.3506 + 0.000642\Psi m - 0.2143VPD$ $R^2=0.74$; p-value<0.01

If $\Psi m>-30$ kPa $\Psi_{stem\ estimated} = -0.1674VPD - 0,3197$ $R^2=0.78$; p-value<0.01

Conclusion

The results obtained in the search for an overall indicator for use in irrigation management suggest the following order: Ψ_{stem} > Ψm > MDS > gs > θv_{FC}. Ψ_{stem} was seen to be the most reliable and stable water stress indicator as it clearly detected irrigation changes. Thus, we propose a Ψ_{stem} estimation model based on two easily available parameters, VPD and Ψm, which continuously register soil and atmosphere water status and obtain indirectly information regarding the plant water status.

ARTICLE II:

Water relations and quality changes throughout fruit development and shelf life of sweet cherry grown under regulated deficit irrigation

Objective

This article aimed at assessing the effects of deficit irrigation on plant and fruit water relations, fruit growth, yield and physicochemical characteristics at harvest and after cold storage and during subsequent retail conditions in ‘Prime Giant’ sweet cherries.

Materials and methods

The study was conducted in a 0.5 ha commercial orchard located in Jumilla (Murcia, Spain, 38° 8' N; 1° 22' W) during two consecutive growing seasons, 2015-2016 and 2016-2017. The plant material consisted of fifteen year-old ‘Prime Giant’ sweet cherry trees (*Prunus avium* L.), grafted on SL64 rootstock, and spaced at 5 m × 3 m. Three irrigation treatments were applied: a control (CTL) irrigated at 110 % ETc and two regulated deficit irrigation treatments (RD): (i) RDM irrigated at 90 % of ETc during pre-harvest, 100 % of ETc during flower differentiation and 65 % of ETc during post-harvest; (ii) RDS, irrigated at 100 % of ETc during pre-harvest and flower differentiation and 55 % of ETc during post-harvest. Treatments were distributed according to a completely randomised block design with four replicates per treatment.

The plant water status was measured every seven-ten days by measuring midday stem water potential (Ψ_{stem}) at noon. On the same days, fruit water potential (Ψ_{fruit}) was measured. Fruit osmotic potential ($\Psi_{\pi fruit}$) was measured in the same picked fruit as used to measure Ψ_{fruit}. Estimated fruit turgor potential (Ψ_{pfruit}) was obtained as the difference between osmotic and fruit water potential according to Milad and Shackel (1992). Fruit size, equatorial and polar diameters (mm), fruit volume (cm^3), fresh and dry unitary mass (g), fruit and pedicel colour, firmness (N), soluble solids concentration (SSC) and titratable acidity (TA) was measured every seven-ten days during fruit development at harvest, after 20 days of cold storage at 2ºC and after 5 days (20 + 5) of shelf life simulation at 15ºC.

Results and discussion

Ψ_{fruit} did not show significant differences among treatments and was strongly related to Ψ_{stem}. Moreover, Ψ_{fruit} was seen to be highly dependent on $\Psi_{\pi\text{fruit}}$. Ψ_{fruit} and $\Psi_{\pi\text{fruit}}$ rapidly decreased as SSC rose after fruit's colour change, during the stage III of fruit development. $\Psi_{\pi\text{fruit}}$ explained changes in Ψ_{fruit} better than $\Psi_{\rho\text{fruit}}$. $\Psi_{\rho\text{fruit}}$ remained positive throughout fruit development. The fruit physical parameters and SSC evolution was characterised by a sigmoid growth pattern. Once fruit started to change colour, RDM led to higher SSC and redder colours than CTL and RDS, but at harvest trees of both deficit irrigation treatments bore darker cherries than CTL.

The year 2016 was a high cropping year and trees produced 43 % more kg per tree than in 2017 (42 vs. 29 kg fruit tree^{-1}). As a result, fruit from 2016 was more prone to crack, 30 % smaller, 40 % firmer, less dark red, less sweet and less acid than the fruit from the same irrigation treatments in 2017. In neither year there were differences among irrigation treatments as regards yield and number of fruit per tree. However, RDM trees tended to produce fruit of smaller size than CTL, although without significant differences; in 2016 fruit from RDM was almost 1 g smaller than that from CTL. Regarding the quality parameters analysed (fruit and pedicel colour, firmness, SSC, AT), in 2016 there were no differences among irrigation treatments; however, in 2017 RDM fruit were sweeter and darker compared to the fruit from CTL. During 2016 storage trial, parameters such as size, SSC and TA remained stable throughout the experiment. On the other hand, fruit firmness increased significantly with time in cold storage and sharply declined during the shelf-life simulation. Fruit and pedicel colour decreased as time passed, particularly during shelf life, but only pedicel colour resulted affected by deficit irrigation. The pedicels from CTL fruit were significantly more brownish than those from RDS and RDM which remained green after storage.

Conclusion

Ψ_{fruit} was not as sensitive as Ψ_{stem} for identifying deficit irrigation. The application of RDM and RDS produced water savings of 36 and 40 % of the water applied to CTL treatment without significantly penalising fruit yield or quality. Fruits from RDS did not show any size reduction compared to CTL. Moreover, pedicel resulted in greener colour in RD fruit than in controls after 20 days at 2ºC. When both RD treatments were compared, RDM did not improve RDS fruit quality.

ARTICLE III:

Vegetative and reproductive response of ‘Prime Giant’ sweet cherry trees to regulated deficit irrigation

Objective

The objective of this article was to study the effects of different deficit irrigation strategies on the water status, yield and vegetative growth of adult ‘Prime Giant’ sweet cherry trees in order to optimise irrigation management in a semiarid area with scarce water resources.

Materials and methods

The experiment was conducted at a 0.5 ha commercial orchard located in Jumilla (Murcia, Spain, 38º 8' N; 1º 22' W, altitude 670 m) from 2015 to 2018. The study was performed in fifteen year-old mature sweet cherry trees (*P. avium* L. ‘Prime Giant’) grafted on SL64 rootstock, at a plant density of 667 trees ha^{-1}. The irrigation was applied during the dry period, from March before flowering until November. The experiment involved four irrigation treatments: (i) a control treatment (CTL) 110 % ETc; (ii) a sustained deficit irrigation treatment (SDI), irrigated at 85 % of ETc during pre- and post-harvest except for the floral differentiation when trees were irrigated at 100 % ETc; (iii) a regulated deficit irrigation treatment (RDI), irrigated at 100 % ETc during pre-harvest and flower differentiation and 55 % of ETc during post-harvest, and (iv) farmer treatment (FRM), irrigated according to the farmer’s normal practice. Treatments were distributed according to a completely randomised block design with four replicates per treatment.

Measures of soil water matric potential (Ψm) and soil water content (θv), midday stem water potential (Ψ_{stem}), stomatal conductance (gs), net photosynthesis (Pn) and branch growth rates (BGR) were taken to evaluate soil and plant water status. At harvest, fruits from 5 central trees of each replicate were harvested and weighed. Similarly, fruits were counted in 5 kg samples to calculate the unitary mass and double and cracked fruit proportion in the sample. The number of fruit per tree was estimated. Vegetative growth was measured as pruning wood, canopy volume, shaded area, cumulate shoot growth and trunk cross-sectional area.

Results and discussion

The reference crop evapotranspiration (ET_0) showed a similar seasonal evolution all the years of the study, with an annual average sum of 1256 mm. Compared to CTL, RDI saved the greatest amount of water, 39 %, while SDI and FRM saved 28 % and 15 % respectively.

The seasonal trends in Ψm and θv distinguished between the different irrigation strategies imposed in the three irrigation phases every year of the study. Ψ_{stem} was clearly influenced by evaporative demand and the applied deficit irrigation. RDI trees reached Ψ_{stem} values below -1.3 MPa all post-harvest; however, minimum value was measured in 2017 in FRM trees which resulted in Ψ_{stem} below -1.8 MPa. RDI trees resulted during post-harvest in gs and Pn significantly lower than CTL trees, 100 mmol m^2 s^{-1} and 10 µmol m^2 s^{-1} respectively. These reductions did not induce negative effects on next year yield and fruit quality; nevertheless, they affected vegetative growth, RDI trees in the last year of experiment resulted in the lowest canopy volume pruning wood and shaded area. BGR resulted in clear differences among treatments according to the irrigation treatment imposed which, at the end of each season, resulted in an accumulated BGR that was 1700 µm lower in RDI trees than in CTL. The slight deficit irrigation applied in SDI trees during pre-harvest did not significantly decrease yield, but resulted in lower vegetative growth, especially in parameters, such as current season shoot growth. Moreover, it induced a slight higher number of fruits per tree and tended to lower size.

There was no significant effect of irrigation on yield any year. However, yield among years was significantly different; consequently fruit unitary mass was strongly influenced. Thus, a linear relationship was obtained [Unitary mass (g) = -0.1021 Yield (kg $tree^{-1}$) + 13.67. The frequency of double fruit was not influenced by the irrigation treatment. On the contrary, cracking incidence was influenced by irrigation. Cherries of CTL were more prone to crack than those of RDI and SDI.

Conclusion

A water saving of 39 % (2700 m^3 ha^{-1}) compared to water applied to CTL in RDI trees did not penalise total fruit yield or quality, particularly fruit size. The regulated water deficit imposed during post-harvest in RDI trees decreased stomatal conductance and stem water potential, which resulted in vegetative growth lower than that obtained in CTL trees.

ARTICLE IV:

High tunnel cultivation of sweet cherry (*Prunus avium* L.): physiological and production variables

Objective

This article aimed at studying the effects of high tunnels environment in sweet cherry trees water status, yield, vegetative growth and fruit quality under a temperate Mediterranean-type climate.

Materials and methods

The trial was conducted in 2017 in a commercial orchard in the Central Valley of Chile (35º 1’ S, 71º 32’ W) with the early and highly-productive cultivar combination of ‘Royal Dawn’ on ‘MaxMa 14’. Trees were trained as a Y-trellis, spaced at 4.5 m x 2.0 m. The experiment involved two treatments: (i) ‘covered’ trees under multi-bay high tunnels and (ii) ‘open’ trees under open field conditions ‘control’. The treatments were distributed in a completely randomised block design with five blocks.

Temperature (T^a), relative humidity (RH) and soil volumetric water content (θv) were recorded inside and outside tunnels. Tree water status was determined weekly by measuring midday stem water potential (Ψ_{stem}) and stomatal conductance (gs). Current season shoot length, leaf number and fruit equatorial diameter per canopy layer at 0.8, 1.5, 2.0 m were measured weekly in marked fruits and shoots. Moreover, fruit growth was characterised each 7-10 days based on measurements of size, unitary mass and soluble solids concentration (SSC). Leaf area (LA) of individual spurs and extension shoots were measured on the same trees to estimate whole canopy LA and the ratio leaf area/fruit number (LA/F) according to Whiting and Lang (2004).

At harvest, yield of each canopy layer was recorded. In addition, 100 fruit per canopy layer per tree were collected for quality determination. Fruit showing visible cracking were recorded for each canopy layer in each tree in each treatment. Moreover, in order to assess fruit cracking potential, the cracking index was determined at laboratory. Fruit quality parameters included fruit size, mass, colour, SSC, titratable acidity (TA) and fruit firmness.

Results and discussion

Compared to the open, the covers increased air temperatures by 5 to 10ºC, slightly increased RH values and resulted in higher θv due to the protected environment inside high tunnels. The higher temperatures inside the high tunnels during fruit development may have speeded cell division and cell expansion, since harvest was 8 days earlier in the covered trees. At harvest, open trees showed Ψ_{stem} values below -0.90 MPa, while Ψ_{stem} values of covered trees were -0.50 MPa, both treatments with stomatal conductance values above 200 mmol m^{-2} s^{-1}. There were no significant differences between the covered and open trees in LA/F ratio, where LA ranged between 186 and 200 cm^2 per fruit.

The total yield of covered and open trees was similar; although the fruit-size distribution in the open trees was concentrated between 26 and 28 mm, while that in the covered trees was between 28 and 32 mm. Regardless of fruit position in the canopy (layer - bottom, middle, top) the fruit from the covered trees was larger but had lower SSC (17 %) and firmness (7 %) than fruit from open trees.

13 days before harvest of the open trees (during Stage III) rain over two days (29 mm rainfall) caused 19 % cracking in the open trees. However, inside the high tunnel the incidence of cracking was only 3 %. Healthy fruit from the trees in the open were of higher cracking susceptibility than that from the covered trees. Fruit on covered trees showed lower cracking index than fruit from the open, suggesting likely better performance during storage.

Conclusion

High tunnels stopped rain reaching the fruit surface and increased air temperatures compared to the open. Trees under high tunnels received 20 % lower irrigation water than open trees. Higher air temperatures under the covers speeded fruit growth and brought forward the dates of bloom and fruit development. As a direct consequence, covered trees were harvested 8 days earlier than trees in the open. There were no detectable differences either in yield, vegetative growth or in the LA/F ratio between covered and open trees. Fruit under the covers was 10 % larger but it had lower SSC and firmness.

CHAPTER 4

GENERAL CONCLUSIONS

The conclusions reported throughout the current PhD thesis dissertation describe~~s~~ the effects of different irrigation strategies (article I, II and III) and two different environments (article IV) on sweet cherry trees' reproductive and vegetative response and assess tree fruit growth, yield, vegetative growth, fruit quality, water savings, water productivity and some of the most common water deficit indicators used in irrigation management.

Water deficit indicators

- MDS was the indicator that first detected water stress. However, it was seen that -1.3 MPa was the threshold value beyond which MDS loses its water deficit detection capacity. So MDS can only be used as a reliable water indicator in slight or mild deficit irrigation strategies.
- Ψ_{stem} was the most reliable water deficit indicator, since, among the studied water deficit indicators, Ψ_{stem} was the one which showed the lowest coefficient of variation and high signal intensity and sensitivity.
- The integration of climatic demand (VPD) and soil water availability (Ψ_{m}) in an equation allows estimating Ψ_{stem} under our trial conditions. The equation distinguished between two situations according to $\Psi_{m.}$

Effects of soil water deficit on agronomic and physiological responses

- Tree's vegetative growth was more sensitive to soil water deficit than yield.
- Slight water deficits throughout the whole growing season resulted in lower vegetative growth without significantly reducing fruit yield. However, trees tended to produce slightly higher number of fruit per tree and fruit of smaller size.
- Trees submitted to postharvest severe water deficit did not result in lower tree yield or lower fruit unitary mass, but it affected tree water status decreasing g_s and $\Psi_{stem,}$ which consequently reduced canopy volume, pruning wood and trunk cross sectional area increased.

Fruit quality

- Trees submitted to deficit irrigation resulted in lower cracking losses, and were not affected by a higher occurrence of double fruit.
- In general, fruit of deficit irrigation treatments resulted neither in higher soluble solids concentration nor in intensive coloration than fruit of control trees, since only one out of four years of the study fruit from deficit trees enhanced SSC and colour.
- Deficit irrigation strategies tested did not penalise any quality parameter at harvest, or after 20 days of cold storage at 2ºC and subsequent period of 5 days at 15ºC.
- Fruit of trees submitted to deficit irrigation reduced its pedicel browning after 20 days at 2ºC compared to fruit of control trees.

Water productivity

- Trees under severe postharvest deficit irrigation resulted in the highest water savings, 39 % of the water applied to control trees, 2700 m^3 ha^{-1} and season, and compared to trees irrigated according to the grower's experience, between 2200 and 1300 m^3 ha^{-1} in 2015 and 2017 respectively.
- Regardless of the applied deficit irrigation strategy, all trees increased significantly water productivity and the ratio between fruit produced per annual trunk cross section increment compared to control trees without decreasing yield. However, only trees submitted to severe postharvest water deficit showed higher intrinsic water use efficiency and yield efficiency.

Environmental conditions

- High tunnels environmental conditions moved sweet cherry harvest forward by more than a week respect to trees in the open; with the consequent water savings (≥ 20 %), and improvement of the marketing conditions.
- Yield, vegetative growth and LA/F ratio did not result affected by protected cultivation; however, trees under high tunnels showed significantly lower cracking incidence and produced larger, less sweet, less firm and less susceptible to crack fruit than that of the trees in the open.

ANNEX I

IMPACT FACTOR

ISI WEB OF KNOWLEDGE. JCR SCIENCE EDITION

Article I

Blanco, V., Domingo, R., Pérez-Pastor, A., Blaya-Ros, P.J., Torres-Sánchez, R., 2018. Soil and plant water indicators for deficit irrigation management of field-grown sweet cherry trees. Agricultural Water Management, 208:83-94. DOI: 10.1016/j.agwat.2018.05.021

Impact factor: 3.182 (Q1; 12/90 Water Resources)

Article II

Blanco, V., Martínez-Hernández, G.B., Artés-Hernández, F., Blaya-Ros, P.J., Torres-Sánchez, R., Domingo R., 2019. Water relations and quality changes throughout fruit development and shelf life of sweet cherry grown under regulated deficit irrigation. Agricultural Water Management, 217:243-254. DOI: 10.1016/j.agwat.2019.02.028

Impact factor: 3.182 (Q1; 10/87 Agronomy)

Article III

Blanco, V., Torres-Sánchez, R., Blaya-Ros, P.J., Pérez-Pastor, A., Domingo, R., 2019. Vegetative and reproductive response of ‘Prime Giant’ sweet cherry trees to regulated deficit irrigation. Scientia Horticulturae, 249:478-489. DOI: 10.1016/j.scienta.2019.02.016

Impact factor: 1.76 (Q1; 8/37 Horticulture)

Article IV

Blanco, V., Zoffoli, J.P., Ayala, M., 2019. High tunnel cultivation of sweet cherry (Prunus avium L.): physiological and production variables. Scientia Horticulturae, 251:108-117. DOI: 10.1016/j.scienta.2019.02.023

Impact factor: 1.76 (Q1; 8/37 Horticulture)

ANNEX II

COMPILATION OF ARTICLES

Article I

Soil and plant water indicators for deficit irrigation management of field-grown sweet cherry trees.

Blanco, V., Domingo, R., Pérez-Pastor, A., Blaya-Ros, P.J., Torres-Sánchez, R., 2018. Agricultural Water Management, 208:83-94.

Article II

Water relations and quality changes throughout fruit development and shelf life of sweet cherry grown under regulated deficit irrigation. Blanco, V., Martínez-Hernández, G.B., Artés-Hernández, F., Blaya-Ros, P.J., Torres-Sánchez, R., Domingo R., 2019. Agricultural Water Management, 217:243-254.

Article III

Vegetative and reproductive response of ‘Prime Giant’ sweet cherry trees to regulated deficit irrigation. Blanco, V., Torres-Sánchez, R., Blaya-Ros, P.J., Pérez-Pastor, A., Domingo, R., 2019. Scientia Horticulturae, 249:478-489.

Article IV

High tunnel cultivation of sweet cherry (*Prunus avium L.*): physiological and production variables.

Blanco, V., Zoffoli, J.P., Ayala, M., 2019. Scientia Horticulturae, 251:108-117.