Universitat de Lleida
Escola Tècnica Superior d'Enginyeria Agrària
Departament de Medi Ambient i Ciències del Sòl

Effects of irrigation and nitrogen application on vegetative growth, yield and fruit quality in peaches (*Prunus persica* L. Batsch cv. Andross) for processing

Xavier Domingo Martínez
Tesi Doctoral
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Effects of irrigation and nitrogen application on vegetative growth, yield and fruit quality in peaches (*Prunus persica* L. Batsch cv. Andross) for processing

memòria presentada per

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al pare i a la mare

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Resum

El presseguer és un fruiter important a la regió fructícola de Lleida (nord-est d'Espanya), amb un augment progressiu durant els darrers anys. Les tendències actuals van cap a plantacions d'alta densitat, noves varietats i sistemes de reg per goteig. Els productors de presseguer estan interessats en gestionar el reg i la fertilització nitrogenada, per què afecten el creixement de l'arbre i poden ajudar a millorar els resultats de collita i qualitat de la fruita. Es va establir un experiment de camp de tres anys (2006-2008) en presseguer cv. Andross en una plantació comercial amb recol·lecció mecànica per a la indústria del processat. Els arbres estaven formats en un sistema de palmeta lliure i sense aclarir la càrrega de fruits. Els arbres es van recol·lectar mecànicament amb un vibrador de tronc continu. El sòl era de textura franca, ben drenat, amb una baixa capacitat de retenció d'aigua (30% en volum d'elements grossos i un horitzó petrocàlcic a 45 cm de profunditat). Es van avaluar tres estratègies de reg d'acord amb les fases de creixement del fruit: reg complet durant tota la temporada de cultiu (FI), restricció del reg durant la fase-II (IR2, 70% de restricció) i restricció del reg durant la fase-III (IR3, 30% de restricció), combinat amb tres tractaments de fertilització nitrogenada: 0, 60 i 120 kg N ha^{-1} any^{-1}. Els arbres es van fertigar diàriament. El disseny experimental va ser en blocs complets a l'atzar amb quatre repeticions. Es va mesurar el creixement estacional del fruit, el contingut d'aigua del sòl, la contracció del tronc, l'estat hídric dels arbres i la nutrició mineral. A la recol·lecció es van determinar els components de la producció i a repòs hivernal el pes de la poda. Els resultats mostren que els canvis diaris en contingut d'aigua del sòl, mesurat amb sondes de capacitància, es poden relacionar amb el dèficit d'aigua en cada fase de desenvolupament, i que el balanç d'aigua pot explicar el curs de la contracció del tronc, mesurat amb dendròmetros. La restricció del reg va afectar el contingut d'aigua del sòl i el potencial hídric de tija al migdia. Durant la fase-III, es va establir un nivell llindar de 0,167 m^3 m^{-3} en contingut d'aigua del sòl per a la disminució del potencial hídric de tija al migdia. La conductància estomàtica al migdia va augmentar al llarg del període de creixement del fruit. En tots els anys, el tractament IR2 va reduir la concentració de K foliar, mentre que va passar el contrari en la concentració en fulla de Ca i Mg. També IR2 va augmentar el pes específic de la fulla i va reduir el pes de la poda. Aquests efectes es van mantenir tot i que el reg complet va ser restablert durant la fase-III. Al contrari, l'estratègia IR3 no va afectar les relacions nutritives ni el pes de la poda. L'aplicació de N va suposar un augment de la concentració de N en fulles, fruits i brots a l'hivern, des del primer any experimental. L'increment de la dosi de N va produir una disminució de la concentració de K en fulla, però va augmentar la concentració de S en fulla. En arbres amb FI, l'aplicació de N va suposar un augment de la càrrega de fruits, de la mida de la copa i de la collita. També l'aplicació de N va augmentar l'índex de productivitat de l'aigua. La collita total va ser menor el 2006 que el 2007 i 2008, a causa de canvis en la càrrega de fruits dels arbres. El 2007, però, l'efecte del reg durant la fase-III va dependre de l'aplicació de N, i es va observar un efecte positiu sobre la collita amb l'increment de N en arbres amb FI, mentre que va passar el contrari en els arbres amb IR3. Així, la collita menor es va obtenir amb IR3 combinat amb N120. Amb IR2, la collita va ser independent de l'aplicació de N. El 2008, amb un major contingut d'aigua del sòl, no hi va haver efecte d'interacció, i l'aplicació de N va augmentar la collita en tots els tractaments de reg. L'aplicació amb IR2 durant l'enduriment de l'os va permetre augmentar l'índex de productivitat de l'aigua i millorar la maduració dels fruits. D'altra banda, IR3 va reduir la mida del fruit i va augmentar sòlids solubles totals

a collita. Amb tots els tractaments es va obtenir una correlació positiva entre el percentatge de matèria seca del fruit i els sòlids solubles totals. Tot i que l'aplicació més elevada de N va retardar la maduració dels fruits, no hi va haver una interacció significativa entre el reg i l'aplicació de N. En general, l'aplicació de 120 kg N ha^{-1} any^{-1} proporciona una dosi màxima de N en les condicions d'aquesta plantació, que podrà ser reduïda sota restricció de reg.

Resumen

El melocotonero es un frutal importante en la región de Lleida (noreste de España), con un aumento progresivo en los últimos años. Las tendencias actuales van hacia plantaciones de alta densidad, nuevas variedades y sistemas de riego por goteo. Los productores de melocotonero están interesados en gestionar el riego y la fertilización nitrogenada, por que afectan el crecimiento del árbol y pueden ayudar a mejorar los resultados de cosecha y calidad de la fruta. Se estableció un experimento en campo de tres años (2006-2008) en melocotonero cv. Andross en una plantación comercial con recolección mecánica para la industria del procesado. Los árboles estaban formados en un sistema de palmeta libre y sin aclarar la carga de frutos. Los árboles fueron cosechados mecánicamente con un vibrador de tronco continuo. El tipo de suelo era de textura franca, bien drenados, con una baja capacidad de retención de agua (30% en volumen de elementos gruesos y un horizonte petrocálcico a 45 cm de profundidad). Se evaluaron tres estrategias de riego de acuerdo con las fases de crecimiento del fruto: riego completo durante toda la temporada de cultivo (FI), restricción del riego durante la fase-II (IR2, 70% de restricción) y restricción del riego durante la fase-III (IR3, 30% de restricción), combinado con tres tratamientos de fertilización nitrogenada: 0, 60 y 120 kg N ha^{-1} año^{-1}. Los árboles se fertigaban diariamente. El diseño experimental fue en bloques completos al azar con cuatro repeticiones. Se midió el crecimiento estacional del fruto, el contenido de agua del suelo, la contracción del tronco, el estado hídrico de los árboles y la nutrición mineral. A cosecha se determinaron los componentes de la producción y en reposo invernal el peso de la poda. Los resultados mostraron que los cambios diarios en contenido de agua del suelo, medidos con sondas de capacitancia, se pueden relacionar con el déficit de agua en cada fase de desarrollo, y que el balance de agua puede explicar el curso de la contracción del tronco, medidos con dendrómetros. La restricción del riego afectó el contenido de agua del suelo y el potencial hídrico de tallo al mediodía. Durante la fase-III, se estableció un nivel umbral de 0,167 m^3 m^{-3} en contenido de agua del suelo para la disminución del potencial hídrico de tallo al mediodía. La conductancia estomática al mediodía aumentó a lo largo del período de crecimiento del fruto. En todos los años, el tratamiento IR2 redujo la concentración de K foliar, mientras que ocurrió lo contrario en la concentración en hoja de Ca y Mg. También IR2 aumentó el peso específico de la hoja y redujo el peso de la poda. Estos efectos se mantuvieron a pesar de que el riego completo fue restaurado durante la fase-III. Al contrario, la estrategia IR3 no afectó las relaciones nutritivas ni el peso de la poda. La aplicación de N supuso un aumento de la concentración de N en hojas, frutos y brotes en invierno, desde el primer año experimental. El incremento de la dosis de N produjo una disminución de la concentración de K en hoja, pero aumentó la concentración en hoja de S. En árboles con FI, la aplicación de N supuso un aumento de la carga de frutos, del tamaño de la copa y de la cosecha. También la aplicación de N aumentó el índice de productividad del agua. El rendimiento total fue menor en 2006 que en 2007 y 2008, debido a cambios en la carga de frutos de los árboles. En 2007, sin embargo, el efecto del riego durante la fase-III dependió de la aplicación de N, y se observó un efecto positivo de la cosecha con en incremento de N en árboles con FI, mientras que ocurrió lo contrario en los árboles con IR3. Así, la cosecha menor se obtuvo con IR3 combinado con N120. Con IR2, la cosecha fue independiente de la aplicación de N. En 2008, con un mayor contenido de agua del suelo, no hubo efecto de interacción, y la aplicación de N aumentó el rendimiento en todos los tratamientos de riego. La aplicación con IR2 durante el endurecimiento del hueso permitió aumentar el

índice de productividad del agua y mejorar la maduración de los frutos. Por otra parte, IR3 redujo el tamaño del fruto y el aumentó de los sólidos solubles totales a cosecha. Con todos los tratamientos se obtuvo una correlación positiva entre el porcentaje de materia seca del fruto y los sólidos solubles totales. Aunque la aplicación más elevada de N retrasó la maduración de los frutos, no hubo una interacción significativa entre el riego y la aplicación de N. En general, la aplicación de 120 kg N ha^{-1} año^{-1} proporciona una dosis máxima de N en las condiciones de esta plantación, que podrá ser reducida bajo restricción de riego.

Summary

Peach is an important fruit tree in the horticultural region of Lleida (Northeast of Spain), with a progressive increase in the last years. Recent trends in peach orchards have been towards high density plantings, new cultivars and drip irrigation systems. Peach producers are interested to manage irrigation and nitrogen fertilization, that affect tree growth and may help to achieve good results in yield and fruit quality. A three year field experiment (2006-2008) on peach cv. Andross was conducted in a commercial orchard for the processing industry. Trees were unthinned and trained on a free palmeta. Trees were mechanically harvested with a continuum trunk shaker. The soil type was loam textured, well drained, with a low water holding capacity (30% volume of coarse elements and a petrocalcic horizon at 45 cm depth). Three irrigation treatments were evaluated according to fruit growth stages: full irrigation during all the growing season (FI), irrigation restriction during stage-II (IR2, 70% restriction) and irrigation restriction during stage-III (IR3, 30% restriction), combined with three nitrogen fertilization treatments: 0, 60 and 120 kg N ha^{-1} $year^{-1}$ Trees were daily fertigated. The experimental design was randomised complete block with four repetitions. Seasonal fruit growth, soil water content, trunk shrinkage, tree water status and mineral nutrition were monitored. Yield components were determined at harvest and pruning weight was determined at tree rest. Results show that daily changes of soil water content, measured with capacitance probes, could be correlated to water deficit for each development stage, and that water balance can explain the daily course of trunk shrinkage, measured with dendrometers. Irrigation restriction affected soil water content and midday stem water potential. For stage-III, a threshold level for the onset of midday stem water potential decline was established at 0.167 m^3 m^{-3} of soil water content. Midday stomatal conductance increased along the fruit growth period. During all years, IR2 reduced leaf K concentration, while the opposite occurred with leaf Ca and Mg concentration. Also IR2 increased the specific leaf weight and reduced the pruning weight. These effects were maintained although complete irrigation was restored during the stage-III. In contrast, IR3 did not affect nutrient relations or pruning weight. N application supposed an increase in N concentration in leaves, fruits and dormant shoots, from the first experimental year. Increasing N application produced a decrease in leaf K, but an increase in leaf S. In FI trees, N application supposed an increase in fruit load, canopy size and yield. Also N application increased the water productivity. Total yield was lower in 2006 than in 2007 and 2008, due to changes in fruit load. Nevertheless, in 2007 the effect of irrigation during stage-III was dependent on N application, and a positive yield effect of N dose in FI trees was observed, while the opposite occurred in IR3 trees. Thus the lowest yield was obtained in the IR3 combined with N120. Under IR2, yield was independent of N application. In 2008, with higher soil water content, there was no interaction effect, and N application increased yield within all irrigation treatments. The application of IR2 during pit hardening allowed to increase the water productivity and enhance fruit ripening. On the other hand, IR3 reduced the fruit size and increased the total soluble solids at harvest. Among all treatments, the percentage of fruit dry matter was positively correlated with the total soluble solids. Although the highest N application delayed fruit ripening, there were no significant interaction between irrigation and N application. As an overall, in FI trees, the application of 120 kg N ha^{-1} $year^{-1}$ provides a maximum N dose in such orchard conditions, which may be reduced under irrigation restriction.

1. Introduction

1.1. Background and objectives

1.1.1. Peach production in Spain

The peach, *Prunus persica* L. Batsch, is native of south-eastern China (Scorza and Okie, 1990). In Spain, peach is an important fruit tree with a progressive increase in the last years (Table 1). In the horticultural region of Lleida (oriental zone of Ebro Valley at the north-eastern Spain), peach is distributed over 14 435 ha, which represents 18% of total national peach cultivated surface (MARM, 2008). Peach production for processing industries is also increasing (Cuadrado *et al.*, 2000). This region is characterized by calcareous soil conditions and semiarid climate during the growing season when the warm summer coincides with a dry environment (Porta and Julià, 1983).

Table 1. Peach production in Spain and in the horticultural region of Lleida (in parenthesis percentage respect total national peach production, MMARM, 2008).

Year	Cultivated surface (ha)		Production (t)	
	Spain	Lleida	Spain	Lleida
2001	74 779	10 595 (14%)	1 081 488	178 767 (17%)
2006	80 528	14 435 (18%)	1 245 527	262 219 (21%)

1.1.2. Fruit tree orchards

Recent trends in fruit tree orchards in the horticultural zone of Lleida have been towards high-density plantings, new cultivars and drip irrigation systems (Urbina *et al.*, 1999; Nolla *et al.*, 2006; Pascual *et al.*, 2007). Tree root and canopy growth can be controlled by rootstock/scion combination and tree spacing to achieve higher yields and earlier returns from the initial investment (Urbina *et al.*, 2007). Breeding programmes have generated different *Prunus* rootstocks to different soil conditions (Iglesias and Carbó, 2006) and a large number of peach, nectarine and clingstone-peach cultivars, which differ in the length of the fruit development period, timing of fruit harvest and fruit quality (Carbó and Iglesias, 2002). The most important benefit of drip irrigation is that it wets only a fraction of the soil volume (Gispert, 2003), maintains high soil water content throughout the season preventing cycles of water deficit (Bryla *et al.*, 2005), root system confinement increases the overall root length density (Ruiz-Sánchez *et al.*, 2005) and increases the irrigation use efficiency (Dasberg and Bresler, 1985). Since drip irrigation affects both spatial root distribution and nutrient distribution (Mmolawa and Or, 2000), this has stimulated interest in fertigation techniques which allow frequent additions of smaller amounts of nutrients, more closely timed to tree demand and reducing nitrate leaching below the rooting zone (He *et al.*, 2003; Paramasivam *et al.*, 2001; Kusakabe *et al.*, 2006).

1.1.3. Irrigation and nitrogen fertilization

In semiarid conditions water and nitrogen (N) application are needed early in the life of the tree to fill its allotted space. Once this has been achieved, efficient irrigation strategies and N fertilization during the current season can control yield components and fruit quality (Faust, 1989). Some responses of irrigation strategies have been obtained in

fruit orchards in the horticultural zone of Lleida, including peach (Marsal, 1996; Gelly, 2003; Lopez, 2006), apple (Rufat, 2003; Reyes, 2006), pear (Marsal *et al*., 2002b), olive (Luna, 2000; Alegre, 2001) and grapevine (Reyes, 2006; Olivo, 2007). The combined effect of irrigation and N application have been studied in apples trees (Rufat, 2003) and there has been an evaluation of N fertilization on different fruit trees (Villar and Arán, 1999).

In peach trees, different processes are sensitive to irrigation restriction, such as root growth, canopy growth, flower bud differentiation, fruit set, fruit cell division, fruit expansion and fruit maturation (Chalmers *et al*., 1983; Behboudian and Mills, 1997; Goodwin and Boland, 2000; Naor, 2006). N fertilization affects quality of peach puree (Olienyk *et al*., 1997), but applying excessive N have few benefits and much disadvantages because of shading by excessive canopy growth, delay of fruit maturation, unbalanced nutrition in calcareous soils and N leaching below the rooting zone (Daane *et al*., 1995; Marcelle, 1995; Crisosto *et al*., 1997; Neilsen and Neilsen, 1997). Whereas, applying insufficient N results in reduced tree growth (Johnson, 1988).

Evapotranspiration becomes a key factor in irrigation scheduling as a management tool (Villar, 2001). An increasing proportion of fruit orchards in the horticultural region of Lleida schedule drip irrigation inputs according to estimations of precipitation and crop evapotranspiration (Nabau, 2004). However irrigation scheduling based alone on meteorological variables, rather than measuring soil water content, do not allow to increase the water use efficiency. Development of electronic capacitance sensors allows to measure the volumetric water content of the soil (Villar and Ferrer, 2005). Soil moisture probes may be installed at different depths in the rooting zone to control irrigation at real time and monitor daily patterns of drip irrigation (O'Connell and Snyder, 2004). Knowing the current soil water content is important to track with both crop evapotranspiration and precipitation (Pla, 1994). Drainage can be measured with gee passive capillary lysimeter buried beneath the soil-rooting zone (Fonseca *et al*., 2007). In semiarid conditions the soil water content at the beginning of the season remains high due to winter precipitation and low evapotranspiration. But as the growing season progresses, tree evapotranspiration exhausts some proportion of the soil water content reservoir since there are not precipitation. Crops are sensible to soil water restriction during some development stages (Doorembos and Kassam, 1979). The main objective of irrigation scheduling is to maintain soil water content between upper drained level and lower level of water extraction, determined in field conditions and according to orchard management (Ferrer *et al*., 2007). Soil water content attains upper level when excess water has drained after an irrigation or precipitation event and lower level when water uptake by roots becomes difficult. The amount of readily available water for root uptake is the difference between upper and lower level and is related to the effective rooting depth of the plant and the water holding capacity of the soil. The water holding capacity depends on soil conditions: texture and coarse elements (Porta *et al*., 1994). In addition, soil salinity produces adverse effects on the physiology of fruit trees (Boland *et al*., 1993; Boland *et al*., 1997).

N is the base for protein synthesis and is an integral component of chlorophyll (Marschner, 1995). Thus, N deficiency results in pale green leaves, reduces leaf growth and leaves tends to abscise as the season progresses. Under low N conditions, anthocyanin production is favoured, and appears a reddish tinge that develops on the petioles, stems and leaf blades. These symptoms can be pronounced in peach (Ogawa *et*

al., 1995; Strand, 1999). Orchard management by N fertilization allows to maintain N tissue concentration and control physiological processes within the tree (Faust, 1989). There are three approaches to diagnostic nutrient problems: soil analysis, leaf analysis and recognition of visual symptoms (Villar and Arán, 2008). The last approach is quickly, but it requires experience in recognising symptoms and often it is not practice to wait until a deficiency appears. Soil analysis at the onset of winter rest indicates the potential availability of N that roots may take up under favourable conditions and is useful to diagnostic problems that may appear during the growing season, because soil particles cannot hold a large reserve of N and it leaches due to water deep percolation. Leaf N analysis is a useful method to diagnostic N deficiency or excess as a complement to soil analysis. Leaf N concentration can be compared with reference levels (Villar and Arán, 2008). Other methods to assess peach tree N status include nutrient analysis of fruits (Taylor and van den Ende, 1970a), winter pruning wood (Johnson *et al*., 2006), flowers (Sanz *et al*., 1995; Zarrouk *et al*., 2005), roots (Taylor and van den Ende, 1969) and leaf relative light absorbance (Rubio-Covarrubias *et al*., 2008).

1.1.4. Objectives

1. Characterization of the developmental stages of clingstone peach cv. Andross, according to vegetative growth and fruit growth, and the contribution of water relations between the soil, the tree and the atmosphere.

2. Assessing the effect of irrigation restriction at certain stages on soil water content, and its effect on tree water status and mineral nutrition, in a soil with a low water holding capacity.

3. Assessing the effects of N application on the dynamics of N and other macronutrients in leaves, fruits and shoots, as well as on yield N exportations and nitrate remaining in the soil.

4. Evaluation of the effects of irrigation restriction and N application on yield components and fruit quality, in a commercial orchard with mechanical harvesting for the processing industry.

5. Analysis of the interaction between irrigation and N application on fruit yield, and determination the N dose to apply, for local conditions.

6. Determination of the water productivity under different irrigation and N strategies.

1.2. Seasonal growth of fruit trees

1.2.1. Root growth

Knowledge of dynamics of peach root growth is important for adjusting irrigation and fertilization. Root growth proceeds by a balance of biomass according to leaf growth (Mediene, 2002), since roots system absorb water and nutrients, whereas canopy intercept radiation and proportionate photo-assimilates (Faust, 1989; Kozlowski and Pallardy, 1997). In young peach trees, root:shoot ratio increases under soil water

restriction (Steinberg *et al.*, 1990; Hipps *et al.*, 1995), soil salinity (Massai *et al.*, 2004) and low N supply (Almaliotis *et al.*, 1997), although this is largely due to the inhibition of shoot growth, rather than to increased root growth. In mature peach trees, any change in the growth ratio between roots:canopy due to tree management is accompanied by a modification of yield components (Marsal *et al.*, 2003; Lopez *et al.*, 2007b).

Root growth can be determined by different methods, such as taking soil cores at different depths and root washing (Smith *et al.*, 2000). Root system comprises a perennial structure and a continuous production of new root during the season (Doussan et a., 1999). Root distribution in the soil depends on soil properties, tree spacing, irrigation system and soil management (Havis, 1938; Mitchell and Black, 1968; 1971; Romo and Díaz, 1985). However, the seasonal studies do not support the observation that root growth stops during periods of high sink demand by fruit growth. In young non-bearing trees grown under field conditions, root growth is active throughout the growing season (Glenn and Welker 1993). Also in young bearing trees grown in pots, seasonal root growth is continuous but with a peak during summer (Williamson and Coston, 1989). Recently, minirhizotron camera has been used as a non-destructive method to measure root length density of young bearing trees in field conditions under drip irrigation (Abrisqueta *et al.*, 2008). Under such conditions, root growth rate is continuous at 0.01 cm cm^{-3} day^{-1}, indicating favourable soil water content and temperature. Although a peak of growth extends from May until mid-August and attains a maximum root growth rate of 0.04 cm cm^{-3} day^{-1} at mid-July. Also roots are mostly located in the upper 0.55 m of soil and are particularly concentrated at 0.40-0.55 m depth, but then declines markedly with depth influenced by soil porosity. More than 88% of these roots are very thin, with diameters of <0.5 mm (Abrisqueta *et al.*, 2008).

1.2.2. Canopy growth

In fruit trees, canopy growth affects radiation interception, water transpiration, CO_2 assimilation, and photo-assimilate translocation to maintain root and fruit growth (Faust, 1989; Kozlowski and Pallardy, 1997). Canopy growth can be determined by different methods, such as on tagged shoots during the season, on trunk cross-section area or on pruning weight at winter (Weibel *et al.*, 2003). On young peach trees, leaf growth decreases under low N supply (Lobit *et al.*, 2001) and soil water restriction (Steinberg *et al.* 1990). Reduced shoot length by soil water restriction is due to differences in internode extension and not to the number of internodes (Hipps *et al.*, 1995). In mature peach trees, trunk growth continues until leaf fall and is affected by soil water restriction (Larson *et al.*, 1988; Girona *et al.*, 2003) and N application (Taylor and van den Ende, 1969). Trunk cross-section area depends on different orchard training systems and therefore canopy volume is preferred (Wright *et al.*, 2002). There is a correlation between canopy volume and annual applied irrigation on cherry trees (Dehghanisanij *et al.*, 2007). Canopy growth is limited under heavy fruit load (Grossman and DeJong, 1995c; Berman and DeJong, 1997a; Berman and DeJong, 2003).

Canopy structure is complex and is organized in multiple leaf levels. Leaf area index can be determined directly as total one-sided leaf area per unit ground area or indirectly making use of radiation transfer methods (Bréda, 2003). The fraction of intercepted PAR (FIPAR) depends on leaf absorption characteristics, leaf angle distribution, tree extinction coefficient and tree orientation, shape and size (Norman and

Campbell, 1989; Campbell and Norman, 1998). Canopy FIPAR is used in peach orchards for irrigation scheduling (Ayars *et al*., 2003; O'Connell *et al*., 2006). Pruning of peach trees under mid-summer decreases FIPAR, reduces the water requirements of the trees (Goodwin at al., 2006) and delays de appearance of leaf wilting symptoms (Lopez *et al*., 2006). N fertilization increases seasonal FIPAR of deciduous trees (Allen *et al*., 2005). In addition, canopy FIPAR is used to analyse yield components by the ratio of sink demand to source strength (Reginato *et al*., 2007) and for the determination of efficiencies in dry matter accumulation (Sofo *et al*., 2005).

1.2.3. Peach fruit growth

Peach flower induction occurs during the initial period of active vegetative growth and floral differentiation starts when canopy growth ceases (Greene, 1996). Full bloom depends on location and cultivar, and after sufficient chilling temperatures have occurred to release from dormancy (Couvillon and Erez, 1985), flowering in the spring is a temperature dependent process (Schwartz *et al*., 1997). Effects on flowering and fruit set by orchard management determine tree fruit load (Faust, 1989; Kozlowski and Pallardy, 1997).

Fruit growth occurs by accumulation of water and dry matter (Fishman and Génard, 1998). There are different methods to measure fruit growth such as diameter, perimeter, volume or fresh weight (Opara, 2000), which are related by several allometric equations (Dalmases *et al*., 1998). Under field non-limiting conditions, fruit growth potential follows a curve that is cultivar specific (Berman *et al*., 1998). Growth curve is monitored according to degree-day accumulation using an upper and lower threshold for peach of 35 and 7ºC, respectively (DeJong and Goudrian, 1989). There is a strong negative correlation between the sum of degree days accumulated in the first month after full bloom and the number of days between full bloom to harvest (Smith, 1985; Ben Mimoun and DeJong, 1999) and fruit size at harvest (Lopez and DeJong, 2007) for several peach cultivars. The interaction of fruit growth potential with additional factors, including fruit load and length of the fruit growth period, determines fruit dry matter at harvest (Berman *et al*., 1998). Interfruit competition limits fruit growth (Johnson and Handley, 1989; Rowe and Johson, 1992; Dalmases *et al*., 2001; Gugliuzza *et al*., 2002; Inglese *et al*., 2002) and fruit thinning is used to attain a desired fruit size (Njoroge and Reighard, 2008). Fruit on late maturing cultivars have higher dry matter proportion than fruit of early maturing cultivars (Berman *et al*., 1998). N fertilization extends fruit development period and increases fruit sink capacity (Saenz *et al*., 1997; Rufat and DeJong 2001).

The peach fruit growth curve is double-sigmoidal with three development stages (Chalmers and van den Ende, 1975). Stage-I comprises an initial phase of rapid fruit growth by cellular division, followed by stage-II of decreasing growth rate that coincides with synthesis of lignin and pit hardening, and finally stage-III of fruit expansive growth until maturation. During stage-I there are considerable demands on storage carbon to growing roots, leaves and fruits. During stage-II, demand for carbon by the fruit decreases and most of the photo-assimilates produced is partitioned into active root and leaf growth. The duration of stage-II is under both genetic and environmental control. Carbon assimilation and supply can be limiting at stage-III of high fruit sink demand. After harvest, carbon demands are reduced considerably especially if leaf growth has ceased (Chalmers *et al*., 1975).

In addition to the rapid changes in growth rate during stage-III, the process of fruit maturation begins, identified by physical and chemical changes in the mesocarp, such as colour, flesh softening, accumulation of sugars and organic acids and production of ethylene and aroma volatile compounds (Chapman *et al*., 1991; Gelly *et al*., 2004). Fruits mature earlier in exposed regions of the canopy (Dann and Jerie, 1988; Marini *et al*., 1991) and applying excessive N rates delay fruit maturation (Crisosto *et al*., 1997). Soil water restriction during stage-III is more decisive in terms of fruit quality, since it increases soluble solids concentration (Besset *et al*., 2001; Ben Mechlia *et al*., 2002).

In peach cultivars with harvest date during early to mid August, like Andross clingstone peach (Girona *et al*., 2005), fruit dry matter accumulation is 2.4 g during stage-I (0.04 g DM day^{-1}), 8.4 g during stage-II (0.21 g DM day^{-1}) and 27 g during stage-III (0.6 g DM day^{-1}), for periods of 60, 40 and 45 days, respectively. On the other hand, approximately 10% of the total fruit growth in fresh weight occurs during active canopy growth, whereas 80% of fruit growth occurs when canopy growth is almost complete. This asynchrous growth of peach fruits and leaves reduces competition between assimilates and water, and provides a basis for application of irrigation efficient strategies with water savings without yield loss in late maturing cultivars (Chalmers *et al*., 1984; Li and Hughet, 1989; Boland *et al*., 1993).

1.3. Nitrogen and interaction between nutrients

1.3.1. Ion uptake

There are three components of ion transport from the soil to the root surface (Marschner, 1995; Fitter and Hay, 2001). Ions may be intercepted during the root elongation process across the soil. Ions dissolved in the soil solution may be transported from the bulk soil to the root surface through mass flow driven by soil water potential gradient. Transport by mass flow depends on ion concentration in the soil solution and root water uptake. N, Ca and Mg are mainly transported by mass flow. In addition, ions may be transported by diffusion driven by concentration gradients and then a depletion zone appears around the root. Transport of potassium (K) and phosphorous (P) are affected by diffusion due to low ion diffusion coefficient in soil pores and high buffer power of clay particles. The soil volume explored by the root hair cylinder becomes important since it is positive correlated with K uptake rate per unit root length. However as root length density increases, the distance between roots decreases and the uptake rate attains a plateau due to inter-root competition for ions. Transport by diffusion depends on soil water content, and as soil dries, the supply of K and P are more impaired than that of calcium (Ca) and magnesium (Mg), which may be increased.

Root ion uptake from the rhizosphere occurs simultaneously with radial flow of water across the apoplast, through interfibrillar pores of the cell walls, until the endodermis. In the endodermis, ions are transported into the symplast (cytoplasm connected by plasmodesmata) via carrier proteins in the plasma membrane. The suberized Casparian strip prevents the back-diffusion of ions. Finally, adjacent parenchyma cells controls loading of ions into the xylem vessels (De Boer and Volkov, 2003). Root ion uptake against an electrochemical potential gradient and xylem loading require metabolic energy (Bowling, 1981). Also, a continual supply of carbon skeletons is required for sustain nitrate assimilation to amino-acids (Rufty *et al*., 1989) and root

nitrate uptake depends on soil temperature (Bhat, 1982; Scholberg *et al*., 2002). Most of the nitrate assimilation occurs on roots but as nitrate concentration increases some proportion is assimilated on leaves (Andrews, 1986) and nitrate is found in the xylem sap (Gojon *et al*., 1991) and leaves (Leece *et al*., 1972). Xylem nitrate translocation shows a diurnal variation, with maximum values in the first half of the illumination period and decreases to the end of light period, independent of nitrate uptake and sap flow (Siebrecht *et al*., 2003).

Xylem vessels are responsible for long distance transport of ions from roots to leaves, both by transpiration stream and root pressure (Mohr and Schopfer, 1995). Root pressure is important under low evaporative demand during the night (Tanner and Beevers, 2001). At spring during bud burst, ions and sugar molecules are increasingly secreted by parenchyma cells of central cylinder into the xylem vessels, which under well soil water conditions osmosis causes a positive pressure within the xylem vessels (Ohkawa, 1981). Resultant pressures may have undesirable consequences such as fruit splitting (Evert *et al*., 1988). The xylem sap can be collected after decapitation and analysed for composition and concentration of ions and organic solutes. Ions, especially K, can be recirculated from the phloem to the xylem, except nitrate and Ca, which are almost phloem immobile (Marschner, 1995). Nitrate and K transport in the xylem are closely related and nitrate depletion causes an increase in the xylem loading of organic anions to maintain electroneutrality (Siebrecht and Tischner, 1999). Al soil dries the composition of the xylem sap changes and pH increases (Gollan *et al*., 1992).

1.3.2. Tree nitrogen dynamics

During the growing season root N uptake comes from mineralization of soil organic matter and from soil N fertilizer, which are reduced and assimilated into amino acids in the roots (Faust, 1989). Other sources of N can be foliar applied urea that is used in combination with soil N fertilization (Johnson *et al*., 2001; Furuya and Umemiya, 2002) and ammonia taken up by leaves that can be important in locations where N deposition is increasing (Pearson and Stewart, 1993). The dynamics of root N uptake and partitioning over the season can be determined in field grown trees by root excavation method (Niederholzer *et al*., 2001) or in sand culture experiments by supplying labelled N isotopes to young potted trees which are destructively harvested (Muñoz *et al*., 1993).

In deciduous trees, root N uptake is relatively low in spring, and early tissue growth occurs at expenses of N stored in perennial organs (Tagliavini *et al*., 1998). An internal cycling comprises the storage of N during winter as protein in the bark and the remobilisation of N when the buds break (Bläsing *et al*., 1990; Millard 1995; Tagliavini and Millard, 2005). The concentration of amino acids in the xylem sap rise following bud burst and decreases during fruit set, coinciding with the period of N remobilisation to growing leaves during spring (Malaguti *et al*., 2001). The amino acid glutamine is the main compound in *Prunus* species (Andersen *et al*., 1995). In peach trees during the first 30 days after full bloom, leaf and fruit growth mainly relies on N remobilised from reserves (Rufat and DeJong, 1999), which accounts for 75-80% of total N in new growth until fruit set (Policarpo *et al*., 2002). Fruit set depends on stored N in apple (Toldam-Andersen and Hansen, 1995).

Tree N demand varies according to metabolic processes in growing tissues (Habib *et al*., 1989). Root N uptake requires the availability of photo-assimilates (Huett, 1996), thus in young peach, root N uptake increases with active leaf growth, remains high during the growth period to a maximum of 3.1 µg N g^{-1} root day^{-1} and then decreased again during leaf senescence (Wallach *et al*., 1990). If photo-assimilate translocation to the root is affected then root N uptake decreases (Jordan *et al*., 1998; 2001). Also root N uptake is a consequence of favourable soil temperatures (Malcolm *et al*., 2008) and soil exploration by roots (Ran *et al*., 1994). Root N uptake is unaffected by removal of ripening fruits and remains high during the period in which canopy growth ceases (Tagliavini *et al*., 1999; Policarpo *et al*., 2002). The average daily N demand per tree remains nearly constant at 1 g N $tree^{-1}$ day^{-1} from 40 days after full bloom to harvest (Rufat and DeJong, 1999). Recovery of applied N fertilizer is 14.9-18.0% (Huett and Stewart, 1999) and 8.3-12.7% (Nario *et al*., 2003) of total N in the peach tree, including fruits and winter pruning. N partitioning changes when leaf growth ceases in late summer, root N uptake is more effective to build up N reserves, especially for root N reserves (Taylor and van den Ende, 1970b; Tagliavini *et al*., 1999; Nario *et al*., 2003). Soil water restriction affects non-structural carbohydrate concentration of roots, but not N concentration of roots during the dormant period (Esparza *et al*., 2001).

During the growing season the leaves are the main N sink and N is incorporated into proteins, the most important of which in C3 plants is rubisco (Marschner, 1995). The internal N cycle ends with leaf senescence in the fall, when a proportion of leaf N is withdrawn, exported to phloem and stored in perennials organs during winter (Tagliavini *et al*., 1997). The resorption of P can also be high whereas Ca and Mg shows low resorption, instead a net increase takes place in leaves, but also leaf abscission to soil litter is a process that allows an external N recycling (Killingbeck, 1996; Kozlowski and Pallardy, 1997). Higher leaf N concentration delays the onset of leaf senescence (Taylor and van den Ende, 1969; Zilkah *et al*., 1996). In peach leaves N resorption is about 45-50% irrespective of tree N status (Castagnoli *et al*., 1990; Tagliavini *et al*., 1997; Niederholzer *et al*., 2001), although in pear leaves N resorption increases in exposed leaves (Sanchez and Righetti, 1990). Tree stores N compounds during winter in the bark of peach shoots (Marquat *et al*., 1999; Bañados *et al*., 2001; González-Rossia *et al*., 2008) and vegetative storage proteins have been detected in the parenchyma and phloem of bark tissues, that are stored in autumn and depleted in spring (Gomez and Faurobert, 2002). But more N is accumulated in peach roots, and occurs largely of soluble organic N fraction with arginine as the major constituent (Taylor and van den Ende, 1970b).

1.3.3. Interaction between nutrients

N is generally the most important nutrient in fruit tree fertilization (Faust, 1989) and leaves are the primary site of physiological processes (Marschner, 1995). Peach trees contain a high proportion of N in leaves (Rincón *et al*., 2004) and N application increases the leaf N concentration (Taylor and van den Ende, 1969). The seasonal pattern in leaf N concentration displays the balance between the root absorption from the soil solution and tree demand (Atkinson, 1997). This pattern has been established for peach leaves and decreases during the leaf development period (Batjer and Westwood, 1958; Carpena and Casero, 1987) because of N mobilization from leaves to fruits (Taylor and van den Ende, 1969). Leaf N concentration decreases more rapidly with time in trees under flooding versus drip irrigation (Romo and Díaz, 1985), low

winter pruning (Hassan, 1990) and high fruit load (Blanco *et al*., 2002a). Leaf N concentration to maintain peach tree growth is between 2.6-3.0% DM, according to a leaf sample taken from mid-shoot at 100 to 125 after full bloom (Daane *et al*., 1995). Leaf physiological processes within this N range are a net CO_2 assimilation rate of 8.4 μmol m^{-2} s^{-1} and a chlorophyll content of 22.9 mg g^{-1} DM (Almaliotis *et al*., 1997). Leaf weight per area explains best the differences in leaf physiology under different fruit loads (Nii, 1997) and sun exposures (Rosati *et al*., 1999). Leaf N content per unit leaf area is highly correlated to leaf weight per area and determines the capacity for net CO_2 assimilation (DeJong and Doyle, 1985).

N application increases fruit N concentration (Taylor and van den Ende, 1970a). Although fruit N demand increases during stage-III (Rufat and DeJong, 2001), fruit N concentration decreases due to N dilution within the growing fruit (Batjer and Westwood, 1958). In fleshy fruits, K is the most abundant nutrient (Tagliavini *et al*., 2000) enhances soluble solids and organic acids content and acts as a osmoticum for the accumulation of water (Habib, 2000), thus K plays an important role in fruit growth (Failla *et al*., 1992; Szücs, 1995) and quality (Marcelle, 1995). N:K ratio in peach leaves is negatively correlated to fruit fresh weight (Stoilov, 1990) and N concentration in kiwi leaves is negative correlated with fruit storage (Tagliavini *et al*., 1995).

The seasonal pattern of leaf concentration in macronutrients display important differences, P and K decreases as leaf matures due to phloem translocation while Ca and Mg accumulate in leaves throughout the season (Batjer and Westwood, 1958; Carpena and Casero, 1987). This seasonal changes affects the relationships between macronutrients during the leaf development (Casero and Carpena, 1987; Sanz and Montañés, 1993; Sanz, 2000). Leaf analysis of macronutrients can be compared with peach reference levels (Villar and Arán, 2008). It is suggested an antagonic effect of N supply respect Ca and Mg concentration in peach leaves (Leece, 1976b; Almaliotis *et al*., 1997) and sometimes respect K concentration (Leece, 1976b) and P concentration (Almaliotis *et al*., 1997). When fruits do not compete with leaves, dry matter accumulates in leaves and leaf weight per area increases (Nii, 1997), decreasing leaf nutrient concentration except for K, which concentration in leaves may increase due to low fruit K demand (Sadowiski *et al*., 1995).

Soil management of fruit orchards influences the chemical properties of the soil under the grass alleyways mowed regularly versus herbicide strips (Komosa, 1990; Sicher *et al*., 1995) and nutrient composition of fibrous tree roots (Baghdadi and Sadowski, 1990). Fertigation affects nutrient distribution from the emitter (Strabbioli and Turci, 1995) and increases the nitrate content during the course of the season under herbicide strips than under grass (Hornig and Bünemann, 1995). In fruit trees some correlations have been obtained between soil chemical characteristics and leaf nutrient concentration (Basso *et al*., 1990; Bogoni *et al*., 1995a). In grapevine, leaf Ca concentration is correlated to soil carbonate and leaf Mg concentration is negatively correlated with soil K (Bogoni *et al*., 1995b). In peach an antagonism between Ca and Mg has been suggested (Van den Ende and Taylor, 1969) since exceeding a threshold of Ca:Mg in the soil decreases leaf Mg concentration (Huett *et al*., 1997). Also soil physical characteristics affect the leaf nutritional concentrations of grapevine since soil water restriction decreases leaf K concentration and increases leaf Ca and Mg concentration, while the opposite occurs by decreasing soil temperature (Bogoni *et al*., 1995b). There is a competitive interaction between K diffusion and Ca and Mg mass-

transport from the soil to the root when soil water content decreases (Giulivo, 1990). The plant growth regulator paclobutrazol, that inhibits shoot growth and increases yield efficiency in peach (Blanco *et al*., 2002b), affects leaf nutrient concentrations and decreases de ratio between K:Ca+Mg (Blanco *et al*., 2002a). Soil water restriction also affects leaf growth, decreases leaf K concentration in apple (Neilsen *et al*., 1995) and sweet cherry (Neilsen *et al*., 2007), especially under drip irrigation and coarse textured soils (Bläsing *et al*., 1990).

1.4. Water uptake and flow

1.4.1. Root water uptake

Water uptake from the root surface to the xylem vessels occurs through a series of tissues and is driven by differences in water potential (Nobel, 2005). Root hydraulic conductance based on the root surface area (L_P, $m\ s^{-1}\ MPa^{-1}$) controls water uptake by the relation between the water flow (ΔQ_V, $m^3\ s^{-1}$) and the difference in water potential ($\Delta\Psi$, MPa):

$$L_P = (1/A)\ (\Delta Q_V/\Delta\Psi) \qquad\qquad \text{equation 1}$$

where A (m^2) is the root surface area. There is a variation in L_P along young roots, showing a decreasing trend from the root tip (Huang and Nobel, 1994). Root morphology such as cortex width is related to L_P in several species and measurements in young peach roots give an L_P of $3.6\times10^{-8}\ m\ s^{-1}\ MPa^{-1}$ (Rieger and Litvin, 1999). Soil water content, salinity and temperature affect root L_P (Kramer and Boyer, 1995). As soil dries, root surface loose contact with soil particles (Stirzaker and Passioura, 1996) and root shrinkage can occur (Huck *et al*., 1970), which gradually decreases the L_P at the soil-root interface (Nobel and Cui, 1992).

Root L_P can be separated into a radial and axial components (Landsberg and Fowkes, 1978). The axial component is generated by water transport through xylem vessels and can limit L_P near the root tip where the conduits are immature (Frensch and Steudle, 1989). However the radial component of the tissues outside the xylem is generally much lower than the axial component (North and Nobel, 1996). A composite transport model has been established to explain the variable L_P to anatomical modifications (Steudle and Peterson, 1998; Steudle, 2000). In the model, three parallel pathways for radial water transport are considered, i.e. the apoplastic, symplastic and transcellular pathways, the latter two representing the cell-to-cell path. The main apoplastic resistances are the exodermis and endodermis, which form the outer and inner boundaries of the root cortex, respectively. The endodermis contains the casparian strip on the radial walls and suberin lamellae that redirects the water flow into the symplast and maintains a positive pressure in the xylem vessels. A suberized exodermis becomes fully developed at varying distances from the root tip. On the other hand, water channels in the plasma membranes of cortex cells affects the cell-to-cell component of radial water flow. In addition, the hydraulic conductivity may be affected by secondary growth, suberized periderm and emergence of lateral roots.

Water uptake capacity of peach roots over-sizes the water transport capacity (Doussan *et al*., 1999) and wetting a part of the root system may be sufficient for water

uptake, maintaining the transpiration rate (Tan and Buttery, 1982). Both row spacing and drip irrigation affect root growth (Chalmers *et al.*, 1981; 1985). Maximum water uptake is from the upper 60 cm of the soil and water restriction induces a shift in water uptake towards deeper layers, but the presence of a calcareous conglomerate in the subsoil limits root growth (Garnier *et al.* 1986). In peach orchards, the success of irrigation efficient strategies during some development stages arises from both an adaptation to moderate soil water restriction in shallow soils and restricted wetted root volume (Girona *et al.*, 2003; 2005). In grapevines, partial rootzone drying (PRD) is an irrigation efficient strategy that allows one part of the root system to dry out while the other part is kept wet by frequent irrigation, and after a certain period of time, irrigation is switched (Marsal *et al.*, 2008).

1.4.2. Xylem anatomy

Xylem hydraulic flow takes place through tracheids and vessels (Tyree and Ewers, 1991; De Boer and Volkov, 2003). In their functional condition these cells are hollow capillary tubes, since the cells are dead with no membranes and with secondary cell walls heavily thickened by lignin. Vessels are typically from 20 μm to as much 500 μm in diameter whereas tracheids are about 15 μm to 80 μm in diameter. Numerous pits in their lateral walls through which water can pass communicate adjacent conduits. These pits are porous regions where the secondary cell wall is absent but primary wall and a middle lamella remains. The shape and pattern of wall pitting vary with species and organ type. In addition, the xylem contains fibre cells, which confer mechanical support, and living parenchyma cells which are involved in ion and water transfer and defence against microorganisms.

Stem hydraulic conductivity (K_H, m^4 s^{-1} MPa^{-1}) evolves from the development and maturation of xylem vessels. However in peach, stem K_H is not only associated with the development of primary structures, but also with secondary radial growth according to diffuse-porous wood. Stem K_H measures the relation between the water flow through an excised stem (ΔQ_V, m^3 s^{-1}) and the pressure gradient ($-\Delta P/L$, MPa m^{-1}) across the length L (Cruiziat *et al.*, 2002):

$$K_H = \Delta Q_V / (-\Delta P/L) \qquad\qquad \text{equation 2}$$

K_H increases with the stem diameter and according the capacity to develop secondary growth and is about 5×10^{-8} m^4 s^{-1} MPa^{-1} for apple stem segment (Atkinson *et al.*, 2003).

In woody plants the largest vessels tend to occur in the early formed wood of an individual growth ring but are much smaller in the late wood. According to the law of Hagen-Poiseuille under laminar flow in capillaries (Cruiziat *et al.*, 2002):

$$K_H = (\pi / 128\eta) \sum d_i^4 \qquad\qquad \text{equation 3}$$

where η is the xylem sap viscosity ($\approx 10^{-9}$ MPa s at 20ºC). From this, a slight increase in number of conduits or capillary diameter ($\sum d_i^4$) causes a considerable increase in stem K_H. Reduced stem K_H by soil water restriction is explained by low average vessel diameter in vine, however the measured K_H is less than the predicted value due to vessel tortuosity (Lovisolo and Schubert, 1998). Also auxin accumulation in the shoot increases the vessel density while decreases vessel diameter, causing a reduction of shoot K_H (Lovisolo *et al.*, 2002).

1.4.3. Xylem water flow

Tree transpiration determines the real tree water consumption. Hydraulic architecture of trees is well structured around the cohesion-tension theory of the ascent of sap, which deals with the physics of water transport, and the electrical analogy used for modelling water flow within the soil-plant-atmosphere continuum (Ksenzhek and Volkov, 1998). Canopy transpiration occurs on leaves and is controlled by stomatal conductance. The energy requirement of transpiration is solar radiation. In contrast to root water uptake, xylem water flow is not sensitive to temperature (Zimmermann, 1964). Under steady state conditions (Koide *et al*., 1989), transpiration creates a water potential difference between the leaves and the roots ($\Delta\Psi = \Psi_{soil} - \Psi_{leaf}$, MPa) which maintains a water flux through the xylem (ΔQ_V, m^3 s^{-1}):

$$Q_V = (\Psi_{soil} - \Psi_{leaf}) / R_{tree} \qquad \text{equation 4}$$

where tree hydraulic resistance (R_{tree}, MPa s m^{-3}) is the series resistance of the tree conducting path. Q_V and Ψ vary during the day, so assuming that R_{tree} changes little during the day, the average total R_{tree} might be determined from the slope of the linear regression of hourly measurements of $\Delta\Psi$ on ΔQ_V from predawn to late afternoon on the same tree. Capacitance of the tree, which in large apple trees can amount to 2 h of transpiration causes hysteresis in the relationship, but may be ignored in field conditions when environment in changing smoothly (Landsberg *et al*., 1976).

The resistance components of trees can be determined by sap flow through the trunk with a calibrated heat pulse probe (Cohen *et al*., 2007). The trunk cross-section consists of an exterior bark, a water conducting outer xylem (sapwood), a non-functional inner xylem (hardwood) and a central pith. The radial distribution of sap velocity is measured from a heating probe with thermistors inserted at different depths in the sapwood (González-Altozano *et al*., 2008). Sap velocity decreases gradually with depth below the bark. The total volumetric sap flow rate is calculated by integrating the sap flux density over the sapwood cross-section area. Sap flow begins around 6:00 h in the morning and ends about 20:00 h in the evening. The hourly values closely follow the diurnal pattern of reference evapotranspiration, although some nighttime water transport occurs.

Ψ_{soil} is taken as predawn Ψ_{leaf} and represents the zero intercept of the plot of $\Delta\Psi$ on Q_V (Cohen *et al*., 1983). Ψ_{leaf} is taken on shaded and sunlit leaves since water flow occurs across these two groups of leaves (Moreshet *et al*., 1990):

$$\Psi_{leaf} = \alpha\ \Psi_{sunlit} + (1\text{-}\alpha)\ \Psi_{shaded} \qquad \text{equation 5}$$

where α is the fraction of sunlit canopy. The Ψ_{stem} of non-transpiring covered leaves in the deep shade of the canopy near the trunk is in equilibrium with the water potential of the conducting trunk vessels below the transpiring canopy. Then the sap flow equation is:

$$Q_V = (\Psi_{soil} - \Psi_{stem}) / R_{root} \qquad \text{equation 6}$$

where R_{root} is the series resistance of trunk and root path. On fruit trees, R_{tree} is around 7×10^8 MPa s m^{-3} (Solari *et al*., 2006), roots impose a high resistance to water flow (Basile *et al*., 2003b) and rootstock affect canopy growth (Solari and DeJong, 2006). Peach rootstock vigour is related to hormone production in the roots (auxins and citokinins), which are translocated in the xylem sap (Sorce *et al*., 2002).

1.4.4. Diurnal trunk shrinkage

Because of tissue xylem elasticity, the tension within de vessel is transmitted to the trunk, thereby causing slight changes in trunk diameter (Kozlowski and Pallardy, 1997). Various electronic displacement transducers, including linear variable differential transformers, can be used to measure the continuous growth of trunk in diameter (Doltra *et al.*, 2007). Superimposed on an overall trunk diameter increase over time, appears a diurnal fluctuation of shrinkage and swelling, even under well soil water conditions (Doltra, 2003). The diurnal fluctuations in diameter are the result of changes in water status in response to environmental conditions, which reflects the diurnal water balance of the whole tree. Maximum trunk diameter is attained on hydrated tissues at predawn. Trunk begins to shrink when the transpiration became active, because of increase in radiation and temperature, and attains its maximum shrinkage at afternoon. When the transpiration decreases towards the night, the trunk restores its water supplies and its diameter increases. Shrinkage of trunk diameter during the afternoon is stronger in the case of heavy fruit load (Intrigliolo and Castel, 2007). In peach trees, the transition from stage-II to stage-III indicates altered diurnal water relations (Marsal *et al.*, 2002a). During stage-III daily shrinkage and nightly swelling are approximately equal, and little net growth is observed. Fruit diameter also displays a diurnal pattern (Ton *et al.*, 2004). During the daytime, when transpiration reaches its maximum value, the fruit fresh weight does not increase or even diminishes, whereas the dry matter accumulates during this time. The most intensive accumulation of fruit fresh weight takes place during the night (Fishman and Génard, 1998).

1.4.5. Leaf water potential

The balance between water uptake by roots and transpiration by leaves, defines at a given time, the water status of the tree (Kramer and Boyer, 1995). The leaf water potential (Ψ_{leaf}) is measured with a pressure chamber (Scholander *et al.*, 1965). Predawn leaf water potential (predawn Ψ_{leaf}) and midday leaf water potentials (midday Ψ_{leaf}) have been proposed for irrigation scheduling in fruit trees (Marsal and Girona, 1997; Naor, 2004) and grapevines (Williams and Araujo, 2002). However, midday stem water potential (midday Ψ_{stem}) is more useful, since it depends on canopy size and fruit distribution (Marsal *et al.*, 2005; Marsal *et al.*, 2006; Lopez *et al.*, 2007a), it is related with fruit growth rate (Girona *et al.*, 2006) and high fruit loads tend to increase the sensitivity to irrigation restriction (Berman and DeJong, 1996; Berman and DeJong, 1997b; Naor *et al.*, 2001; Girona *et al.*, 2004a). In addition, diurnal changes of Ψ_{stem} influences the peach stem growth rate that attains its minimum at midday (Weibel *et al.*, 2003; Berman and DeJong, 1997b; Basile *et al.*, 2003a). Visible leaf wilting occurs when midday Ψ_{stem} reaches –1.8 MPa (Lopez *et al.*, 2007b). Under well soil water conditions, midday Ψ_{stem} decreases with increasing evaporative demand of the air because of the high resistance of water flow through the xylem vessels. As a result, the water balance is affected and midday Ψ_{stem} decreases (McCutchan and Shackel, 1992). The relation between midday Ψ_{stem} to maximum vapour pressure deficit can be utilized on grapevines to correct the values and thus reduce irrigation dose on days of high evaporative demand (Olivo, 2009). Soil clay content and drip wetted volume affect midday Ψ_{stem} in pear trees (O'Connell and Goodwin, 2004).

1.5. Stomatal conductance

1.5.1. Stomatal mechanics

In peach leaves, stomata are present in the epidermis of the abaxial leaf side, (Leece, 1976a; Baldini *et al*., 1997), with a density of 221 stomata mm^{-2} and a length of 26.1 μm (Fernadez *et al*., 2008). The pore of the open stomata occupies 0.2% to 2% of the total leaf surface area and guard cells contain chloroplasts (Nobel, 2005). The mechanism of stomatal opening (Roelfsema and Hedrich, 2005) is controlled by active changes in the osmotic potential of the guard cells that affects its turgor and ultimately its cell volume. When the guard cells are flaccid, the stomatal pore is nearly closed. Stomata open by active H^+ extrusion from de guard cells, which hyperpolarizes the membrane potential (lowers the electrical potential inside relatives to outside) as well as lowers the cytosol H^+ concentration. The lowered membrane potential favours passive K^+ uptake through K^+ channels, which may increase in concentration from 0.3 to 2.4 nM in a cell, that is electrically balanced mainly by the production of organic anions like malate in the guard cell and partly by Cl^- influx. As osmotically effective solutes accumulates in the guard cell the osmotic potential decreases, and thus lowers the internal water potential. Water then flows from subsidiary cells into the guard cells. This water entry leads to an increase in the turgor, which causes them to expand. The formation of the pore is a consequence of the anisotropic properties of the cell wall. The open pore width attains about 15 μm. The mechanism of stomatal closure (MacRobbie, 1998) is probably caused via the opening Ca^{2+} channels in the plasma membrane, thus enabling the rise in Ca^{2+} concentration in the cytosol and a depolarisation of the plasma membrane, which triggers the K^+ efflux. The increase in osmotic potential causes water to move out, which in turn causes turgor to decrease, leading to stomatal closure. A hydropassive stomatal closure (Jones, 1992) can result when guard cells lose water directly by evaporation and so lose turgor.

1.5.2. Stomatal control of transpiration

Drought tolerance involves primarily two mechanisms: reduction of water loss and maintenance of water uptake. However, stomatal control of transpiration is complex with interactions with a wide range of environmental factors (Jones, 1992). It is possible to measure canopy conductance with a sap flow sensor on the trunk (Granier and Bréda, 1996; Zhang *et al*., 1997; Gong *et al*., 2005). For well-coupled canopies such as isolated trees, where aerodynamic conductance (due to boundary layer conductance) is relative large to canopy conductance (due to stomatal conductance), heat and mass transfer are very efficient so that leaf temperature approaches air temperature whatever the input radiation (McNaughton and Jarvis, 1983). Under such conditions, Penman-Monteith equation of transpiration rate (E, mmol m^{-2} s^{-1}) simplifies to (Köstner *et al*., 1992):

$$E = k \text{ VPD } g_t \qquad \qquad \text{equation 7}$$

where g_t is the total conductance of the pathway between the evaporating sites in the mesophyll until the bulk air (mmol m^{-2} s^{-1}), VPD is the vapour pressure deficit of the air (kPa) and k is 7.6630×10^{-6} kPa^{-1}. Tree transpiration is more linked to stomatal opening than to boundary layer conductance (Pataki *et al*., 1998). In young apricot trees the coefficient of stomatal control of transpiration rate is $1-\Omega = 0.89$ (Barradas *et al*., 2005), while in young lemon trees $1-\Omega = 0.86$ to 0.92 (Nicolás *et al*. 2008). The decoupling coefficient (Ω) represents the control exerted by all other environmental factors on transpiration rate (McNaughton and Jarvis, 1983).

1.5.3. Environmental conditions

Stomatal responses at daily and seasonal scales in woody trees are influenced by environmental conditions, soil water content, canopy size and root system characteristics (Kramer and Boyer 1995; Kozlowski and Pallardy, 1997) and increases with fruit load and changes with leaf development (Yoon and Richter, 1990; Marsal and Girona, 1997; Mpelasoka *et al*., 2001). It is possible to measure leaf stomatal conductance (g_s) with a portable porometer in the field (Jones and Higgs, 1989; Matsumoto *et al*., 2005).

A diurnal pattern of g_s is observed on sunlit mature peach leaves (Garnier and Berger, 1987). Stomata open at the beginning of the day, as a result of increased solar radiation, when Ψ_{leaf} is not the limiting factor. Daily maximum g_s is measured between 06:30 to 08:30. Full stomatal opening is achieved for solar radiation values between 250 and 300 W m^{-2}, whereas minimum light intensity required for stomatal opening is 50 W m^{-2}. This process reflects the photoactive feedback system (Roelfsema and Hedrich, 2005). When illumination starts, the CO_2 concentration within the intercellular air space of the mesophyll decreases by photosynthesis. The CO_2 sensor of guard cells measures the CO_2 concentration in the substomatal cavity, which triggers stomatal opening, via ion import or export. Then CO_2 can enter and photosynthesis can continue. In the turgid leaf there is a relation between stomatal conductance and the rate of photosynthesis (Girona *et al*., 1993; Cheng *et al*., 1996). The CO_2 feedback loop is probably important only for very low and very high light fluxes. In normal daylight the direct control by light signals is more important, independent of the response to CO_2. These signals are received in the guard cells by chlorophyll and a blue light photoreceptor (direct control by light) that work together (Roelfsema and Hedrich, 2005). Stomatal opening to the early morning tends to optimise carbon assimilation in relation to water transpiration (Cowan, 1982).

A reduction in g_s occurs when VPD is above a threshold of 1.2 kPa and after the early morning peak, peach g_s decrease gradually during the rest of the day with no apparent afternoon recovery (Garnier and Berger, 1987). Under well soil water conditions, increasing the VPD around a leaf or plant results in decreasing g_s through two ways (Jones, 1992). Since an increase in VPD will increase E, the Ψ_{leaf} may decrease, leading to a reduction in g_s which finally has a negative feedback effect on E. Alternatively, the VPD may influence the g_s directly without influencing the bulk Ψ_{leaf}. This feed forward mechanism increases the rate of peristomatal transpiration and lowers guard-cell water potential, leading to stomatal closure. Both feedback and feed forward g_s responses to VPD depends on tree species (Turner *et al*., 1984; Pataki *et al*., 1998). Actually g_s responds to changes in E rather than VPD (Monteith, 1995).

If the evaporation demand is maintained at a high level during midday, Ψ_{leaf} remains low (Olsson and Milthorpe, 1983; Larsen *et al*., 1989) since transpiration exceeds the uptake of water through the roots (Kramer and Boyer, 1995). This effect on g_s can be analysed by treating VPD as a driving variable, although there is a mechanistic link through Ψ_{leaf} (Olivo, 2009). Leaf g_s can decrease gradually with Ψ_{leaf} (Garnier and Berger, 1987) or more strongly below a critical Ψ_{leaf} depending on the environmental conditions (Gollan *et al*., 1985). Furthermore, g_s can be reduced without Ψ_{leaf} mediation (Bates and Hall, 1981) and decreased g_s can act as a regulator of Ψ_{leaf}, leading to more negative Ψ_{leaf} values in well-watered plants that in restricted ones (Jones, 1998).

In peach trees, leaf g_s is strongly affected by soil water conditions (Rieger *et al*., 2003) and begins to decrease as available soil water content is extracted by roots (Sadras and Milroy, 1996; Girona *et al*., 2002). Under soil water restriction daily maximum g_s decreases and the depression of g_s after the morning peak is greatest (Garnier and Berger, 1987; Correira *et al*., 1997; Gong *et al*., 2005). Although Ψ_{leaf} recovers within a week after returning water supply (Goldhamer *et al*., 2002), g_s takes an additional week to recover (Marsal and Girona, 1997).

1.5.4. Chemical signalling from roots to leaves

Under soil water restriction, hydraulic signalling combine with chemical signalling from roots to leaves to modify g_s (Tardieu and Davies, 1993) There is evidence from split-root trees grown in containers (Gowing *et al*., 1990) that root drying during the day can induce abscisic acid (ABA) synthesis in the root tips and then transported thought the xylem to the leaves where it participates in the regulation of g_s and leaf growth (Liu *et al*., 2001). Coupled to this process is an increase in the pH of the xylem sap (Wilkinson and Davies, 1997). Also, ABA may be synthesized in the leaf, and can be loaded to the phloem and transported to the roots where one part may be recirculated to the xylem (Hartung *et al*., 2002). In the leaf, ABA accumulates in the apoplast next to guard cells (Hartung *et al*., 1998) where inhibits secretion of H^+ and induces an efflux of K^+ and anions from guard cells, leading to stomatal closure by a hydroactive feedback system (MacRobbie, 1998). At the end of the water restricted period, the ABA content usually falls rapidly, because of breakdown (Hartung *et al*., 2002).

In irrigated peach trees, the ABA concentration in the xylem sap is maintained between 0.25 to 0.5 mmol m^{-3} during the course of the day, while in water restricted trees, the ABA concentration attain a daytime value between 0.6 to 1 mmol m^{-3} (Correira *et al*., 1997). The diurnal changes in g_s are associated with changes in the relationship to xylem ABA and stomatal responsiveness is enhanced throughout the day (Correira *et al*., 1997). High cytokinin concentration at morning in the xylem sap of lysimeter grown almond trees influence stomatal conductance, acting as a antagonist to ABA (Fuβeder *et al*., 1992). In anisohydric species, like peach tree, xylem ABA concentration via root drying accounts for changes in g_s regardless of Ψ_{leaf} (Tardieu and Simonneau, 1998), although there is a relationship between Ψ_{leaf} and g_s (Garnier and Berger, 1987). Leaf water status may be more important in other tree species, since Ψ_{leaf} is a consequence of the balance of g_s and water flux thought the xylem (Fuchs and Livigston, 1996).

The seasonal course of ABA concentration in the xylem sap showed a rise from may to a maximum on July, such in almond of 0.5 mmol m^{-3} (Wartinger *et al*., 1990) or in maple of 0.2 mmol m^{-3} (Schill *et al*., 1996), which coincides with the period of leaf growth (Gong *et al*., 2005) and root growth (Abrisqueta *et al*., 2008). During the course of the season there was an inverse relationship between the average ABA concentration in the xylem sap and maximum g_s as measured in the morning in almond trees (Wartinger *et al*., 1990) but in apricot ABA appears to be relatively unimportant (Loveys *et al*., 1987). The onset of dormancy was associated with low levels of citokinins and high contents of ABA (Alvim *et al*., 1976).

1.6. Net CO_2 assimilation

1.6.1. Environmental conditions

The leaf net CO_2 assimilation rate (A_n) characteristics of mature peach leaves are typical of C3 plants (DeJong, 1983). Response curve of A_n to increasing photosynthetic photon flux density (PPFD) is asymptotic with a PPFD compensation point at 20-30 μmol m^{-2} s^{-1} and a PPFD saturation point at 400-700 μmol m^{-2} s^{-1}. The maximum net CO_2 assimilation rate (A_{max}) is 13.6 μmol m^{-2} s^{-1} at 27ºC, saturating PPFD levels and ambient CO_2 concentration of 320 μL CO_2 L^{-1}. Apparent quantum efficiencies vary from 0.04 to 0.06 mol CO_2 fixed mol^{-1} PPFD for sun grown leaves. However, response curve for whole canopy do not show a point of saturation, because leaf shading and leaves in the interior receive PPFD levels less than saturation (Flore, 1994). Diurnal leaf A_n shows a maximum peak before noon and then declines during the afternoon (Chalmers *et al*., 1975). Peach leaves have a linear A_n responses to changing intercellular CO_2 concentration between 50 and 250 μL CO_2 L^{-1} with a CO_2 compensating point of 66 μL CO_2 L^{-1} (DeJong, 1983). Peach leaves exhibit a typical parabolic relationship between A_n and temperature (Crews *et al*., 1975). Under low PPFD conditions, optimum leaf temperature is 26ºC (Tan and Buttery 1986), whereas under field conditions leaves can adapt to higher temperatures until 32ºC (Girona *et al*., 1993). N increases leaf area (Taylor and van den Ende, 1969) and chlorophyll content (Almaliotis *et al*., 1997). There is a correlation between leaf A_{max} and leaf N content per unit leaf area basis (N_A) for 5 *Prunus* species (DeJong, 1983). Therefore leaf N_A determines leaf assimilation capacity (DeJong, 1983). Root-zone salinity affects leaf A_n (Massai *et al*., 2004).

Water vapour diffuses through the same stomatal pore as CO_2, so any assimilation is accompanied by transpiration. There is an asymptotic relationship between g_s and A_n until a g_s threshold of 400 μmol m^{-2} s^{-1} with a maximum A_n of 14 μmol m^{-2} s^{-1} (Girona *et al*., 1993; Cheng *et al*., 1996) and changes in g_s explain most of the variation in A_n along the growing period (Marsal and Girona, 1997; Rieger *et al*., 2003). Two simple models have been derived to relate assimilation to environment conditions (Campbell and Norman, 1998). Since leaf temperature tends to be quite close to air temperature when stomata are open and leaves are in the sun, Tanner and Sinclair (1983) obtained a simple mechanistic model relating leaf A_n to environment:

$$A_n = k \, E \, / \, DPV \qquad\qquad \text{equation 8}$$

where k is a proportional constant cultivar specific, E is leaf transpiration and VPD is vapour pressure deficit (Ehlers and Goss, 2003). N fertilization increases seasonal intercepted radiation and biomass accumulation in woody trees (Allen *et al*., 2005). During seasonal development of whole canopy the assimilation is optimised by allocating N_A to leaves at higher light exposures (DeJong and Doyle, 1985).

Monteith (1977) developed an empirical model relating tree biomass accumulation to accumulated solar radiation intercepted by the canopy:

$$A_n = \varepsilon \, f \, PPFD \qquad\qquad \text{equation 9}$$

where f is the fraction of incident PPFD intercepted by the canopy. The quantity of incident PPFD depends on latitude of the location and day of the year. Typically the

conversion efficiency ε is 0.01 to 0.03 mol CO2 fixed mol^{-1} PPFD for field canopies (Campbell and Norman, 1998). The correlation between the fraction of intercepted PPFD at harvest and the total aboveground biomass in peach orchards is the same under different training systems (Sofo *et al*., 2005).

1.6.2. Source strength of leaves

In higher plants the photo-assimilate products are starch, insoluble residue and soluble intermediates, which may be stored in the leaf blade (Moing *et al*., 1994). Sorbitol, a sugar alcohol, is reported to be a major soluble compound in woody Rosaceae (Moing *et al*., 1992). In peach leaves, soluble fraction reveals that 68% is sorbitol, 17% is sucrose, 14% is glucose + fructose and 1% is myo-inositol (Nadwodnik and Lohaus, 2008). Starch, which accumulates in the chloroplast, is a temporary storage carbohydrate, while sorbitol and sucrose, which accumulates in cytosol, may be exported via phloem (Moing *et al*., 1997) to growing peach fruits (Lo Bianco and Rieger, 2002a; 2002b). Phloem sap is rich in organic compounds and the concentration change during the season (Keller and Loescher, 1989). Long distance transport in the phloem (Mohr and Schopfer, 1995) takes place in the sieve tubes that are living cells connected by sieve plates. Sieve tubes are associated with companion cells and parenchyma cells. Solutes are loaded in the phloem of source leaves and water is sucked by osmosis according to Münch mechanism, creating a positive internal pressure that induces a mass flow to sink organs where solutes are unloaded.

Environment conditions affect leaf growth by the relationship between dry matter accumulation and leaf area expansion. The earliest effect of mild water deficit is to reduce leaf expansion, a process that is mediated by biophysical events (Kozlowski and Pallardy, 1997). Thus, as the water content of the leaf decreases, the cell walls relax and result in lower leaf turgor (P). Leaf expansion rate (GR) is directly dependent on the effective turgor by the relationship:

$$GR = m\,(P - Y) \qquad\qquad \text{equation 10}$$

where Y is the turgor threshold for irreversible plastic deformation and *m* is the leaf extensibility. It is therefore understandable that leaf growth rate is particular sensitive to a decrease in leaf turgor. However, under mild water deficit, leaf A_n can continue (Andersen and Brodbeck, 1988) and sorbitol accumulates in leaves (Lo Bianco *et al*., 2000; Rieger *et al*., 2003). Leaf A_n typically declines when Ψ_{stem} falls to -1.5 MPa (Rieger and Dummel, 1992). Leaf A_n can decrease via stomatal closure alone (Flore *et al*., 1985; Bois *et al*., 1985; Deng *et al*., 1989) and also by a decrease in RuBPCase activity (Vu and Yelenosky, 1988; Sharkey and Seemann, 1989). The fact that leaf A_n is less affected than g_s allows to increase the leaf water use efficiency (Ranney *et al*., 1990; Girona *et al*., 1993).

1.6.3. Sink demand of fruits

Seasonal leaf A_n is under the control environment conditions and fruit sink demand. Response of leaf A_n is modulated by photo-assimilate demand and fruits act as a strong carbon sinks (Chalmers *et al*., 1975) a mechanism that is important for delaying leaf senescence (Nii, 1997). On peach branches, leaves adjacent up to 45 cm distance away from a fruit have higher leaf A_n (Crews *et al*., 1975) and higher fruit growth rate

during stage-III increases leaf An (Chalmers *et al*., 1975; Besset *et al*., 2001). Under high fruit loads, apple leaf A_n increases from midseason until fruit harvest (Wünsche *et al*., 2000). In apple trees, open transparent cuvettes are used to evaluate whole canopy net CO2 exchange rate (canopy NCER) according to fruit load (Wünsche *et al*., 2000; Reyes *et al*., 2006). High fruit loads increases canopy NCER and a positive linear trend appears between canopy NCER per unit leaf area and fruit load (Wünsche *et al*., 2000). Fruit thinning shows immediate effects on canopy NCER and after fruit harvest, differences between previous fruit loads on canopy NCER are reversed because canopy leaf area of thinned fruit trees is higher (Reyes *et al*., 2006). Sorbitol accumulates on leaves as sink demand decreases (Lo Bianco *et al*., 2000) and leaf starch concentration increases linearly as fruit load decreases, increasing the leaf weight per area (Nii, 1997). Leaf An is negatively correlated with an increase in the sorbitol and sucrose content of leaves, providing a down-regulation of photosynthesis on trees with low fruit loads (Layne and Flore, 1995).

1.6.4. Osmotic adjustment

Soil water restriction, particularly when soil water content decreases relatively slowly, induces a decrease of Ψ_π by accumulation of osmotically effective solutes by cells (Tyree and Jarvis, 1982). In field conditions osmotic adjustment usually takes weeks or even months (Arndt *et al*. 2000). The compartmentation of ions, specially K, during active osmotic adjustment occurs within the vacuole, where do not interfere with enzyme functions, whereas compatible organic solutes must accumulate in the cytoplasm to maintain water potential equilibrium within the cell, such as specific accumulation of soluble carbohydrates, organic acids or free aminoacids (Taiz and Zeiger, 1998). In addition to active osmotic adjustment, physical changes in cell size and cell wall elasticity can promote passive adjustment and may be important for concentrating solutes when leaves undergo dehydration (Marsal and Girona, 1997; Dichio *et al*., 2003; Saito and Terashima, 2004). Furthermore, the water potential gradient between leaf and root is increased, and thus the uptake of water by roots is stimulated (Kramer and Boyer, 1995). Peach leaves that are capable of osmotic adjustment can maintain turgor over a wider range of low water potential (Steinberg *et al*. 1989). Turgor regulation enables the continuation of metabolic activity (Andersen and Brodbeck, 1988), but leaf expansion rate was inhibited (Woodruff *et al*., 2004) and cell wall extensibility is reduced (Roden *et al*., 1990). Also osmotic adjustment maybe a cost, since does not have a major effect on productivity (Munns, 1988) and there is a shift in carbon partitioning, since sorbitol accumulates in leaves (Lo Bianco *et al*. 2000; Rieger *et al*. 2003) and starch decreases in roots (Arndt *et al*., 2000; Lopez *et al*., 2007b). Osmotic adjustment of 0.4-0.5 MPa were observed in mature leaves, stems, and roots of apple (Wang *et al*., 1995) and sweet cherry (Keller and Loescher, 1989) while a significant higher adjustment of 1.0 MPa was detected in expanding leaves of apple (Wang *et al*., 1995) and peach (Steinberg *et al*., 1989; Rieger, 1995).

2. Materials and methods

2.1. Site description

2.1.1. Location

The experimental plot was established in a commercial peach orchard for producing processed purees, in Torres de Segre, within the horticultural zone of Lleida (41º35'N, 0º26'E and 240 m above sea level), on the eastern plain of the Ebro Valley (Figures 1 and 2).

2.1.2. Soil

The soil of the experimental plot is moderately deep, well drained, of medium texture, and with a high content of coarse elements. The water holding capacity is low. This soil have evolved on a platform from quaternary deposits of residual type, resulting in this zone in Serra Pedregosa (IGME, 1999), with a slight slope of less than 2%. Until recently, this soil had got a restricted crop use, with a low productivity by lack of water. However, the transformation to irrigated land with high frequency systems allows to increase its productivity. The main limiting factor of this soil is the presence of a cemented crust of calcium carbonate, which was ripped in some stretches before establishing a peach orchard.

There is a superficial horizon which is ploughed (Ap) of 40 cm thick. The content of coarse elements is high (30% by volume). The texture is loam. The presence of organic matter gives a relatively dark colour 7.5 YR 4 / 4 (wet). Next, there is a cemented crust (Bkm) with a thickness between 5-10 cm (petrocalcic horizon). The cemented crust has been ripped in the tree rows, which allows root penetration and water percolation. But in the tree alleys the crust have been not ripped, although it is not completely continuous. Then, until 75-80 cm depth, there is a calcaric horizon (Bkn) with abundant nodules, 2-5 cm diameter, rounded and very hard to break even with a hammer. There are roots and animal activity. Organic material is from sedimentary origin. Below 80 cm deep there are different lithologic discontinuities (2C, · C, until the maximum depth described which is at 300 cm. In these layers there are sand, silt and clay, granite blocks from Pyrenees foothills deposits, and many coarse elements of different shapes and sizes. There are no stains or cracks along the profile.

The soil is classified at the sub-level as Petrocalcids xeric (Soil Survey Staff, 1999). At the level of order belongs to Aridisol and at the suborder belongs to Calcisols (for the presence of carbonate accumulation). Since the soil contains a petrocalcic horizon within the first 100 cm depth, at the group level it belong to Petrocalcids. The subgroup is Petrocalcids xeric since the moisture regime is aridic but nearby to xeric.

World reference base for soil resources (IUSS Working Group WRB, 2006) classifies this soil within the group Calcisols (Petric Calcisols).

Ebro River Basin
Total area = 85,362 km^2
Irrigated land = 783,948 ha
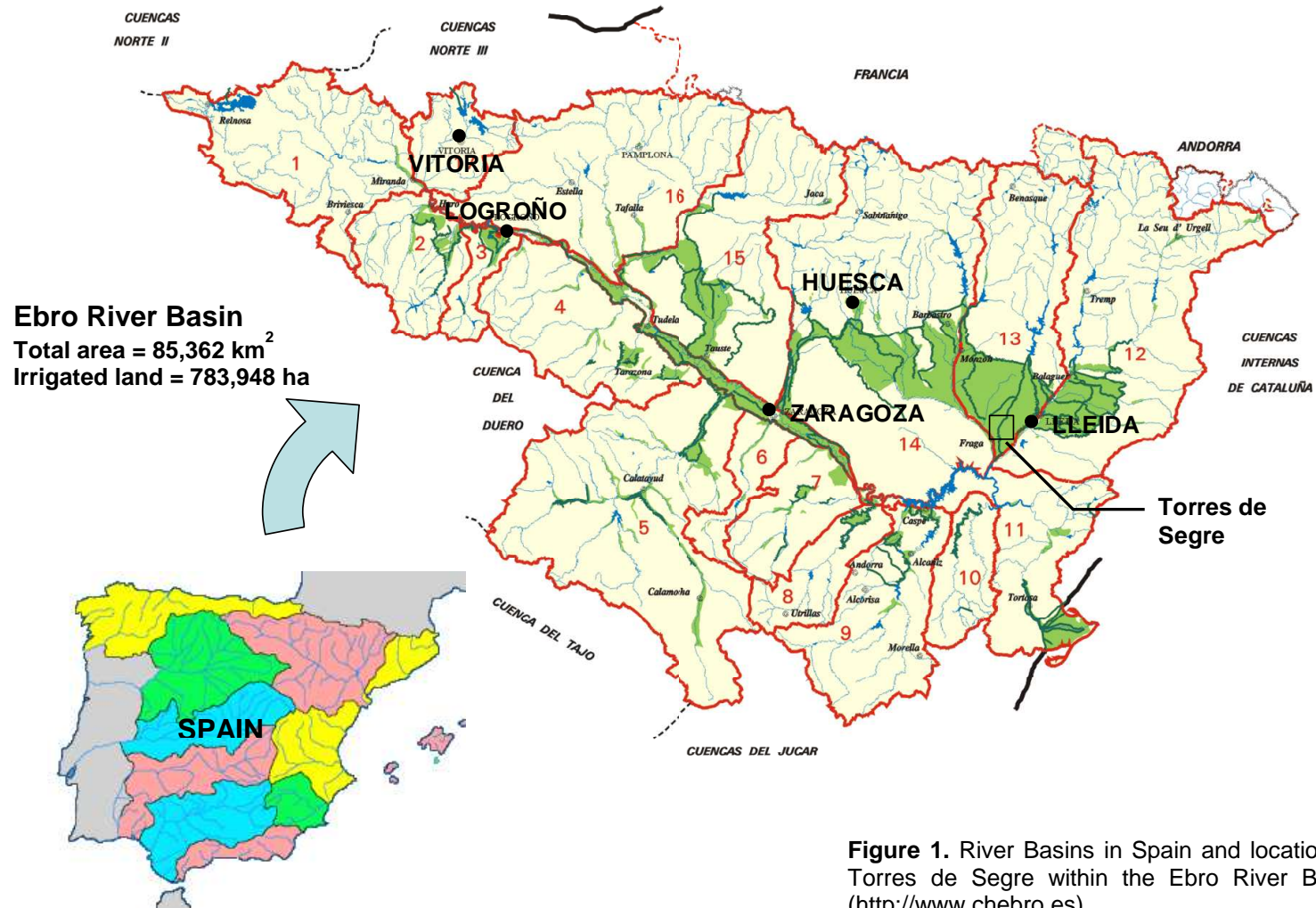
Figure 1. River Basins in Spain and location of Torres de Segre within the Ebro River Basin (http://www.chebro.es).

Figure 2. Experimental plot of 1.5 ha within a commercial peach orchard of 120 ha for producing processed purees, from Agrocemeli SCCL.

2.1.3. Climate

The weather station of Lleida was taken for the climate classification (1971-2000), since the distance to the experimental plot was 22 km and similar climatic factors (INM, 2002). Figure 3 shows the ombrothermic diagram with monthly mean values of temperature and precipitation. The autumn is warmer than spring. The average annual temperature is 14.7ºC with a high annual temperature oscillation. The hottest month is July with 24.7ºC and the coldest month is January with 5.3ºC. The precipitations are scarce and seasonal, of moderate intensity (between 1 to 4 mm h^{-1}). We observe two maxims of precipitation (Figure 3), one in May and another less pronounced between September and October. There is one minimum of precipitation in February and another in July. Seasonal precipitation shows two maximums, one in spring (32.0%) and another in autumn (30.1%) and two minimums, one in summer (19.0%) and another in winter (18.9%). So we can see an annual pattern of rainfall: spring > autumn > summer > winter. The annual precipitation is 354.7 mm. There is a dry period from July to September, according to the ombrothermic diagram (Figure 3). The climate is continental dry Mediterranean (Martín-Vide, 1992).

Annual pattern of mean monthly temperature (*T*) was fitted to a periodic Fourier curve of second order (Little and Hills, 1976), with a coefficient of determination of 99.82%:

$$T = 14.7000 - 9.3438 \cos CX - 0.7242 \sin CX + 0.3917 + \cos 2CX + 1.4289 \sin 2CX$$

where $X = 0$ for 15 January, $X = 1$ for 15 February and so one until $X = 11$ for 15 December and $C = \pi/6$ converts to radians (Figure 3).
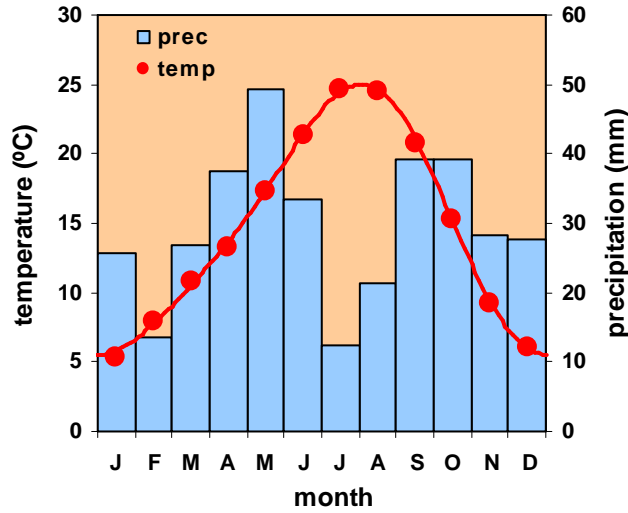
Figure 3. Ombrothermic diagram (Lleida, 1971-2000).

Table 2 shows the statistical analysis (Colomer, 1996; Castellví and Elías, 2001) of monthly mean values of precipitation and reference evapotranspiration for Lleida (1971-2000). The time series of precipitation was fitted to a gamma distribution (with α and β parameters), according to Kolmogórov-Smirnov test with a significance level of 5%. The equation defining the probability density function is:

$$f(x;\alpha,\beta) = \begin{cases} \dfrac{1}{\Gamma(\alpha)\beta^{\alpha}} x^{\alpha-1} e^{-x/\beta} & \text{for } x > 0 \text{ and } \alpha, \beta > 0 \\[2ex] 0 & \text{for } x \leq 0 \end{cases} \qquad \text{equation 11}$$

The parameters *p* and *q* are included to correct the gamma distribution function, where *q* is the probability of a month without precipitation and $p = 1 - q$. On the other hand, the time series of reference evapotranspiration follows a gaussian distribution function (with μ and σ parameters as mean and standard deviation, respectively) according to Kolmogórov-Smirnov test with a significance level of 5%. The equation defining the probability density function is:

$$f(x;\mu,\sigma) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \qquad \text{equation 12}$$

Table 2. Statistical analysis of monthly values of precipitation according to a gamma distribution function with α, β, p and q parameters and reference evapotranspiration according to a gaussian distribution function. n is the length of the time series, μ the mean, σ the standard deviation and CV is the coefficient of variation (Lleida, 1971-2000).

Month	Precipitation (mm)							Evapotranspiration (mm)			
	n	m	s	CV	α	β	p	q	n	m	s	CV
January	28	25.8	31.8	1.23	0.8582	30.0130	1.00	0.00	24	24.0446	7.5194	0.31
February	29	13.7	12.3	0.90	1.1919	12.3736	0.93	0.07	28	47.2942	8.7856	0.19
March	28	26.7	32.3	1.21	0.7635	34.2163	1.00	0.00	28	81.3348	10.0965	0.12
April	29	37.4	21.7	0.58	2.6906	13.9157	1.00	0.00	29	110.8272	11.5728	0.10
May	26	49.3	37.3	0.76	1.8134	27.1957	1.00	0.00	29	139.2112	12.9470	0.09
June	28	33.5	29.9	0.89	1.0035	33.3780	1.00	0.00	26	169.868	15.7296	0.09
July	29	12.5	13.0	1.04	0.8938	14.5335	0.97	0.03	29	188.2253	10.9222	0.06
August	28	21.4	16.3	0.76	1.9486	11.4059	0.96	0.04	28	161.6876	10.4989	0.06
September	28	39.1	32.8	0.84	0.9618	40.6602	1.00	0.00	27	110.7454	9.6502	0.09
October	25	39.3	32.9	0.84	1.5337	26.6995	0.96	0.04	27	67.0511	6.7629	0.10
November	29	28.3	23.1	0.82	1.0791	26.2452	1.00	0.00	28	31.9900	5.6389	0.18
December	27	27.7	24.1	0.87	1.0228	27.0642	1.00	0.00	28	19.5276	4.5175	0.23

Figure 4 shows the expected monthly precipitation and reference evapotranspiration for different probabilities, according to the distribution function. Note that almost all months have a very high inter-annual variation in precipitation, which is reflected in the large range of probability of precipitation between 95% and 5% in contrast to evapotranspiration. Annual reference evapotranspiration is 1172.2 mm, has a maximum in July with 187.2 mm and a minimum in December with 16.4 mm (Figure 4B).
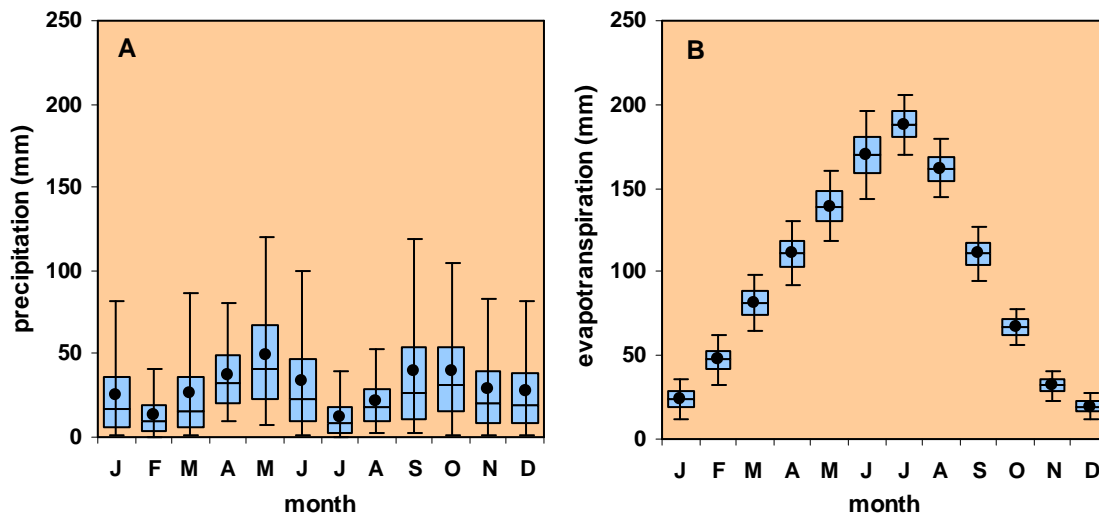
Figure 4. Expected monthly precipitation (A) and reference evapotranspiration (B) for different probabilities according to the distribution function (95% lower point, 75% lower line of the box, 50% inner line of the box, 25% upper line of the box and 5% upper point). Black dots are monthly mean values (Lleida, 1971-2000)

2.2. Experimental plot

2.2.1. Plant material

For conducting the experiment, peach trees (*Prunus persica* (L.) Batsch. cv. Andross) were used, grafted on GF-305 (a French peach seedling rootstock) at 5×2.8 m and trained in hedge until 3.5 m high. The peach orchard was established in 1999.

The cultivar Andross was obtained at the University of California in 1964. Full bloom is around mid march and harvest on second week of August and is a reference cultivar within this maturation period. The length of the fruit development, from full bloom to harvest is 139 days. Shows aptitude for both fresh consumption and for processing. Noted for its production and quality. Fruit is round to slightly oval with little apparent suture. The flesh is yellow with some pigment around the pit. It has a medium size of 79 mm, a soluble solids concentration of 12.3°Brix (Carbó and Iglesias, 2002).

2.2.2. Irrigation water

The water used for irrigation comes from the Canal of Aragón and Catalunya, and contained Ca as a dominant cation and bicarbonate as the dominant anion (Table 3). The electrical conductivity was 0.30 dS m^{-1} at 25 ° C, the pH was 7.8 and the SAR was 0.49. Presented very low salinity and sodicity (Ayers and Westcot, 1987). Nitrate concentration was low (0.03 meq L^{-1}).

Table 3. Chemical analysis of irrigation water from Canal of Aragón and Catalunya.

Cations	meq l^{-1}	mg l^{-1}	Anions	meq l^{-1}	mg l^{-1}
Ca^{2+}	2.14	42.88	Cl^{-}	0.31	10.99
Mg^{2+}	0.35	4.25	SO$_4^{2-}$	0.81	38.90
Na^{+}	0.55	12.65	CO$_3^{2-}$	inap.	inap.
K^{+}	inap.	inap.	HCO$_3^{-}$	1.90	115.92

2.2.3. Soil

At the beginning of the experiment, a composite soil sample was taken from the surface layer (0-30 cm) with an auger. The soil texture was loam with 40.3% sand, 39.8% silt and 19.9% clay (gravimetric method with discontinuous sedimentation). The concentration of organic matter was 3.3% (Walkey-Black volumetric method) and the equivalent CaCO$_3$ was 22.2% (Bernard mechanic-volumetric method). The soil pH of 8.3 was moderately basic (1:2.5 suspension) and not presented salinity problems with electrical conductivity of 0.32 dS m^{-1} at 25ºC (1:5 suspension). Initial soil NO$_3$-N content was 8 ppm (extracted with water, FIA method), 17 ppm for P-Olsen (spectrophotometric method), 185 ppm for K (extracted with ammonium acetate, ICP method) and 185 ppm for Mg (extracted with ammonium acetate, ICP method).

The gravimetric water content of a soil sample sieved at 2 mm was determined with Richards plates at 0.033 and 0.15 MPa and the obtained values were $W_{0.033} = 0.239$

g g^{-1} and $W_{0.15} = 0.127$ g g^{-1}, respectively. The water holding capacity of the soil (*H*) was calculated as:

$$H = (W_{0.033} - W_{0.15}) \times \left(\frac{\rho_{bulk} - V\rho_{stones}}{\rho_{water}} \right) \times Z \qquad \text{equation 13}$$

where ρ_{bulk} is the bulk density of the soil (1518 kg m^{-3} by field excavation method), *V* is the fraction of coarse elements in the soil (0.3 m^{-3} m^{-3}), ρ_{stones} is the density of coarse elements (2191 kg m^{-3}), ρ_{water} is the density of water (1000 kg m^{-3}) and *Z* is the effective root depth (450 mm since there was a limiting petrocalcic horizon at this level). Thus the *H* = 43.3 mm.

2.2.4. Experimental design

Three irrigation strategies were evaluated according to irrigation water requirements: 100% full irrigation all the season (FI), 70% restriction during stage-II (IR2) and 30% restriction during stage-III (IR3), combined with three annual doses of N fertilizer: 0 kg N ha^{-1} (N0), 60 kg N ha^{-1} (N60) and 120 kg N ha^{-1} (N120). A randomised complete block design with four repetitions was established. The number of experimental plots was 36. Each plot consisted of three contiguous rows of trees, 30 trees in total, and monitoring was done on the 5 central trees. The total surface of the experiment was 1.5 ha. The experiment was established in 2006 and during 2008 was completed the third year.

2.2.5. Weekly scheduling irrigation

Irrigation was supplied by a localized high-frequency system with drip emitters (18 L tree^{-1} h^{-1}) from the beginning of the growing season (first March) to post-harvest (late October). Reference evapotranspiration (ETo) and precipitation (Prec) of the previous week were obtained from two near weather stations (Raïmat and Aitona), located 10 km from the site study. Effective precipitation (Pefec) was calculated as:

if	Prec ≤ 10 mm week^{-1}	then	Pefec = 0 mm week^{-1}	
if	10 < Prec ≤ 70 mm week^{-1}	then	Pefec = Prec/2 mm week^{-1}	equation 14
if	Prec > 70 mm week^{-1}	then	Pefec = 35 mm week^{-1}	

Irrigation dose (D) was determined by the FAO-56 simple water budget methodology as (Allen *et al.*, 1998):

$$\text{Irrig} = \text{Kc} \times \text{ETo} - \text{Pefec} \qquad \text{equation 15}$$

No leaching fraction was computed. Crop coefficient (Kc) was obtained from values adjusted for local peach orchards (Table 4). Peach trees were daily irrigated and irrigation time was introduced in an automatic controller. The amount of water applied was measured with a flow meter in each experimental plot.

Table 4. Crop coefficient (Kc) for peach orchards in the horticultural zone of Lleida (Girona, 1996).

Month	Mar	Mar	Apr	Apr	May	May	Jun	Jun	Jul	Jul	Aug	Aug	Sep	Sep	Oct	Oct
Days	1-15	16-31	1-15	16-30	1-15	16-31	1-15	16-30	1-15	16-31	1-15	16-31	1-15	16-30	1-15	16-31
Kc	0.26	0.35	0.43	0.58	0.72	0.81	0.95	0.98	1.09	1.10	1.09	0.95	0.87	0.81	0.73	0.62
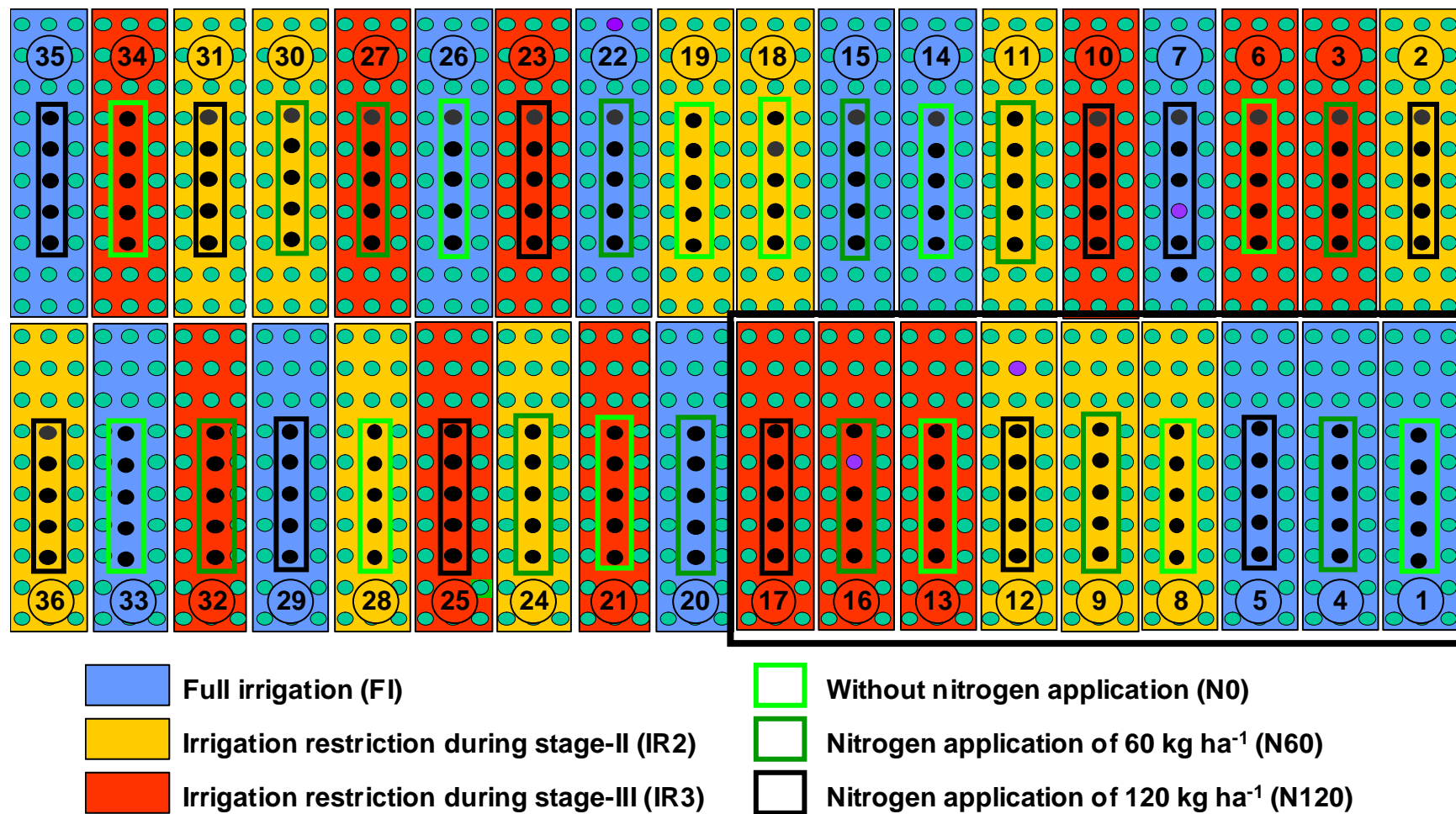
Figure 5. Experimental plot of irrigation and nitrogen treatments according to a randomised complete block design with four repetitions.

2.2.6. Nitrogen application

Nutrients (N, P, K and Fe-chelates) were supplied by a fertigation system with an injection pump. N 32% fertilizer was used (32-0-0).

2.2.7. Orchard management

Soil management was performed by mowing the grass in the tree alleys and herbicide application under the tree rows (Figure 6A). Trees were pruned but were not fruit thinned (Figure 6B). The harvest was mechanical with a continuum trunk shaker (Figure 6C and 6D). Pesticide applications were performed according to minimum residue, because the fruits are produced for processing and are used in baby food.

Figure 6. Peach orchard at mid May (A), fruit of cv. Andross (B) and mechanical harvesting with a continuum trunk shaker (C and D).

2.3. Monitoring, collecting samples and determinations

2.3.1. Seasonal growth of shoots and fruits

The length and diameter at the base of 6 tagged shoots and the equatorial diameter of 6 tagged fruits per experimental plot were measured at weekly intervals. Growth was monitored according to thermal time by accumulated degree days from full bloom, taking 7ºC as base temperature and 35ºC as upper temperature for peach (Zalom *et al.*, 1983).

2.3.2. Daily patterns of soil water content

Soil water content was monitored continuously with ECH2O-20 capacitance probes (Decagon Devices Inc., Pullman, Washington, USA) that outputs the volumetric water content of the surrounding soil. Four moisture probes were inserted in the soil of a representative tree in each irrigation treatment, such as full irrigation during all the season, irrigation restriction during stage-II and irrigation restriction during stage-III. Probes were installed at 70 cm at each side of the trunk and 15 cm and 30 cm deep inside the wet bulb. The same installation was repeated in two soil profiles. The time interval of measurement was 15 minutes. Soil relative water content (RWC) was determined according to the upper drained level and the lower level:

$$soil\ RWC\ (\%) = (100 - D) + D \times \left(\frac{ECH2O - low}{up - low} \right) \qquad \text{equation 16}$$

which could be obtained for each probe from measurements recorded in the field during irrigation events and then let the water to drain into the soil (Figure 7). These two levels were measured in spring, when all the treatments were equally irrigated. The maximum allowable depletion, which was set at $D = 50\%$.
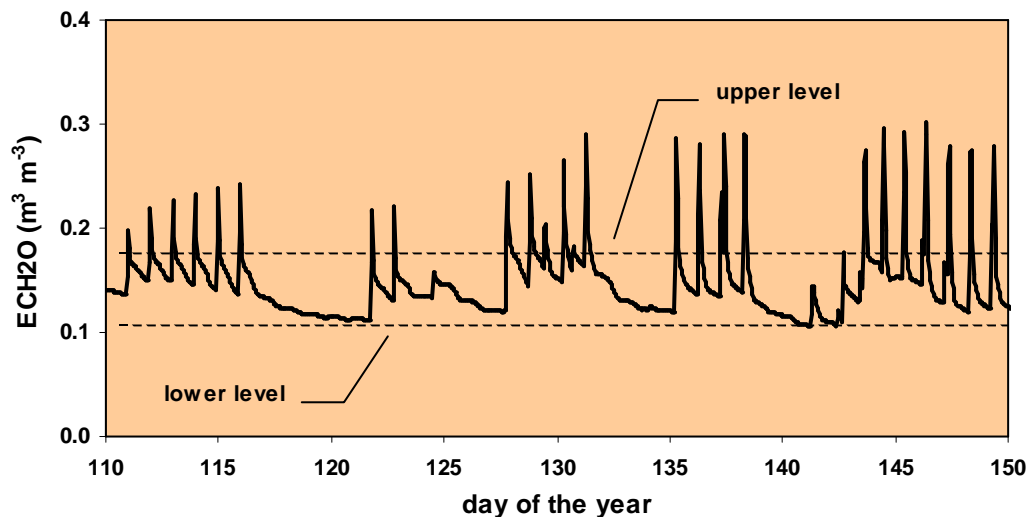
Figure 7. Determination of the upper level and the lower level of soil water content from measurements recorded in the field with capacitance probes.

2.3.3. Trunk radius changes

Trunk radius changes were measured with point dendrometers (Phytech Co. Ltd., Israel) on three trees of a single experimental plot. The trees received full irrigation during all the season combined with 60 kg N ha^{-1}. The dendrometers were attached to the trunk at 50 cm above the ground level and placed at the north side. The electronic part of the dendrometer was mounted on a carbon fibre frame which was fixed to the stem by one stainless steel threaded rod implanted into the heartwood. Changes in trunk external radius were measured with a micrometric LVDT sensor (Linear Variable Differential Transformers) positioned perpendicularly to the trunk. The contact point of the dendrometer head was positioned 1–3 mm into the bark surface, but still within the

outermost layer of the bark. The sensors were built with aluminium and invar material (an alloy of Ni and Fe) with a very low thermal sensitivity. Each sensor was connected to a specific Phytech datalogger which recorded data every hour. The time series of trunk radius included periods of shrinkage and swelling, mainly the bark (Figure 8). These data enabled to calculate the difference between the maximum and the actual radius of the trunk as an average over the whole day:

$$shrinkage = \sum (\, r_{max} - r_i \,) \, / \, 24 \qquad \qquad \text{equation 17}$$

which is a measure of tree water status (Zweifel *et al*., 2006).
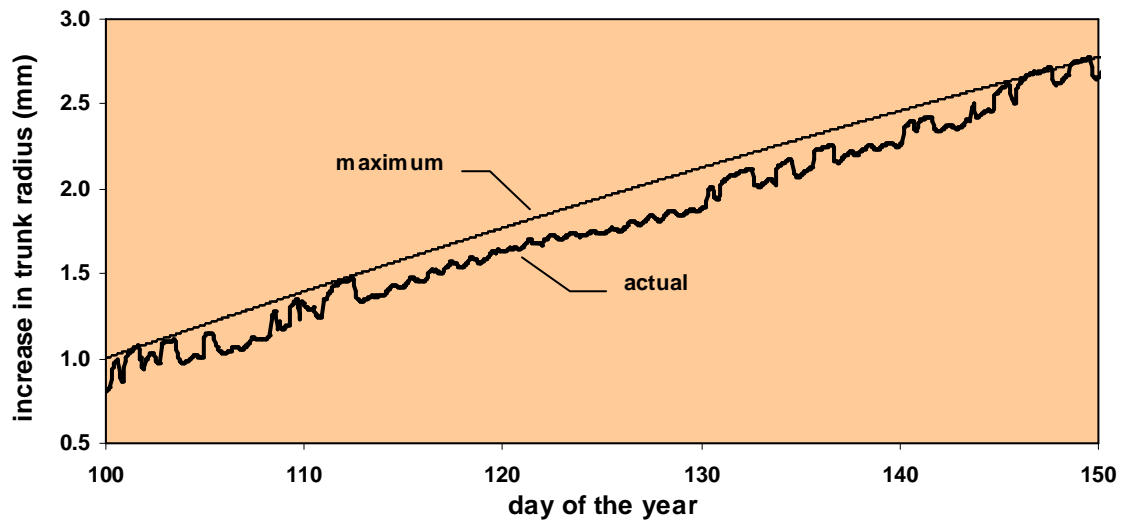
Figure 8. Increase in trunk radius measured with LVDT dendrometers.

2.3.4. Stem water potential

The midday stem water potential (Ψ_{stem} at 12:00 h solar time) was measured periodically over the season, on completely clear days. Three mature leaves per plot were taken close to the main trunk of the tree. Leaves were inserted into a small black plastic bag and covered with aluminium foil, for at least 2 hours before detaching the leaf from the tree (McCutchan and Shackel, 1992). One day in stage-III, the predawn leaf water potential was measured before sunrise and a diurnal trend of Ψ_{stem} was obtained from morning to afternoon. Measurements were taken using the pressure chamber technique (model 3005, Soil Moisture Equipment Corp, Santa Barbara, CA, USA) as described by Scholander *et al*. (1965).

2.3.5. Stomatal conductance

The midday stomatal conductance (g_s) was measured periodically over the season at midday (12:00 h solar time) under light-saturated conditions, on completely clear days. Three mature leaves per plot were measured using a steady-state diffusion porometer (model LI-1600, LI-COR Inc., Lincoln, Nebraska, USA) as described by Pearcy *et al*. (1989). One day in stage-III, a diurnal trend of g_s was obtained from morning to afternoon.

2.3.6. Leaf relative light absorbance

Leaf relative light absorbance (α_r) was measured in the orchard using an SPAD-502 (Konica Minolta Ltd., Hong Kong, Japan). The hand-held meter has two LEDs that emit in different wavelengths through an intact leaf. Chlorophyll absorbance is measured at red (650 nm) and nonchlorophyll absorbance at infrared (940 nm). The ratio of these two measures provides automatically the relative light absorbance of the leaf, which is highly correlated with leaf chlorophyll content on leaf area basis (Marquard and Tipton, 1987). The sample size was 50 leaves per experimental plot, chosen randomly from the middle of the shoots, including both sides of the tree rows.

2.3.7. Specific leaf weight

Specific leaf weight (SLW) was calculated as leaf dry weight to leaf area from 50 leaves in each experimental plot (leaf lamina and petiole were included). Leaf area was determined using an LI-3100 area meter (LI-COR, Inc., Lincoln, Nebraska, USA).

2.3.8. Analysis of the mineral nutrition of leaves, fruits and dormant shoots

Leaf samples were collected in 2006 at the end of stage-III (7 August), in 2007 at the end of stage-II (19 June), at the end of stage-III (24 July) and before leaf fall (22 October), and in 2008 at the end of stage-II (18 June), at the end of stage-III (16 July) and before leaf fall (17 October). The sample size was 50 leaves, fully developed from the middle of the shoots. Fruit samples were collected in 2006 at harvest (7 August), in 2007 at the end of stage-II (15 June) at harvest (9 August), and in 2008 at the end of stage-II (18 June) and at harvest (12 August). The sample size was 10 fruits. Shoot samples were collected during winter pruning (in February), and sample size was 50 shoots. Each sample was collected randomly within each experimental plot, including both sides of the tree row. The samples were kept cooled until they were weighted in a precision balance to obtain fresh weight. The samples were oven-dried at 65ºC to a constant weight and ground in a cyclone mill to pass a 40-mesh screen for dry tissue tests. An aliquot of each sample was sent to a recognized fertilization testing laboratory (Applus Agroambiental, Sidamon, Lleida). The dry tissue was analysed for total N concentration by the Kjeldhal method and for P, K, Ca, Mg and S by atomic emission spectroscopy using a ICP analyser (Inductively Coupled Plasma).

2.3.9. Analysis of soil nitrates

For each individual plot, a composite soil sample was taken from the surface layer (0-30 cm) within the wet bulb during the rest period, in winter, following the growing season (Kusakabe et al., 2006). All samples were kept cooled until they were air-dried and sieved (2 mm). An aliquot of each sample was sent to a recognized fertilization testing laboratory (Applus Agroambiental, Sidamon, Lleida). The soil extract from 1:2 soil-water solution was determined spectro-photometrically for NO_3-N with a flow injection analyser (FIA).

2.3.10. Yield components

Before commercial harvest, fruits on the ground of each tree were counted and weighted. At commercial harvest, all trees of the experiment were harvest during the

same day. In total 180 trees. Fruit harvest was achieved mechanically using a continuum trunk shaker (Cepparo, Pomport, France). The harvester efficiency was determined. The remaining fruit on the tree were counted and weighted. Yield components were determined for each tree according to total fruit load, total yield and average fruit weight.

2.3.11. Water productivity

Water productivity (WP) was determined as the total yield per unit of water used. The amount of water consumed was computed as the sum of effective precipitation plus irrigation water applied during whole fruit growing period. This index was calculated for fresh and dry yield.

2.3.12. Fraction of PAR intercepted

The interception of photosynthetically active radiation (PAR) by the trees was determined using an Accupar Linear PAR Ceptometer (Decagon Devices Inc., Pullman, WA, USA), on completely clear days at solar noon. Row orientation was east to west and incident PAR (PAR_0) was measured outside the orchard. PAR not intercepted (PAR_{ni}) was measured at ground level from a grid of 15 measurements per tree: 5 equidistant transects (at 0, 1 and 2 m from the trunk, on both sides of the tree row) and 3 measurements per transect. The fraction of PAR intercepted (FIPAR) was determined as $(1 - PAR_{ni})/PAR_0$ just after fruit harvest, in two trees per experimental plot.

2.3.13. Pruning weight

At tree rest, pruning fresh weight was determined in the orchard for each experimental plot using a roman balance and then converted to dry weight from subsamples dried to 65ºC in an oven.

2.3.14. Percentage of fruit dry matter

Samples of 5 fruits were colleted from both sides of the tree row at 1.5 m above ground level and preserved in a portable cooler (following fruit quality analysis were performed from this sample). Fruit samples were weighted in a precision balance to obtain fresh weight and then dried in a oven at 65ºC until constant weight to obtain fruit dry weight. Percentage of fruit dry matter was calculated as $100 \times$ (dry weight / fresh weight).

2.3.15. Fruit total soluble solids

All years, the total soluble solids (TSS) of the juice was determined using a termocompensated digital refractometer (Atago Co Ltd., Tokyo, Japan) and expressed in ºBrix. In 2008, the puree TTS was also determined.

2.3.16. Fruit flesh firmness

The flesh firmness of the fruit was measured using an electronic penetrometer (Penefel, France) with an 8 mm tip, using two readings from two opposite peeled sides. The penetration force was expressed in kg cm^{-2} and converted to newtons (N).

2.3.17. Fruit puree consistency

In 2008, fruit purees were obtained from different treatments. Puree consistency was measured with a Bostwick consistometer in centimetres of flow for 30 seconds at 20ºC.

2.3.18. Fruit flesh colour

In 2007, fruit flesh colour was measured on individual fruits with a Minolta CR-200 Chroma Meter portable tristimulus colorimeter (Minolta Co., Osaka, Japan) with C illuminant. Measurements were carried out at two opposite locations of every fruit. The results were expressed in L*, a* and b* space colour CIELAB coordinates. The L* value is the luminosity of colours ranging from 0 = dark to 100 = light. The a* coordinate is negative for green and positive for red, while b* coordinate is negative for blue and positive for yellow. Also the hue (hº) and chroma (C*) were calculated. The hº value was calculated as $\tan^{-1}$ (b*/a*) and represents an angle in a colour wheel, with 0º, 90º, 180º and 270º corresponding to red, yellow, green and blue, respectively. The C* value was calculated as $\sqrt{a*^2 + b*^2}$ and represents the intensity of the hue.

2.4. Statistical analysis

Data for each year was analysed using analysis of variance (ANOVA) considering a randomised complete bloc design with four repetitions. The coefficient of variation (CV) was included to compare among years. The LSD test was applied a posteriori as a multiple range test between irrigation treatments with a significance level of 5%. The polynomial contrasts were used as planned tests for lineal (L) and quadratic (Q) trends by nitrogen application. All statistical analyses were performed using the software SAS v9.1 package (SAS Institute, Cary, NC, USA).

3. Results

3.1. Growth pattern of fruits and shoots

3.1.1. Development stages

Table 5 shows the development stages of peach trees during the three experimental years (2006-2007). Irrigation and N application did not affect flower phenology in any year. As an average, full bloom occurred on 15 March, stage-II lasted from 18 May until 17 Jun and commercial harvest was on 10 August, which are common in the area for the peach cv. Andross. Development stages were also monitored according to accumulated thermal time from full bloom, taking 7 and 35ºC as base and

Table 5. Development stages of peach cv. Andross (2006-2008)

Year	Stage	Date	Day of the year	Thermal time (degree days)
2006	Full bloom	20/03/2006	79	0
	Begin stage-II	16/05/2006	136	494
	End stage-II	15/06/2006	166	893
	Harvest	07/08/2006	219	1882
	50% leaf fall	11/11/2006	315	3059
2007	Full bloom	14/03/2007	73	0
	Begin stage-II	19/05/2007	139	495
	End stage-II	15/06/2007	166	863
	Harvest	10/08/2007	222	1784
	50% leaf fall	30/10/2007	303	2757
2008	Full bloom	12/03/2008	72	0
	Begin stage-II	18/05/2008	139	497
	End stage-II	21/06/2008	173	892
	Harvest	12/08/2008	225	1812
	50% leaf fall	10/11/2008	315	2775

upper temperature, respectively. Thus, the mean duration of stage-I was 495 degree days (63 days), stage-II was 388 degree days (31 days) and stage-III was 943 degree days (53 days). The thermal time from full bloom until harvest was 1826 degree days. The fall of 50% of leaves occurred during the first week of November.

3.1.2. Fruit growth

Fruit growth pattern in diameter was double-sigmoidal (Figure 9A). The thermal time (τ) was used in order to compare the fruit diameter (y) of different years. The following equation was fitted to the data using non-linear regression analysis:

$$y = \frac{y_i}{1 + \left(\dfrac{\tau}{\tau_i}\right)^{-bi}} + \frac{y_e}{1 + \left(\dfrac{\tau}{\tau_e}\right)^{-be}}$$

equation 18

where the parameters y_i and y_e are for fruit size, τ_i and τ_e are for thermal time and b_i and b_e are for the slope to the curve. Subscripts *i* and *e* represent the stages of cell division and cell expansion during fruit growth, respectively. Table 6 shows the estimated parameters for FI strategy during 2006-2008. Fruit growth rate in diameter, determined as $\Delta y / \Delta \tau$, increased during stage-I and slowed down during stage-II, when attained its minimum growth rate. Then, growth rate increased again during stage-III of expansive fruit growth (Figure 9B).

Different measures of fruit growth were compared (Figure 10). Fruit diameter was measured in the orchard. Fruit fresh weight (M, g) was calculated as a function of fruit diameter (D, mm) by an allometric relationship using non-linear regression analysis:

$$M = a\,D^{\,b}$$

equation 19

carried out from fruit set until fruit harvest, with parameters $a = 0.0029$ g and $b = 2.58$ and a coefficient of determination of 98%.

Fruit dry weight was calculated according to relative dry weight of the fruit obtained from fruit samples along the season. Fruit size at $\tau = 1826$ degree days (fruit harvest) was used to standardize fruit growth curves between different years during 2006-2008. The double-sigmoidal equation was fitted to the standardized data using non-linear regression analysis. Also the respective fruit growth rate was calculated relative to its maximum value. The results are shown in Figure 10 carried out with data for FI strategy.

Fruit growth in diameter was 43% in stage-I, 12% in stage-II and 45% in stage-III. When considering fruit fresh weight, expansive growth in stage-III took more importance, since it was 12% in stage-I, 9% in stage-II and 79% in stage-III. In dry weight, fruit growth gained importance at stage-II of pit hardening, since it was 10% in stage-I, 18% in stage-II and 72% in stage-III. Growth rate attained a maximum in mid-stage-I and then decreased until end stage-II, from where it increased again to another maximum in mid-stage-III. Growth rate decreased during the last days of fruit ripening. Growth rate in diameter was at its maximum in stage-I while it represented only 50% in stage-III. In contrast, the growth rate in fresh weight and dry weight was higher in stage-III than in stage-I. The minimum growth rate at end stage-II was less pronounced in dry weight (44%) than in fresh weight (15%).
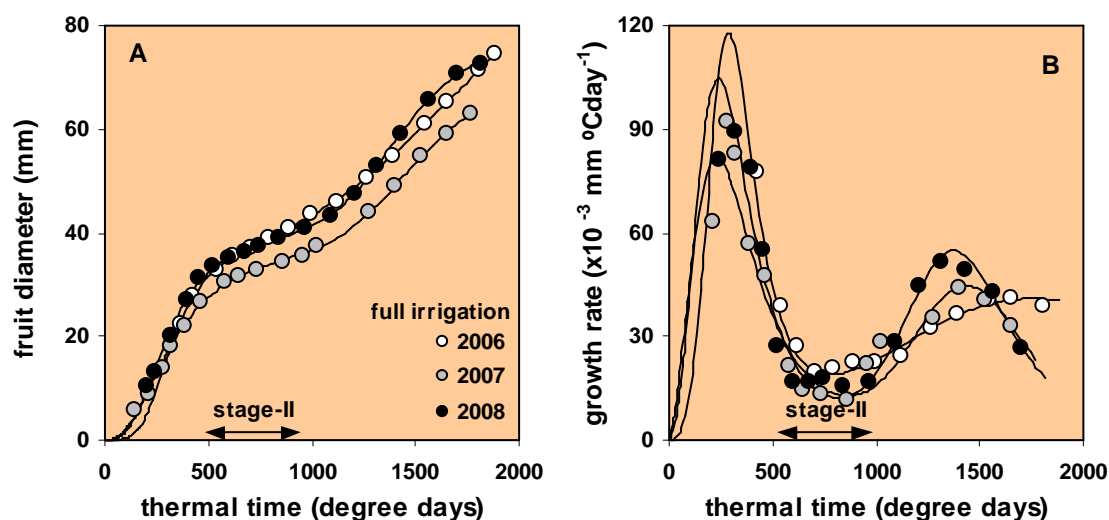
Figure 9. Fruit growth pattern in diameter (A) and its growth rate (B) under full irrigation of peach cv. Andross according to the experimental year (2006-2008).

Table 6. Estimated parameters and 95% confidence intervals for fruit growth pattern in diameter of peach cv. Androsss (2006-2008).

Independent variable	Dependent variable	Year	Parameters for cell division stage			Parameters for cell expansion stage		
			y_i	τ_i	b_i	y_e	τ_e	b_e
Thermal time (degree days)	Fruit diameter (mm)	2006 FI	37.1±3.8	329.7±11.1	3.88±1.18	92.1±60.2	2100.0±661.1	3.41±1.15
		2007 FI	37.8±2.9	331.1±28.1	2.41±0.37	32.0±9.4	1482.6±98.7	7.86±2.97
		2008 FI	40.8±1.5	311.5±12.2	2.81±0.27	36.8±3.8	1420.1±34.2	8.16±1.30

Figure 10. Standardized fruit growth curve in diameter (A), fresh weight (B) and dry weight (C) respect to maximum fruit weight at 1826 degree days during 2006-2008 of peach cv. Andross under full irrigation (red dots are observed data and red line is adjusted curve) and its respective standardized growth rate respect to maximum value (blue dots are observed data and blue line is calculated from growth curve).

Table 7 shows the effect of irrigation and N application on fruit growth in diameter and its average growth rate for each stage. In 2006 and 2007, IR2 reduced significantly fruit growth rate during stage-II, but after restoring complete irrigation, fruit growth rate recovered during stage-III, and its diameter at harvest was not different from FI fruits. In 2008, IR2 also reduced fruit growth rate during stage-II, however the growth rate did not recover during stage-III, and final fruit diameter was lower than FI fruits. In contrast, IR3 produced important effects on fruit growth rate during stage-III, which was significantly lower than FI fruits in 2007 and 2008. Also IR3 reduced fruit diameter at harvest, but the effect was only significantly in 2007.

On the other hand, fruit growth tended to decrease with higher N doses in the three growing seasons, but the effect was only with significant in 2007. In that year, fruit growth rate was higher at N0 followed in order by N60 and N120, indicating a decreasing trend as N application increased. Also fruit diameter at harvest was higher in trees without N application.

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Table 7. Effect of irrigation and N application on fruit growth in diameter for each stage of peach cv. Andross (2006-2008).

Year	Effect	Fruit diameter (mm)			Fruit growth rate (mm day^{-1})		
		End stage-I	End stage-II	End stage-III	Stage-I	Stage-II	Stage-III
2006	CV	9.63%	8.15%	9.40%	9.63%	16.49%	17.54%
	Block	ns	0.0101	0.0006	ns	0.0001	0.0010
	Irrigation	ns	ns	ns	ns	<0.0001	0.0314
	FI	31.0 ± 0.6	41.1 ± 0.9	74.3 ± 2.2	0.543 ± 0.011	0.337 ± 0.013 a	0.622 ± 0.033 a
	IR2	30.9 ± 0.6	40.0 ± 0.7	72.1 ± 2.0	0.543 ± 0.011	0.290 ± 0.013 b	0.606 ± 0.032 ba
	IR3	30.3 ± 0.8	40.9 ± 1.0	70.1 ± 2.2	0.531 ± 0.015	0.335 ± 0.016 a	0.551 ± 0.031 b
	Nitrogen	ns	ns	ns	ns	0.0407	ns
	N0	31.1 ± 0.6	41.3 ± 0.8	73.4 ± 2.1	0.545 ± 0.011	0.332 ± 0.016	0.597 ± 0.034
	N60	30.4 ± 0.8	40.6 ± 0.8	72.3 ± 2.3	0.534 ± 0.015	0.322 ± 0.013	0.601 ± 0.032
	N120	30.7 ± 0.7	40.2 ± 0.9	71.1 ± 2.0	0.538 ± 0.011	0.310 ± 0.015	0.582 ± 0.032
	L	ns	ns	ns	ns	0.0171	ns
	Q	ns	ns	ns	ns	ns	ns
	Irrig × Nit	ns	ns	0.0428	ns	ns	ns
2007	CV	6.10%	6.11%	9.82%	6.10%	17.40%	18.88%
	Block	0.0389	0.0111	ns	0.0389	ns	ns
	Irrigation	ns	0.0429	0.0011	ns	<0.0001	<0.0001
	FI	28.4 ± 0.6	34.3 ± 0.6 ba	63.5 ± 1.9 a	0.430 ± 0.009	0.231 ± 0.013 a	0.518 ± 0.026 a
	IR2	28.6 ± 0.4	34.0 ± 0.4 b	63.2 ± 1.7 a	0.433 ± 0.006	0.200 ± 0.010 b	0.523 ± 0.029 a
	IR3	29.0 ± 0.5	34.9 ± 0.5 a	59.3 ± 1.9 b	0.440 ± 0.008	0.226 ± 0.011 a	0.437 ± 0.028 b
	Nitrogen	ns	0.0009	0.0032	ns	0.0063	0.0188
	N0	29.1 ± 0.6	35.2 ± 0.5	64.5 ± 2.0	0.441 ± 0.010	0.232 ± 0.013	0.524 ± 0.030
	N60	28.4 ± 0.4	34.0 ± 0.4	59.7 ± 1.9	0.431 ± 0.006	0.208 ± 0.010	0.463 ± 0.033
	N120	28.4 ± 0.5	34.1 ± 0.6	61.1 ± 1.6	0.431 ± 0.007	0.214 ± 0.011	0.478 ± 0.023
	L	ns	0.0027	0.0048	ns	0.0020	0.0120
	Q	ns	0.0217	0.0052	ns	0.0267	0.0216
	Irrig × Nit	ns	ns	0.0370	ns	ns	0.0322
2008	CV	6.45%	6.92%	10.84%	6.45%	17.43%	19.56%
	Block	ns	ns	ns	ns	ns	ns
	Irrigation	ns	ns	ns	ns	0.0335	0.0016
	FI	32.6 ± 0.5	40.0 ± 0.8	71.5 ± 2.6	0.486 ± 0.008	0.219 ± 0.009 a	0.622 ± 0.035 a
	IR2	32.5 ± 0.5	39.6 ± 0.8	68.8 ± 2.3	0.485 ± 0.007	0.193 ± 0.010 b	0.557 ± 0.040 b
	IR3	32.0 ± 0.5	39.8 ± 0.9	67.6 ± 2.2	0.478 ± 0.007	0.222 ± 0.014 a	0.523 ± 0.038 b
	Nitrogen	ns	ns	ns	ns	ns	ns
	N0	32.4 ± 0.5	40.7 ± 1.0	70.1 ± 2.7	0.483 ± 0.008	0.225 ± 0.012	0.574 ± 0.047
	N60	32.4 ± 0.5	39.1 ± 0.6	70.4 ± 2.3	0.484 ± 0.007	0.208 ± 0.010	0.581 ± 0.041
	N120	32.3 ± 0.5	39.7 ± 0.7	67.6 ± 2.2	0.481 ± 0.008	0.208 ± 0.012	0.549 ± 0.035
	L	ns	ns	ns	ns	ns	ns
	Q	ns	ns	ns	ns	ns	ns
	Irrig × Nit	ns	ns	ns	ns	ns	ns

Within each year and column, the CV is the coefficient of variation according to ANOVA results ($\alpha = 0.05$). Irrigation treatments followed by different letters indicate significant differences by LSD multiple range test. Lineal (L) and quadratic (Q) contrast indicate significant trends by N application. Errors are 95% confidence interval of the mean.

3.1.3. Shoot growth

Shoot growth pattern in length was sigmoidal (Figure 11A). The thermal time (τ) was used in order to compare the shoot length (y) of different years. The logistic equation was fitted to the data using non-linear regression analysis:

$$y = \frac{k}{1 + \left(\dfrac{k - y_0}{y_0}\right)\exp(-r\tau)} \qquad \text{equation 20}$$

where the parameters y_0 is the initial shoot length, r is the relative growth rate and k is the asymptotic shoot length. Table 8 shows the estimated parameters for FI strategy, from 2006 to 2008. Growth rate in length, determined as $\Delta y/\Delta \tau$, attained its maximum value at the beginning of stage-II and slowed down until stage-III, when growth rate had been stopped (Figure 11B).

Shoot growth in diameter increased from bud sprouting until ending stage-II and also this pattern could be fitted to a logistic equation (Figure 12A). However shoot growth in diameter began from an initial high diameter, in comparison to its asymptotic shoot diameter. Table 8 shows the estimated parameters for FI strategy, from 2006 to 2008. Growth rate in diameter attained its maximum value during stage-I and tended to decrease during stage-II (Figure 12B).
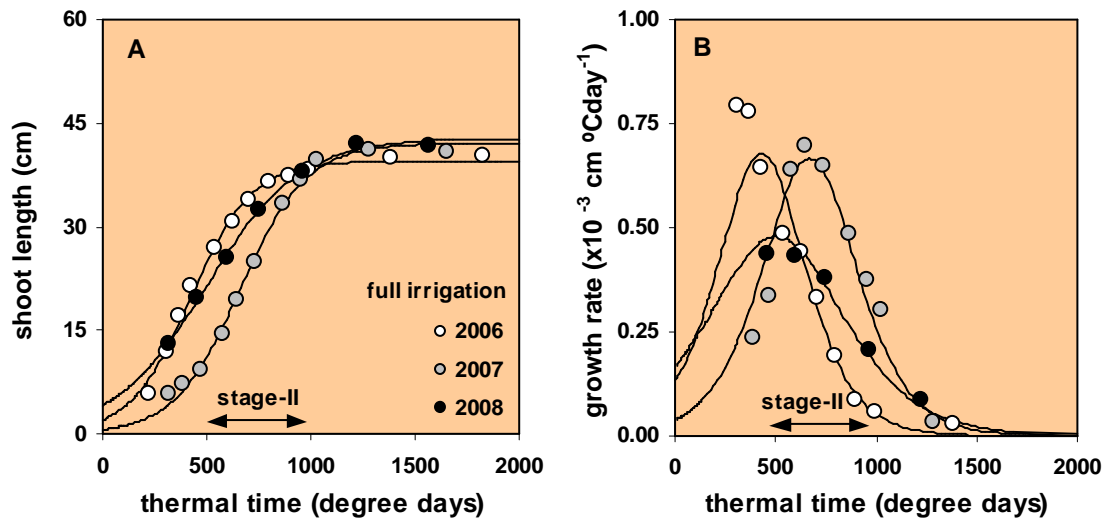
Figure 11. Shoot growth pattern in length (A) and its growth rate (B) under full irrigation of peach cv. Andross according to the experimental year (2006-2008).
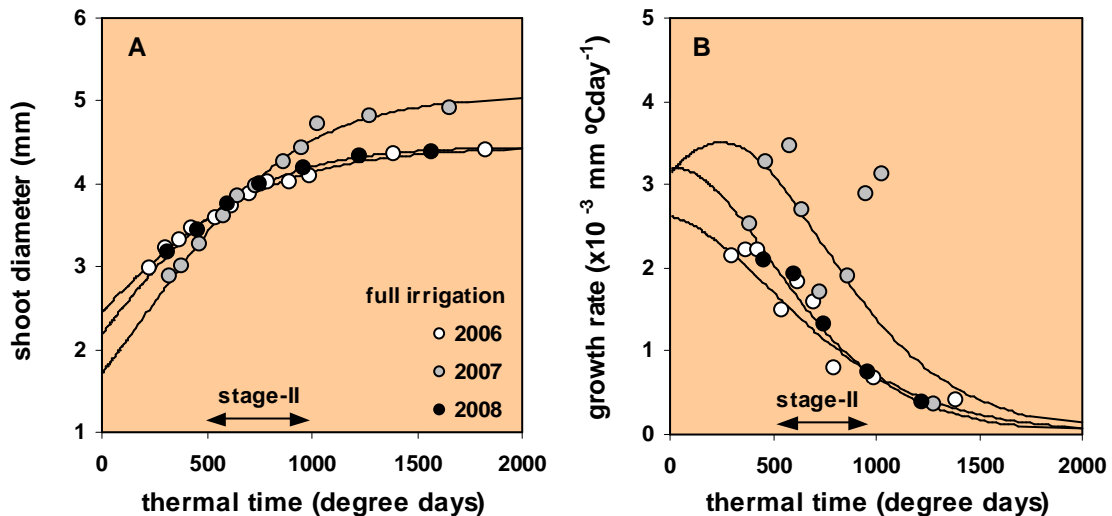
Figure 12. Shoot growth pattern in diameter (A) and its growth rate (B) under full irrigation of peach cv. Andross according to the experimental year (2006-2008).

Table 8. Estimated parameters and 95% confidence intervals for shoot growth pattern in length and diameter of peach cv. Androsss (2006-2008).

Independent variable	Dependent variable	Year	Parameters		
			y_0	r $(\times 10^{-3})$	k
Thermal Time (degree days)	Shoot length (cm)	2006 FI	2.0±0.8	6.862±1.009	39.5±1.4
		2007 FI	0.6±0.3	6.337±0.844	42.1±1.8
		2008 FI	4.2±1.4	4.480±0.728	42.8±1.7
	Shoot diameter (mm)	2006 FI	2.5±0.1	2.374±0.315	4.5±0.1
		2007 FI	1.7±0.3	2.765±0.508	5.1±0.2
		2008 FI	2.2±0.2	2.873±0.542	4.5±0.1

Table 9 shows the effect of irrigation and N application on shoot growth in length and its average growth rate for each stage. There were no significant effects due to the application of different treatments. However, according to results, IR2 reduced shoot growth and its growth rate during stage-II, and the effect was maintained during stage-III. But IR3 did not affect shoot growth when shoot extension had ceased. On the other hand, N application increased the shoot growth and its growth rate during all the stages.

Table 9. Effect of irrigation and N application on shoot growth in length for each stage of peach cv. Andross (2006-2008).

Year	Effect	Shoot length (cm)			Shoot growth rate (cm day^{-1})		
		End stage-I	End stage-II	End stage-III	Stage-I	Stage-II	Stage-III
2006	CV	44.49%	64.50%	73.11%	44.49%	123.38%	297.92%
	Block	ns	ns	ns	ns	ns	ns
	Irrigation	ns	0.0337	0.0275	ns	ns	ns
	FI	24.8 ± 2.4	37.5 ± 5.4 a	40.4 ± 6.8 a	0.435 ± 0.042	0.424 ± 0.113	0.054 ± 0.034
	IR2	20.7 ± 2.0	28.6 ± 3.7 b	29.3 ± 4.0 b	0.362 ± 0.036	0.264 ± 0.068	0.014 ± 0.009
	IR3	24.2 ± 2.8	36.0 ± 6.2 a	38.5 ± 7.5 a	0.425 ± 0.049	0.394 ± 0.129	0.046 ± 0.031
	Nitrogen	ns	ns	ns	ns	0.0465	ns
	N0	24.5 ± 2.7	37.3 ± 6.3	40.4 ± 7.9	0.430 ± 0.047	0.426 ± 0.132	0.058 ± 0.037
	N60	22.1 ± 2.4	29.7 ± 4.4	30.7 ± 4.8	0.388 ± 0.043	0.255 ± 0.079	0.018 ± 0.014
	N120	23.1 ± 2.2	35.1 ± 4.9	37.1 ± 5.8	0.405 ± 0.039	0.400 ± 0.101	0.038 ± 0.025
	L	ns	ns	ns	ns	ns	ns
	Q	ns	ns	ns	ns	0.0142	ns
	Irrig × Nit	ns	ns	ns	ns	ns	ns
2007	CV	47.95%	44.23%	52.39%	47.95%	51.43%	107.65%
	Block	0.0298	ns	ns	0.0298	ns	ns
	Irrigation	ns	ns	ns	ns	ns	ns
	FI	9.9 ± 1.1	33.5 ± 3.5	41.1 ± 5.0	0.150 ± 0.017	0.873 ± 0.109	0.136 ± 0.033
	IR2	10.0 ± 1.2	30.3 ± 3.2	37.0 ± 4.5	0.151 ± 0.018	0.752 ± 0.087	0.120 ± 0.029
	IR3	9.5 ± 1.1	32.6 ± 3.5	40.6 ± 5.3	0.143 ± 0.016	0.857 ± 0.108	0.143 ± 0.039
	Nitrogen	ns	ns	ns	ns	ns	ns
	N0	9.5 ± 1.1	30.1 ± 3.3	36.7 ± 4.9	0.144 ± 0.017	0.765 ± 0.097	0.117 ± 0.032
	N60	9.5 ± 1.2	33.9 ± 3.4	41.9 ± 4.9	0.144 ± 0.018	0.905 ± 0.104	0.142 ± 0.034
	N120	10.4 ± 1.1	32.3 ± 3.5	40.1 ± 5.0	0.157 ± 0.016	0.813 ± 0.104	0.139 ± 0.035
	L	ns	ns	ns	ns	ns	ns
	Q	ns	ns	ns	ns	ns	ns
	Irrig × Nit	ns	0.0151	ns	ns	0.0122	ns
2008	CV	42.63%	61.07%	65.79%	42.63%	98.62%	340.79%
	Block	0.0076	ns	0.0539	0.0076	ns	ns
	Irrigation	0.0142	ns	ns	0.0142	ns	ns
	FI	21.7 ± 2.3 a	37.6 ± 5.6	42.1 ± 6.9	0.324 ± 0.258 a	0.469 ± 0.116	0.085 ± 0.058
	IR2	17.6 ± 1.9 b	30.4 ± 4.5	33.7 ± 5.4	0.263 ± 0.300 b	0.374 ± 0.090	0.065 ± 0.062
	IR3	19.2 ± 1.9 ba	37.0 ± 5.0	39.3 ± 5.6	0.287 ± 0.315 ba	0.523 ± 0.108	0.043 ± 0.029
	Nitrogen	0.0185	ns	ns	0.0185	ns	ns
	N0	17.3 ± 2.0	32.0 ± 5.1	33.8 ± 5.8	0.258 ± 0.030	0.432 ± 0.106	0.034 ± 0.055
	N60	20.1 ± 2.0	37.2 ± 5.1	41.4 ± 6.0	0.300 ± 0.030	0.503 ± 0.107	0.081 ± 0.043
	N120	21.1 ± 2.1	35.8 ± 5.0	39.9 ± 6.2	0.315 ± 0.031	0.431 ± 0.104	0.079 ± 0.056
	L	0.0064	ns	ns	0.0064	ns	ns
	Q	ns	ns	ns	ns	ns	ns
	Irrig × Nit	ns	ns	ns	ns	ns	ns

Within each year and column, the CV is the coefficient of variation according to ANOVA results ($\alpha = 0.05$). Irrigation treatments followed by different letters indicate significant differences by LSD multiple range test. Lineal (L) and quadratic (Q) contrast indicate significant trends by N application. Errors are 95% confidence interval of the mean.

3.2. Water relations

3.2.1. Weather conditions and irrigation dose

Table 10 shows the development stages and the mean values of the meteorological conditions prevailing along the three experimental years (2006-2008). During the three years, temperature and solar radiation were higher during stage-III, while the relative humidity was lower, leading to higher VPD under such conditions in stage-III. Wind speed was higher during stage-I and stage-II. VPD from stage-I to stage-III was higher in 2006 than both in 2007 and 2008, due to higher maximum temperature and lower minimum relative humidity in the first experimental year.

Table 10. Development stages of peach cv. Andross and meteorological conditions according to weather stations of Raïmat and Aitona (2006-2008). Mean daily values of maximum temperature (t_{max}), minimum temperature (t_{min}), maximum relative humidity (RH_{max}), minimum relative humidity (RH_{min}), vapour pressure deficit (VPD), wind speed velocity at 2 m (U_2) and solar radiation (SR).

Year	Stage	Duration		t_{max}	t_{min}	RH_{max}	RH_{min}	VPD	U_2	SR
		(days)	(degree days)	(°C)	(°C)	(%)	(%)	(kPa)	(m s^{-1})	(MJ m^{-2} day^{-1})
2006	Rest period	135	-	10.9	0.4	92	59	0.33	1.05	8.3
	Stage-I	57	494	23.0	7.6	89	33	1.02	1.09	21.6
	Stage-II	31	399	29.2	11.6	82	23	1.72	1.10	27.8
	Stage-III	52	990	34.0	17.6	84	26	2.15	0.87	26.1
	Post-harvest	96	-	26.1	12.6	91	43	1.13	0.89	16.2
	Stage-I, II and III	140	1882	28.4	12.2	85	28	1.59	1.01	24.7
2007	Rest period	123	-	12.7	2.0	92	59	0.40	0.86	7.5
	Stage-I	66	495	20.9	7.1	89	38	0.91	1.22	18.8
	Stage-II	28	369	28.1	13.0	86	30	1.48	1.26	25.7
	Stage-III	55	921	31.3	15.8	84	28	1.82	1.17	26.7
	Post-harvest	81	-	26.7	11.3	90	36	1.27	0.76	17.9
	Stage-I, II and III	149	1784	26.1	11.4	86	33	1.35	1.21	23.0
2008	Rest period	134	-	13.2	0.4	91	53	0.43	0.87	8.6
	Stage-I	67	497	21.2	7.1	85	34	0.94	1.46	19.7
	Stage-II	35	395	25.2	11.9	91	39	1.09	0.86	23.1
	Stage-III	51	920	32.4	16.9	85	30	1.87	0.84	26.8
	Post-harvest	90	-	24.4	11.0	91	43	1.04	0.76	15.6
	Stage-I, II and III	153	1812	25.8	11.5	87	34	1.28	1.12	22.8

Table 11 shows the duration of the development stages and the water balance according to the experimental year (2006-2008). Precipitation showed considerable variation between years, while ETo was less variable. Thus, total precipitation during fruit growth (including stage-I, II and III) was 27 mm in 2006, and increased to 146 mm in 2007 and 221 mm in 2008. However, for the three years, almost all precipitation was concentrated to stage-I and II, with no substantial precipitation during stage-III. Total ETo during fruit growth attained a rather constant value of 593 mm averaged between the three years. But, daily ETo showed a rapid increase from stage-I (3.12 mm day^{-1}), through stage-II (4.39 mm day^{-1}) until stage-III of fruit growth (4.92 mm day^{-1}). Total irrigation during fruit growth was 467 mm in 2006, 357 mm in 2007 and 467 mm in 2008.

During stage-II, VPD was higher in 2006 (1.72 kPa) than in 2007 and 2008 (1.48 and 1.09 kPa, respectively), due to higher maximum temperature and lower minimum relative humidity in the first experimental year (Table 10). In addition, the meteorological deficit, determined as ETo – Pefec (Table 11), was more severe in 2006 (4.7 mm day^{-1}) than in 2007 and 2008 (3.7 and 3.1 mm day^{-1}, respectively). Thus, the irrigation dose was greater in 2006 (4.81 mm day^{-1}) than in either of the two following years (3.14 mm day^{-1} in 2007 and 2.23 mm day^{-1} in 2008). Along the three years, IR2

allowed to save irrigation water respect to FI by 57%, 62% and 56%, respectively. The corresponding water balance during stage-II, determined by K_{ratio} = (Pefec + Irrig) / ETo was higher for FI in contrast to IR2 trees (Table 11).

As in stage-II, during stage-III, VPD was higher in 2006 (2.15 kPa) than in 2007 and 2008 (1.82 and 1.87 kPa, respectively), due to higher maximum temperature and lower minimum relative humidity in the first experimental year (Table 10). The meteorological deficit, determined as ETo – Pefec (Table 11), was similar between 2006 and 2007 (4.77 and 4.76 mm day^{-1}, respectively) and the irrigation dose was also similar (3.98 and 4.07 mm day^{-1}, respectively). However, irrigation dose in 2008 (5.72 mm day^{-1}) was slightly higher for the corresponding meteorological deficit (4.92 mm day^{-1}), because crop coefficient (Kc) was increased. Along the three years, IR3 allowed to save irrigation water respect to FI by 24%, 27% and 23%, respectively. The corresponding water balance during stage-III, determined by K_{ratio} was higher for FI in contrast to IR3 trees (Table 11).

Table 11. Development stages and water balance according to irrigation of peach cv. Andross (2006-2008). Precipitation (Prec), effective precipitation (Pefec), reference evapotranspiration (ETo), irrigation dose applied (D), percentage respect full irrigation within brackets and coefficient K_{ratio} = (Irrig + Pefec) / ETo.

Year	Stage	Duration (days)	Duration (degree days)	Prec (mm)	Pefec (mm)	ETo (mm)	FI Irrig (mm)	FI K_{ratio}	IR2 Irrig (mm)	IR2 K_{ratio}	IR3 Irrig (mm)	IR3 K_{ratio}
2006	Rest period	135	-	98	31	117	0	-	0	-	0	-
	Stage-I	57	494	13	2	189	110	0.60	112	0.61	112	0.61
	Stage-II	31	399	0	0	146	149	1.02	65 (57%)	0.44	153	1.05
	Stage-III	52	990	13	4	252	207	0.84	193	0.78	157 (24%)	0.64
	Post-harvest	96	-	119	37	257	141	0.70	145	0.71	140	0.69
	Stage-I, II and III	140	1882	27	7	587	467	0.81	370 (21%)	0.64	422 (10%)	0.73
2007	Rest period	123	-	70	25	105	0	-	0	-	0	-
	Stage-I	66	495	96	40	188	45	0.45	44	0.45	47	0.46
	Stage-II	28	369	44	19	123	88	0.87	34 (62%)	0.43	88	0.87
	Stage-III	55	921	6	0	262	224	0.86	218	0.83	164 (27%)	0.63
	Post-harvest	81	-	30	10	235	120	0.55	121	0.56	121	0.56
	Stage-I, II and III	149	1784	146	60	573	357	0.73	296 (17%)	0.62	298 (16%)	0.63
2008	Rest period	134	-	43	17	134	6	-	6	-	6	-
	Stage-I	67	497	106	38	214	98	0.64	98	0.64	99	0.64
	Stage-II	35	395	89	34	142	78	0.78	34 (56%)	0.48	73	0.75
	Stage-III	51	920	26	11	262	292	1.16	296	1.17	225 (23%)	0.90
	Post-harvest	90	-	141	47	245	159	0.84	162	0.85	157	0.83
	Stage-I, II and III	153	1812	221	83	619	467	0.89	428 (8%)	0.83	397 (15%)	0.78

3.2.2. Daily patterns of soil water content

Soil relative water content (RWC) was measured within the wet bulb of drip irrigated trees and showed daily patterns as a result of water dynamics (Figure 13). Daily values of ETo were higher in July and then irrigation supply was increased. During a given period, ETo was lower in cloudy days, and specially in days with high rainfall. Soil RWC increased by irrigation and rainfall events, showing RWC peaks, which exceeded the level of 100%. This level was maintained along the irrigation time. When irrigation was switched-off, soil RWC decreased sharply since gravitational water drained into the soil until the slope of the RWC curve changed. This change may be associated with the transition from macro-pore to the onset of unsaturated flow within the micro-porosity. In contrast, when rainfall was finished, soil RWC decreased steadily, because rainfall wets the whole soil surface. Soil RWC decreased by root water uptake from the beginning of the day, and was depleted until lower levels in days with higher ETo. In addition, higher water depletion was observed in July, when canopy size was maximum.
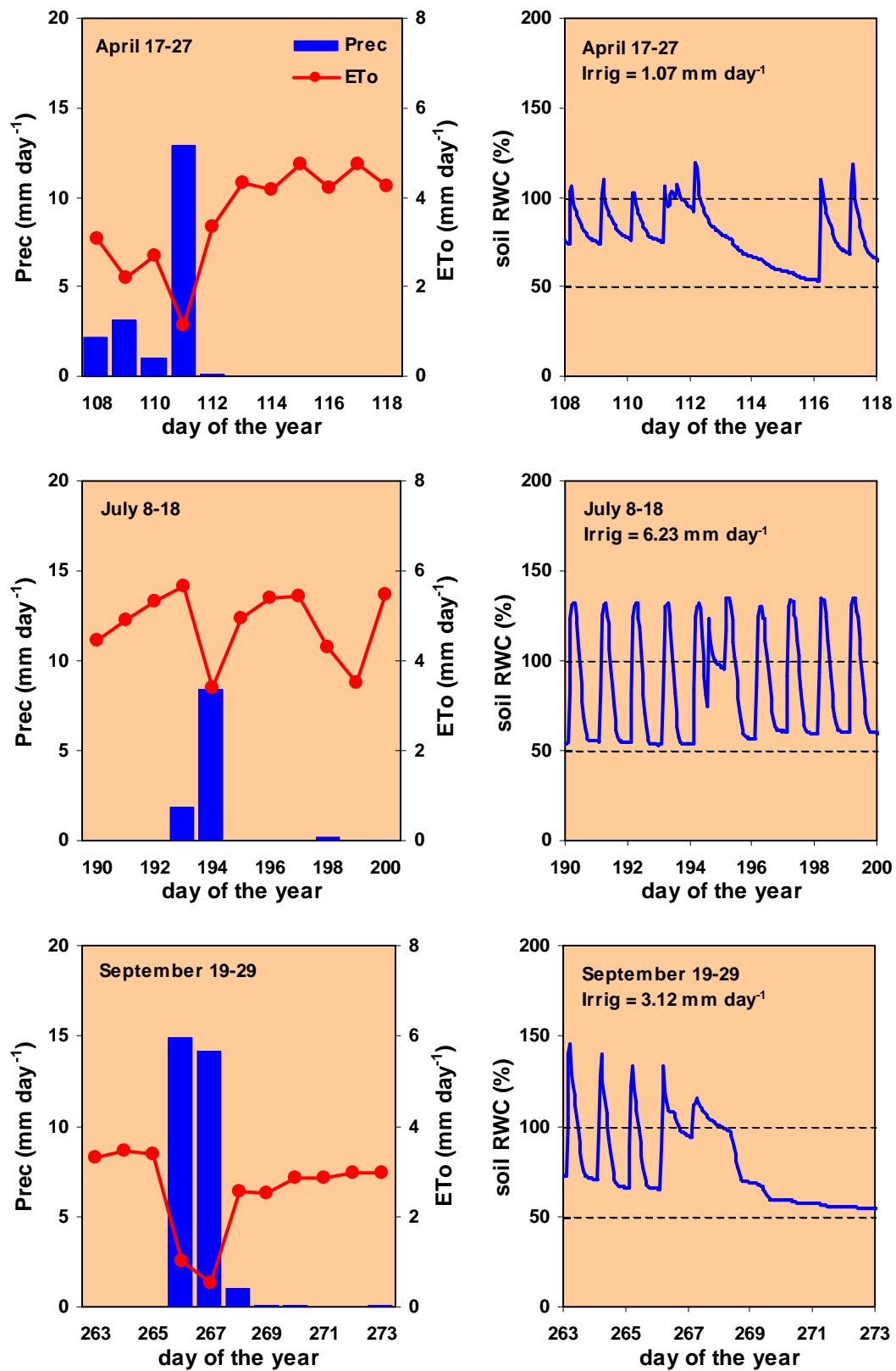
Figure 13. Evolution of weather conditions and soil RWC under full irrigation during three different periods in 2008.

Some similarities between 2007 and 2008 can be observed in soil RWC evolution during stage-II (Figure 14). In spring several rainy days occurred and there were days without irrigation, then soil RWC patterns were irregular. Under FI strategy, soil RWC peaks exceeded the level of 100% on both years. In contrast, under IR2 strategy RWC peaks did not reached the level of 100% in comparison to FI strategy. Upon end of stage-II, complete water supply was restored to IR2 trees and soil RWC tended to increase. But soil RWC under IR2 did not attain FI strategy, except in 2008.
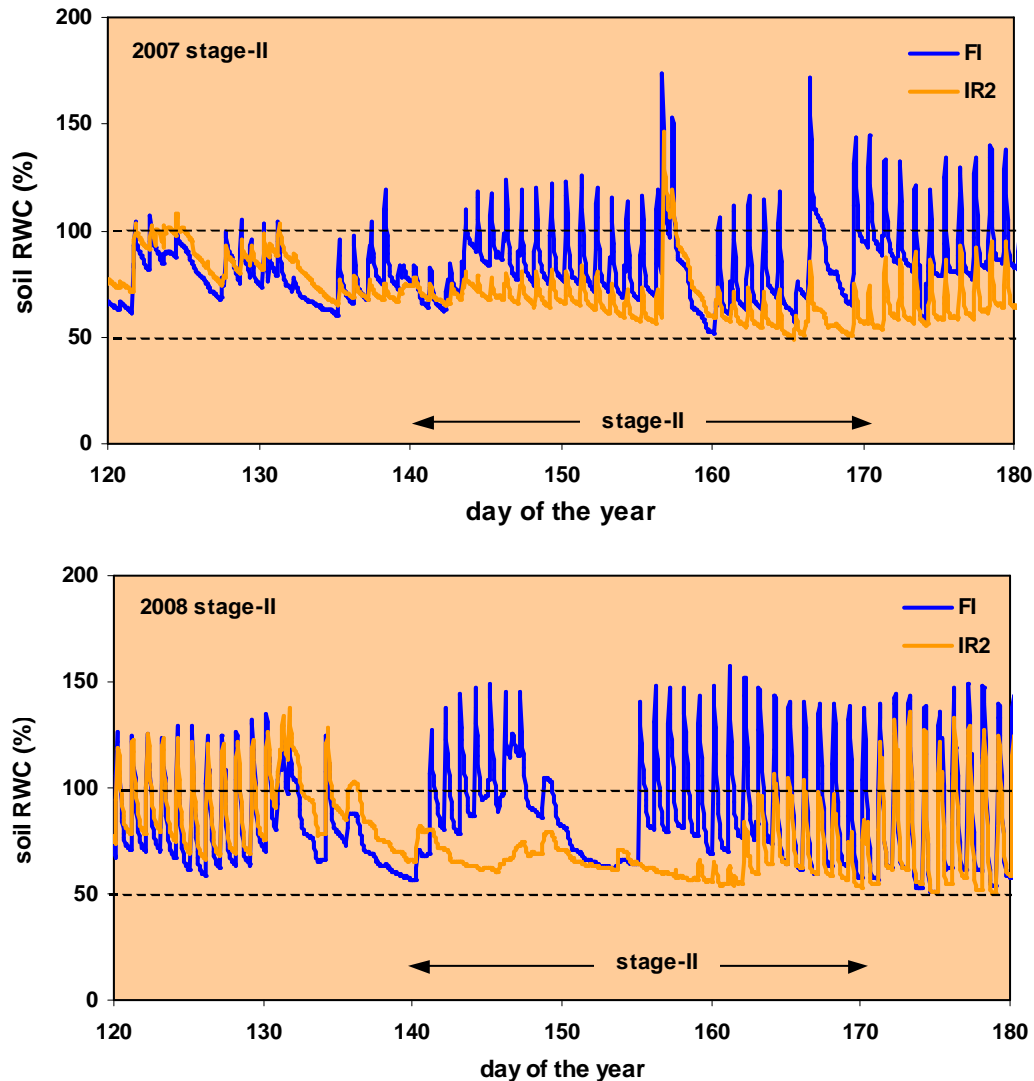
Figure 14. Daily patterns of soil RWC under full irrigation and irrigation restriction during stage-II in 2007 and 2008.

Between different years, important differences occurred in soil RWC evolution during stage-III (Figure 15). The higher K_{ratio} during stage-III in 2008 in comparison to 2006 and 2007 (Table 11) could have favoured higher soil RWC peaks under FI strategy, that exceed the level of 100% in 2008. But in all three years, water uptake reduced soil RWC until low levels. In addition, IR3 trees depleted soil RWC even more during stage-III, specially in 2006 and 2007. In 2008, IR3 strategy only affected slightly the daily pattern of soil RWC, although with lower RWC peaks that dried faster than FI strategy. Irrigation dose was higher in 2008 than in 2007 (Table 11).
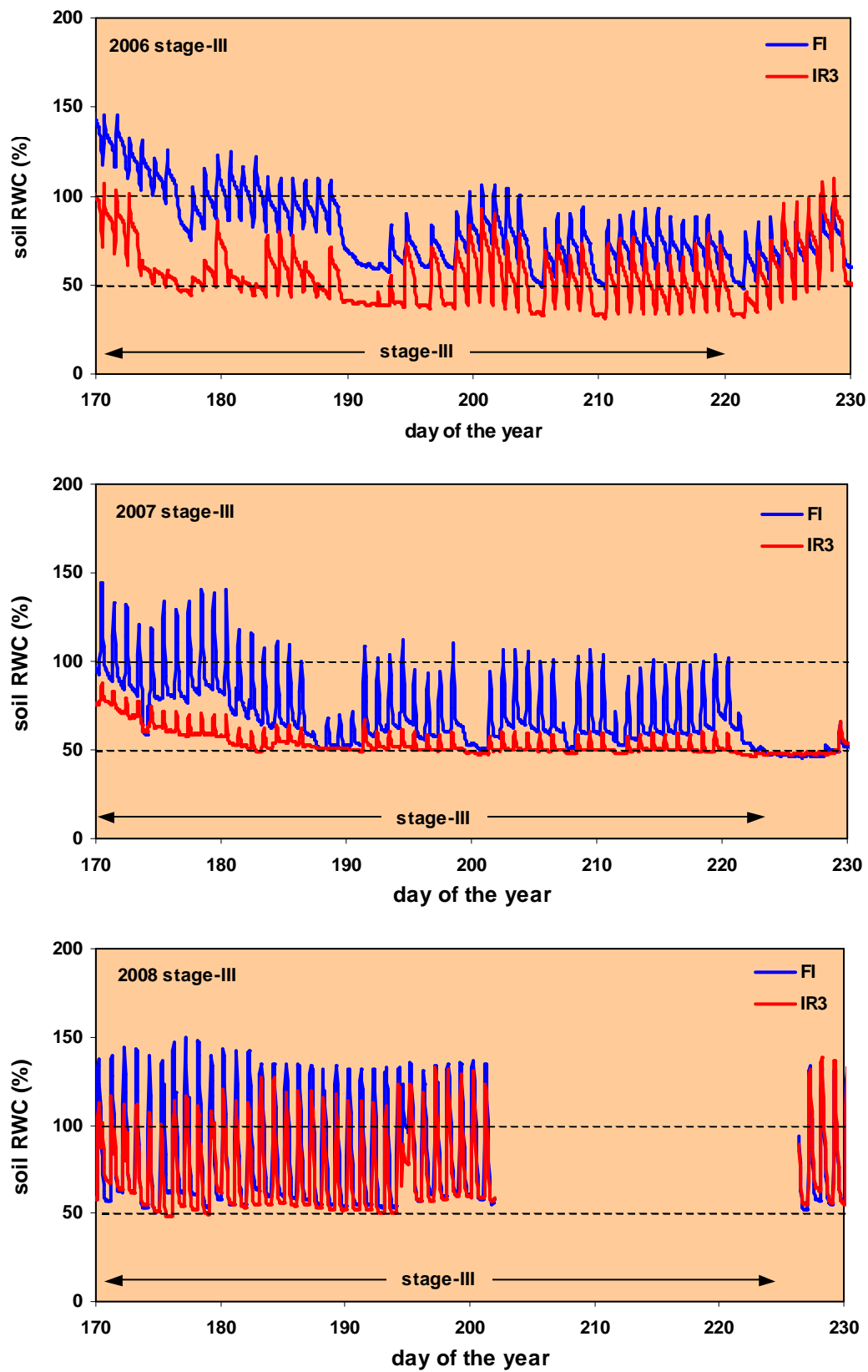
Figure 15. Daily patterns of soil RWC under full irrigation and irrigation restriction during stage-III in 2006, 2007 and 2008.

3.2.3. Seasonal patterns of soil water content

Daily patterns of soil relative water content (RWC) can be averaged for each development stage to show its evolution, from 2006 to 2008 (Figure 16). Soil RWC under FI strategy followed the same pattern along the three years. Thus, average values were always within the range of 50% and 100%, but maintained higher values from stage-I to stage-III, due to drip irrigation, and lower values during post-harvest and rest period. Also, minimum values were similar between different years, however maximum values were lower in 2006 and 2007 than in 2008. In general during rest period there was little variation in soil RWC.

Soil RWC decreased under irrigation restriction during stage-II and stage-III, but some differences occurred when complete water supply was restored (Figure 16). Soil RWC recovery was slower after IR2 than IR3 strategy, except in 2008. Higher water depletion was observed early in stage-III, when shoot growth rate was still high and ETo was maximum, than after harvest, when trees were without fruit load and with lower ETo values. Soil RWC recovery after IR2 in 2008, was partly favoured by higher water supply during stage-III (Table 11).
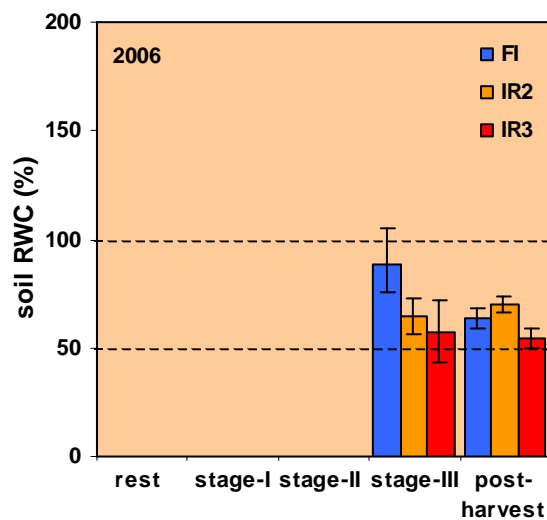
Figure 16. Comparison of average values of soil RWC for each development stage and effect of irrigation restriction (2006-2008). Also shown the average values of daily maximum and minimum soil RWC.
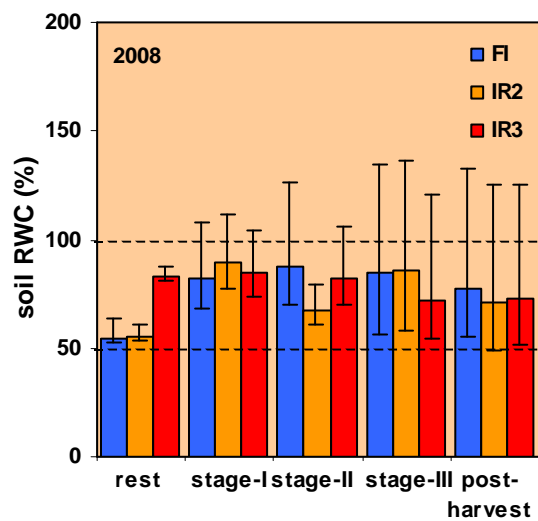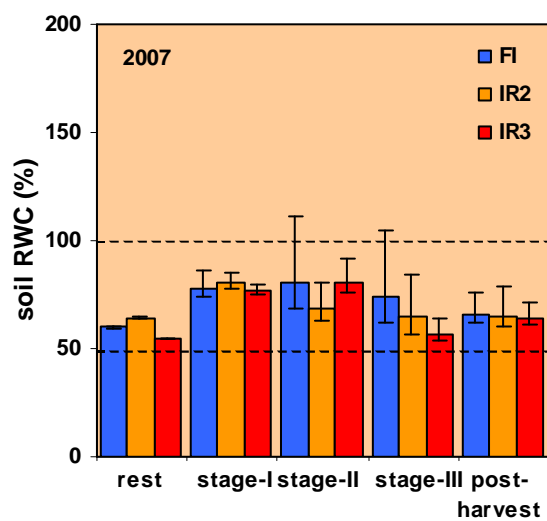
3.2.4. Water deficit and soil water content

Water deficit was determined by a simplified water balance formula, as ETo – (Pefec + Irrig). Mean values of soil relative water content (RWC) were calculated for each day. Also daily ETo and Pefec values were obtained from two nearby weather stations, but irrigation supply was not known for daily time steps. Thus, time series analysis was performed for soil RWC and water deficit with five days moving average. Change in soil RWC was dependent on water deficit in two consecutive days. Table 12 shows the existing correlations between these two variables of water dynamics. In all three years, there was a negative correlation for each development stage. Thus, soil RWC decrease was higher for days with higher water deficit. However, this correlation was not significant for stage-II, which coincided with several rainy days and irrigation was switch-off.

Table 12. Correlation between daily changes of soil RWC and water deficit. Also shown the estimated parameters and 95% confidence intervals of the lineal regression (2006-2008).

| Independent variable	Dependent variable	Year	Stage	Number of days	Parameters		Correlation coefficient	p-value
					Intercept	Slope		
Variation in water deficit (mm day^{-1})	Variation in soil RWC (% day^{-1})	2006	Stage-I	-	-	-	-	-
			Stage-II	-	-	-	-	-
			Stage-III	51	-0.6970±0.4060	-3.6736±1.0999	-0.4695	<0.0001
			Post-harvest	95	-0.0770±0.3300	-2.6517±0.5243	-0.5073	<0.0001
		2007	Stage-I	65	0.2928±0.3809	-0.4217±0.6587	-0.0898	ns
			Stage-II	27	-0.0675±0.5882	-0.8604±0.9432	-0.1965	ns
			Stage-III	54	-0.2888±0.2765	-2.0431±1.2134	-0.2520	0.0011
			Post-harvest	45	0.3522±0.2640	-2.2723±0.6061	-0.5365	<0.0001
		2008	Stage-I	66	0.0529±0.3116	-1.4914±0.5810	-0.3378	<0.0001
			Stage-II	34	0.1158±0.6679	-0.8105±0.8937	-0.1745	ns
			Stage-III	25	0.1581±0.3372	-1.4614±0.6708	-0.4456	<0.0001
			Post-harvest	72	0.1046±0.3345	-2.0612±0.6284	-0.4019	<0.0001

3.2.5. Water dynamics and trunk shrinkage

Trunk shrinkage was dependent on water dynamics between the soil and the atmosphere. A time series analysis was performed for trunk shrinkage, soil relative water content (RWC) and water deficit with three days moving average. For each development stage, change in trunk shrinkage was a negative correlated with changes in soil RWC between two consecutive days (Table 13), but positively correlated with water deficit (Table 14).

Table 13. Correlation between daily changes in soil RWC and trunk shrinkage. Also shown the estimated parameters and 95% confidence intervals of the lineal regression (2006-2008).

Independent variable	Dependent variable	Year	Stage	Number of days	Parameters		Correlation coefficient	p-value
					Intercept ($\times10^{-3}$)	Slope ($\times10^{-3}$)		
Variation in soil RWC (% day^{-1})	Variation in trunk shrinkage (mm day^{-1})	2006	Stage-I	-	-	-	-	-
			Stage-II	-	-	-	-	-
			Stage-III	-	-	-	-	-
			Post-harvest	-	-	-	-	-
		2007	Stage-I	12	6.5756±6.4585	0.1096±1.7012	0.0427	ns
			Stage-II	27	0.1790±3.9762	-1.4506±0.7530	-0.6134	0.0005
			Stage-III	54	-0.8963±2.7689	-1.7809±0.7502	-0.5474	<0.0001
			Post-harvest	33	5.2769±3.9781	-2.4636±1.5757	-0.4906	0.0032
		2008	Stage-I	59	2.2108±5.0498	-1.7112±1.2716	-0.3334	0.0092
			Stage-II	34	-0.9492±6.9190	-0.8847±1.1247	-0.2684	ns
			Stage-III	26	-0.8032±3.9403	-1.2098±1.7255	-0.2775	ns
			Post-harvest	47	0.8547±3.6073	-2.0554±0.7558	-0.6281	<0.0001

However, important differences occurred in the statistical significance of these correlations between 2007 and 2008, that were related to water dynamics. Soil water conditions in 2008 were better than in 2007 (Figure 16), and trunk shrinkage was better correlated with soil RWC changes during 2007 (Table 13). In contrast, trunk shrinkage was better correlated with water deficit during 2008 (Table 14). Thus tree water status was linked to the environmental factor more limiting, which can be the soil or the atmosphere.

Table 14. Correlation between daily changes in water deficit and trunk shrinkage. Also shown the estimated parameters and 95% confidence intervals of the lineal regression (2006-2008).

Independent variable	Dependent variable	Year	Stage	Number of days	Parameters		Correlation coefficient	p-value
					Intercept ($\times 10^{-3}$)	Slope ($\times 10^{-3}$)		
		2006	Stage-I	-	-	-	-	-
			Stage-II	-	-	-	-	-
			Stage-III	-	-	-	-	-
			Post-harvest	-	-	-	-	-
Variation in water deficit (mm day^{-1})	Variation in trunk shrinkage (mm day^{-1})	2007	Stage-I	12	8.5127 ± 5.7367	7.2195 ± 7.2625	0.5507	ns
			Stage-II	27	-0.1171 ± 4.7810	3.1903 ± 3.9137	0.3122	ns
			Stage-III	54	-0.0961 ± 3.1495	10.843 ± 10.116	0.2832	0.0361
			Post-harvest	33	3.2778 ± 3.1661	4.8355 ± 6.2787	0.2166	ns
		2008	Stage-I	59	2.0095 ± 4.8761	8.6054 ± 4.9594	0.4149	0.0010
			Stage-II	34	-1.2744 ± 6.4152	6.5016 ± 4.6366	0.4448	0.0074
			Stage-III	26	-1.6438 ± 4.0034	7.3487 ± 6.2228	0.3443	0.0225
			Post-harvest	47	-0.1890 ± 2.9636	9.7543 ± 3.2475	0.6251	<0.0001

3.2.6. Seasonal pattern of midday Ψ_{stem} and g_s under full irrigation

Figure 17 shows the values of solar radiation and VPD attained at solar noon while taking measures of midday Ψ_{stem} and g_s under FI strategy, from 2006 to 2008. In all three years, solar radiation tended to increase until the end of June, when maximum values were obtained and then decreased progressively. In contrast, VPD was maximum one month later, at the end of July. However, VPD were higher in 2006 than during following years, except two days in summer 2008, which attained the highest values of the period. Under FI strategy, midday Ψ_{stem} followed the same seasonal pattern and attained similar values among the three years (Figure 17C), irrespective of weather conditions. Mean values of midday Ψ_{stem} decreased along the fruit growth period, from stage-I (−0.34 MPa) to stage-II (−0.51 MPa) and attained the lowest value in stage-III (−0.82 MPa), which coincided to expansive fruit growth. After harvest, trees were without fruit load and there was an increase of midday Ψ_{stem} to less negative values (−0.68 MPa). High VPD on 2006 did not affected midday Ψ_{stem}. In contrast, midday g_s (Figure 17D) increased from stage-I (251 mmol m^{-2} s^{-1}) to stage-II (275 mmol m^{-2} s^{-1}), maximum values were attained in stage-III (349 mmol m^{-2} s^{-1}) and decreased at post-harvest (245 mmol m^{-2} s^{-1}). However in 2006, under high VPD, midday g_s in stage-III remained low (232 mmol m^{-2} s^{-1}).

3.2.7. Comparison of midday Ψ_{stem} and g_s under irrigation restriction

Figure 18 shows the effect of irrigation restriction on seasonal values of Ψ_{stem} and g_s according to experimental year. Irrigation restriction produced important effects on midday Ψ_{stem} especially in 2006. There were not significant differences of irrigation restriction on midday g_s, although midday g_s under IR3 was lower than FI strategy during stage-III. Unlike irrigation, there were no significant differences of N application on midday Ψ_{stem} and g_s.
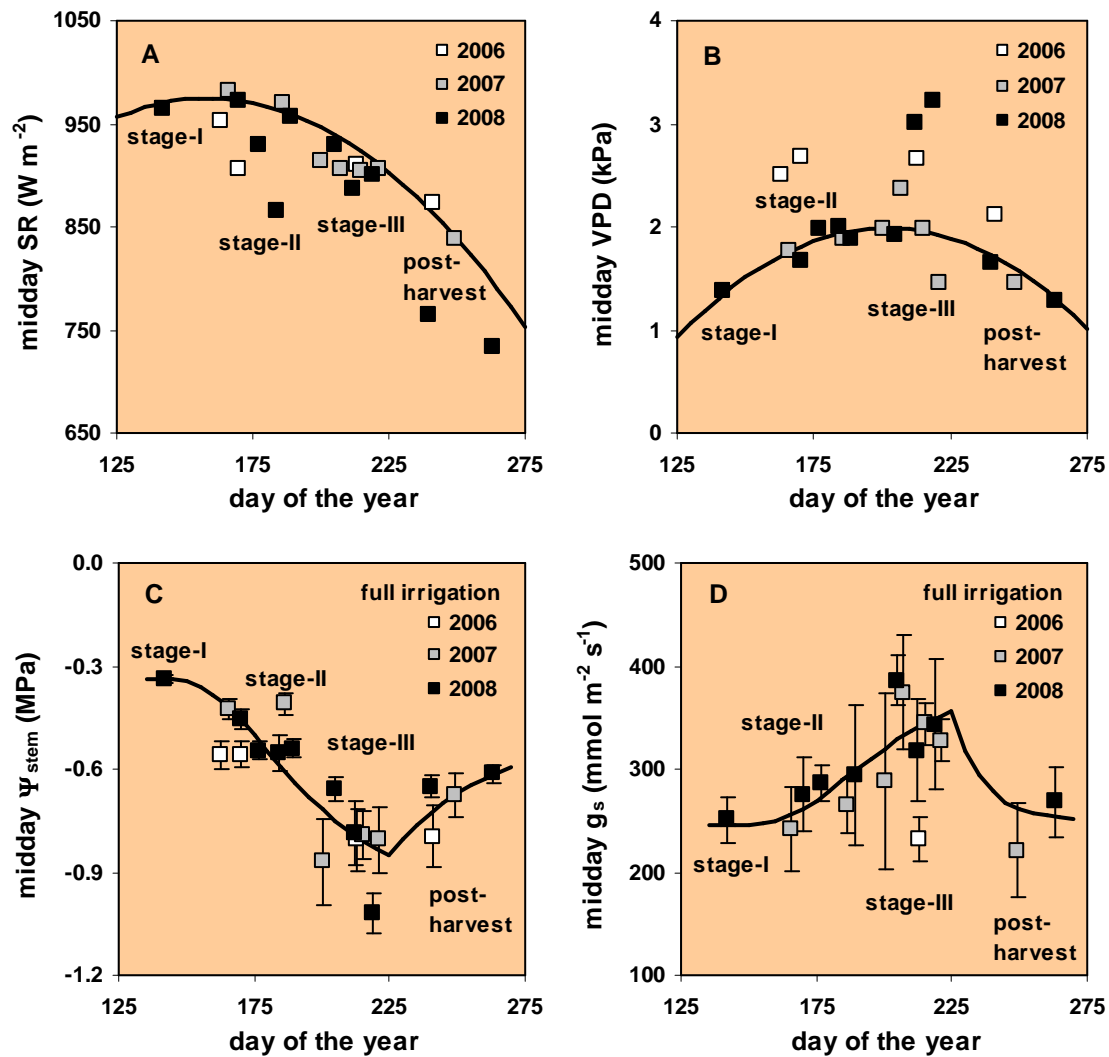
Figure 17. Solar radiation (A) and VPD (B) attained at solar noon while taking measures of midday Ψ_{stem} (C) and g_s (D) under full irrigation of peach cv. Andross according to the experimental year (2006-2008). Error bars are 95% confidence intervals.

In 2006, IR2 decreased midday Ψ_{stem} at the end of stage-II up to –1.16 MPa, while FI strategy maintained –0.56 MPa (Figure 18). In trees under IR3, midday Ψ_{stem} was –0.55 MPa not different from FI, since the two strategies received the same complete water supply. But IR3 decreased midday Ψ_{stem} at the end of stage-III up to –1.57 MPa, while FI strategy maintained –0.81 MPa. Trees under IR2 attained –0.95 MPa during stage-III not different from FI strategy, due to complete water supply. Also at post-harvest trees under IR3 recovered complete water supply and midday Ψ_{stem} increased to –0.80 MPa not different from FI strategy.

The effect of irrigation restriction on midday Ψ_{stem} was significant in 2007 and 2008, although to a lesser extend than 2006 (Figure 18). Thus, under IR2, midday Ψ_{stem} at the end of stage-II was less negative in 2007 and 2008 (–0.52 and –0.57 MPa, respectively), than in 2006 (–1.16 MPa). Also, at end of stage-III midday Ψ_{stem} values under IR3, were higher in 2006 than in 2007 and 2008 (from –1.57 to –1.19 and –0.93 MPa, respectively).
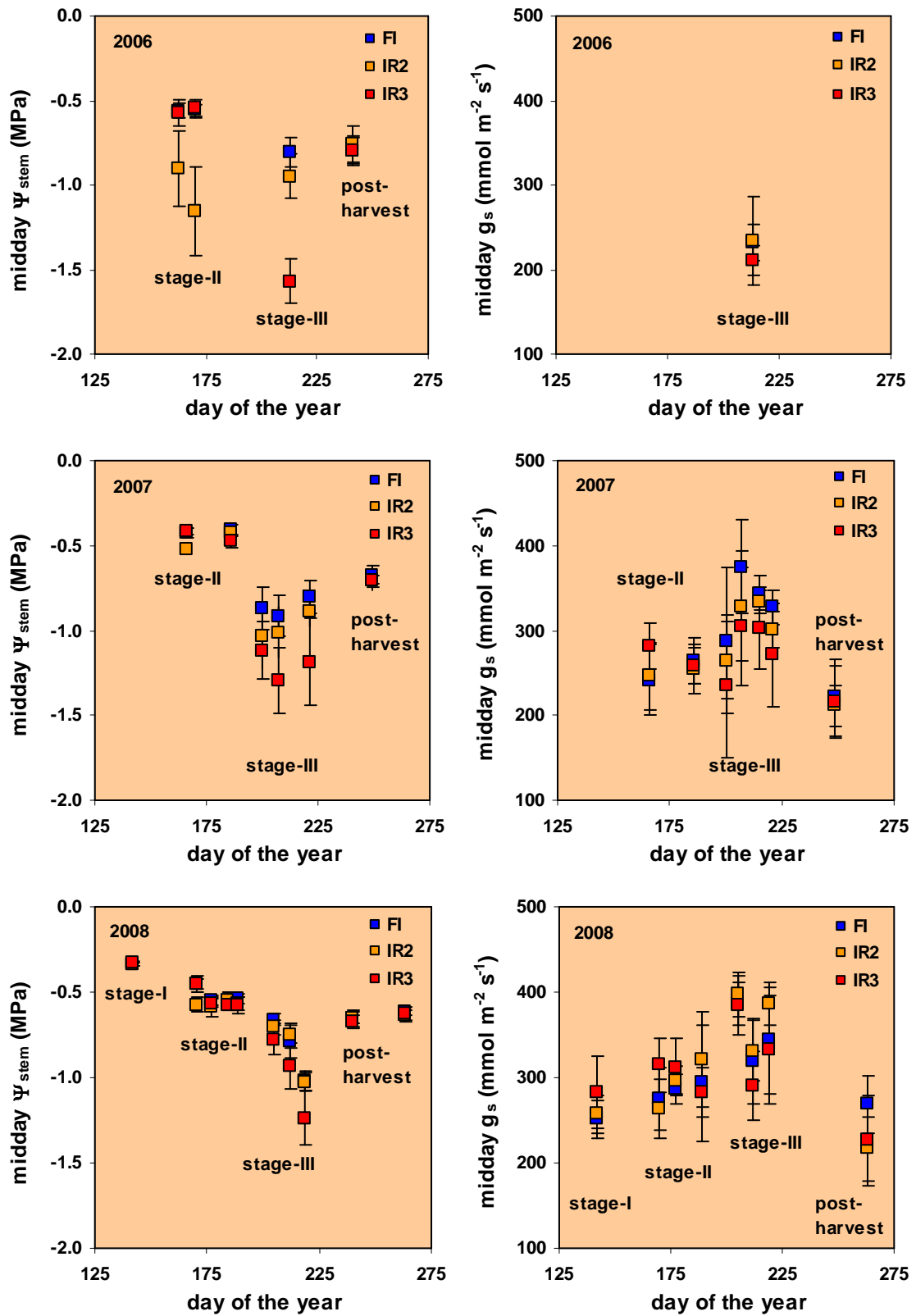
Figure 18. Effect of irrigation restriction on seasonal values of midday Ψ_{stem} and g_s of peach cv. Andross, from 2006 to 2008. Error bars are 95% confidence intervals.

3.2.8. Soil water content and tree water status in stage-III

Figure 19A shows the Cate-Nelson scatter diagram (Cate and Anderson, 1977) between the average values obtained during stage-III of midday Ψ_{stem} versus daily mean soil relative water content (RWC). The overlay was moved to the point where data in the +/+ quadrants were at a maximum, and a critical midday Ψ_{stem} of –0.9 MPa was attained by a soil RWC of 72%, which corresponds to 0.167 m^3 m^{-3}. The 100% upper level was 0.220 m^3 m^{-3}, while the 50% lower level was 0.125 m^3 m^{-3}.

Figure 19B shows the lineal correlation between the average values of midday g_s and Ψ_{stem} in peach leaves obtained in stage-III. Trees maintained lower values of midday g_s in 2006 than both in 2007 and 2008. In 2006 it was found that a decrease in midday Ψ_{stem} caused a little change in g_s. However, in 2007 and 2008, midday g_s decreased largely as Ψ_{stem} became more negative.
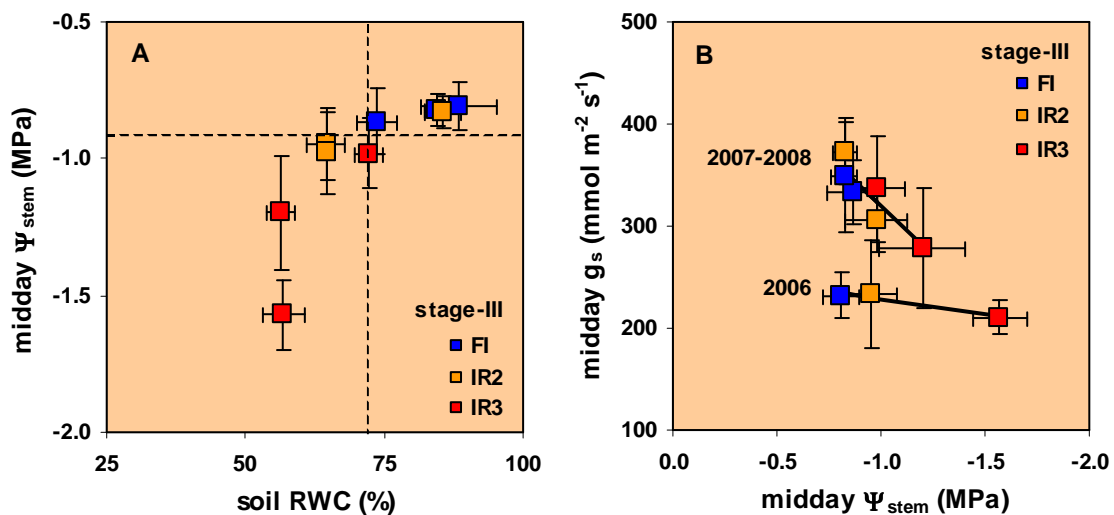
Figure 19. Scatter diagram between mean values obtained during stage-III of midday Ψ_{stem} versus daily mean soil RWC (A). Lineal correlation between midday g_s and midday Ψ_{stem} in peach leaves for 2006 with y = 259 + 30.5x (r = 0.972) and for 2007-2008 with y = 513 + 193.9x (r = 0.971). Error bars are 95% confidence intervals.

3.2.9. Diurnal trend of tree water status

Figure 20A shows the diurnal pattern of solar radiation and VPD for July 5 2007, which corresponds to beginning of stage-III (1169 degree days). Solar radiation followed a symmetrical pattern, since increased from sunrise (04:20 h) to midday, when reached its maximum value of 972 W m^{-2} (solar noon), and decreased again towards sunset (19:30 h). Also, VPD increased at the beginning of the day, but reached its maximum value of 3.08 kPa during the afternoon (17:00−18:00 h).

Soil relative water content (RWC) increased at 09:00 h due to an irrigation event, attaining its maximum value at solar noon (Figure 20B), which coincided with maximum solar radiation. Then soil RWC decreased progressively. In FI trees, the RWC peak attained the 100% level, but did not surpass this level. Irrigation supply under IR2 was the same as FI. Soil RWC under IR3 maintained lower values all the day and showed a little RWC peak than FI strategy.

A diurnal trend of Ψ_{stem} was obtained from predawn to midday (Figure 20C). Under FI strategy, Ψ_{stem} decreased from predawn (−0.22 MPa) to midday (−0.41 MPa). Ψ_{stem} in IR2 was not different from FI, but Ψ_{stem} in IR3 was slightly more negative all the time than FI, including at predawn. On the other hand, g_s under FI strategy decreased around midday (from 346 to 264 mmol m^{-2} s^{-1}), without significant differences between irrigation strategies (Figure 20D).

Figure 20. Diurnal pattern of solar radiation and VPD (A) and effect of irrigation restriction on soil RWC (B), Ψ_{stem} (C) and g_s (D) of peach cv. Andross on July 5 2007. For each point, different letters indicate significant differences by LSD multiple range test ($\alpha = 0.05$).

Also, a diurnal trend of Ψ_{stem} and g_s was obtained on July 23 2008 (Figure 21), under maximum solar radiation of 929 W m^{-2} (solar noon) and maximum VPD of 3.42 kPa (16:00 h). Sunrise was on 4:40 h and sunset on 19:15 h. These weather conditions were very similar to that attained on July 5, 2007, although on different fruit growth development stages, since it now coincided with higher fruit growth rate of end stage-III (1431 degree days).

At 03:00 h irrigation was switched-on and soil RWC increased suddenly during night hours. The soil RWC peak surpassed the 100% level and attained its maximum value at 06:00 h (Figure 21B), which coincided in early morning. Then soil RWC decreased progressively during daylight hours. Soil RWC pattern was not different between FI and IR2, with the same irrigation supply. Although soil RWC under IR3 overpass the 100% level, values were lower and decreased faster than FI strategy. In all treatments soil RWC was always above the 50% level.

Under FI strategy, Ψ_{stem} decreased from predawn (-0.31 MPa) to midday (-0.66 MPa), and there was not a recovery at 15:00 h (-0.69 MPa). IR3 caused a reduction in the trend of Ψ_{stem}, significant in midday, but not at predawn (Figure 21C). On the other hand, g_s in FI was 449 mmol m^{-2} s^{-1} before midday and decreased to 341 mmol m^{-2} s^{-1} after midday, without significant differences between irrigation strategies (Figure 21D).
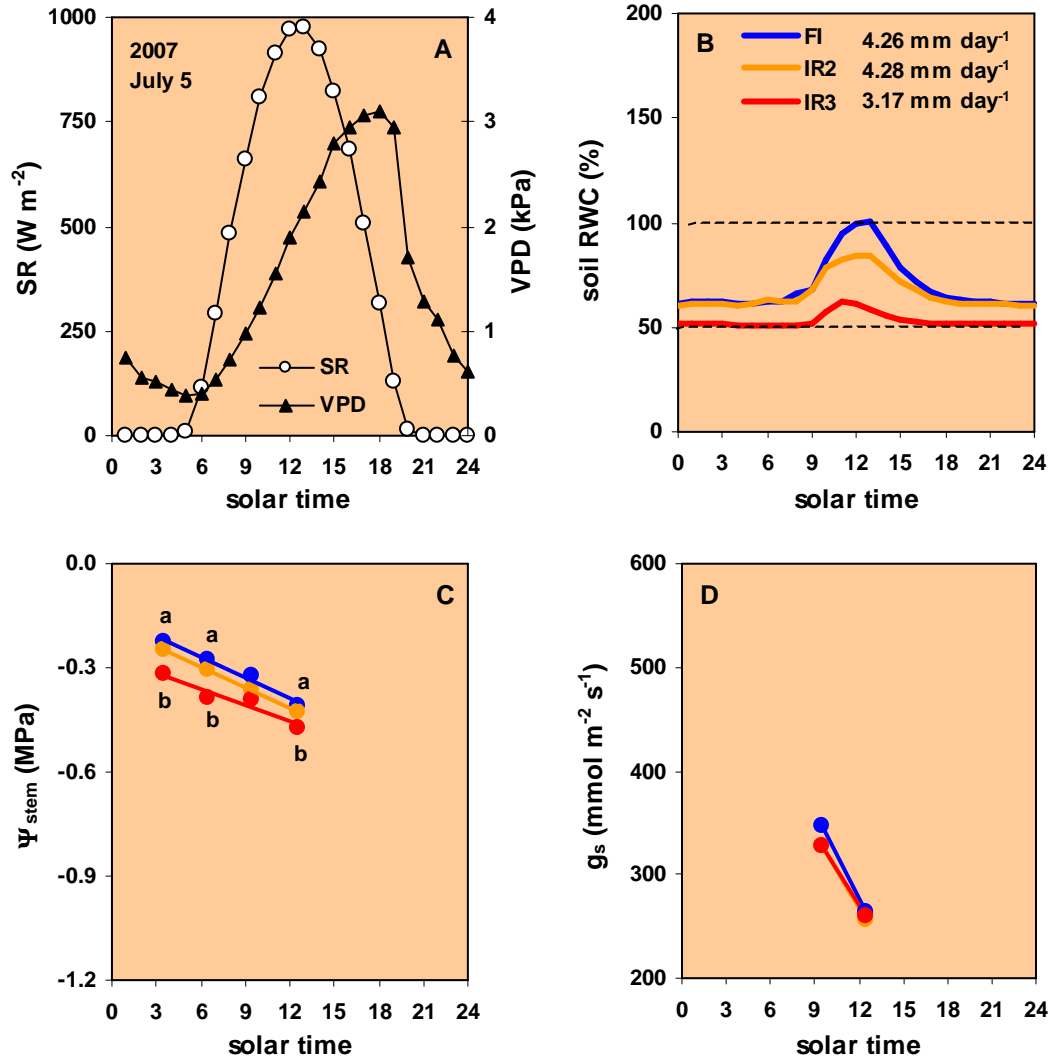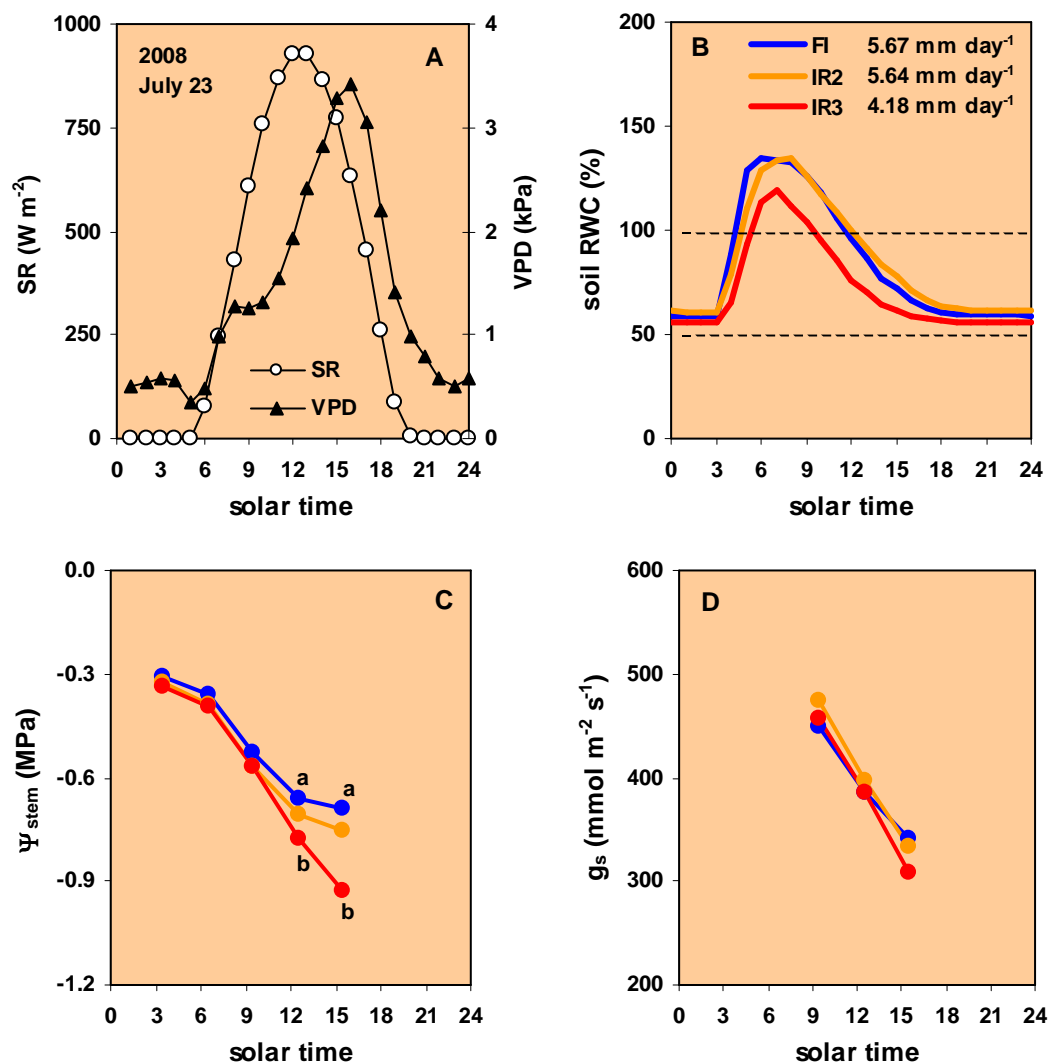

Figure 21. Diurnal pattern of solar radiation and VPD (A) and effect of irrigation restriction on soil RWC (B), Ψ_{stem} (C) and g_s (D) of peach cv. Andross on July 23 2008. For each point, different letters indicate significant differences by LSD multiple range test ($\alpha = 0.05$).

3.3. Mineral nutrition

3.3.1. Specific leaf weight

The specific leaf weight (SLW) values did not changed between the end of stage-II and the end of stage-III, but increased at post-harvest (Table 15). In 2006, irrigation restriction and N application did not affect the SLW as evidenced by the non-significant p-values. In 2007 and 2008, IR2 increased the SLW at the end of stage-II, and this effect was significant until post-harvest. In 2007, N application did not produce significant effects on SLW values, however in 2008, the SLW decreased linearly with N dose, and especially at post-harvest. In leaf samples collected at end stage-III, higher SLW values were found in 2006 than in 2007 and 2008.

3.3.2. Leaf relative light absorbance

Leaf relative light absorbance (α_r) increased from stage-I to stage-III, and attained maximum values after fruit harvest, then decreased until leaf fall (Figure 22). There were no significant differences in leaf α_r values by irrigation restriction (Table 15). However, leaf α_r values increased linearly with N application. This effect was significant at any stage, from 2006 to 2008. In leaf samples measured at end stage-III, leaf α_r values decreased from 2006 to 2008.
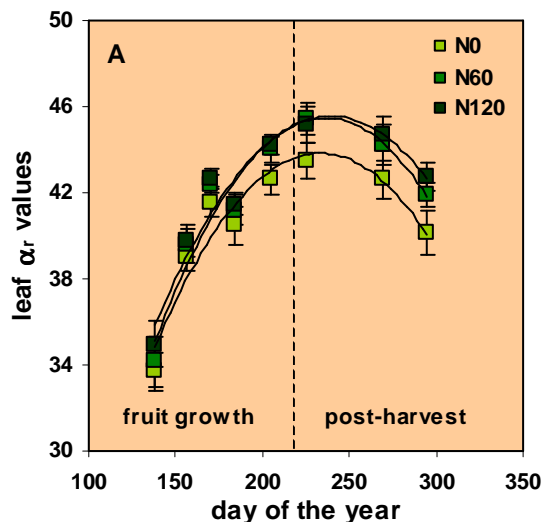
Figure 22. Seasonal pattern of leaf α_r values during 2007 according to N application. Error bars are 95% confidence intervals of the mean.

3.3.3. Nitrogen

Leaf N concentration decreased specially between the end of stage-II and the end of stage-III, and to a lesser extend until post-harvest (Table 16). The leaf N concentration was not significantly affected by irrigation restriction. The leaf N concentration increased linearly with N application, however this effect was only significant in 2007 at the end of stage-II and at post-harvest, and in 2008 at the end of stage-III. In leaf samples collected at the end of stage-III, the leaf N concentration decreased from 2006 to 2007, and maintained these values in 2008, except in trees without N application, which decreased also in 2008.

Table 15. Effect of irrigation and N application on specific leaf weight and leaf α_r values of peach cv. Andross (2006-2008).

Year	Effect	Specific leaf weight (g DM m^{-2})			Leaf α_r values		
		end stage-II	end stage-III	post-harvest	end stage-II	end stage-III	post-harvest
2006	**CV**		6.40%			2.12%	
	Block		0.0105			0.0187	
	Irrigation		ns			ns	
	FI	-	77.7±2.8	-	-	45.52±0.63	-
	IR2	-	81.7±4.1	-	-	44.88±0.88	-
	IR3	-	78.7±4.3	-	-	44.86±0.85	-
	Nitrogen		ns			0.0007	
	N0	-	78.6±3.2	-	-	44.14±0.79	-
	N60	-	78.9±4.0	-	-	45.27±0.65	-
	N120	-	80.7±4.4	-	-	45.85±0.55	-
	L		ns			0.0002	
	Q		ns			ns	
	Irrig × Nit		ns			ns	
2007	**CV**	7.20%	2.73%	3.40%	1.46%	1.52%	2.13%
	Block	0.0012	0.0001	ns	0.0076	0.0055	0.0431
	Irrigation	0.0042	0.0001	0.0025	0.0470	ns	ns
	FI	59.9±2.5 b	61.6±1.5 b	80.9±1.5 b	41.95±0.69 b	43.22±0.95 b	41.21±1.50
	IR2	65.1±5.1 a	64.9±1.9 a	85.1±1.9 a	42.58±0.46 a	43.74±0.59 ba	41.77±0.58
	IR3	58.8±2.1 b	61.7±1.7 b	81.7±2.3 b	42.11±0.53 ba	43.90±0.65 a	41.82±0.79
	Nitrogen	ns	ns	ns	0.0004	<0.0001	<0.0001
	N0	61.8±3.1	63.7±2.4	82.8±1.8	41.55±0.66	42.61±0.71	40.13±1.00
	N60	60.1±2.7	62.6±1.3	81.3±2.4	42.41±0.41	44.03±0.61	41.93±0.55
	N120	61.8±5.4	61.9±1.9	83.6±2.3	42.68±0.39	44.22±0.48	42.74±0.65
	L	ns	ns	ns	0.0001	<0.0001	<0.0001
	Q	ns	ns	ns	ns	0.0158	ns
	Irrig × Nit	ns	0.0067	ns	ns	0.0031	0.0020
2008	**CV**	4.75%	4.26%	3.42%	2.87%	2.40%	
	Block	ns	0.0130	0.0003	ns	ns	
	Irrigation	0.0270	0.0199	0.0017	ns	ns	
	FI	62.9±2.4 b	62.2±1.7 b	81.5±2.7 b	39.34±1.35	41.53±1.10	-
	IR2	65.7±1.4 a	65.6±1.5 a	86.2±2.1 a	39.21±1.01	41.25±1.14	-
	IR3	62.4±2.5 b	63.7±2.9 ba	83.1±3.1 b	39.03±1.11	41.33±1.26	-
	Nitrogen	ns	ns	0.0180	<0.0001	<0.0001	
	N0	65.3±2.0	65.0±1.7	85.7±2.3	37.40±0.66	39.46±0.70	-
	N60	63.5±1.7	63.6±2.6	82.9±3.0	39.41±0.72	41.65±0.52	-
	N120	62.2±2.8	62.9±2.4	82.3±3.1	40.77±0.79	42.99±0.75	-
	L	ns	ns	0.0082	<0.0001	<0.0001	
	Q	ns	ns	ns	ns	ns	
	Irrig × Nit	ns	ns	ns	ns	ns	

Within each year and column, the CV is the coefficient of variation according to ANOVA results (α = 0.05). Irrigation treatments followed by different letters indicate significant differences by LSD multiple range test. Lineal (L) and quadratic (Q) contrast indicate significant trends by N application. Errors are 95% confidence interval of the mean.

Fruit N concentration decreased from end stage-II to harvest (Table 16). Irrigation restriction had no effect on fruit N concentration, but was higher by N application. This N effect was significant only in 2008 at the end of stage-II and at harvest, when a significant increasing trend was obtained. In fruit samples collected at harvest, fruit N concentration maintained similar values among different experimental years.

Irrigation restriction had no effect on N concentration of dormant shoots, but was higher by N application (Table 16). This N effect was significant in 2007.

Leaf samples collected at the end of stage-III in three experimental years, showed a positive correlation between the N concentration and α_r values (Figure 23). Thus, N concentration was higher for leaves with higher α_r values.
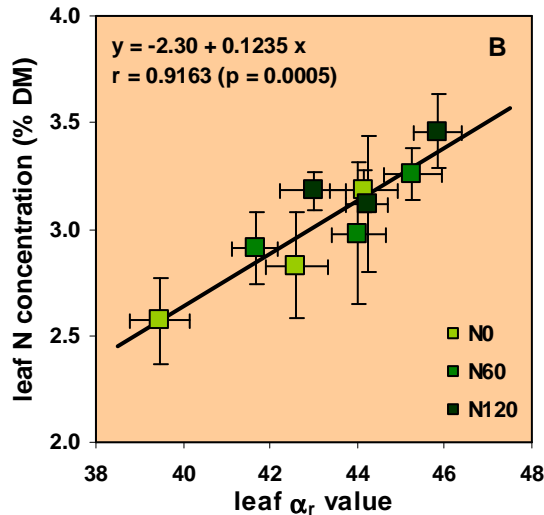
Figure 23. Correlation between leaf N concentration and leaf α_r values at the end of stage-III at contrasting N doses during three experimental years (2006-2008). Error bars are 95% confidence intervals of the mean.

Table 16. Effect of irrigation and N application on N concentration in leaves, fruits and shoots of peach cv. Andross (2006-2008).

Year Effect	Leaf N concentration (% DM)			Fruit N concentration (mg g^{-1} DM)		Shoot N concen. (% DM)
	end stage-II	end stage-III	post-harvest	end stage-II	harvest	winter pruning
2006 CV		6.49%			21.87%	8.18%
Block		ns			ns	ns
Irrigation		ns			ns	ns
FI	-	3.32±0.15	-	-	7.13±1.09	1.17±0.06
IR2	-	3.28±0.13	-	-	6.52±1.03	1.15±0.08
IR3	-	3.30±0.18	-	-	6.64±0.90	1.17±0.05
Nitrogen		ns			ns	ns
N0	-	3.18±0.10	-	-	5.74±0.57	1.14±0.06
N60	-	3.26±0.12	-	-	7.27±1.01	1.18±0.07
N120	-	3.46±0.17	-	-	7.28±1.06	1.17±0.05
L		ns			ns	ns
Q		ns			ns	ns
Irrig × Nit		ns			ns	ns
2007 CV	5.74%	15.49%	4.54%	15.45%	20.01%	10.57%
Block	ns	ns	ns	ns	ns	ns
Irrigation	0.0017	ns	ns	ns	ns	ns
FI	3.86±0.20 a	3.07±0.31	2.42±0.10	16.90±1.07	7.85±0.95	1.49±0.09
IR2	3.61±0.18 b	2.93±0.30	2.39±0.06	16.45±1.48	8.39±1.42	1.37±0.11
IR3	3.97±0.12 a	2.92±0.32	2.43±0.14	17.56±2.10	7.66±1.02	1.42±0.13
Nitrogen	0.0017	ns	<0.0001	ns	ns	0.0050
N0	3.61±0.15	2.83±0.25	2.25±0.10	16.29±1.66	6.93±1.15	1.31±0.12
N60	3.86±0.21	2.98±0.33	2.49±0.05	17.63±1.97	8.56±1.01	1.43±0.11
N120	3.97±0.15	3.12±0.32	2.51±0.05	16.98±0.98	8.41±1.02	1.54±0.05
L	0.0005	ns	<0.0001	ns	ns	0.0013
Q	ns	ns	0.0060	ns	ns	ns
Irrig x Nit	ns	ns	ns	ns	ns	ns
2008 CV	12.93%	8.07%	6.79%	14.48%	13.60%	
Block	ns	ns	ns	ns	ns	
Irrigation	ns	ns	ns	ns	ns	
FI	3.29±0.20	2.82±0.30	2.85±0.15	12.66±1.69	6.12±0.77	-
IR2	3.00±0.30	2.94±0.12	2.79±0.09	11.68±1.70	5.98±0.68	-
IR3	3.07±0.31	2.89±0.22	2.81±0.16	12.13±1.08	6.34±0.72	-
Nitrogen	ns	<0.0001	ns	<0.0001	0.0003	
N0	2.84±0.24	2.57±0.20	2.68±0.10	10.21±0.99	5.28±0.50	-
N60	3.13±0.28	2.91±0.17	2.83±0.16	12.04±1.16	6.26±0.54	-
N120	3.39±0.21	3.18±0.09	2.94±0.10	14.21±1.13	6.90±0.68	-
L	ns	<0.0001	ns	<0.0001	0.0001	
Q	ns	ns	ns	ns	ns	
Irrig x Nit	ns	ns	ns	ns	ns	

Within each year and column, the CV is the coefficient of variation according to ANOVA results ($\alpha = 0.05$). Irrigation treatments followed by different letters indicate significant differences by LSD multiple range test. Lineal (L) and quadratic (Q) contrast indicate significant trends by N application. Errors are 95% confidence interval of the mean.

Total fruit N exportation was calculated at harvest from total yield, percentage of dry matter and N concentration. Higher N was exported by N application, and this effect was significant in 2007 and 2008. However, fruit N exportation under N60 was not significantly different from the N120 (Figure 24A).

Soil samples were collected at the beginning of the experiment and also each year after the growing season for soil NO_3-N determination (Figure 24B). The initial soil NO_3-N level was not different across the different treatments. After one year, N application did not affect the soil NO_3-N level. But after two years, N application showed significant differences. The soil NO_3-N level was maintained under N120 application, while decreased under N60 and specially N0. However, after three years, under N120 dose the soil NO_3-N level had also decreased as well as under N0 and N60 doses.
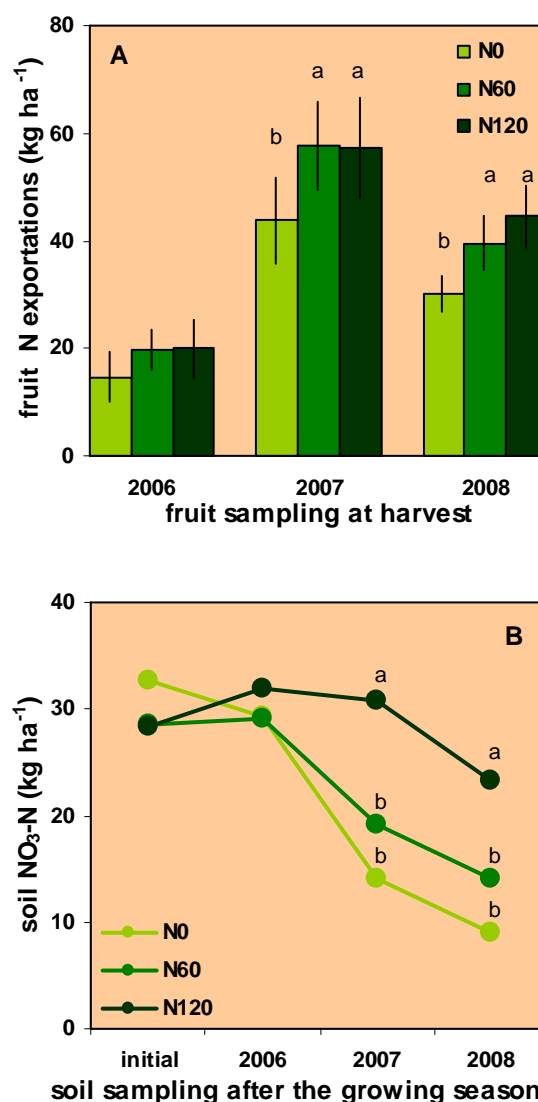
Figure 24. Effect of N application on fruit N exportations at harvest (A) and soil NO_3-N level after the growing season, with data collected in February of each year. For each point, different letters indicate significant differences by LSD multiple range test ($\alpha = 0.05$). Error bars are 95% confidence intervals.

3.3.4. Phosphorous

Leaf P concentration decreased specially between the end of stage-II and the end of stage-III, and to a lesser extend until post-harvest. Fruit P concentration decreased from the end of stage-II to harvest. There were no significant differences of P concentration in leaves, fruits or dormant shoots when treated with different irrigation strategies and N doses, except in 2008 at the end of stage-III, when N application tended to decrease leaf N concentration (Table 17).

Table 17. Effect of irrigation and N application on P concentration in leaves, fruits and shoots of peach cv. Andross (2006-2008).

Year	Effect	Leaf P concentration (% DM)			Fruit P concentration (mg g^{-1} DM)		Shoot P concen. (% DM)
		end stage-II	end stage-III	post-harvest	end stage-II	harvest	winter pruning
2006	**CV**		8.96%			18.88%	7.51%
	Block		0.0010			ns	ns
	Irrigation		ns			ns	ns
	FI	-	0.141±0.009	-	-	0.95±0.11	0.097±0.004
	IR2	-	0.135±0.008	-	-	0.93±0.14	0.098±0.005
	IR3	-	0.134±0.011	-	-	0.90±0.13	0.098±0.005
	Nitrogen		ns			ns	ns
	N0	-	0.138±0.008	-	-	0.93±0.11	0.102±0.004
	N60	-	0.138±0.010	-	-	0.94±0.14	0.094±0.003
	N120	-	0.134±0.011	-	-	0.91±0.12	0.098±0.006
	L		ns			ns	ns
	Q		ns			ns	ns
	Irrig x Nit		ns			ns	ns
2007	**CV**	5.81%	4.69%	12.88%	11.17%	18.14%	9.79%
	Block	ns	0.0099	ns	ns	ns	ns
	Irrigation	ns	ns	ns	ns	ns	ns
	FI	0.278±0.011	0.188±0.015	0.150±0.016	1.89±0.05	1.13±0.10	0.149±0.012
	IR2	0.263±0.008	0.183±0.020	0.148±0.007	1.90±0.13	1.14±0.14	0.148±0.009
	IR3	0.278±0.012	0.185±0.009	0.140±0.012	1.93±0.16	1.00±0.14	0.142±0.008
	Nitrogen	ns	ns	ns	ns	ns	ns
	N0	0.272±0.011	0.178±0.015	0.153±0.015	1.92±0.13	1.09±0.14	0.146±0.010
	N60	0.276±0.010	0.180±0.013	0.142±0.011	1.95±0.14	1.13±0.10	0.151±0.011
	N120	0.272±0.012	0.190±0.013	0.143±0.007	1.85±0.09	1.06±0.15	0.143±0.009
	L	ns	ns	ns	ns	ns	ns
	Q	ns	ns	ns	ns	ns	ns
	Irrig x Nit	ns	ns	ns	ns	ns	ns
2008	**CV**	6.51%	4.31%	6.13%	7.18%	10.76%	
	Block	ns	ns	0.0158	ns	ns	
	Irrigation	ns	ns	ns	ns	ns	
	FI	0.240±0.011	0.211±0.006	0.146±0.007	1.76±0.08	1.18±0.10	-
	IR2	0.234±0.007	0.215±0.003	0.150±0.008	1.83±0.08	1.18±0.08	-
	IR3	0.239±0.013	0.211±0.007	0.142±0.010	1.79±0.06	1.13±0.10	-
	Nitrogen	ns	ns	<0.0001	ns	ns	
	N0	0.235±0.009	0.217±0.006	0.158±0.008	1.78±0.06	1.21±0.10	-
	N60	0.237±0.011	0.211±0.005	0.143±0.005	1.78±0.09	1.12±0.06	-
	N120	0.242±0.012	0.209±0.006	0.138±0.007	1.82±0.07	1.17±0.10	-
	L	ns	ns	<0.0001	ns	ns	
	Q	ns	ns	ns	ns	ns	
	Irrig x Nit	ns	ns	ns	ns	ns	

Within each year and column, the CV is the coefficient of variation according to ANOVA results (α = 0.05). Irrigation treatments followed by different letters indicate significant differences by LSD multiple range test. Lineal (L) and quadratic (Q) contrast indicate significant trends by N application. Errors are 95% confidence interval of the mean.

3.3.5. Potassium

Leaf K concentration decreased from the end of stage-II to the end of stage-II, and at a higher amount to the end of post-harvest (Table 18). As principal effects, there was significant differences in leaf K concentration when treated with different irrigation

strategies and N doses, from 2006 to 2008. IR2 trees had lower leaf K concentration at the end of stage-II than in trees under FI, and this effect was maintained until post-harvest. In contrast, IR3 strategy had no effect on leaf K concentration. The leaf K concentration was highest at N0 followed by N60 and N120, indicating a decreasing trend as N application increased in 2006 and 2008.

Fruit K concentration decreased from the end of stage-II to harvest (Table 18). Irrigation restriction and N application had no effect on fruit K concentration, except in 2008 at harvest, when N application tended to decrease fruit K concentration.

In 2006, there were significant differences in shoot K concentration at winter pruning when treated with different irrigation strategies and N doses (Table 18). IR2 trees had lower shoot K concentration. Also shoot K concentration decreased linearly with N application. In 2007 these effects were not observed.

Table 18. Effect of irrigation and N application on K concentration in leaves, fruits and shoots of peach cv. Andross (2006-2008).

Year	Effect	Leaf K concentration (% DM)			Fruit K concentration (mg g^{-1} DM)		Shoot K concen. (% DM)
		end stage-II	end stage-III	post-harvest	end stage-II	harvest	winter pruning
2006	CV		9.33%			10.31%	5.61%
	Block		0.0019			ns	ns
	Irrigation		<0.0001			ns	<0.0001
	FI	-	1.86±0.08 a	-	-	11.43±0.98	0.45±0.02 a
	IR2	-	1.25±0.14 b	-	-	10.12±0.53	0.40±0.02 b
	IR3	-	1.82±0.16 a	-	-	11.45±0.51	0.44±0.02 a
	Nitrogen		0.0322			ns	0.0094
	N0	-	1.74±0.25	-	-	10.67±0.73	0.45±0.03
	N60	-	1.62±0.18	-	-	11.46±0.80	0.42±0.02
	N120	-	1.56±0.23	-	-	10.88±0.83	0.43±0.02
	L		0.0109			ns	0.0317
	Q		ns			ns	0.0202
	Irrig x Nit		ns			ns	ns
2007	CV	7.71%	8.47%	12.99%	7.96%	11.56%	6.29%
	Block	ns	ns	0.0223	ns	ns	ns
	Irrigation	ns	<0.0001	0.0036	ns	ns	ns
	FI	2.50±0.13	2.03±0.10 a	1.15±0.10 a	18.53±0.59	13.40±0.73	0.49±0.02
	IR2	2.33±0.14	1.71±0.14 b	0.96±0.08 b	17.25±0.87	12.84±1.08	0.48±0.01
	IR3	2.59±0.09	2.14±0.09 a	1.14±0.11 a	18.90±1.05	12.40±0.82	0.49±0.02
	Nitrogen	ns	ns	ns	ns	ns	ns
	N0	2.50±0.15	2.00±0.21	1.09±0.13	18.26±1.01	12.89±1.06	0.49±0.02
	N60	2.50±0.09	1.96±0.10	1.08±0.11	18.64±0.95	13.38±0.72	0.48±0.01
	N120	2.41±0.16	1.92±0.16	1.09±0.09	17.78±0.90	12.37±0.85	0.48±0.01
	L	ns	ns	ns	ns	ns	ns
	Q	ns	ns	ns	ns	ns	ns
	Irrig x Nit	ns	ns	ns	ns	ns	ns
2008	CV	9.36%	10.19%	12.79%	6.61%	7.03%	
	Block	ns	ns	0.0056	ns	0.0352	
	Irrigation	0.0009	0.0002	<0.0001	ns	ns	
	FI	2.04±0.15 a	1.84±0.13 a	0.94±0.08 a	16.18±0.69	12.28±0.59	-
	IR2	1.79±0.17 b	1.56±0.20 b	0.67±0.06 c	16.19±0.76	11.56±0.85	-
	IR3	2.09±0.12 a	1.90±0.11 a	0.83±0.10 b	16.23±0.56	11.78±0.46	-
	Nitrogen	0.0007	0.0009	ns	ns	0.0440	
	N0	2.14±0.13	1.89±0.13	0.86±0.09	16.34±0.51	12.31±0.77	-
	N60	1.98±0.08	1.82±0.10	0.83±0.12	16.70±0.69	11.90±0.47	-
	N120	1.80±0.20	1.59±0.23	0.76±0.11	15.56±0.58	11.40±0.65	-
	L	0.0002	0.0003	0.0327	ns	0.0135	
	Q	ns	ns	ns	ns	ns	
	Irrig x Nit	ns	0.0341	ns	ns	ns	

Within each year and column, the CV is the coefficient of variation according to ANOVA results (α = 0.05). Irrigation treatments followed by different letters indicate significant differences by LSD multiple range test. Lineal (L) and quadratic (Q) contrast indicate significant trends by N application. Errors are 95% confidence interval of the mean.

3.3.6. Calcium

Leaf Ca concentration increased from the end of stage-II to the end of stage-III, and at a higher amount at the end of post-harvest (Table 19). In 2007 and 2008, there were significant differences in leaf Ca concentration when treated with different irrigation strategies and N doses, but not in 2006. IR2 trees had higher leaf Ca concentration at the end of stage-II than those under FI, and this effect was maintained until post-harvest. In contrast, IR3 strategy had no effect on leaf Ca concentration. N application reduced the leaf Ca concentration, significantly in 2007. In leaf samples collected at the end of stage-III, leaf Ca concentration decreased from 2006 to 2007, and maintained these values in 2008. Fruit Ca concentration decreased from end stage-II to harvest (Table 19). Irrigation restriction and N application had no effect on fruit Ca concentration, except in 2008 at the end of stage-II, when IR2 trees had higher fruit Ca concentration. In 2007, there was significant differences in shoot Ca concentration at winter pruning, when IR2 trees had higher shoot Ca concentration (Table 19).

Table 19. Effect of irrigation and N application on Ca concentration in leaves, fruits and shoots of peach cv. Andross (2006-2008).

Year	Effect	Leaf Ca concentration (% DM)			Fruit Ca concentration (mg g^{-1} DM)		Shoot Ca concen. (% DM)
		end stage-II	end stage-III	post-harvest	end stage-II	harvest	winter pruning
2006	**CV**		9.14%			27.29%	10.65%
	Block		ns			ns	ns
	Irrigation		ns			ns	ns
	FI	-	4.22±0.33	-	-	0.62±0.10	1.39 ± 0.08
	IR2	-	4.45±0.28	-	-	0.68±0.14	1.32 ± 0.12
	IR3	-	4.29±0.21	-	-	0.68±0.13	1.36 ± 0.09
	Nitrogen		ns			ns	ns
	N0	-	4.36±0.33	-	-	0.63±0.12	1.39 ± 0.10
	N60	-	4.43±0.15	-	-	0.68±0.13	1.32 ± 0.05
	N120	-	4.17±0.31	-	-	0.66±0.12	1.36 ± 0.12
	L		ns			ns	ns
	Q		ns			ns	ns
	Irrig x Nit		ns			ns	ns
2007	**CV**	7.48%	7.55%	5.96%	16.22%	23.19%	6.50%
	Block	ns	ns	ns	ns	ns	0.0269
	Irrigation	0.0001	0.0131	<0.0001	ns	ns	0.0391
	FI	2.27±0.08 b	2.66±0.11 ba	3.99±0.19 b	1.39±0.16	0.63±0.07	1.72 ± 0.11 ba
	IR2	2.57±0.13 a	2.78±0.18 a	4.37±0.18 a	1.42±0.20	0.64±0.10	1.75 ± 0.07 a
	IR3	2.23±0.13 b	2.51±0.15 b	3.79±0.16 b	1.42±0.08	0.63±0.09	1.64 ± 0.07 b
	Nitrogen	ns	0.0032	0.0321	ns	ns	ns
	N0	2.40±0.14	2.83±0.13	4.21±0.24	1.37±0.13	0.66±0.12	1.77 ± 0.09
	N60	2.36±0.08	2.58±0.11	3.94±0.20	1.33±0.12	0.63±0.06	1.66 ± 0.07
	N120	2.33±0.21	2.54±0.18	4.00±0.24	1.53±0.18	0.61±0.07	1.69 ± 0.10
	L	ns	0.0018	0.0481	ns	ns	ns
	Q	ns	ns	ns	ns	ns	ns
	Irrig x Nit	ns	ns	ns	ns	ns	ns
2008	**CV**	6.40%	5.82%	5.47%	8.56%	18.41%	
	Block	0.0009	ns	ns	0.0076	ns	
	Irrigation	0.0216	ns	0.0028	0.0002	ns	
	FI	3.22±0.26 b	3.58±0.13	4.23±0.17 b	0.90±0.06 b	0.43±0.06	-
	IR2	3.44±0.13 a	3.69±0.15	4.51±0.15 a	1.07±0.08 a	0.48±0.05	-
	IR3	3.22±0.16 b	3.56±0.14	4.15±0.22 b	0.96±0.04 b	0.47±0.04	-
	Nitrogen	0.0059	ns	0.0340	ns	ns	
	N0	3.16±0.18	3.53±0.07	4.41±0.13	0.94±0.07	0.48±0.06	-
	N60	3.46±0.22	3.68±0.16	4.33±0.18	1.00±0.09	0.45±0.04	-
	N120	3.27±0.15	3.62±0.17	4.15±0.25	0.98±0.07	0.44±0.05	-
	L	ns	ns	0.0121	ns	ns	
	Q	0.0027	ns	ns	ns	ns	
	Irrig x Nit	ns	ns	ns	ns	ns	

Within each year and column, the CV is the coefficient of variation according to ANOVA results (α = 0.05). Irrigation treatments followed by different letters indicate significant differences by LSD multiple range test. Lineal (L) and quadratic (Q) contrast indicate significant trends by N application. Errors are 95% confidence interval of the mean.

3.3.7. Magnesium

Leaf Mg concentration increased from the end of stage-II to the end of stage-III, and at a higher amount at the end of post-harvest (Table 20). As principal effects, there were significant differences in leaf Mg concentration when treated with different irrigation strategies and N doses, from 2006 to 2008. Thus, IR2 trees had higher leaf Mg concentration at the end of stage-II than under FI, and this effect was maintained until post-harvest. In contrast, IR3 strategy had no effect on leaf Mg concentration. However, the effect of N application on leaf Mg concentration changed among years, since N application reduced leaf Mg concentration in 2006 and 2007, but increased such concentration in 2008.

Fruit Mg concentration decreased from end stage-II to harvest (Table 20). Irrigation restriction and N application had no effect on Mg concentration of fruits and dormant shoots (Table 20).

Table 20. Effect of irrigation and N application on Mg concentration in leaves, fruits and shoots of peach cv. Andross (2006-2008).

Year	Effect	Leaf Mg concentration (% DM)			Fruit Mg concentration (mg g^{-1} DM)		Shoot Mg concen. (% DM)
		end stage-II	end stage-III	post-harvest	o end stage-II	harvest	winter pruning
2006	**CV**		4.99%			14.28%	7.09%
	Block		ns			ns	ns
	Irrigation		<0.0001			ns	ns
	FI	-	0.73±0.03 b	-	-	0.50±0.04	0.123 ± 0.007
	IR2	-	0.82±0.04 a	-	-	0.48±0.06	0.115 ± 0.006
	IR3	-	0.73±0.02 b	-	-	0.50±0.04	0.119 ± 0.005
	Nitrogen		ns			ns	ns
	N0	-	0.77±0.06	-	-	0.47±0.03	0.123 ± 0.007
	N60	-	0.77±0.02	-	-	0.52±0.04	0.115 ± 0.006
	N120	-	0.74±0.04	-	-	0.49±0.06	0.119 ± 0.006
	L		ns			ns	ns
	Q		ns			ns	ns
	Irrig x Nit		0.0010			ns	ns
2007	**CV**	5.38%	5.66%	6.90%	8.28%	14.99%	4.77%
	Block	0.0068	ns	ns	ns	ns	ns
	Irrigation	<0.0001	0.0002	0.0002	ns	ns	ns
	FI	0.54±0.02 b	0.58±0.02 b	0.73±0.04 b	1.01±0.04	0.61±0.04	0.181 ± 0.006
	IR2	0.60±0.03 a	0.62±0.04 a	0.82±0.04 a	0.97±0.06	0.63±0.08	0.184 ± 0.004
	IR3	0.52±0.03 b	0.56±0.02 b	0.72±0.03 b	1.03±0.05	0.58±0.05	0.177 ± 0.006
	Nitrogen	ns	0.0014	ns	ns	ns	ns
	N0	0.57±0.04	0.62±0.04	0.78±0.06	1.02±0.04	0.58±0.06	0.181 ± 0.007
	N60	0.55±0.02	0.58±0.01	0.75±0.03	1.00±0.06	0.64±0.05	0.179 ± 0.005
	N120	0.54±0.03	0.57±0.03	0.75±0.04	0.99±0.06	0.59±0.06	0.182 ± 0.005
	L	ns	0.0006	ns	ns	ns	ns
	Q	ns	ns	ns	ns	ns	ns
	Irrig x Nit	0.0243	0.0421	ns	ns	ns	ns
2008	**CV**	5.05%	6.01%	7.30%	7.46%	12.12%	
	Block	0.0158	ns	ns	ns	ns	
	Irrigation	0.0004	ns	0.0001	ns	ns	
	FI	0.68±0.02 b	0.74±0.02	0.81±0.03 b	0.93±0.04	0.63±0.05	-
	IR2	0.74±0.03 a	0.78±0.03	0.94±0.06 a	0.96±0.04	0.60±0.05	-
	IR3	0.67±0.03 b	0.74±0.03	0.83±0.04 b	0.96±0.04	0.60±0.05	-
	Nitrogen	0.0338	ns	ns	ns	ns	
	N0	0.68±0.02	0.74±0.02	0.87±0.06	0.94±0.03	0.60±0.06	-
	N60	0.70±0.03	0.75±0.02	0.83±0.03	0.95±0.06	0.63±0.03	-
	N120	0.71±0.04	0.77±0.04	0.87±0.07	0.96±0.03	0.61±0.05	-
	L	0.0118	ns	ns	ns	ns	
	Q	ns	ns	ns	ns	ns	
	Irrig x Nit	ns	ns	0.0362	ns	ns	

Within each year and column, the CV is the coefficient of variation according to ANOVA results (α = 0.05). Irrigation treatments followed by different letters indicate significant differences by LSD multiple range test. Lineal (L) and quadratic (Q) contrast indicate significant trends by N application. Errors are 95% confidence interval of the mean.

3.3.8. Sulphur

Leaf S concentration decreased from end stage-II to end stage-III, and at a higher amount to end of post-harvest (Table 21). Irrigation restriction had no effect on leaf S concentration, but was significantly higher by N application at each stage, from 2006 to 2008. The leaf S concentration was lower at N0 followed by N60 and N120, indicating an increasing linear trend as N application increased.

Fruit S concentration decreased from end stage-II to harvest (Table 21). Irrigation restriction and N application had no effect on fruit S concentration, except in 2008 at end of stage-II, when N application tended to increase fruit S concentration.

There was no significant differences in shoot S concentration when treated with different irrigation strategies and N doses (Table 21), except in 2006, when IR2 trees had lower shoot S concentration than those under FI.

Table 21. Effect of irrigation and N application on S concentration in leaves, fruits and shoots of peach cv. Andross (2006-2008).

Year	Effect	Leaf S concentration (% DM)			Fruit S concentration (mg g^{-1} DM)		Shoot S concen. (% DM)
		end stage-II	end stage-III	post-harvest	end stage-II	harvest	winter pruning
2006	**CV**		6.46%			23.23%	9.58%
	Block		ns			ns	0.0011
	Irrigation		ns			ns	0.0402
	FI	-	0.150±0.005	-	-	0.267±0.041	0.062±0.005 a
	IR2	-	0.146±0.006	-	-	0.225±0.039	0.056±0.004 b
	IR3	-	0.149±0.007	-	-	0.225±0.029	0.061±0.004 a
	Nitrogen		ns			ns	ns
	N0	-	0.143±0.006	-	-	0.217±0.025	0.063±0.004
	N60	-	0.150±0.007	-	-	0.250±0.043	0.058±0.006
	N120	-	0.152±0.005	-	-	0.250±0.043	0.058±0.004
	L		ns			ns	0.0417
	Q		ns			ns	ns
	Irrig x Nit		ns			ns	ns
2007	**CV**	3.56%	6.83%	7.56%	13.42%	20.04%	8.87%
	Block	ns	0.0001	ns	ns	ns	ns
	Irrigation	0.0003	ns	ns	ns	ns	ns
	FI	0.225±0.007 a	0.193±0.014	0.734±0.037	0.758±0.033	0.325±0.039	0.089±0.006
	IR2	0.213±0.007 b	0.191±0.010	0.818±0.044	0.733±0.073	0.325±0.039	0.088±0.005
	IR3	0.228±0.005 a	0.193±0.013	0.721±0.031	0.800±0.072	0.300±0.047	0.088±0.004
	Nitrogen	0.0001	0.0221	ns	ns	ns	ns
	N0	0.213±0.006 b	0.183±0.013 b	0.781±0.058	0.792±0.063	0.292±0.033	0.086±0.005
	N60	0.226±0.007 a	0.196±0.010 a	0.745±0.032	0.750±0.074	0.342±0.033	0.088±0.006
	N120	0.228±0.006 a	0.198±0.011 a	0.748±0.044	0.750±0.051	0.317±0.053	0.093±0.003
	L	0.0001	0.0100	ns	ns	ns	0.0487
	Q	ns	ns	ns	ns	ns	ns
	Irrig x Nit	ns	ns	ns	ns	ns	ns
2008	**CV**	5.79%	5.98%	4.86%	11.10%	19.04%	
	Block	ns	ns	ns	ns	ns	
	Irrigation	ns	ns	ns	ns	ns	
	FI	0.167±0.009	0.158±0.008	0.144±0.006	0.625±0.067	0.308±0.042	-
	IR2	0.158±0.005	0.162±0.005	0.142±0.005	0.583±0.046	0.292±0.033	-
	IR3	0.165±0.009	0.160±0.008	0.140±0.007	0.583±0.025	0.300±0.038	-
	Nitrogen	0.0002	0.0051	0.0006	0.0091	ns	
	N0	0.154±0.005 c	0.153±0.007 b	0.135±0.004 b	0.550±0.033 b	0.283±0.046	-
	N60	0.163±0.007 b	0.159±0.007 b	0.143±0.006 a	0.600±0.054 ba	0.300±0.000	-
	N120	0.173±0.007 a	0.168±0.005 a	0.148±0.005 a	0.642±0.042 a	0.317±0.046	-
	L	<0.0001	0.0014	0.0002	0.0024	ns	
	Q	ns	ns	ns	ns	ns	
	Irrig x Nit	ns	ns	0.0170	ns	ns	

Within each year and column, the CV is the coefficient of variation according to ANOVA results (α = 0.05). Irrigation treatments followed by different letters indicate significant differences by LSD multiple range test. Lineal (L) and quadratic (Q) contrast indicate significant trends by N application. Errors are 95% confidence interval of the mean.

3.4. Yield components

3.4.1. Total fruit load

In Table 22 is shown the treatment effects on fruit load. In 2006, fruit load was low (with 126 fruit tree[-1], averaged over FI trees), due to previous winter pruning for control of canopy size. During this year there was no significant effect of irrigation and N application on fruit load. The significant interaction was not consistent because the data presented a high coefficient of variation. In comparison to 2006, fruit load was higher in 2007 and 2008 (with 509 and 459 fruit tree[-1] respectively, averaged over FI trees). In both years the irrigation strategies had no significant effect on fruit load, but fruit load showed an increasing lineal trend by N application. Also in 2007 there was a significant interaction and fruit load was independent of N dose in IR2 trees.

3.4.2. Canopy growth

The pruning weight was measured at tree rest and the results are shown in Table 22. In 2006 the treatments had no significant effect on the pruning weight as evidenced by the non-significant p-values. However in 2007 and 2008, IR2 trees had significant lower pruning weight than those under FI. In contrast, IR3 strategy had no effect on pruning weight. Also in 2007 and 2008, pruning weight tended to increase linearly by N application, but this effect was significant only in 2008.

The fraction of PAR intercepted (FIPAR) was measured just after fruit harvest in 2008 and the results are shown in Figure 25. FIPAR values in IR2 was significantly lower compared to FI trees, but IR3 strategy had no effect on FIPAR. Also FIPAR tended to increase linearly by N application, and this effect was observed within all irrigation strategies.
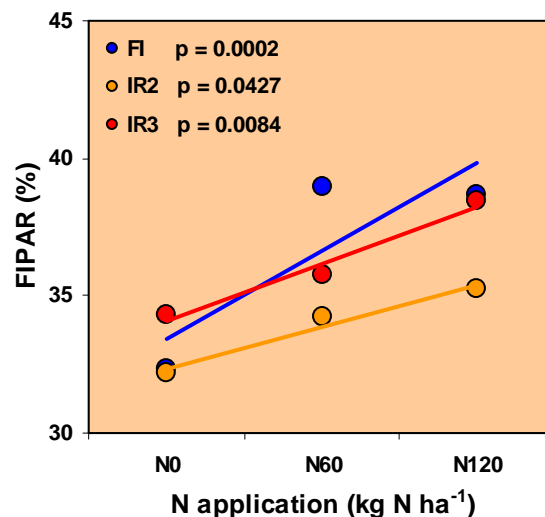

Figure 25. Effect of N application on the fraction of PAR intercepted just after fruit harvest in 2008 within each irrigation strategy. The p-value is the significance of the lineal contrast.

3.4.3. Fruit load/Pruning weight ratio

The ration between fruit load per pruning weight (Q/P ratio) is shown in Table 22. This ratio was lower in 2006 than in 2007 and 2008. Irrigation restriction increased the Q/P ratio, this effect was specially significant in IR2 trees from 2006 to 2008, whereas in IR3 trees only in 2006 and 2008. Also, the Q/P ratio tended to decrease linearly by N application, but this effect was significant in 2008.

3.4.4. Average fruit weight

Table 22 shows the treatment effects on average fresh fruit weight and dry fruit weight. Since fruit load changed among years, fruit weight was higher in 2006 than in 2007 and 2008 (fruit fresh weight was 195, 131 and 149 g fruit^{-1} respectively, averaged over FI trees). There were significant differences in fruit weight when treated with irrigation restriction. From 2006 to 2008, the fruit fresh weight was significantly highest at FI followed in order by IR2 and IR3. However, in fruit dry weight these differences were only found in 2006 and 2007, but not in 2008. There were no significant effects of N application on fruit weight.

Table 22. Effect of irrigation and N application on yield components of peach cv. Andross (2006-2008).

Year	Effect	Total fruit load (fruits tree^{-1})	Pruning weight (kg DM tree^{-1})		Q/P ratio (fruits kg^{-1} DM)		Average fruit weight (g FM fruit^{-1})		(g DM fruit^{-1})	
2006	CV	46.04%	27.52%		56.25%		10.81%		10.07%	
	Block	0.0002	ns		<0.0001		0.0031		0.0316	
	Irrigation	ns	ns		0.0023		0.0311		0.0422	
	FI	126 ± 15	4.83 ± 0.86		27.5±3.9	b	195 ± 12	a	29.5±1.8	a
	IR2	146 ± 19	4.25 ± 0.92		39.7±6.7	a	175 ± 15	b	26.9±2.1	b
	IR3	152 ± 21	4.68 ± 0.65		36.3±6.2	a	175 ± 18	b	26.7±2.4	b
	Nitrogen	ns	ns		ns		ns		ns	
	N0	129 ± 20	4.40 ± 0.78		33.7±6.7		188 ± 19		29.1±2.9	
	N60	147 ± 17	4.77 ± 0.96		36.2±6.0		181 ± 15		27.4±1.5	
	N120	147 ± 20	4.60 ± 0.74		33.5±4.6		175 ± 14		26.6±2.0	
	L	ns	ns		ns		ns		0.0412	
	Q	ns	ns		ns		ns		ns	
	Irrig x Nit	0.0001	ns		0.0002		ns		ns	
2007	CV	14.93%	19.92%		25.16%		7.38%		8.49%	
	Block	<0.0001	0.0409		<0.0001		0.0369		ns	
	Irrigation	ns	0.0126		<0.0001		0.0001		0.0373	
	FI	509 ± 25	3.31 ± 0.55	a	160.5±10.3	b	131 ± 8	a	19.0±1.3	a
	IR2	518 ± 20	2.55 ± 0.36	b	213.8±15.8	a	122 ± 7	b	17.8±1.2	ba
	IR3	527 ± 30	3.14 ± 0.40	a	173.4±12.9	b	111 ± 7	c	17.3±1.0	b
	Nitrogen	0.0002	ns		ns		ns		ns	
	N0	483 ± 23	2.67 ± 0.43		192.3±15.8		126 ± 9		18.6±1.4	
	N60	538 ± 27	3.21 ± 0.55		178.7±15.1		120 ± 11		17.7±1.3	
	N120	533 ± 23	3.13 ± 0.40		176.6±11.9		118 ± 6		17.9±0.8	
	L	0.0006	ns		ns		ns		ns	
	Q	0.0163	ns		ns		ns		ns	
	Irrig x Nit	<0.0001	ns		0.0043		0.0084		0.0132	
2008	CV	22.18%	21.14%		29.14%		8.89%		11.11%	
	Block	ns	ns		<0.0001		ns		ns	
	Irrigation	ns	0.0282		<0.0001		0.0007		0.0487	
	FI	459 ± 26	4.54 ± 0.70	a	107.3±9.4	c	149 ± 7	a	19.5±0.9	a
	IR2	491 ± 33	3.55 ± 0.47	b	143.5±12.2	a	128 ± 9	b	17.4±1.6	b
	IR3	490 ± 27	4.29 ± 0.74	a	121.2±9.6	b	133 ± 6	b	18.0±0.7	ba
	Nitrogen	0.0009	0.0096		0.0013		ns		ns	
	N0	443 ± 30	3.50 ± 0.64		137.5±14.7		138 ± 11		18.6±1.5	
	N60	479 ± 23	4.19 ± 0.66		121.1±8.9		139 ± 8		18.4±1.0	
	N120	517 ± 30	4.69 ± 0.57		113.4±7.6		135 ± 10		17.8±1.3	
	L	0.0002	0.0026		0.0004		ns		ns	
	Q	ns	ns		ns		ns		ns	
	Irrig x Nit	ns	ns		ns		ns		ns	

Within each year and column, the CV is the coefficient of variation according to ANOVA results (α = 0.05). Irrigation treatments followed by different letters indicate significant differences by LSD multiple range test. Lineal (L) and quadratic (Q) contrast indicate significant trends by N application. Errors are 95% confidence interval of the mean.

In order to compare among irrigation strategies, also the relationship between fruit weight at commercial harvest (M) versus Q/P ratio was determined (Figure 26). A potential equation was fitted to the data using non-linear regression analysis:

$$M = a \, (Q/P)^b \qquad \qquad \text{equation 21}$$

where parameter *a* was maintained fixed in the regression equations, while *b* changed according to irrigation strategy. The results are shown in Table 23 carried with data from 2006-2008. For fruit fresh weight, irrigation restriction reduced significantly the *b* parameter respect to FI strategy, specially under IR3. In contrast, for fruit dry weight, only IR3 reduced significantly the *b* parameter respect to FI strategy.
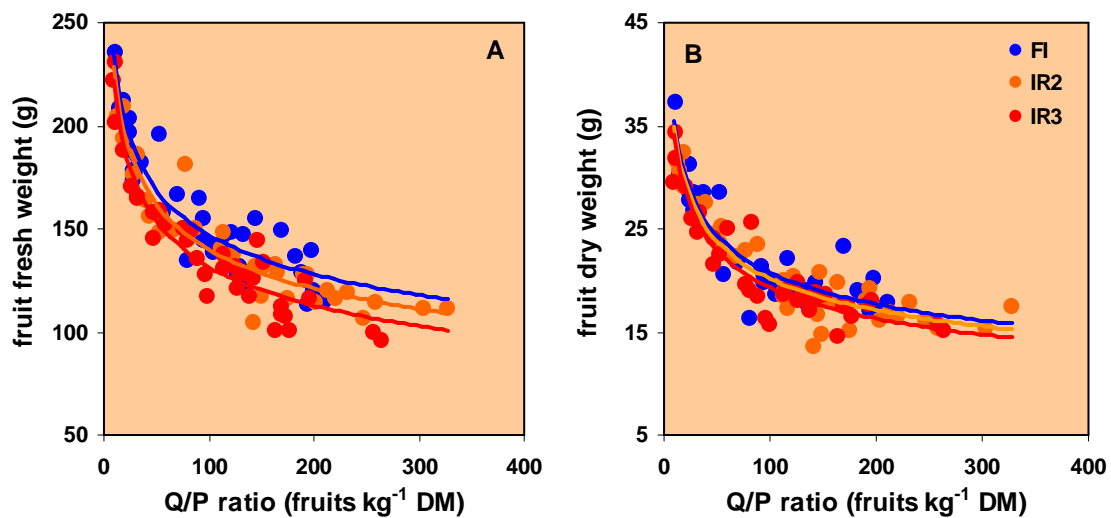
Figure 26. Potential relationship between fruit fresh weight (A) and fruit dry weight (B) respect to Q/P ratio according to irrigation strategy with data from 2006-2008.

Table 23. Estimated parameters and 95% confidence intervals for the potential equation fitted to fruit weight versus Q/P ratio. Differences in b parameter were tested with pairwise t-test.

Independent variable	Dependent variable	Irrigation	Number of observations	Parameters			Determination coefficient
				a	b		
Q/P ratio (fruits kg^{-1} DM)	Fruit fresh weight (g FM fruit^{-1})	FI	36	369.14	-0.2000±0.0058	a	86.52%
		IR2	36	369.14	-0.2104±0.0054	b	88.58%
		IR3	36	369.14	-0.2239±0.0054	c	91.47%
	Fruit dry weight (g DM fruit^{-1})	FI	36	59.81	-0.2298±0.0073	a	85.56%
		IR2	36	59.81	-0.2360±0.0066	a	88.15%
		IR3	36	59.81	-0.2456±0.0071	b	86.48%

Average values of soil RWC and Ψ_{stem} were calculated for stage-III according to irrigation strategy, from 2006 to 2008. Also fruit growth rate in fresh weight and dry weight were calculated from beginning of stage-III until harvest. Table 24 shows the existing correlations among these variables in stage-III. There was a significant positive correlation between fresh weight and water status, both in the soil and the tree. Thus, fruit growth rate in fresh weight increased with water status in stage-III. However, this correlation was not significant for fruit growth rate in dry weight, which was independent of water status, both in the soil and in the tree.

Table 24. Correlation between fruit growth rate in stage-III and average water status. Also shown the estimated parameters and the 95% confidence intervals of the lineal regression (2006-2008).

Independent variable	Dependent variable	Number of observations	Parameters		Correlation coefficient	Durbin-Watson
			Intercept	Slope		
Soil RWC (%)	Fresh growth rate (g day^{-1})	9	1.1156±0.4028 p = 0.0003	0.0124±0.0055 p = 0.0011	0.8943 p = 0.0011	2.0279 ns
	Dry growth rate (g day^{-1})	9	0.2353±0.0651 p = 0.0001	0.0004±0.0009 ns	0.4094 ns	1.9192 ns
Midday Ψ_{stem} (MPa)	Fresh growth rate (g day^{-1})	9	2.4771±0.4598 p = <0.0001	0.4724±0.4481 p = 0.0414	0.6858 p = 0.0414	1.9421 ns
	Dry growth rate (g day^{-1})	9	0.2867±0.0469 p < 0.0001	0.0191±0.0457 ns	0.3499 ns	1.4722 ns

3.4.5. Total fruit yield

Table 25 shows the treatment effects on total fruit yield. Since fruit load changed among years, fruit yield was lower in 2006 than in 2007 and 2008 (fruit fresh yield was 24.2, 65.6 and 67.8 kg tree^{-1} respectively, averaged over FI trees). Figure 27 shows these results as total orchard yield in tons per hectare. The same effect was obtained on fruit fresh yield and dry yield. In 2006 there was no significant effect of irrigation restriction and N application on fruit yield. The significant interaction was not consistent because the data presented a high coefficient of variation. In 2007 there was a significant interaction between irrigation × N and the effect of N application changed within each irrigation strategy. In FI trees fruit yield was significantly lowest at N0 followed in order by N60 and N120, indicating an increasing linear trend as N dose increased. In IR2 trees fruit yield was independent of N dose. Under IR3 trees a quadratic trend was obtained and fruit yield did not change between N0 and N60, but decreased at N120. However in 2008, fruit yield was not affected by irrigation and interaction. The increase in fruit yield was positively dependent on N application.
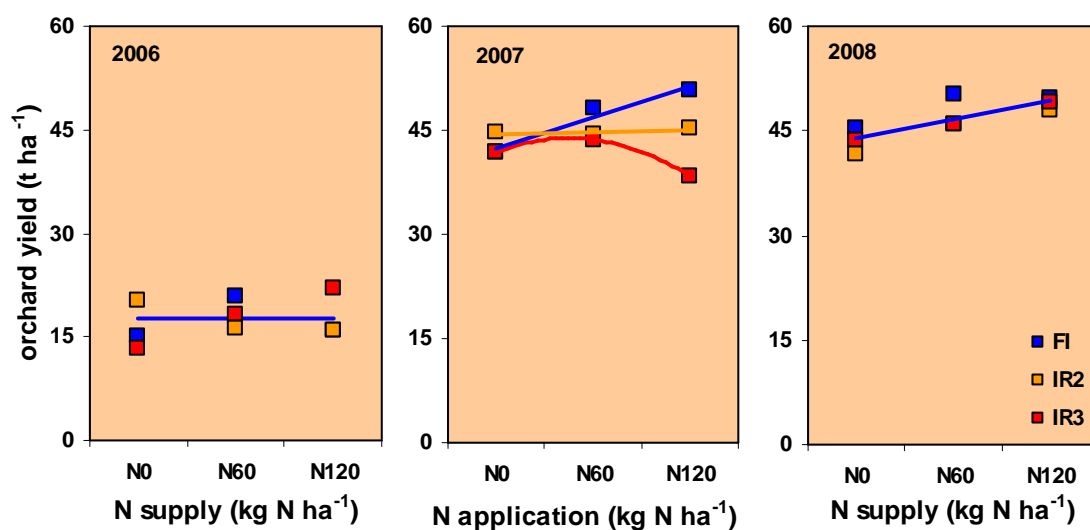

Figure 27. Total orchard yield according to irrigation and N application from 2006 to 2008.

3.4.6. Water productivity

In Table 25 is shown the treatment effects on water productivity (WP). Since fruit load changed among years, WP was lower in 2006 than in 2007 and 2008 (3.80, 11.37 and 8.82 kg m^{-3} respectively, averaged over FI trees). Irrigation affected significantly the WP during the three years. Thus WP of IR2 trees was significantly higher compared to FI trees in 2006 and 2007. While WP of IR3 was significantly higher than FI in 2007 and 2008. N application increased WP under FI. The same effect was obtained on WP in fresh and dry weight.

Table 25. Effect of irrigation and N application on total fruit yield and water productivity of peach cv. Andross (2006-2008).

Year	Effect	Total fruit yield				Water productivity			
		in fresh weight (kg FM tree^{-1})		in dry weight (kg DM tree^{-1})		in fresh weight (kg FM m^{-3})		in dry weight (kg DM m^{-3})	
2006	CV	38.15%		37.96%		38.18%		38.07%	
	Block	0.0024		0.0003		0.0023		0.0002	
	Irrigation	ns		ns		0.0003		0.0001	
	FI	24.2 ± 2.6		3.64 ± 0.38		3.80 ± 0.42	b	0.573 ± 0.062	b
	IR2	24.4 ± 2.5		3.76 ± 0.38		5.02 ± 0.51	a	0.772 ± 0.078	a
	IR3	25.0 ± 2.9		3.84 ± 0.44		4.19 ± 0.49	b	0.644 ± 0.075	b
	Nitrogen	ns		ns		ns		ns	
	N0	22.8 ± 2.7		3.50 ± 0.41		4.19 ± 0.57		0.644 ± 0.086	
	N60	25.8 ± 2.4		3.95 ± 0.39		4.42 ± 0.40		0.679 ± 0.066	
	N120	25.1 ± 2.8		3.80 ± 0.40		4.40 ± 0.49		0.667 ± 0.071	
	L	ns		ns		ns		ns	
	Q	ns		ns		ns		ns	
	Irrig x Nit	<0.0001		0.0008		<0.0001		<0.0001	
2007	CV	12.48%		12.29%		12.58%		12.77%	
	Block	0.0003		0.0118		0.0107		0.0661	
	Irrigation	<0.0001		0.0278		0.0004		0.0005	
	FI	65.6 ± 2.4	a	9.54 ± 0.35	a	11.37 ± 0.38	b	1.656 ± 0.062	b
	IR2	62.7 ± 1.8	b	9.14 ± 0.25	ba	12.37 ± 0.37	a	1.802 ± 0.048	a
	IR3	57.8 ± 2.5	c	9.00 ± 0.35	b	11.51 ± 0.48	b	1.793 ± 0.072	a
	Nitrogen	0.0339		0.0044		ns		ns	
	N0	60.0 ± 2.0		8.83 ± 0.28		11.58 ± 0.43		1.707 ± 0.063	
	N60	63.5 ± 2.3		9.40 ± 0.33		11.96 ± 0.40		1.776 ± 0.068	
	N120	62.7 ± 2.8		9.46 ± 0.35		11.71 ± 0.44		1.769 ± 0.058	
	L	0.0153		0.0028		ns		ns	
	Q	ns		ns		ns		ns	
	Irrig x Nit	<0.0001		0.0003		0.0001		0.0004	
2008	CV	18.26%		18.95%		18.52%		19.41%	
	Block	ns		ns		ns		0.0072	
	Irrigation	ns		ns		0.0113		0.0005	
	FI	67.8 ± 3.3		8.87 ± 0.46		8.82 ± 0.45	b	1.154 ± 0.061	b
	IR2	63.1 ± 2.9		8.31 ± 0.41		8.84 ± 0.40	b	1.163 ± 0.056	b
	IR3	64.8 ± 3.2		8.76 ± 0.45		9.64 ± 0.49	a	1.306 ± 0.071	a
	Nitrogen	0.0025		0.0025		0.0078		0.0071	
	N0	61.0 ± 3.2		8.05 ± 0.43		8.55 ± 0.46		1.130 ± 0.064	
	N60	66.2 ± 3.2		8.82 ± 0.43		9.26 ± 0.43		1.236 ± 0.064	
	N120	68.5 ± 2.9		9.07 ± 0.41		9.49 ± 0.45		1.257 ± 0.064	
	L	0.0007		0.0009		0.0029		0.0033	
	Q	ns		ns		ns		ns	
	Irrig x Nit	ns		ns		ns		ns	

Within each year and column, the CV is the coefficient of variation according to ANOVA results (α = 0.05). Irrigation treatments followed by different letters indicate significant differences by LSD multiple range test. Lineal (L) and quadratic (Q) contrast indicate significant trends by N application. Errors are 95% confidence interval of the mean.

3.4.7. Fruit drop

Figure 28 shows the effect of irrigation and N application on fruit drop before commercial harvest. From 2006 to 2008, fruit drop in IR2 trees was significantly higher than FI trees. In, contrast, IR3 had no effect on fruit drop. There was no significant effects by N application, however fruit drop in N60 and N120 was lower than N0.
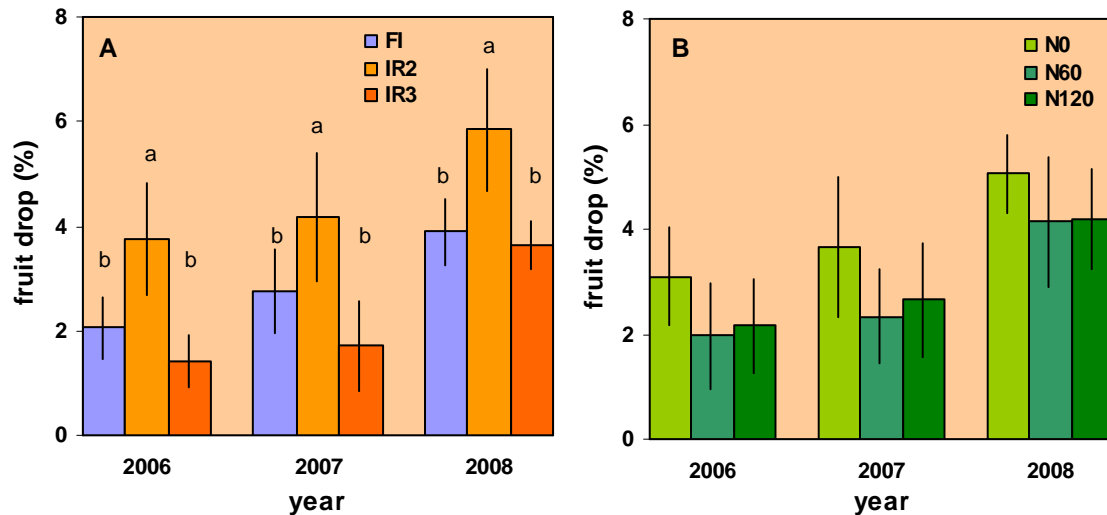

Figure 28. Fruit drop before commercial harvest according to irrigation (A) and N application (B) from 2006 to 2008

3.4.8. Harvester efficiency

The harvester efficiency was lower in 2007 than in 2008 (Table 26), due to changes in the frequency on the trunk shaker. In both years, efficiency was not different between FI and IR3 trees. However, efficiency increased in IR2 trees. In addition, within IR2 trees, efficiency was higher in N0 and N60 than in N120 trees.

Table 26. Effect of irrigation and N application on harvester efficiency of peach cv. Andross (2006-2008).

Year	FI			IR2			IR3		
	N0	N60	N120	N0	N60	N120	N0	N60	N120
2006	-	-	-	-	-	-	-	-	-
2007	78%	80%	79%	86%	86%	79%	80%	81%	83%
2008	87%	87%	89%	92%	89%	86%	89%	87%	86%

3.5. Fruit quality

3.5.1. Percentage of fruit dry matter

The percentage of fruit dry matter (PDM) increased during stage-II of pit hardening and then decreased during stage-III of expansive fruit growth (Figure 29A). The mean values measured at harvest decreased from 2006 to 2008. Table 27 shows the treatment effects on PDM of the fruit. During the three years, IR2 increased significantly the PDM of the fruit measured at end of stage-II, however after restoring complete irrigation during stage-III the PDM of the fruit at harvest was not different from FI. But IR3 increased the PDM of the fruit at the end of stage-III, although it was only significant different in 2007. N application not produced significant differences in the PDM of the fruit and there was not an interaction effect with irrigation strategies.

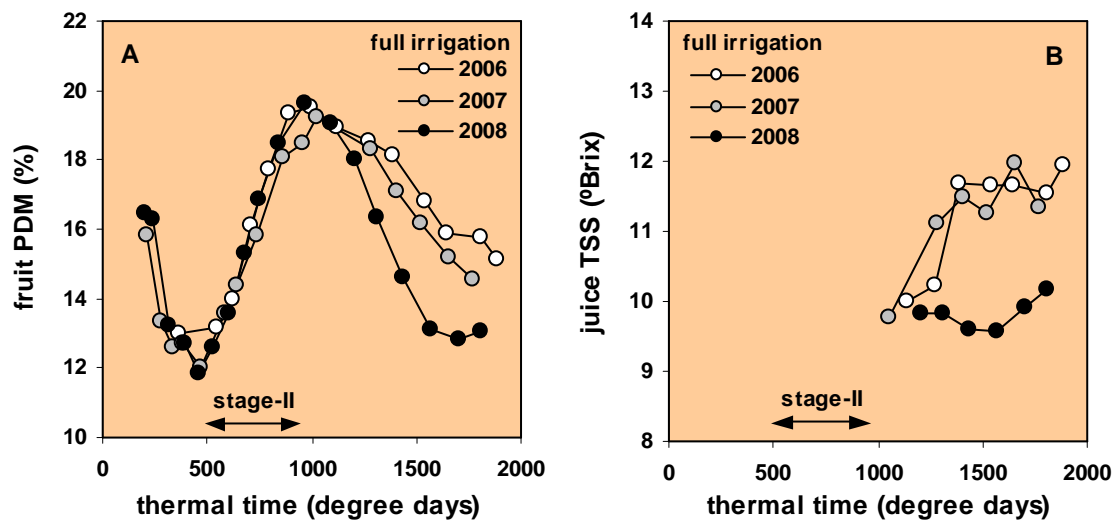### 3.5.2. Total soluble solids of the juice

The total soluble solids (TSS) of the juice increased along stage-III and attained some stable values during the last weeks of fruit ripening (Figure 29B). As an overall average, juice TSS measured at harvest decreased from 2006 to 2007, and specially in 2008. Table 27 shows the treatment effects on TSS of the juice. In the three years, the TSS of the juice at harvest under IR2 was not different from FI, because of restoring complete irrigation during stage-III. However IR3 reduced significantly the TSS of the juice at harvest. N application did not produce significant differences in the TSS of the juice and there was not and interaction effect with irrigation strategies.

Figure 29. Seasonal pattern of percentage dry matter (PDM) of the fruit (A) and total soluble solids (TSS) of the juice (B) under full irrigation in peach cv. Andross according to the experimental year (2006-2008).

The fruit samples obtained at harvest from three years, showed a linear relationship between the TSS of the juice respect to the PDM of the whole fruit. The TSS of the juice was higher for peach fruits with a higher PDM (Figure 30).
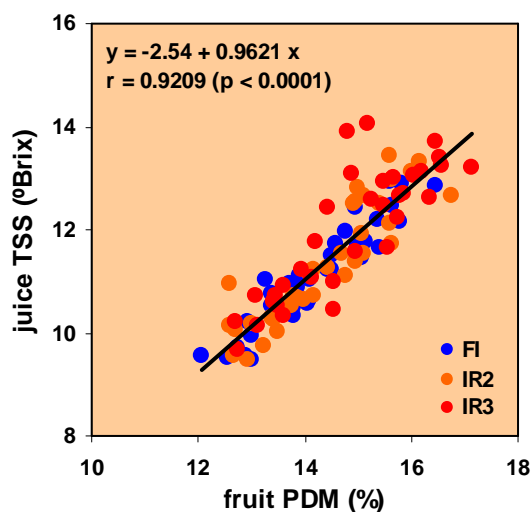
Figure 30. Correlation between the TSS of the juice respect to the PDM of the fruit measured at harvest according to irrigation strategy in peach cv. Andross (2006-2008).

3.5.3. Fruit flesh firmness

The fruit flesh firmness decreased at a constant rate during last weeks of stage-III (Figure 31). The firmness during fruit ripening was lower in 2008 than in 2006 and 2007. In Table 27 is shown the treatment effects on firmness at harvest. In each year, the firmness of IR2 fruits was lower than in FI fruits, although this difference was not significant any year. In contrast, the firmness of IR3 fruits was significantly higher than FI fruits in 2007, but was not different in 2006 and 2008. N application tended to increase firmness linearly and this effect was significant both in 2007 and 2008.

Table 27. Effect of irrigation and N application on fruit quality of peach cv. Andross (2006-2008).

Year	Effect	Percentage dry matter of the fruit (%)			Total soluble solids (ºBrix) at harvest		Flesh firmness (N) at harvest	
		end stage-I	end stage-II	end stage-III				
2006	CV	2.50%	3.22%	4.61%	5.06%		14.74%	
	Block	0.0086	0.0042	0.0353	ns		ns	
	Irrigation	ns	<0.0001	ns	0.0018		ns	
	FI	13.20±0.23	19.36±0.32 b	15.15±0.43	11.95 ± 0.40	b	37.4 ± 4.0	
	IR2	13.41±0.29	20.99±0.68 a	15.46±0.40	12.64 ± 0.40	a	33.5 ± 3.4	
	IR3	13.19±0.20	19.31±0.27 b	15.29±0.65	13.07 ± 0.47	a	36.2 ± 3.0	
	Nitrogen	ns	ns	ns	ns		ns	
	N0	13.42±0.28	19.95±0.68	15.45±0.33	12.54 ± 0.42		34.6 ± 2.8	
	N60	13.18±0.21	19.89±0.64	15.21±0.64	12.48 ± 0.66		35.1 ± 4.1	
	N120	13.19±0.23	19.81±0.75	15.25±0.51	12.53 ± 0.48		37.3 ± 3.6	
	L	ns	ns	ns	ns		ns	
	Q	ns	ns	ns	ns		ns	
	Irrig x Nit	ns	ns	ns	ns		ns	
2007	CV	1.84%	2.64%	3.85%	5.75%		9.69%	
	Block	0.0276	0.0456	0.0357	0.0061		ns	
	Irrigation	ns	0.0001	0.0001	0.0012		0.0009	
	FI	12.02±0.17	18.48±0.27 b	14.55±0.41 b	11.34 ± 0.49	b	42.4 ± 4.0	b
	IR2	11.94±0.17	19.52±0.46 a	14.60±0.36 b	11.39 ± 0.41	b	41.9 ± 4.3	b
	IR3	11.83±0.13	18.67±0.30 b	15.61±0.48 a	12.38 ± 0.60	a	48.8 ± 3.3	a
	Nitrogen	ns	ns	ns	ns		<0.0001	
	N0	12.04±0.16	19.08±0.43	14.75±0.43	11.73 ± 0.56		38.5 ± 3.5	
	N60	11.89±0.15	18.70±0.41	14.84±0.59	11.69 ± 0.69		46.8 ± 3.9	
	N120	11.86±0.17	18.89±0.50	15.17±0.52	11.69 ± 0.53		47.7 ± 2.8	
	L	ns	ns	ns	ns		<0.0001	
	Q	ns	ns	ns	ns		0.0217	
	Irrig x Nit	ns	ns	ns	ns		ns	
2008	CV	1.51%	1.54%	3.88%	4.01%		17.74%	
	Block	0.0046	ns	ns	0.0008		ns	
	Irrigation	ns	0.0007	ns	0.0113		ns	
	FI	11.87± 0.14	19.64±0.20 b	13.06±0.32	10.17 ± 0.40	b	19.0 ± 3.9	
	IR2	11.86±0.17	20.10±0.16 a	13.13±0.29	10.15 ± 0.28	b	17.8 ± 3.8	
	IR3	11.91±0.12	19.61±0.20 b	13.52±0.40	10.65 ± 0.33	a	18.2 ± 2.0	
	Nitrogen	ns	ns	ns	ns		<0.0001	
	N0	11.94±0.17	19.79±0.25	13.18±0.32	10.38 ± 0.33		13.9 ± 1.6	
	N60	11.87±0.13	19.80±0.24	13.31±0.44	10.36 ± 0.44		18.1 ± 2.7	
	N120	11.82±0.13	19.76±0.23	13.23±0.31	10.23 ± 0.32		22.9 ± 2.6	
	L	ns	ns	ns	ns		<0.0001	
	Q	ns	ns	ns	ns		ns	
	Irrig x Nit	ns	ns	ns	ns		ns	

Within each year and column, the CV is the coefficient of variation according to ANOVA results (α = 0.05). Irrigation treatments followed by different letters indicate significant differences by LSD multiple range test. Lineal (L) and quadratic (Q) contrast indicate significant trends by N application. Errors are 95% confidence interval of the mean.
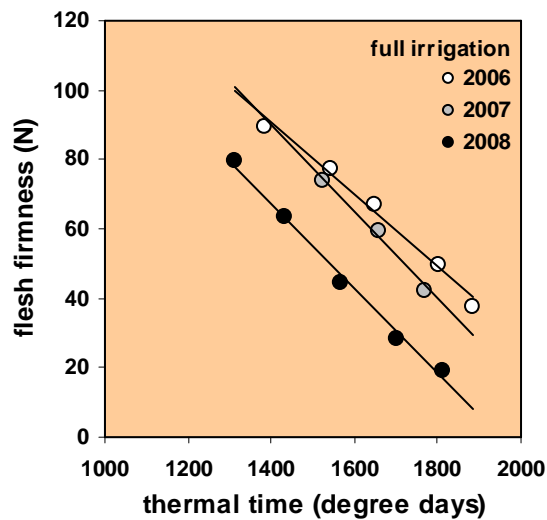
Figure 31. Flesh firmness evolution during fruit ripening under full irrigation according to the experimental year (2006-2008).

3.5.4. Total soluble solids of the puree

In 2008, peach purees were obtained from different treatments of peach fruits. The irrigation strategies affected the TSS of the puree at harvest (Table 28). The N application and the interaction effect did not affect the TSS of the puree of peach fruits significantly. The TSS of the puree under IR2 was not different from FI, because of restoring complete irrigation during stage-III. However, IR3 reduced significantly the TSS of the puree at harvest.

Table 28. Effect of irrigation and N application on puree quality of peach cv. Andross at harvest in 2008.

Year	Effect	Total soluble solids (%)		Consistency (cm)
2008	**CV**	3.92%		7.30%
	Block	0.0050		0.0122
	Irrigation	0.0044		ns
	FI	10.29 ± 0.34	b	8.96 ± 0.69
	IR2	10.39 ± 0.28	b	8.88 ± 0.60
	IR3	10.87 ± 0.30	a	8.41 ± 0.52
	Nitrogen	ns		0.0001
	N0	10.67 ± 0.31		9.34 ± 0.53
	N60	10.46 ± 0.31		8.95 ± 0.49
	N120	10.41 ± 0.39		7.96 ± 0.46
	L	ns		<0.0001
	Q	ns		ns
	Irrig x Nit	ns		ns

Within each year and column, the CV is the coefficient of variation according to ANOVA results ($\alpha = 0.05$). Irrigation treatments followed by different letters indicate significant differences by LSD multiple range test. Lineal (L) and quadratic (Q) contrast indicate significant trends by N application. Errors are 95% confidence interval of the mean.

The TSS values measured in puree samples were slightly higher than that measured in juice samples (Figure 32) since were different products, although were correlated ($r = 0.6632$ with $p < 0.0001$). Also it is shown how IR3 maintained higher TSS in comparison with FI and IR2.

Figure 32. Relation between the TSS of the puree respect to the TSS of the juice measured at commercial harvest in 2008.
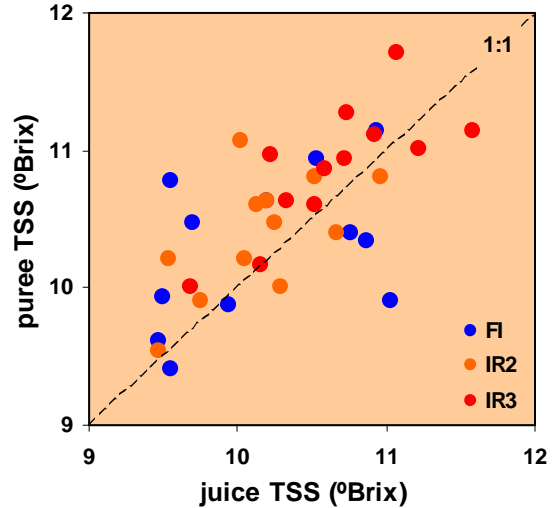
3.5.5. Fruit puree consistency

In 2008, fruit purees were obtained from different treatments. Irrigation strategy had not effect on puree consistency as evidenced by the non-significant p-value (Table 28). In contrast, when puree consistency of peach fruits was measured at different N doses, puree consistency decreased significantly as N dose increased.

In order to compare the peach purees according to three N doses, the time-dependent progress of their puree consistency were measured during fruit ripening. The results are shown in Figure 33A carried with five sampling times until commercial harvest. A monomolecular equation was fitted using non-linear regression analysis:

$$CS = k - b \exp(-r\tau) \qquad \text{equation 22}$$

where *CS* is the puree consistency as a function of thermal time (τ) and *k*, *b* and *r* are regression parameters. The parameters *b* and *r* were maintained fixed in the regression equations, while *k* changed according to N dose (Table 29). Thus, *k* parameter was lower for peach purees with higher fruit N concentration, and the linear relationship is illustrated in Figure 33B. This supports the result that fruit N concentration is the main nutrient responsible for the consistency properties of peach purees.
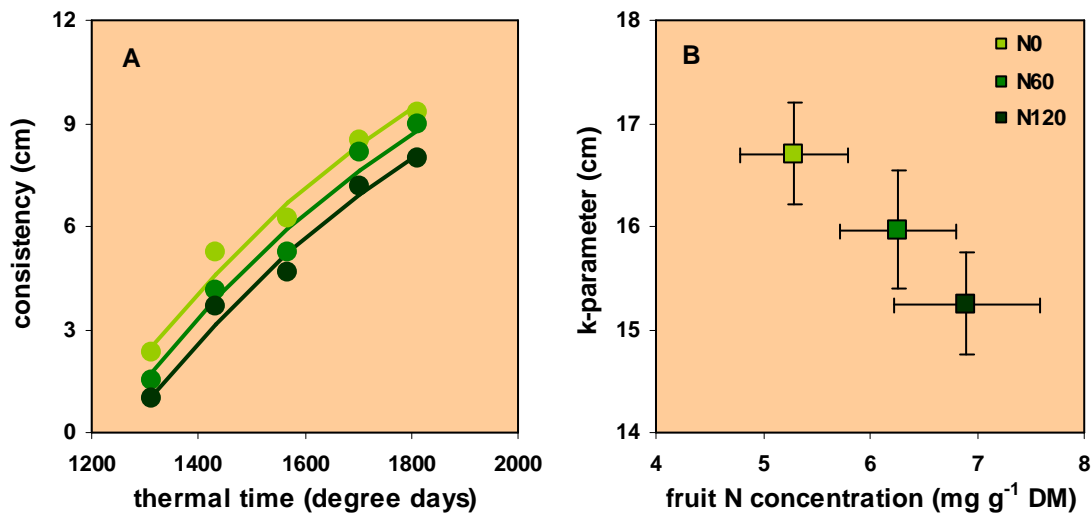
Figure 33. Thermal-time dependent progress of puree consistency according to N application in 2008 (A) and correlation of k-parameter on fruit N concentration in 2008 (B).

Table 29. Estimated k-parameters and its 95% confidence interval for the relationship between puree consistency with thermal time in 2008 according to N application.

Independent variable	Dependent variable	N application	Number of observations	Parameters			Determination coefficient
				b	r	k	
Thermal time (degree days)	Puree consistency (ºBostwick)	N0	5	85.94	0.00137	16.71±0.50 a	97.91%
		N60	5	85.94	0.00137	15.97±0.57 b	97.64%
		N120	5	85.94	0.00137	15.25±0.49 c	98.01%

3.5.6. Fruit flesh colour

In 2007, the flesh colours (luminosity, a* and b* coordinates, chroma and hue angle) were obtained from the different samples of peach fruits (Table 30). The irrigation strategies had no significant effect on the flesh colour of peach fruits as evidenced by the non-significant p-value. N application did not produce significant effects on luminosity values of flesh colour. However, the a* coordinate of peach flesh was lower under N application. The decrease in a* was accompanied by an increase in b*, indicating that the fruit flesh colour under N application was less red and more yellow than N0. The chroma of peach flesh under N application was significantly more saturated compared to the N0. Likewise, the hue angles were significantly higher than that of N0.

There was a significant interaction effect of irrigation strategy and N dose on a* coordinate and hue angle (Figure 34). Higher a* value was obtained under IR2 strategy combined with N0, while the lowest a* value under FI strategy combined with N120. On the other hand, higher hue angle was obtained under FI strategy combined with N60, while the lowest a* value under IR2 strategy combined with N0.

Table 30. Effect of irrigation and N application on flesh colour of peach cv. Andross in 2007.

Year	Effect	Luminosity	a* Coordinate	b* Coordinate	Chroma	Hue (º)
2007	CV	3.16%	109.27%	4.79%	4.75%	3.53%
	Block	<0.0001	<0.0001	0.0017	0.0027	<0.0001
	Irrigation	ns	ns	ns	ns	ns
	FI	68.82±0.71	3.20 ± 0.99	65.02 ± 0.78	65.21±0.78	87.17±0.88
	IR2	68.61±0.81	3.83 ± 1.10	65.01 ± 0.92	65.26±0.91	86.61±0.99
	IR3	68.51±0.69	2.50 ± 1.11	65.15 ± 0.83	65.33±0.83	87.82±0.99
	Nitrogen	ns	0.0007	0.0214	0.0294	0.0002
	N0	68.29±0.84	4.59 ± 0.92 a	64.21 ± 0.97 b	64.48±0.93 b	85.82±0.85 b
	N60	68.70±0.66	2.30 ± 1.06 b	65.17 ± 0.72 ba	65.33±0.74 ba	88.03±0.92 a
	N120	68.95±0.69	2.64 ± 1.15 b	65.80 ± 0.79 a	66.00±0.79 a	87.75±1.01 a
	L	ns	0.0024	0.0060	0.0082	0.0008
	Q	ns	0.0170	ns	ns	0.0113
	Irrig x Nit	ns	0.0161	ns	ns	0.0159

Within each year and column, the CV is the coefficient of variation according to ANOVA results (α = 0.05). Irrigation treatments followed by different letters indicate significant differences by LSD multiple range test. Lineal (L) and quadratic (Q) contrast indicate significant trends by N application. Errors are 95% confidence interval of the mean.
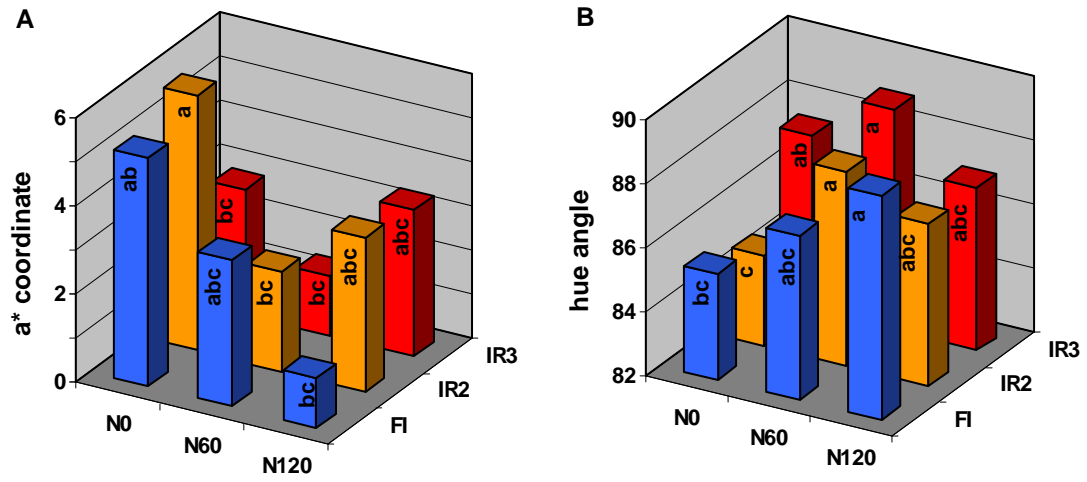
Figure 34. Effects of irrigation and N application on a* coordinate (A) and hue angle (B) measured in the flesh of peach fruits at commercial harvest 2007. Different letters indicate significant differences by LSD multiple range test ($\alpha = 0.05$).

4. Discussion

4.1. Introduction

Proper irrigation and N fertilization is essential to maintain tree growth and optimum orchard yield. In addition, producers for the processing industries are interested to provide high quality fruits (Figure 35).

Input   **Tree growth dynamics**   **Output**

Irrigation
N fertilization
Interaction

Source strength of leaves

Sink demand of fruits

Yield

Fruit quality

Environmental
factors
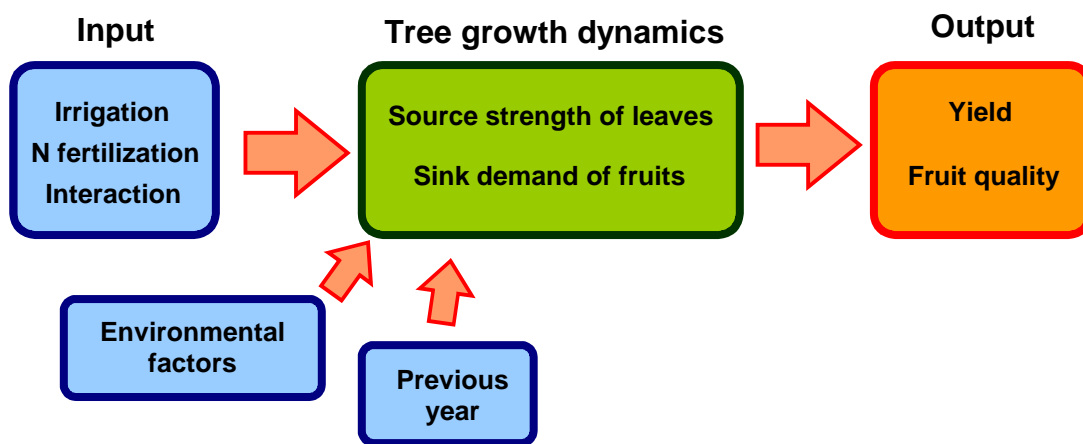
Previous
year

Figure 35. Schematic representation of irrigation and N fertilization effects on yield and fruit quality, via tree growth dynamics. Also are included the environmental factors and the history of previous year, which determines the reserves of the tree.

4.2. Growth patterns of fruits and shoots

4.2.1. Fruit growth curves

Stone-fruits such as peach, apricot, plum and cherry and some non-stony fruits like fig, grape and currant have a double-sigmoid growth curve (Opara, 2000). However, this curve does not seem to be distinctive of different morphological types of fruits. The whole fruit growth is the expression of its constituents tissues (Faust, 1989). In peach, an empirical approach can be used to model fruit growth in diameter (Génard *et al*., 1991). In our study, growth curve in diameter was modelled by the sum of two logistic equations with its correspondent parameters. The first equation described the initial exponential fruit growth and the lag phase. There were little measures of initial fruit growth fruit from full bloom until fruit set. The second equation described the second exponential fruit growth leading up to harvest. The temperature is important in fruit development (Faust, 1989) and degree day accumulation was used to measure thermal time (Figure 9A). The accumulated degree days from full bloom until harvest was similar to the value of 1850 degree days established for the Andross cultivar (Berman *et al*., 1998). Obtained parameters may be subsequently compared between years to explain different environmental conditions and endogenous tree factors (Table

6). There is a positive correlation between flesh soluble solids concentration at harvest and high and late maximal growth rates during stage-III (Génard *et al.*, 1991). With this model it was possible to identify the three stages of fruit development (Chalmers and van den Ende, 1975), originated by the growth of its constituent tissues, the embrio+endosperm (seed or kernel), the endocarp (pit or stone) and the mesocarp (flesh). The growth rate in diameter was useful to compare critical stages of fruit development (Figure 9B), management practices, experimental treatments and responses to the environment (Opara, 2000).

Fruit size and shape are related by simple allometric functions, which are the result of coordinated growth (Mohr and Schopfer, 1995). Dalmases (1998) used allometric functions to study the growth of peach fruits based on diameter, perimeter, volume and fresh weight. Deviations from the reference relationship have been associated with susceptibility to split-pit in peach fruits, presumably due to inter-relatedness between shape and growth (Opara, 2000). Allometric relationship are particularly useful in predicting estimates of fruit fresh weight based on diameter during fruit development when experimental measurement cannot be carried out (Equation 19). To convert fruit diameter to fresh weight, Génard and Huguet (1996) used $a = 0.0027$ and $b = 2.55$, similar to our results (equation 19). It was considered that the function precision was adequate to meet industry requirements for monitoring fruit weight during the season. To convert fruit fresh weight to dry weight it was necessary to know the percentage of fruit dry weight.

4.2.2. Fruit growth versus shoot growth

The double-sigmoidal curve of fruit growth and the changes in growth rate that cause it are apparent in both fresh weight and dry weight graphs (Figure 10B and C, respectively). Several physiological hypothesis attempt to explain the regulation of these patterns by endogenous factors (Faust, 1989). During stage-I, cell division and some cell enlargement contribute to rapid fruit growth. When growth rate in fresh weight began to decline, growth rate in dry weight was still increasing. At this time, it appears a strong competition between stone and flesh for the supply of assimilates, and there is a change in dry weight from flesh growth to stone growth. Also the seed attains its final size, but its dry weight is still low. The synthesis of lignin occurs during this stage-II of pit hardening. When growth rate in dry weight is at its minimum, flesh growth rate is still low, and this allow assimilates to replenish the seed during stage-III (Batjer and Wetwood, 1958; Chalmers and van den Ende, 1975; Dann and Jerie, 1988). The flesh regain their capacity to expand rapidly at stage-III, however flesh growth doesn't depend upon the presence of the seed (Chalmers and van den Ende, 1975). The development of intercellular air spaces is important during stage-III, which is observed in a decrease in the fruit density (Faust, 1989). In addition during stage-III the process of fruit maturation begins (Chapman *et al.*, 1991).

During stage-II, fruit sink demand decreases and most of assimilates are allocated to active growth in leaves (Faust, 1989). Shoot growth rate in length was maximum at the beginning of stage-II and ceased in mid-summer (Figure 11), which occurs in similar varieties (Grossman and DeJong, 1995; Girona *et al.*, 2003; Weibel *et al.*, 2003). This growth pattern is observed in leaf dry weight which shows a limiting period from 200-700 degree days (Grossman and DeJong, 1995). In contrast, shoot growth rate in diameter was maximum at stage-I and did not cease after harvest (Figure 12). Also

shoot dry weight and trunk radial growth continues through post-harvest (Grossman and DeJong, 1995; Girona *et al*., 2003; Weibel *et al*., 2003), although decrease in stage-III (Li *et al*., 1989; Marsal *et al*., 2002). In peach, the logistic growth equation was used to compare shoot and leaf growth (Steinberg *et al*., 1990). In our study, the growth curve of shoots in length and diameter at the base was modelled by a logistic equation with its correspondent parameters according to thermal time (Table 8). Shoot growth has a high variability (Marini, 1985), since shoot growth depends on environmental factors and tree endogenous factors (Kozlowski and Pallardy, 1997). Fruits are considered important sinks for assimilates in fruit trees and fruit growth competes with leaf growth in stage-I and stage-II but not thereafter (Berman and DeJong, 2003). However the presence of fruits reduces trunk radial increment (Grossman and DeJong, 1995) and wood dry weight (Berman and DeJong, 2003) during all stages. At the begging of stage-III canopy growth is almost complete and net assimilation on leaves maintain sink demand of fruits (Chalmers *et al*., 1983).

There is a relation between the relative growth rate of fruit dry weight (log transformed) respect to thermal time, with a negative slope that is similar between varieties. But the slope shift to zero at different transition points. These two log-lineal periods indicate distinct periods of sink activity (DeJong and Goudrian, 1989). The transition point is at 704 degree days for a variety with a development period similar to Andross.

Maximum fruit growth potential is genetically determined and is attained under optimal environmental conditions without resource limitation, in Andross is 240 g FM and 32 g DM, which corresponds to a relative dry weight of 13.5% (Berman *et al*., 1998). Grossman and DeJong (1995a,b) used the empirical approach to model fruit growth potential in dry weight during the season according to different thinning treatments. Fruit growth curves were obtained by fitting cubic splines to log transformed dry weight data according to the thermal time. The length of the fruit development period was similar to Andross. The fruit dry weight at harvest in trees thinned just before full bloom was not different from trees thinned 4 weeks later (166 degree days after full bloom). However, fruit dry weight decreased in trees thinned at 521 degree days, 822 degree days and especially in trees without thinning (Grossman and DeJong, 1995b). Our results show that fruit growth rate increased to an initial maximum at about 500 degree days, reached a minimum at about 900 degree days, then increased until 1700 degree days (Figure 10C) and was similar to the curve obtained by Grossman and DeJong (1995b). Fruit growth was source limited during the two periods of dry weight increase (Grossman and DeJong, 1995a), which correspond in our results from 200-700 degree days and from 1300-1900 degree days.

Mechanistic models are used to explain the underlying processes of fruit growth (Fishman and Génard, 1998). The accumulation of water is the sum of the water inflow from xylem and phloem and the water outflow due to fruit transpiration. On the other hand, the accumulation of dry matter is the difference between the uptake from phloem and loss through fruit respiration. Biophysical equations are used to calculate the phloem and xylem transport to the fruit and the respiration and transpiration to the ambient air. The model was suitable in simulating growth of fleshy fruits, such as stage-III of peach fruit growth and can explain diurnal fruit shrinkage by combined effects of water status and fruit load (Fishman and Génard, 1998).

4.3. Water relations

4.3.1. Weather conditions, soil water content and water dynamics

Weather conditions

The total water requirement is the amount of water necessary for tree growth and yield, which can be satisfied by irrigation in combination with rainfall (Doorembos and Kassam, 1979). The total water supply (Pefec + Irrig) in the experimental plots was determined at the end of each stage (Table 11), as an important step in comparing among years. The daily water requirement varies during the season, and includes tree transpiration and soil evaporation. The water requirement is dependent on plant, soil and weather conditions. In this study, the equation used to calculate ETc was developed by FAO-56 as ETc = Kc × ETo, with a single coefficient (Allen *et al*., 1998). ETo depends on solar radiation, but also on the drying effect of the wind and of the vapour pressure deficit of the air. On the other hand, ETo is modified by an empirical crop coefficient (Kc) which reflects the water use of the tree during the season. This coefficient includes tree density, training system and tree height, which contribute to the roughness of the tree and soil evaporation that occur during the early period of canopy growth (Girona *et al*., 2004b). In fruit trees water use also depends on fruit load (Mpelasoka *et al*., 2001). In this study, the experimental plots under full irrigation were daily irrigated according to a water budget of the previous week and the crop coefficient (Kc) was obtained from adjusted values to peach orchards in local conditions (Girona, 1996).

Also, the K_{ratio} was calculated to compare different stages, as the total water supply (Pefec + Irrig) divided by total ETo (Table 11). Therefore, during stage-I, K_{ratio} did not meet 1. But at stage-II and stage-III during canopy growth, K_{ratio} approached 1 or would even exceed it. At post-harvest, K_{ratio} again decreased. Because of this variation the total water supply from stage-I to stage-III was 70-90% of cumulative ETo (Table 11). Based on Ben Mechlia *et al*. (2002) such K_{ratio} could be used to compare fruit yield among different years and to determine the effect of irrigation restriction on total soluble solids of the fruit.

Better predictions of ETc may be obtained by the dual crop coefficient methodology, determined as ETc = (Kcb + Ke) × ETo, where Kcb is the crop transpiration coefficient and Ke is the soil evaporation coefficient (Allen *et al*., 1998) and has been be used in peach orchards (O'Connell *et al*., 2006). This Kcb value was obtained from ETc determinations using a large weighing lysimeter (Ayars *et al*., 2003), soil capacitance probes (Parkes *et al*., 2005), a calibrated heat pulse probe (Goodwin *et al*., 2006) or the eddy covariance method (Paço *et al*., 2006). Tree transpiration component was related to effective canopy cover (ECC) at solar noon made from FIPAR determinations during the growing season, then Kcb = 1.5 ECC (Ayars *et al*., 2003; Goodwin *et al*., 2006). Soil evaporation was low under drip irrigation due to low wetted area, then Ke = 0.1 (O'Connell *et al*., 2006).

Soil water content

The amount of water that can be extracted from the soil depends on the depth of the root system and the volume of coarse elements (Porta *et al*., 1994). In this study, the soil orchard was shallow with a high content coarse elements. A shallow root

distribution prevents the water uptake from greater depth (Garnier *et al.*, 1986). Furthermore, peach trees were drip irrigated, which maintains the soil wetter in spots near the trees (Dasberg and Bresler, 1985). Under drip irrigation root system are mostly located in the upper part of soil (Ruiz-Sánchez *et al.*, 2005) and root length density increases within the wet bulb (Abrisqueta *et al.*, 2008). Irrigation water was supplied directly to the tree depending on its requirement, and soil water content changed accordingly. Soil water content decreased from the beginning of the day, and was depleted until lower levels in days with higher ETo (Figure 13). In peach trees, wetting only a part of the root system can maintain the transpiration rate (Doussan *et al.*, 1999). In addition, higher water depletion was observed in July (Figure 13), when canopy size was maximum. At high soil water content, the major resistance to water uptake is located inside the root, as a consequence, root water uptake is proportional to the rooting length density (Mmolawa and Or, 2000). Thus soil water content fluctuations were due to irrigation events and root water uptake within the wet bulb, but root length density is seldom measured (Abrisqueta *et al.*, 2008).

Availability of stored water is determined by limits set by soil physics (Pla, 1994). The water retention points were measured at a suction of 0.033 MPa and 1.5 MPa in the laboratory. The amount of available water was 43.4 mm by taking this difference and soil physical properties. The use of such approach is essential for evaluating soils, that in this orchard presented a low water holding capacity. However, the upper drained level and the lower level of water extraction, need to be determined in the field so that actual changes in soil water content can be observed. For lysimeter grown trees it was found that allowable depletion had to be maintained approximately until 50% for an unrestricted evapotranspiration (Girona *et al.*, 2002). The goal of a well-managed irrigation program is to maintain soil water content between these two levels. In this study, soil water content was measured with capacitance probes (Villar and Ferrer, 2005). But soil heterogeneity required to calculate the soil relative water content (RWC) with the two levels of water extraction obtained for each probe. Soil water content in FI trees followed the same pattern along the three years, with average values always within the range of 100% and 50%, but daily minimums were lower during stage-III (Figure 16). It has been shown that soil water content decreases during the period of fruit growth in peach (Garnier *et al.*, 1986) and in grapevine (Ortega-Farías *et al.*, 2004). According to daily drip irrigation, soil water content is maintained high in apple trees during fruit growth (Ton *et al.*, 2004), but with higher fluctuations from above the 100% level just after an irrigation event until 50% level by soil drying (Figure 15). After fruit harvest soil water content tended to increase. Autumn and winter precipitation were important for recovery of soil water content after post-harvest period (Figure 16).

Water dynamics

Water deficit was determined by a simplified water balance formula (Villar *et al.*, 2002), as ETo – (Pefec + Irrig). The change in soil water content could be correlated to water deficit for each development stage (Table 12). Thus, soil water content decrease was higher for days with higher water deficit. The importance of water balance on soil water content have been reported in different soil types (Pla, 1994).

Also, trunk shrinkage was correlated with soil water content for each development stage (Table 13). The trees were growing on a soil with a low water holding capacity, in which the changes of soil water content on trunk shrinkage were higher under low soil water conditions than when these conditions were better, such as in 2008. In contrast,

the effect of water deficit on trunk shrinkage was higher during 2008 than in 2007 (Table 14). Thus, soil water content and water deficit were found to be the main factors in explaining the course of trunk shrinkage. These results are in agreement with forest tree studies showing that trunk radial changes are correlated with water balance (Bouriaud *et al*., 2005; Zweifel *et al*., 2006). The tree water status is expressed in trunk radius changes and it takes into account that all living parts of a tree are hydraulically interconnected (Fereres and Goldhamer, 2003; Doltra *et al*., 2007; Steppe *et al*., 2008). But according to the results, tree water status was dependent on the environmental factor more limiting, which can be the soil or the atmosphere.

During stage-III, irrigation restriction affected soil water content (Figure 15) and consequently midday Ψ_{stem} (Figure 19A). A threshold level for the onset of Ψ_{stem} decline was established at 72% of soil RWC. This threshold corresponds to an average soil water content of 0.167 m^3 m^{-3} measured with capacitance probes in the soil orchard. This threshold is higher in coarse textured soils than in fine textured soils (Sadras and Milroy, 1996). Thus this threshold reflects that soil water content affects tree physiology (Girona *et al*., 2002).

4.3.2. Fruit growth, weather conditions and changes in Ψ_{stem} and g_s

Seasonal patterns of Ψ_{stem} and g_s under full irrigation

In FI trees, midday Ψ_{stem} decreased along the fruit growth period and attained the lowest value in stage-III (Figure 17C), which coincided to expansive fruit growth. This seasonal pattern of midday Ψ_{stem} has been observed in peach trees (Berman and DeJong, 1996; Goldhamer *et al*., 2002; Bryla *et al*., 2005) and grapevines (Marsal *et al*., 2008; Ortega-Farias *et al*., 2004). This supports the observation that midday Ψ_{stem} is a sensitive indicator of tree water status in stone-fruits, including nectarine (Naor *et al*., 2001), Japanese plum (Naor, 2004; Intrigliolo and Castel, 2006) and French prune (Lampinen *et al*., 2008), and also in grapevines (Williams and Araujo, 2002). After harvest, there was an increase of midday Ψ_{stem} to less negative values (Figure 17C).

In FI trees, midday g_s was low in stage-I, but its pattern changed in comparison to Ψ_{stem}, since g_s increased during the period of fruit growth (Figure 17D), attaining maximum values at the end of stage-III (Marsal and Girona, 1997; Marsal *et al*., 2002). After fruit harvest midday g_s tended to decrease (Figure 17D), which is consistent with the observed behaviour in other species (Yoon and Richterm 1990). However, this seasonal pattern is not always observed in peach trees grown in deep soils (Girona *et al*., 2005). According to Chalmers *et al*. (1983) the development stages of peach are better described according to fruit growth rate in dry weight, because the changes in sink demand of fruits explains the effect on leaf g_s.

Fruits and leaves can be considered as competing sinks for water and assimilates. In trees which are in the stage of high fruit growth rate, assimilates produced in leaves are transported rapidly to fruits, and a substantial level of assimilates are accumulated in fruits toward the end of its development. Thus fruit growth produces a progressive decrease on Ψ_{leaf} (Taiz and Zeiger, 1998). This effect can explain the mechanism that links fruit growth with leaf transpiration and net assimilation rate (Chalmers *et al*., 1983). Fruit thinning and summer pruning can be used to improve tree water status (Marsal *et al*., 2005; Marsal *et al*., 2006; Lopez *et al*., 2006).

Daily patterns of Ψ_{stem} and g_s under full irrigation

A diurnal trend of Ψ_{stem} and g_s was obtained during two different days in stage-III, but with similar weather conditions (Figure 20 and 21, respectively). At the beginning of stage-III, Ψ_{stem} decreased steadily from predawn to midday. But at the end of stage-III, Ψ_{stem} decreased at a higher rate from predawn to midday. In peach trees, Ψ_{stem} shows a recovery at 16:00 of solar time (Garnier and Berger, 1987; Girona *et al*., 1993; Berman and DeJong, 1997a). Diurnal changes of Ψ_{stem} influences peach shoot growth rate that attains its minimum at midday (Weibel *et al*., 2003; Berman and DeJong, 1997b; Basile *et al*., 2003a). Fruit diameter also displays a diurnal pattern (Ton *et al*., 2004). During the daytime, when transpiration reaches its maximum value, the fruit fresh weight does not increase or even diminishes, whereas the dry matter accumulates during this time. The most intensive accumulation of fruit fresh weight takes place during the night (Fishman and Génard, 1998).

The daily pattern of g_s obtained is in the range of other fruit trees (Naor *et al*., 1995; Doltra *et al*., 2007) and forest trees (Köstner *et al*., 1992; Zhang *et al*., 1997), which showed a decreasing trend from the morning, with no apparent recovery in afternoon (Figure 20 and 21). In peach trees, when hourly g_s values are plotted against Ψ_{leaf} values a hysteresis loop appears during the course of the day (Garnier and Berger, 1987). Hourly g_s increases at the beginning of the day, showing a morning peak, with a correspondent decrease in Ψ_{leaf}. Stomatal closure occurs thereafter, but not prevents Ψ_{leaf} to fall further in the midday. Diurnal changes in Ψ_{leaf} not exert a major influence on g_s, whereas stomata closure allows the recovery of Ψ_{leaf} in the evening.

In trees, stomata open at the beginning of the day, as a result of increased solar radiation (Köstner *et al*., 1992), and stomata closes during afternoon in response to increasing VPD (Pataki *et al*., 1998). In peach leaves, a reduction of g_s after the morning peak occurs when the VPD is above a threshold of 1.2 kPa (Garnier and Berger, 1987).

VPD is an important environmental factor controlling stomatal response at daily scale (Jones, 1992). The response of g_s to VPD may be non-linear, which suggests a feed-back control of g_s by VPD. An increase in VPD will involve an increase in leaf transpiration, and consequently a decrease in Ψ_{leaf} that will regulated the stomatal aperture. Also VPD may affect directly g_s thought a feed-forward control, and then g_s decreases linearly with VPD.

Effect of irrigation on Ψ_{stem} and g_s

Irrigation restriction affected midday Ψ_{stem}, which decreased in IR2 trees, but especially in IR3 trees (Figure 18), since stage-III was longer than stage-II (Table 10). Average values were always above the threshold of –1.8 MPa, when visible leaf wilting occurs (Chalmers *et al*., 1983). In contrast, midday g_s was not affected in IR2 trees, and was slightly reduced in IR3 trees (Figure 18). The effect of irrigation restriction is greater on midday Ψ_{stem} than on g_s (Girona *et al*., 2005). After the period of irrigation restriction, complete irrigation supply was restored and midday Ψ_{stem} and g_s tended to recover (Figure 18). However, the recovery of midday Ψ_{stem} is faster than g_s (Natali *et al*., 1985). This delay in g_s recovery may be explained because the leaf has to regain turgor previously (Torrecillas et el., 1996).

In FI trees, the midday Ψ_{stem} followed the same seasonal pattern and attained similar values among the three experimental years (Figure 18), in spite of lower fruit load in 2006 than in 2007 and 2008 (Table 22). This result appears in well irrigated trees, in which midday Ψ_{stem} is independent of fruit load, but under irrigation restriction midday Ψ_{stem} decreases with increasing fruit load (Berman and DeJong 1996; Naor, 2004). However, this later effect was not observed, since midday Ψ_{stem} attained lower values during irrigation restriction, especially in 2006 with low fruit load (Figure 18). Then, weather conditions may explain this behaviour under irrigation restriction, because during the fruit growth period, VPD was higher in 2006 than in 2007 and 2008 (Table 10). Under irrigation restriction, midday Ψ_{stem} decreases with increasing evaporative demand of the air because of the high resistance of water flow through the xylem vessels. As a result, the water balance is affected and midday Ψ_{stem} decreases (McCutchan and Shackel, 1992; Fereres and Goldhamer, 2003). The relation between midday Ψ_{stem} to maximum VPD can be utilized on grapevines to correct the values and thus reduce irrigation dose on days of high evaporative demand (Olivo, 2009).

Predawn Ψ_{leaf} is related to soil water content since it represents the water availability in the soil after the equilibrium of water potential between the soil and the root at the end of the night (Natali *et al*., 1985; Girona *et al*., 1993). Thus, when irrigation was delayed until midday, the predawn Ψ_{leaf} was lower in IR3 than in FI trees, (Figure 20). However, when irrigation was supplied before sunrise, the predawn Ψ_{leaf} was not different between IR3 and FI trees, (Figure 21). Also it was observed how predawn Ψ_{leaf} decreased during stage-III, which occurs during fruit growth (Marsal and Girona, 1997).

During stage-III midday Ψ_{stem} was affected by soil water content (Figure 19A) and midday g_s was negatively correlated with midday Ψ_{stem} (Figure 19B), which is consistent with previous reports (Naor, 2004). In 2007 and 2008, midday g_s decreased largely as Ψ_{stem} became more negative. During a drying period, soil water content is a strong regulator of g_s (Granier and Bréda, 1996) and this stomatal closure may be induced in response to soil drying by a hydraulic feedback through water potential (Jones, 1998).

However, the trees maintained lower values of midday g_s in 2006 as opposed to 2007 and 2008, and it was found that a decrease in midday Ψ_{stem} caused a little change in g_s (Figure 19B). This down-shift is associated with lower fruit load (Marsal *et al*., 2008) or higher VPD (Flore *et al*., 1985) for 2006. The effect of fruit load on g_s from other studies is not clear. Thus, g_s in apple trees without fruits is lower than in trees with fruits during the daytime and along the season (Reyes *et al*., 2006). But this response to fruit load changes in lysimeter-grown apple trees, and g_s is higher in trees with low fruit load, although tree water use is lower, than in trees with higher fruit load (Mpelasoka *et al*., 2001). Also VPD affects stomatal aperture in well watered trees (equation 7), causing a decrease in g_s as VPD increases.

Mechanistic models are used to explain the underlying response of canopy conductance (g_c) to environmental conditions, soil water content and canopy size (Granier and Bréda, 1996). Under non-limiting conditions the maximum canopy conductance (g_{cmax}) depends on light intensity and VPD. Then g_{cmax} is reduced by using multiplicative limiting functions, which depends on soil water content and canopy

growth. Each component function is obtained from appropriate experiments and take a non-lineal form. The Penman-Monteith equation for transpiration has been used with an estimate of g_c to calculate tree water use in peach (Gong *et al.*, 2005).

4.3.3. Effects of irrigation on growth

In peach trees, IR2 strategy reduces shoot extension (Girona *et al.*, 2003). Maximum shoot growth rate coincided with the beginning of stage-II (Figure 11). Also IR2 reduced shoot extension, although without significant effects (Table 9). The effect of irrigation was more important in pruning weight and FIPAR, because these are measures of the whole canopy growth (Dehghanisanij *et al.*, 2007). In IR2 trees canopy size was lower than in FI trees, while IR3 strategy did not affect canopy size when canopy growth had been ceased (Figure 25 and Table 22).

The earliest effect of even mild water deficit is to reduce shoot and leaf growth rate (equation 10; Andersen and Brodbeck, 1988; Stoneman *et al.*, 1994). However, as Ψ_{stem} decreases, leaf growth is inhibited before than leaf assimilation rate (A_n). Rieger and Dummel (1992) demonstrated that leaf A_n (μmol m^{-2} s^{-1}) decreased linearly with Ψ_{stem} (MPa) in peach trees by $A_n = 14.1 + 4.9\ \Psi_{stem}$. Under mild water deficit there is a shift in assimilate partitioning, dry matter accumulates in leaves and leaf weight per area increases (Munns, 1988). SLW was higher in IR2 trees than in FI trees, and this effect was maintained until post-harvest (Table 15). However, IR3 strategy had no effect on SLW. This different effect of irrigation restriction on canopy growth and SLW may be explained by a higher effect of IR2 during active canopy growth, than when shoot growth have been ceased during stage-III (Figure 11).

Peach fruits can experience compensatory growth rates after restoring complete irrigation, following mild IR2, whereas growth rate of fruits on FI irrigated trees remained essentially unchanged (Chalmers *et al.*, 1981; Li *et al.*, 1989). These effects were observed in 2006 and 2007 (Table 7), but not in 2008. In this year, IR2 reduced fruit growth rate in diameter during stage-II, but after restoring complete irrigation during stage-III, growth rate was lower than FI strategy (Table 7). On the other hand, fruit growth is highly responsible to IR3 (Besset *et al.*, 2001) and during all three growing seasons, IR3 reduced fruit diameter growth rate during stage-III (Table 7).

4.4. Mineral nutrition

4.4.1. Leaf nitrogen concentration

Seasonal tree growth is linked to N dynamics (Rufat and DeJong, 2001). The seasonal growth of shoots in length was sigmoidal, with its maximum growth rate during stage-II and then during stage-III growth rate had been stopped (Figure 11). N application increases shoot extension and leaf area (Taylor and van den Ende, 1969; Jia *et al.*, 1999). But there was not a clear effect of N dose on shoot growth (Table 9), probably because shoot extension is highly variable (Marini, 1985). However it was observed that N application increased pruning weight (Table 22) and FIPAR (Figure 25), since these are measures of whole canopy growth. On the other hand, trunk growth continues until leaf fall (Goldhamer *et al.*, 2002; Weibel *et al.*, 2003; Girona *et al.*, 2005) and is affected by N supply (Taylor and van den Ende, 1969). Root N uptake

requires the availability of assimilates (Huett, 1996), thus increases with active leaf growth and remains high during the growth period, then decreases again during leaf senescence (Wallach *et al.*, 1990). Also, white root growth in trees with N application show a rapid increase during May and early June followed by a decrease in mid-June, then there is a rapid decrease because of suberification (Jia *et al.*, 1999).

The application of N maintained higher leaf N concentration and shoot N concentration (Table 16). The effect of N application was also observed in leaf relative light absorbance (α_r) values (Table 15). This response in peach trees was observed since the first experimental year. However, there was not an effect of irrigation restriction on leaf N concentration. In other reports, N application in peach trees also increased leaf chlorophyll content (Almaliotis *et al.*, 1997; Jia *et al.*, 1999), leaf α_r values (Rubio-Covarrubias *et al.*, 2008), leaf N concentration (Taylor and van den Ende, 1969; Rufat and DeJong, 2001) and shoot N concentration (Johnson *et al.*, 2006). Peach differs from other deciduous fruit trees by higher N requirements, and N fertilization is necessary to maintain a suitable tissue N concentration (Faust, 1989). Leaf α_r values and leaf N concentration determined at end stage-III showed a decreasing pattern along the three years, especially in N0 trees. A minimum leaf N concentration of 2.45% was measured in 2008 in N0 trees, but the leaves did not show deficiency symptoms. In peach trees, the range considered as adequate in leaves collected at mid-July is 2.0-3.5% DM (Villar and Arán, 2008). This range is higher for peach trees for processing, reaching 2.6-3.5 % DM (Ogawa *et al.*, 1995), because these trees have to sustain a higher fruit load.

Leaf α_r and N concentration are useful indicators of N status in peach trees (Rubio-Covarrubias *et al.*, 2008). There was a positive relationship between leaf α_r and N concentration at the end of stage-III (Figure 23). Similar results are observed in other woody trees (Porro *et al.*, 2001; Chang and Robison, 2003), although the regression equation changes between species. These changes may be due to leaf thickness and water content (Chang and Robison, 2003). Further analysis show that this equations are also stage specific, in which the slopes are similar among stages, but the intercepts are much more variable (Porro *et al.*, 2001).

Unlike irrigation, there was no a significant effect of N application on midday g_s, although N application increased leaf N concentration (Table 16) and canopy growth (Figure 25). Similar results have been reported in woody trees (Allen *et al.*, 2005). In peach trees net assimilation rate of leaves decreases by high N application (Almaliotis *et al.*, 1997; Jia *et al.*, 1999). N application tended to decrease SLW in peach leaves (Table 15) and in other woody trees (Walters and Reich, 1989). SLW is highly correlated to leaf N content per unit leaf area in peach leaves, at contrasting sun exposures in the field, although the slope increases with N application (Rosati *et al.*, 1999). Also SLW determine the capacity for net CO_2 assimilation rate in different fruit species, linking different leaf physiological processes to environmental conditions (DeJong and Doyle, 1985). The specific leaf weight (SLW) of mid-shoot leaves was higher in 2006 than in 2007 and 2008 (Table 15), because when fruits do not compete with leaves, dry matter accumulates in leaves (Dichio *et al.*, 2007) and leaf weight per area increases (Nii, 1997).

Leaves accumulate the highest N content among all organs during the season and mature leaves were capable of translocating nitrogenous compounds to other organs

(Policarpo *et al*., 2002). According to the results, leaf N concentration decreased from the end of stage-II to the end of stage-III (Table 16). This pattern has been established for peach leaves and decreased during the leaf development period (Batjer and Westwood, 1958; Carpena and Casero, 1987).

4.4.2. Fruit nitrogen concentration

Batjer and Westwood (1958) determined the seasonal pattern of N concentration in the peach flesh, which decreased during stage-I, but tended to increase at the beginning of stage-II of pit hardening. This upward trend continued during stage-II and then declined during stage-III of fruit expansive growth. According to the analysis of the whole fruit, N concentration decreased from the end of stage-II to the end of stage-III (Table 16). This pattern resulted from the balance between fruit dry growth and N accumulation within the fruit (Batjer and Westwood, 1958). Although fruit N demand increased during stage-III (Tagliavini *et al*., 2000), N concentration decreased, due to a dilution effect by rapid increase in dry weight (Rufat and DeJong, 2001).

N application increased fruit N concentration at harvest, but were not significant different between N60 and N120 (Table 16). Fruits are stronger sinks for N than leaves, particularly under low N application (Rufat and DeJong, 2001). In other experiments, N application also increased fruit N concentration of peach (Rufat and DeJong, 2001), apple (Rufat, 2003), apricot (Bussi *et al*., 2003) and cherry (Neilsen *et al*., 2007). However, there was not an effect of irrigation restriction on fruit N concentration (Table 16). In peach there is little information about the effects of irrigation restriction on nutrient composition of fruits (Behboudian and Mills, 1997). The plant growth regulator paclobutrazol, that inhibits shoot growth and increases yield efficiency in peach, did not affect fruit N concentration (Blanco *et al*., 2002b). Under severe irrigation restriction during the fruit expansive stage of apple, accumulation of soluble sugars, amino acids and K occurred in fruits (Failla *et al*., 1992).

Taylor and van den Ende (1970a) obtained a further interesting response to N application on various fruit parts of peach at harvest. Thus, N dose increased markedly the concentration and content of N in the epicarp + mesocarp and in the whole fruit, but only slightly in the endocarp. However, N dose did not influence the N concentration and content of the seed. Seed dry weight was low in comparison to other fruit parts (0.2 g DM), but seed N concentration was very high (42.66 g N mg^{-1} DM) irrespective of N dose (Taylor and van den Ende, 1970a).

On the other hand, fruits without N application showed higher growth rates and higher fruit diameters particularly during stage-II and stage-III, although only with significant effects in 2007 (Table 7), possible because in N0 trees the fruit load was lower and maturity occurred earlier. Rufat and DeJong (2001) observed in peach that low N application stimulated fruit growth, with higher fruit dry weight at harvest. As reported by Saenz *et al*. (1997), N application extended the fruit development period, increasing assimilate availability for fruit growth. High fruit load also extends the fruit development period, and is associated with interfruit competition for assimilates, but the effect of N is greater than fruit load (Saenz *et al*., 1997). In other experiments N application did not significantly influence the dry weight of the fruit parts or whole fruit of peach (Taylor and van den Ende, 1970a).

4.4.3. Nutrient relations

Among the macronutrients analysed in leaves at end stage-III, Ca concentration was the greatest (3.53%), followed in order by N (3.05%), K (1.79%), Mg (0.70%), P (0.18%) and S (0.17%). Similar values were obtained by Batjer and Westwood (1958) and Carpena and Casero (1987). However, the seasonal pattern of leaf concentration in macronutrients displays important differences, P and K decreases as leaf matures due to phloem translocation, while Ca and Mg accumulate in leaves throughout the season (Batjer and Westwood, 1958; Carpena and Casero, 1987; Blanco *et al.*, 2002a). According to the results, leaf P and K concentration decreased from end stage-II to end stage-III, while Ca and Mg increased (Table 17, 18 19 and 20, respectively). Leaf S concentration decreased slightly during the same period (Table 21).

On the other hand, it was observed that increasing the N dose produced a decrease in leaf K, but an increase in leaf S. The effect of N dose on leaf Ca and Mg changed from 2007 to 2008, since N application reduced leaf Ca and Mg in 2007 but increased such concentrations in 2008. Leece (1976b) and Almaliotis *et al.* (1997) analysed peach nutritional status and found that N application was accompanied by a decrease in K, Ca and Mg leaf concentration. In *Citrus* trees, leaf P, Ca and Mg concentration not respond to N application, but leaf K concentration decreases slightly (He *et al.*, 2003). The increase in leaf S concentration by N application may be associated with proteins, because S is the constituent of the amino acids cysteine and methionine, and with the tripeptide glutathione which serves many metabolic functions (Marshner, 1995). Arginine is another amino acid that contains N, and it has been shown the concentration of arginine in roots in dormant trees is the most sensitive indicator of the N status of peach trees (Taylor and van den Ende, 1969).

The IR2 strategy affected the relationship between K, Ca and Mg in leaves (Table 18, 19 and 20, respectively). The strategy IR2 reduced leaf K concentration, while the opposite occurred with leaf Ca and Mg concentration. Furthermore, these effects were maintained after restoring complete irrigation during stage-III. These results are consistent with the importance to K uptake at low soil water content, especially under drip irrigation and coarse textured soils (Bläsing *et al.*, 1990). There is a competitive interaction between K diffusion and Ca and Mg mass-transport from the soil to the root when soil water content decreases (Giulivo, 1990). In grapevines, soil water restriction decreased leaf K concentration and increased leaf Ca and Mg concentration (Bogoni *et al.*, 1995b). The plant growth regulator paclobutrazol, that inhibits shoot growth and increases yield efficiency (Blanco *et al.*, 2002b), affected leaf nutrient concentrations and decreases K while increases Ca and Mg (Huett *et al.*, 1997; Blanco *et al.*, 2002a). Irrigation restriction decreased leaf K concentration in apple (Neilsen *et al.*, 1995) and sweet cherry (Neilsen *et al.*, 2007). During stage-III shoot extension had ceased, and leaf nutrient concentration, measured in IR3 trees was not different from FI trees.

Analysis carried out in winter pruning shoots did not show consistent differences between different treatments, except for N. As an overall average, of the macronutrients analysed in the shoots at winter pruning, Ca concentration was greatest (1.53%), followed in order by N (1.30%), K (0.46%), Mg (0.15%), P (0.12%) and S (0.07%).

4.4.4. Fruit nitrogen exportation and residual soil NO$_3$-N

The annual N fertilizer requirement depends on the tree N demand and the soil N supply, adjusted for the efficiency of N fertilizer uptake (e_f) (Scott *et al.*, 2004):

$$N_f = \frac{N_{demand} - N_{supply}}{e_f}$$

equation 25

The efficiency of N fertilizer uptake for a whole *Citrus* tree is 75% grown in a container with drip irrigation (Quiñones *et al.*, 2003), but may be 13% in a peach orchard with a single N application (Nario *et al.*, 2003).

In fruit trees, a complete N demand balance needs the measurement of the biomass and N concentration of all the various plant components: foliage, fruits, branches and roots (Rufat and DeJong, 2001). However the fruit component is the most important because fruit yield was exported outside the orchard, whereas foliage, pruning branches and roots remain in the orchard and eventually becomes in organic matter. The increase in fruit N concentration by N application was expressed in an increase in fruit N exportation (Figure 24A). For N60 dose, fruit N exportations increased from 19.8 kg N ha^{-1} in 2006, to 57.6 kg N ha^{-1} in 2007 and decreased to 39.6 kg N ha^{-1} in 2008. These fruit N exportations were not different between N60 and N120. Moreover, there was not an effect of irrigation restriction on fruit N exportations.

On the other hand, N supply comes from soil N available during the growing season (Villar *et al.*, 2002). Soil NO$_3$-N was determined in February of each year, after the growing season (Figure 24B). The initial soil NO$_3$-N was 29.8 kg ha^{-1}. Soil NO$_3$-N in N0 and N60 treatments tended to decrease in 2008, while N120 maintained higher values and not decreased until 2009. In peach orchards, soil NO$_3$-N increased linearly with N application until 250 kg N ha year^{-1} (Daane *et al.*, 1995). Reference levels of soil NO$_3$-N are between 10-15 ppm (Villar and Arán, 2008) and higher concentration indicate potential N leaching below the rooting zone (Daane *et al.*, 1995). These levels correspond to 38.7 and 58.1 kg ha^{-1} for this soil, which were not attained in any year (Figure 24B). Also there is a N supply in deciduous trees due to an internal resorption of N from leaves to perennial organs prior to senescence (Killingbeck, 1996). In the following season tree N reserves are used for flower development and new leaf growth (Muñoz *et al.*, 1993).

4.5. Yield components

4.5.1. Total fruit yield and water productivity

Full irrigation

In FI trees, favourable soil water conditions were maintained during the whole period of fruit development. However, yield was lower in 2006 than in 2007 and 2008, due to changes in fruit load (Table 22). Yield increases proportionally with fruit load, up to a threshold. This fruit load threshold and the maximum yield are higher in late maturing cultivars. A lower increase in yield is noticeable when the number of fruits per tree is increased further, probably because of increasing source limitation (Johson and Hanley, 1989). Fruit thinning is used in commercial fruit orchards to adjust the number

of fruits per tree. Although yield is reduced, fruit size is increased, which usually results in greater economic return to the grower. In peach trees, yield is improved if trees are thinning early, either at blooming or when the fruit is recently set (Miranda and Royo, 2002). Hand thinning at 20 days after full bloom is considered the best time to thin peach trees (Njoroge and Reighard, 2008). However, for peach trees for processing, the highest economic return is achieved at a high fruit load with a relatively small fruit size (Reginato *et al*., 2007). In FI trees from 2006 to 2008, total fruit load was 126, 509 and 459 fruit tree^{-1}, respectively. On the other hand, fruit fresh weigh was 195, 131 and 149 g fruit^{-1}, respectively.

N application increases yield (Taylor and van den Ende, 1970a; Saenz *et al*., 1997). The N effect on yield was not significant during 2006. But, in 2007 and 2008, N application supposed an increase in fruit load, canopy size and yield. Also N application increased water productivity (WP) (Table 25), because higher N uptake allowed to increase yield with the same amount of water. However, the increase in fruit yield might diminish by an excess of N application (Kusakabe *et al*., 2006).

Irrigation restriction during stage-II of pit hardening

In early experiments conducted in Australia, irrigation dose was restricted to 50-60% during stage-II to reduce excessive canopy growth and to enhance fruit yield (Chalmers *et al*., 1981). In subsequent experiments IR2 reduced excessive canopy growth (Boland *et al*., 1993) without yield losses (Li *et al*., 1989). However, soil orchard conditions (soil depth and water holding capacity) can affect the response to irrigation restriction (Behboudian and Mills, 1997) in addition to fruit load (Naor, 2006). In small soil volume, irrigation restriction reduced shoot growth much easily (Boland *et al*., 2000). Also, in a shallow soil profile, the relief after IR2 was rapid in less than a week (Marsal and Girona, 1997) but in deep soil profile may take several weeks (Girona *et al*., 1993), determined according to midday Ψ_{leaf}. Under low fruit load, midday Ψ_{stem} tended to recover following IR2 (Naor *et al*., 1999), by reducing tree water consumption (Ayars *et al*., 2003).

From the results of this study in a shallow soil profile (with a low water holding capacity) and unthinned trees, it is shown how IR2 reduced significantly canopy size (Figure 25), without significant effects on yield (Figure 27). Same results are obtained in peach orchards grown in shallow soils (Girona *et al*., 2003) and deep soils (Girona *et al*., 2005) with relatively high fruit load. Adequate irrigation is needed during stage-I when fruit cell division is occurring (Chalmers *et al*., 1981). Once on stage-II of pit hardening, most of the dry matter and water are needed for leaf growth and irrigation restriction reduces canopy growth (Boland *et al*., 1993). Under IR2, there was not an effect of N application on yield in 2007, but in 2008 a positive yield trend of N dose was obtained for both total fresh yield and dry yield (Table 25). Soil water conditions were lower in 2007 than in 2008 (Figure 16).

The application of IR2 strategy, provides a basis for increasing WP, with irrigation water savings but without yield loss (Chalmers *et al*., 1981; Li *et al*., 1989). Thus, IR2 allowed to increase the WP in 2006 and 2007 respect to FI strategy, however IR2 not affected WP in 2008.

Irrigation restriction during stage-III of flesh growth

Tree water requirements in stage-III are much higher than in stage-II (Boland *et al*., 1993; Ayars *et al*., 2003) and fresh yield is more affected than dry yield to IR3, although high fruit loads tend to increase yield sensitivity to irrigation restriction (Berman and DeJong, 1996; Girona *et al*., 2004).

In 2006, an irrigation × N interaction was obtained but it was not consistent, because the data presented a high coefficient of variation (Table 25). Nevertheless, in 2007, the effect of irrigation was dependent on N application (Table 25), and a positive yield effect of N dose in FI trees was observed, while the opposite occurred in IR3 trees. In Figure 27 is shown that higher orchard yield in FI trees were obtained in combination with N120, while in IR3 trees by N60. Thus the lowest orchard yield was obtained in IR3 trees combined with N120. It is interesting to note that in 2008, with higher soil water conditions (Figure 16), the interaction effect disappeared and N application increased fruit yield within all irrigation (Table 25). Yield increases by irrigation up to a threshold level (Naor *et al*., 1999). In Figure 27 is shown that higher orchard yield was obtained in combination with N120.

Although IR3 saved irrigation water, the WP was not different from FI trees, since IR3 decreased significantly fruit fresh yield in 2006 and 2007 (Table 25). In 2008, however, WP of IR3 trees was higher than FI trees, because of irrigation water savings maintaining total yield.

There is a fairly constant relationship in peaches between the cessation of vegetative growth and time of flower initiation (Faust, 1989). After harvest, trees were without fruit load and there was an increase of midday Ψ_{stem} to less negative values (Figure 17C). In early maturing cultivars, with long periods between harvest and leaf fall, irrigation may be restricted after harvest to save irrigation water (Dichio *et al*., 2007). But severe irrigation restriction can have a detrimental effect on yield components in the subsequent season (Naor *et al*., 2005) due to lower fruit set (Girona *et al*., 2003). Irrigation restriction during post-harvest increases the flower density of the following season, but unfortunately also increases the occurrence of double fruits (Johnson *et al*., 1992). In fruit thinned trees, there were no differences between treatments according to fruit yield or fruit size, but fruit ripening was somewhat delayed (Larson *et al*., 1988). Complete irrigation supply during post-harvest to all the treatments and autumn precipitation was therefore important for maintaining soil water conditions (Figure 16).

4.5.2. Fruit weight at harvest

Average fruit fresh weight at harvest was affected by irrigation water supply. Also fruit dry weight depended on the relationships between the total fruit load and the canopy size.

Fruit load/Pruning weight ratio

Important effect of IR2 was the reduction of pruning weight respect to FI, while N application tended to increase pruning weight. Pruning weight is well correlated with leaf area (Naor *et al*., 2002), and therefore, may serve as a practical indicator of canopy growth. Since fruit load (Q) and pruning weight (P) were different among years, the Q/P

ratio was determined (Table 22). Irrigation restriction increased the Q/P ratio in comparison to FI trees, particularly in IR2 trees. In contrast, the Q/P ratio decreased under N application. The decrease of Q/P ratio is related with an increase of the source strength of leaves since it favours the availability of assimilates to sink demand for fruit growth (Reginato *et al*., 2007). The Q/P ratio was used to compare the fruit weight under different irrigation strategies to obtain a potential relationship (Table 23). Irrigation restriction reduced significantly the fruit fresh weight respect to FI strategy, mainly under IR3. In contrast, only IR3 reduced significantly the fruit dry weight respect to FI strategy.

Fruit growth is highly affected by IR3 (Berman and DeJong, 1996; Girona *et al*., 2004), as an important proportion of water and assimilates are accumulated in the fruit during stage-III (Figure 10). In addition, high fruit loads tend to increase the sensitivity of fruit growth to IR3 (Berman and DeJong, 1996; Girona *et al*., 2004). Any factor that reduces the leaf A_n during the stage-III, have a greatest influence on fruit growth, when the fruits are the major sink of assimilates (Chalmers *et al*., 1983). In IR3 trees, the leaf A_n decreases and shows an earlier saturation as the PPFD rises (Besset *et al*., 2001), and incident PPFD is most important during the second half of stage-III (Marini *et al*., 1991). Therefore in a shallow soil profile, IR2 reduced fruit fresh weight at harvest as an indirect effect through Q:P ratio, while fruit dry weight was not affected (Figure 26). On the other hand, IR3 reduced fruit fresh weight and dry weight at harvest (Figure 26), as a direct effect through a restricted water supply and changes in leaf functioning (Besset *et al*., 2001).

Water status and fruit growth in stage-III

There was a significant positive correlation between fresh growth rate and water status during stage-III, both measured as mean daily soil RWC and midday Ψ_{stem} (Table 24). Thus, fresh growth rate increased with water status in stage-III. However, this correlation was not significant for dry growth rate, which was independent of water status, both in the soil and in the tree. Fruit fresh weight at harvest decreases under lower midday Ψ_{stem} during stage-III in Japanese plum (Naor, 2004) and grapevine (Olivo, 2007). When IR3 is applied to peach trees, fresh growth rate decreases as midday Ψ_{stem} decreases, but dry growth rate is not affected for values of midday Ψ_{stem} less negative than -1.12 MPa (as an average during stage-III), but decreases linearly below this threshold (Girona *et al*., 2006). This threshold was surpassed in IR3 trees during the stage-III of 2006 and 2008, but not in 2008 (Figure 18). According to Naor *et al*. (2001) the sink:source ratio is an important tree factor that affects tree water status. Consequently, average fruit size at harvest depended on both the Q:P ratio and the tree water status.

4.6. Fruit quality

Irrigation restriction during stage-II of pit hardening

In addition to rapid changes in the growth rate during stage-III, the process of fruit maturation begins, identified by physical and chemical changes (Chapman *et al*., 1991; Jia *et al*., 1999; Gelly *et al*., 2004). Chalmers and van Ende (1975) reported that fruit chlorophyll concentration increased during stage-I, then decreased rapidly during the first half of stage-II, and declined less rapidly through the first half of stage-III before

declining rapidly during second half of stage-III. The percentage of fruit dry matter (PDM) increases during stage-II of pit hardening and then decreases during stage-III of flesh expansion (Girona *et al*., 2005). Also flesh firmness declined rapidly during stage-III (Figure 31). Sucrose, which is the major sugar constituent of peach fruits, contributes largely to the increase in total sugar concentration during the ripening stage, although fructose, glucose and sorbitol decreases and inositol remains very low (Jia *et al*., 1999). Malic acid, which is the prominent acid in peach fruits, decreases rapidly during the ripening stage (Jia *et al*., 1999).

During the three growing seasons, IR2 increased significantly the fruit PDM at the end of stage-II (Table 27), however after restoring complete irrigation, the fruit PDM at the end of stage-III was not different from FI trees (Girona *et al*., 2005). IR2 increased the total soluble solids (TSS) at harvest only in 2006, when fruit size was higher, but not in 2007 or 2008 (Table 27). In IR2 trees flesh firmness and puree TSS was higher than FI fruits in all the sampling times (Table 27 and 28), although these effects were not significant. In a previous reports IR2 increase the TSS of peach fruits, but not affect flesh firmness (Gelly *et al*., 2004). Also, IR2 did not affect fruit quality at harvest measured according to puree consistency (Table 28). Nevertheless, during the three growing seasons, IR2 increased fruit drop (Figure 28A) and harvester efficiency (Table 26), which are indirect measures of fruit ripening. Conversely, IR3 had no effect on fruit drop or harvester efficiency. The effect of IR2 is consistent with other ripening processes. Fruit of IR2 strategy start the climacteric phase earlier than FI fruits and ethylene production increases, which is the most sensitive parameter of fruit ripening (Gelly *et al*., 2004). This effect occur although complete irrigation is restored during stage-III. Also, within IR2 trees, harvester efficiency was higher in trees without N application (Table 26). In addition, IR2 tends to turn red the peach skin colour with high a* coordinate and lower hue angle than FI fruits (Gelly *et al*., 2004), which was observed in IR2 fruits but without significant effect (Table 30). Enhancement of colour is an indirect effect of reduced canopy growth, which affects intercepted radiation. Summer pruning improved light penetration in tree alleys (Marini *et al*., 1991) like as IR2 strategy increased the fraction of PAR transmitted to the ground (Figure 25). Peach fruit covered for 20 days and then exposed to full sun for 20 days before harvest developed better skin colour than if continually exposed (Marini *et al*., 1991).

Irrigation restriction during stage-III of flesh growth

Irrigation restriction during the final stage of fruit growth is more decisive in terms of fruit quality, since IR3 reduces fruit size (Behboudian and Mills, 1997). IR3 increased significantly the juice TSS (Table 27) and puree TSS (Table 28) at harvest, although TSS measure in puree were higher than the correspondent juice samples (Figure 32). Nowadays fruit sugar concentration did not suppose any extra price, but it is appraised by processing industry. Irrigation restriction produces sweeter fruits in a wide range of species (Li *et al*., 1989; Crisosto *et al*., 1994; Besset *et al*., 2001; Mpelasoka *et al*., 2001; Ben Mechlia *et al*., 2002; Pérez-Pastor *et al*., 2007). The primary factor affecting elevated concentrations of fruit sugars under IR3 was the result primarily from high sugar concentration, low water content, and small fruit size, but not more sugar per fruit (Behboudian and Mills, 1997). The fruit samples obtained at harvest from the three years, showed a linear relationship between juice TSS and fruit PDM (Figure 30). The increase in TSS is related to an increase of fruit PDM in apple (Kilili *et al*., 1996; Mpelasoka *et al*., 2001), suggesting part of the increase in TSS is due to water loss from the fruit. Fruit TSS is negatively correlated with fruit load

(Crisosto *et al*., 1997) and increases with increasing leaf area to fruit weight ratio (Naor *et al*., 2002). However, severe irrigation restriction can elicit specific metabolic effects that are manifested in changes of specific sugars, like increase in fruit sorbitol concentration under soil water restriction (Failla *et al*., 1992). On the other hand, IR3 increased flesh firmness in 2007, but this effect was not observed in 2006 and 2008 (Table 27). Fruit firmness depends of fruit size, with smaller fruits being generally firmer than large fruits due to higher cellular density. Then the influence of irrigation on fruit firmness has to account the relation with fruit size (Behboudian and Mills, 1997). However IR3 did not affect puree consistency (Table 28) or flesh colour (Table 30). Fruit nutrient demand increased during stage-III (Tagliavini *et al*., 2000), but IR3 did not affect the fruit nutrient concentration. As an overall mean, of the macronutrients analysed in the fruit at harvest, K concentration was greatest (11.92 mg g^{-1}), followed in order by N (6.96 mg g^{-1}), P (1.06 mg g^{-1}), Ca (0.58 mg g^{-1}), Mg (0.57 mg g^{-1}) and S (0.29 mg g^{-1}).

Nitrogen application

Although N application significantly affected fruit quality, there was no significant interaction between irrigation and N application (except in flesh colour). Similar results were obtained in *Citrus* trees (He *et al*., 2003). Fruit fresh weight decreases by excess N application in peach (Saenz et al., 1997) and *Citrus* (Andrews and Brathwaite, 2006). This effect was observed in 2007 during seasonal fruit growth (Table 7), and may be associated with higher fruit loads (Table 22). Moreover, excess N application delays ethylene production during fruit ripening in apple fruits (Rufat, 2003) and impairs the quality parameters at harvest of peach fruit (Daane *et al*., 1995) and of the peach puree obtained (Olienyk at el., 1997). According to the results, the application of 120 kg N ha^{-1} year^{-1} provides a higher N dose for this peach orchard, since it delayed fruit ripening: increased flesh firmness (Table 27), decreased puree consistency (Table 28) and delayed flesh colour changes (Table 30). However, N application did not affect the fruit PDM (Table 27), the juice TSS (Table 27) or the puree TSS (Table 28). Under highest N application, the decrease in the a* coordinate was accompanied by an increase in b* coordinate (Table 30), indicating that the flesh colour was less red and more yellow than in fruits without N application (Jia *et al*., 1999). The chroma of peach flesh under high N application was significantly more saturated compared to the N0. Likewise, the hue angle was significantly higher than that of N0 (Table 30). Flesh firmness and ground colour generally are used as indices of maturity negatively correlated in peach fruits (Crisosto *et al*., 1997) and flesh firmness and ethylene production are negatively correlated in apple fruits (Rufat, 2003). In the obtained peach puree, consistency decreased significantly as N dose increased (Figure 33) and fruit N concentration was the main nutrient responsible for the consistency properties of the purees (Table 29). N application increased fruit N concentration at harvest, significantly in 2008 (Table 16). Whole fruit nutrient concentration did not show consistent differences between different treatments, except for N.

5. Conclusions

In a shallow soil, irrigation restriction affected soil water content and tree water status. Trunk shrinkage, measured with dendrometers, showed a negative correlation with soil water content, measured with capacitance probes. There was also a positive correlation between soil water content with water deficit determined by the water balance equation (ETo – (Irrig + Pefec)). During stage-III, a threshold of 0.167 m^3 m^{-3} of soil water content was established based on midday values of Ψ_{stem}. Unlike irrigation, there were no significant effects of N application on tree water status.

Water relations and N dynamics affected canopy growth and mineral nutrition with consequences for yield and fruit quality. N application increased linearly the N concentration in leaves, fruits and dormant shoots. Thus, N application brought an increase in fruit load and canopy size. In FI trees, the application of N120 increased the total fruit yield by 13% in comparison to trees without N application. Therefore N application increased the water productivity.

Fruit growth rate has an important effect on seasonal changes of midday Ψ_{stem} and g_s. Their pattern was modified by VPD and to a lesser extent by fruit load. The fruit dry weight at harvest decreased non-linearly with increasing source limitation, determined as fruit load divided by pruning weight. In all years, the percentage of fruit dry matter was positively correlated with the total soluble solids, determined at harvest.

The application of IR2 during pit hardening reduced significantly the pruning weight, without significant effects on total fruit yield. This allowed an increase in the water productivity up to 12.37 kg m^{-3} for IR2 trees in comparison to 11.37 kg m^{-3} for FI trees in 2007. IR2 strategy also enhanced fruit ripening. On the other hand, IR2 reduced leaf K concentration, while the opposite occurred with leaf Ca and Mg concentration. Also, IR2 increased the specific leaf weight. These effects were maintained although full irrigation was restored during the stage-III.

The application of IR3 during flesh growth decreased fruit size at harvest by 12% but increased the total soluble solids by 8% in comparison to FI trees. During stage-III, there was a negative correlation between fresh growth rate and water status, measured as soil water content and midday Ψ_{stem}, but dry growth rate was less affected by water status. In addition, under low water conditions during stage-III, N application reduced yield. Thus the lowest yield was obtained in the IR3 combined with N120.

The harvester efficiency was about 85% and there was no statistical differences between treatments in this parameter.

Under the experimental conditions, the optimal N application would be between 60 and 120 kg N ha^{-1} $year^{-1}$, since the highest N application delayed fruit ripening, observed in flesh firmness, puree consistency and flesh colour.

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