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DOTTORATO DI RICERCA INTERNAZIONALE IN INGEGNERIA AGRARIA

XXV CICLO

Dott.ssa Rosaria Parisi

Deficit Irrigation Strategies on young orange trees (*cv* Tarocco Sciara)

TESI DI DOTTORATO

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1. Introduction

1.1 Foreword

The continuous growth of population, together with the improving desire for higher live standard, are straining the water resources all over the world, not only in traditionally arid and semi-arid areas, but also in regions where rainfall is abundant. This problem particularly involve food production systems for several reasons: such as the fact that agriculture represents the major user worldwide; another reason is the intensifying competition for water between different economic sectors.

The environmental and economical sustainability of citrus orchards has to cope with the availability and management of water resources for irrigation. The irrigation requirements of citrus vary with climatic conditions and variety. Less rainfall usually results in higher irrigation requirements, but even in an extremely wet year considerable irrigation may be needed because of poor rainfall distribution in subtropical climates such as Mediterranean area. Among the Mediterranean countries, Italy is the third largest citrus producer after Spain and Egypt (Fao, 2010). Sicily (South Italy), represents almost 55% of total area covered by citrus in Italy, when orange orchards represent one of the most relevant components in the agricultural economy, as well as in the exploitation of water resources. About 37,000 farms extend for about 71,000 hectares, with 2.478,000 tonnes of harvested production (Eurostat 2006 and ISTAT 2010). The amount of water used for these productions is approximately 300-350*10^6 m^3/year.

One issue that adds uncertainty to the future water supply is that of climate change: if the predictions of climatic change is materialized, increased droughts will cause serious damage especially to agricultural production (Hsiao *et al.*, 2007). Further, energy analysis of agricultural operations has shown that irrigation consumes a significant amount of energy as compared to other operations. For these reasons, there is an urgent need to use water resources efficiently by enhancing crop water productivity: accurate irrigation scheduling is one of the major tools farmers can utilize to achieve this goal. Irrigation scheduling has been studied in detail for decades, and significant progress has been achieved over the years in the understanding of water transport through the soil-plant-atmosphere continuum (Naor and Cohen 2003). Furthermore, for correct water resource management, several tools and decision-making systems are necessary while paying close attention to aspects such as profitability, water cost, etc.

In Europe, the policies relating to water use (Directive 2000/60/EC) pay particular attention to the need of its protection and conservation. To ensure this, a large number of measures, including the establishment of prices which really correspond to their usage costs, were exposed (Ortega *et al.*, 2004). The debate over the price of water is complex, considering that it is a natural environmental resource.

It is generally accepted that many factors (environmental, landscape, social, cultural, etc.) influence the economic valuation of water. The efficient use of water resources will be a fundamental target for farmers and water management. For this purpose, there is an urgent need of methodologies that allow us to analyse, as precisely as possible, the effect of water price on the agricultural production process. The analysis must focus, mainly, on irrigation strategies to maximise gross margins and profits, taking into account the limits and restrictions imposed by the sustainability of the production system. The price of water is obviously not the only factor taken into account in this process. There are other factors to be considered, e.g. distribution uniformity, application efficiency, and irrigation scheduling (Ortega *et al.* 2004). Therefore, innovations are needed to increase the water use efficiency (WUE), ratio between crop production and irrigation water, and to develop new irrigation scheduling approaches, not necessarily based on full crop water requirement, but something designed to ensure the optimal use of allocated water. There are several irrigation technologies which can be adapted for more-effective and rational uses of limited water supplies; for example, drip and sprinkler irrigation methods are preferable to less efficient traditional surface methods (Goodwin and Boland, 2000).

To cope with scarce supplies, one way to optimize water resources, by reducing losses and defining more efficient water allocation during water scarce periods or droughts, is to employ Deficit Irrigation (DI) strategy (Fereres *et al.*, 2007). By means these strategies the crops are exposed to a certain level of water stress either during a particular period or throughout the whole growing season. The major obstacles are that DI involves the use of precision irrigation[1] and some risks associated with the uncertainty of the knowledge required.

Regulated Deficit Irrigation (RDI) and Partial Root Drying (PRD) are two Deficit Irrigation strategies. RDI was developed (Goodwin and Boland, 2000) to improve control of vegetative vigour in high-density orchards in order to optimize fruit size and quality. RDI usually applied during certain phenological phases more tolerant to water stress, but it can also be applied after harvest in early-maturing varieties. Furhermore, RDI can generate considerable water saving. Thus, it is useful for reducing excessive vegetative vigour, and also for minimizing irrigation and nutrient loss through leaching (Chalmers *et al.*, 1984).

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[1] Precision irrigation provides a means for evaluating a crop's water requirement and a means for applying the right amount at the right time. often, in the literature, precision irrigation is referred to as irrigation scheduling; it is based on environmental data, whether that data comes from local field sensors or from more global sources such as regional meteorological information (Marks, 2010).

The success of the Partial Root Drying (PRD) is based on maintaining alternate regions of wet and dry soil within the crop root zone: a percentage of crop evapotranspiration is applied to alternate plant sides, allowing part of the root system to be in contact with wet soil all the time (Capra *et al.*, 2008). This approach of watering alternate sides of the plant induces the plant to set up a hormonal/chemical response that increases crop water use efficiency.

Moreover, DI techniques allow the application of irrigation below the full crop evapotranspiration (ET): for these reasons, to quantify the level of DI it is at first necessary to define the full crop ET requirements. Measurements of ET_c are often highly variable due to variations in measurement techniques and the differences in their relative accuracies. There is no unerring method to obtain an accurate measure of ET_c due to the variability and complexity of climatic factors and biophysical variables, including plant density, species diversity, height, number of leaves, leaf characteristics, etc., involved in the process (Consoli *et al.*, 2006). At present, the Penman-Monteith equation is the estabilished method to determine the ET of the major herbaceus crops with sufficient precision for management purposes, while, there is more uncertainty when the same approach is used to determine the ET requirements of tree crops and vines (Fereres *et al.*, 2007). Nevertheless, DI strategies involves the use of highly efficient irrigation systems (e.g., microirrigation) that favour water saving and it also requires knowledge also on crop response to water deficit and the prediction of the cost function and crop price (English and Raja 1996).

1.2. Objectives

The aim of this work is the evaluation of the effects of Deficit Irrigation (DI) strategies on growth, production features of young orange orchards in the Mediterranean climate environment of Eastern Sicily (Italy).

During the three years of experimental works (2010-2012), were applied two of the most interesting applications of irrigation deficit techniques, and more specifically: RDI strategy (Regulated Deficit Irrigation), involving the reduction of irrigation supply at fixed stages of citrus vegetative development; PDR (Partial Rootzone Drying) strategy, through which the irrigation volume is applied only to one side of root system and the system is switched to the other side to create a wet area (wet) as opposed to a dry area (dry).

Experimental trials have involved:

- The evaluation of Deficit Irrigation effects on orange orchards production features by monitoring soil water transfer and selected physiological plants parameters;
- The comparison of different DI strategies, such as RDI (Regulated Deficit Irrigation) and PRD (Partial Rootzone Drying);
- The possibility to achieve water savings, a significant control vegetative and reproductive growth.

Furthermore, the application of DI strategies is integrated with the adoption of highly performance irrigation technologies, and in particular Surface Drip Irrigation (SDI) and Sub-Surface Drip Irrigation (SSDI), designed to allow the application of the selected deficit conditions.

The research program will contribute to evaluate the suitability of DI strategies and their application of orange orchard stands that represent the main crops in the Sicilian agriculture context. These crops contribute in a substantial way to the economy and productivity of the primary sector of MED island. Thus, more efficient water allocation strategies are needed to sustain these crops productivity within a general decreasing trend context for water supply. If the results obtained, partial though they are, will be confirmed in the next years by productivity data, they could have a great practical importance because of a relevant water saving, since farmers use volumes even twice over the full irrigated thesis.

2. Deficit Irrigation

2.1 Concept and definitions of Deficit Irrigation

The term mainly refers to irrigation below full crop evapotranspiration (ET_c), but it also includes other concepts. English defines DI as the "deliberate and systematic under-irrigation of crops" (English, 1990; English and Raja, 1996) and develops an analytical framework to estimate the profit-maximizing level of water use.

The concept of deficit irrigation was born in the 1970s. In 1971, James *et al.* used the term DI in a book on the economics of water resource planning, and the first research into DI appeared in the early '80s (English and Nuss, 1982; Hargreaves and Samani, 1984), even though the most significant literature on DI regards the last two decades. Although the DI concept dates back to the 1970s, this technique is not usually adopted as a practical alternative to full irrigation by either academics or practitioners. Until the 1990s, for example, the main text books dealing with irrigation system design described formal operations under the paradigm of providing sufficient water to avoid water deficits at all time, thus to achieve maximum yields. Recently, an amount of research into DI is available in the literature , although it has been characterized by slow progress and several obstacles. One obstacle is related to the need for precision irrigation required by DI strategies, e.g. knowledge of crop evapotranspiration and crop response to water deficit, the use of highly efficient irrigation systems that favour water saving, and prediction of the cost function and crop price. This knowledge spans a wide range of disciplines, from ecophysiology and plant sciences to hydrology, engineering end economics. Considering the current trend towards specialization in each discipline, the approach to DI may often be hard.

Another reason for the slow progress of DI is the risk associated with the uncertainty of the knowledge required.

English (English, 1990; English and Raja, 1996) defines DI as the deliberate and systematic under-irrigation of crops and it is the optimization strategy whereby net returns are maximized by reducing the amount of irrigation water applied to a crop to a level that results in some yield reduction caused by water stress. Nevertheless, a certain yield reduction is necessary in the DI concept and crops are subjected to under-irrigation during the entire biological cycle.

The English definition of DI was interpreted in several ways by various authors: a number of papers on DI, adopting the English definition, have created some misunderstanding because they only deal with the physiological and agronomical aspects of this strategy without any economic evaluation, while a few papers use the English definition in its complete sense, e.g. the economics of deficit irrigation.

In his study Lecler (1998) made the definition of English more explicit: DI is an optimization strategy whereby net returns are maximized by reducing the amount of irrigation water applied to a crop to a level that results in some yield reduction caused by water stress.

Supplemental irrigation (SI), used in both humid and arid temperate zones, is a measure to integrate rainfall and stabilize production. In drier areas, SI can be a form of RDI; in fact, the few (one or two) applications of SI were performed in appropriate crop growing stages in order to maximize crop yield, efficiency and profit (Oweis and Hachum 2006).

Brugere and Lingard (2003) maintains that DI should be renamed “irrigation deficit (ID)” when deficit is a forced choice for resource-poor cultivators. Nevertheless, intentional DI implies risk, while forced ID implies vulnerability; according to Capra (Capra *et al.*, 2008), it would probably be more correct to deal with crop production functions instead of DI. In fact, the analyst must rely upon a crop production function that relates water use to crop yield in order to plan, design or manage irrigation systems for DI. When no economic analysis is made, it is difficult to choose the optimal depth of irrigation water, mainly in cases where crop yields corresponding to different water depths are very close.

Deficit irrigation strategies answer the questions "Under-irrigate by how much?" and "When should deficit be imposed?"; another question concerning the DI approach is "How should the deficit be imposed" (Capra *et al.*, 2008). To answer the last question, it is necessary to define particular kinds of DI:

I. *Regulated o Controlled Deficit Irrigation* (RDI - CDI), whereby the plants are generally irrigated to replace 100% ET_c; while during certain phenological phases more tolerant to water stress irrigation water decreased and ET_c is reduced by a certain percentage and a little yield losses are expected.

II. *Partial Root Drying* (PRD), where the irrigation is periodically applied only to one side of root system and the system is switched to the other side to create a wet area (wet) as opposed to a dry area (dry).

2.2 Economics of Deficit Irrigation

Recognition of the following four key factors is extremely important to understand the potential benefits of DI (English, 1990; English and Raja, 1996; Lecler, 1998):

I. The efficiency of irrigation water decreases as the application depth increases.

II. The application of irrigation water is expensive.

III. The water saved by reducing irrigation depth can be used to extend the amount of land irrigated (opportunity cost of water).

IV. The determination of an optimal irrigation strategy depends on whether a shortage of land or of water is the limiting production factor.

2.2.1 Efficiency of the strategy

Generally, deficit irrigation increases water use efficiency for several reasons (Hsiao *et al.*, 2007; Sepaskhah and Ghahraman 2004). Firstly, increases in application efficiency (E_{appl}) occur when the amount of water applied is lower than full ET, because the water applied remains in the root zone (e.g. water lost by run-off and deep percolation decreases). The consumption efficiency (E_{et}) (i.e the ratio between the amount of evapotranspired water and the amount of water in the root zone) may increase because crops are forced to extract higher water levels from the soil. Furthermore, the yield efficiency (E_{yld}) (e.g. the proportion of biomass in the harvested product) may be enhanced due to an excessive vegetative growth of some crop species (cotton and grapevines, for example) during full irrigation.

In order to plan, design, or manage irrigation systems for Deficit Irrigation, the researcher must rely upon crop production functions (Fig. 2.1) that relate water use to crop yields and may generally be expressed by a quadratic form eq. 2.1:

$$y(w) = a_1 + b_1 w + c_1 w^2 \qquad (2.1)$$

But the inherent uncertainty of production functions makes it virtually impossible to predict yields exactly; hence, it is impossible to know precisely what level of water use will maximize profits.

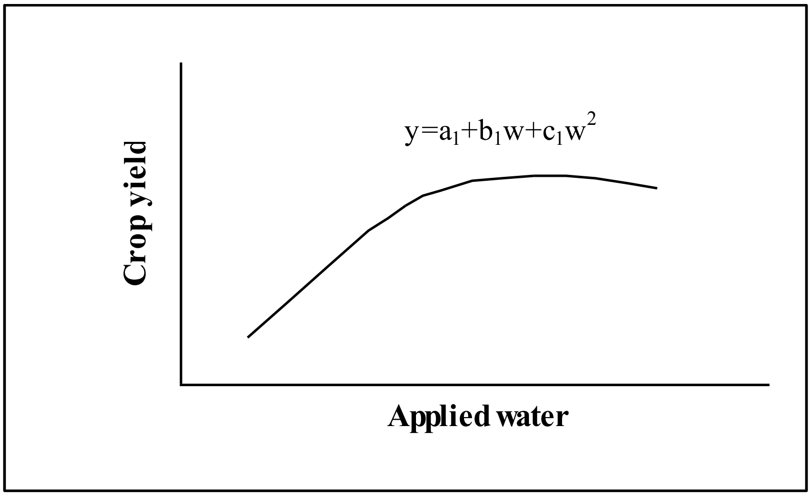


Fig. 2.1 General form of crop production function (English and Raja, 1996).

The analytical framework leads to estimates of the profit-maximizing level or water use for any given set of circumstances. It also provides estimates of the range of water use within which DI is more profitable than full irrigation (English, 1990).

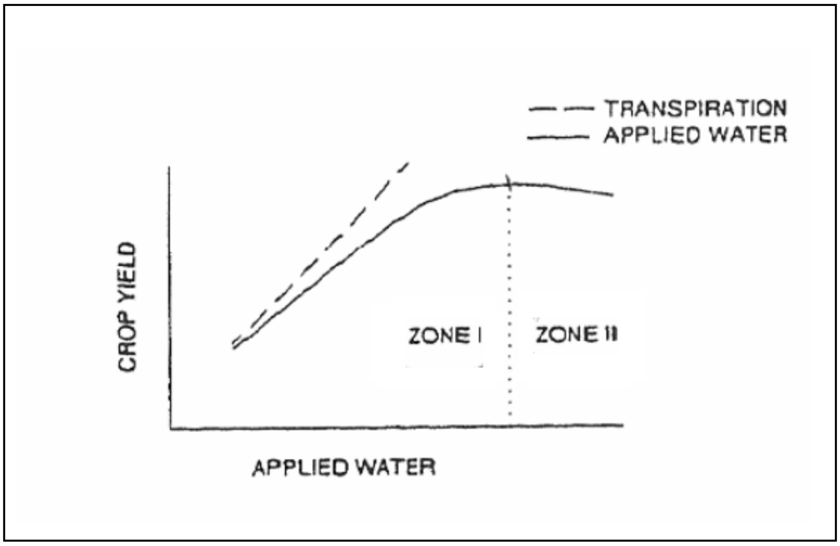


Fig. 2.2 Relation between transpiration and water applied (English, 1990).

In the Fig. 2.2 the dotted line represents the relationship between transpiration and yield, and the solid line represents the relationship between water applied and yield.

The applied water curve is divided into two zones: zone I can be characterized as the under-irrigation zone, and zone II as the over-irrigation zone. When a small amount of water is applied it will be almost completely used by the crop. The transpiration and applied water curves will be roughly coincident. At higher levels of applied water the function begins to curve over, reflecting various water losses that develop as water use approaches full irrigation. Deep percolation increases with increasing applied water. If the increase in applied water is associated with higher irrigation frequencies, greater evaporation may occur with relatively little increase in yields. This decline in efficiency is largely associated with variability in applied water, crop and soil characteristics (English 1990).

The applied water curve in zone I will therefore roughly coincide with the linear transpiration line for low level of water use, but will curve away from the transpiration-yield line at an accelerating rate as higher levels of water use are reached. The shape of the curve in zone II is influenced by other factors. The curve begins to decline as a consequence of such things as reduced aeration in the root zone, leaching of nutrients, and diseases associated with wet soil. Since the factors that influence yields in zone II are altogether different from those in zone I, a different mathematical formulation will be appropriate for zone II (Solomon, 1985).

Hart *et al.* (1980) have suggested that when applied water exceeds crop water requirement, the net income will decline as a linear function of applied water. On the basis of these considerations, Solomon (1985) suggested that in zone II yields might reasonably be approximated by a function that declines linearly with excess water use.

According to English and Raja (1996), the potential benefits of Deficit Irrigation derive from three factors: increased irrigation efficiency, reduced costs of irrigation and the opportunity costs of water.

Estimated revenue from irrigation of this field can be represented by a revenue function relating gross income to applied water. The revenue function would be the product of the production function and the crop price, defined by the eq. 2.2:

$$R(w) = P_c\, y(w) \tag{2.2}$$

where *R(w)* is revenue per hectare, y(w) is the crop production function (Fig. 2.1), *w* is the depth of water applied and P_c is the price per unit weight paid for the crop.

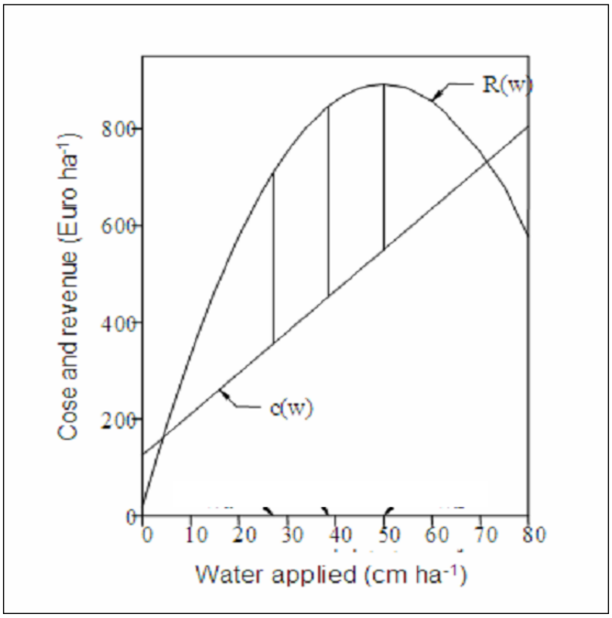


Fig. 2.3 Revenue and Cost functions modify.

The straight line in Fig. 2.3 is a simple cost function, with an intercept that represents fixed costs and a slope that represents variable costs:

$$c(w) = a^2 + b^2 w \tag{2.3}$$

The cost function has three important features. The first is its lower limit, the intercept with the vertical axis, which is associated with capital costs, taxes, insurance, and other fixed costs of irrigation, as well as fixed costs of tillage, planting, chemical use and harvest. The second feature of the cost function is the slope, which represents the marginal variable costs of production. These include the variable costs of irrigation, such us pumping costs, labor, and maintenance. Other costs may also vary with yield, as yield varies with water use. The third feature of the cost function is the upper limit, shown as a straight line nella fig precedente, which represents the maximum water delivery capacity of the system. Profit, which is calculated by subtracting costs from revenues, is indicated by the vertical difference between these two lines (Fig 2.3).

$$R(n) = R(w) - c(w) \tag{2.4}$$

The economics of Deficit Irrigation developed into a set of mathematical expressions for determination of optimum water use under deficit irrigation. These expressions also can be used to estimate the range of water use within which Deficit Irrigation would be more profitable than full irrigation. The expressions are completely general in the sense that they can be used with any crop production functions and cost functions.

English (1990) and English and Raja (1996), analyzing the economic feasibility of Deficit Irrigation techniques, have identified some variables (W_m, W_l, W_w, W_{el}, W_{ew}) which represent the optimum levels of applied water, which provide maximum profit and food production with a limited availability of both land and water resources (Fig. 2.4).

(a) level at which crop yield per unit of land is maximized, $W_{m;}$

(b) level at which net income per unit of land is maximized, $W_{l;}$

(c) level at which net income per unit of water is maximized, $W_{w;}$

(d) level at which net income equals that at full irrigation when land is limited, $W_{el;}$

(e) level at which net income equals that at full irrigation when water is limited, $W_{ew.}$

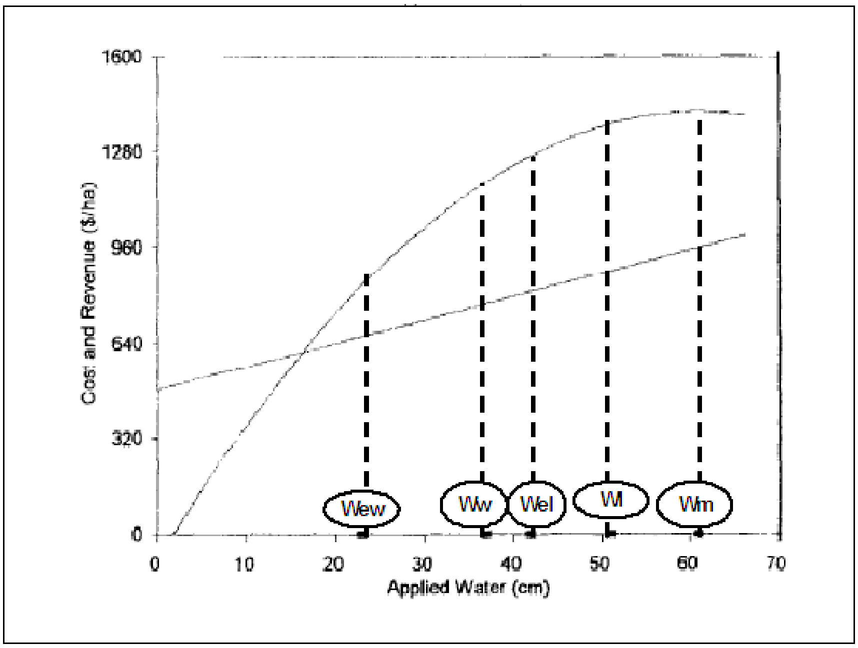


Fig. 2.4 Cost and revenue functions (English and Raja, 2006) modify.

At the W_m level, marginal water use efficiency is zero, thus the application of additional water does not increase yield. When the amount of applied water is below W_m, the marginal efficiency of the last water increment will be greater than zero, since water increments determine some crop yield increments; marginal water use efficiency increases as water depth decreases.

Profit per unit of land reaches its maximum when the level of applied water is W_l; at this point the cost line slope equals that of the revenue line and the net income per unit of water (difference between revenue and cost) is maximum. Within the range between W_l and W_m growers may benefit from cost reductions. If additional land can be irrigated, the optimal water use strategy to maximize profit could be to irrigate below W_l, indicated as the W_{el} level. At optimal levels W_{el} (land-limiting case) and W_{ew} (water-limiting case) the vertical difference between the revenue and cost lines equals that at level W_m. Within the range between W_{el}, for the land-limiting case, or W_{ew}, for the water-limiting case, and W_m (named range of profitable deficits) the net income associated with the level of deficit is at least as great as it is at full irrigation. The increase of the profitable deficit range may represent an indication of the potential risk related to deficit irrigation strategies.

English (1990) derived general expressions to estimate the above-mentioned optimal application levels. Assuming that the production function has a quadratic polynomial form (see eq. 2.1) and a linear cost function form (see eq.2.3), the author proposed the following explicit expressions (eq. 2.5 to eq. 2.11) for W_m, W_l, W_w, W_{el} and W_{ew} (Capra *et al.*, 2008).

Equation (2.5) evaluates the yield maximizing level of water use, W_m

$$W_m = -\frac{b_1}{2c_1} \tag{2.5}$$

Equation (2.6) evaluates the profit maximizing level when land is limited

$$W_1 = -\frac{b_2 - P_c b_1}{2P_c c_1} \tag{2.6}$$

Equation (2.7) evaluates the profit maximizing level when water is limited

$$W_w = \left(\frac{P_c a_1 - a_2}{P_c c_1} \right)^{1/2} \tag{2.7}$$

Equations (2.8) and (2.9) estimate the level of deficit irrigation at which net income equals that at full irrigation when land is limited:

$$W_{el} = \left(\frac{b_2 - P_c b_1 + Z_1}{2 P_c c_1} \right) \tag{2.8}$$

with

$$Z_1 = \left[\left(P_c b_1 - b_2 \right)^2 - 4 P_c c_1 \left(\frac{P_c b_1^{\ 2}}{4 c_1} - \frac{b_1 b_2}{2 c_1} \right) \right]^{1/2} \tag{2.9}$$

Equations (2.10) and (2.11) estimate the level of deficit irrigation at which net income equals that at full irrigation when water is limited:

$$W_{ew} = \frac{-Z_2 + \left[Z_2^2 - 4 P_c c_1 \left(P_c a_1 - a_2 \right) \right]^{1/2}}{2 P_c c_1} \tag{2.10}$$

with

$$Z_2 = \frac{P_c b_1^2 - 4a_2 c_1 + 4P_c a_1 c_1}{2b_1} \tag{2.11}$$

Furthermore, equations (2.12) to (2.18) can be used when both the production (eq. 2.1) and cost (eq. 2.12) functions have a quadratic form (Capra and Scicolone, 2007).

$$c(w) = a_2 + b_2 w + c_2 w^2 \tag{2.12}$$

$$W_1 = -\frac{b_2 - P_c b_1}{2(P_c c_1 - c_2)} \tag{2.13}$$

$$W_w = \left(\frac{P_c a_1 - a_2}{P_c c_1 - c_2}\right)^{1/2} \tag{2.14}$$

$$W_{el} = \left(\frac{b_2 - P_c b_1 + Z_1}{2(P_c c_1 - c_2)}\right) \tag{2.15}$$

with

$$Z_1 = \left[\left(P_c b_1 - b_2\right)^2 - 4\left(P_c c_1 - c_2\right)\cdot\left(\frac{b_1\left(P_c b_1 - b_2\right)}{2c_1} - \frac{b_1^2\left(P_c c_1 - c_2\right)}{4c_1^2}\right)\right]^{1/2} \tag{2.16}$$

$$W_{ew} = \frac{-Z_2 + \left[Z_2^2 - 4\left(P_c a_1 - a_2\right)\left(P_c c_1 - c_2\right)\right]^{1/2}}{2\left(P_c c_1 - c_2\right)} \tag{2.17}$$

with

$$Z_2 = \frac{4(P_c a_1 - a_2)c_1 + b_1^2(P_c c_1 - c_2)}{2b_{1c_1}} \tag{2.18}$$

The economic convenience of DI depends even on the type of crop. The profit to be realized from irrigation will be determined by the amount of water applied, antecedent moisture, the shape of the crop production function, the variable and fixed costs of irrigation, and crop price. These factors will differ for every farm and every year. In addition, farms may choose different cropping patterns as conditions change, and these decisions will influence the availability of water and land (Hargreaves and Samani, 1984).

2.3 Opportunity costs of water

Farm operations are often constrained by a shortage of irrigation water. When that is the case, the water saved by deficit irrigation of one piece of land might be used to irrigate additional land, thus increasing farm income. The potential increase in farm income is an opportunity cost of the water. Where water supplies are limited, opportunity costs may be the most important consideration in water management.

When the amount of land under irrigation is constrained by a limited water supply, the economic return to water will be maximized by reducing the depth of water applied and increasing the area of land under irrigation until the marginal profit per hectare multiplied by the number of hectare irrigated just equals the total profit per hectare.

Since the optimal level of irrigation when land is limiting (W_{el}) or when water is limiting (W_{ew}) will be less than the yield maximizing level (W_m), capital costs might be reduced by designing a lower capacity system. Such as system might use smaller mainlines, fewer distribution laterals and smaller or fewer wells and pumps.

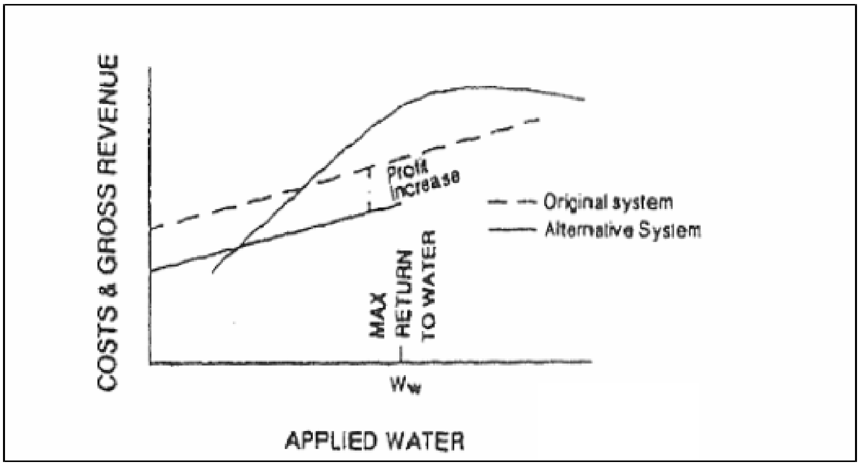


Fig. 2.5 Reduced system capacity (English, 1990).

The potential for increased profit is illustrated in the Fig. 2.5, which shows an alternative cost function based on a distribution system designed for irrigation when water is limited.

2.4 Deficit Irrigation strategies

2.4.1. Regulated Deficit Irrigation

Regulated Deficit Irrigation (RDI) or Controlled Deficit Irrigation (CDI), as introduced by English (1990), is an irrigation strategy based only on a reduction of irrigation amounts during certain plant cycle phases. RDI is an ideal water saving technique. Its application and adaptation in various environments have led to improved understanding of the process, the benefits, and the requirements for adoption.

RDI was applied to both herbaceous and tree crops. Among herbaceous crops, RDI has been applied to sugar beet, cotton, tomatoes, wheat. Most studies on peach, pear, apple, have shown that mild water stress applied during the period of slow fruit growth controlled excessive vegetative growth while maintaining or even increasing yields, while were found positive effects of RDI mainly highlighted on grape and wine quality, showing that RDI not only increases water productivity, but also farmers' profits (Fereres *et al.*, 2007). RDI applied to olives over a ten-week period following pit hardening had no adverse effect on oil production and moderate levels of water stress applied to prunes, by withholding irrigation in a deep soil during stage II of fruit growth, increased return fruit bloom, crop load, and total fruit dry matter yield.

However, it can also be applied after harvest in early maturing varieties. Therefore, the control of vegetative growth and establishment of RDI depends on the interaction between rainfall/evaporation, available soil volume for root exploration and the readily available water (Goodwin and Boland, 2000).

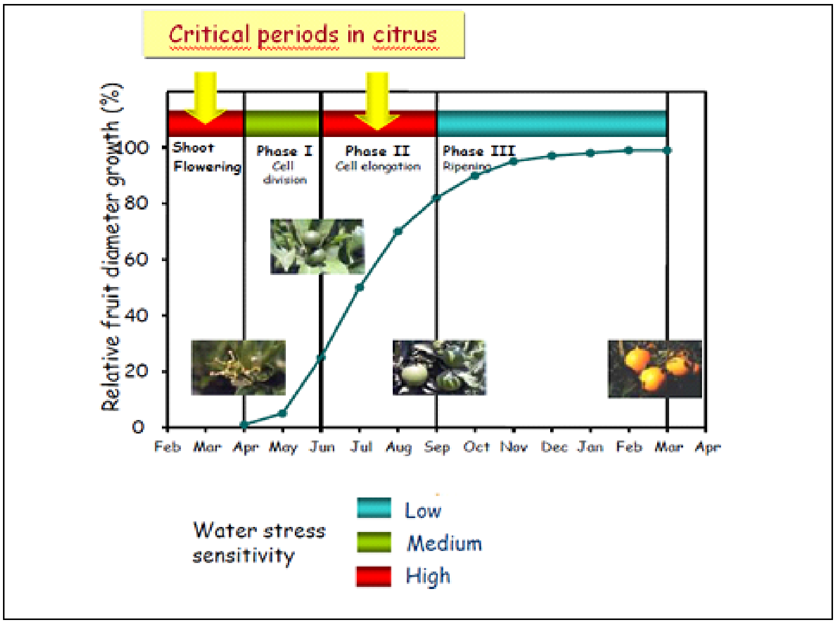


Fig. 2.6 Water stress sensitivity in citrus trees (Pérez Pérez et al. 2010).

Several trials were carried out on citrus; the Fig. 2.6 shows the critical phenological phases in citrus, that highlights the more sensitive periods to water stress, i.e. shoot flowering and cell elongation phases.

The application of RDI improves water use efficiency (WUE). Increased WUE under RDI is due largely to reductions in transpiration, attributable to partial stomatal closure. Despite reduced transpiration, measured increases in fruit osmotic potential indicate that fruit dry weight accumulation is not impaired. Both the timing and level of water stress are critical to the success of RDI. These factors need to be considered in relation to what is understood of the growth and development of the species in question. In addition, it is necessary to adopt modern techniques for scheduling irrigation that allow adequate assessment of water stress (Goodwin and Boland, 2000): precision irrigation strategies, e.g. microirrigation, are paramount for a successful application of RDI, as well as the use of rootstocks that impart high shoot vigour, improve plant nutrition and soil water monitoring.

A form of RDI, especially in drier areas, can be the Supplemental Irrigation (SI), used in both humid and arid temperate zones: it is a measure to integrate rainfall and stabilize production; in fact, the few applications of SI were performed in appropriate crop growing stages in order to maximize crop yield, efficiency and profit (Capra *et al.*, 2008).

2.4.2. Partial Rootzone Drying

Partial Rootzone Drying (PRD) is a irrigation technique that improves the water use efficiency of several crops without significant yield reduction.

PRD uses biochemical responses of plants to water stress to achieve a balance between vegetative and reproductive development. In particular, the technique was developed on the basis of knowledge of the mechanisms controlling transpiration: a percentage of crop evapotranspiration is applied to alternate plant sides, allowing part of the root system to be in contact with wet soil.

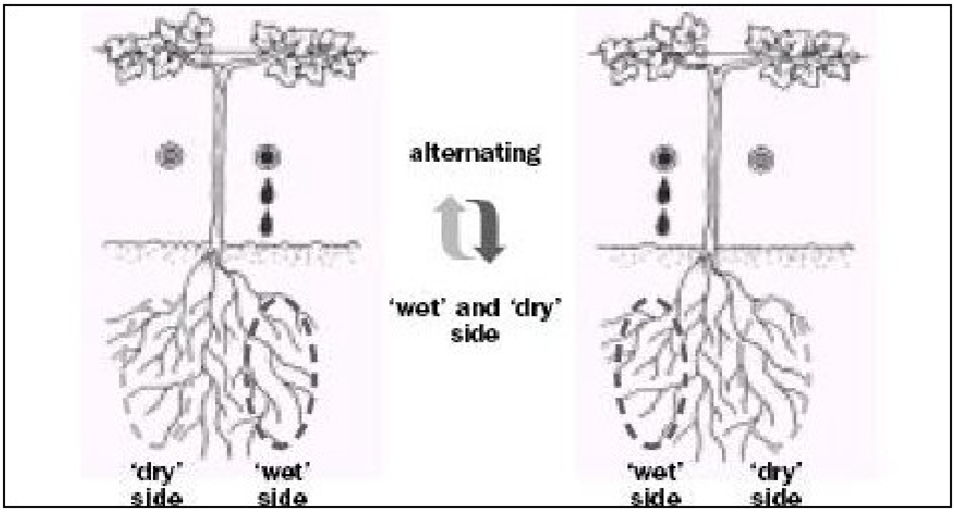


Fig. 2.7 Physical overview of PRD (Kriedemann and Goodwin, 2003).

The applying water to only one side of the plant root mass determine a 'wet' and 'dry' side of the plant, as shown in Fig. 2.7 (McKeering, 2004).

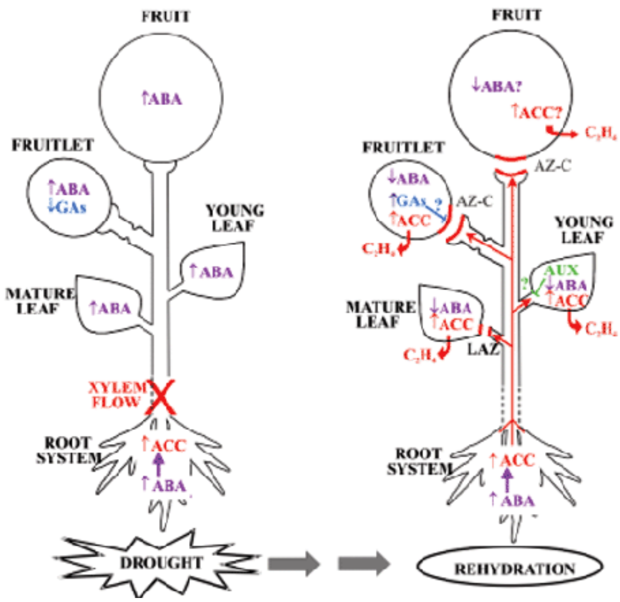


Fig. 2.8 Regulation of water stress-induced abscission (Iglesias et al., 2007).

The 'dry' side of the plant then induces a hormonal response through the production of abscisic acid (ABA) (Fig. 2.8). In stressed roots, severe water-stress induces interruption of xylem flow and accumulation of abscisic acid (ABA). Subsequently, ABA drives 1-aminocyclopropane-1-carboxylic acid (ACC, the immediate precursor of ethylene) accumulation. In the aerial parts of the plant, water stress induces ABA increases and gibberellin (GAs) decreases while ACC is not modified. Re-hydration restores xylem movement and reduces ABA and ACC levels in roots. After re-hydration, ABA decreases in aerial organs whereas ACC is actively transported to leaves, fruitlets and fruit where is catabolized to ethylene (C_2H_4), the hormonal activator of abscission. In non-abscising fruitlets, a rise in GA levels appears to act as a negative regulator of abscission. Reproductive organs (fruitlets and fruits) and mature leaves are shed through the calyx abscission zone (AZ-C) and laminar abscission zone (LAZ), respectively. However, young leaves do not shed after re-hydration. Young leaves are rich sources of endogenous plant hormones such as auxins (AUX) that may operate as abscission inhibitors. Up and down minor arrows near hormone names indicate increase or decrease in hormone levels, respectively. Arrows and T-shaped lines indicate positive and negative regulation, respectively (Iglesias *et al.*, 2007).

Many experiments confirm the existence of relationships between various parts of the chain (i.e. between soil water potential, xylem ABA content and stomatal conductance). During periods of water deficiency, plants show a reduction in plant growth and stomatal conductance, because the stomatal opening is reduced. Moreover, ‘wet’ and ‘dry’ of the plant must be alternated to maintain the plant hormonal responses. These chemical signals pass from roots to leaves and the result is the reduction of the excessive vegetative growth.

Besides ABA, cytokinins are considered by many researchers to be one of the most important plant hormones in the root to shoot signalling processes. Cytokinins are growth promoting hormones and therefore work against ABA in its efforts to induce dormancy and decrease stomatal conductance. The closure of the stomata and the increased presence of ABA in the shoots, combined with the decreased amounts of cytokinins, reduces excessive vegetative growth and encourages fruiting. This could be due to the impacts of ABA and cytokinins on ethylene production. Increased ABA and decreased cytokinins both act to decrease ethylene production. Ethylene is a growth promoting hormone in young seedlings and reduction in ethylene would result in restriction of vegetative growth. A reduction in excessive vegetative growth is advantageous because it enhances the availability of excess plant sugars and nutrients required for fruit set and development. Stomatal sensitivity to xylem ABA can be effected by many other things, including leaf water potential; for example, xylem sap pH also has an effect on stomatal closure: an increase in pH in the transpiration stream increases the sensitivity of leaf stomata to ABA.

Ethylene, salicylic acid and methyl jasmonates are other plant hormones that are known to interact during plant water deprivation and stomatal closure. For example, ABA is known to be an inhibitor of ethylene production and ethylene production due to cytokinin actions appear to be of particular importance during periods of plant water stress.

Also auxins and gibberellins are considered important hormones involved in root to hoot signalling. As well as these plant hormones, root to shoot signalling is effected by inorganic materials (e.g. hydrogen ions, nitrates and calcium), mainstream metabolites (e.g. ethanol) and water and solutes situated outside of the plant roots. Nitric oxide is another component of ABA induced stomatal closure, known to affect stomatal closure and interact with the ABA signalling pathways.

Unfortunately, if the same side of the plant is kept dry for extended periods of time, it no longer continues its biosynthesis of ABA, therefore the stomata re-opens and the plant reverts back to its normal water consumption. The amount of time between these alternations is dependant on environmental conditions, soil type, plant species and other site-specific details (McKeering, 2004).

Therefore, the application of this strategy provides a secondary goal of significant improvement in production per unit of irrigation water applied. It has been a consistent feature of all trials that, even though the irrigation amount was halved, there was no significant reduction in yield due to PRD treatment. This feature is contrasts with RDI strategy, where savings in irrigation application have often been at the expense of yield (McCarthy *et al.*, 2000).

Table 2.1 is summarizes the factors that determine the choice of RDI and/or PRD as a Deficit Irrigation method.

Tab. 2.1 Relevant factors in choosing RDI or PRD.

Regulated Deficit Irrigation *(RDI)*	***Partial Rootzone Drying*** *(PRD)*
Can be used with furrow irrigation	Drip irrigation preferred
control of fruit size and quality can be achieved	alternate row furrow possible
vegetative growth can be controlled	no effects on fruit size
RDI causes potential yield losses	vegetative growth can be controlled
positive effects of RDI mainly recorded on grape and wine quality	positive effects on irrigated crop quality
marginal water savings	significant water savings
soil water monitoring is recommended	significant cost increase for doubling laterals in cases where it is not necessary for technical reasons
Soil water monitoring recommended	
High level management skills required	

2.5 The risk associated with Deficit Irrigation

Although the theoretical basis and analytical frameworks for DI are well established, its practical application is difficult; DI is still far from being a deliberate and rational choice made by farmers (Capra *et al.*, 2008). There is uncertainty associated with the above estimates of optimal water use. The production function (eq.2.1) cannot be known “a priori”, since yields will be affected by a number of unpredictable factors, including such things as climate, lack of accuracy in crop ET data irrigation system failures, germination rates and the incidence of disease. Consequently, the production function used in the above equations will only be an estimate of the true relationship. The cost function and crop price may be relatively more predictable, but will be uncertain nevertheless. The use of these uncertain functions in the foregoing equations implies that the resulting estimates of optimum water use will also be uncertain, and these uncertainties imply risk (English and Raja, 1996). The fact that there is risk does not preclude using deficit irrigation. The concern for risk implies that crop yield models should be used not only to predict yields but also to quantify the uncertainty of yield predictions. English (1981) has shown that farmers will adjust their water use to reduce risk, but will accept some degree of risk in exchange for potential economic gains.

The range of profitable deficits, e.g. the range between W_m, the yield maximizing level, and W_{el} or W_{ew}, the levels of DI where net income will at least equal that at full irrigation, is a qualitative indication of a potential risk. If the profitable deficit range is narrow there is little margin for error in estimation of optimum water use. If the range is wide there is greater margin for error (English and Raja,1996).

Published results of experimental research into crop response to water and progress in hydrological and crop growth/yield models could contribute to the application of DI strategies. Simulation models concerning DI may be: irrigation scheduling models CROPWAT (Smith, 1992), ISAREG (Teixeira *et al.*, 1992; 1995; Popova *et al.*, 2006), soil water balance models, soil water dynamics and crop growth simulations, integrated models based on crop yield, irrigation system characteristics, scheduled irrigation strategy and profit. Before their application, simulation models should be calibrated or validated for local conditions.

2.6 Research into Deficit Irrigation

Part of the research into DI proposes its application in a "complete sense" by merging agronomic and economic evaluations (English, 1990; English and Raja, 1996), while a large amount of published research has evaluated the feasibility of DI and whether significant savings in irrigation water are possible without affecting yields.

Among the wide literature existing on DI the following main topics can be distinguished:

i) maximization of economic benefits (Romero *et al.*, 2006a; García-Vila, 2009; English, 2002);

ii) increase in WUE by adopting RDI (or CDI), and PRD agronomic strategies (Hutton *et al.*, 2011; Pérez-Pérez *et al.*, 2008 and 2009; Treeby *et al.*, 2007; Jones, 2004);

iii) scheduling DI on the basis of physiological features and other related vegetation indicators (De Souza *et al.*, 2005; Allen *et al.*, 2009; Marin *et al.*, 2011; Cuevas *et al.*, 2010; Li *et al.*, 2004);

iv) optimization of water allocation for planning purposes over large areas (Alba *et al.*, 2003, Zairi *et al.*, 2003; Lorite *et al.*, 2004; Abrisqueta *et al.*, 2008; Garcia-Tejero *et al.*, 2010; Marshal *et al.*, 2010).

Table 2.2 repots some works on the application of deficit irrigation techniques carried out by different authors, on different crops, taking into account different parameters useful for assessing the effects of deficit irrigation techniques; many other studies have been carried out in different parts of the world and different crops.

Tab. 2.2 Review of Deficit Irrigation strategies in the literature (Capra et al. 2008) modify.

Author	***Year***	***Region***	***Method***	***Crop***	***Main effects***
Research focusing on the maximization of economic benefit approach					
English and Raja	1996	NW USA, California, Zimbabwe	maximization of economic benefit	wheat, cotton, maize	optimal net return for 15-59% of deficit
Imitiyaz *et al.*	2000	Botswana		broccoli, carrot, rape, cabbage	optimal net return for 20% of deficit
Sepaskhah and Gharaman	2004	Iran		barley, sorghum, maize	optimal net return for 0.6 of irrigation efficiency
Romero *et al.*	2006 a	Spain		almond orchard	45% of water saved using RDI with a maximum production reduction of 17%
Pérez-Pérez *et al.*	2010	Spain		Citrus orchard	Greater yield, fruit size and higher price for trees on Carizo that on Citrange
Research focusing on the increase of WUE by RDI (or CDI) and PRD techniques					
Fabeiro Cortes *et al.*	2003 (a)	Spain	CDI	garlic	negative effects at the bulbification and ripening stages
Fabeiro Cortes *et al.*	2003 (b)	Spain		beet	no effects on total production and industrial quality index
Yuan *et al.*	2003	Japan	RDI	potato	decrease in tuber quantity, some positive effects on tuber quality
Kirda *et al.*	2004	Turkey	PRD	greenhouse tomato	10-27% additional marketable yield over DI

Tab. 2.2 Continued.

Author	***Year***	***Region***	***Method***	***Crop***	***Main effects***
Dorji *et al.*	2005	New Zealand	PRD	pepper	no effect on total dry mass, significant water savings
Girona *et al.*	2005	Spain	RDI	peach	no effects of RDI on fruit production
Wakrim *et al.*	2005	Morocco	PRD+RDI	bean	decrease in leaf water potential, shoot and pod biomass
Liu *et al.*	2006	Denmark	PRD+RDI	potato	increase in biomass allocation to root; decrease in leaf area; 37% water saved
Spreer *et al.*	2006	Thailand	PRD+RDI	mango	decrease in yield, increase in fruit size and edible fraction
Webber *et al.*	2006	Uzbekistan	DI	bean, green gram	WUE increase for green gram and constant for bean
Zhang *et al.*	2006	China	RDI	spring wheat	increase in yield, biomass, harvest index and WUE
Webber *et al.*	2006	Uzbekistan	DI	Common bean and winter wheat	Increase in yield, biomass and WUE
Bekele and Tilahun	2007	Ethiopia	RDI	onion	6-13% increase in WUE
Shahnazari *et al.*	2007	Denmark	PRD	potato	30% of water saved maintaining tuber yield, 61% increase of WUE
Research scheduling DI on the basis of physiological features and other related vegetation indicators					
De Souza *et al.*	2003	Portugal	Stomatal aperture and carbon uptake under PRD and DI	grapevine	decrease in stomatal conductance under PRD
Xue *et al.*	2003	USA	Physiological features under DI	winter wheat	high shoot dry weight on DI

Tab. 2.2 Continued.

Author	***Year***	***Region***	***Method***	***Crop***	***Main effects***
Ortuño *et al.*	2004	Spain	Trunk diameter changes and Sap flow	lemon trees	increase in MDS-maximum trunk diameter shrinkage
Karam *et al.*	2005	Lebanon	K_c-based irrigation scheduling	rye grass, soybean	K_c fluctuation negatively affected leaf area, biomass, dry matter accumulation
Bañon *et al.*	2006	Spain	DI+low air humidity	oleander	reduction in mortality rate under DI; positive changes in stomatal regulation and osmotic adjustment
Intrigliolo and Castel	2006	Spain	Stress indicators (MDS, TDV, Ψ_m, LAI, etc.)	Plum	good response of indicators to plant stress under DI
Xue *et al.*	2006	USA	Physiological features under DI	winter wheat	increase in wheat yield and WUE under jointing and anthesis
Suleiman *et al.*	2007	USA	K_c-based irrigation scheduling	cotton	information on K_c values was useful in effective irrigation planning
Velez *et al.*	2007	Spain	MDS	citrus trees	good feedback using MDS to schedule DI
Stagno *et al.*	2008	Sicily	RDI	citrus trees	In RDI decrease in yield and fruit weight than FI
Pérez-Pérez *et al.*	2009	Spain	DI	citrus trees	Increase of TSS and TA and decreased of juice percentage
Garcia-Tejero *et al.*	2010	Spain	Water Stress Ratio	citrus trees	DI results in water savings and yield and fruit quality
Research on the optimization of water allocation for planning purposes over large areas					
Reca *et al.*	2001	Spain	optimal water allocation model	wheat, corn	DI results in irrigation efficiency increases
Shangguan *et al.*	2002	China		wheat, corn, oilseed	water saving, increase in irrigation efficiency, reduction of water shortages
Alba *et al.*	2003	Italy	irrigation scheduling simulation model	citrus orchards	DI criteria useful for water savings
Rodriguez *et al.*	2003	Portugal		maize, sunflower	the best practice is to limit the area cropped and apply near optimal irrigation

Tab. 2.2 Continued.

Author	***Year***	***Region***	***Method***	***Crop***	***Main effects***
Zairi *et al.*	2003	Tunisia	irrigation scheduling simulation model	winter wheat, potato, tomato	feasibility of DI for wheat crop with good water valorisation; low feasibility of DI for tomato and potato
Lorite *et al.*	2004-2007	Spain	optimal water allocation model	winter cereal, sunflower, garlic, cotton	best strategy in terms of net income corresponds to 40% water deficit

2.6.1. Economic return of Deficit Irrigation strategies

In the works listed in Tab. 2.2, the authors admitted and recognised a certain level of yield reduction during the whole physiological plant cycle subjected to DI. For example English and Raja (1996) analysed the potential benefits of DI and the range of profitable deficits in different contexts (i.e. wheat in North-Western USA, cotton in California and maize in Zimbabwe). For each selected case study, the authors derived crop production functions, cost functions and the corresponding optimal levels of applied water as proposed by English (1990).

Imtiyaz *et al.*, (2000) determined the yield and economic return some of vegetable crops (winter broccoli, carrot, rape and cabbage) under deficit irrigation in Botswana (south Africa). The results suggested that crops should be irrigated at 80% evaporation replenishment, in order to obtain an optimum marketable yield, irrigation production efficiency and net return. The net return from the vegetables investigated increased from 20% to 80% evaporation replenishment. The net return at 100% evaporation replenishment increased slightly because there was no significant change in marketable yield.

Sepaskhah and Gharhaman (2004) incorporated irrigation efficiency in a DI analysis in Iran. They concluded that water reductions for barley and sorghum were economically feasible at irrigation efficiency (n_f) values lower than 1, while water reduction for maize was not economically feasible at any irrigation efficiency value. Water reduction for wheat was economically feasible at n_f values of 0.6 or smaller, especially with higher gross cost values. Furthermore, a considerable reduction in applied water and an insignificant decrease in yield may result in higher water use efficiency for sorghum, barley and wheat crops.

Romero *et al.*, (2006a) studied the economic aspects, by a cost-benefit analysis, of long-term deficit irrigation strategies applied under sub-drip irrigation (SDI), compared to a full irrigation treatment (100% ET_c) in an almond orchard in South-Eastern Spain. The economic profitability of several RDI strategies under SDI was evaluated and compared to an irrigation regime covering 100% ET_c. RDI was applied before kernel-filling period, obtaining 45 % water saving, while almond production was reduced by only 17% with increases in WUE if compared to the control irrigation regime. In addition, water saving determined 45% saving in the cost of water and the corresponding saving in electricity.

The effect of four different irrigation levels on the marketable yield and economic return of summer-growth lettuce was evaluated in Eastern Sicily (Italy) by Capra *et al.* (2008) during 2005 and 2006 Italy. The viability of deficit irrigation was evaluated by estimating optimum applied water levels. The results show that average lettuce weight was influenced by the different rates of applied irrigation water; deficit irrigation criteria, on the contrary, did not influence nonmarketable yields.

Pérez-Pérez *et al.* (2010), evaluated the profitability of DI treatment in mature 'Lane late' navel orange trees grafted on two different drought-tolerant rootstocks, 'Cleopatra' mandarin and 'Carrizo' citrange in South-eastern Spain. Under DI in semi-arid regions 'Cleopatra' mandarin can mitigate more the negative effects of drought stress on yield and fruit quality than ‘Carrizo’ citrange: orchards of ‘Carrizo’ being more profitable than those of ‘Cleopatra’ due to the greater yield and fruit size and higher price for trees on ‘Carrizo’; the quality of fruits from trees on ‘Carrizo’ under DI was affected more than that of fruits from trees on ‘Cleopatra’. Furthermore, the application of the DI treatment increased the profit for ‘Carrizo’ since the decrease in pruning costs was greater than the reduction of incomes, while the profit of ‘Cleopatra’ under DI decreased due to yield reduction.

2.6.2. Water use efficiency (WUE) and Deficit Irrigation

Generally, a large amount of literature on DI focuses on management strategies supplying lower levels of water with respect to full ET_c, aiming to obtain maximum crop yield (English *et al.*, 1990).

According to Wang *et al.* (2007) WUE is defined as the net dry matter production (DM) per unit of consumptive water use; it is a vital variable for plant growth, yield, and irrigation-management models.

Goodwin and Boland (2000) evaluated the application of RDI strategy on peach and pear trees for optimizing water use efficiency. RDI was applied from the first week of November to the last week of December, to provide approximately 40 percent of evaporation; control trees received full irrigation. Soil suction was maintained between 0 and 65 kPa on the control treatment and between 0 and 200 kPa on the RDI treatment. For the remainder of the season, soil suction was maintained between 0 and 50 kPa on all of the trees. There was no apparent difference in fruit size between the RDI trees and the control. There was a reduction in the water applied under RDI management with a significant water saving. Furthermore, fruit size and yield were maintained, and vegetative vigour appeared to be reduced.

DI and furrow irrigation techniques were evaluated for two legumes, grown as a second crop, after winter wheat harvest, in the Fergana Valley of Uzbekistan (Webber *et al.*, 2006). The results of this study indicate the WUE for both commercial yield and biomass were approximately twice as high for green gram as bean. Conversely, the water use efficiency for root biomass in bean was slightly higher than in green gram. These results suggest that common bean is not as well suited to water scarce conditions as green gram. Alternate furrow irrigation and deficit irrigation are appropriate methods to increase WUE, allowing application of less irrigation water, particularly, for green gram production.

Liu *et al.*, (2006) investigated the effect of PRD as compared with full irrigation (FI) and deficit irrigation (DI) on potatoes at the tuber initiation stage. Photosynthesis, stomatal conductance and transpiration were generally greater in FI plants. Compared to FI, both DI and PRD significantly decreased leaf area and biomass. PRD increased biomass allocation to roots. Water use on DI and PRD plants was 37% less than FI. Water use efficiency (WUE) and transpiration efficiency were similar for PRD and FI plants, and were significantly less than those of DI plants. To conclude, given the same amount of irrigation, PRD has no advantages compared to DI in terms of biomass production and WUE in potato at the tuber initiation stage.

Zhang *et al.*, (2006) proposed and evaluated the use of RDI in spring wheat in China. Three RDI treatments designed to subject the crops to various degrees of soil water deficit at different stages of crop development and a no-soil-water-deficit control were established. The results show that grain yield, biomass, harvest index and WUE in spring wheat were all improved under RDI strategies. The patterns of soil moisture were similar in the RDI treatments and the soil moisture contents were decreased by RDI during wheat growing seasons.

Bekele and Tilahun (2007) conducted an experiment of RDI on onions in Ethiopia. It was observed that all RDI strategies increased the WUE of onions from a minimum of 6% to a maximum of 13%. But in no cases were the yields higher than that in optimum (full) irrigation.

Deficit irrigation (DI) has been widely investigated as a valuable and sustainable production strategy in dry regions by Geerts *et al.* (2009). By limiting water applications to drought-sensitive growth stages, this practice aims to maximize water productivity and to stabilize yields. The results confirm that DI is successful in increasing water use efficiency (WUE) for various crops without causing severe yield reductions. Nevertheless, a certain minimum amount of seasonal moisture must be guaranteed. DI requires precise knowledge of crop response to drought stress, as drought tolerance varies considerably by genotype and phenological stage. In developing and optimizing DI strategies, field research should therefore be combined with crop water productivity modelling.

Field experiments carried out in 2006-2008 at the Luancheng Agro-Ecosystem Experimental Station of the Chinese Academy of Sciences on the winter wheat (Quanqi *et al.*, 2010). Experiments involving winter wheat with three irrigation applications at jointing, heading, were conducted, and the total irrigation water supplied was maintained at 120 mm. The results indicated that irrigation during the later part of the winter wheat growing season and increase in irrigation frequency decreased the available soil water; this result was mainly due to the changes in the vertical distribution of root length density. This work shows that irrigation at the jointing and heading stages results in high grain yield and WUE.

Deficit irrigation almost always increases WUE of a crop, for several reasons. Firstly, as the applied water is less than the depletion by ET, efficiency application increases because most or all of the applied water remains in the root zone. In addition, ET may be somewhat higher because the crops are forced to extract more water from the soil. Further, harvest index and hence yield efficiency may be enhanced because full irrigation can lead to excessive vegetative growth of some crop species (Hsiao *et al.*, 2007).

Consequently, devising cropping systems that maximize WUE is a challenge (Pala *et al.* 2007). In this context it occurs developing strategies for increasing the crop water use efficiency of irrigated crops, especially in the semiarid regions of the world (Li and Yu, 2007).

There is increasing worldwide interest in improving plant water use efficiency, since water is increasingly scarce, especially in regions where precipitation is low (i.e. 200–600 mm/year), the evapotranspiration is high and drought periods are frequent (Pala *et al.* 2007), in particular, Mediterranean climates, which are characterized by long periods of intense irradiance and high temperatures, with average midday temperatures frequently reaching 30 °C or more (Li and Yu, 2007). These characteristics may result in a transpiration rate which exceeds water absorption capacity. It is very well known that plant water uptake depends on both physiological and environmental factors, especially solar radiation and vapour pressure deficit, and from the coupling degree of the plant with the atmosphere. For example, shading nets have been used to reduce the radiation load in crops, since nets reduce and redistribute the radiation load more efficiently to the plants growing underneath. Nets also reduce turbulence and produce a humid blanket, which contributes to decreasing environmental evaporative demand (Barradas *et al.*, 2005).

2.6.3. Deficit Irrigation scheduling: physiological mechanisms and plant indicators

Water deficit is one of the most important environmental factors inhibiting photosynthesis, growth and production under field conditions in the Mediterranean. Deficit irrigation practices differ from traditional water supplying practices. Before implementing a deficit irrigation programme, it is necessary to know crop yield responses to water stress, both during defined growth stages and throughout the whole season. In order to ensure successful strategies outcomes, it is necessary to consider the physiological parameters of the crop submitted to water deficit, as well the soil and the climatic conditions of the environment around. Generally, detailed physiological plant responses to deficit irrigation strategies (both RDI and PRD) under natural field conditions have not received much attention. The use of plant indicators (i.e. plant water status, sap flow, stomatal conductance, LAI (Leaf Area index), PAR (Photosynthetically Active Radiation), leaf water potential, leaf temperature, trunk diameter fluctuation, root growth, etc., may be the ideal methods for irrigation scheduling due to the dynamic nature of plant water status.

Furthermore, the high-yielding varieties (HYVs) are more sensitive to water stress than low yielding varieties; instead, crops that are the most suitable for deficit irrigation are those with a short growing season and drought tolerant.

Under deficit irrigation strategy, also agronomic practices may require modification, e.g. decrease plant population, apply less fertilizer, adopt flexible planting dates, and select shorter-season varieties (Goodwin and Boland, 2000).

Castel and Buj (1990) valuated the response of Salustiana oranges to high frequency deficit irrigation. Fruit number was not affected by the irrigation treatments, therefore differences in yield were due to effect on average fruit weight. Treatments did not affect juice and pulp content, maturity index of fruits nor maturation time.

A water saving of 30 and 20% was achieved in the T-1 (100% ET_c all year) and T-2 (70% ET_c during the rapid fruit growth period) on Fino lemon trees grafted on orange in the south-eastern Mediterranean coast of Spain (Domingo *et al.*, 1996). The results showed that the plant responses to irrigation treatments were similar in all the years studied, leaf water potential decreased during deficit irrigation periods both T-1 that T-2 treatments.

Physiological mechanisms contributing towards increasing water use efficiency under deficit irrigation were investigated by Xue *et al.* (2006). In 2003, the authors investigated the effect of available water on root and shoot growth, and root water uptake in winter wheat under DI. Deficit irrigated crops presented higher shoot dry weight than those that received irrigation at middle grain filling. The mean water uptake rate decreased as available soil water decreased. In 2006, the same authors analysed the effects of different water regimes on the leaf water potential, net photosynthetic rate, stomatal conductance and leaf area index of winter wheat. The results of the study showed that DI between jointing and anthesis stages significantly increased wheat yield and water use efficiency through increasing both current photosynthesis and the remobilization of pre-anthesis carbon reserves.

In the study of Ortuño *et al.* (2004) were compared sap flow measurements and trunk diameter fluctuations in potted young lemon trees grafted on sour orange rootstock submitted to high frequency deficit irrigation. This result shown that Maximum Diameter Shrinkage (MDS) and sap Flow (SF) are inversely: the first detectable response to the deficit irrigation was a marked increase in MDS followed by a decrease in SF, predawn leaf water potential and leaf conductance values. Daily maximum

(MXTD) and minimum (MNTD) trunk diameters were directly influenced by the plant water supply from the soil. In addition, during the first days of deficit irrigation, when trunk growth was very low, MDS and SF served as the best plant water status indicators. Further, when water stress was more pronounced and trunk growth was greater, MNTD, MXTD and SF were the most reliable indicators.

The feasibility of deficit irrigation scheduling, using maximum daily trunk shrinkage (MDS), was evaluated during two consecutive seasons in a citrus orchard planted with mature 'Clementina de Nules' trees by Velez *et al.* (2007). This experimental work showed that the absolute values of MDS cannot be employed as the only variable to schedule irrigation, because MDS in well irrigated trees varied largely according to the environmental conditions. Despite the large variability observed in the MDS measurements in both years no significant reduction in yield and fruit weight was observed in the deficit irrigated treatment compared with the control, allowing seasonal water saving between 18 and 12%.

Abrisqueta *et al.* (2008) carried out research on the root dynamics of young early season peach trees subjected to the deficit irrigation techniques. He showed that the root length density was reduced by 73% in the continuous deficit irrigated treatment and by 42% in the PRD treatment respect to the well irrigated treatment.

Stagno *et al.* (2008) analysed the effects of RDI treatment on mature orange trees cv Tarocco, on sour orange rootstock during 3 years between 2003 and 2005. RDI treatments showed a significant decrease in yield and fruit weight than fully irrigated treatment, with a slower fruit growth rate compared to full irrigation treatments. Total soluble solids, anthocyanin, titratable acidity and vitamin C contents were higher in all RDI treatments.

Nevertheless the commercial value of the fruit was reduced caused by a decreased size.

An irrigation experiment involving pistachio was performed by Gijòn *et al.* (2009) over a four-year period in central Spain in which he determined the effect of RDI on nut yield and quality. The RDI trees were only significantly water stressed during split nuts phase, showing midday water potentials of around 1.4 MPa, while leaf conductance was not significantly affected in any of the irrigation treatments. Moreover, the RDI trees showed a total yield and percentage of split nuts similar to those of the controls, even though they received around 20% less water. This experiment shows that pistachio has a degree of drought-resistance, reducing the likelihood of water stress and, therefore, allowing more severe RDI scheduling.

Deficit Irrigation strategy could be useful for improving the final content of total soluble solids (TSS) and the titratable acidity (TA). In particular, Pèrez-Pèrez *et al.* (2009) applied a strategy of deficit irrigation to improve the final fruit quality in 10 year old Lane late sweet orange grafted on Carrizo citrange in an experimental orchard located in Torre Pacheco (Murcia, south-east Spain). The deficit irrigation treatment consisted of the stopping of irrigation in the last phase of fruit growth. The irrigation cut-off in this phenological phase reduced the midday stem water potential (C_{md}), the plant water status being heavily influenced by rainfall. In both years, the DI treatment did not alter fruit yield although mean fruit weight was slightly reduced. The main effects of DI on the final fruit quality were increases of TSS and TA and a decrease of juice percentage without altering the final maturity index. Plant water-stress was correlated positively with TSS and TA and negatively with juice percentage.

Deficit irrigation after harvest has been proven to be a more profitable strategy for producing loquats due to its effects on promoting earlier flowering and harvest date next season Cuevas *et al.* (2009). To determine water, an experiment was established to compare phenology, fruit quality and yield in 'Algerie' loquats over two consecutive seasons. In this experimental work some trees were programmed to receive 50%, 25% or 0% of the water applied to controls RDI (50%), RDI (25%), and RDI (0%), respectively from mid-June to the end of July. All deficit irrigation treatments promoted earlier flowering when compared to fully irrigated trees; the greatest advancement in full bloom date (27 days) was achieved with RDI (0%) and RDI (25%). Productivity and fruit size were not diminished by reduced irrigation in either season. Fruit size and grading was enhanced thanks to RDI in both seasons.

Garcìa-Tejero *et al.* (2010) evaluated the response of citrus trees, grafted onto carrizo citrange, to DI during different phenological periods in relation to yield, fruit quality, and water productivity. Deficit irrigation based on a different water-stress ratio (WSR) applied in each phenological stage. The midday stem water potential and stomatal conductance were measured during the periods considered, and these parameters were used to estimate the plant-water status. Integrated stem-water potential and integrated stomatal conductance were calculated for all treatments and used as a water-stress indicator for the crop. Reference equations were formulated to quantify the relations between these water-stress indicators and the crop response, expressed as yield, and fruit-quality parameters under limited seasonal water availability. The main effects were detected in treatments with a water-saver stress applied during the flowering and fruit-growth phases When this degree of stress was applied during the maturity phase, it was reflected mainly in fruit-quality parameters (i.e. total soluble solids, and titrable acidity). These results lead to the conclusion that in mature orange trees deficit irrigation affects yield and fruit quality, while enabling water savings of up to 1000 m^3 ha^{-1}. Regarding the water-stress indicators used, stomatal conductance and stem-water potential, showed highly significant correlations with the yield and fruit-quality parameters.

Marsal *et al.*, (2010) examined over the postharvest seasons of three consecutive years, RDI for its potential of saving water and maintaining fruit yield and quality in 'Summit' sweet cherry. Midday stem water potential (Ψ_{stem}) was used for assessing plant water status. The postharvest irrigation treatments were: RDI-80% of water and RDI-50% of water. Relationship between postharvest Ψ_{stem} and crop load in the following season varied according to the year. Moreover, RDI-50% firstly applied in an off year, after crop has been harvested, can maintain fruit yield at similar levels to fully irrigated trees while saving water by 45%.

RDI and PRD were compared over three consecutive growth seasons on almond trees in a semiarid climate in SE Spain (Egea *et al.*, 2010). The results showed that all deficit irrigation treatments have a negative impact on trunk growth parameters. In addition, the magnitude of the reduction in trunk growth rate was strongly correlated through a linear relationship with the annual volume of water applied per tree. In contrast, leaf-related attributes and some yield-related parameters were not significantly affected by the irrigation treatments.

However, there are circumstances where deficit irrigation is not appropriate. For example, in the case of potatoes in the northwestern USA, soil moisture deficits that have little effect on yield may cause significant changes in tuber shape, an important determinant of quality. Larsen and McMaster (1965) found that early season moisture stress which caused a 15% reduction in total yield of Russet Burbank potatoes resulted in a 27% decline in the highest valued component of yield. Conversely, water stress may enhance quality in other crops. For example, deficits may improve the protein percentage of wheat and other grains, increase the fiber length and strength of cotton, and increase the sugar percentages in grapes, sugar beets and other crops.

2.6.4 Optimization of water allocation over large areas for planning purposes

Numerous studies have been devoted to the identification and evaluation of measures to cope with water deficit conditions and their impact on irrigated agriculture (Beruardo, 1988; Jackson *et al.*, 1991; Batini *et al.*, 1999; Pereira, 2003; Rossi 2003). These measures are typically those that contribute towards reducing the demand for irrigation water, or to adjusting the water supply depending on availability. Demand management includes several aspects such as deficit irrigation scheduling, the improvement of farm irrigation systems, and the adoption of crop and soil management for water conservation.

Shangguan *et al.*, (2002), developed a recurrence control model for the combined optimal allocation of multiple water resources in a semi-arid region of China. The model presents a new approach to improving irrigation efficiency, implementing water saving irrigation and solving the problem of water shortage.

Alba *et al.*, (2003) validated the ISAREG irrigation scheduling simulation models with data collected in the orchards of the Catania Plain (Sicily). Simulations were performed for different levels of climatic demand: average, high and very high. The results show the usefulness of simulation models to identify and evaluate strategies for DI.

Zairi *et al.*, (2003) applied the ISAREG irrigation scheduling simulation model in Central Tunisia to deficit irrigation of winter wheat, tomato and potato crops. Alternative schedules were evaluated through the combined use of indicators relating to the reduction in demand for irrigation water, the consequent yield reduction and the impacts on farmers' income. The results indicate that for average demand the adoption of DI criteria is generally feasible for all the crops considered. Under high demand conditions, the gross margin per unit of water applied decreases for potato and tomato crops but increases for wheat crop.

Lorite *et al.* (2004) developed a model to evaluate the irrigation performance of a large number of farmers in an area subjected to deficit irrigation. It has been created a model simulating water balance and irrigation performance at plot and scheme levels, to carry out scenario analyses in an irrigation scheme in Southern Spain. The main crops in the scheme are winter cereals, sunflower, garlic, and cotton. The model simulated the scheme performance for different allocation levels of 500, 1500, 2500 m^3 ha^{-1}, and full irrigation supply in terms of gross and net income, irrigation water productivity (IWP) and labour needs. The results showed that at supply levels of 1500 m^3 ha^{-1}, the best strategy in terms of net income was the one that allocated the water to crops with high water productivity. However, when water supply is very low (500 m^3 ha^{-1}) scheme net income is maximised by adjusting the cropping pattern. As supply increased to 2500 m^3 ha^{-1}, there were no differences in scheme net income between the three strategies.

3. Complementary methods to application of Deficit Irrigation techniques

3.1 Determination of Crop Evapotranspiration (ET_c)

Evapotranspiration (ET) is an important agrometeorological parameter for climatological and hydrological studies, as well as for irrigation planning and management (Sentelhas *et al.*, 2010). Evapotranspiration process constituted by the combination of two separate processes whereby water is lost from the soil surface by evaporation and from the crop by transpiration.

Evaporation is the process whereby liquid water is converted to water vapour and removed from the evaporating surface, such as lakes, rivers, soils and wet vegetation. Where the evaporating surface is the soil surface, the degree of shading of the crop canopy and the amount of water available at the evaporating surface are other factors that affect the evaporation process (Allen *et al.*, 1998).

Transpiration consists of the vaporation of liquid water contained in plant tissues and the vapour removal to the atmosphere and crops predominately lose their water through stomata; there are small openings on the plant leaf through which gases and water vapour pass. Water, together with some nutrients, is taken up by the roots and transported through the plant. The vaporation occurs within the leaf, namely in the intercellular spaces, and the vapour exchange with the atmosphere is controlled by the stomatal aperture. Nearly all water taken up is lost by transpiration and only a tiny fraction is used within the plant. The transpiration rate is influenced by crop characteristics, environmental aspects and cultivation practices (Allen *et al.*, 1998). However, evaporation and transpiration occur simultaneously and there is no easy way of distinguishing between the two processes. When the crop is small, water is predominately lost by soil evaporation, but once the crop is well developed and completely covers the soil, transpiration becomes the main process.

A large number of more or less empirical methods have been developed over the last 50 years by numerous scientists and specialists worldwide to estimate evapotranspiration from different climatic variables. Relationships were often subject to rigorous local calibrations and proved to have limited global validity. The techniques listed below detail some methods to calculate the reference crop evapotranspiration (ET_o) such as Penman-Monteith, energy balance, soil water balance, Hargreaves, Pan evaporation and Blaney-Criddle methods.

FAO-56 Penman–Monteith (FAO PM) is considered as a standard, and the most precise method to estimate ET_o. It was considered to offer the best results with minimum possible error in relation to a living grass reference crop. It is a method with strong likelihood of correctly predicting ET_o in a wide range of locations and climates and has provision for application in data-short situations. It is physically based, and explicitly incorporates both physiological and aerodynamic parameters. It is expressed as:

$$ET_0 = \frac{0{,}408(R_N - G) + \gamma \dfrac{C_n}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \qquad (3.1)$$

where, ET_o is the grass reference evapotranspiration [mm day_{-1}]; D is the slope of the saturated vapor pressure curve (kPa °C^{-1}); Rn is the net radiation [MJ m^{-2} day^{-1}], G is the soil heat flux density [MJ m^{-2} day^{-1}], considered as null for daily estimates; T is the daily mean air temperature [°C], at 2 m, based on the average of maximum and minimum temperatures; U_2 is the average wind speed at 2 m height [m s^{-1}]; e_s is the saturation vapor pressure [kPa], e_a is the actual vapor pressure [kPa], (es - ea) is the saturation vapor pressure deficit at temperature T; g is the psychrometric constant (0.0677) [kPa °C^{-1}].

Evaporation of water requires relatively large amounts of energy, either in the form of sensible heat or radiant energy. Therefore the evapotranspiration process is governed by energy exchange at the vegetation surface and is limited by the amount of energy available. Because of this limitation, it is possible to predict the evapotranspiration rate by applying the principle of energy conservation. The energy arriving at the surface must equal the energy leaving the surface for the same time period. All fluxes of energy should be considered when deriving an energy balance equation. The equation for an evaporating surface can be written as:

$$R_n - G - \lambda ET - H = 0 \qquad (3.2)$$

where R_n is the net radiation, H the sensible heat, G the soil heat flux and λET the latent heat flux. The various terms can be either positive or negative. Positive Rn supplies energy to the surface and positive G, λET and H remove energy from the surface. In eq. 3.2 only vertical fluxes are considered and the net rate at which energy is being transferred horizontally, by advection, is ignored. Therefore the equation is to be applied to large, extensive surfaces of homogeneous vegetation only. The equation is restricted to the four components: Rn, λET, H and G. Other energy terms, such as heat stored or released in the plant, or the energy used in metabolic activities, are not considered These terms account for only a small fraction of the daily net radiation and can be considered negligible when compared with the other four components. The latent heat flux (λET) representing the evapotranspiration fraction can be derived from the energy balance equation if all other components are known. Net radiation (Rn) and soil heat fluxes (G) can be measured or estimated from climatic parameters. Measurements of the sensible heat (H) are however complex and cannot be easily obtained. H requires accurate measurement of temperature gradients above the surface. Another method of estimating evapotranspiration is the mass transfer method. This approach considers the vertical movement of small parcels of air (eddies) above a large homogeneous surface. The eddies transport material (water vapour) and energy (heat, momentum) from and towards the evaporating surface. By assuming steady state conditions and that the eddy transfer coefficients for water vapour are proportional to those for heat and momentum, the evapotranspiration rate can be computed from the vertical gradients of air temperature and water vapour via the Bowen ratio. Other direct measurement methods use gradients of wind speed and water vapour. These methods and other methods such as eddy covariance, require accurate measurement of vapour pressure, and air temperature or wind speed at different levels above the surface. Therefore, their application is restricted to primarily research situations (Allen *et al.*, 1998).

Evapotranspiration can also be determined by measuring the various components of the soil water balance. The method consists of assessing the incoming and outgoing water flux into the crop root zone over some time period. Irrigation (I) and rainfall (P) add water to the root zone. Part of I and P might be lost by surface runoff (RO) and by deep percolation (DP) that will eventually recharge the water table. Water might also be transported upward by capillary rise (CR) from a shallow water table towards the root zone or even transferred horizontally by subsurface flow in (SF_{in}) or out of (SF_{out}) the root zone. In many situations, however, except under condititions with large slopes, SFin and SFout are minor and can be ignored. Soil evaporation and crop transpiration deplete water from the root zone. If all fluxes other than evapotranspiration (ET) can be assessed, the evapotranspiration can be deduced from the change in soil water content (ΔSW) over the time period:

$$ET = I + P - RO - DP + CR \pm \Delta SF \pm \Delta SW \quad (3.3)$$

Some fluxes such as subsurface flow, deep percolation and capillary rise from a water table are difficult to assess and short time periods cannot be considered. The soil water balance method can usually only give ET estimates over long time periods of the order of week-long or ten-day periods.

The difference between the maximum and minimum air temperature ($T_{max} - T_{min}$) can be used as an indicator of the fraction of extraterrestrial radiation that reaches the earth's surface. This principle has been utilized by Hargreaves and Samani to develop estimates of ET_o using only air temperature data. The Hargreaves' radiation formula (eq. 3.4), adjusted and validated at several weather stations in a variety of climate conditions:

$$Rs = k_{Rs} (T_{max} - T_{min}) R_a \quad (3.4)$$

where R_a is the extraterrestrial radiation [MJ m^{-2} d^{-1}], T_{max} is the maximum air temperature [°C], T_{min} is the minimum air temperature [°C], k_{Rs} is an empirical coefficient [°C] (Allen, 1998).

Pan Evaporation method provide a measurement of the combined effect of temperature, humidity, wind speed and sunshine on the reference crop evapotranspiration ET_o :

$$ET_o = K_{pan} \times E_{pan} \quad (3.5)$$

where ET_o is the reference crop evapotranspiration; K_{pan} is the pan coefficient and E pan is the pan evaporation.

When using the evaporation pan to estimate the ET_o, a comparison is made between the evaporation from the water surface in the pan and the evapotranspiration of the standard grass. The water in the pan and the grass do not react in exactly the same way to the climate. Therefore a special coefficient is used (K_{pan}) to relate one to the other (eq. 3.6)

$$K_p = 0{,}108 - 0{,}0286 \cdot u_2 + 0{,}0422 \cdot \ln(FET) + 0{,}1434 \cdot \ln(RH_{avg}) - 0{,}000631 \cdot \left[\ln(FET)^2 \cdot \ln(RH_{avg})\right] \quad (3.6)$$

where u_2 is the average wind speed at 2 m height [m s^{-1}]; FET = 100 m; RH_{avg} is the average relative humidity [%].

The pan coefficient, K_{pan}, depends on the type of pan used, the pan environment. Many different types of evaporation pans are being used. The best known pans are the Class A evaporation pan (circular pan) and the Sunken Colorado pan (Fig 3.1).

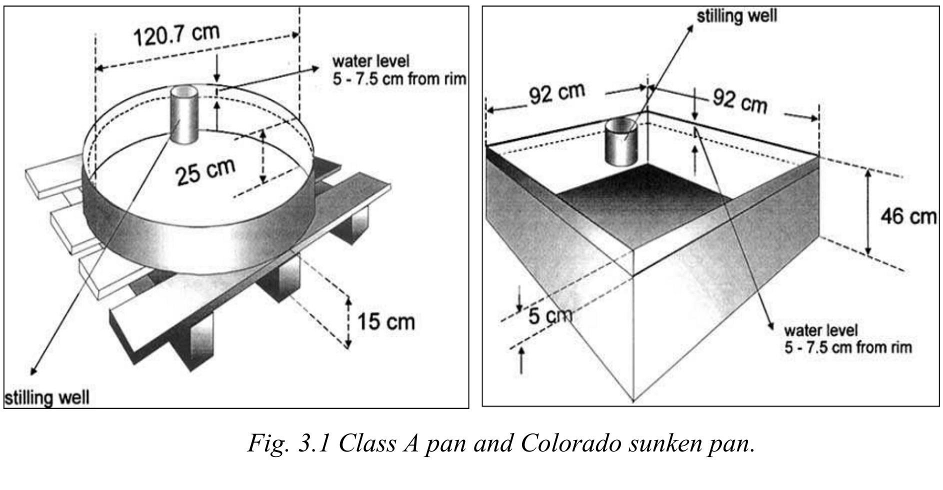


Fig. 3.1 Class A pan and Colorado sunken pan.

The Blaney-Criddle method is simple, using measured data on temperature only. The Blaney-Criddle formula (eq. 3.7) was first developed from soil moisture depletion and air temperature and humidity measurements in alfalfa and cotton (Blaney and Criddle, 1950):

$$ET = K_c \times \Sigma F \qquad (3.7)$$

where,

$$F = (T \times p) / 100 \qquad (3.8)$$

where F is the monthly consumptive water use factor; T is the mean monthly temperature [°C]; p is the mean daily percentage of annual daytime hours. The crop coefficient K_c is an empirical seasonal factor relating the seasonal plant water usage for a specific crop to the total seasonal consumptive water use factor generated under experimental conditions. The eq. 3.7 can be applied on a monthly basis by calculating F for each month and scaling it by a monthly kc, which is dependent on the growth development rate of the crop. However, this method is not very accurate: it provides a rough estimate or "order of magnitude" only. Especially under "extreme" climatic conditions the Blaney-Criddle method is inaccurate; in windy, dry, sunny areas, the ET_o is underestimated up to some 60 percent, while in calm, humid, clouded areas, the ET_o is overestimated up to some 40 percent (Sammis 2011).

The variable performance of the different methods depending on their adaptation to local conditions and often may require local calibration of the microclimatic parameters to achieve satisfactory results.

Several papers show that underestimation was the common problem, especially for cold months. By substituting recalibrated values for the original constant values (Xu and Singh, 2000), the ET equations appear to be more accurate for determining the mean annual evaporation values.

To evaluate the performance of these and other estimation procedures under different climatological conditions, a major study was undertaken under the auspices of the Committee on Irrigation Water Requirements of the American Society of Civil Engineers (ASCE). The ASCE study analysed the performance of 20 different methods, using detailed procedures to assess the validity of the methods compared to a set of carefully screened lysimeter data from 11 locations with variable climatic conditions. The ASCE study proved very revealing and showed the widely varying performance of the methods under different climatic conditions. In a parallel study commissioned by the European Community, a consortium of European research institutes evaluated the performance of various evapotranspiration methods using data from different lysimeter studies in Europe (Allen *et al.*, 1998).

By multiplying ET_o by the crop coefficient, ET_c is determined by eq. 3.9:

$$ET_c = ET_0 \times K_c \tag{3.9}$$

where ET_c crop evapotranspiration [mm d^{-1}], K_c crop coefficient [dimensionless], ET_o reference crop evapotranspiration [mm d^{-1}].

Crop coefficient predominately varies with the specific crop characteristics and only to a limited extent with climate. For normal irrigation planning and management purposes, for the development of basic irrigation schedules, and for most hydrologic water balance studies, average crop coefficients are relevant and more convenient than the K_c computed on a daily time step using a separate crop and soil coefficient (K_c). Only when values for K_c are needed on a daily basis for specific fields of crops and for specific years, must a separate transpiration and evaporation coefficient be considered: a basal crop (K_{cb}) and a soil evaporation coefficient (K_e) (i.e., $K_c = K_{cb} + K_e$). Fig. 3.2 show that only three values for K_c are required to describe and construct the crop coefficient curve: those during the initial stage (K_c ini), the mid-season stage (K_c mid) and at the end of the late season stage (K_c end) (Allen *et al.*, 1998).

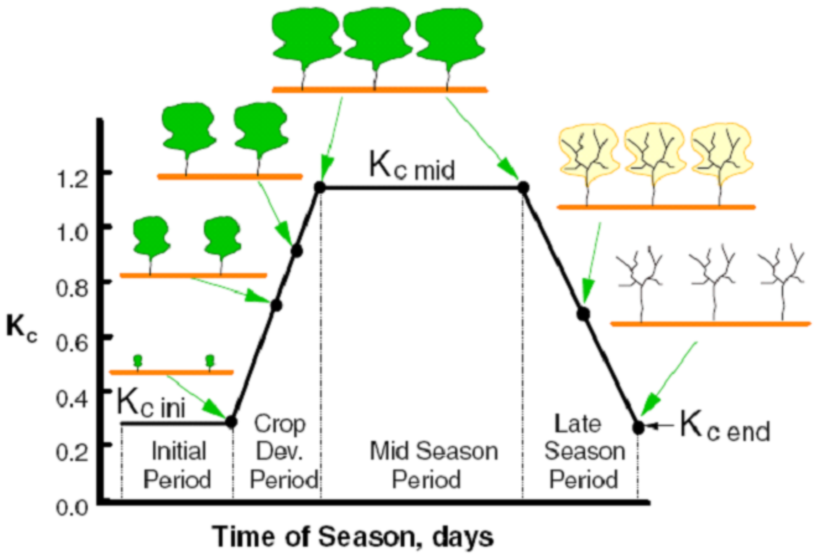


Fig. 3.2 FAO segmented crop coefficient curve and four growing stages (FAO 56).

Measurements of ET_c are often highly variable due to variations in measurement techniques and the differences in their relative accuracies. There is no foolproof method to obtain an accurate measure of ET_c due to the variability and complexity of climatic factors and biophysical variables, including plant density, species diversity, height, number of leaves, leaf characteristics, etc., involved in the process (Consoli *et al.*, 2006).

3.2 Physical, chemical and hydrological properties of soil

3.2.1. Soil physical properties

The soil is a matrix of solids including sand, silt, clay, and organic matter particles as well as aggregates of various sizes formed from them, and pore space, which may be filled with air or water. Thus, depending on the mix of environmental variables, prevailing conditions can vary quite over distances on the order of a few millimeters.

Soil texture is one of the most important soil properties governing most of the physical, chemical and hydrological properties of soils. Indeed, variability in soil texture may contribute to the variation in nutrient storage and availability, water retention and transport and binding and stability of soil aggregates. Spatial variability is a well known phenomenon of soil systems (Burrough, 1993). However, some of this variability may also be induced by tillage and other soil management practices and are in many cases influenced by the factors like soil erosion. Variation in soil texture in the field directly contributes to the variation in nutrient storage and availability, water retention, availability and transport hence may influence the yield potential of any site. Warric and Gardner (1983) found a significant impact of this variability on soil performances and therefore the crop yield. Similarly, Tanji (1996) has shown that among the different soil physico-chemical properties measured, variability in soil texture component is a primary soil factor influencing crop yield. Reynolds (1970) and Crave and Gascuel-Odoux (1997) all found that variation in soil moisture content were directly related to the soil textural variability.

Soil texture refers to the proportion of the soil separates that make up the mineral component of soil. These soil separates have the following size ranges:

Sand = < 2 to 0.05 mm; Silt = 0.05 to 0.002 mm and Clay = < 0.002 mm.

Sand and silt are the inactive part of the soil matrix, because they do not contribute to a soil’s ability to retain soil water or nutrients. These separates are commonly comprised of quartz or some other inactive mineral. Because of its small size and sheet-like structure, clay has a large amount of surface area per unit mass, and its surface charge attracts ions and water. Because of this, clay is the active portion of the soil matrix. For all mineral soils, the proportion of sand, silt, and clay always adds up to 100 percent. These percentages are grouped into soil texture classes, which have been organized into a textural triangle (Fig.3.3).

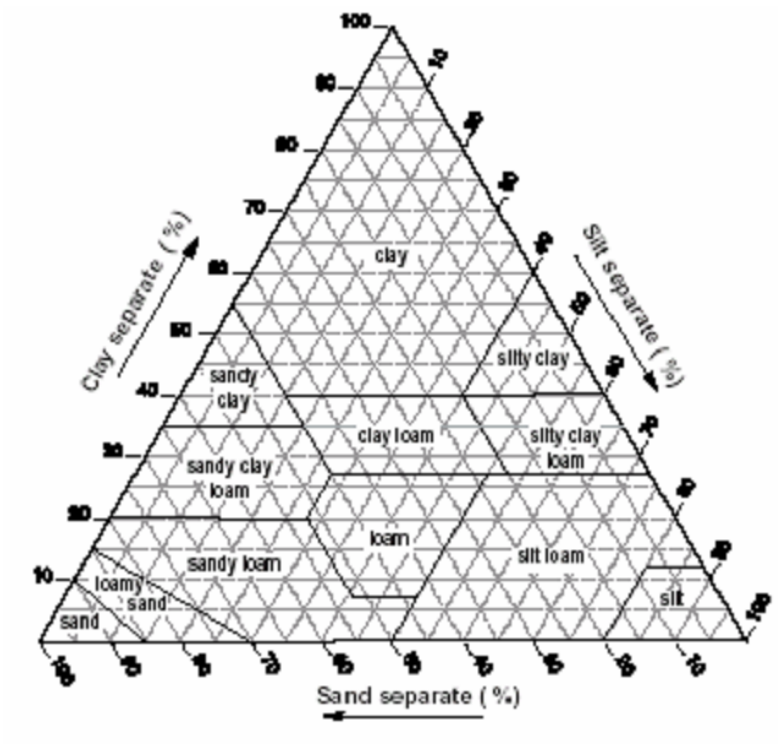


Fig. 3.3 Textural triangle.

Soil consistence and Bulk density are related to soil structural characteristics, whose knowledge is useful for hydraulic properties determine.

Soil consistence refers to the ease with which an individual ped can be crushed by the fingers. Soil consistence depends on soil moisture content. Terms commonly used to describe consistence are moist, wet and dry soil. Bulk density is the proportion of the weight of a soil relative to its volume. It is expressed as a unit of weight per volume, and is commonly measured in units of grams per cubic centimeters (g/cc). Bulk density is an indicator of the amount of pore space available within individual soil horizons and it is inversely proportional to pore space.

3.2.2. Soil chemical properties

Soils are chemically different from the rocks and minerals from which they are formed by containing less of the water soluble weathering products, calcium, magnesium, sodium, and potassium, and more of the relatively insoluble elements such as iron and aluminium. Eight chemical elements comprise the majority of the mineral matter in soils. Of these eight elements, oxygen, a negatively charged ion (anion) in crystal structures, is the most prevalent on both weight and volume basis. The next most common elements, all positively charged ions (cations), in decreasing order are silicon, aluminum, iron, magnesium, calcium, sodium, and potassium. Ions of these elements combine in various ratios to form different minerals. More than eighty other elements also occur in soils and the earth's crust, but in much smaller quantities.

Some chemicals are leached into the lower soil layers where they accumulate. Other chemicals, more insoluble, are left in the upper layers of the soil. The most rapid removed chemicals are chlorides and sulphates, followed by calcium, sodium, magnesium and potassium. The silicates and oxides of iron and aluminium decompose very slowly and are rarely leached. When some of these products come into contact with the air in the soil, chemical reactions occur, such as oxidation in particular, which results in the formation of chemicals either more soluble or more fragile than the original ones. This results in an acceleration of the weathering processes, increased leaching of chemicals, and further changes in the soil chemical composition. The air present in the soil also contains carbon dioxide. This gas combined with water can form a weak acid (carbonic acid) which will then react with some of the soil chemicals to form new ones.

Soils may have either an acid or an alkaline reaction, or may be neutral. The measure of the chemical reaction of the soil is expressed by its pH value. By definition, pH is a measure of the active hydrogen ion H^+ concentration and it is also an indication of the acidity or alkalinity of a soil, known as soil reaction. The pH scale ranges from 0 to 14, with values below 7.0 acidic, and values above 7.0 alkaline. A pH = 7 indicating that the soil has a neutral reaction. A pH of 4.0 is ten times more acidic than a pH of 5.0. The most important effect of pH in the soil is on ion solubility, which in turn affects microbial and plant growth. A pH range of 6.0 to 6.8 is ideal for most crops because it coincides with optimum solubility of the most important plant nutrients. Some minor elements (e.g., iron) and most heavy metals are more soluble at lower pH. This makes pH management important in controlling movement of heavy metals (and potential groundwater contamination) in soil.

In acid soils, hydrogen and aluminum are the dominant exchangeable cations. The latter is soluble under acid conditions, and its reactivity with water (hydrolysis) produces hydrogen ions. Calcium and magnesium are basic cations; as their amounts increase, the relative amount of acidic cations will decrease. Factors that affect soil pH include parent material, vegetation, and climate. Some rocks and sediments produce soils that are more acidic than others, for example, quartz sandstone is acidic, limestone is alkaline.

Some types of vegetation, particularly conifers, produce organic acids, which can contribute to lower soil pH values. In humid areas soils tend to become more acidic over time because rainfall washes away basic cations and replaces them with hydrogen. Addition of certain fertilizers to soil can also produce hydrogen ions.

3.2.3. Soil hydrological properties

Soil moisture is an important component in the atmospheric water cycle. Water status in soils is characterized by both the amount of water present and its energy state.

Soil moisture determinations measure either the soil water content and the soil water potential.

Soil water content is an expression of the mass or volume of water in the soil, while the soil potential is an expression of the soil water energy status (WMO, 2008). The relation between content and potential is not universal and depends on the characteristics of the soil. Such as soil density and soil texture. Soil water content on the basis of mass is expressed in the gravimetric soil moisture content, θg, defined by:

$$\theta_g = M_{water}/M_{soil} \qquad (3.10)$$

where M_{water} is the mass of the water in the soil sample and M_{soil} is the mass of dry soil that is contained in the sample. Values of θ_g in meteorology are usually expressed in per cent. Because precipitation, evapotranspiration and solute transport variables are commonly expressed in terms of flux, volumetric expressions for water content are often more useful. The volumetric soil moisture content of a soil sample, θ_v, is defined as:

$$\theta_v = V_{water}/V_{sample} \qquad (3.11)$$

where V_{water} is the volume of water in the soil sample and V_{sample} is the total volume of dry soil + air + water in the sample. Again, the ratio is usually expressed in per cent. The relationship between gravimetric and volumetric moisture contents is:

$$\theta_v = \theta_g \; (\rho_b/\rho_w) \tag{3.12}$$

where ρ_b is the dry soil bulk density and ρ_w is the soil water density.

Soil water potential describes the energy status of the soil water and is an important parameter for water transport analysis, water storage estimates and soil-plant-water relationships. A difference in water potential between two soil locations indicates a tendency for water flow, from high to low potential. When the soil is drying, the water potential becomes more negative and the work that must be done to extract water from the soil increases. This makes water uptake by plants more difficult, resulting in plant stress and, eventually, severe wilting (WMO, 2008). The water potential is a measure of the ability of soil water to perform work, or, in the case of negative potential, the work required to remove the water from the soil. The total water potential ψt, the combined effect of all force fields, is given by:

$$\psi_t = \psi_z + \psi_m + \psi_o + \psi_p \tag{3.13}$$

where ψ_z is the gravitational potential, based on elevation above the mean sea level. The numerical value of ψ_z itself is thus not important because it is defined with respect to an arbitrary reference level; what is important is the difference, or gradient in ψ_z between any two points of interest. This value is invariant of the reference level location (Or *et al.*, 2005).

ψ_m is the matric potential resulting from the combined effects of capillarity and adsorptive forces within the soil matrix. The primary mechanisms for these effects include: (i) capillarity caused by liquid-gas interfaces forming and interacting within the irregular soil pore geometry; (ii) adhesion of water molecules to solid surfaces due to short-range London-van der Waals forces and extension of these effects by cohesion through hydrogen bonds formed in the liquid; and (iii) ion hydration and water participating in diffuse double layers (particularly near clay surfaces). The value of ψm ranges from zero when the soil is saturated to increasingly negative values as the soil becomes drier (Or *et al.*, 2005).

ψ_o is the solute or osmotic potential, due to energy effects of solutes in water; which lower its potential energy and its vapor pressure. The effects of ψ_o are important when: (i) there are appreciable amounts of solutes in the soil; and (ii) in the presence of a selectively permeable membrane or a diffusion barrier which transmits water more readily than salts. The two most important diffusion barriers in the soil are: (i) soil-plant root interfaces (cell membranes are selectively permeable); and (ii) air-water interfaces (Or *et al.*, 2005).

ψ_p is the pressure potential, the hydrostatic pressure below a water surface that saturates the soil. ψ_p is always positive below a water table, or zero if the point of interest is at or above the water table. In this sense non-zero magnitudes of ψ_p and ψ_m are mutually exclusive: either ψ_p is positive and ψ_m is zero (saturated conditions), or ψ_m is negative and ψ_p is zero (unsaturated conditions), or $\psi_p = \psi_m = 0$ at the free water table elevation.

The potentials which are not related to the composition of water or soil are together called hydraulic potential, ψ_h. In saturated soil, this is expressed as $\psi_h = \psi_z + \psi_p$, while in unsaturated soil, it is expressed as $\psi_h = \psi_z + \psi_m$ (WMO, 2008).

The gradients of the separate potentials will not always be significantly effective in inducing flow. For example, ψ_0 requires a semi-permeable membrane to induce flow, and ψ_p will exist in saturated or ponded conditions, but most practical applications are in unsaturated soil.

If a large quantity of water is added to a block of otherwise dry soil, some of it will drain away rapidly by the effects of gravity through any relatively large cracks and channels. The remainder will tend to displace some of the air in the spaces between particles, the larger pore spaces first. Broadly speaking, a well-defined wetting front will move downwards into the soil, leaving an increasingly thick layer retaining all the moisture it can hold against gravity. That soil layer is then said to be at field capacity, a state that for most soils occurs about $\psi \approx 10$ kPa (pF ≈ 2). This state must not be confused with the undesirable situation of saturated soil, where all the pore spaces are occupied by water. After a saturation event, such as heavy rain, the soil usually needs at least 24 h to reach field capacity. When moisture content falls below field capacity, the subsequent limited movement of water in the soil is partly liquid, partly in the vapour phase by distillation (related to temperature gradients in the soil), and sometimes by transport in plant roots. Plant roots within the block will extract liquid water from the water films around the soil particles with which they are in contact. The rate at which this extraction is possible depends on the soil moisture potential. A point is reached at which the forces holding moisture films to soil particles cannot be overcome by root suction plants are starved of water and lose turgidity: soil moisture has reached the wilting point, which in most cases occurs at a soil water potential of –1.5 MPa (pF = 4.2). In agriculture, the soil water available to plants is commonly taken to be the quantity between field capacity and the wilting point, and this varies highly between soils: in sandy soils it may be less than 10 volume per cent, while in soils with much organic matter it can be over 40 volume per cent (WMO, 2008).

Soil water is at equilibrium when the net force on an infinitesimal body of water equals zero everywhere, or when the total potential is constant in the system. The difference in chemical and mechanical potentials between soil water and pure water at the same temperature is known as the soil water potential (ψ_w):

$$\psi_w = \psi_m + \psi_o + \psi_p \tag{3.14}$$

The gravitational component (ψ_z) is absent in eq.3.14; soil water potential is thus the result of inherent properties of soil water itself, and of its physical and chemical interactions with its surroundings, whereas the total potential includes the effects of gravity. Total soil water potential and its components may be expressed in several ways depending on the definition of a unit quantity of water. Potential may be expressed as (i) energy per unit of mass; (ii) energy per unit of volume; or (iii) energy per unit of weight. A summary of the resulting dimensions, common symbols, and units are presented in Table 3.1, where μ has actual units of potential; ψ has units of pressure, and h of head of water.

Tab. 3.1 Units, Dimensions and Common Symbols for Potential Energy of Soil Water (OR et al., 2005)

Units	Symbol	Name	Dimensions*	SI Units	cgs Units
Energy/Mass	μ	Chemical Potential	L^2/t^2	J/kg	erg/g
Energy/Volume	ψ	Soil Water Potential, Suction, or Tension	$M/(Lt^2)$	N/m^2 (Pa)	erg/cm^3
Energy/Weight	h	Pressure Head	L	m	cm

* L is length, M is mass, and t is time

3.3 Main physiological characteristics of citrus fruits for the water stress assessment

The dynamic nature of plant water status, the dependence of the water stress effects on its severity, duration, and timing of occurrence during the crop cycle, and the developmental rate of events are among the major difficulties encountered in modelling crop-water relations. The restriction of canopy development is the first line of defence of a crop when water deficit develops during growth. Shortly after, the root-shoot ratio is affected, and later an osmotic adjustment may take place. Only when water stress is advanced and intense enough to have reached a threshold in leaf water potential (Ψ), stomata start to close followed by consequent leaf wilting or rolling. All the conditions are then favorable for an acceleration of senescence (Steduto, 1997).

3.3.1 Root growth and rootstock

Among the different organs, roots are the principal water absorbing organs and play a crucial role in plant development, so that an understanding of root dynamics and their competition with aerial parts is essential, especially when water is limited, in order to define critical periods and to identify the stages of development affected by water deficit (Syvertsen, 1990).

Water deficit usually affects vegetative growth more than fruit growth and often leads to restrictions in root growth (Chalmers *et al.*, 1984); although Deficit Irrigation has also been shown to stimulate root growth (Romero *et al.*, 2006b) especially in the deeper soil layers (Abrisqueta, 2008). The root system's capacity to transport water to the shoot also depends on the water extraction efficiency of individual roots (Castle and Krezdorn, 1977). If root temperatures are above or below optimum, water conductivity of roots may be reduced. This may indirectly affect stomatal conductance in leaves and, hence, CO_2 assimilation and subsequent translocation of carbohydrates. Any stress-induced change in the root system's capacity to supply water to the shoot can influence the tree's tolerance to low temperatures. Indeed, citrus roots growing in cool soil can have higher conductivities per unit root length of individual roots (Syvertsen *et al.*, 1983) than roots growing in warm soil. This may partially compensate for reduced root growth at cool soil temperatures (Styvertsen, 1990). Inadequate soil moisture not only limits water supply to the roots, but also reduces root conductivity directly (Wiersum and Barmanny, 1983), perhaps because of increased suberization of roots.

The root-shoot ratio (R/S) of many crops increases with water stress, although the extent to which the ratio may vary will decrease from early growth to reproduction under water stress also significantly depends on the higher ability of the roots to undergo osmotic adjustment. The partitioning of assimilates between root and shoot can be viewed as an optimization in resource use where carbon is ‘invested’ in roots to the ‘expense’ of the shoot to ‘gain’ more water to sustain the assimilation of more carbon. (Steduto, 1997).

Water relations and tolerance to abiotic stresses vary significantly between rootstock (Syvertsen and Levy 2005). Rootstocks present genetically-determined characteristics that affect plant water relations (Castle and Krezdorn 1977). These characteristics are associated with differences in root hydraulic conductance (Sinclair and Allen 1982; Syvertsen and Graham 1985), which determine the ability of the rootstock to supply water and nutrients to the plant. This ability could be the main factor influencing fruit development in citrus trees, determining the strength of the grafted variety and its tolerance to water stress.

Citrus rootstocks with higher root conductivities also tend to have higher concentrations of mineral nutrients in their leaves than rootstocks with lower conductivities (Syvertsen and Graham, 1985). Competition between roots and shoots for carbohydrates is also important since canopy shading, drought, severe defoliation, or heavy crop load can all lead to decreases in root growth of citrus. Since the source of carbohydrates is in the leaves and shoots, shoots typically compete better for photosynthates than roots. This is an important factor when considering how a tree recovers from partial defoliation caused by drought, salinity, or freezes (Styvertsen, 1990).

Romero *et al.* (2006b) evalueted differences between rootstocks, ‘Cleopatra’ mandarin and ‘Carrizo’ citrange, in soil plant water relations and the influence of these factors on vigor, crop yield, fruit quality and mineral nutrition were evaluated in field-grown Clemenules mandarin trees irrigated a different irrigation regime. After 3 years of deficit irrigation treatment, trees on ‘Cleopatra’ were able to tolerate moderate water stress, whereas trees on ‘Carrizo’were more sensitive to changes in soil water content.

Furthermore, according to Pérez-Pérez (2008), flowering, fruit abscission and fruit growth of trees on ‘Carrizo’ were more affected by DI than on ‘Cleopatra’; deficit irrigation reduced yield in both rootstocks due mainly to a decrease in the number of fruits. The phase most sensitive to drought stress was phase I (cell division).

Treeby *et al.* (2007) showed that rootstock is not a significant source of variation in fruit fresh weight or diameter at any developmental stage, although rootstock is also an important factor in the accumulation of sugar by fruit.

3.3.2 Respiration mechanism

The two major contact points between plants and their external environment are: 1) between the root and the soil where water, mineral nutrients and oxygen enter the system and carbohydrates, aminoacids, other exudates, and CO_2 can leave the plant and enter the soil; and 2) between shoot tissues and their aerial environment where CO_2 and oxygen are exchanged and H_2O vapor inevitably diffuses out of stomata. Thus, plants that fix the most carbon and produce the most dry weight also transpire the most water. These plant environment interfaces are critical control points where environmental factors and physiological mechanisms interact to regulate exchanges of energy and materials (Syvertsen, 1990).

The respiration represents a determinant component of the carbon balance, or carbon budget, of crops as it is responsible for the use of assimilated carbon for all the catabolic and anabolic reactions of the metabolism involved during the lifec ycle ofa plant. The energy cost of respiration (R) can be satisfactorily subdivided into two components: maintenance (R_m) and growth (R_g) respiration, there by $R=(R_m)+(R_g)$. Maintenance respiration (R_m) supplies energy for turnover of proteins and lipids and maintenance of electrochemical gradients across membranes. Growth respiration (R_g), instead, supplies energy for the synthesis of compounds and structures for additional biomass, accumulation of compounds in temporary pools for subsequent use, differentiation in secondary products, and translocation of compounds. In terms of respiration dependence one nviromental factors, temperature represents the main influencing variable, essentially through R_m. This is of particular relevance in arid and semi-arid regions, as water deficit periods are coincidental with high temperature regimes. The respiration is generally depressed when water deficit is sufficiently great to close stomata, although the extent of reduction in respiration is comparatively less than in photosynthesis. This is also in agreement with the general observation that any factor that reduces photosynthesis, and therefore growth, should reduce the rate of respiration (Amthor, 1989). This is particularly valid for water stress due to the strict relationship between biomass and water transpired although, on a shortterm basis, water stressed plants may accumulate large amounts of organic solutes requiring a higher maintenance respiration. In fact, there is some increase in respiration during early stress with subsequent decrease with stress development (Steduto, 1997).

3.3.3 Leaves and evaporative demand

When available soil water is limited, water movement through the plant system is regulated primarily by soil water supply and conductivity of the roots. When soil water is adequate, water movement is controlled by root conductivity and transpiration. This water movement through the tree is regulated by both stomatal aperture and evaporative demand. Plant water deficits can be caused by an inadequate water supply or by high evaporative demand (Syvertsen, 1990). A direct consequence of stomatal closure is a tendency for reduced water uptake and transport, and for reduced gas exchange by the leaves, especially of water vapor and CO_2. Given adequate leaf water status to maintain turgor, stomata may respond directly to CO_2 concentrations, resulting in the rate of CO_2 photosynthesis affecting stomatal conductance rather than the reverse. Stomatal limitations on photosynthesis are probably not as great as is generally believed until extreme drought stress causes leaves to wilt.

Cell expansion of many crops has been shown to be the most sensitive process to water stress (Steduto, 1997). The implication of this sensitivity is that, during crop development, leaf area may be reduced with consequent reduction in light interception, and thus in the whole source size for assimilates. This leaf area reduction may be quite strong even at mild water stress, and with no effect at all on stomatal closure. The leaf area that intercepts radiation can be modified by drought-induced wilting, curling of leaves, solar tracking, and leaf shedding. During extreme drought, leaf loss can enhance tree survival by decreasing the evaporative surface. The cessation of new leaf growth is a means by which the tree can acclimate to drought stress conditions (Syvertsen, 1982). Young leaves lose turgor and wilt during water stress before mature leaves. Thus, initiation and growth of new leaves is very sensitive to water deficits.

Reductions in leaf area by decreased growth and accelerated leaf drop caused by water stress can reduce photosynthetic capacity by reducing the leaf area. Remaining leaves can partially compensate for leaf area losses by enhancing CO_2 assimilation rates. Such changes influence carbon budgets through carbohydrate production, loss, and allocation to leaf and fruit growth.

Furthermore, there is usually an increase in leaf temperature associated with a greater disposition of the absorbed energy into sensible heat transfer rather than evaporation. Perhaps the most significant effect is that on CO_2 exchange which can directly regulate photosynthesis. Leaf area index (LAI) and absorption of photosynthetically active radiation (PAR), defined as the energy flux in the waveband 400–700 nm, are interrelated: once the canopy reaches full development, the plant is limited by the amount of incident radiation. During this stage, the plant is less sensitive to water stress as further leaf area growth would not significantly increase the amount of incident PAR.

3.3.4 Tissue capacitance

Most estimates of the efficiency of water transport in the xylem come from measurements of leaf water status at different transpiration rates. The conductivity of water by xylem can be a factor in the development of plant water deficits in citrus. In large trees, stored water in the trunk can provide a significant water source that is available to augment transpirational requirements (Chaney, 1981). Seasonal and diurnal variations in sapwood water content can, therefore, be used as estimates of transpirational demand. Diurnal and seasonal dimensional changes in leaves, fruit, stems, the size of the vessels have been used as quantitative estimates of tissue water changes. In particular, the reduction of the vessels diameter is a mechanism that limits the flow of water and prevents loss of cavitation xylem functionality. The plants are subject to a daily trunk diameter variation that depends on water conditions.

During the early hours of the morning there is a contraction of vascular organs, due to the re-opening of the stomata that triggers the transpiration, followed by a partial water loss of the leaves. Indeed, during the late afternoon stomatal closure follows a decrease of transpiration and radical absorption is more than the loss of water by transpiration, it follows an increase of the stem diameter. Some authors (Goldhamer and Fereres, 2003) have shown that it is currently one of the most reliable parameters for the evaluation of plants water stress and for irrigation scheduling.

Water status of various plant tissues quantitatively reflect internal competition for water. Redistribution of water is a function of both water status and resistance to transport. Thus, daily changes in tissue water content, relative thickness of leaves, and fruit diameter are indicative of interactions in the water transport system. Since these factors are linked by way of leaf transpiration, which is a function of both conductivity and vapor pressure gradients, their relationship may not always be simple (Syvertsen, 1982).

Furthermore, citrus leaves subjected to alternate drying and irrigation cycles become physiologically hardened to drought stress and thereby enhance their tolerance to subsequent drought. Plant water deficits routinely occur during the day, not only in response to an inadequate water supply or an insufficient water transport system, but also in response to normal increases in evaporative demand. Daily increases in vapor pressure deficits increase the difference between the absolute humidity of leaves and air, and stomatal conductance generally decreases.

3.3.5 Osmoregulation mechanism

Osmoregulation, or osmotic adjustment (Steduto, 1997) is a relevant physiological mechanism adopted by plants to tolerate water stress. Since total water potential in plant cells (Ψ), at the same reference level, is the sum of osmotic or solute potential (Ψ_s) and turgor or pressure potential (Ψ_p) with $\Psi_s < 0$ and $\Psi_p \geq 0$, any increase in osmotic potential, compatible with the cell biochemistry, allows a corresponding increase in turgor. This enables plants to maintain root and leaf expansion and photosynthesis activity at levels of stress which are not possible in its absence. During a water deficit event, any loss of water from cells generally induces an increase in Ψ_s as a consequence of increased concentration. This is considered simply a passive adjustment in Ψ_s**.** In addition to the effect of solute concentration, plants have the ability to actively trigger osmotic adjustment to counteract water stress. The solutes that accumulate during adjustment may be of various nature depending on species and timing of the cycle, but all can be reconducted to typical cell compounds such as soluble carbohydrates, organic acids, proline, exchangeable ions, etc. Since also the solutes of the rooting medium affect the water potential in plants, salinity conditions in soils and water may represent an additional source of osmoticum (Lerner *et al.*, 1994).

Osmotic adaptation of roots is also an important mechanism to allow preferential growth of roots under stress. Osmotic adjustment enables plants to deplete the soil water to a lower soil water potential and to explore a larger volume of soil by roots. While the additional water made available by decreasing the soil water potential is likely to be small, the additional water made available by the exploration of a larger soil volume could be significant. Beyond the effects on cell growth, the maintenance of turgor by osmotic adjustment of leaves may also have a significant effect more directly on final yield. There is evidence suggesting that maintenance of turgor in leaves reduces the abscissic acid (ABA) produced, which in turn reduces the viability of the pollen. However, there are costs for osmotic adjustment which can be identified as energy costs and enzyme inhibition.

The fig 3.4 show the adaptive changes in crop plants in response to the gradual development of water stress in the field.

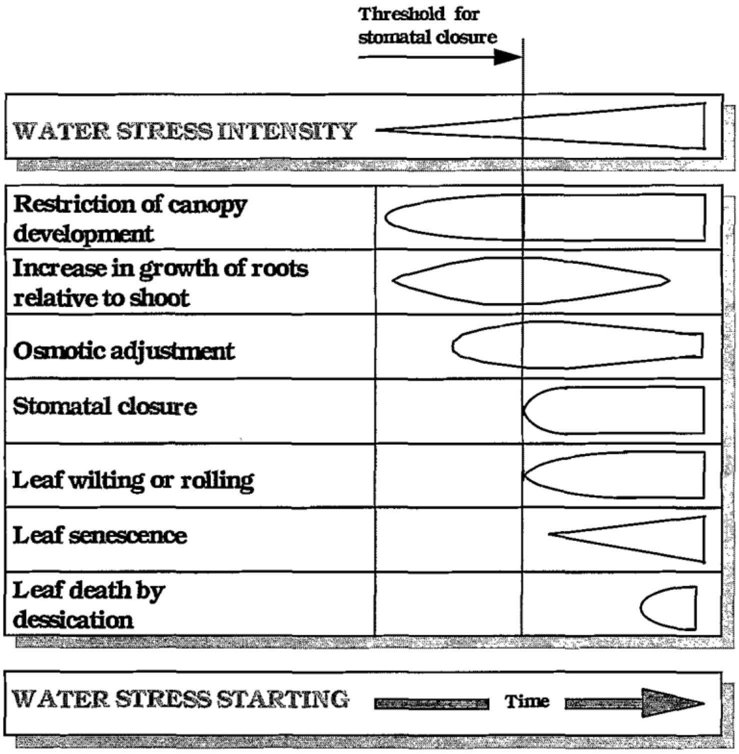


Fig 3.4 Crop and water stress relationship (Steduto, 1997).

The width of a band represents the relative magnitude of the response; the shape of a band reflects the variation of responses with increasing stress intensiv and duration; the starting position of a band on the time scale indicates the water stress threshold for eliciting the response.

3.3.6 Reproductive Growth

Differentiation of vegetative or reproductive tissue is directly affected by water deficits and indirectly affected by the availability and distribution of photosynthates and plant hormones. Decreases in vegetative growth and flower bud initiation due to drought stress can hasten fruit growth of remaining fruit by decreasing competition for water and carbohydrates, but water deficits also can delay fruit maturation. Water loss directly from flowers can be quite high. Flower and fruit can have functioning stomata, although the importance of water loss from oranges diminishes as fruit mature. Leaves and fruit compete for a limited water supply diurnally as well as seasonally. Early fruit abscission of weak young fruit (June drop) has been related to drought stress (Iglesias, 2007). Limited soil water usually results in yield losses but may enhance water use efficiency.

Reproductive yield usually is adversely affected by inadequate soil moisture. High temperatures and evaporative demand during flowering and fruit set can be disastrous. Hoderate drought stress can increase percentage of flower abscission and, thus, reduce fruit yield. Yield usually is decreased by inadequate soil moisture, but moderate drought stress can enhance fruit quality by decreasing the size of citrus fruit and decrease dilution effects in citrus. Changes in fruit volume or dry matter content may be of use in scheduling irrigations (Syvertsen, 1982).

3.4 Plant nutrition

Knowledge of the phenological processes of trees is important for adjusting not only irrigation but also fertilization programmes. Tree nutrition interacts with soil water supply, but the relationship can be complicated by vegetative growth responses and internal redistribution of minerals. Adequate mineral nutrients can enhance root growth and hence surface area contact with soil. This becomes especially important when soil moisture is limiting. Some improvements in plant water relations can be attributed to improved phosphorous nutrition. Mineral nutrient deficiency can also limit the hydraulic conductivity of roots. The development of new roots at the expense or delay of additional shoot or top growth is one way a tree can recover from stress. For example, when nutrients in the soil are insufficient, the tree may produce more root growth than shoot growth; the tree is exploring additional soil volume in an attempt to satisfy overall nutrient demand (Syvertsen and Hanlon, 2008).

The most important management practices influencing fruit quality are irrigation and nitrogen (N), phosphorus (P), potassium (K), and magnesium (Mg), while some micronutrients like boron (B) and copper can also affect fruit quality, but only if they are deficient in the tree. In general, when any nutrient element is severely deficient, fruit yield and fruit quality will be negatively affected. Table 3.2 show specific effects on juice and external fruit qualities.

Tab.3.2 Effects of mineral nutrition and irrigation on citrus fruit quality (Zekri et al., 2003).

Variable	N	P	K	Mg	Irrigation
Juice Quality					
Juice Content	+	0	-	0	+
Soluble Solids (SS)	+	0	-	+	-
Acid (A)	+	-	+	0	-
SS/A Ratio	-	+	-	+	+
Juice Color	+	0	-	?	0
Solids/Box	+	0	-	+	-
Solids/Acre	+	+	+	+	+
External Fruit Quality					
Size	-	0	+	+	+
Weight	-	0	+	+	+
Green Fruit	+	+	+	0	+
Peel Thickness	+	-	+	-	-

Increase (+), Decrease (-), No change (0), No information (?)

This summary is based on numerous field experiments conducted over many years that evaluated the response of oranges to irrigation and fertilization practices. Most of these effects were consistently observed, but some of them appeared to depend on local conditions and growing regions. These observations are useful in developing a strategy to improve fruit quality for a particular variety or location.

4. Application of Deficit Irrigation strategies on young citrus in eastern Sicily

4.1. Location of experimental site

The application of deficit irrigation strategies on young citrus trees was carried out from 2010 to 2012 within the experimental farm "Palazzelli" (N 37°20'14.56", E 14°53'35.37"), managed by the Sicilian Citrus Research Center (CRA-ACM). The study was located in the surroundings of Lentini's area, 50 km far from Catania (Sicily).

Experimental farm is located 50 meters above sea level, it extends for about 25 hectares, in one of the most suitable areas for citrus cultivation, expecially pigmented oranges production. The farm stands on a rectangular ground with a slight slope, and it is divided into two parts by a main road that, from the entrance gate, reaches the opposite border. Moreover, the whole area was divided into plots planted with different varieties of citrus trees; they are marked with a different number from 1 to 11 and bordered by others smaller roads (Fig. 4.1).

Farm's climatic and soil conditions related to irrigation water quality are the perfect combination to citrus yield, therefore the soil is deep, middle mixture and clay.

The farm is managed by a centralized irrigation system which includes:

- Two wells;
- One irrigation pool with the capacity of 300 m^3;
- An irrigation pump that injects water at irrigation system;
- Several kinds of irrigation systems: drip and localized type, semi-localized sprinkler and hydrodynamic under-tree system;
- A frost protection system to protect the production and the varietal collection.

Fig. 4.1 Location of experimental site.

Furthermore, within plot n. 2 there are:

- a greenhouse glass (Fig. 4.1), housing rootstocks nursery (i.e. sour orange, Troyer citrange, Carrizo citrange);
- a screen house (Fig. 4.1), covered with a double layer of insect mesh, to ensure maximum protection to the population of hosted plants.

4.2 Experimental methods

4.2.1. Experimental design and irrigation treatments

The study area is about 0.7 ha (Fig. 4.2), where in 2009 were planted about 380 orange trees, *cv. Tarocco Sciara*, grafted on Citrange Carrizo, at a spacing of 6x4 m.

The experimental area was divided into 3 blocks (Fig. 4.3), each includes 4 different theses. The theses were three times replicated, in a randomized block design, and each includes 24-27 plants.

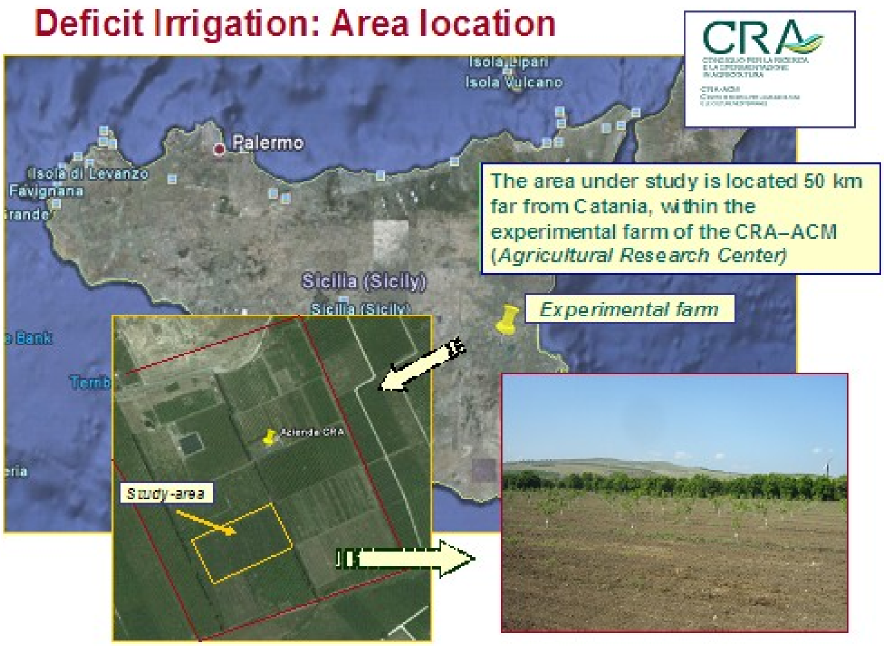


Fig. 4.2. Sicilian Citrus Research Centre and study area.

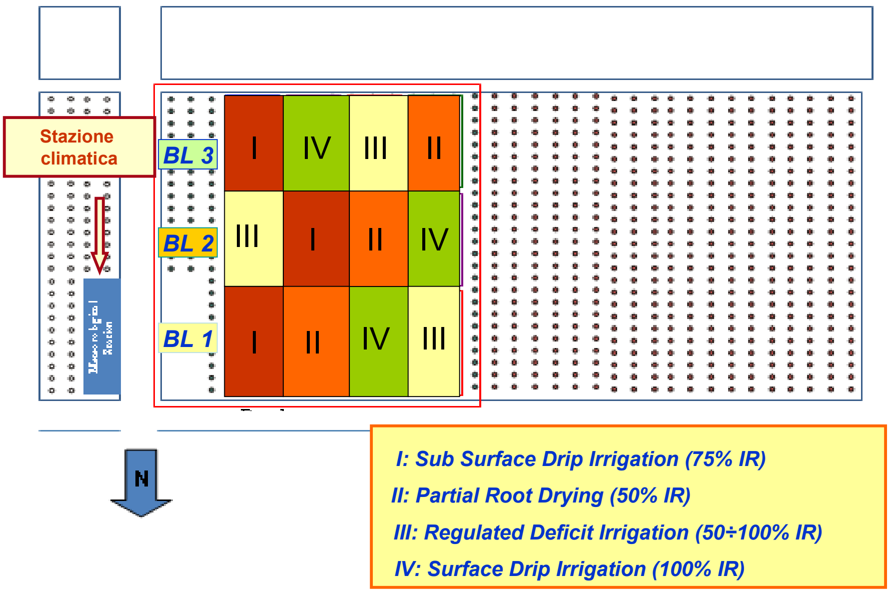


Fig. 4.3. Randomized block design for DI strategies application.

As well known from literature, crop evapotranspiration (ET_c) is one of the main irrigation parameter used to schedule DI strategies. In the study, ET_c (eq. 3.9) was calculated as the product of reference ET_0 (eq. 3.1) using the Penman-Monteith methodology (Allen *et al.*, 1998) and the seasonal crop coefficient for immature orange orchards (K_c=0.45, Consoli *et al.*, 2006). Climatic data to apply the Penman-Monteith method were recorded at the climatic station located within the Sicilian Citrus Research Centre (Fig. 4.4). The station comprises, following the methods indicated dall'UCEA, Central Bureau of Agricultural Ecology, the monitoring of solar radiation (R_s, W/m^2), air temperature (T, °C), relative air humidity (RH,%), speed (u, m s^{-1}) and wind direction. The station is connected to “Class A” pan evaporimeter for hourly and daily evaporation measurement.

Fig. 4.4. Climate station and pan evaporimeter

After determining ET_c, we proceeded to calculate the Irrigation Requirement (IR), taking into account appropriate location factors and correction coefficients relating to the distribution system performance.
In particular, IR ($m^3 ha^{-1}$) was determined as follows:

$$IR = ET_c \times K_1 \times K_2 \times K_3 \qquad (4.1)$$

where K_1 “irrigation location ”factor:

$$K_1 = \frac{P_c}{100} + 0.5\left(1 - \frac{P_c}{100}\right) \qquad (4.2)$$

with:

$$P_c = 100 \times \frac{\sup foliage}{\sup plant} \qquad (4.3)$$

The coefficient K_2 takes into account the irrigation efficiency, while the coefficient K_3 takes into consideration the distribution uniformity. IR values obtained, the applied volume was determined as follows:

V = a x b x IR (liters/period) (4.4)

with a = 4 m e b = 6 m

The duration of each daily irrigation was calculated as:

t = V/(n x q) (hours/day) (4.5)

where:

n = number of drippers per plant

q = the nominal flow rate ($L\ h^{-1}$) delivered by single dripper.

Accordingly, irrigation was scheduled weekly with a frequency of two times per week.

As shown by Fig. 4.3, the different thesis have the following characteristics:

- *Sub Surface Drip Irrigation – SSDI (Thesis I)*, where it is applied 75% of Irrigation Requirement (IR), by means of a sub surface drip irrigation system.
- *Partial Root Drying – PRD (Thesis II)*, where it is applied 50% IR, through a micro-flow surface irrigation system.
- *Regulated Deficit Irrigation – RDI (Thesis III*) where it is applied 50÷100% IR, as function of the phenological stage in which the plant could withstand water stress, through micro-flow surface irrigation system.
- *Surface Drip Irrigation – SDI (Thesis IV),* where it is applied 100% IR, by means of a sub surface drip irrigation system.

For each thesis was applied a different kind of microirrigation system. In particular, in the thesis SSDI (Thesis I) two lateral pipes with in-line labyrinth drippers and with spacing of 0.6 m were buried 35 cm deep (Fig. 4.5). The dripper flow rate is 6 L h^{-1} (a drip line delivers 4 L h^{-1} for each dripper, while the other drip line delivers 2 L h^{-1}) at a pressure of 120 kPa .

In PRD (Thesis II), two surface lateral pipes with in-line labyrinth drippers and with spacing of 0.6 m located 0.35 m from the trunk of the plant on a different side. flow rate is 4 l/h at a pressure of 120 kPa for each dripper. Irrigation is applied only to one side and the system is switched to the other side every week (Fig. 4.6).

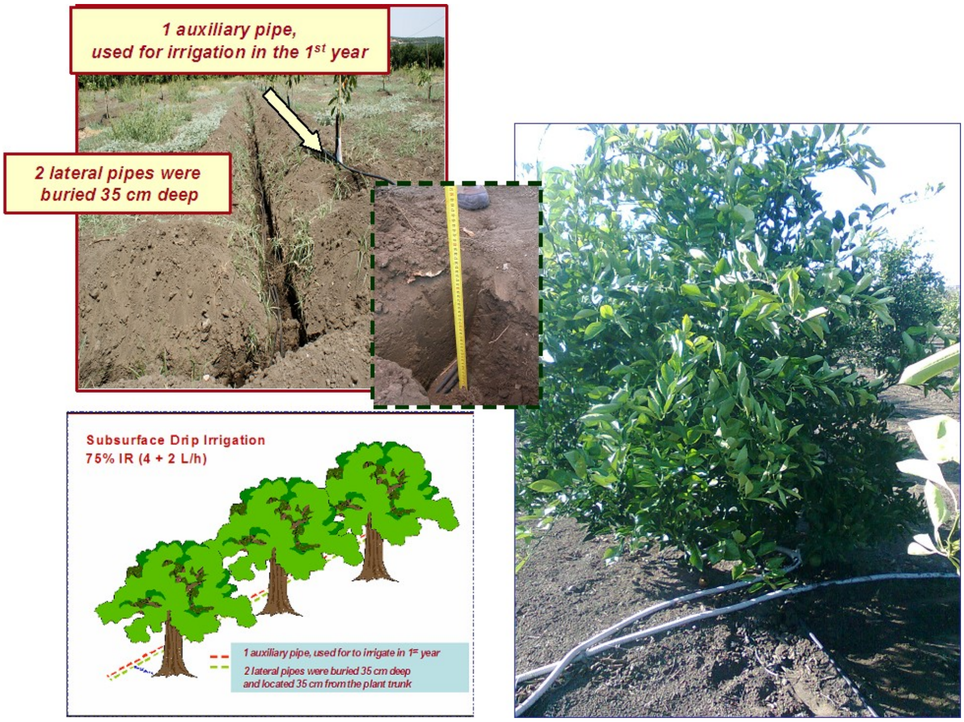


Fig. 4.5. Thesis I – Sub Surface Drip Irrigation (SSDI) strategy.

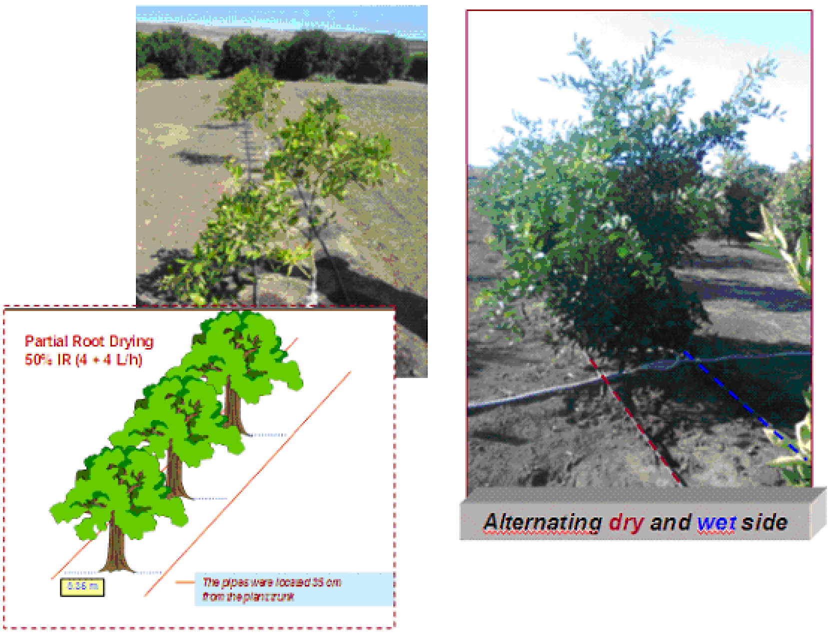


Fig. 4.6. Thesis II – Partial Root Drying (PRD) strategy.

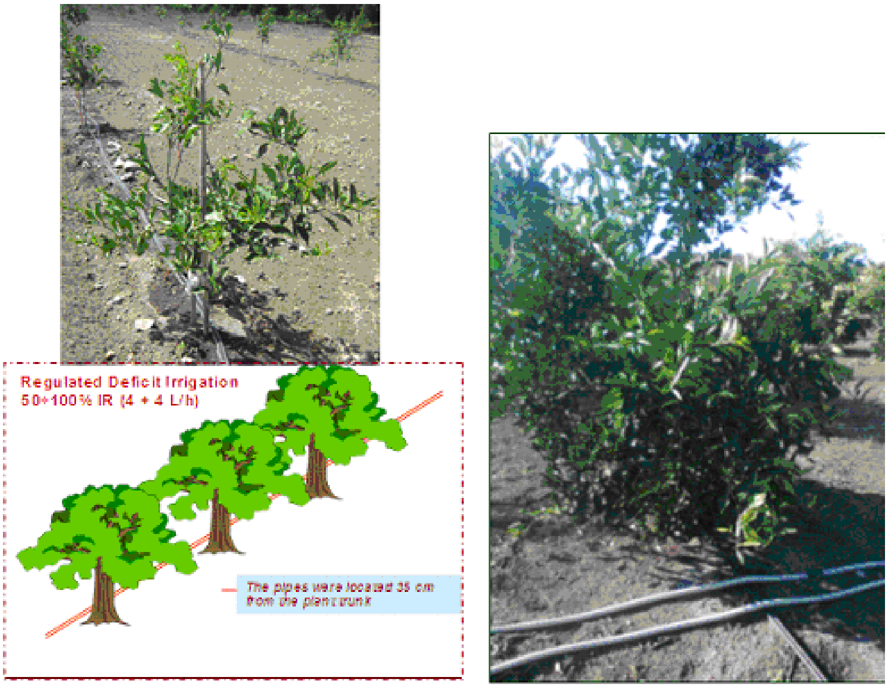


Fig. 4.7. Thesis III – Regulated Deficit Irrigation (RDI) strategy.

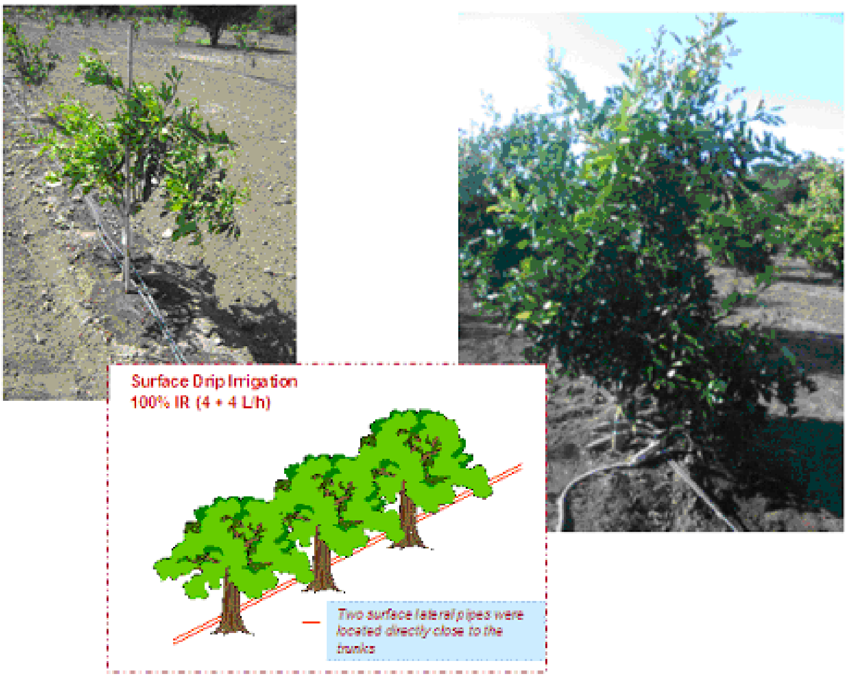


Fig. 4.8. Thesis IV – Surface Drip Irrigation (SDI) strategy.

In RDI (Thesis III), two lateral pipes were located directly close to the trunks, with 4 l/h drippers, 60 cm spaced within each line. Trees are generally irrigated to replace 100% IR; during certain phenological phases, more tolerant to water stress, irrigation water is reduced to 50% IR (Fig. 4.7).

In SDI (Thesis IV) two surface lateral pipes were located directly close to the trunks, with 4 l/h drippers at a pressure of 120 kPa, 60 cm spaced within each line (Fig. 4.8).

The irrigation materials has been supplied by Irritec s.r.l and Siplast S.p.A. The irrigation system is served by a main pipe with a diameter of 63 mm (Fig. 4.9.) which delivers, at a pressure of about 175 kPa, the water volumes predetermined by an experimental system through the 12 sub-main line control groups connected with the distribution pipes with ø 40 mm (Fig. 4.10), installed adjacent to each thesis and having an operating pressure of about 120 kPa. In the main line control group, the water filtration system was carried out with more filters planned in series (Fig. 4.9.) and it is constituted by a metal hydrocyclone water filter and plastic net filter (120 mesh). Furthermore, the control unit presents the fittings predisposing the system to the installation of a fertigation, used to supply either fertilizer or drip lines cleaning operations.

Fig. 4.9. Main line control group.

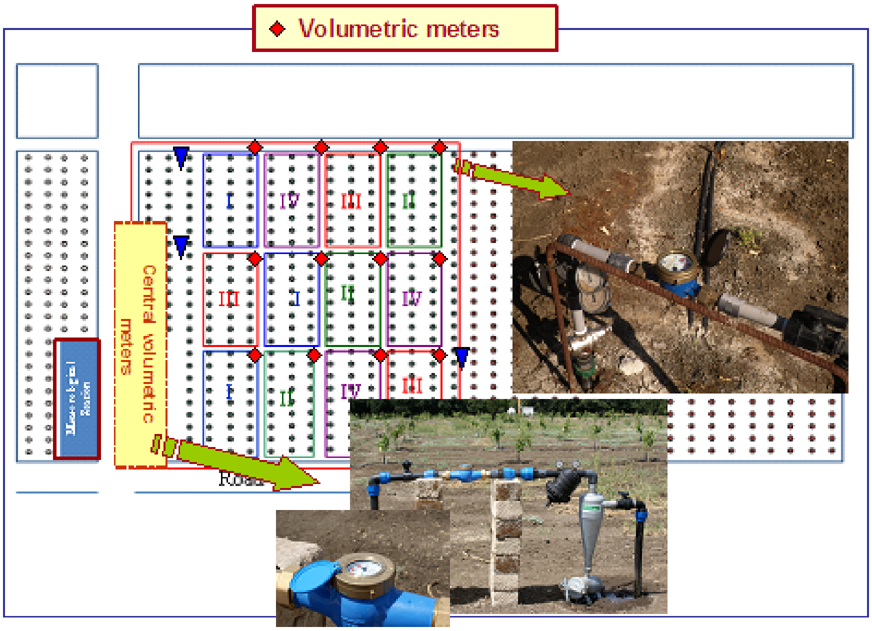


Fig. 4.10. Volumetric meters, main and sub-main control groups. I, II, III and IV are SSDI, PRD, RDI and SDI thesis, respectively..

Fig. 4.11 shows the irrigation system layout. Each thesis is equipped with a shut-off valve, a volumetric meter, a pressure regulating valve, two pressure gauges to monitor water pressure before and after water filtration. In particular, the Fig. 4.12 shows the details of the irrigation system in the thesis I and IV where there is only one water distribution line.

The thesis II and III (Fig. 4.13) were provided with two water distribution lines in order to be able to close a drip line and managed by two closing-opening valves. In this way it is possible to exclude (from time to time) irrigation to half of the root system.

The driplines ø 16 mm used in Thesis II, III and IV (PRD, RDI, SDI) belongs to TANDEM type (2 L h^{-1} and 4 L h^{-1}), realised with a polyethylene pipe with an incorporated dripper in phase of extrusion.

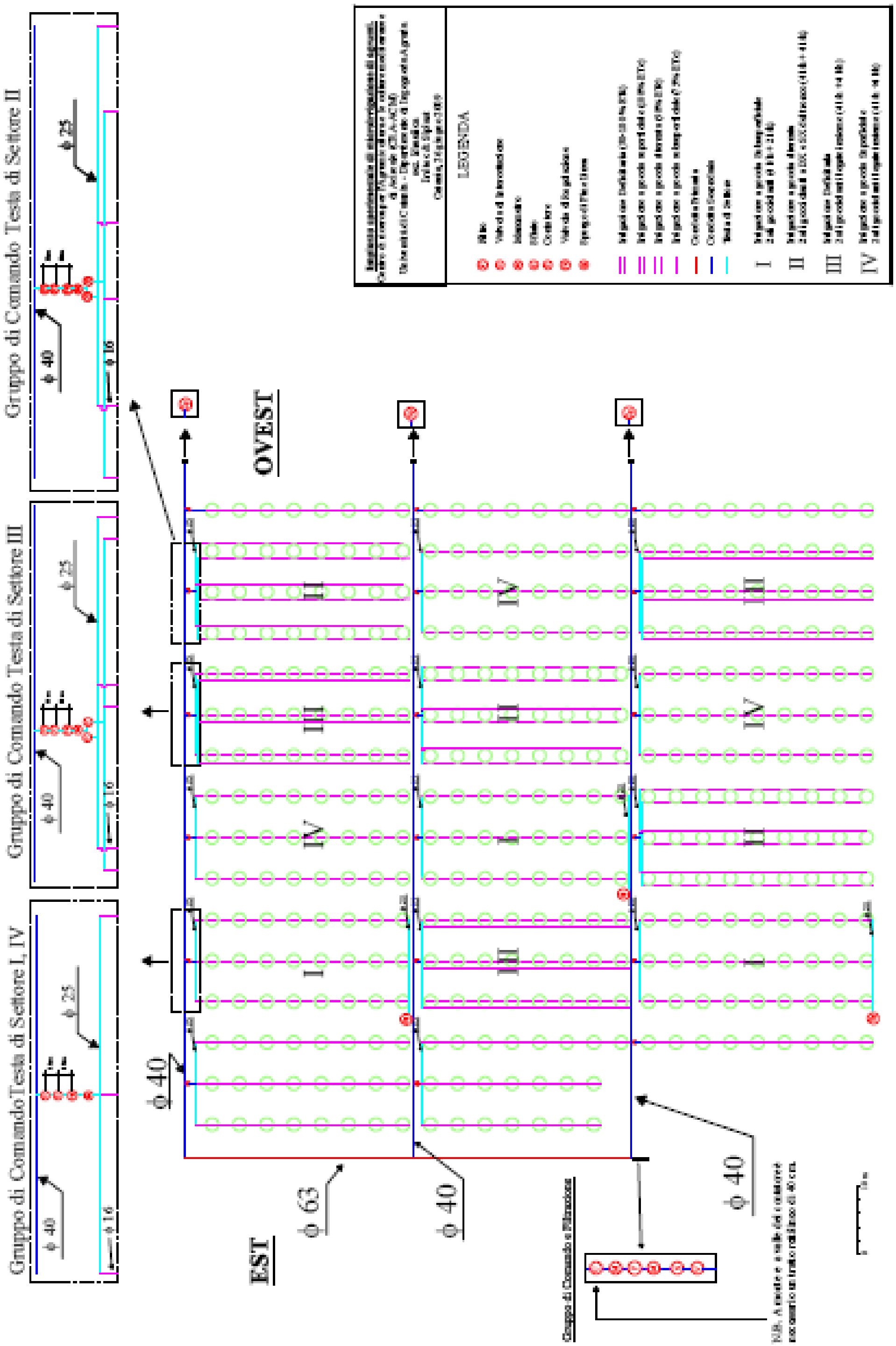


Fig. 4.11. Irrigation system layout.

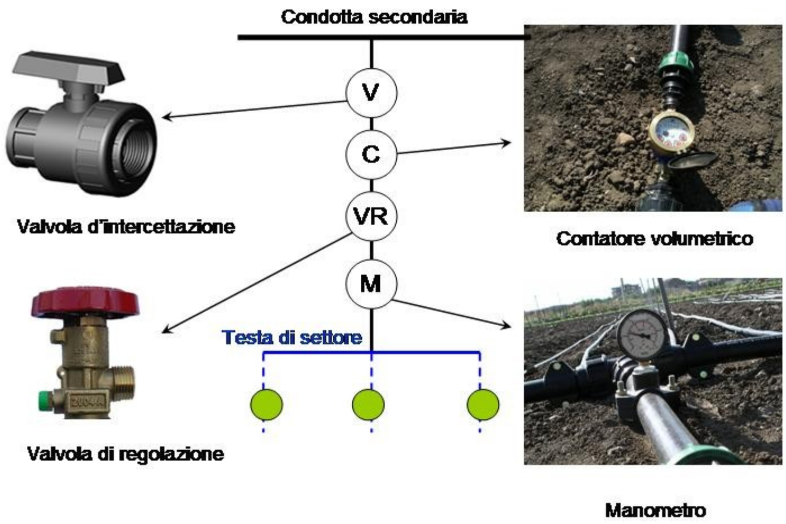


Fig. 4.12. Details of the irrigation system in the thesis I and IV.

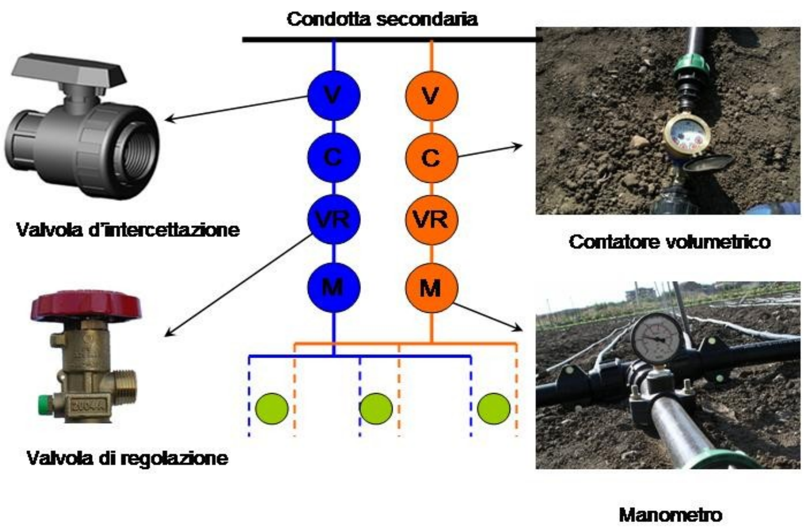
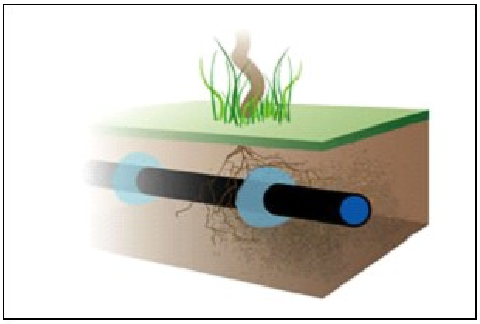


Fig. 4.13 Detail of the irrigation system in the thesis II and III.

The turbolent flow labyrinth (self cleaning) avoids sedimentations inside the labyrinth itself; the dripper endowed with a filter notably reduces occlusion risks (Fig. 4.14).

Fig. 4.14 Tandem coextruded dripline.



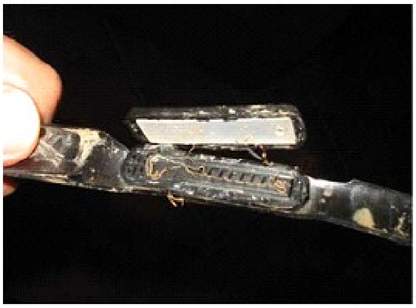


Fig. 4.15 Rootguard - Subsurface irrigation systems

The driplines ø 16 mm used in Thesis I (SSDI), belongs to ROOTGUARD type, radical anti-intrusion device that avoids specific issues to drip during periods when the irrigation system is not active (Fig. 4.15).

4.2.2. Preliminary activities for the irrigation season.

At the beginning of each irrigation season an overall control of the experimental irrigation system experimental was made through:

- The drip cleaning;
- The volumetric meters calibration;
- Texts for irrigation uniformity;
- Irrigation water analysis;

- Samples plants selection.

To avoid drippers occlusion during winter season, when the system is off, were carried cleaning operations of drip lines. This process, made at the beginning and at the end of each irrigation season, was carried out using sulfuric acid (2.15 L of sulfuric acid diluted in 400 L of water, so as to obtain a pH in the drips of about 4.5) and hydrochloric acid at 5.25% diluted in 300 L of water (Fig. 4.16).

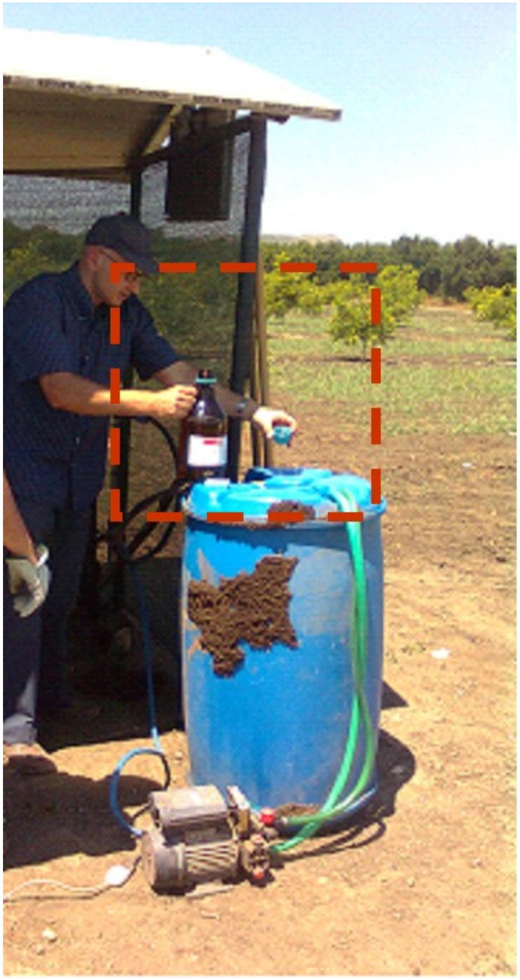


Fig. 4.16 Drip lines cleaning operation.

The volumetric meters calibration was made taking into consideration the percentage error of the volumes actually delivered by the irrigation system (Fig. 4.17). It consists of reading each counter before and after the filling of a container, whose volume is known, with water supplied by the same control group.

Fig. 4.17 Counters calibration in order to calculate the percentage error of the volumetric meters.

Emission uniformity (EU) has been one of the most frequently used criteria for microirrigation design and evaluation. The original emission uniformity formula, which was derived by a worst combination of hydraulic variation and manufacturer's variation, can provide a very conservative design with a smaller value for EU than that measured in the field. A revised formula for emission uniformity derived by a statistical approach can provide a more realistic emission uniformity for microirrigation in the field (Barragan *et al.*, 2006).

The data were then elaborated through the following equation:

$$\text{Emission Uniformity (\%)} = \frac{\textit{Avg. discharge of the 25\% sampled emitters with the least discharge}}{\textit{Avg. discharge rate of all the sampled emitters}} \times 100 \tag{4.6}$$

Emission uniformity is expressed as a percentage, and is a relative index of the variability between emitters in an irrigation block. Emission uniformity is defined as the average discharge of 25% of the sampled emitters with the least discharge, divided by the average discharge of all sampled emitters.

For each irrigation thesis, was calculated the average of all your discharge rate measurements. To identify the 25% sampled emitters with the least discharge rate, the discharge rate of all sampled emitters should be ranked from lowest to highest. Then 25% of the emitters with the lowest discharge rate should be averaged together (Tab. 4.1).

Tab. 4.1 Example of Uniformity Emission (%) calculation.

BLOCCO 2 TESI 2 4 +4 l/h	ala centrale est	ala centrale ovst	Tempo	ala est + ala ovest	ala est + ala ovest	in ordine decrescente	Q ordinata [l h-1]
Gocciolatori	(mL)	(mL)	sec	[ml s-1]	[l h-1]		ala est + ala ovest
1	63	60	60	2.05	7.38	1	8.16
4	68	60	60	2.13	7.68	2	8.10
7	69	67	60	2.27	8.16	3	7.92
10	63	64	60	2.12	7.62	4	7.74
13	68	67	60	2.25	8.10	5	7.74
16	55	65	60	2.00	7.20	6	7.68
19	66	60	60	2.10	7.56	7	7.68
22	64	65	60	2.15	7.74	8	7.62
25	66	62	60	2.13	7.68	9	7.62
28	64	68	60	2.20	7.92	10	7.62
31	62	62	60	2.07	7.44	11	7.56
34	58	65	60	2.05	7.38	12	7.44
37	63	64	60	2.12	7.62	13	7.44
40	57	70	60	2.12	7.62	14	7.38
43	62	62	60	2.07	7.44	15	7.38
46	56	65	60	2.02	7.26	16	7.26
49	65	64	60	2.15	7.74	17	7.20
media gocciolatori	7.62	media ultimo Quartile	7.31	UE [%]	95.87		

Emission uniformity tests were carried out only in some theses with surface irrigation system (Fig. 4.18).

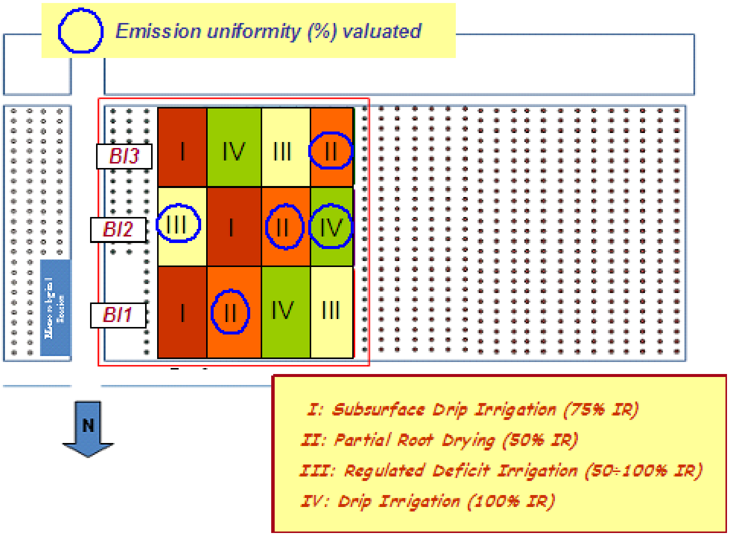


Fig. 4.18 Emission Uniformity layout.

As regards irrigation water analysis (Fig. 4.19), were monitored pH (measure of the water hydrogen ion concentration), electrical conductivity EC (estimates the amount of total dissolved salts, or the total amount of dissolved ions in the water), as well as some microelements, for example, BOD_5 and COD (biological and chemical oxygen demand), suspended solids, nitric nitrogen, total nitrogen, etc.

Fig. 4.19 Meters and probes to measure pH and electrical conductivity.

Table 4.2 shows an increase of the salt concentration in the irrigation water, with an increasing trend of pH, EC and nitrogen between 2010 and 2012, probably due to groundwater contamination with percolated fertilizers. However, these values may be considered suitable for irrigation practice.

Tab.4.2 Irrigation water analysis during the experimental period.

Irrigation water analysis		May, 5 2010	Sept, 12 2011	Jun, 7 2012
pH	0 ÷ 14	6.75	7.80	7.97
EC	$\mu S*cm^{-1}$	1865	1948	2140
BOD_5	mg/l O_2	< 5	N.D	N.D
COD	mg/l O_2	6.90	<5	<5
SST	mg/l	5.10	3.50	6.50
$N_{Ammon.}$	mg/l N	absent	absent	absent
$N_{Nitrous}$	mg/l N	<0,01	0.03	<0,01
N_{Nitric}	mg/l N	15.67	16.77	16.23
$N_{Organic}$	mg/l N	1.70	0.64	1.90
N_{Tot}	mg/l N	17.37	17.44	22.53
Orthophosphates	mg/l P	0.37	0.16	0.12
P_{Tot}	mg/l P	0.60	N.D	N.D

Farming techniques has provided both weeding and minimum tillage (10 cm). During the trials plant's fertilization was made with standard doses for young citrus orchard to ensure plant growth and canopy architecture The amount of N, P_2O_5 and K_2O were supplied in May, June and July of each year with three operations. Table 4.3 show the amount of nutrients applied.

Tab. 4.3 Nutrients applied during the trial

Fertilization	N	P_2O_5	K_2O
kg ha^{-1} 2011	50	25	42
kg ha^{-1} 2012	62	25	57

During the first year of research, within the experimental areas were selected 12 samples plants distributed throughout the plot (Fig. 4.20).

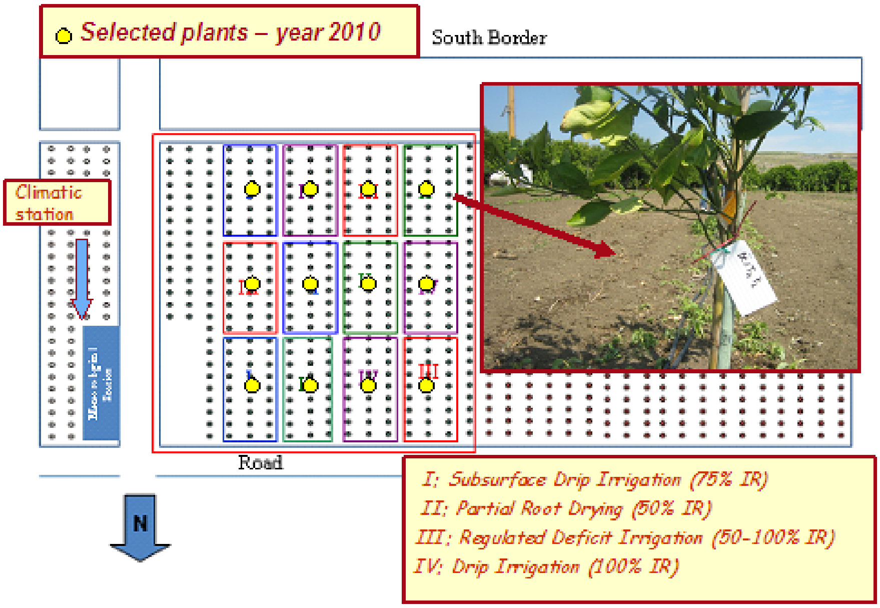


Fig. 4.20 Selected plants, year 2010.

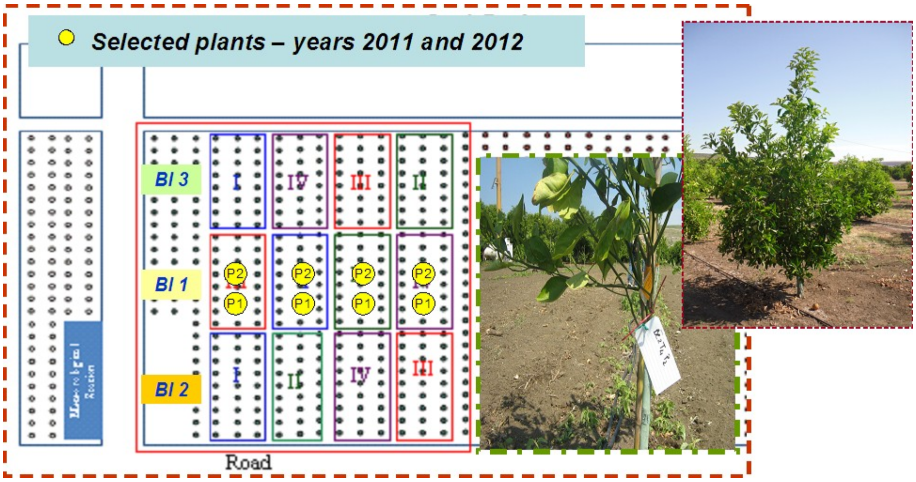


Fig. 4.21 Selected plants, year 2011 and 2012.

In 2011 and 2012, instead, 8 plants (2 from each thesis) were selected for measurements and localized within central block (Fig. 4.21) where have been installed sensors for measuring trunk diameter variation.

4.2.3 Soil water content monitoring

During 2010, tests were conducted to evaluate soil water characteristics, both in field and in laboratory.

The double disc infiltrometer were used in the field to measure the rate of water infiltration into soil (Fig. 4.22). Indeed, these instrument allow the estimation of soil hydraulic properties at the near zero soil water pressure head. The relatively rapid and portable nature of this technique and its easy applicability in situ makes the disc infiltrometer a very valuable tool in many hydrological and soil science studies. Soil hydraulic properties such as hydraulic conductivity (K), the size and number of the soil's macro and meso water conductive pores are commonly calculated from the cumulative water infiltration curves measured with the disc infiltrometer.

Fig. 4.22 Double ring infiltrometer.

Indisturbed soil samples were collected to performe permeability laboratory tests, through the use of the permeameter (Fig. 4.23).

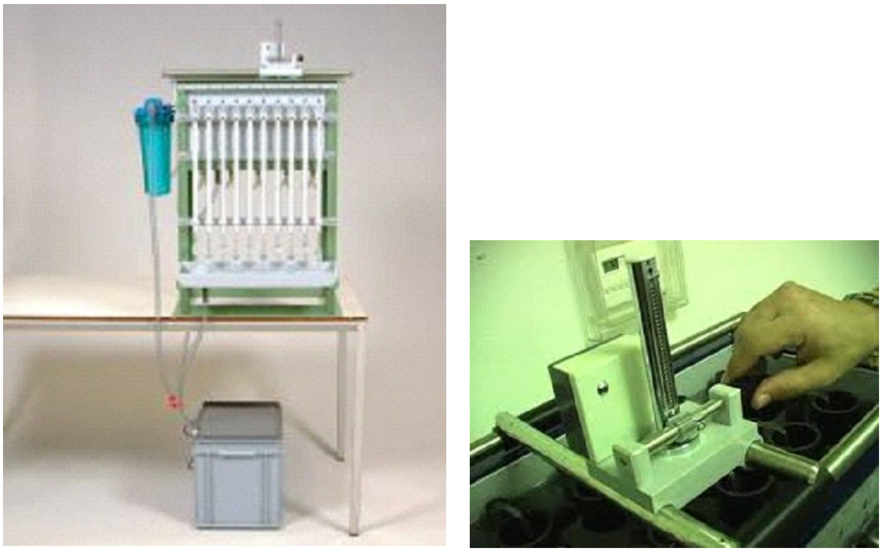


Fig. 4.23 Laboratory permeameter – closed system (left) and measuring saturated hydraulic conductivity of Soil Samples (right) (Eijkelkamp).

A closed or an open system can be applied. In case of a closed system a storage cistern, a circulation pump and a filter are provided. If an open system is applied these attributes are not needed, as in this case the setup allows a connection to the main water supply and drainage to take place in a washing basin. The hydraulic conductivity gives accurate information about the presence of disturbing soil layers which prevent a speedy outflow of precipitation; the correlation between permeability and other soil properties such as porosity, granular composition; the vertical and horizontal permeability, etc.

For the determination of the moisture characteristic are used the sandbox method (Fig. 4.24). The instrument consists of the sandbox with control panel, suction levelling stand, water supply bottle with stand, filter cloth (140-150 micron), a number of containers synthetic sand, grain size approximately 73 micron and various accessories.

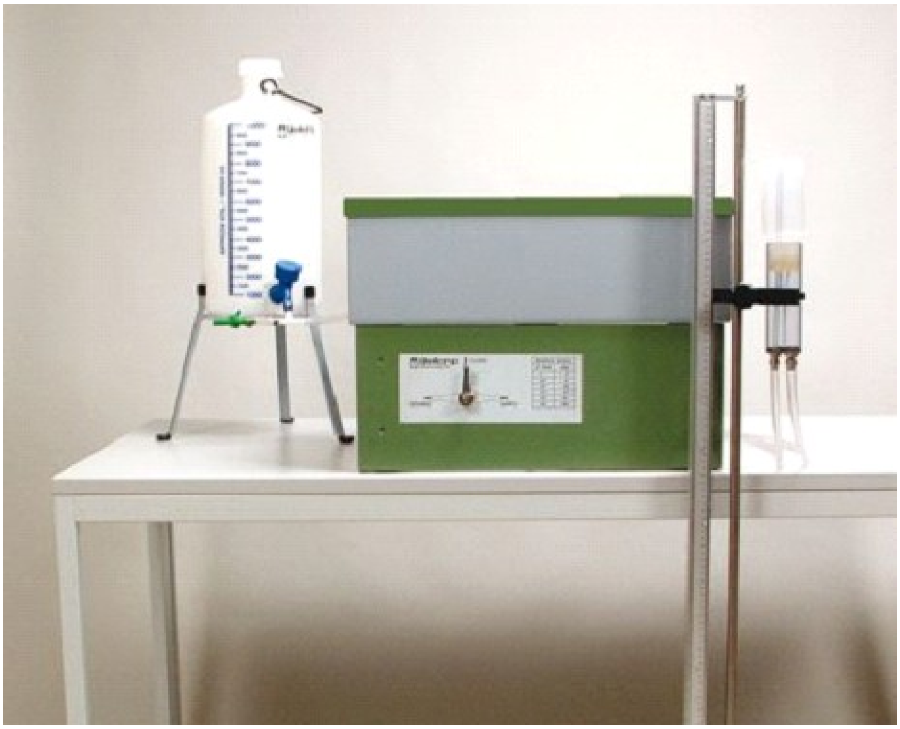


Fig. 4.24 Sanbdox for pF determination (Eijkelkamp).

Undisturbed samples are needed for this method: the samples are taken in the field using stainless steel soil sample rings. After, in the laboratory, the samples are saturated and subsequently balanced with respect to the increasing values of the moisture tension.

For each level of pressure (or suction) making a gravimetric measurement in order to get the water content of the sample. The water loss is determined by weighing the entire soil column apparatus each day until it stops losing weight. Depending on the texture of the soil, this may take up to a month or more. Once the water loss has stopped, the amount of water remaining in the soil column is calculated. This entire process is then repeated at several different levels of vacuum until a moisture retention curve (Fig. 4.25) is developed for that soil sample.

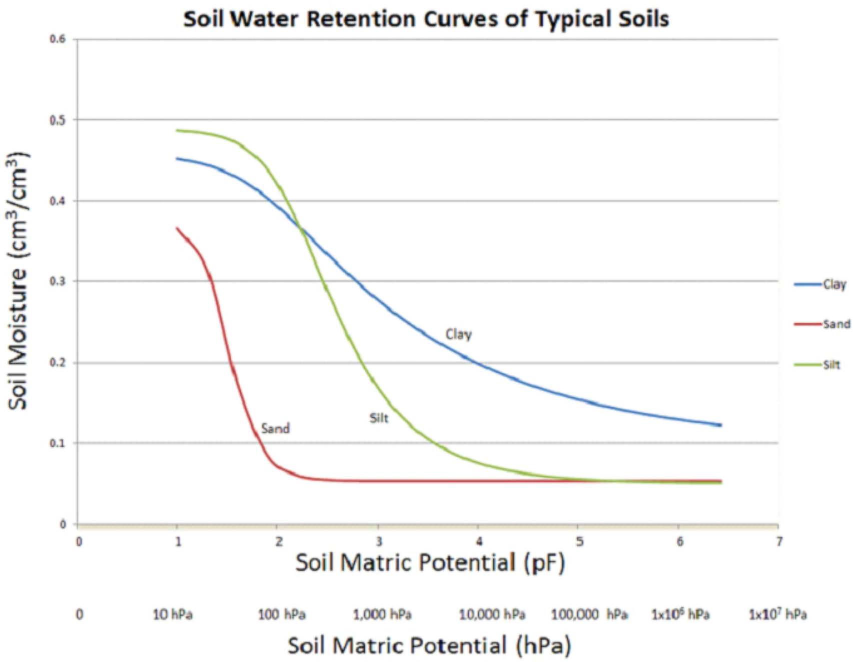


Fig. 4.25 The soil water retention curves for common sand, silt, and clay soils (source: www.stevenswater.com)

The time required to develop a water retention curve for a sample can easily be a few months or more. Once a moisture retention curve is developed, the unsaturated hydraulic conductivity test is then conducted. This method relates the potential with soil water content and determines how fast water will flow through a soil that has different initial water contents. This information is important for predicting how nutrients or pesticides may move through a soil profile.

During the measurements in laboratory the matrix potential can reach high values if espressed in cm of water column; for this reason it was introducted (Schofield, 1935) a new unit of measurement (pF) defined as logarithm to the base 10 of the suction force expressed in cm:

$$pF = \log_{10} h \tag{4.7}$$

where h represents the suction (or pressure) expressed in cm of water column.

The values of pF for the full range of soil varies from 0 to 7, having indicated with the pF 0 in correspondence of total saturation and with 7 that in correspondence drying total. Table 4.4 shows the values of potential commonly used to construct the retention curve. Values are expressed in terms of pF (log10), pressure (kPa) and height of the water column (cm).

Tab. 4.4 Soil water potenzial value.

pF	kPa	cm (H_2O)
1	1	10
1,78	6	60
2	10	100
2,3	20	200
2,5	33,3	333
2,7	50	500
3	100	1000
3,5	300	3000
4,2	1500	15000

Furthermore, in the years 2011 and 2012, for evaluating soil water content, soil samples were taken on a weekly basis, close to selected plants (Fig. 4.26), at two different depths, i.e. 15 and 30 ÷ 35 cm; these samples were used to evaluate the potential soil moisture (pF), using a psychrometer (Fig. 4.27).

WP4 psychrometer measures the vapor pressure inside a sealed chamber, equilibrated with the soil sample. It uses the dew point method to measure the vapor pressure, and also accurately measures the sample temperature.

Fig. 4.26 Soil samples collection close to selected plants.

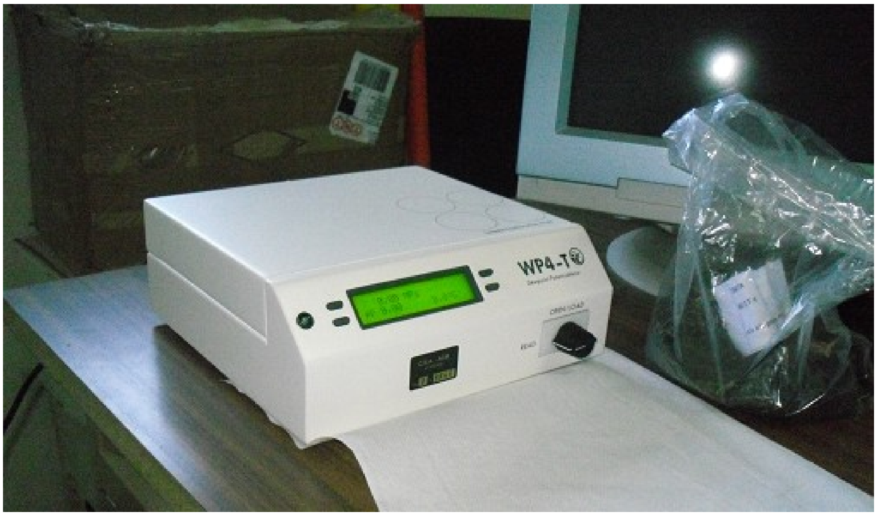


Fig. 4.27 Water potential measurement using psychrometer, WP4 (Decagon Devices)

The psychrometer adds water to the air in order to measure its vapor pressure, but in the dew point method, the air is cooled without changing its water content until the air just saturates. The vapor pressure is computed from this dew point temperature. The water potential of the sample is linearly related to the difference between the sample temperature and the dew point temperature (Decagon Devices).

The same sample after having been analyzed through the psychrometer, then were weighed and placed in a stove (Fig. 4.28) to estimate the gravimetric and volumetric water content (%).

Fig. 4.28 Soil samples weighting and placement in a stove at 105 °C.

The samples and container are weighed in the laboratory both before and after drying, the difference being the mass of water originally in the sample. The drying procedure consists in placing the open container in an electrically heated oven at 105°C until the mass stabilizes at a constant value. The drying times required usually vary between 24 and 28 h. Drying at 105°±5°C is part of the usually accepted definition of “soil water content”, originating from the aim to measure only the content of “free” water which is not bound to the soil matrix (WMO, 2008).

Although the gravimetric water content for the finer soil fraction, $\theta_{g,fines}$, is the value usually used for spatial and temporal comparison, there may also be a need to determine the volumetric water content for a gravelly soil. The latter value may be important in calculating the volume of water in a root zone. The relationship between the gravimetric water content of the fine soil material and the bulk volumetric water content is given by:

$$\theta_{v,stony} = \theta_{g,fines} \left(\rho_b / \rho_v \right)\left(1 + M_{stones}/M_{fines}\right) \tag{4.8}$$

where $\theta_{v,stony}$ is the bulk volumetric water content of soil containing stones or gravel and M_{stones} and M_{fines} are the masses of the stone and fine soil fractions (WMO, 2008).

During the last irrigation season it was made an estimation of some physico-chemical and hydraulic properties of the experimental area. The measurements were made within a rectangular area, whose vertices are fixed through GPS coordinates; within this area soil samples were taken following a rectangular mesh grid; the samples was carried out at the corners and the center of each plot (Fig. 4.29).

Within the area 32 points of sampling have been individualized, and for every point two undisturbed soil samples to 0-5 cms and 5-10 cms of depth have been collected, for the hydraulic characterization of the grounds, and an altered soil sample, for the chemical-physics analyses. For the undisturbed soil sampling it has been used a cylindrical sampler of 5 cm in height and 5 cm in diameter while for the altered soil sampling were collected soil samples of about 200 g in weight. For each sampling point, particle size analysis were carried out.

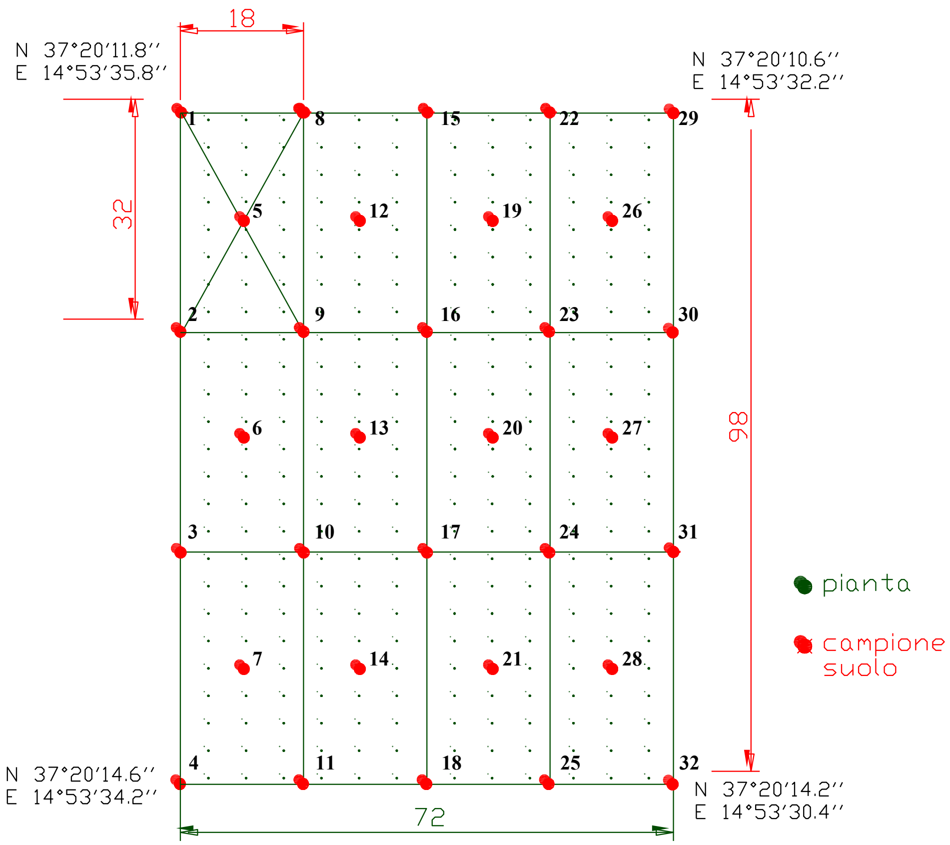


Fig. 4.29 Soil samples area for physico-chemical and hydraulic properties measurements.

These values have allowed the determination of the type of soil textural analyzed (%) and the corresponding classification system according to the USDA, of the volumetric water content (%), by applying imposed tensions from 300 cm to 15000 cm, trough the Richards plate, and the percentage of organic matter using the Walkley-Black method.

4.2.4 Monitoring of some crop physiological variables

In order to compare the different irrigation regimes, we proceeded to the monitoring of some physiological characteristics of sampled plants.

In 2010, the monthly monitoring of physiological parameters of the selected plants was limited to control:

- Shoots growth;
- Stem water potential (MPa), evaluated through the use of the Scholander pressure chamber, before enveloping two shoots per plant sample exposed shade (Fig. 4.30);
- LAI (Leaf Area Index, m^2m^{-2}) and PAR (Photosintetically Active Radiations, $\mu Mol/m^2s^{-1}$), using ceptometer (Fig. 4.31), making 5÷6 readings per plant samples;
- Leaves nitrogen content, obtained through laboratory analysis;
- Chlorophyll content in young leaves, through the use of a SPAD colorimeter (Fig. 4.32), after washing and cleaning selected leaves plant samples.

In 2011, a control unit was installed to plants samples (Fig. 4.33) connected with some sensors (dendrometers) used in order to measure periodically the trunk diameter. These include the assessment of stem water status, the understanding of short term growth responses to changing environmental conditions and the generation of templates that relate temporal measurements of growth and climate to spatial measurements of wood properties. Data were weekly downloaded from a data logger connected to the control unit and then processed using specific software.

Furtermore, for 2011 and 2012 the fortnightly monitoring covered the measurements of:

- Stem water potential;
- LAI and PAR;
- Stomatal conductance ($mmol/m^2s^{-1}$), using a porometer (Fig. 4.34); it was applied on four leaves per plant samples, respectively two sunlit leaves and two shade leaves;
- Leaves temperature (°C), using a IR thermometer (Fig. 4.35); the measurement was perfomed on two sun leaves per plant sample;

- Air temperature (°C) and air humidity (%), through the use of a thermo hygrometer (Fig. 4.36), it made possible a single reading per plant sample.

Fig. 4.30 Stem water potential (Scholander pressure chamber) measurement.

Fig. 4.31 LAI and PAR measurements (AccuPAR LP80 - Decagon).

Fig. 4.32 Color measurement, SPAD.

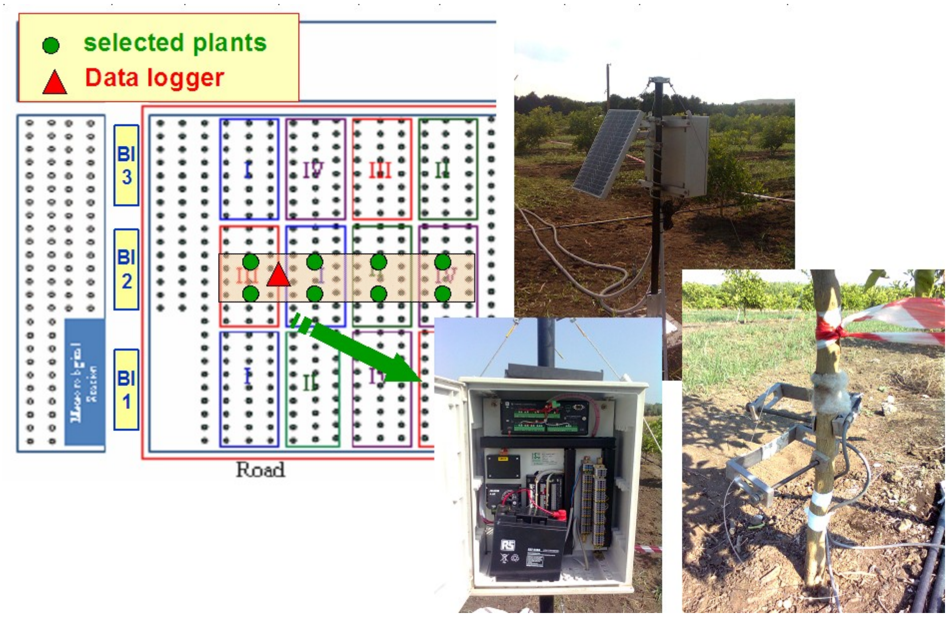


Fig. 4.33 Dendrometer (Dynamax Inc) installation

Fig. 4.34 Stomatal conductance (LP 80 – Decagon) measuremets.

Fig. 4.35 Leaves temperature maesurements (Everest 100szL).

Fig. 4.36 Thermo hygrometer (HI 8564 – Hanna instruments), air temperature (°C) and humidity (%) measurements.

4.3 Statistical analysis

Some parameters analyzed (Leaf temperature, LAI, volumetric soil water content and stem water potential,) data were subjected to a variance analysis (ANOVA) with four irrigation treatment and 4, 40, 10, 16, replicates per thesis and for each measurement, Leaf temperature, LAI, volumetric soil water content and stem water potential, respectively, for using Tukey's test for mean separations ($P<0.05$). These statistical analysis were carried out with the support of CRA – ACM staff.

5. Results and Discussion

5.1 Weather condition and irrigation applied

Meteorological data recorded by the climatic station show the typically Mediterranean trend. During the experimental period, the average annual rainfall was about 500 mm, with a predominant winter rainfall; mean minimum and maximum daily temperature ranges were 0÷5°C and 35÷37 °C respectively, with a particularly hot summer, in 2012 (Fig. 5.1).

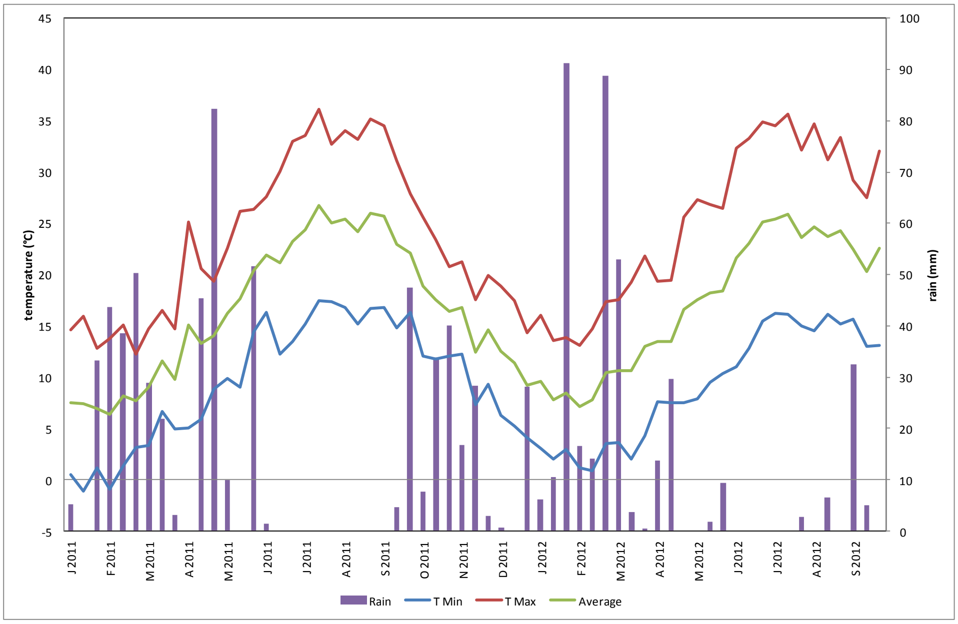


Fig. 5.1 Values of temperature (mean, maximum and minimum) and rainfall in the study area during 2012 experimental activity.

In the first year of research activity (2010), DI strategies were not applied in order to facilitate the transplanting of the young citrus trees and their rooting. Therefore, the total amount of water, applied in May÷October 2010, was of 1.168 m^3 ha^{-1}. In 2011 DI strategies were started and total water amounts of about 570, 545, 530, 358 m^3 ha^{-1} for SDI (100%IR), SSDI (75%IR), RDI (50-100%IR) and PRD (50%IR) respectively were supplied during June÷October (Fig. 5.2). Since Aug 23 2011, RDI theses were modified in the irrigation scheduling by supplying 50% of IR. In this case, the low IR amount was supplied during the phenological phase of cell division, when citrus are less sensitive to water stress.

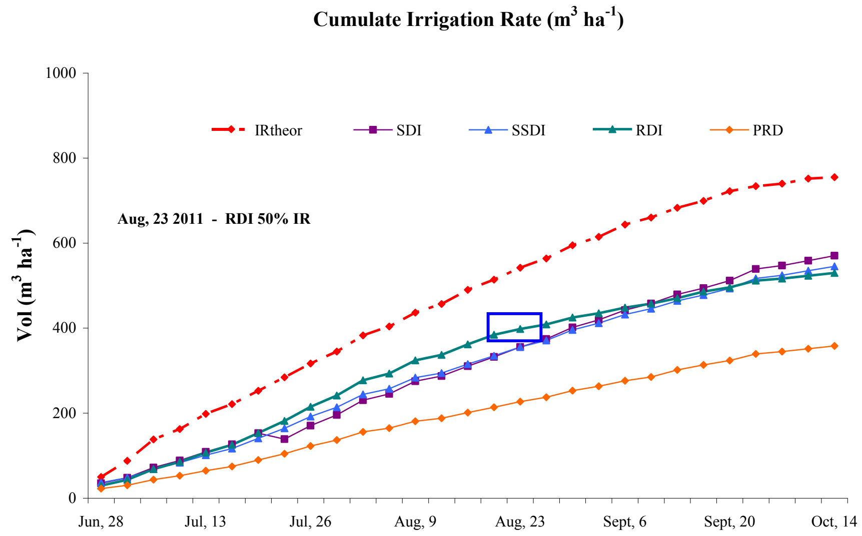


Fig. 5.2 Cumulative IR (m^3 ha^{-1}) supplied to the experimental plot in 2011.

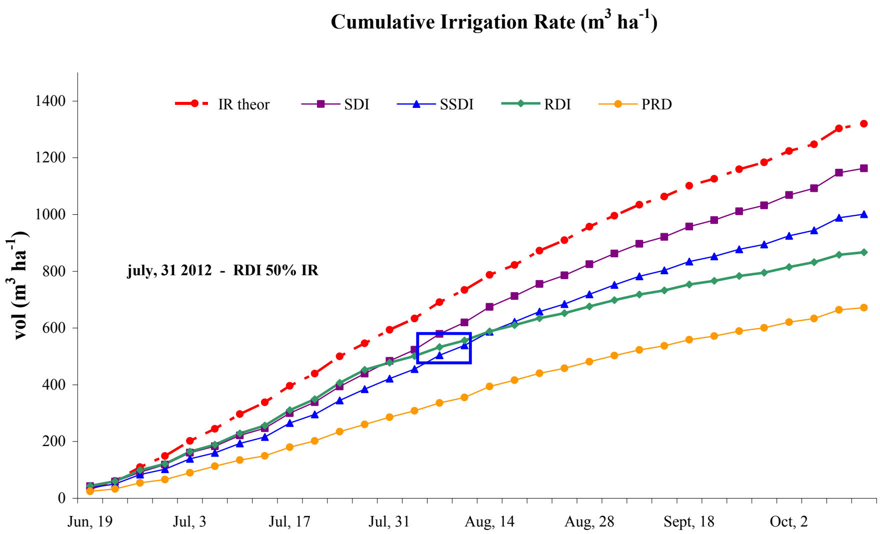


Fig. 5.3 Cumulative IR (m^3 ha^{-1}) supplied to the experimental plot in 2012.

Between June 19 and October 19 2012, total water amounts supplied to the plot, were of about 1.162, 1.001, 867, 672 m^3 ha^{-1} respectively for SDI (100%IR), SSDI (75%IR), RDI (50-100%IR) and PRD (50%IR) (Fig. 5.3). Since July 31 2012, RDI theses supplied 50% of IR.

The real water volumes supplied to the different theses, in 2012, were slightly different (Tab. 5.1) theoretical ones (IR_{theor}). While in 2011 in SDI theses the difference between IR_{theor} and water volume effectively supplied were greater, probably due to an inefficient control of water pressure during some irrigation operation.

Tab. 5.1 Total water amount supplied in 2011 and 2012 at the experimental field.

DI Theses	Water supplied in 2011 ($m^3 ha^{-1}$)	Water supplied in 2011 compared to IR_{theor} (%)	Water supplied in 2012 ($m^3 ha^{-1}$)	Water supplied in 2012 compared to IR_{theor} (%)
IR_{theor}	755	-	1319	-
SDI (100% IR)	570	75	1162	88
SSDI (75% IR)	545	72	1001	76
RDI (50÷100%IR)	530	70	867	66
PRD (50% IR)	358	47	672	51

In 2012, water amount applied for irrigation was increased due to the plant growth and the higher temperature conditions recorded.

5.2 Monitoring soil moisture content

The result of the textural analysis carried out on soil samples collected during the trial evidenced the following percentages: 69.7 % of sand, 10.5 % of clay, 19.8 % of silt, with a sandy loam soil texture, according USDA method (Fig. 5.4).

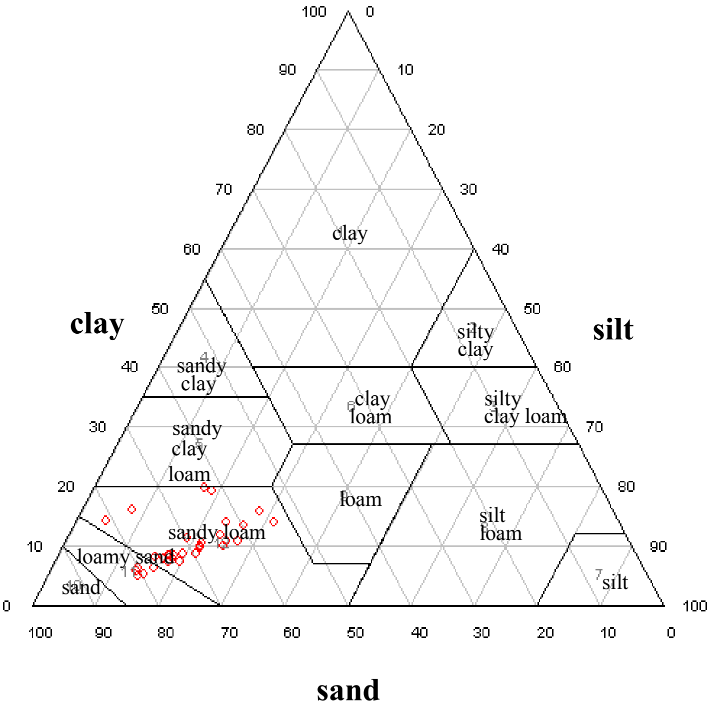


Fig. 5.4 Soil texture of the experimental field (USDA method).

Organic matter content of the soil was 1.25%, obtained with Walkley-Black method and showed a normal presence of this element.

Hydraulic conductivity (K_S), determined both in field and in laboratory had values respectively of $1.8*10^{-2}$ (mm s^{-1}) and $6,5*10^{-2}$ (mm s^{-1}) respectively. Differences on these values of K_s depend on the different conditions in field and in laboratory, such as greater soil volume in the field than in laboratory.

Table 5.2 shows the volumetric water content (%) obtained with applied potential between 300 and 15000 (cm of water column) by means of the Richards plate. Water content at field capacity (FC) was 38.8 % (pF = 2,5) and water content at wilting point was 24.4 % (pF = 4,2).

Values of Ks fitted well with the analysed soil texture (sandy-loam).

Tab. 5.2 Volumetric soil water content (%) obtained by Richards plate.

32 samples	Soil water potential value used to construct the retention curve (cm of water column)				
	300	1000	3000	6000	15000
Mean value (%)	38.84	32.70	28.31	25.43	24.45

Changes in soil water content in the 15÷30 cm soil column during the experimental activity are shown in the Figures 5.5 and 5.6.

In 2011, soil water potential (pF) values measured in field by psychrometer measurements (Fig.5.5 and Table A.1 in Appendix A) were in the range between 3.2 and 3.5 pF with mean value 3.2 pF. In 2012, values of pF were slightly different from the previous years and were in the range between 3.4 to 3.9 with mean value 3.6 pF (Fig.5.6 and Table A.2 in Appendix A).

As shown in Fig. 5.5 and 5.6, soil samples show the higher soil water potential, indicative of less water available for plants, was measured in PRD and SSDI theses.

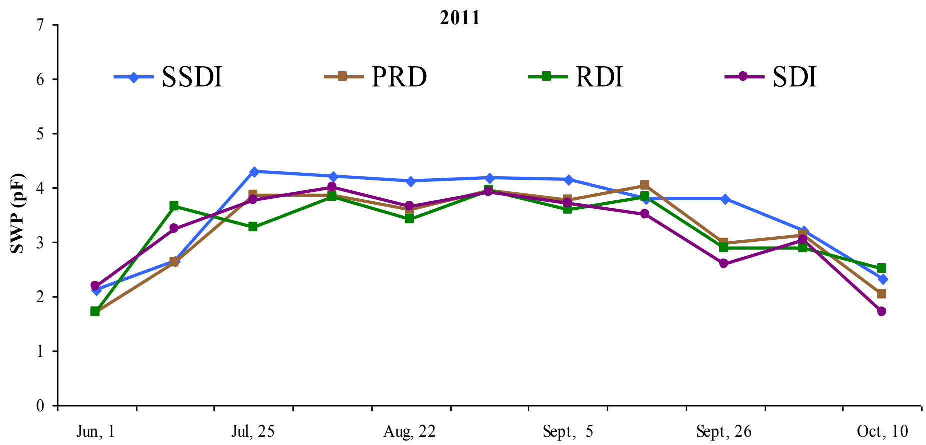


Fig 5.5 Soil water potential (SWP) in investigated theses in 2011.

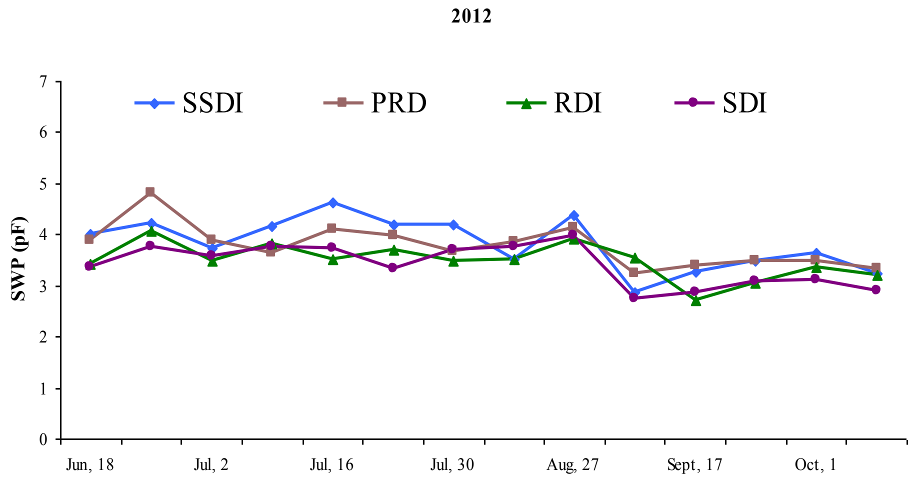


Fig 5.6 Soil water potential (SWP) in investigated theses in 2012.

Volumetric soil water content (VWC) (%) in the full watered treatment (SDI) had an average between 27÷29% in the investigated soil profile, while PRD, RDI and SSDI theses show VWC of 5%, 8% and 15%, less than SDI respectively (Tab. 5.3 and Fig. 5.7).

On both the monitored years VWC was quite below the Field Capacity. Statistical differences were found in VWC between treatments as shows by the Tukey's test (Tab. 5.3); most likely data on VWC and relative standard deviation of SSDI thesis were affected by the sampling depht (0.30 m) above the irrigation line (0.35 m deep).

Tab. 5.3 Weekly values of volumetric soil water content (%) and ±SD measured in 2011 and 2012.

VWC (%)	*2011*	*±SD 2011*	*2012*	*±SD 2012*
SSDI	21.99 a	*5.04*	25.76 ab	*3.49*
PRD	25.78 b	*2.82*	27.71 ab	*1.51*
RDI	26.26 b	*3.98*	25.53 a	*3.35*
SDI	27.05 b	*3.67*	29.10 b	*2.99*

** Treatments sharing the same letters are not significantly different at the chosen level (P<0,05).*

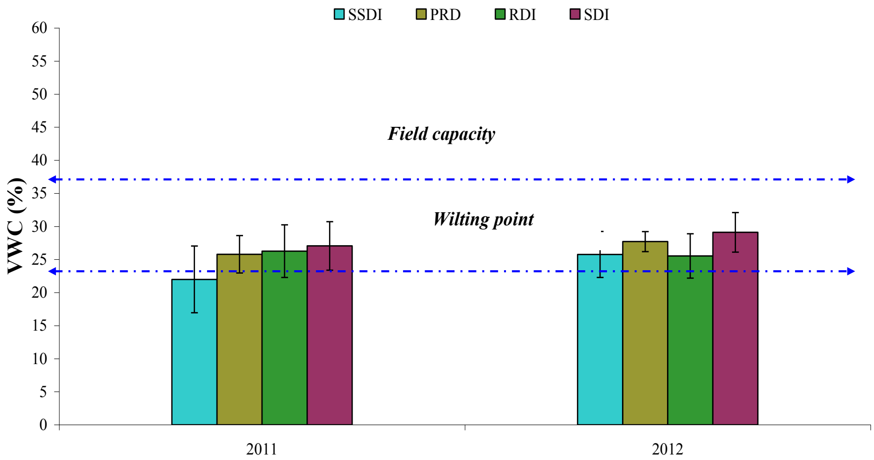


Fig 5.7 Mean values and ±SD of volumetric soil water content during experimental activity.

5.3 Plant physiological monitoring within the different DI theses

5.3.1 Chlorophyll and nitrogen analysis

In 2010 plant leaf chlorophyll and nitrogen content were analyzed in the selected plants (Table 5.4).

Tab. 5.4 Mean values of leaf chlorophyll (SPAD, chlorophyll meter) and nitrogen content.

Thesis	SPAD unit	Leaf nitrogen content (%)
1. SSDI	79.87	2.64
2. PRD	78.20	2.80
3. SDI	75.90	2.74
4. RSDI	81.90	2.76

Data were considered low variable. Plants show leaf chlorophyll (in terms of SPAD unit) fairly high and a good nitrogen content in the leaves. Thus they may be susceptible to a roboust growth process.The leaf nitrogen content was found to have a significant and positive correlation with the leaf chlorophyll values (Yang *et al.*, 2003; Nachimuthu *et al.*, 2007); mean value of leaf nitrogen (2.7%) and of leaf chlorophyll (79 SPAD unit) showed a high health tree condition.

5.3.1. Stem water potential

The predawn stem water potential (SWP) of the selected plants was measured by a "pressure chamber" (Fig. 5.8 and Fig. 5.9). The full data are shown in Appendix A (Tab. A.3, A.4, A.5).

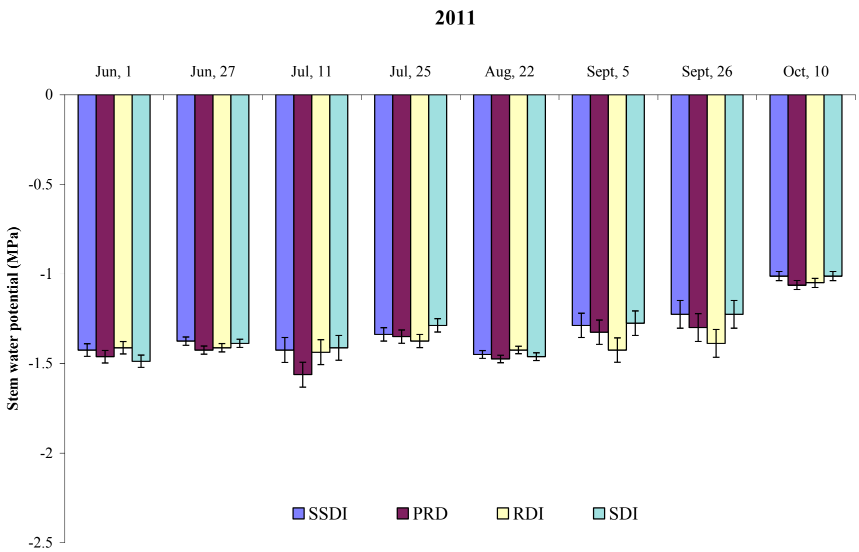


Fig 5.8 Mean values (measured every 2 weeks) and ± SD of stem water potential (Ψ_{PD}) in June-October 2011.

Results show a slight variation between the investigated theses (Tab. 5.5). As water deficit increased stem water potential became more negative. On the whole data were higher than critical values found in literature indicating plant stress conditions.

Data found during the experimental activity, varied between -1.32 to -1.37 MPa in 2011 and between -1.53 to -1.68 MPa in 2012. In 2011, PRD and RDI theses showed a slightly lower stem water potential compared to other theses. In 2012, only in PRD theses the reduction of stem water potential resulted significant.

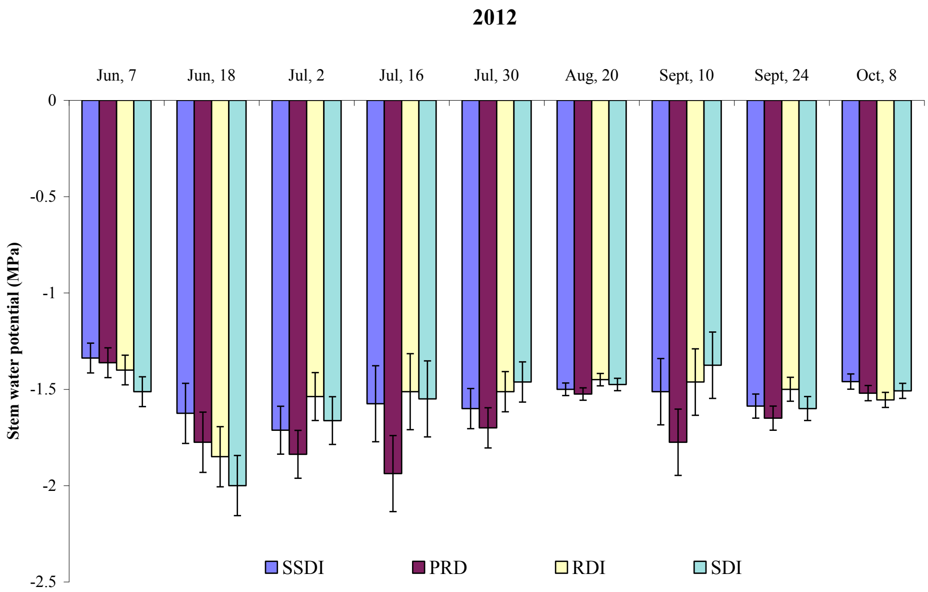


Fig 5.9 Mean values (measured every 2 weeks) and ± SD of stem water potential (Ψ_{PD}) in June-October 2012.

Tab. 5.5 Mean values of stem water potential (MPa) of in 2011 and 2012.

Stem water potential (MPa)	Theses	Stem water potential
2011	SSDI	-1.31 b
	PRD	-1.37 a
	RDI	-1.37 a
	SDI	-1.32 b
2012	SSDI	-1.55 b
	PRD	-1.68 a
	RDI	-1.53 b
	SDI	-1.57 b

**Treatments sharing the same letters are not significantly different at the chosen level (P<0,05).*

5.3.2. Leaf Area Index

Leaf Area Index (LAI) of selected plants was measured by a ceptometer. No significant differences in LAI among SDI, PRD and SSDI theses were found during two years, only RDI thesis has shown lower value (Fig. 5.10 and Tab. 5.6).

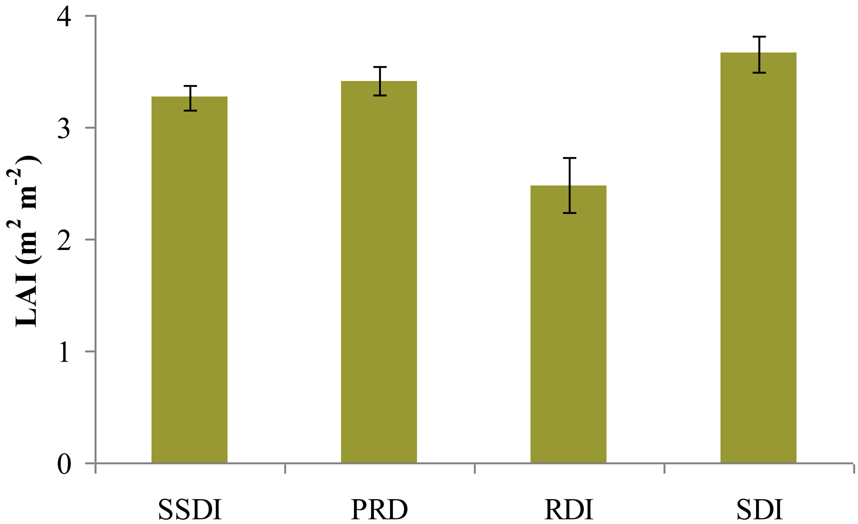


Fig 5.10 LAI mean values (m^2 m^{-2}) of the two experimental years (2011 and 2012).

Tab. 5.6 LAI mean values (m^2 m^{-2}) of the two experimental years (2011 and 2012).

Theses	LAI (m2 m^{-2})
SSDI	3.26 b
PRD	3.41 b
RDI	2.48 a
SDI	3.65 b

**Treatments sharing the same letters are not significantly different at the chosen level (P<0,05).*

5.3.3 Stomatal conductance and leaf temperature

Stomatal conductance, was measured with the porometer (Fig. 5.11 and 5.12), the full data are shown in Appendix A (Tab. A.7, A.8, A.9 and A.10).

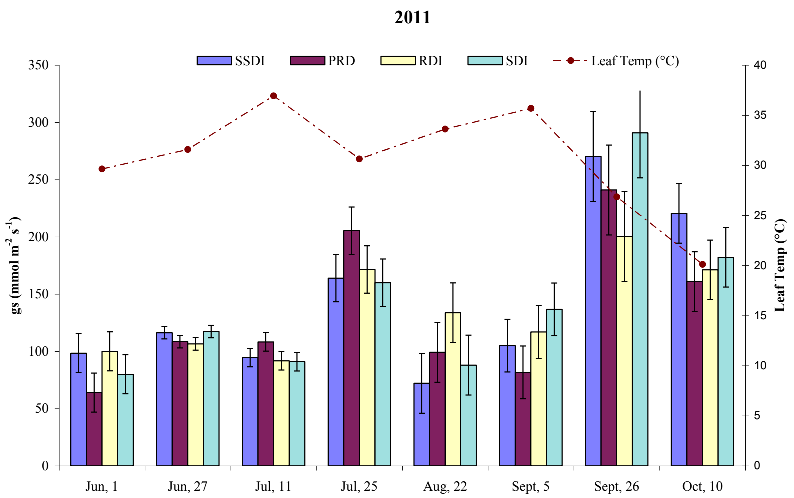


Fig. 5.11 Mean values (measured 2 times per month) of stomatal conductance (gs, mmol m^2 s^{-1}) of citrus leaves in the four treatments compared to leaf temperature (°C) in 2011.

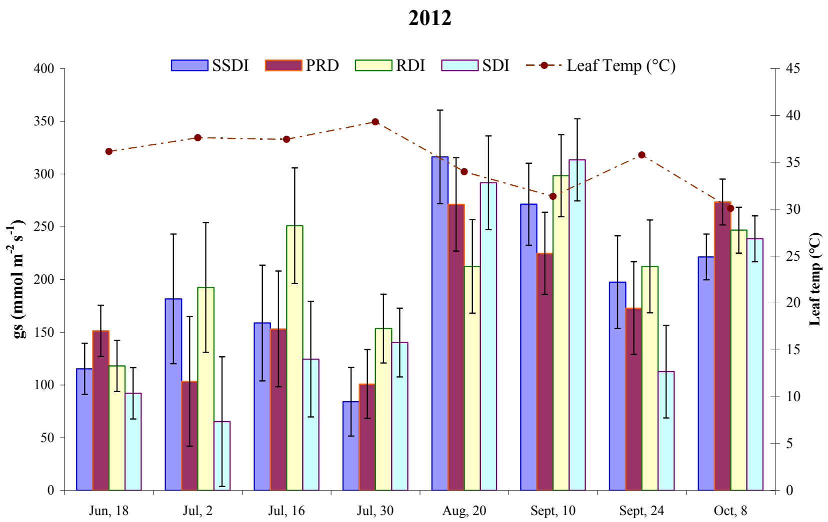


Fig. 5.12 Mean values (measured 2 times per month) of stomatal conductance (gs, mmol m^2 s^{-1}) of citrus leaves in the four treatments compared to leaf temperature (°C) in 2012.

Mean leaf temperature was inversely correlated with stomatal conductance; the higher stomatal conductance values were obtained when leaf temperature values varied between 20 and 31°C in 2011 and between 30°C and 34°C in 2012, while the high leaf temperature of 31°C in 2011 and 34°C in 2012 has driven the lower stomatal conductance values. Therefore, these results can be considered just below the mid-range of stress for citrus orchard, since the values of stress are below 150 mmol $m^{-2}s^{-1}$ (Stagno *et al.*, 2008). Plants stomatal conductance appears more affected to temperature and vapour pressure deficit trend than to the imposed deficit irrigation regimes. In fact, plants seem to increase their stomatal conductance when the weather regime was more temperate (i.e. temperature decrease and rainfall increase).

Leaf temperature (°C) was measured (Fig. 5.13 and Fig. 5.14) remotely by the infrared thermometer (IRT).

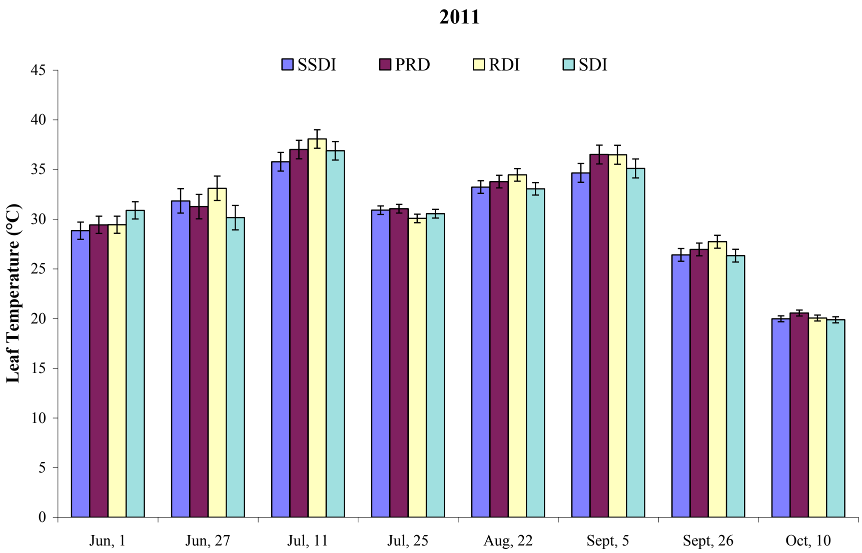


Fig. 5.13 Mean values (measured 2 times per month) of Leaf temperatures (°C) Measurements were driven on the sunlight side canopies in the midday in June-October 2011.

In 2011 leaf temperature was lowest than 2012, with mean value of 31°C and 35 °C, respectively (Tab. A.11, A.12, A.13 and A.14 in Appendix A).

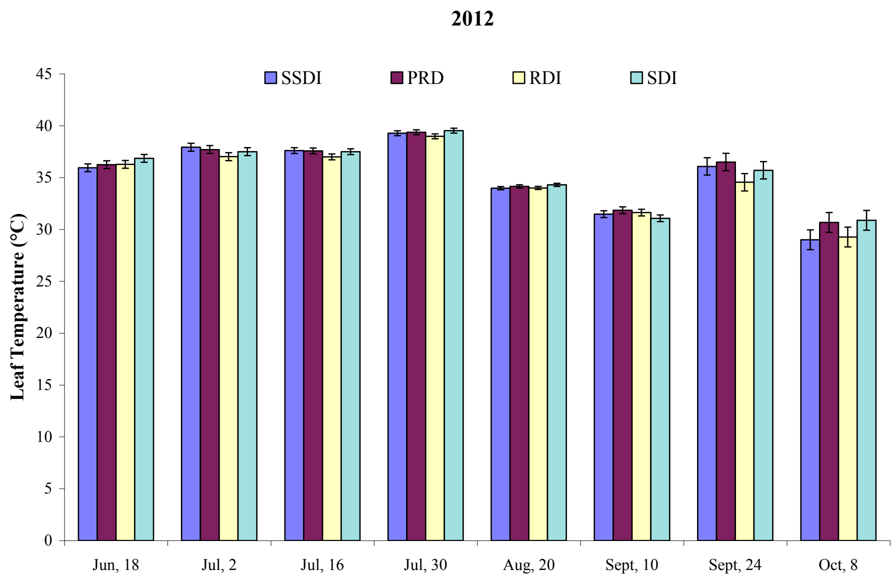


Fig. 5.14 Mean values (measured 2 times per month) of Leaf temperatures (°C) Measurements were driven on the sunlight side canopies in the midday in June-October 2012.

In the first year significant differences were founded between RDI and SSDI theses, while in 2012 differences were detected between RDI and PRD. Table 5.7 shows that during the two seasons there were significant sources of variation for leaf temperature between means at P=0.05.

Tab. 5.7 Annual mean leaf temperature (°C) monitored in June-October during the experimental periods (2011 and 2012).

Thesis	Leaf Temperature (°C) 2011	Leaf Temperature (°C) 2012
SSDI	30.20 a	35.16 ab
PRD	30.81 ab	35.51 b
RDI	31.17 b	34.84 a
SDI	30.35 ab	35.41 ab

Leaf temperature by IRT method resulted fairly correlated with stem water potential and, thus, may be a simple, easy to obtain parameter for detecting plant water stress. Plants on PRD have showed stem water potential and leaf temperature, generally, higher than the other theses; this may be interpreted as a tendency by PRD plant to be less able for water stress compensation.

5.3.4 Trunk dimension

Trunk measurements did not show statistically significant differences; however, plants tend to reduce their dimension and vegetative growth on PRD and RDI. Plants on SSDI have showed characteristics fairly similar to those of the SDI reference thesis.

Tab. 5.8 Circumference and diameter increase (cm) of trunks in the different theses between 2010 and 2012.

2010-2012	circumference increase (cm)	*Standard error*	diameter increase (cm)	*Standard error*
SSDI	17.8	*0.7*	5.7	*0.2*
PRD	17.1	*0.9*	5.4	*0.3*
RDI	16.3	*0.5*	5.2	*0.2*
SDI	17.9	*0.8*	5.7	*0.2*

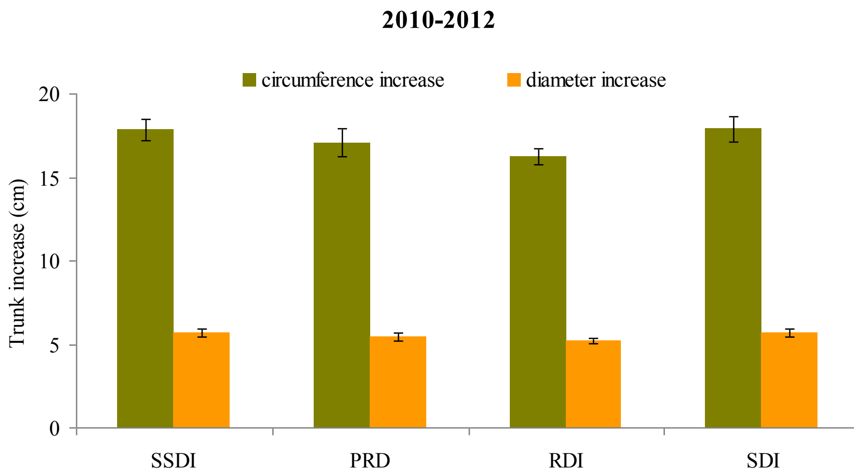


Fig. 5.15 Trunk circumference and diameter increase (± standard error) during the experimental years.

During the experimental period (2010-2012) trunk circumference and diameter growth were measured. Table 5.8 shows a slight difference of the trunk dimensions between theses, with lower values for RDI and PRD (Fig. 5.15), probably due to the low Irrigation Requirement (IR) applied, as well as environmental condition and inherent characteristics of the plant samples.

6. Conclusions

The application of Deficit Irrigation strategies on young orange orchard at the experimental field of Palazzelli (Eastern Sicily), has determined significant results to be commented. In particular the young oranges irrigated with DI strategies were globally able to sustain the imposed stress conditions. They did not showed significant signs of stress on canopy growth and physiological features. Plants result more affected by the variation of the climatic conditions in the study area than the deficit irrigation strategies applied. The experiment has combined the use of DI strategies with high technological irrigation methods (SDI and SSDI). This interaction was well suited to determine high performance and reliable results from the study.

The adopted DI strategies require a systematic control of soil water status in order to avoid that the VWC to approach or decrease below the permanent wilting point. The soil water content during irrigation season was, as expected, generally below the field capacity conditions, allowing plants to dispose of a low water availability rate. This could induce plants to use less water and reduce evapotranspiration fluxes.

Moreover, the study has evidenced the important role played by the leaves temperature, directly related to stomatal conductance, to detect plant stress signs. This shows a potential of both indices for scheduling deficit irrigation in citrus orchards.

Plants growth in PRD and RDI theses, supplied with the lowest IR rates, have showed clear stress signs, although they may considered sustainable by plant themselves. These symptoms regard, specifically, stem water potential, stomatal conductance, leaves temperature that seems to be the reliable parameters to be monitored.

PRD and RDI have also offered the advantage to allow a significant (about 50%) water saving, increasing the efficiency of this important resource, with high economic value per unit of water and social benefits.

Futher research activities are needed, particularly on the effects of DI strategiese on productive crop features.

The main findings of this study may have relevant pratical relevance, since can support the agricultural sector in coping water scarcity for irrigation. However, a strong effort should be done to transfer the research results among the farmers that usuallly apply, when water resources are available, more water than crop irrigation requirement.

List of References

Abrisqueta J.M., Mounzer O., lvarez S.A., Conejero W., Garcı´a-Orellana Y., Tapia L.M., Vera J., Abrisqueta I., Ruiz-Sa´nchez M.C. (2008). Root dynamics of peach trees submitted to partial rootzone drying and continuous deficit irrigation. *Agricultural water management* 95, 959-967.

Alba I., Rodriguez P.N., Pereira L.S. (2003). Irrigation scheduling simulation for citrus in Sicily to cope with water scarcity. *Tools for drought mitigation in Mediterranean regions*, 44 Kluwer.

Allen R., Pereira L., Smith M., Raes D. (1998). Crop evapotranspiration (Guidelines for computing crop water requirements). *Irrigation and Drainage* FAO, Paper n 56.

Allen R.G., Pereira L.S. (2009). Estimating crop coefficients from fraction of ground cover and height. *Irrigation Science* Volume 28, Number 1,17-34.

Amthor J.S. (1989). Respiration and Crop Productivity. *S. pringer-Verlag*, New York.

Barradas V.L., Nicolàs E., Torrecillas A., Alarcòn J.J. (2005). Transpiration and canopy conductance in young apricot (Prunus armenica L.) trees subjected to different PAR levels and water stress. *Agricultural Water Management* 77, 323–333.

Barragan J., Bralts V., Wu I.P. (2006). Assessment of Emission Uniformity for Micro-irrigation Design. *Biosystems Engineering* 93 (1), 89–97

Batini G., Rossi G., Benedini M., Monacelli G. (1999). Territorial planning and coping with effects of drought. *Proc. int. workshop, Taormina, Italy*. Presidenza del Consiglio dei Ministri, Dip. Servizi Tecnici Nazionali, Roma.

Bekele S., Tilahun K. (2007) Regulated deficit irrigation scheduling of onion in a semiarid region in Ethiopia. *Agricultural Water Management*, published on line 20 February.

Beruardo D.J. (1988). Irrigation optimization under water supply. *ASAE 31* (3), 712-719.

Blaney H.F. and Criddle.W.D. (1950). Determining Water Requirements in Irrigated Areas from Climatological and Irrigation Data. *USDA, SCS-TP*-96, 50 .

Brugere C., Lingard J. (2003). Irrigation deficits and farmers' vulnerability in Southern India. *Agricultural Systems* 77, 65–88.

Burrough P.A. (1993). Fractals and Geostatistical methods in landscape studies. *N. Lam & L. de Cola (eds) Fractals in geography.* Prentice Hall, Englewood Clifts, NJ, 87-112.

Capra A,, Consoli S., Scicolone B. (2008). Deficit Irrigation: Theory and Practice. *Agricultural Irrigation Research progress,* Capter 4.

Capra A., Consoli S., Russo A., Scicolone B. (2008). Integrated Agro-Economic Approach to Deficit Irrigation on Lettuce Crops in Sicily (Italy). *Journal of Irrigation and Drainage engineering, july-august,* 437-445.

Capra A., Scicolone B. (2007). Progettazione e gestione degli impianti di irrigazione. Criteri di impiego e valorizzazione delle acque per uso irriguo. (Irrigation system design and maintenance. Use and valorisation criteria of irrigation water). Bologna, Italy: *Edagricole, Edizioni agricole de Il sole 24 Ore* , 297.

Castel J.R., Buj A. (1990). Response of *Salustiana* oranges to high frequency deficit irrigation. *Irrigation science* Volume 11, Issue 2 April 1990, 121-127.

Castle W.S., Krezdorn A.H. (1977) Effect of citrus rootstocks on root distribution and leaf mineral content of Orlando Tangelo trees. *J. Am. Soc. Hortic. Sci.* 100, 1 – 4.

Chalmers D.J., Mitchell P.D., Jerie P.H. (1984). The physiology of growth control of peach and pear trees using reduced irrigation. *Acta Horticulturae* (FAO cap 8)146, 143-149.

Chaney V. R. (1981). Water Deficits and Plant Growth. Sources of water, vol. VI Academic Press, New York, 1- 47.

Consoli S., O'Connell N., Snyder R. (2006). Estimation of Evapotranspiration of Different-Sized Navel-Orange Tree Orchards Using Energy Balance. *Journal of irrigation and drainage engineering* © *Asce*. January/February 2006.

Crave A., Gascuel-Odoux C. (1997). The influence of topography on time and space distribution of soil surface water content. *Hydrological Processes*, 11, 203–210.

Cuevas J., Pinillosa V., Cañetea M.L., González M., Alonso A., Fernández M.D., Hueso J.J. (2009). Optimal levels of postharvest deficit irrigation for promoting early flowering and harvest dates in loquat (*Eriobotrya japonica* Lindl.). *Agricultural Water Management* Vol 96, Issue 5, 831-838.

Cuevas M.V., Torres-Ruiza J.M., Álvarezb R., Jiménezb M.D., Cuervab J., Fernández J.E. (2010). Assessment of trunk diameter variation derived indices as water stress indicators in mature olive trees. *Agricultural Water Management* Volume 97, Issue 9, September 2010, 1293–1302.

De Souza C.R., Maroco J.P., Dos Santos T.P., Rodrigues M. L., Lopes C.M., Pereira J.S., Chaves M.M. (2005). Impact of deficit irrigation on water use efficiency and carbon isotope composition (d13C) of field-grown grapevines under Mediterranean climate. *Journal of Experimental Botany*, Vol. 56, No. 418, 2163–2172, August 2005

De Souza C.R., Maroco J.P., Dos Santos T.P., Rodrigues, M.L., Lopes C., Pereira J.S, Chaves M.M. (2005). Control of stomatal aperture and carbon uptake by deficit irrigation in two grapevine cultivars. *Agriculture, Ecosystems & Environment* Volume 106, Issues 2–3, 2 April 2005, 261–274.

Domingo R., Ruiz-Sánchez M.C., Sánchez-Blanco M.J., Torrecillas A. (1996). Water relations, growth and yield of Fino lemon trees under regulated deficit irrigation. *Irrigation Science* 16, 115-123.

Egea G., Nortes P.A., Gonzàlez-Real M.M, Baille A., Domingo R. (2010). Agronomic response and water productivity of almond trees under contrasted deficit irrigation regimes. *Agricultural Water Management* 97, 171–181.

English M. (1990). Deficit Irrigation. I: Analytical Framework. *Journal of irrigation and drainage engineering.*

English M. (2002). Irrigation Advisory Services and Participatory Extension in Irrigation Management. Workshop organised. *FAO–ICID Irrigation advisory services for optimum use of limit water. 24 July 2002. Montreal, Canada.*

English M., Raja S.N. (1996). Perspectives on deficit irrigation. *Agricultural Water Management* 32, 1 – 14.

English M.J. (1981). The uncertainty of crop models in irrigation optimization. *Trans. ASAE*, 24(4), 917-921, 928.

English M.J., Nuss G.S. (1982). Designing for deficit irrigation. *J. Irrigation and Drainage Engineering,* ASCE, 108(2), 91-106.

Eurostat (2010). Agriculture and Fishery statistics.

Fabeiro Cortés, C.; Martín de Santa Olalla, F.; López Urrea R. (2003a). Production of garlic (Allium sativum L.) under controlled deficit irrigation conditions in a semi-arid climate. *Agricultural Water Management*, 59, 155–167.

Fabeiro Cortés, C.; Martín de Santa Olalla, F.; López R.; Domínguez, A. (2003b). Production and quality of the sugar beet (Beta vulgaris L.) cultivated under controlled deficit irrigation conditions in a semi-arid climate. *Agricultural Water Management*, 62, 215–227.

Fao (2010). Top production orange.

Fereres E., Soriano M.A. (2007). Deficit irrigation for reducing agricultural water use. *Journal of Experimental Botany,* Vol 58, No. 2, 147-159.

Garcìa-Tejero I., Romero-Vicente R., Jiménez-Bocanegra J.A., Martìnez-Garcìa G., Duràn-Zuazo V.H., Muriel-Fernàndez J.L. (2010). Response of citrus trees to deficit irrigation during different phenological periods in relation to yield, fruit quality, and water productivity. *Agricultural Water Management* Vol 97, Issue 5, 689–699.

García-Vila M., Fereres E., Mateos L., Orgaz F., Steduto P. (2009). Deficit Irrigation Optimization of Cotton with AquaCrop. *Agronomy Journal* Volume 101, Issue 3.

Geerts S., Raes D. (2009). Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agricultural Water Management* 96, 1275–1284.

Gijòn M.C., Guerrero J., Couceiro J.F., Moriana A. (2009). Deficit irrigation without reducing yield or nut splitting in pistachio (Pistacia vera cv Kerman on Pistacia terebinthus L.). *Agricultural Water Management* 96, 12-22.

Goldhamer D.A., Fereres E. (2003). Irrigation scheduling protocols using continuosly recorded trunk diameter measurements. *Irrig. Sci.* 20, 115 - 125.

Goodwin I., Boland A.M. (2000). Scheduling deficit irrigation of fruit trees for optimizing water use efficiency. *Deficit Irrigation Practices,* Capter 8.

Hargreaves, G.H. and Samani, Z.A. (1984). Economic considerations of deficit irrigation. *J. Irrigation and Drainage Division,* ASCE, 110(4), 343-358.

Hart W.E., Norum D.I., Peri G. (1980). Optimal seasonal irrigation application analysis. *J. Irrig. And Drain. Div.,* ASCE, 106(3), 221-235

Hsiao T.C. , Steduto P, Fereres E. (2007). A systematic and quantitative approach to improve water use efficiency in agriculture. *Irrigation Science*, 25, 209-231.

Hutton R.J., Loveys B.R. (2011). A partial root zoone drying irrigation strategy for citrus-Effects on water use efficiency and fruit characteristics. *Agricultural water management* 98, 1485-1496.

Iglesias D.J., Cercós M., Colmenero-Flores J.M., Naranjo M.A., Ríos G., Carrera E., Ruiz-Rivero O., Lliso I., Morillon R., Tadeo F.R., Talon M. (2007). Physiology of citrus fruitine. Brazilian Journal of Plant Physiology vol.19 no.4 Londrina Oct./Dec. 2007.

Imitiyaz M., Mgadla N.P., Manase S.K., Chendo K., Mothobi E.O. (2000). Yield and economic return of vegetable crops under variable irrigation. *Irrigation Science*, 19, 87-93.

ISTAT (2010). VI Censimento generale dell'agricoltura.

Jackson B.S., Gerik T.J., Wanjura D.F. (1991). Use of COTTAM for scheduling limited irrigation. *J. Prod. Agric.* 3(4), 420-425.

James, L.D. and Lee, R.R. (1971). *Economics of water resources planning*. New York, USA, McGraw-Hill, 325.

Jones H.G. (2004). Irrigation scheduling: advantages and pitfalls of plant-based methods. *Journal of Experimental Botany* Volume 55, Issue 407, 2427-2436.

Kriedemann P.E., Goodwin I., (2003). Regulated Deficit Irrigation and Partial Rootzone Drying Irrigation Insights n. 4 - Land and Water Australia.

Larsen D.C., McMaster G.M. (1965). First irrigation of potatoes. *Idaho Agricultural Experiment Station*, Current Information Series No. 13.

Lecler N.L. (1998). Integrated methods and models for deficit irrigation planning. In Pert R.M., Curry R.B. (Eds), *Agricultural systems modelling and simulation*, *Marcel Dekker, Inc.*

Lerner H.R., Amzallag G.N., Friedman Y., Goloubinoff P. (1994). The response of plants to salinity.From turgor adjustments to genome modification. *Israel J. Plant Sci.,*4 (2), 285-300.

Li L., Yu O. (2007). Quantifying the effects of advection on canopy energy budgets and water use efficiency in an irrigated wheat field in the North China Plain. *Agricultural Water Management* 89, 116-122.

Li Y., Cohen Y., Wallach R., Cohen S., Fuchs M. (2004). On quantifying soil water deficit of a partially wetted root zone by the response of canopy or leaf conductance. *Agricultural Water Management* Volume 65, Issue 1, 15 February 2004, 21–38.

Liu F., Shahnazari A., Andersen M., Jacobsen S., Jensen C. (2006). Effects of deficit irrigation (DI) and partial root drying (PRD) on gas exchange, biomass partitioning and water use efficiency in potato. *Scientia Horticulturae* 109, 113-117.

Lorite I.J., Mateos L., Fereres E. (2004). Evaluating irrigation performance in a Mediterranean environment. II. Variability among crops and farmers. Irrigation Science 23, 85–92.

Marin F.R., Angelocci L.R. (2011). Irrigation requirements and transpiration coupling to the atmosphere of a citrus orchard in Southern Brazil. *Agricultural Water Management* - Volume 98, Issue 6, April 2011, 1091–1096.

Marks G. (2010). A method to save water and energy white increasing crop yield, a targeted approach for California agriculture. *Precision Irrigation* March 2010.

Marsal J., Lopez G., Del Campo J., Mata M., Arbones A., Girona J. (2010). Postharvest regulated deficit irrigation in 'Summit' sweet cherry: fruit yield and quality in the following season. *Irrigation Science* 28, 181–189.

McCarthy M.G., Loveys B.R., Dry P.R., Stoll M. (2000). Regulated deficit irrigation and partial rootzone drying as irrigation management techniques for grapevines. *Deficit Irrigation Practices,* Capter 9.

McKeering L.M. (2004). Evaluating the Potential to Impose Partial Root Zone Drying (PRD) on Clay Soils in Commercial Cotton Production Systems.

Nachimuthu G., Velu V., Malarvizhi P., Ramasamy S., Bose J. (2007). Relationship Between Index Leaf Nitrogen and Leaf Colour Chart (LCC) Values in Direct Wet Seeded Rice (Oryza sativa L.). Asian Journal of Plant Sciences, 6: 477-483.

Naor A., Cohen S. (2003). Sensitivity and variability of maximum trunk shrinkage, midday stem water potential, and transpiration rate in response to withholding irrigation from field-grown apple trees. *Hortscience* 38(4), 547-551.

Olivo N., Girona J., Marsal J. (2009). Seasonal sensitivity of stem water potential to vapour pressure deficit in grapevine. *Irrigation Science* 27, 175–182.

Or D., Tuller M., Wraith J.M. (2005). Soil Water Potential. *Encyclopedia Of Soils in the Environment*, 270 - 277, Elsevier Science, Oxford.

Ortega J.F., De Juan J.A., Tarjuelo J.M. (2004). Evaluation of the water cost effect on water resource management: Application to typical crops in a semiarid region. *Agricultural Water Management* 66, 125–144.

Ortuño M.F., Alarcón J.J., Nicolás E., Torrecillas A. (2004). Interpreting trunk diameter changes in young lemon trees under deficit irrigation. *Plant Science* 167, 275–280.

Oweis T., Hachum A. (2006). Water harvesting and supplemental irrigation for improved water productivity of dry farming systems in West Asia and North Africa. *Agricultural Water Management*, 80, 57-73.

Pala M., Ryan J., Zhang H., Singh M., Harris H.C. (2007). Water-use efficiency of wheat-based rotation systems in a Mediterranean environment. *Agricultural Water Management* 93, 136-144.

Pereira L.S. (2003). Irrigation demand management to cope with drought and water scarcity. *Tools for drought mitigation in Mediterranean regions*, 44 Kluwer.

Pérez-Pérez J. G., Romero P., Navarro J.M., Botìa P. (2008). Response of sweet orange cv ‘Lane late’ to deficit-irrigation strategy in two rootstocks. II: Flowering, fruit growth, yield and fruit quality. *Irrig Sci* 26, 519–529.

Pérez-Pérez J., Garcìa J., Robles J.M., Botìa P. (2010). Economic analysis of navel orange cv. 'Lane late' grown on two different drought-tolerant rootstocks under deficit irrigation in South-eastern Spain. *Agricultural Water Management* 97, 157–164.

Pèrez-Pèrez J.G., Robles J.M., Botìa P. (2009). Influence of deficit irrigation in phase III of fruit growth on fruit quality in 'lane late' sweet orange. *Agricultural Water Management* 96, 969–974.

Popova Z., Eneva S., Pereira L.S. (2006). Model validation, crop coefficients and yield response factors for maize irrigation scheduling based on long-term experiments. *Biosystems Engineering*, 95(1), 139-149.

Quanqi L., Baodi D., Yunzhou Q., Mengyu L., Jiwang Z. (2010). Root growth, available soil water, and water-use efficiency of winter wheat under different irrigation regimes applied at different growth stages in North China. *Agricultural Water Management* Volume 97, Issue 10, October 2010, 1676–1682.

Reynolds S.G. (1970). The gravimetric method of soil moisture determination, I: A study of equipment and methodological problems. *Hydrology*, 11, 258–273.

Romero P., Garcia J., Botia P. (2006a). Cost-benefit analysis of a regulated deficit-irrigated almond orchard under subsurface drip irrigation conditions in South-eastern Spain. *Irrigation Science* 24, 175-184

Romero P., Navarro J.M., Pérez-Pérez J., García-Sánchez F., Gómez-Gómez A., Porras I., Martinez V., Botía P. (2006b). Deficit irrigation and rootstock: their effects on water relations, vegetative development, yield, fruit quality and mineral nutrition of Clemenules mandarin. *Tree Physiology* 26, 1537-1548.

Rossi G. (2003). An integrated approach to drought mitigation in Mediterranean regions. *Tools for drought mitigation in Mediterranean regions*, 44 Kluwer.

Sammis T.W. (2011). The transition of the blaney-criddle formula to the penman-monteith equation in the western United States. *Journal of Service Climatology* Volume 5, Number 1, 1-11.

Sentelhas P.C., Gillespie T.J., Santos E.A. (2010). Evaluation of FAO Penman–Monteith and alternative methods for estimating reference evapotranspiration with missing data in Southern Ontario, Canada.

Agricultural Water Management Volume 97, Issue 5, May 2010, 635–644.

Sepaskhah A.R., Ghahraman B. (2004). The effects of irrigation efficiency and uniformity coefficient on relative yield and profit for deficit irrigation. *Biosystems Engineering*, 87(4), 495-507.

Shangguan Z., Shao M., Horton R., Lei T., Qin, L., Ma, J. (2002). A model for optimal allocation of irrigation water resources under deficit irrigation and its application. *Agricultural Water Management* 52, 139-154.

Schofield R.K. (1935). The pF of the water in soil. *Trans.Int. Congr.Soil Sci. 3rd* II, 38-48.

Sinclair T.R., Allen L.H. (1982). Carbon dioxide and water vapour exchange of leaves on field-grown citrus trees. *J. Exp. Bot.* 33, 1166 – 1175.

Smith M. (1992). CROPWAT. A computer program for irrigation planning and management. *Fao irrigation and drainage Paper 46.*

Solomon, K.H. (1985). Typical crop water production functions. Paper N. 85-2596, Winter Meeting, Amer.soc. of agric. Engrs., Chicago, III., 17-20.

Stagno F., Germanà C., Giuffrida A., Tribulato E., Intrigliolo F., Continella A. (2008), Productive and qualitative responses to deficit irrigation on orange trees. *11° International Citrus Congress,* Cina 26-30 ottobre 2008.

Steduto P. (1997). Modelling for crop response to water: physiological aspects. *Options Mediterraneennes,* ser.A/n.31.

Syvertsen J. P., Zablotowicz R.H., Smith H.L. (1983). Soil temperature and flooding effects on two species of citrus. I. Plant growth and hydraulic conductivity. *Plant and Soil* 72, 3-12.

Syvertsen J., Hanlon E.A. (2008). Citrus Tree Stresses: Effects on Growth and Yield. *Horticultural Sciences Department*, Florida, May 2008

Syvertsen J.P. (1982) Minimum Leaf Water Potential and Stomatal Closure in Citrus Leaves of Different Ages. Ann. Bot. 49, 827-834.

Syvertsen J.P. (1990). Physiological aspects of citrus water relations. *Florida Agricultural Experiment Station,* Journal Series No. N-OO209.

Syvertsen J.P., Graham J.H. (1985). Hydraulic conductivity of roots, mineral nutrition, and leaf gas exchange of Citrus rootstocks. *J. Amer. Soc. Hort.* Sci 110, 865 – 869.

Syvertsen J.P., Levy Y. (2005). Salinity interactions with other abiotic and biotic stresses in citrus. *HortTech* 15, 100-103.

Tanji K.K. (1996). Agricultural salinity assessment and management. *ASCE*, New York.

Teixeira J.L., Fernando R.M., Pereira L.S. (1995). Irrigation scheduling alternatives for limited water supply and drought. ICID Bulletin, 44(29), 73-88.

Teixeira J.L., Pereira L.S. (1992). ISAREG, an Irrigation scheduling simulation model. *ICID Bulletin*, 41(2), 29-48.

Treeby M.T., Henriod R.E., Bevington K.B., Milne D.J., Storey R. (2007). Irrigation management and rootstock effects on navel orange [*Citrus sinensis* (L.) Osbeck] fruit quality. *Agricultural Water Management* Volume 91, Issues 1–3, 16 July 2007, 24–32.

Velez J.E., Intrigliolo D.S., Castel J.R. (2007). Scheduling deficit irrigation of citrus trees with maximu daily trunk shrinkage. *Agricultural water management,* 197-204.

Wang J., Miller D.R., Sammis T.W., Gutschick V.P., Simmons L.J., Andales A.A. (2007). Energy balance measurements and a simple model for estimating pecan water use efficiency. *Agricultural water management* 91, 92-101.

Warrick A.W., Gardner W.R. (1983). Crop yield as affected by spatial variations of soil and irrigation. *Water Resource*, 19, 181–186.

Webber H.A., Madramootoo C.A., Bourgault M., Horst M.G., Stulina G., Smith D.L. (2006). Water use efficiency of common bean and green gram grown using alternate furrow and deficit irrigation. *Agricultural Water Management* 86, 259-268.

Wiersum L.K., Barmanny K. (1983). Changes in the water permeability of roots of some trees during drought stress and recovery, as related to problems of growth in an urban environment. *Plant and Soil* 75, 443-448.

WMO A.A. (2008). Guide to Meteorological Instruments and Methods of Observation. *WMO-No. 8 Seventh edition 2008*.

Xu C.Y., Singh V.P. (2000). Evaluation and generalization of radiation-based methods for calculating evaporation. *Hydrological Processes* Volume 14, Issue 2, 339–349.

Xue Q., Zhu Z., Musick J.T., Stewart B.A., Dusek D.A. (2006). Physiological mechanisms contributing to the increased water-use efficiency in winter wheat under deficit irrigation. *Journal of Plant Physiology* Volume 163, Issue 2, February 2006, 154–164.

Yang W.-H., Peng S., Huang J., Sanico A.L., Buresh R.J., Witt C. (2003). Using Leaf Color Charts to Estimate Leaf Nitrogen Status of Rice. *Agronomy Journal –American Society of Agronomy* Vol. 95, 212–217.

Zairi A., El Amami H., Slatin A., Pereira A., Pereira L.S., Rodrigues P.N., Machado T. (2003). *Tools for drought mitigation in Mediterranean regions*, 44 Kluwer.

Zekri M., Obreza T.A., Koo R. (2003). Irrigation, Nutrition, and Citrus Fruit Quality. *University of Florida – institute of food and Agricultural sciences*.

Zhang B., Li F.M., Huang G., Cheng Z.Y., Zhang Y. (2006). Yield performance of spring wheat improved by regulated deficit irrigation in an arid area. *Agricultural Water Management* 79, 28-42.

Appendix A

Tab. A.1 Mean values of soil water potential (SWP) in 2011.; SD = Standard Deviation.

SWP (MPa) in 2011	Jun, 1	Jun, 27	Jul, 25	Aug, 1	Aug, 22	Aug, 29	Sept, 5	Sept, 12	Sept, 26	Oct, 3	Oct, 10	*Average*	*SD*
SSDI*	2.1	2.7	4.3	4.2	4.1	4.2	4.1	3.8	3.8	3.2	2.3	*3.5*	*0.8*
PRD**	1.7	2.6	3.8	3.9	3.6	3.9	3.8	4.0	3.0	3.1	2.0	*3.2*	*0.8*
RDI***	1.7	3.6	3.3	3.8	3.4	3.9	3.6	3.8	2.9	2.9	2.5	*3.2*	*0.7*
SDI****	2.2	3.2	3.8	4.0	3.6	3.9	3.7	3.5	2.6	3.0	1.7	*3.2*	*0.8*
SD	*0.25*	*0.49*	*0.42*	*0.18*	*0.30*	*0.12*	*0.24*	*0.23*	*0.52*	*0.14*	*0.35*		

SSDI=Subsurface Drip Irrigation; **PRD=Partial Root drying;*RDI=Regulated Deficit Irrigation; ****SDI=Surface Drip Irrigation.*

Tab. A.2 Mean values of soil water potential (SWP) in 2012. SD = Standard Deviation.

SWP (MPa) in 2012	Jun, 18	Jun, 25	Jul, 2	Jul, 9	Jul, 16	Jul, 24	Jul, 30	Aug, 20	Aug, 27	Sept, 10	Sept, 17	Sept, 24	Oct, 1	Oct, 8	*Average*	*SD*
SSDI*	4.0	4.2	3.7	4.2	4.6	4.2	4.2	3.5	4.4	2.9	3.3	3.5	3.6	3.2	*3.82*	*0.51*
PRD**	3.9	4.8	3.9	3.7	4.1	4.0	3.7	3.9	4.1	3.3	3.4	3.5	3.5	3.3	*3.78*	*0.42*
RDI***	3.4	4.1	3.5	3.8	3.5	3.7	3.5	3.5	3.9	3.6	2.7	3.0	3.4	3.2	*3.49*	*0.35*
SDI****	3.4	3.8	3.6	3.8	3.7	3.3	3.7	3.8	4.0	2.7	2.9	3.1	3.1	2.9	*3.41*	*0.40*
SD	*0.33*	*0.45*	*0.18*	*0.21*	*0.49*	*0.38*	*0.31*	*0.17*	*0.20*	*0.37*	*0.32*	*0.23*	*0.22*	*0.18*		

SSDI=Subsurface Drip Irrigation; **PRD=Partial Root drying;*RDI=Regulated Deficit Irrigation; ****SDI=Surface Drip Irrigation.*

Tab. A.3 Mean values of stem water potential (Ψ_{PD}) (MPa) in 2011. SD = Standard Deviation.

Ψ_{PD} (MPa) in 2011	Jun, 1	Jun, 27	Jul, 11	Jul, 25	Aug, 22	Sept, 5	Sept, 26	Oct, 10	*Average*	*SD*
SSDI*	-1.43	-1.38	-1.43	-1.34	-1.45	-1.29	-1.23	-1.01	*-1.32*	*0.14*
PRD**	-1.46	-1.43	-1.56	-1.35	-1.48	-1.33	-1.30	-1.06	*-1.37*	*0.15*
RDI***	-1.41	-1.41	-1.44	-1.38	-1.43	-1.43	-1.39	-1.05	*-1.37*	*0.13*
SDI****	-1.49	-1.39	-1.41	-1.29	-1.46	-1.28	-1.23	-1.01	*-1.32*	*0.15*
SD	*0.034*	*0.023*	*0.070*	*0.037*	*0.021*	*0.068*	*0.077*	*0.026*		

SSDI=Subsurface Drip Irrigation; **PRD=Partial Root drying;*RDI=Regulated Deficit Irrigation; ****SDI=Surface Drip Irrigation.*

Tab. A.4 Standard Error (SE) of stem water potential (MPa) developed by CRA-ACM.

SE of stem water potential (MPa) in 2011	*Jun, 1*	*Jun, 27*	*Jul, 11*	*Jul, 25*	*Aug, 22*	*Sept, 5*	*Sept, 26*	*Oct, 10*
SSDI*	*0.025*	*0.048*	*0.014*	*0.055*	*0.046*	*0.024*	*0.014*	*0.024*
PRD**	*0.024*	*0.048*	*0.038*	*0.020*	*0.032*	*0.032*	*0.020*	*0.024*
RDI***	*0.013*	*0.024*	*0.031*	*0.014*	*0.014*	*0.048*	*0.080*	*0.020*
SDI****	*0.024*	*0.013*	*0.055*	*0.052*	*0.024*	*0.032*	*0.032*	*0.024*

SSDI=Subsurface Drip Irrigation; **PRD=Partial Root drying;*RDI=Regulated Deficit Irrigation; ****SDI=Surface Drip Irrigation.*

Tab. A.5 Mean values of stem water potential (Ψ_{PD}) (MPa) in 2012. SD = Standard Deviation.

Ψ_{PD} (MPa) in 2012	Jun, 7	Jun, 18	Jul, 2	Jul, 16	Jul, 30	Aug, 20	Sept, 10	Sept, 24	Oct, 8	*Average*	*SD*
SSDI*	-1.34	-1.63	-1.71	-1.58	-1.60	-1.50	-1.51	-1.59	-1.46	*-1.55*	*0.11*
PRD**	-1.36	-1.78	-1.84	-1.94	-1.70	-1.53	-1.78	-1.65	-1.52	*-1.68*	*0.18*
RDI***	-1.40	-1.85	-1.54	-1.51	-1.51	-1.45	-1.46	-1.50	-1.56	*-1.53*	*0.13*
SDI****	-1.51	-2.00	-1.66	-1.55	-1.46	-1.48	-1.38	-1.60	-1.51	*-1.57*	*0.18*
SD	*0.077*	*0.156*	*0.124*	*0.198*	*0.104*	*0.032*	*0.172*	*0.062*	*0.039*		

SSDI=Subsurface Drip Irrigation; **PRD=Partial Root drying;*RDI=Regulated Deficit Irrigation; ****SDI=Surface Drip Irrigation.*

Tab. A.6 Standard Error (SE) of stem water potential (MPa) developed by CRA-ACM.

SE of stem water potential (MPa) in 2012	*Jun, 7*	*Jun, 18*	*Jul, 2*	*Jul, 16*	*Jul, 30*	*Aug, 20*	*Sept, 10*	*Sept, 24*	*Oct, 8*
SSDI*	*0.024*	*0.032*	*0.013*	*0.032*	*0.035*	*0.020*	*0.024*	*0.024*	*0.022*
PRD**	*0.031*	*0.066*	*0.069*	*0.013*	*0.020*	*0.014*	*0.032*	*0.065*	*0.059*
RDI***	*0.074*	*0.159*	*0.024*	*0.038*	*0.024*	*0.020*	*0.024*	*0.058*	*0.060*
SDI****	*0.024*	*0.079*	*0.024*	*0.020*	*0.013*	*0.032*	*0.014*	*0.041*	*0.039*

SSDI=Subsurface Drip Irrigation; **PRD=Partial Root drying;*RDI=Regulated Deficit Irrigation; ****SDI=Surface Drip Irrigation.*

Tab. A.7 Mean values of stomatal conductance (gs) (mmol $m^{-2}s^{-1}$) and mean values of Leaf Temperature (°C) in 2011. SD = Standard Deviation.

gs *(mmol $m^{-2}s^{-1}$)* in 2011	Jun, 1	Jun, 27	Jul, 11	Jul, 25	Aug, 22	Sept, 5	Sept, 26	Oct, 10	*Average*	*SD*
SSDI*	98,45	116.31	94.55	164.00	72.15	105.02	270.25	220.55	*142.66*	*69.85*
PRD**	64,03	108.52	108.30	205.45	99.22	81.65	240.99	161.03	*133.65*	*62.61*
RDI***	100,04	106.59	91.78	171.54	133.74	116.96	200.34	171.21	*136.52*	*39.86*
SDI****	80,00	117.37	91.00	160.00	88.04	136.73	290.93	182.21	*143.28*	*69.79*
Leaf Temperature (°C)	30	32	37	31	34	36	27	20		
SD	*17.033*	*5.437*	*8.074*	*20.696*	*26.114*	*23.031*	*39.289*	*26.014*		

SSDI=Subsurface Drip Irrigation; **PRD=Partial Root drying;*RDI=Regulated Deficit Irrigation; ****SDI=Surface Drip Irrigation.*

Tab. A.8 Standard Error (SE) of stomatal conductance (mmol $m^{-2}s^{-1}$) developed by CRA-ACM.

SE of stomatal conductance (mmol $m^{-2}s^{-1}$) in 2011	*Jun, 1*	*Jun, 27*	*Jul, 11*	*Jul, 25*	*Aug, 22*	*Sept, 5*	*Sept, 26*	*Oct, 10*
SSDI*	*26.683*	*20.460*	*15.417*	*12.358*	*11.876*	*26.413*	*10.582*	*24.649*
PRD**	*5.957*	*19.986*	*5.424*	*18.494*	*18.842*	*6.128*	*13.983*	*19.484*
RDI***	*7.710*	*14.963*	*17.866*	*25.792*	*19.274*	*24.994*	*33.912*	*35.543*
SDI****	*0.401*	*27.594*	*19.381*	*19.313*	*13.899*	*20.970*	*21.135*	*16.204*

SSDI=Subsurface Drip Irrigation; **PRD=Partial Root drying;*RDI=Regulated Deficit Irrigation; ****SDI=Surface Drip Irrigation.*

Tab. A.9 Mean values of stomatal conductance (gs) (mmol $m^{-2}s^{-1}$) and mean values of Leaf Temperature (°C) in 2012. SD = Standard Deviation.

gs *(mmol $m^{-2}s^{-1}$) in* 2012	Jun, 18	Jul, 2	Jul, 16	Jul, 30	Aug, 20	Sept, 10	Sept, 24	Oct, 8	*Average*	*SD*
SSDI*	115.25	181.60	158.73	84.10	316.15	271.33	197.38	221.33	*193.23*	*76.84*
PRD**	151.28	103.37	153.10	100.83	271.20	224.80	172.78	273.43	*181.35*	*68.43*
RDI***	118.05	192.40	250.93	153.45	212.38	298.38	212.38	246.73	*210.58*	*57.08*
SDI****	92.05	65.23	124.45	140.25	291.75	313.38	112.58	238.53	*172.28*	*95.13*
SD	*24.378*	*61.465*	*54.844*	*32.583*	*44.317*	*38.889*	*43.945*	*21.706*		
Leaf Temperature (°C)	36	38	37	39	34	31	36	30		

SSDI=Subsurface Drip Irrigation; **PRD=Partial Root drying;*RDI=Regulated Deficit Irrigation; ****SDI=Surface Drip Irrigation.*

Tab. A.10 Standard error of stomatal conductance (mmol $m^{-2}s^{-1}$) developed by CRA-ACM.

SE of stomatal conductance (mmol $m^{-2}s^{-1}$) in 2012	*Jun, 18*	*Jul, 2*	*Jul, 16*	*Jul, 30*	*Aug, 20*	*Sept, 10*	*Sept, 24*	*Oct, 8*
SSDI*	*32.029*	*29.529*	*25.441*	*2.685*	*46.622*	*58.285*	*41.259*	*15.733*
PRD**	*24.066*	*23.365*	*24.985*	*17.591*	*78.840*	*39.544*	*15.373*	*12.772*
RDI***	*23.795*	*22.427*	*21.054*	*9.450*	*17.967*	*13.083*	*30.652*	*25.551*
SDI****	*11.510*	*4.383*	*10.814*	*29.279*	*15.592*	*14.760*	*21.227*	*8.942*

SSDI=Subsurface Drip Irrigation; **PRD=Partial Root drying;*RDI=Regulated Deficit Irrigation; ****SDI=Surface Drip Irrigation.*

Tab. A.11 Mean values of Leaf Temperature (°C) measurements in 2011. SD = Standard Deviation.

Leaf Temperature (°C) in 2011	Jun, 1	Jun, 27	Jul, 11	Jul, 25	Aug, 22	Sept, 5	Sept, 26	Oct, 10	*Average*	*SD*
SSDI*	28.84	31.84	35.78	30.90	33.23	34.65	26.40	19.98	*30.20*	*5.13*
PRD**	29.43	31.26	37.00	31.05	33.78	36.50	26.95	20.55	*30.81*	*5.37*
RDI***	29.44	33.10	38.07	30.08	34.45	36.48	27.73	20.05	*31.17*	*5.73*
SDI****	30.88	30.15	36.88	30.55	33.05	35.10	26.33	19.88	*30.35*	*5.33*
SD	*0.867*	*1.228*	*0.936*	*0.433*	*0.631*	*0.949*	*0.646*	*0.300*		

SSDI=Subsurface Drip Irrigation; **PRD=Partial Root drying;*RDI=Regulated Deficit Irrigation; ****SDI=Surface Drip Irrigation.*

Tab. A.12 Standard Error (SE) of Leaf Temperature (°C) developed by CRA-ACM.

SE of leaf temperature in 2011 (°C)	*Jun, 1*	*Jun, 27*	*Jul, 11*	*Jul, 25*	*Aug, 22*	*Sept, 5*	*Sept, 26*	*Oct, 10*
SSDI*	*0.76*	*1.22*	*0.51*	*0.33*	*0.44*	*0.62*	*0.92*	*0.32*
PRD**	*0.80*	*0.64*	*0.42*	*0.32*	*0.14*	*0.69*	*0.26*	*0.16*
RDI***	*0.29*	*0.69*	*1.60*	*0.42*	*0.56*	*0.62*	*1.14*	*0.18*
SDI****	*0.84*	*0.07*	*0.13*	*0.17*	*0.17*	*0.19*	*1.09*	*0.26*

SSDI=Subsurface Drip Irrigation; **PRD=Partial Root drying;*RDI=Regulated Deficit Irrigation; ****SDI=Surface Drip Irrigation.*

Tab. A.13 Mean values of Leaf Temperature (°C) in 2012. SD = Standard Deviation.

Leaf Temperature (°C) in 2012	Jun, 18	Jul, 2	Jul, 16	Jul, 30	Aug, 20	Sept, 10	Sept, 24	Oct, 8	*Average*	*SD*
SSDI*	35.95	37.93	37.60	39.28	33.98	31.48	36.08	29.00	*35.16*	*3.48*
PRD**	36.25	37.70	37.58	39.38	34.15	31.85	36.50	30.68	*35.51*	*3.03*
RDI***	36.28	37.03	37.00	38.98	34.00	31.63	34.55	29.28	*34.84*	*3.18*
SDI****	36.85	37.50	37.50	39.53	34.30	31.08	35.70	30.88	*35.42*	*3.13*
SD	*0.376*	*0.383*	*0.282*	*0.232*	*0.151*	*0.326*	*0.837*	*0.956*		

SSDI=Subsurface Drip Irrigation; **PRD=Partial Root drying;*RDI=Regulated Deficit Irrigation; ****SDI=Surface Drip Irrigation.*

Tab. A.14 Standard Error (SE) of Leaf Temperature (°C) developed by CRA-ACM.

SE of leaf temperature (°C) in 2012	*Jun, 18*	*Jul, 2*	*Jul, 16*	*Jul, 30*	*Aug, 20*	*Sept, 10*	*Sept, 24*	*Oct, 8*
SSDI*	*0.21*	*0.13*	*0.47*	*0.64*	*0.27*	*0.45*	*0.81*	*0.47*
PRD**	*0.21*	*0.28*	*0.65*	*0.55*	*0.17*	*0.63*	*0.84*	*0.37*
RDI***	*0.48*	*0.61*	*0.56*	*0.51*	*0.12*	*0.33*	*0.61*	*0.78*
SDI****	*0.09*	*0.18*	*0.49*	*0.42*	*0.11*	*0.44*	*0.84*	*0.82*

SSDI=Subsurface Drip Irrigation; **PRD=Partial Root drying;*RDI=Regulated Deficit Irrigation; ****SDI=Surface Drip Irrigation.*