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Irrigation in Mediterranean Fruit Tree Orchards

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1. Introduction

The Mediterranean environment alters the ecophysiology of plants, especially during summer as a consequence of the combined effects of high light, high air temperature, high vapour pressure deficit and low rainfall. The high evapotranspirative demand which characterises the Mediterranean climate has, in the past affected land use with farmers tending to choose drought-tolerant species, such as olives, almond etc (Dichio et al., 2006). In recent years, major investments have been made in agriculture that have led to a 25% increase in the area of the Earth's surface under irrigated crops. However, despite these investments, an increasing number of countries in arid and semi-arid regions face severe water shortages because of reduced annual rainfall (Mutke et al., 2005; Cislighi et al., 2005) and because their existing water resources are already fully or over exploited. The availability of water (agriculture, industry and domestic) in several countries of the Mediterranean basin is well below the level associated with the achievement of a modern standard of living (1,000 m³ per capita per year) (Rana and Katerji, 2000). Prospects for the future suggest increasing difficulty will be experienced in this area (Smith, 2000). They also indicate that dependency on water for future development has now become critical. For agriculture this has triggered many studies on drought mitigation measures as applied to large-scale networks (Rossi et al., 2005).

Actually, about 75% of the available water in the Mediterranean area is used for agricultural purposes. It is unfortunate that this occurs with very low efficiency of conveyance between reservoir and field. In this chapter, we do not deal with possible improvements in water conveyance to the farms (large-scale networks) but instead we focus on irrigation criteria and methods that can reduce on-farm water losses and can also optimise crop water use. Water losses on the farm account for approximately 40% of total farm water usage. Also, poor irrigation management has direct effects on production as a result of crop stress induced either by water shortage or by waterlogging. Both water deficit and water excess reduce crop yield and quality.

In addition, common cultural practices (empirical irrigation, soil and fertilisation management) also aggravate the decline in soil resources and have negative impact on the environment by contaminating both ground and surface water with various nutrients and pesticides.

Recognising that in the Mediterranean basin, rainfall occurs primarily during the dormant season many horticultural crops are dependent upon stored soil water during rainfall season and on irrigation during the summer period. Therefore, accurate determinations of irrigation timing and volumes are essential if sustainable agricultural development and environmentally sound water management are to be achieved.

A sound knowledge of crop characteristics such as soil volume explored by roots, their sensitivity to water stress and their seasonal water requirements, are of primary importance. These information are required not only to improve understanding the underlying processes of plant physiology and their control (Dragoni et al., 2005), but also for improving the design of irrigation systems and irrigation scheduling. Due to the scarcity of water resources, accurate evaluation of water use efficiency by the different crops is also very important. However, in spite of the large number of methods to measure or estimate plant water use (for a review, see Rana and Katerji, 2000) further efforts are required to improve our understanding of crop water-use efficiency. Moreover, practical application of the scientific findings should be better discussed and be available to growers for both to conserve water resources and also to control environmental pollution .

Based on our own experimental results and also on information from the literature, the aim of the present Chapter is to provide information and appropriate criteria to enable the sustainable management of irrigation at farm level in semi-arid environments such as in Southern Italy.

Nowadays irrigation requires special attention to optimize the management of all components of the orchard system in order to increase water use efficiency and reduce environmental impacts (e.g. soil salinisation, degradation of underground/surface waters). Knowledge on basic plant water relations are widely available, however fewer attempts have been made to link such a information to irrigation schedule at field scale. In addition, irrigation for tree crops should take into account their distinctive traits (e.g. the soil volume explored by roots, type of rootstock) as combined with some soil hydrological features such as the soil water holding capacity.

We would also provide recommendations to drive the water application in fruit tree orchards through adoption of soil-water balance procedures as determined by soil, environment and crop data interaction.

Sustainable irrigation, which includes the application of the regulated deficit irrigation and specific crop coefficients to calculate the plant water requirement, reduces irrigation-induced salinisation risk and increases yield and quality. Our contribution would cover also the synergistic effect of others orchard practices (e.g. soil management, fertilization and canopy management) towards optimal irrigation.

2. Choice and design of irrigation method

Except in soils of low water-holding capacity, localised irrigation methods (drip irrigation or sub-irrigation) are best for all fruit tree species grown in the Mediterranean area. However, in the case of kiwifruit (*Actinidia* spp) because of its physiology and its root system characteristics (Ferguson, 1984; Xiloyannis et al., 1993) irrigation methods that wet the whole soil surface should be considered instead. Additionally, the adoption of localised irrigation

methods require water availability almost every day (June-September, Northern Hemisphere) and often current networks irrigation-Agency (responsible for water management at regional scale) cannot adequately meet the water supply demands. In medium to large farms these timing difficulties can be overcome by the construction of on-farm reservoirs that allow crops to be irrigated even when water is not available in the regional network. This avoids excessively long intervals between irrigations. To choose the most appropriate irrigation method and design one must know: soil characteristics, water requirements of the crop, water availability and water quality.

2.1 Soil water-holding capacity

The soil can store huge amounts of water. In particular, rain water accumulates in autumn and in winter when plant water use rates are low. Deep, loamy soils can hold up to $2,000 \text{ m}^3 \text{ ha}^{-1}$ if a 1 m rooting depth is assumed. The water contained in such a volume of soil is sufficient to meet about 30-40% of an orchard's annual water requirement. In light, shallow soils, and in areas having a shallow water table where the root systems cannot develop to very great depth, the amount of water that can be stored in the soil is much more limited and, consequently, plants are more likely to be exposed to water-deficit induced injury in the summer period.

In soils with high water holding capacities ($1,500\text{-}2,000 \text{ m}^3 \text{ ha}^{-1}$) and, in the absence of irrigation the soil-water content decreases slowly during the season. This allows the plants to adapt gradually and thus limit the damages from water-stress. Conversely, in light and/or shallow soils, and in the case of rootstocks whose rooting depth is shallow, the effective volume of the soil water reserve can be very limited indeed. In this case, sudden variations in soil moisture and in plant turgor will occur and this will cause severe injury to plants that are unable to adapt fast enough to mitigate the effects of a sudden onset of water stress.

Soil management under water scarcity conditions should aim at: (i) improving the soil's water holding capacity during rainfall season and (ii) reducing soil surface evaporation and transpiration from fruit trees and cover crops.

To achieve the former objective, the infiltration rate and water holding capacity can be significantly enhanced by increasing the soils organic matter content and also its hydraulic conductivity. Sloping land, if not adequately managed, usually has a low water holding capacity. Similarly, water holding capacity is reduced in flat land that has been frequently tilled, and always to the same depth where the formation of a 'plough sole' hampers downward infiltration of water. Unfortunately, permanent cover crops are not a good solution to the problem because they compete for water with the crop. Therefore, we would recommend temporary cover crops (November-March) both to increase the soil's water storage capacity (increased organic matter) and also to limit its erosion (especially on slopes) (Photo 1).

Water loss by surface evaporation can be as high as 50% of precipitation and can amount to about 30% of yearly evapotranspiration. Soil surface evaporation losses increase with decreasing of the Leaf Area Index (LAI) (m^2 of leaf per m^2 of soil), and with increasing numbers of irrigation events, especially if using methods that wet the whole soil surface. The distribution efficiency of the various irrigation methods applied to full bearing orchards

varies from 50 to 90%, because of the different amounts of water evaporating from the soil between irrigation events and also during distribution. In young orchards, where the root systems are not fully developed and where ground cover is limited, the efficiency of the various irrigation methods varies from between 10 to 95%. So, in Southern Italy, localized irrigation methods (particularly drip and subirrigation) are a “must” for new plantations. Replacement of low efficiency methods by high efficient - possibly even through public subsidises - should be actively promoted.



Photo 1. Olive orchard grown in South Italy on a slope. Soil is tilled and prone to dramatic erosion during the winter.

Soil evaporation can also be reduced by mulching, using either plant residues resulting from local agricultural practices or one of many other low-cost materials that might happen to be available locally.

2.2 Characteristics of cultivated species

For best choice and design of the irrigation method as well as for its correct management, especially in the early years of orchards establishment, one should estimate the soil volume explored by roots and also the leaf area per hectare. Since the bulk of crop water usage (99.5%) is through foliar transpiration, the considerable variation in LAI that occurs during the early years of establishment (Fig. 1) and during each vegetative season, significantly affects water use. Not surprisingly, in mature orchards leaf area variations during the season are greatest in deciduous species and least in evergreen species.

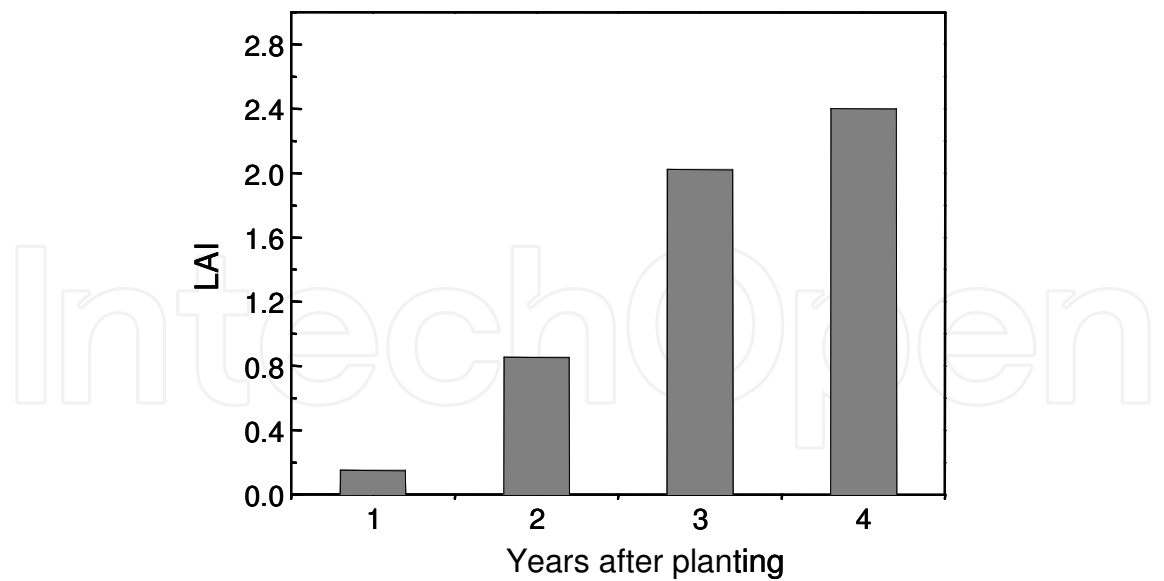


Fig. 1. Variation of the Leaf Area Index (LAI) in kiwifruit vines (cv Hayward) trained at T-bar (4.5 m × 3 m) during the four years after planting. (Adapted from Xiloyannis et al., 1993).

Knowledge of the volume explored by the roots, and also the soil’s hydrological characteristics allows calculation of the soil’s effective water holding capacity and thus the volume of water that is available to the plant.

Such information is indispensable both for the design of the irrigation system (spacing, discharge rates, number of emitters etc.) and also for its correct management, in particular for defining irrigation volumes and frequencies. During the early years of an orchard’s development the soil volume explored by the roots changes considerably. This occurs as the root systems extend both outwards and downwards. Volumes tend to stabilise once the trees are mature (Tab. 1). In parallel, the leaf area per plant and the available water change accordingly (Tab. 2).

Species/ ‘rootstock	m³ tree ⁻¹			
	1 st	2 nd	3 rd	4 th year
Peach cv Vega/ ‘Missour’	1.22	3.39	3.60	3.60
Peach cv Vega/ ‘Mr.S. 2/5	0.56	1.97	2.80	2.80
Kiwifruit cv“Hayward”	0.13	0.83	1.35	1.41
Olive cv “Coratina”	0.50	2.90	8.60	12.25

Table 1. Soil volume explored by roots of peach (cv ‘Vega’, grafted on to two rootstocks planted at 4.5 × 1.5 m spacing, flood irrigation), kiwifruit (cv ‘Hayward’ at 4.5 × 3.0 m spacing, microjet irrigation) and olive trees (cv ‘Coratina’, at 6 × 3 m spacing microjet irrigation) during the first 4 years after planting (Adapted from Xiloyannis et al. 1993).

Root density affects water availability and *vice versa*. High root density means reduced average distance between roots, steeper water potential gradients and steeper concentration gradients of mineral nutrients in the soil and, consequently, a greater use efficiency of water and mineral resources present in the soil volume explored by roots . Root density is usually

expressed either as a root dry weight in the volume of the soil explored, or as a root length. Such expressions are useful for making comparisons between species, but are less useful for defining the water and mineral nutrient uptake efficiency. For this purpose, the surface of roots in contact with the soil and their age-related uptake efficiency require to be known. In all fruit tree species, except kiwifruit, root density is much lower than in the grasses and conifers where it is relatively high (Xiloyannis et al., 1992).

<i>Years after planting</i>	I	II	III	IV
Kiwifruit: cv. Hayward (4.5 × 3.0m)				
Leaf area (m ² p ⁻¹)	1.7	8.9	16.5	17.2
Available water (L p ⁻¹)	12.8	72.3	147.4	154.0
Available water/leaf area (L m ⁻²)	7.5	8.1	8.9	9.0
Peach: Vega/Missour (4.5 × 1.25m)				
Leaf area (m ² p ⁻¹)	3.8	11.8	16.5	16.5
Available water (L p ⁻¹)	137.9	383.1	406.8	406.8
Available water/leaf area (L m ⁻²)	36.3	32.5	24.6	24.6
Olive: cv. Coratina (6.0 × 3.0m)				
Leaf area (m ² p ⁻¹)	0.6	1.9	6.1	6.9
Available water (L p ⁻¹)	160	910	2,710	3,950
Available water/leaf area (L m ⁻²)	263	481	443	571

Table 2. Leaf area, soil available water and leaf area/available water ratio in three fruit tree species during the early four years after planting.

Tree crop species differ in their sensitivity to water deficit and the extent of deficit injury depending on the growth stage of the crop (Tab. 3).

Fruit tree species	Growth stage especially sensitive to water deficit
Apricot, cherry, plum and early-harvest peach	From bloom to harvest
Plum and late-ripening peach	1 st and 3 rd fruit growth stages
Citrus fruit	Bloom and fruit-set
Olive	Bud break, bloom, first and 3 rd fruit growth stage (especially table olive)
Pome fruit	Bloom, fruit set, fast fruit growth stage
kiwifruit	Throughout the whole growing season

Table 3. Growth stage especially sensitive to water deficit in some fruit tree species.

2.3 Canopy architecture, canopy management and ‘water use efficiency’

The term ‘water use efficiency’ is defined as the ratio of the mass of carbon dioxide (CO₂) that is fixed to the cumulative mass of water transpired. Out of the total water absorbed by

roots and transferred to the shoot, about 99.5% is released again to the atmosphere through leaf stomatal and cuticular transpiration. Transpiration of the fruits accounts only for about 0.5% of the plant's total, however fruits may increase leaf transpiration of about 5-10%. Leaves that receive sufficient light to achieve maximum photosynthetic rates ($800\text{--}1,000\ \mu\text{mol m}^{-2}\text{ s}^{-1}$ PPFD), although transpiring more, also have higher water use efficiencies (about 10 fold) than shaded leaves (receiving <20% of incoming radiation). For example, a volume of 1,000 litres of water transpired from sunlit leaves yields about 3 kg of fixed carbon, whereas shaded leaves scarcely produce 0.3 kg carbon with the same amount of water. This amount is insufficient even to meet night-time respiration carbon use. Thus, the portion of the canopy receiving less than 20% of available radiation, represents not a source of photosynthates for the orchard but a sink, and with significant water usage that can reach about 30% of total consumption in some training systems (e.g. pergola for kiwifruit and table grapevines) (Xiloyannis et al., 1999).

Therefore, in choosing the training system one should remember that water use efficiency increases with an increasing ratio of exposed/shaded leaves. Increased efficiency is possible through reducing the tree size (Photo 2) adopting training systems that maximise the proportion of fully sunlit leaves, minimising shading, and carrying out summer pruning (Fig. 2).



Photo 2. High density apple plantation. The reduced tree size maximises the exposure to irradiance (Photo by Vivai Mazzoni).

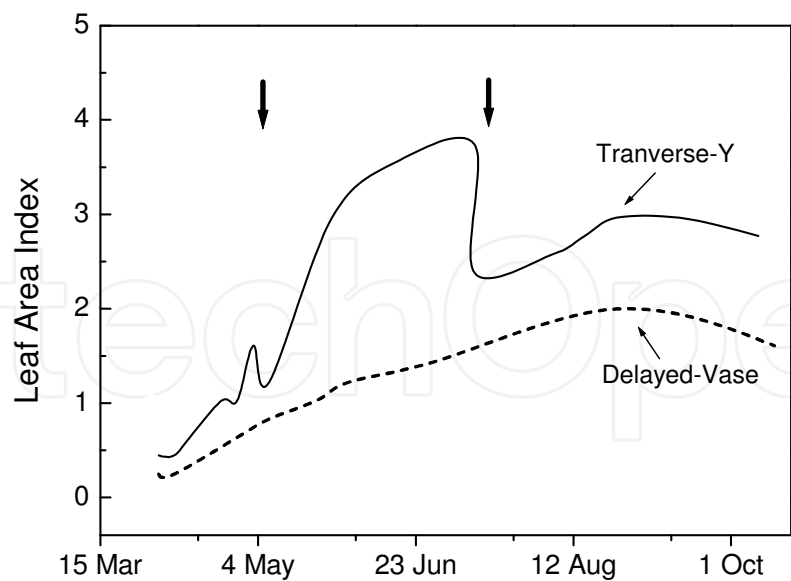


Fig. 2. Leaf Area Index (LAI, m² leaves/m² soil) variations during the third year after planting in peach trees (cv ‘Springcrest’) trained to transverse Y (continuous line) (1,100 plants ha⁻¹) and Delayed-vase (dotted line) (416 plants ha⁻¹). Arrows indicate summer pruning (Transverse-Y orchard), performed twice during spring-summer, reducing the LAI and water use, and improving yield quality, water use efficiency and cropping potential for the following year. (Redrawn from Nuzzo et al., 2003).

As for canopy management of bearing orchards, one should certainly be careful to carry out summer pruning, whereas for newly established orchards, a choice of training system should be made with canopy water use efficiency in mind (Fig. 3).

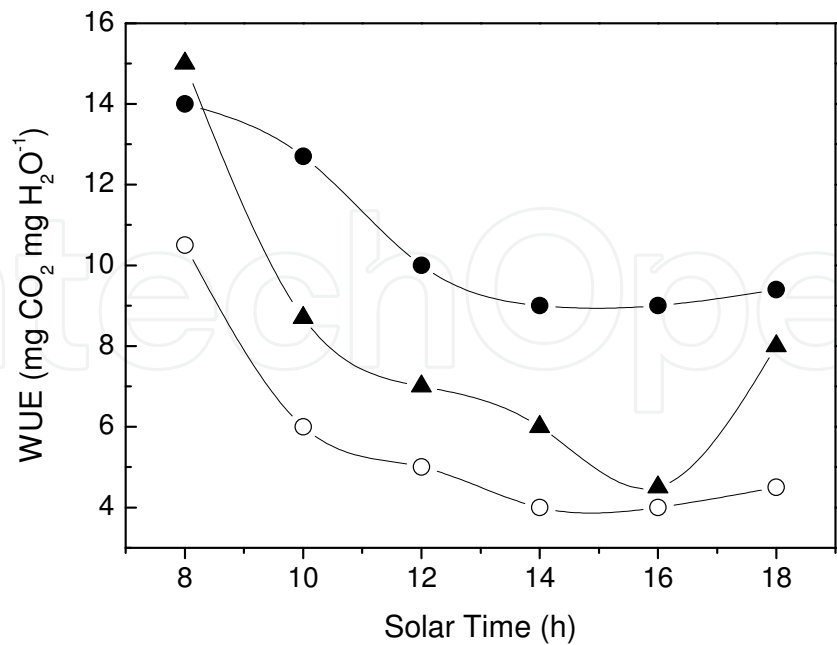


Fig. 3. Daily variation in Water Use Efficiency (WUE) (mg CO₂ mg H₂O⁻¹) in a whole peach canopy trained to Transverse-Y (●), Delayed-vase (▲) and Palmette (○). (Adapted from Giuliani et al. 1999).

It is recommended that all wood that is not necessary for the subsequent year's production should be removed through summer pruning. In this way, the leaf area and water consumption are reduced, water use efficiency increases, the exposure of fruits to light is increased, and the growth and quality of the remaining one-year old fruiting shoots to support the next season's fruit bearing is optimised.

In areas with high evaporative demand and limited water, fruit thinning should aim at leaving fewer fruits per m² of leaves (-20% approximately), especially in early ripening cultivars and orchards established on shallow and/or light soils.

It is also worthwhile to carry out "winter" pruning early (e.g. in August) for orchards where the harvest has already been done by that time. In other cases, pruning should be carried out as soon as possible after harvest. Shade nets (30-40% shading) can considerably reduce water usage and improve the photosynthetic activity of exposed leaves.

3. Regulated deficit irrigation

For sound management of water resources aimed at responding to the increasingly frequent "droughts" in southern Italian orchards, specialised water saving techniques, like Regulated Deficit Irrigation (RDI), are to be recommended. They allow considerable reductions in irrigation volumes and also ensure good yield and good quality. The RDI is a method by which irrigation volumes to fruit crops can be reduced (Behboudian and Mills, 1997) by only partially replenishing the water used by crop evapotranspiration. Replenishment is carried out up to pre-established threshold values of water deficit in the soil and in the plant. The applicability of RDI has been extensively studied (Shackel et al., 1997; McCutchan and Shackel, 1992; Naor, 2000), but further effort is needed to bring this technique into more common usage. Recently, the possibility of reducing irrigation volumes by up to 50% has been evaluated in Southern Italy with early-ripening peach cultivars during the post-harvest period thereby achieving a water saving of about 1,800 m³ha⁻¹ per year (3-year average), a good yield and a greater accumulation of carbohydrates in the roots and the wood, as a result of reduced vegetative growth (Fig. 4 and 5) (Dichio et al., 2007).

Nowadays, it has been pointed out that a prolonged and often severe water deficit imposed through RDI could decrease yield in fruit trees when deficits are applied over successive seasons (Pérez-Pastor et al., 2009). Hence, more information is needed to accurately and safely manage RDI in the field and for successive growing seasons. Irrigation and the RDI in particular should be considered within a wider management system including other agronomic practices and land resources.

Recently, at a peach orchard in a recent 6-year comparative study (Dichio et al., 2011) of conventional and sustainable orchard management practices (the conventional practices are representative of usual grower practice in the region while the sustainable practices aim to save water) it has been shown that RDI can maximize water productivity without impairing long-term yield. Briefly, conventional orchard management (C) (continuous soil tillage, mineral fertilizers, irrigation scheduling decisions exclusively based on grower experience) adopted by local farmers, was compared with sustainable orchard practices (S) (no tillage, cover crop, organic fertilizer, summer pruning and sustainable irrigation). Drip-irrigation (8 L h⁻¹ with 2 drippers per plant) in both S and C treatments was scheduled in the C plot every approx. 10 days starting in April, while in the S plot, irrigation requirements (I) were

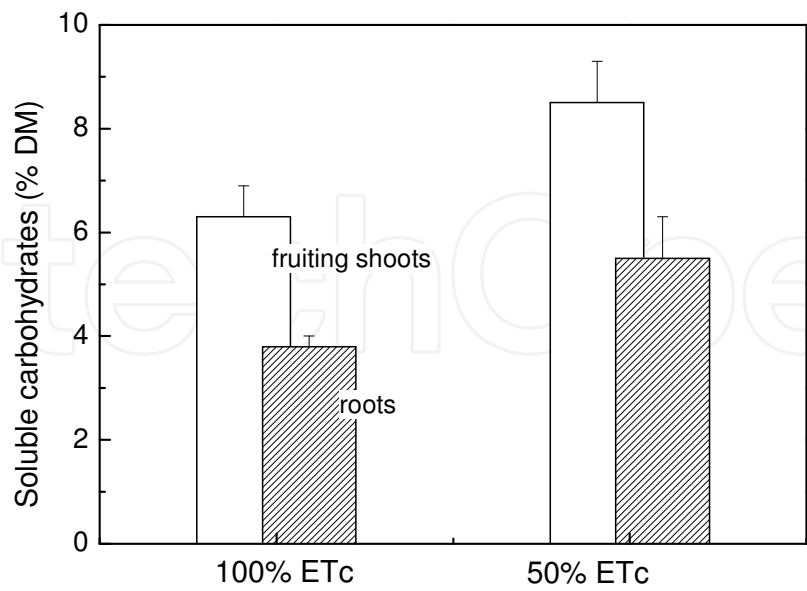


Fig. 4. Concentration of reducing soluble carbohydrates (% DM, \pm SE) in roots (grey column) and fruiting shoots (white column) in a well-watered peach tree (100% ETc) and subjected to Regulated Deficit Irrigation (RDI) (50% ETc). Measurements were made in November at the end of the second year of RDI application. (Adapted from Dichio et al. 2007).

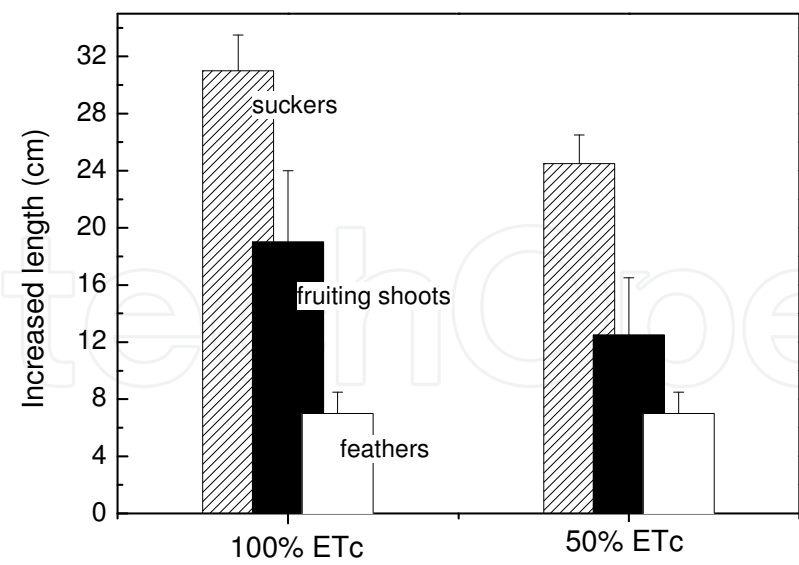


Fig. 5. Increased length (cm \pm SE) of suckers (grey column), feathers (white column) and fruiting shoots (black column) observed in peach between late June (beginning of regulated deficit irrigation) and early October in well-watered trees (100% ETc) and in trees subjected to Regulated Deficit Irrigation (RDI) (50% ETc) (Adapted from Dichio et al. 2007).

calculated by the equation $I = ET_0 \times K_c / 0.9-1$, assuming 90% distribution efficiency. In the S plot, crop coefficients (K_c) during the pre-harvest stage in April, May and June were 0.6, 0.8 and 1.2, respectively as resulting from adjustment of previous own experiments carried out in the area (Dichio et al., 2007). During the postharvest stage, from July to September, RDI was applied by reducing the irrigation to approximately 50 % of plant requirement (Dichio et al., 2007). The summer pruning was performed on mid-June and on end of July. The S plot received $15 \text{ t ha}^{-1} \text{ yr}^{-1}$ of compost (24.8 % moisture content) containing approximately 35% carbon on a dry matter basis. Fertilisation was based on concentrations (% dry matter, DM) of various plant tissues, whole plant DM per plant and on availability in the soil of the various essential plant nutrients. In particular, the concentration of soil nitrates was monitored in the top 40 cm of soil and N distributed via fertigation each time the concentration fell below 20 ppm. Plant water status was monitored in the S plot on 5 trees per plot ($\times 5$ leaves a plant) by measurement of midday stem water potential at weekly intervals following the procedure reported by Dichio et al. (2007).

Large differences in seasonal irrigation volumes were seen for the two irrigation methods (Fig. 6). Average annual irrigation volume applied in the S plot was approximately 23 % lower than in the C plot, a saving of $1450 \text{ m}^3 \text{ ha}^{-1}$ gained during the post-harvest stage. Despite the lower irrigation volume, after six year the cumulative yield was substantially higher (30 %) in the S than in C plots reaching 140 and 115 t ha^{-1} .

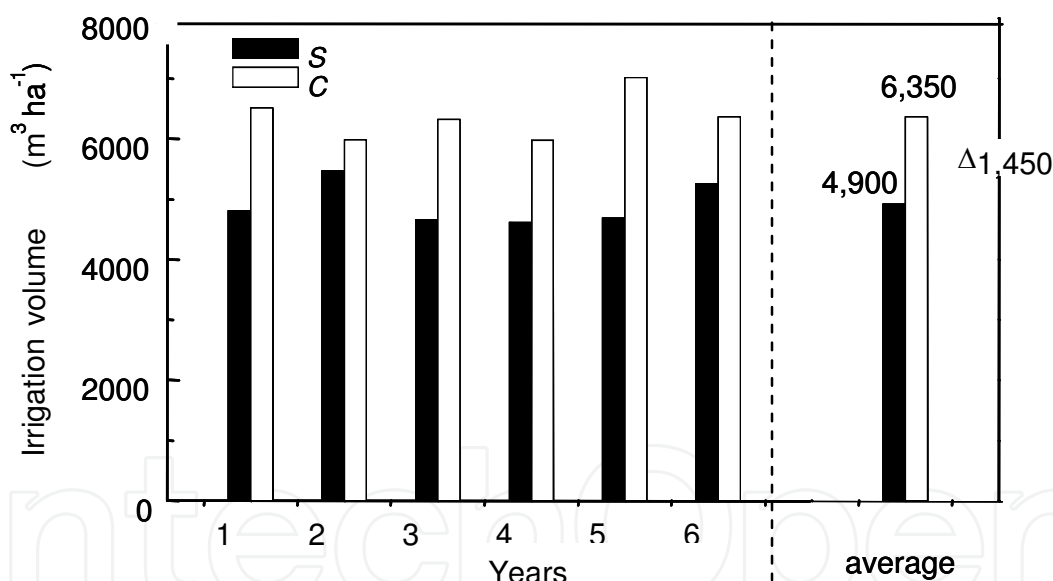


Fig. 6. Annual irrigation volumes ($\text{m}^3 \text{ ha}^{-1}$) and 2004–2009 mean volume applied in the sustainable (S) and conventional (C) plots. Note, on average, $1450 \text{ m}^3 \text{ ha}^{-1}$ were saved on the S plot. (Redrawn from Dichio et al., 2011).

The regulation of vigor due to moderate water stress possibly reduced the competition for assimilates between reserve tissues and the vegetative apexes resulting in better light interception and lower water use (Boland et al., 2000). In the S plot, summer pruning was performed twice a year reducing the leaf area in all by approximately $10 \text{ m}^2 \text{ plant}^{-1}$. Considering a daily mean leaf transpiration rate of $3 \text{ mmol m}^{-2} \text{ s}^{-1}$ (Dichio et al., 2007), the summer pruning in turn had contributed to reduce the transpired water by about $800 \text{ m}^3 \text{ ha}^{-1}$ over approx. 40 days from August.

Irrigation management in that study integrated other sustainable practices concerned with soil rehabilitation like increasing the soil carbon level. On average, in the *S* plot, 21.1 t ha⁻¹ yr⁻¹ carbon was returned to soil, compared to 6.1 t ha⁻¹ yr⁻¹ in the *C* plot. Increased soil carbon is a prerequisite for soil fertility remediation, mineral element supply and better soil water holding capacity (Montanaro et al., 2010). Therefore, higher carbon input in the *S* plot may have increased the retention of winter rainfall in the soil resulting in a likely higher soil available water compare to the *C* plot.

Recently, emphasis has been placed on the concept of water productivity (WP), defined either as the yield or net income per unit of evapotranspiration (Fereres and Soriano, 2007). We evaluated the effect of orchard management practices on economic water productivity (E_{WP}), defined as the economic value of the marketable yield per unit of irrigation applied. Marketable yield value depends on fruit quality and in particular on fruit size distribution, that in turn may affect E_{WP} as a result of applying sustainable orchard practices. E_{WP} index therefore seems to be an appropriate method of assessing the impact of irrigation technique on productivity. We believe that a water saving *per-se* does not necessarily result in increased yield, and that higher yield sometimes leads to reduced fruit size. On a six-year average, based on the annual fruit price and marketable yield, the E_{WP} was 2.11 and 1.34 € m⁻³ for the *S* and *C* plots, respectively. This was evidently related to the increased yield and reduced irrigation in the *S* plot (Fig. 6). Based on the above mentioned beneficial effect of the carbon on soil water holding capacity, the high carbon input in *S* plot possibly contributed to increased E_{WP} via reducing the irrigation volumes.

This paragraph demonstrated that integrating RDI into a wider sustainable fruit tree orchard management regime with increased soil carbon inputs, resulted in high and stable yields and a high E_{WP} over the medium term (six years). This information should encourage water-management policy makers to promote strategies that promote industry wide adoption of RDI in order to reduce agricultural water use. For example, offering adequate extension service and, at the same time, introducing volumetric charges for irrigation water and economic penalties for excessive water consumption will almost certainly lead to a higher E_{WP} . However, using price policies to promote the economic productivity of water requires significant government intervention in order to ensure equity of access to public water. We believe E_{WP} should be a useful tool to evaluate the impact of alternative water management technologies on farm- and regional-scale economies.

4. Management of the irrigation method

4.1 Evapotranspiration and irrigation requirements

Evapotranspiration is the most important term in water balance for irrigation. When plant transpiration and other evapotranspiration components cannot be calculated separately, the simplest and most widely adopted approach is the “two-step method”. As a first step, reference evapotranspiration (ET_0) is estimated. As a second step, crop coefficient (K_c) is introduced to account for the evapotranspiration aspects related to crop growth stage.

This estimation results in $ET_C = ET_0 \times K_c$ and expresses the water use of a crop grown under standard conditions.

More specifically, K_c includes average soil evaporation but doesn't include cover crop transpiration, unless expressly specified.

This approach is often criticized but still remains the most commonly used compared to any other method to calculate water requirements of any crop, including tree crops.

In the FAO Irrigation and Drainage Paper 24 (Doorenbos and Pruitt, 1977) and in the subsequent revised FAO Paper 56 (Allen et al., 1998), the yearly growing cycle of orchard (deciduous fruit trees) is divided into four growth stages: initial, crop development, mid-season and late season. The length of the initial period is relatively short. Subsequently, leaf area grows quite rapidly and reaches its highest values between the end of June and mid-July. Such values keep throughout October, leaf senescence starts in November and then finishes in December.

To draw the seasonal K_c curve, three K_c values are enough, namely: the initial stage crop coefficient ($K_{c\text{ ini}}$), the mid-season crop coefficient ($K_{c\text{ mid}}$) and the late-season crop coefficient ($K_{c\text{ end}}$). The seasonal K_c curve can be obtained graphically by joining all the starting and ending points of the concerned growth stages or numerically by assuming that K_c varies linearly over the stages. For evergreen crops, the crop coefficient doesn't vary greatly during the season since variations in leaf area during the year are negligible (full bearing mature orchards).

The crop coefficients of the major fruit species are reported in the FAO Irrigation and Drainage Paper 56. They combine the effect of transpiration and soil evaporation for mature orchards (that have achieved full development), thereby some adjustment might be required to adapt them to actual field conditions (e.g. for young plantations).

Of course, experimentally determined crop coefficients for a given crop, specific conditions and areas are to be preferred whenever available.

4.2 Importance of the soil volume explored by roots

To optimize the use of water in fruit farming, the size and characteristics of the soil volume explored by roots have to be considered.

Soil exploration by roots mostly depends on orchard age, planting density, rootstock and soil type. A vigorous rootstock generally explores a greater soil volume than the one reducing plant vigour (Fig. 7). In irrigation, a different soil volume explored by roots also results in a different amount of water globally available to the plant. This is particularly important for calculating the amount of rainfall water stored and potentially usable by the plant.

For irrigation management purposes, and especially when localised irrigation methods are used, the total soil volume explored by roots can be assumed as consisting of two components (Fig. 8):

- a. *Volume 1* corresponding to the soil volume wetted by irrigation where roots are also present
- b. *Volume 2* corresponding to the soil volume explored by roots and not wetted by irrigation.

Comparing such soil volumes to containers, it is extremely important to know the dimensions of the container and the hydrological characteristics of the soil. In localized irrigation, container 1 represents the portion of soil that will receive the irrigation volume

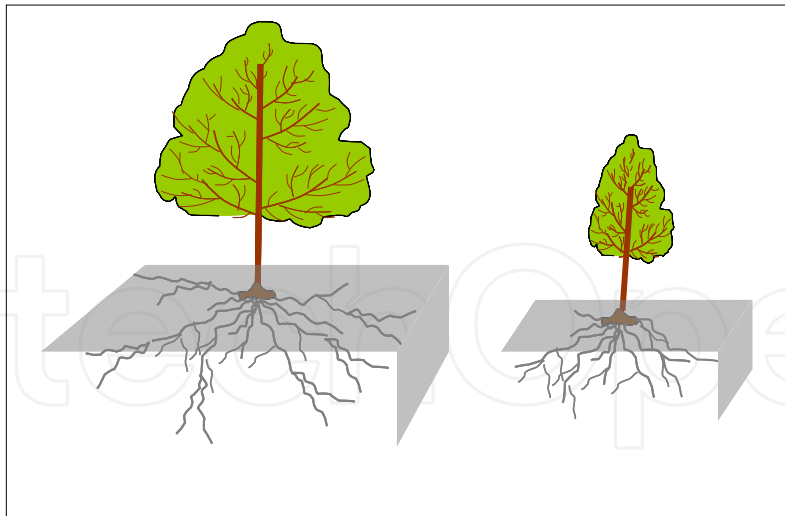


Fig. 7. Schematic representation of the effect of rootstock vigour on tree size and soil volume explored by roots. On left, the highly vigorous rootstock.

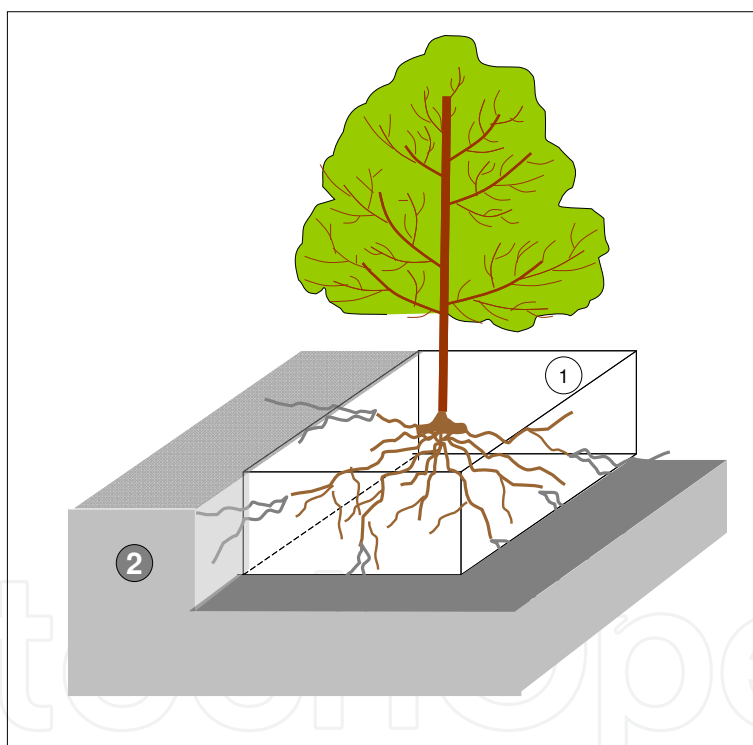


Fig. 8. Tree's root system reaches some meters from trunk in mature trees. However, the soil volume wetted by localised irrigation (transparent parallelepiped, container n.1) is explored only by part of total root system (brown roots), while the others roots (grey) explore a not-irrigated soil (filled parallelepiped, container n. 2).

as determined by any selected estimation method. The determination of the hydrological characteristics and water holding capacity (i.e. available water, *AW*, and the readily available water *RAW*) is crucial to define the amount of water that can be applied and held in the reference container. For instance, the application of irrigation volumes greater than the amount of water the soil volume in container 1 can hold might cause percolation and/or

water-logging with subsequent leaching of nutrients and asphyxia processes. Moreover, considering that most of absorbing roots develop in this container, its characterization is important for correct fertigation management.

Its dimension varies depending on the adopted irrigation method, the physical characteristics of the soil and the water volumes applied.

Under localized irrigation, container 2 receives no irrigation water but only rainfall water. The rainfall water stored in this container represents a significant amount of soil water storage that needs to be considered and managed during the irrigation season. For instance, it could be usefully kept (by starting the irrigation season early) to meet peak water requirements or in cases of sudden interruption in water supply, whereas regulated deficit irrigation could be applied to fully use soil moisture storage at stages in which the crop is less sensitive to water deficit.

Complete depletion of the two containers at the end of the irrigation season allows storing more rainfall water in winter season.

4.3 Irrigation scheduling using a water balance

Once ET_C is estimated, the orchard irrigation water requirements can be assessed through a daily water balance based on the following equation: (adeguare le abbreviazioni in inglese)

$$(IrrVol \times 10) = (ET_C + D + R - Pe - G - SW) / Deff \quad (m^3/ha)$$

Where:

IrrVol = Irrigation volume to replenish the soil moisture to the desired level ($m^3 ha^{-1}$)

Deff = Distribution efficiency of the irrigation system (0.3 ÷ 0.95 for full bearing orchards)

10 = Conversion coefficient from mm to m^3/ha

ET_C = Crop evapotranspiration (mm)

D = Drainage and deep percolation losses (mm)

R = Surface runoff losses (mm)

Pe = Effective precipitation (mm)

G = groundwater contribution (mm)

SW = soil water reservoir (mm)

This equation can be calculated for long periods (several years, a year, a season) or short periods (months, ten-day periods or days). Accuracy depends both on the possibility of measuring each single term of the equation and the extent of the areas it is intended to be applied to. Water balance is adopted for experimental purposes to measure the total amount of water used by the orchard.

If irrigation volumes are correctly managed and groundwater is deep, the terms D, R, G are negligible and the equation (1) can thus be simplified as:

$$IrrVol (m^3 ha^{-1}) = [(ET_C - Pe) / Deff] \times 10$$

In view of the small number of variables to be measured, the simplified water balance can also be applied for irrigation scheduling.

Distribution efficiency expresses the percentage ratio of the amount of water held in the soil and potentially available to the plant to the amount of water applied. Distribution efficiency largely depends on the irrigation method as well as on the farmers' skill. Determining it properly is thus important for correct irrigation.

When managing localized irrigation methods, the simplified water balance has to be referred to the volume of soil wetted by irrigation (container 1) considering that under optimal management conditions almost all the water used by the plant is taken up from such soil volume where most absorbing roots are present. The irrigation volume has to replenish container 1, and it is thus necessary to quantify the amount of water in the container (AW and RAW) and define the irrigation amount and timing.

Water balance is calculated when the soil is at field capacity. In order to preserve the water stored in the soil volume not wetted by irrigation (container 2), irrigation events have necessarily to start early, namely, when water evapotranspiration losses exceed inputs by precipitation. If the objective of irrigation is to refill the amount of water lost by evapotranspiration from container 1, by computing water balance on daily basis the amount of water to be applied is determined. The daily irrigation volumes can be cumulated and subsequently applied by irrigation whenever the readily available water of Container 1 is depleted. Based on this criterion, the irrigation volume is thus equal to RAW of container 1.

By this method, the irrigation frequency is also automatically defined and is equal to the time interval needed for the plants to extract the readily available water from the soil. For localized irrigation methods, this time interval (irrigation frequency) can range from 1 to 6 days depending on the environmental variables affecting the orchard water use. Obviously, irrigation intervals are necessarily shorter (1-2 days) in hotter months.

4.4 Irrigation scheduling using soil moisture monitoring

Currently, an increasingly applied method to schedule irrigation is soil moisture monitoring. Having direct measurements of the amounts of water available in the soil is undoubtedly a useful tool for decision support to irrigation management.

The tools for measuring soil water status and soil water potentials are available since long, but electronics has now made such measurements simpler and inexpensive.

Some of the traditional soil-based sensors are tensiometers, which measure soil water tension, and gypsum blocks (e.g. Bouyoucos blocks), which measure electrical resistance. They both make use of a porous medium (the ceramic tip or the gypsum blocks, respectively). When the porous medium is placed in contact with the soil, its moisture content tends to equal the moisture content of the surrounding soil.

Advancement in technology has led to the use of electrical properties to read soil moisture and, consequently, sensors have been developed which estimate soil moisture through the electrical resistance created between two block-embedded electrodes spaced out at a known distance.

If the sensors used in these methods are adequately calibrated to the soil type, they can give accurate measurements and be adopted even in salt-affected soils.

One major advantage of these new sensors is that they provide continuous measurement of soil moisture, and allows automating the readings and data processing through data loggers that can be connected to the network through automated irrigation management systems.

In general, the adopted approach of this method is based on defining a threshold soil water content beyond which irrigation has to be applied to re-establish optimal moisture values. Since it gives continuous soil moisture measurements, irrigation scheduling can be based on the soil water content pattern rather than on an absolute threshold value.

The decision on the right position of the sensors in the soil and the determination of the number of sensors to be used are critical in the application of this method.

For this purpose, it is necessary to know the characteristics of containers 1 and 2. In particular, in the case of localized irrigation, monitoring the water content of the soil volume of container 1 (Fig. 9) is crucial. To get information also on soil water storage depletion, it is recommended to install two sensors at the same position but at different depths: the former at 25-30 cm depth to monitor the upper layer of container 1 and the latter at 60 -70 cm depth to monitor the water content in the portion of the underlying container 2.

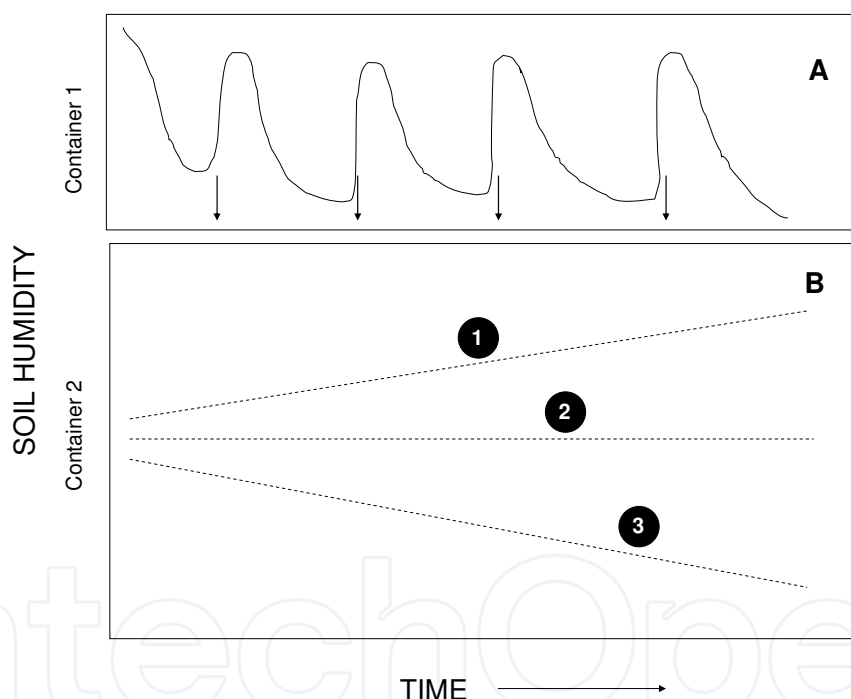


Fig. 9. Schematic representation of the within-irrigation changes of soil water content in container 1 (A) and 2 (B), the arrow represents the water application. When the irrigation volume supplied to the container 1 is higher than evapotranspiration, the water content in the deeper layer (container 2) increases (see line 1); by contrast when the irrigation water is lower, the plant takes up water from deeper layers and, consequently, soil water content in container 2 reduces (line 3). The soil humidity in the container 2 is roughly stable (line 2) in the case irrigation water is adequately supplied to the container 1.

Therefore, in order to preserve the amount of water in deep layers, irrigation can be applied whenever the amount of water equal to *RAW* is depleted in the first container. If, during irrigation, the amount of applied water is lower than evapotranspiration, the plant takes up

water from deeper layers and, consequently, soil water content in container 2 reduces. On the contrary, if excess water is applied, water content in deep layers over time continuously increases (Fig. 9). Under correct irrigation management, water content values in deep soil layers will vary around the same value. Therefore, monitoring soil moisture in the deeper layer provides additional information that usefully contributes to correct irrigation management.

4.5 Irrigation scheduling using plant water status monitoring

Direct monitoring of plant water status is a valid indicator for correct irrigation management. In the literature, many studies about methods to measure plant water status and its relationship with the plant physiological processes are available. Unfortunately, fewer efforts have been made to define protocols for applying these measurements to irrigation scheduling. The major difficulty in the use of plant-related indicators is the dynamic nature of plant water status that is influenced by the soil water status and the surrounding environment. For instance, plant water status changes during the day and over the season thus making it difficult to define univocal threshold values to be applied in irrigation.

The most widely applied parameters to characterize plant water status are water potential in plant tissues and canopy temperature.

5. Irrigation and environmental impact

The benefits of irrigation on yield and fruit quality are well known, but mismanagement of irrigation can result in a waste of the water and also in strong negative impacts on the environment. Paradoxically, irrigation is one triggering element in desertification, in particular in those environments having high evaporative demand and scarce rainfall (Fig. 10). Matters are made worse still if low-quality irrigation water is used. Out of 145 million irrigated hectares worldwide, about 2 million hectares have been irreversibly degraded due to salinisation and about 41 million hectares now show signs of reversible forms of degradation (Katyal and Vlek, 2000). In Southern Italy, irrigation plus intensive cultivation techniques (continuous tillage, almost exclusive use of mineral rather than organic fertilisers, etc.) and climatic conditions that favour mineralization, have caused structural deterioration of the soils mainly due to impoverishment in organic matter. In fact, in the soils of Southern Italy, the organic matter content has reached levels of ~1%. This low level corresponds to the threshold that classified these soils as “degraded” (an early stage of desertification due to a lack of biologically active organic matter).

In arid and semi-arid areas, like those in the Mediterranean basin, good quality water is becoming increasingly scarce and, consequently, “priority” is being given to the provision of drinking water to municipal sectors. So, because the availability of good-quality water for agriculture is dwindling, the usage by agriculture of low quality water is now increasing. In order to identify an best irrigation technique, knowledge of this water’s chemical composition is required along with an assessment of various associated factors such as climate, soil characteristics, drainage conditions, the irrigation methods used etc.

The risk of soil degradation is due to the combined effects of the salt content in irrigation water, the high seasonal irrigation volumes applied due to the high annual water deficit (Fig. 10). This calls for implementation of a monitoring plan of soil quality that should make

a distinction, within the orchard, between the wetted areas (i.e. below the drippers with localized irrigation), and those receiving only rainfall water.

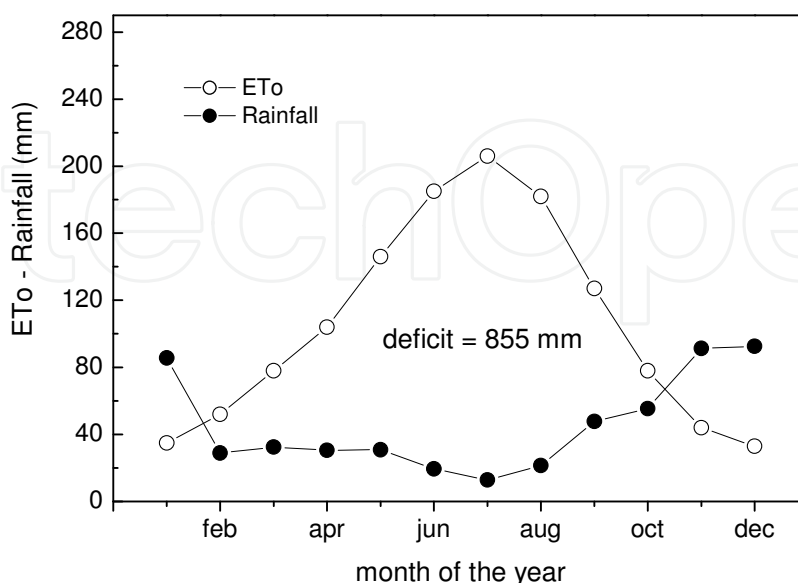


Fig. 10. Monthly precipitation (mm) and potential evapotranspiration (ET₀) (mm) in Mediterranean area (N 40° 23' E 16° 45'). Data are mean of 17-year period. (Redrawn from Montanaro et al., 2010).

Knowing the chemical composition of irrigation water is also absolutely necessary to establish an appropriate fertilisation schedule, both in regards to the choice of fertiliser and also to its rate of application. It is quite a common practice for farmers to apply fertilisers although the amounts supplied through irrigation are often higher than those used by the orchard.

The high amounts of water used in agriculture (60-70% of total water consumption) have a strong environmental impact also in view of the fact that water withdrawals from surface and/or subsurface water bodies often modify natural hydrological balances. In particular, continuous and unrestrained withdrawal of subsurface waters in amounts greater than the recharge rate, often causes groundwater drawdown with subsequent increases in pumping costs, deterioration in water quality and sea water intrusion in coastal areas. Moreover, mismanagement of irrigation may be conducive to a degradation of the physio-chemical and biological properties of the soil (a more massive structure, alteration of pore morphology and size, greater migration of clay particles from the upper ploughed horizon downward). Irrigation may also pollute surface and subsurface waters through the transport, by surface runoff or deep percolation, of mineral elements (nitrates in particular), pesticides and herbicides that have been applied to the soil surface.

Sound management (frequent or daily irrigation intervals and with low volumes to meet orchard water requirements) and the use of localised application emitters (drip and subsurface irrigation) all help to reduce the pollution of surface and subsurface bodies of water.

Moreover, zero or low tillage, fertigation and practices to increase soil organic matter content, are all tools that can help to mitigate the environmental impact of irrigation.

Fertigation in particular, plays a decisive role in controlling denitrification losses. In fact, micro-fertigation on a daily basis in summer ensures regular water and mineral supply to the plant with positive effects on yield and fruit quality (regular transport into fruits of mineral elements, especially those scarcely mobile, through the phloem such as calcium). It also reduces fluctuations towards extreme soil moisture values (high and low) thus reducing denitrification and preventing the removal by leaching from the root zone of soluble forms of nitrogen. In calcareous soils, good irrigation management allows the control of iron-induced chlorosis by avoiding water excesses and hence hydrolysis of CaCO_3 to HCO_3^- .

Finally, micro irrigation plays a role in conserving soil organic matter as, due to the smaller wetted soil surface reducing the mineralization process and the CO_2 soil emissions by soil respiration.

6. Conclusions

At present, limited water resources hamper further expansion of the more profitable crops that also have social value in increased opportunities for local employment because of their greater requirements for management intervention.

A number of possible key-factors to save water at farm level have been presented. It is suggested that in fruit tree orchards increased water use efficiency may be achieved not only through a sound management of the irrigation method but also by a correct choice and management of the canopy. The last 4-5 decades soils in south Italy lost about 30% of their soil water holding capacity reducing the possibility to store rainfall water due to the decreased of organic matter and soil hydrological characteristics.

Through sustainable orchard management we should be able to improve soil fertility and increase the storage of water in the soil volume explored by root system during the rainfall season (especially in sloppy areas). It has been emphasised that mismanagement of irrigation strongly alters soil characteristics. Hence we conclude that appropriate design and management of irrigation methods can at the same time save water and mitigate harm to the environment. All are essential tools to deal with Mediterranean field conditions.

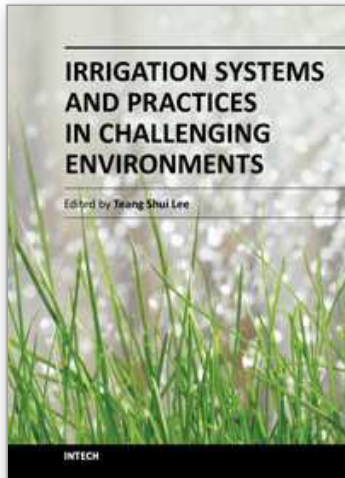
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The book *Irrigation Systems and Practices in Challenging Environments* is divided into two interesting sections, with the first section titled *Agricultural Water Productivity in Stressed Environments*, which consists of nine chapters technically crafted by experts in their own right in their fields of expertise. Topics range from effects of irrigation on the physiology of plants, deficit irrigation practices and the genetic manipulation, to creating drought tolerant variety and a host of interesting topics to cater for the those interested in the plant water soil atmosphere relationships and agronomic practices relevant in many challenging environments, more so with the onslaught of global warming, climate change and the accompanying agro-meteorological impacts. The second section, with eight chapters, deals with systems of irrigation practices around the world, covering different climate zones apart from showing casing practices for sustainable irrigation practices and more efficient ways of conveying irrigation waters - the life blood of agriculture, undoubtedly the most important sector in the world.

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