Irrigation water saving strategies in Citrus orchards: analysis of the combined effects of timing and severity of soil water deficit

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Abstract

The knowledge of the crop response to soil water deficit is essential to predict the actual crop water requirements under limited soil water conditions. The mathematical schematization of the crop response under RDI can allow identifying the exact irrigation timing. The threshold of soil water status below which crop transpiration decreases represents a key parameter for the water stress functions. The main objective of this paper was to investigate the effects of several RDI treatments, applied during the three stages of fruit growth, on soil-plant-water relations of drip-irrigated mandarin trees. Experiments were carried out in seven irrigation treatments: a control, irrigated at 125% of potential evapotranspiration measured in weighting lysimeters, ET_{lys}, during the whole year, and six RDI treatments in which 25% and 50% of ET_{lys} were applied during each of the three stages of fruit growth.

The critical threshold of soil water status expressed in terms of soil water depletion below which predawn (PLWP) and midday (MSWP) leaf water potential is affected by decreasing soil water content, were identified. The dependency of crop water status from the climate forcing, occurring under soil water contents higher than the critical threshold was also demonstrated. Moreover, a strong relationship between water stress integral (S_{MSWP}) evaluated during the three stages of fruit growth, and the corresponding amount of water applied (irrigation and precipitation) was observed after normalizing the variables. The robust relationship between these two variables (R^2 = 0.83) confirmed that the water stress integral represents a good indicator of the plant-water relationship and allows the prediction of the total irrigation depth to be applied to achieve a desired stress level during the fruit growth. Moreover, this relationship depends on the irrigation schedule adopted to regulate the deficit, which includes the irrigation variables, such as irrigation dose and its variability.

Keywords: deficit irrigation, depletion factor, irrigation dose, water stress integral

1. Introduction

In the Mediterranean basin, approximately 30% of the cultivated area is under irrigation, which represents the biggest consumer of freshwater from the region (Harmanny and Malek, 2019). Specifically, the irrigated land in Spain accounts for 80% of global water consumption (MAPA, 2019). Citrus spp. is the crop most cultivated fruit tree in Spain with a surface extended 307.560 ha in 2019, of which 93% is irrigated, represents the crop with the highest irrigated area (MAPA, 2019). Moreover, Spain is one of the main producing countries worldwide of citrus spp., with an average annual production of around 6.3 Mt in 2019; more than a third of this production comes from the mandarin group, being 'Clementina de Nules' one of the most common cultivars (MAPA, 2019). Thus, it is important to determinate the citrus water requirements by designing simple, practical and precise methods to optimize irrigation and to adopt precise irrigation scheduling and management techniques (Gasque et al., 2016).

Water-saving strategies, such as deficit irrigation (DI), have been studied as a promising alternative for growers of citrus spp., mainly in areas characterized by water shortcomings and increasing frequency of drought phenomena (Ferreres and Soriano, 2007; Carr, 2012; Rocamora et al., 2013). Under regulated deficit irrigation, water is generally supplied at levels below full crop transpiration during specific periods of the fruit growing season. Operating in this way, it is possible to balance the plant vigour with the potential production by limiting the irrigation volumes (Costa et al., 2007; Rallo et al., 2017).

Therefore, deficit irrigation has been considered as a strategy to save water and to increase water productivity. Besides, this strategy may have positive impacts on fruit quality and composition parameters that contrast the possible side effects on fruit size and weight due to water stress (Ballester et al., 2011), with the consequent upgrade of yield values (García-Tejero et al., 2010; Carr, 2012; Consoli et al., 2014).

Nonetheless, the application of DI requires monitoring in real-time the crop water status and soil water content to control the level of water stress reached by the crop, and hence, to prevent crop damage and yield losses (Rallo et al., 2017). In this direction, plant-based indicators of water status have been widely used, namely predawn or midday stem water potential (Jones et al., 2004). These indicators are discrete measurements that represent a snapshot in time of the crop water status and their measurement require expert knowledge. Moreover, plant-based indicators integrate the effects of soil water availability and the atmospheric evaporative demand, thus, it could be complicated to establish irrigation thresholds only considering measurements of tree water status (Ortuño et al., 2006; Ortuño et al., 2009 a,b). To complement them another index, the water-stress integral calculated as the summation of pre-dawn or midday leaf water potential measurements over a chosen period, summarizes the cumulative stress reached by the crop throughout a certain period (Myers, 1988).

Besides that, soil moisture sensors such as neutron probes, frequency domain reflectometry (FDR or capacitance probe), time-domain reflectometry (TDR) and fiber-optic sensors, provide feedback on the soil moisture and can be acquired automatically (Fares and Alva 2000; Evett et al 2008; Gil-Rodríguez et al., 2013). For these reasons, soil water contents have been frequently used in precise irrigation scheduling and as a tool for efficient irrigation (Evett et al 2008; Vera et al., 2019). However, diverse studies have highlighted the spatial heterogeneity of soil water content and the inaccuracies derived on scheduling irrigation only based on soil moisture measurements (Intrigiolo et al., 2004; Agüero Alcaras et al., 2016; Rallo et al., 2017; Dominguez-Nuñez et al., 2020). The heterogeneous patterns of soil moisture depend on many factors such as irrigation depth, quantity and frequency of irrigation, the type of water distribution system and the relative design plan (Grant et al., 2009; Dominguez et al., 2020). Specifically, Guswa et al. (2004) highlighted the impact that the spatial distribution of soil moisture in the root volume has on the total root water uptake. The crop water stress response to soil water status is, in fact, not linear and not uniquely associated, but rather depend on a large extent on the degree of wetting uniformity of the root zone.

Therefore, besides the agronomic related results derived from the application of water-saving strategies, is essential to study the hydraulic and hydrologic parameters that could affect the crop functioning and performance. However, most studies on the effects of water-saving strategies on the crop system are focused on agronomic methods and less emphasis has been placed on agro-hydrological approaches.

In this sense, further studying of the ecophysiological relationships according to different levels of water stress imposed could provide knowledge on the crop water dynamics and thus, on adequate irrigation management techniques (Ginestar and Castel, 1996; Agüero Alcaras et al., 2016; Rallo et al., 2017). Understanding these relationships could help to identify the maximum allowable depletion (MAD), which represents a basic knowledge for irrigation scheduling (Allen et al., 1998). The depletion coefficient, *p*, generally used to identify the MAD provides information about the crop resistance to water stress; for citrus spp., table 22 of FAO56 paper indicates to assume a value of p=0.50 (Allen et al., 1998). However, the value of this coefficient could vary with the different citrus spp., canopy architecture, plant density, fraction of ground cover and training system. Thus, local calibration of the p coefficient could represent more accurately the crop response to water stress.

In this study, a robust database of soil and crop data collected in previous research conducted by González-Altozano and Castel (1999) was used to i) study the eco-physiological response of a citrus crop (*Citrus clementina,* Hort *ex* Tan.) to different timing and magnitude of deficit irrigation; ii) identify the threshold of soil water status to implement water-saving strategies in citrus orchards; iii) assess the effect of irrigation management variables on the cumulated water stress and crop yield response.

2. Materials and Methods

2.1 Characteristics of the experimental field

Field data were collected in a citrus orchard during two consecutive years, 1995 (from June to December) and 1996 (from January to December) in the experimental farm of "Instituto Valenciano de Investigaciones Agrarias", located in Moncada, Spain (39°35'17.5"N 0°23'59.7"W, 68 m a.s.l.). The orchard was extended 2 ha and planted with the variety 'Clementina de Nules' (*Citrus clementina,* Hort ex Tan.) grafted on Citrange Carrizo (*Citrus sinensis,* L. Osb. x *Poncirus trifoliata,* L. Raf.), with plants spaced 3.85 m along the row, and 6.0 m between rows (density of 433 trees/ha). The trees were ten years old at the time of field experiments.

González-Altozano and Castel (1999) formerly described the orchard, which was pruned annually and with phytosanitary treatments performed according to the usual practices of the area.

The soil was calcareous with an effective depth of 0.5±0.6 m limited by a petrocalcic horizon and soil texture ranging from sandy-loam to sandy-clay-loam (USDA, 2017). The average field capacity and the soil wilting point resulted in 0.27 $m^3\ m^{-3}$ and 0.15 $m^3\ m^{-3}$, respectively. The soil was poor in organic matter (0.7%) and without salinity limitations (< 0.5 dS m^{-1}). Irrigation water, coming from a well located on the farm, had an electrical conductivity of 1.2 dS m^{-1} (at 25º C) (González-Altozano and Castel, 1999).

The climate of the area is the Mediterranean, with mild winters and scarce precipitations during the growth season. Climatic parameters were recorded by an automated meteorological station installed in the eastern corner of the plot. Reference evapotranspiration (ET_0, mm d^{-1}) was calculated with the FAO56 Penman-Monteith (Allen et al., 1998).

The trees were irrigated with a drip irrigation system, with two lateral pipes placed in parallel to the plant rows at a distance of 0.75 m from each side of the trunk, and four 4 L h^{-1} emitters per tree spaced 1.25 m.

2.2 Irrigation treatments

Irrigation was scheduled based on the daily evapotranspiration measured in a weighing lysimeter (ET_{lys}) installed in the orchard. The weighing lysimeter, with dimensions of 4.0 x 4.0 x 1.5 m and precision of ±0.25 mm of daily ET, was installed in 1989, and planted with a single tree similar to the rest of the orchard (Castel, 1991). The tree in the lysimeter was irrigated with the same drip irrigation system as the rest of the plot, and with doses corresponding to 125% of the measured ET_{lys}. This percentage allowed accounting for the possible inefficiency of the irrigation plant.

The volumes applied with irrigation and the weight of the lysimeter were automatically recorded hourly, with a datalogger CR10 (Campbell Inc.).

The experimental design consisted of a control treatment (CTRL), irrigated at 125% of ET_{lys} during the whole year, and the following six irrigation treatments under regulated deficit irrigation, RDI, in which 25% (25%-I, 25%-II, 25%-III) and 50% (50%-I, 50%-II, 50%-III) of ET_{lys}, were applied during each of the three stages of fruit growth (I: cell division; II: cell elongation; III: fruit maturation), as indicated in figure 1.

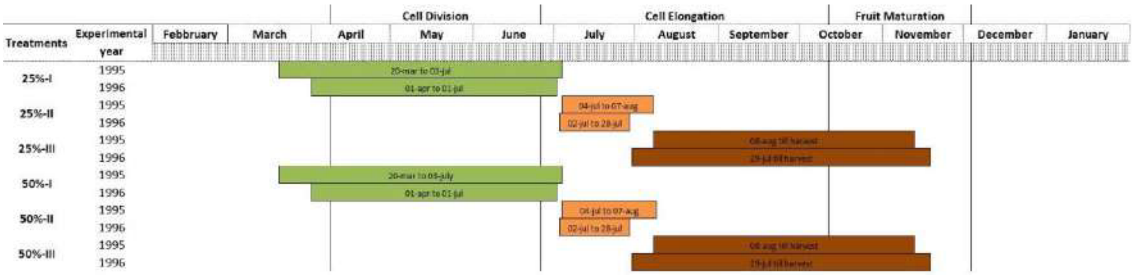

Figure 1 – Regulated Deficit Irrigation treatments

The duration of each period of deficit irrigation (Figure 1) was based on phenological observations and measurements of pre-dawn leaf water potential (PLWP). The phenological stages were defined after direct observations, following the classification proposed for citrus by Limón de la Oliva et al. (1972). The periods of the phenological phases, and thus the timing of the irrigation treatments were:

-Phase I of fruit growth corresponding to flowering-fruit set: from March 20 to July 3 in 1995 and from April 1 to July 1 in 1996;

-Phase II of fruit growth corresponding to the initial fruit enlargement phase: from July 4 to August 7 in 1995 and from July 2 to 28 in 1996;

-Phase III of fruit growth corresponding to the final growth and maturation: from August 8 in 1995 and from July 29 in 1996 until harvesting.

All the treatments were irrigated every five, four and two days per week in winter, spring-autumn and summer, respectively. The experimental design included randomized blocks with three replications per treatment. Further details about the distribution and the replicates of the applied treatments can be found in Ginestar and Castel (1996), González-Altozano and Castel, (1999) and González-Altozano and Castel (2000).

2.3 Measurements of soil and tree water status

The soil water content was monitored with a Trase TDR system (Soil Moisture Equipment Corp.) and probes installed at distances of 0.2 m and 0.4 m from the emitters. TDR stainless steel rods, 0.47 m length, were installed in one tree per each plot, thus three trees per treatment were monitored. Measurements of soil water content and leaf water potential were contextually acquired, in days without irrigation, every 7 days in 1995, and every 1 or 2 weeks in 1996.

The tree water status was quantified by pre-dawn leaf (PLWP, MPa) and midday stem (MSWP, MPa) water potential, measured with a Scholander chamber (Soil Moisture Equip. Corp.), following the recommendations of Turner (1981). For each determination, five mature leaves on two representative trees per treatment were used. Leaves exposed to North-West were used for the pre-dawn measurements and to South for the midday measurements. Two hours before the measurement of MSWP, the leaves were covered with silver foils and inserted in plastic bags.

For each treatment, the water stress integral ($S_{MSWP,}$ MPa per day) in each period of deficit irrigation and for the whole year were calculated by using the measurements of MSWP. The water stress integral was computed from the midday stem water potential as (Myers, 1988):

$$S_{MSWP} = \left[\sum_{i=0}^{i=i}\left(MSWP_{i,i+1} - c\right)n\right] \quad (1)$$

where $MSWP_{i,i+1}$ is the average midday water potential measured in the time interval *i,i+1*, *c* is the maximum predawn leaf water potential measured during the study period in the control treatment, which resulted of -0.8 MPa, and *n* is the number of days of the period.

2.4 Yield determination

The yield was determined at the time of commercial harvest at the end of each season, which took place around mid-December. The average fruit weight was obtained by counting the number of fruits in 15 boxes per each experimental plot (about 20 kg/box), which were randomly selected and previously weighed with a resolution of 20 g. Fruit of low commercial value, e.g. off-season and fruit with creasing were left on the trees and picked and counted later.

3. Results

3.1. Agrometeorological characteristics and lysimeter-based crop evapotranspiration

The dynamic of daily standard meteorological variables during the two experimental years is presented in Figure 2. During the fruit growth stage I (flowering and fruit set phases), precipitation and crop water evapotranspiration (ET_{lys}) in 1995 resulted lower than in 1996. During the phenological stage II (initial phases of fruit enlargement) there were more scarce precipitations and greater evaporative demand (ET_0) compared to the phase I. The stage III (final phases of fruit enlargement and maturation), occurring in both years at the end of summer, in 1995 was characterized by higher precipitations and lower ET_0. The maximum daily evapotranspiration in the lysimeter, ET_{lys}, was registered around the beginning of stage III.

The cumulated precipitation during the fruit growth cycle in 1996 was higher of about 130 mm compared to 1995. The rainfall events were rare in stage II, and mainly concentrated during stage III.

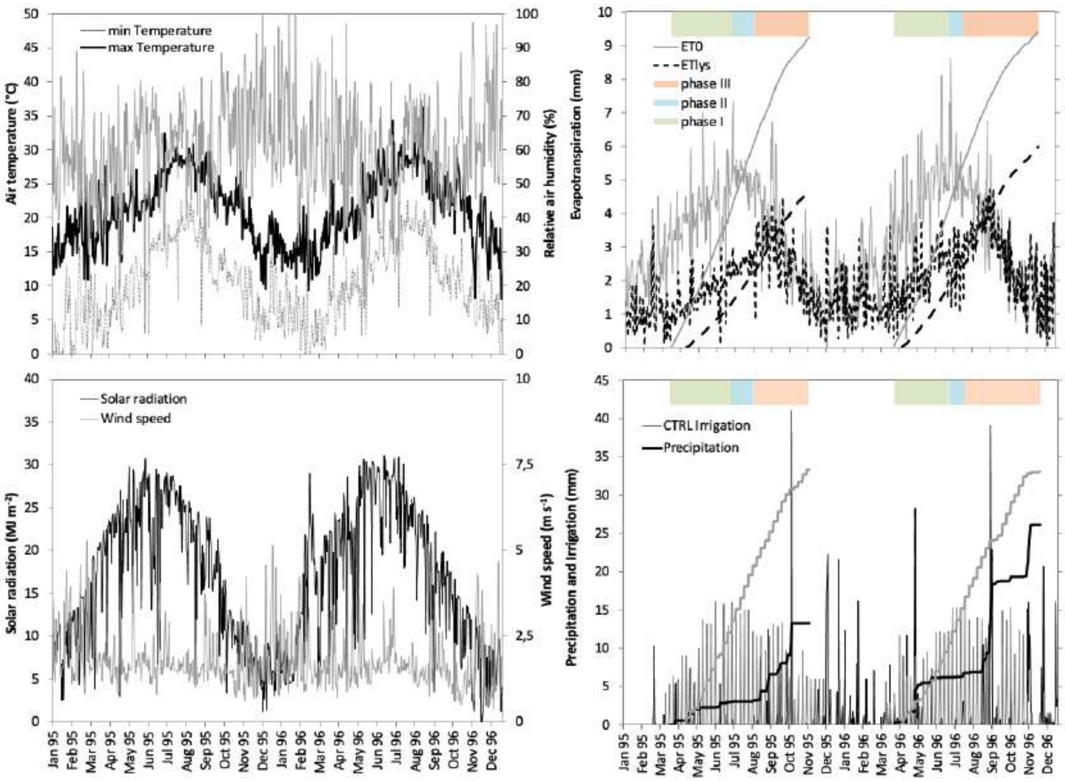

Figure 2a - d - Daily values measured in 1995 and 1996 of (a) minimum and maximum air temperature, and average relative air humidity; (b) global solar radiation, and wind at 2.0 m above the soil surface, v; (c) reference, ET_0, lysimeter evapotranspiration, ET_{lys}, and their cumulated values; (d) precipitation, P, irrigation, I, and their cumulated values.

3.2 Eco-physiological crop response to soil water deficit

Figure 3 shows the average soil water content (SWC) as a function of the indicators of plant water status, represented by the pre-dawn leaf (PLWP) and midday steam (MSWP) water potentials, for the control (CTRL) and the deficit irrigation (DI) treatments.

For the higher values of soil water content, both the indicators resulted around a constant value, corresponding to about -0.4 MPa and -1.0 MPa in terms of PLWP and MSWP, respectively; for soil water content below a certain threshold, the values of leaf/stem water potential started to sharply decrease. Similarly to what observed by Ballester et al. (2011) for the same citrus spp., this pattern was more accentuated in the 25% DI than in the 50% DI treatments.

Despite the dispersion of data makes difficult to identify a clear threshold of SWC, it is plausible to assume a value of SWC around 20%, below which both the PLWP and MSWP decline at decreasing SWC, whose lower limit resulted of about 10%. According to Pellegrino et al. (2006), this lower limit of soil water status can be considered close to the wilting point. Therefore, assuming these thresholds of SWC and a soil field capacity of 0.27 cm^3 cm^{-3}, the investigated soil is characterized by a depletion of 70 mm m^{-1}, and a depletion factor (p) value of 0.41. As expected, the lowest PLWP and MSWP values were reached in the 25% treatments, due to the lower amount of water applied with irrigation. Regarding the 25% DI, the lowest values of SWC, PLWP and MSWP were registered when the timing stress was applied in the stages II and III of fruit growth.

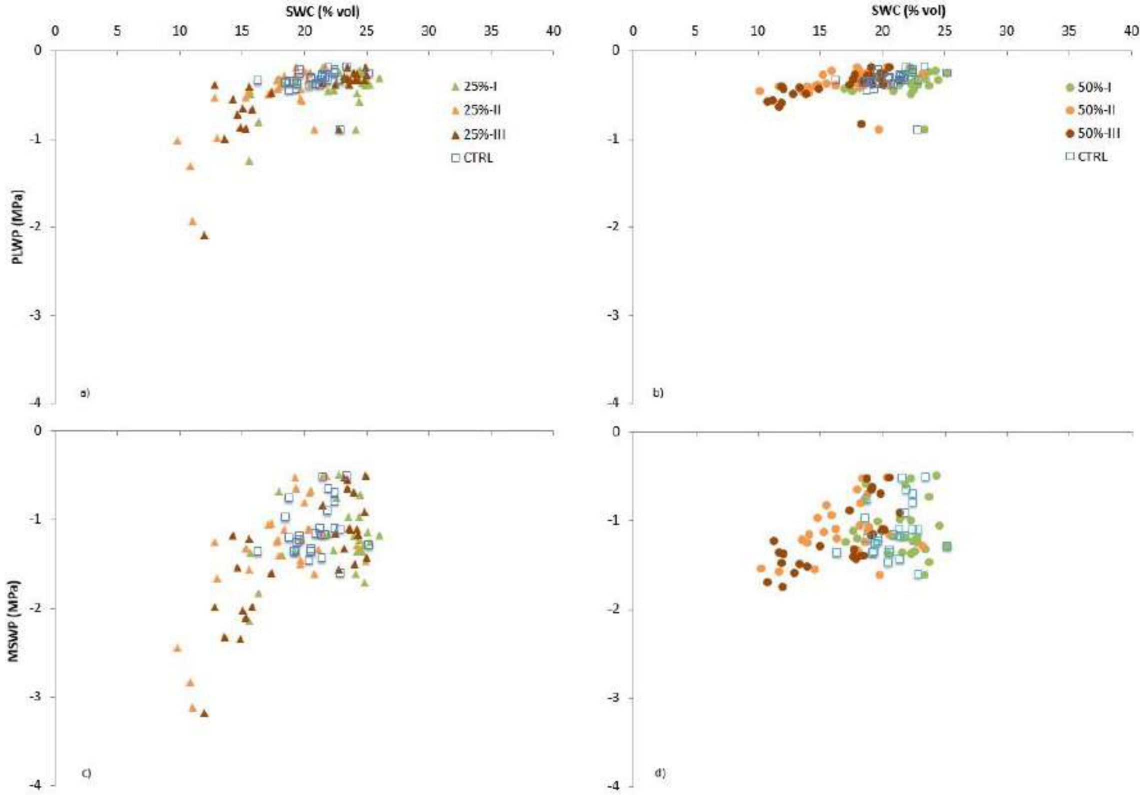

Figure 3a-d - Experimental values of Predawn (PLWP) and Midday (MLWP) Leaf Water Potential as a function of soil water content, SWC

Therefore, the intensity and timing of DI treatments affected the crop water status, which was well represented by the plant and soil water status indicators, and their relationship.

The different crop response, particularly evident when considering the dispersion of MSWP (Fig. 3c-d) for any fixed SWC, could be associated to the quite high spatial variability of soil water content associated to the microirrigation system, as well as to the different evaporative demand. The largest dispersion of the measured variables was observed during the periods of water deficit application. This dispersion could be due to the partial wetting of the root system, with the wetted volume becoming smaller at decreasing water doses (increasing water stress levels), as well as to the three-dimensional soil moisture gradients around the water emission points characterizing the localized irrigation system. To support these hypotheses, Guswa et al. (2004) observed that for similar values of average soil water contents, in the treatments characterized by higher water stress levels (lower irrigation doses for a fixed frequency) the root volume in which the water is readily available is more limited and consequently root water uptake is lower.

3.2. Water stress integral and effects due to irrigation variables

The water stress integral (S_{MSWP}) approach is used to assess the relationship between crop water status and the total water supplied by precipitation and/or irrigation. At the same time, S_{MSWP} was related to the average irrigation dose, *Id*, supplied in each watering event. The S_{MSWP} was calculated based on the values of MSWP potential measured during the three fruit growth stages.

As discussed above, the computation of S_{MSWP} started on the first of June, because no data were available before that date. The *c* value in eq. (1), which was assumed as the maximum leaf water potential measured in the control treatment was -0.8 MPa.

For all the treatments, table 1 shows the cumulated water stress integral during each of the three fruit growth stages in which the different irrigation treatments were applied in 1995 and 1996. As expected, the cumulated water stress integral was higher for the 25% DI treatments in both the experimental years, due to the lower amount of water supplied. The 25%-III treatment presented the highest S_{MSWP} value, which was higher in 1996 compared to 1995. This confirms the sensitivity of Clementina de Nules variety to water deficit applied during the stage III of crop growth, as previously observed by González-Altozano and Castel (1999) and Ballester et al. (2011). In both the experimental years, the second-highest S_{MSWP} was observed in the 25%-II treatment, due to the scarce precipitation and high atmospheric evaporative demand characterizing both the summer periods. As expected, the control treatment was associated with the smallest S_{MSWP}.

Table 1 – Summary of water stress integral, precipitation, total irrigation amount, average irrigation doses and its variability applied during the three stages of fruit growth in 1995 and 1996. The symbols μ *and* CV *represent the mean and the coefficient of variation of irrigation doses*

		Water Stress Integral, S_{MSWP}	Precipitation, *P*	Irrigation total, *I*	Irrigation doses, *Id* μ	CV
Treatment	**year**	**[MPa]**	**[mm]**	**[mm]**	**[mm]**	**[-]**
25%-I	1995	65.8	109.9	202.3	8.8	0.5
	1996	100.4	257.5	253.9	7.8	0.8
25%-II	1995	79.0	109.9	197.9	8.6	0.6
	1996	105.2	206.5	235.8	9.1	0.5
25%-III	1995	87.9	109.9	157.8	6.9	0.9
	1996	123.7	257.5	206.4	6.0	0.9
50%-I	1995	56.2	109.9	228.9	10.0	0.4
	1996	77.0	257.5	274.7	8.4	0.6
50%-II	1995	60.0	109.9	214.7	9.3	0.5
	1996	74.9	257.5	298.6	9.1	0.4
50%-III	1995	71.2	109.9	174.7	7.6	0.7
	1996	81.6	257.5	238.9	7.3	0.6
CTRL	1995	60.0	102.2	229.1	11.3	0.3
	1996	74.1	257.5	339.7	10.0	0.4

When considering the 50% DI treatments, slight differences with the CTRL were recognized in terms of S_{MSWP}, especially in 1995. As a result, the application of 50% DI treatments is likely to cause significant crop water stress only during irrigation seasons with low rainfall and high evaporative demand. Even for the 50% DI treatments, stage III of crop growth was the most sensitive to water stress.

Figure 4a-b shows the S_{MSWP} (MPa per day) of the DI treatments during the three fruit growth stages versus the total amount of water applied, e.g. precipitation and irrigation (mm), both in absolute (fig. 4a) and normalized (fig. 4b) terms. The normalization was obtained as the ratio between the variable obtained in DI treatment and the corresponding associated to the CTRL. The normalization procedure allowed excluding the effects deriving from the different atmospheric conditions registered in the two experimental years.

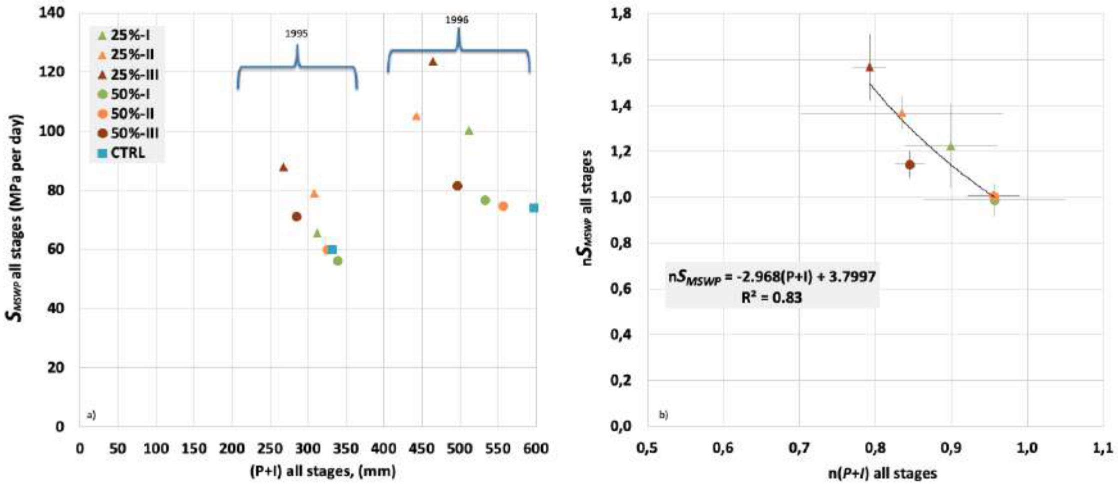

Figure 4a-b – Relationship between the water stress integral in all stages and the water supply (precipitation plus irrigation) in a) absolute and b) normalized terms

There is a trend between the S_{MSWP} for all stages and the total amount of water applied (P+I) in absolute terms for each experimental year. The values of S_{MSWP} decreased at increasing the amount of water applied. Moreover, a robust (R^2= 0.83) relationship between the normalized water stress integral, nS_{MSWP}, and the corresponding normalized water supplied, n(P+I), can be observed (Fig. 4b). The decreasing regression curve shows how the crop water stress becomes smaller as the water supplied regime of the DI treatments tend to the CTRL one. As observed in previous studies (García-Tejero et al., 2010; Goldhamer, 2012; Rallo et al., 2017), the S_{MSWP} can be used as an indicator to predict the seasonal amount of water, necessary to accomplish a desired level of stress.

Figure 5a-b illustrates the relationship between S_{MSWP} cumulated during the whole season (Fig. 5a) and stage II (Fig. 5b) of fruit growth, and the corresponding amount of irrigation applied during the same periods in both the experimental years. The relationships in Fig. 5b was compared with the relationship identified by Rallo et al. (2017) for an orange citrus orchard under DI applied during only the phase II fruit growth stage.

The value of S_{MSWP} decreased at increasing of the total irrigation, *I*, supplied, being the lowest values obtained for the control treatment (CTRL). Moreover, the 50%-I and 50%-II treatments showed values closed to the CTRL one.

As shown in Fig. 5b, the S_{MSWP} and the *I* obtained for the 25%-II and 50%-II are very close to the empirical relationship proposed by Rallo et al. (2017), confirming that during stage II of citrus fruit growth it is feasible to predict the amount of irrigation necessary to achieve the desired level of crop water stress.

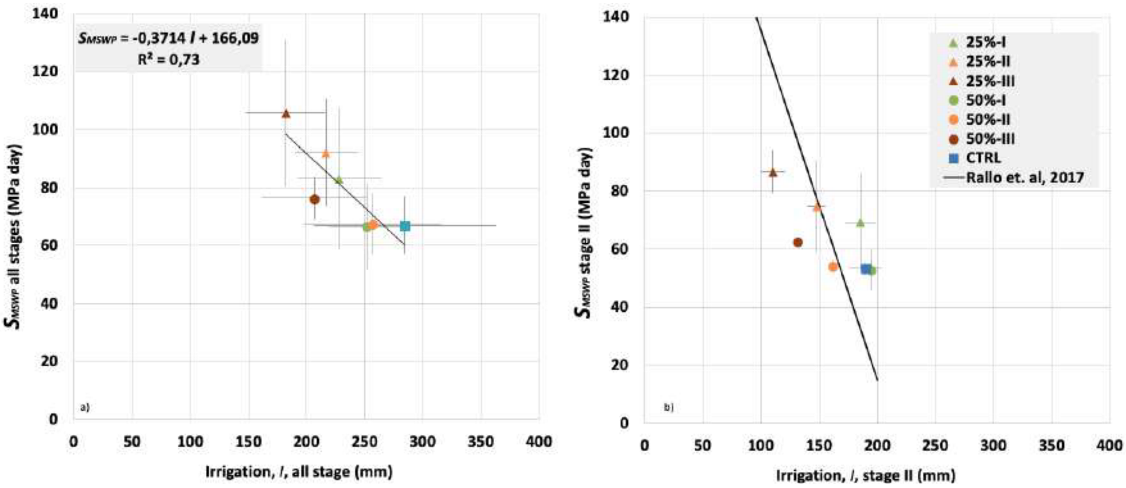

Figure 5a-b – Relationship between the water stress integral, S_{MSWP}, and the relative total amount of irrigation, I, applied during a) the whole year and b) the stage II of fruit growth. The model proposed by Rallo et al. (2017) is also reported in b)

Figure 6a-b shows the effects of the average irrigation doses applied in each watering, *Id*, on the S_{MSWP} observed during the whole period of water deficit application (Fig. 6a) and during the phase II of fruit growth (Fig. 6b). The analysis of the relationship in fig. 6a shows that S_{MSWP} also depends on the quantity of water applied in each watering, which could suggest the relevance of this irrigation management variable in the designing of the water saving strategies.

The relationship found between S_{MSWP} and *Id* under water deficit in the stage II of fruit growth (Fig. 6b) evidences a different regression curve that the one observed in Rallo et al. (2017). The different shape of the curves is probably due to the different methods used to determine the irrigation doses, *Id*, which were the lysimeter-based in this experiment, and according to the weather-based method in Rallo et al. (2017).

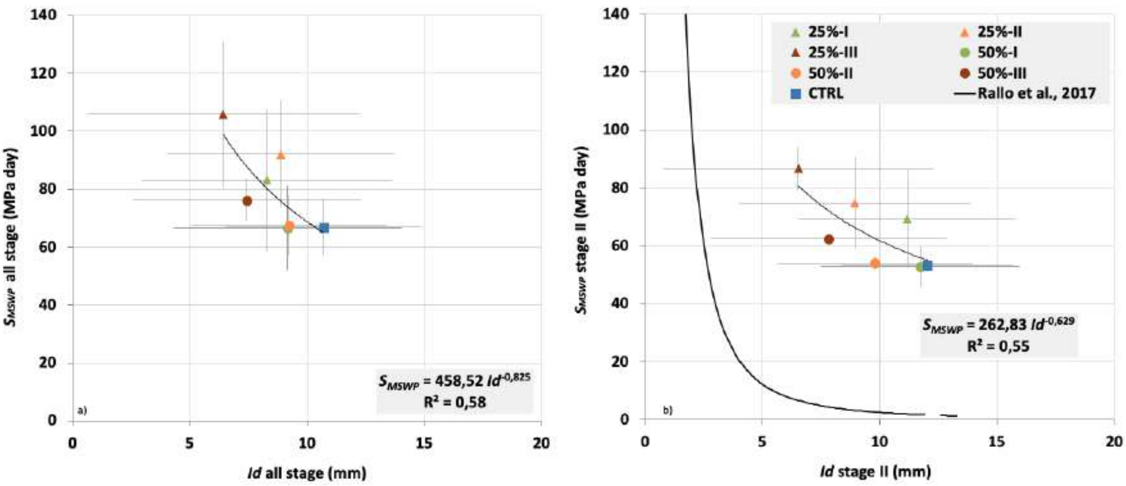

Figure 6a-b - Relationship between the S_{MSWP}, and average irrigation depth, Id, applied in each watering during a) the whole period of water deficit application and b) the phase II of fruit growth. The relationship from Rallo et al. (2017) is also displayed in b)

3.3. Effect of irrigation depth variability on crop water stress and crop yield

Figure 7a shows the relationship (R^2= 0.71) between the cumulated water stress integral, S_{MSWP}, in all the stages of fruit growth and the coefficient of variation of irrigation doses applied in each watering (CV-*Id*). The relationship confirms that the level of water stress increased with the irrigation doses variability. The most severe DI treatment (DI 25%-III) was characterized by the highest variability of CV-*Id*, whereas the control treatment was characterized by the lowest CV-*Id.* As referred, the irrigation depth was calculated based on the ET_{lys} and, thus, the *Id* depends on the atmospheric demand of the days included among consecutive watering: two, three or five days, respectively for summer, spring and autumn periods. Therefore, the irrigation volumes supplied during each irrigation event were different being based on the ET demand and the imposed reductions of irrigation volumes.

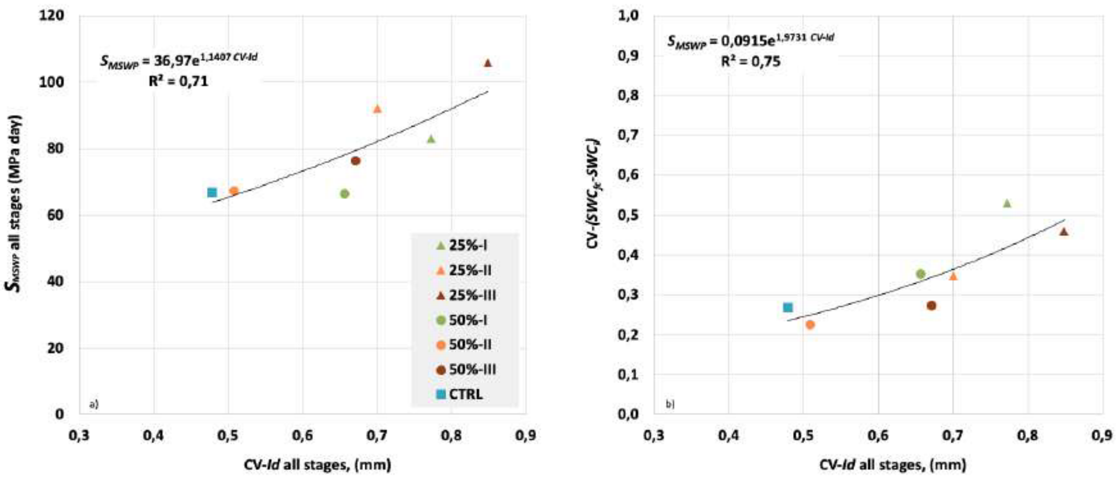

Figure 7a-b – Relationship between a) the water stress integral, S_{MSWP}, and b) the coefficient of variation of available soil water content, CV-*(SWC_{fc}-SWC_i), with the coefficient of variation of the irrigation depth,* CV-*Id*

As stated in section 3.2, the effect of *Id* variability on the cumulated water stress integral could be explained following the consideration of Guswa et al. (2004). As shown in figure 7a, the lowest variability of the supplied irrigation volume was associated to the control treatment, in which the highest irrigation doses (125% ET_{lys}) allowed to wet more homogeneously the crop root volume. Thus, crop water uptake was not affected by the soil water deficit conditions because a higher fraction of roots was moistened at soil water content close to the soil field capacity (SWC_{fc}), before starting the drying process.

On the other hand, in the DI treatments, the plant started to increase the cumulated stress originated from lower and more time-variable irrigation doses supplied in each event. The root system could have experimented soil water content quite lower than that corresponding to the field capacity, even after irrigation events, when part of the root system was differently moistened. The reasons behind this behavior are mainly due to the smaller water doses and the localized irrigation system, which generates high three-dimensional soil moisture gradients around the water emission points.

The crop water stress was consequent to the root water uptake lower than the maximum in a bigger fraction of the root volume, in which water was not readily available. Hence, the plant needed to extract water from further wet regions to compensate for the limitations occurring in the dry root volume. Therefore, the CV-*Id* depended on the magnitude of irrigation doses, because the higher quantity of water supply allowed moistening more uniformly wider fraction of the root zone, with more readily water available for the crop.

As observed, the CV-*Id* would influence the variability of the available soil water content (SWC_{fc}-SWC_i) in the root volume. For the different treatments, figure 7b shows the correlation between the coefficient of variation of the available soil water content, CV-(SWC_{fc}-SWC_i) and the CV-*Id* measured during all the fruit growth stages. The variability of the difference between the field capacity and the actual soil water content, CV-(SWC_{fc}-SWC_i) becomes higher as the CV-*Id* increases. Thus, this difference would become wider under the most severe treatment, in which the actual soil water contents are quite lower than the soil field capacity (SWC_{fc}).

The effect of irrigation depth variability, and consequently with the available water variability, on crop water stress could justify the yield decrease showed in figure 8. There is, in fact, a high correlation (R^2=0.74) between the crop yield and the observed CV-(SWC_{fc}-SWC_i).

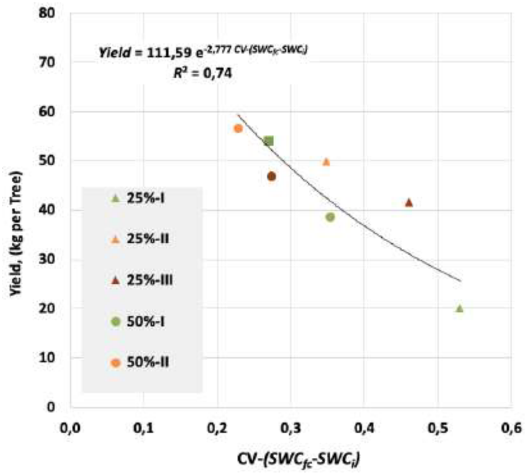

Figure 8 – Relationship between crop yield and the coefficient of variation of available soil water content, CV-*(SWC_{fc}-SWC_i), observed during the three stages of crop growth*

4. Discussion

The effects of deficit irrigation treatments on the woody perennial crops have been mainly studied by following the agronomic approach (Chai et al., 2016). However, investigating the impact of soil water deficit from an agro-hydrological point of view could help to deepen the understanding of the crop ecophysiological relationships with hydraulic and hydrological parameters of the agro-ecosystem. In this work, the relationships between the crop water status and soil water content under deficit irrigation treatments characterized by different timing and intensity have been investigated in a citrus orchard. The cumulated water stress in each of the three-fruit growth stage was correlated to parameters of irrigation management, such as the amount of water applied and the variability of the irrigation doses.

The relationship between measured predawn leaf and midday stem water potential with soil water content allowed identifying a threshold in terms of depletion factor, *p*, representing a basic parameter for a feed-back control (soil moisture-based) of irrigation scheduling. The depletion factor obtained in this study (p=0.41) was lower than that tabulated for citrus spp. in the FAO56 paper (Allen et al., 1998). In this sense, compared to other citrus spp. Clementina de Nules is characterized by a lower resistance to water stress, as stated in previous studies (González-Altozano and Castel, 1999; Ballester et al., 2011). Similar thresholds of soil moisture content have been reported for citrus spp. and woody perennial crops in Mediterranean areas by plotting leaf water potential with measurements of soil water content (Ginestar and Castel, 1996; Rallo and Provenzano, 2013 Agüero Alcaras et al., 2016; Rallo et al., 2017). In the same line, a previous study by Rallo et al. (2017) carried out in an orange orchard reported a threshold of soil depletion when MSWP started to decrease corresponding to a p-factor equal to 0.20; this value, lower than that obtained in this study, could have been due to the different soil texture, citrus spp., age, crop practices and irrigation management. Continuous and automatic measurements of soil water content have been suggested as accurate methods for the feedback control of irrigation in fruit trees (Agüero Alcaras et al., 2016; Gasque et al., 2016; Rallo et al., 2017; Vera et al., 2013 Vera et al., 2019; Domínguez-Niño et al., 2020). Therefore, the identified threshold of soil water status is useful to design accurate and easy site-specific irrigation scheduling protocol in Clementina de Nules.

The cumulated water stress index (S_{MSWP}) was used to assess the link between the crop water status in the three fruit growth stages and the total water supplied (precipitation plus irrigation) in the field. It was observed that the S_{MSWP} is an useful indicator for scheduling irrigation in citrus trees when a degree of soil water deficit is imposed, and for evaluating the effects of soil water deficit on the crop water status. Literature for citrus and woody perennial crops has reported strong correlations between indicators of crop water stress with actual evapotranspiration, trunk growth, volumetric soil water content, irrigation depth and crop yield (Ginestar and Castel., 1996a; Gasque et al., 2016; De la Rosa et al., 2016; Rallo et al., 2017; Gonzalez-Benecke and Dinger., 2018; Martinez-Gimeno et al., 2018). Specifically, Rallo et al. (2017) observed a robust relationship between the S_{MSWP} and irrigation depth in an orange orchard under deficit irrigation applied during stage II of crop growth. Overall, the response of the citrus crop to the imposed stress conditions varied in terms of timing and intensity (magnitude of the imposed deficit), confirming what already stated in previous studies on citrus orchards (Glodhammer, 2012, Ballester et al., 2014). Moreover, in line with the conclusions of Treeby et al. (2007), the crop response to the lower water supply depends on the timing and severity of the treatments, as well as on the species, soil type, and other site-specific factors.

Even the dispersion characterizing the soil moisture measurements and commonly associated to the drip-irrigated orchards, which was higher in the most severe DI treatments, has been observed in previous studies (Intrigliolo and Castel, 2004; Rallo et al., 2017). Nonetheless, to our knowledge, there are no studies that have related the effects produced on crop yield by the magnitude and variation of irrigation doses (*Id*). As evidenced by Guswa et al. (2004), higher the variability of soil water content, wider the fraction of the root zone not wetted up to the soil field capacity. This lag determines the lowering of the plateau of the water stress function and hence the increase of the crop stress level. This assumption was confirmed by the fact that the coefficient of variation of the irrigation doses (CV-*Id*) affects the crop stress level and, at the same time, influences the variability of the difference between the field capacity and the actual soil water content, CV-$(SWC_{fc}\text{-}SWC_i)$. Hence, the variability of the available water, CV-$(SWC_{fc}\text{-}SWC_{i,}$ due to the combined effect of the micro-irrigation system, its management and the adopted water-saving protocol, can have effects on crop yield.

5. Conclusions

The results achieved in this study reinforce the importance to consider, in woody perennial crops, the relationships between hydrological and hydraulic variables as indicators of irrigation management. The ecophysiological relationships evidence the significance of monitoring the soil-plant-atmosphere continuum to define accurate thresholds of allowable soil depletion for precise irrigation scheduling. A threshold in terms of depletion factor (p=0.41) was recognized for Clementina de Nules to design location-specific irrigation scheduling protocol.

Large dispersion of MSWP measurements for any fixed SWC data was observed in the most severe deficit irrigation treatments (e.g. 25% DI), as a consequence of the localized irrigation system and the variability of the applied irrigation doses. At the same time, the tree water status was differently affected by the timing and the severity of applied stress conditions.

The cumulated water stress integral (S_{MSWP}) has been validated as an appropriate crop water status indicator for irrigation scheduling to predict specific levels of crop water stress. The S_{MSWP} was well correlated to the total amount of water supplied by precipitation and irrigation and the average irrigation doses applied on each watering event, confirming the significance of these hydraulic variables to design appropriate water-saving strategies. The normalized S_{MSWP} index, whose calculation allows accounting for the different atmospheric conditions observed during the two experimental years, was highly correlated to the normalized total amount of water supplied.

The variability of the irrigation doses (*CV-Id)* produced effects either on the crop water status and yield production. The relationship between the S_{MSWP} and the *CV-Id* showed that the deficit irrigation treatments characterized by the relatively higher variability of irrigation doses are associated with the higher crop stress levels observed on the crop. The lower and more time-variable irrigation doses in deficit treatments moistened wider fractions of the root zone with water not readily available for the crop. Thus, *CV-Id* influences the variability of the available soil water content in the root volume, CV-(SWC_{fc}-SWC_i), which affects the final performance in terms of crop yield.

Therefore, the accurate assessment of the impact of deficit irrigation on crop water status and agronomic performance has to consider variables of irrigation management, such as the irrigation amount and the variability of irrigation doses. When designing a drip irrigation system, it is also necessary to consider the fraction of the root volume to wet.

CRediT authorship contribution statement

Angela Puig-Sirera: Conceptualization, Methodology, Data curation, Writing - original draft. **Giuseppe Provenzano:** Validation, Writing - review & editing. **Pablo González-Altozano:** Investigation, Validation, Writing - review & editing. **Diego Intrigliolo:** Validation, Writing - review & editing. **Giovanni Rallo:** Conceptualization, Methodology, Data curation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The research was carried out in the frame of "Progetto OP-Illuminati Frutta-Rallo" (University of Pisa, 1048 MIPAF-Regione Toscana) and "ATMOSMART-dimostratore tecnologico" (University of Pisa).

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Conflict of Interest

Declaration of interests

☐ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Irrigation water saving strategies in Citrus orchards: analysis of the combined effects of timing and severity of soil water deficit

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Abstract

~~Environmental policies identify resilient water-saving strategies as necessary tools to cope with climate change. Regulated deficit irrigation (RDI) is a sustainable strategy for crop production in water-limited regions because it allows the reduction of water supply during specific stages of fruit growth without significantly affecting the crop yield. Consequently, T~~the knowledge of the crop response to soil water deficit is essential to predict the actual crop water requirements under limited soil water conditions. The mathematical schematization of the crop response under RDI can allow identifying the exact irrigation timing. The threshold of soil water status below which crop transpiration decreases represents a key parameter for the water stress functions. The main objective of this paper was to investigate the effects of several RDI treatments, applied during the three stages of fruit growth, on soil-plant-water relations of drip-irrigated mandarin trees. Experiments were carried out in seven irrigation treatments: a control, irrigated at 125% of potential evapotranspiration measured in weighting lysimeters, ET_{lys}, during the whole year, and six RDI treatments in which 25% and 50% of ET_{lys} were applied during each of the three stages of fruit growth.

The critical threshold of soil water status expressed in terms of soil water depletion below which predawn (PLWP) and midday (MSWP) leaf water potential is affected by decreasing soil water content, were identified. The dependency of crop water status from the climate forcing, occurring under soil water contents higher than the critical threshold was also demonstrated. Moreover, a strong relationship between water stress integral (S_{MSWP}) evaluated during the three stages of fruit growth, and the corresponding amount of water applied (irrigation and precipitation) was observed after normalizing the variables. The robust relationship between these two variables (R^2 = 0.83) confirmed that the water stress integral represents a good indicator of the plant-water relationship and allows the prediction of the total irrigation

depth to be applied to achieve a desired stress level during the fruit growth. Moreover, this relationship depends on the irrigation schedule adopted to regulate the deficit, which includes the irrigation variables, such as irrigation dose and its variability.

Keywords: deficit irrigation, depletion factor, irrigation dose, water stress integral~~, deficit irrigation timing~~

1. Introduction

~~In many areas of the world, irrigated agriculture, which is the sector with the largest consumption of fresh available water, has to face the pressure derived from the increasing water scarcity (Ferreres and Soriano, 2007; Martínez-Gimeno et al., 2020)). In the Mediterranean basin, the agricultural sector is particularly affected by water shortages due to semi-arid conditions, scarce and irregularly distributed precipitation throughout the year, increasing competition for water resources, as well as the increasing drought phenomena and more arid conditions projected for the next decades (Stagakis et al., 2012). Thus, the agricultural sector is forced to improve the efficient use of water.~~

In the Mediterranean basin, approximately 30% of the cultivated area is under irrigation, which represents the biggest consumer of freshwater from the region (Harmanny and Malek, 2019). Specifically, the irrigated land in Spain accounts for 80% of global water consumption (MAPA, 2019). Citrus spp. is the crop most cultivated fruit tree in Spain with a surface extended 307.560 ha in 2019, of which 93% is irrigated, represents the crop with the highest irrigated area (MAPA, 2019). Moreover, Spain is one of the main producing countries worldwide of citrus spp., with an average annual production of around 6.3 Mt in 2019; more than a third of this production comes from the mandarin group, being 'Clementina de Nules' one of the most common cultivars (MAPA, 2019). Thus, it is important to determinate the citrus water requirements by designing simple, practical and precise methods to optimize irrigation and to adopt precise irrigation scheduling and management techniques (Gasque et al., 2016).

Water-saving strategies, such as deficit irrigation (DI), have been studied as a promising alternative for growers of citrus spp., mainly in areas characterized by water shortcomings and increasing frequency of drought phenomena (Ferreres and Soriano, 2007; Carr, 2012; Rocamora et al., 2013). Under regulated deficit irrigation, water is generally supplied at levels below full crop transpiration during specific periods of the fruit growing season. Operating in this way, it is possible to balance the plant vigour with the potential production by limiting the irrigation volumes (Costa et al., 2007; Rallo et al., 2017).

Therefore, deficit irrigation has been considered as a strategy to save water and to increase water productivity. Besides, this strategy may have positive impacts on fruit quality and composition parameters that contrast the possible side effects on fruit size and weight due to water stress

(Ballester et al., 2011), with the consequent upgrade of yield values (García-Tejero et al., 2010; Carr, 2012; Consoli et al., 2014).

Nonetheless, the application of DI requires monitoring in real-time the crop water status and soil water content to control the level of water stress reached by the crop, and hence, to prevent crop damage and yield losses (Rallo et al., 2017). In this direction, plant-based indicators of water status have been widely used, namely predawn or midday stem water potential (Jones et al., 2004). These indicators are discrete measurements that represent a snapshot in time of the crop water status and their measurement require expert knowledge. Moreover, plant-based indicators integrate the effects of soil water availability and the atmospheric evaporative demand, thus, it could be complicated to establish irrigation thresholds only considering measurements of tree water status (Ortuño et al., 2006; Ortuño et al., 2009 a,b). To complement them another index, the water-stress integral calculated as the summation of pre-dawn or midday leaf water potential measurements over a chosen period, summarizes the cumulative stress reached by the crop throughout a certain period (Myers, 1988).

Besides that, soil moisture sensors such as neutron probes, frequency domain reflectometry (FDR or capacitance probe), time-domain reflectometry (TDR) and fiber-optic sensors, provide feedback on the soil moisture and can be acquired automatically (Fares and Alva 2000; Evett et al 2008; Gil-Rodríguez et al., 2013). For these reasons, soil water contents have been frequently used in precise irrigation scheduling and as a tool for efficient irrigation (Evett et al 2008; Vera et al., 2019). However, diverse studies have highlighted the spatial heterogeneity of soil water content and the inaccuracies derived on scheduling irrigation only based on soil moisture measurements (Intrigiolo et al., 2004; Agüero Alcaras et al., 2016; Rallo et al., 2017; Dominguez-Nuñez et al., 2020). The heterogeneous patterns of soil moisture depend on many factors such as irrigation depth, quantity and frequency of irrigation, the type of water distribution system and the relative design plan (Grant et al., 2009; Dominguez et al., 2020). Specifically, Guswa et al. (2004) highlighted the impact that the spatial distribution of soil moisture in the root volume has on the total root water uptake. The crop water stress response to soil water status is, in fact, not linear and not uniquely associated, but rather depend on a large extent on the degree of wetting uniformity of the root zone.

Therefore, besides the agronomic related results derived from the application of water-saving strategies, is essential to study the hydraulic and hydrologic parameters that could affect the crop functioning and performance. However, most studies on the effects of water-saving strategies on the crop system are focused on agronomic methods and less emphasis has been placed on agro-hydrological approaches.

In this sense, further studying of the ecophysiological relationships according to different levels of water stress imposed could provide knowledge on the crop water dynamics and thus, on adequate irrigation management techniques (Ginestar and Castel, 1996; Agüero Alcaras et al., 2016; Rallo et al., 2017). Understanding these relationships could help to identify the maximum allowable depletion (MAD), which represents a basic knowledge for irrigation scheduling (Allen et al., 1998). The depletion coefficient, *p*, generally used to identify the MAD provides information about the crop resistance to water stress; for citrus spp., table 22 of FAO56 paper indicates to assume a value of *p*=0.50 (Allen et al., 1998). However, the value of this coefficient could vary with the different citrus spp., canopy architecture, plant density, fraction of ground cover and training system. Thus, local calibration of the p coefficient could represent more accurately the crop response to water stress.

In this study, a robust database of soil and crop data collected in previous research conducted by González-Altozano and Castel (1999) was used to i) study the eco-physiological response of a citrus crop (*Citrus clementina,* Hort *ex* Tan.) to different timing and magnitude of deficit irrigation; ii) identify the threshold of soil water status to implement water-saving strategies in citrus orchards; iii) assess the effect of irrigation management variables on the cumulated water stress and crop yield response.

2. Materials and Methods

2.1 Characteristics of the experimental field

Field data were collected in a citrus orchard during two consecutive years, 1995 (from June to December) and 1996 (from January to December) in the experimental farm of "Instituto Valenciano de Investigaciones Agrarias", located in Moncada, Spain (39°35'17.5"N 0°23'59.7"W, 68 m a.s.l.). The orchard was extended 2 ha and planted with the variety 'Clementina de Nules' (*Citrus clementina,* Hort ex Tan.) grafted on Citrange Carrizo (*Citrus sinensis,* L. Osb. x *Poncirus trifoliata,* L. Raf.), with plants spaced 3.85 m along the row, and 6.0 m between rows (density of 433 trees/ha). The trees were ten years old at the time of field experiments.

González-Altozano and Castel (1999) formerly described the orchard, which was pruned annually and with phytosanitary treatments performed according to the usual practices of the area.

The soil was calcareous with an effective depth of 0.5±0.6 m limited by a petrocalcic horizon and soil texture ranging from sandy-loam to sandy-clay-loam (USDA, 2017). The average field capacity and the soil wilting point resulted in 0.27 m^3 m^{-3} and 0.15 m^3 m^{-3}, respectively. The soil was poor in organic matter (0.7%) and without salinity limitations (< 0.5 dS m^{-1}). Irrigation water, coming from a well located on the farm, had an electrical conductivity of 1.2 dS m^{-1} (at 25º C) (González-Altozano and Castel, 1999).

The climate of the area is the Mediterranean, with mild winters and scarce precipitations during the growth season. Climatic parameters were recorded by an automated meteorological station installed in the eastern corner of the plot. Reference evapotranspiration (ET_0, mm d^{-1}) was calculated with the FAO56 Penman-Monteith (Allen et al., 1998).

The trees were irrigated with a drip irrigation system, with two lateral pipes placed in parallel to the plant rows at a distance of 0.75 m from each side of the trunk, and four 4 L h^{-1} emitters per tree spaced 1.25 m.

2.2 Irrigation treatments

Irrigation was scheduled based on the daily evapotranspiration measured in a weighing lysimeter (ET_{lys}) installed in the orchard. The weighing lysimeter, with dimensions of 4.0 x 4.0 x 1.5 m and precision of ±0.25 mm of daily ET, was installed in 1989, and planted with a single tree similar to the rest of the orchard (Castel, 1991). The tree in the lysimeter was irrigated with the same drip irrigation system as the rest of the plot, and with doses corresponding to 125% of the measured ET_{lys}. This percentage allowed accounting for the possible inefficiency of the irrigation plant.

The volumes applied with irrigation and the weight of the lysimeter were automatically recorded hourly, with a datalogger CR10 (Campbell Inc.).

The experimental design consisted of a control treatment (CTRL), irrigated at 125% of ET_{lys} during the whole year, and the following six irrigation treatments under regulated deficit irrigation, RDI, in which 25% (25%-I, 25%-II, 25%-III) and 50% (50%-I, 50%-II, 50%-III) of ET_{lys}, were applied during each of the three stages of fruit growth (I: cell division; II: cell elongation; III: fruit maturation), as indicated in figure 1.

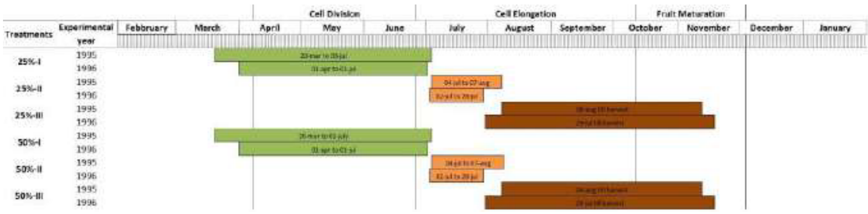

Figure 1 – Regulated Deficit Irrigation treatments

The duration of each period of deficit irrigation (Figure 1) was based on phenological observations and measurements of pre-dawn leaf water potential (PLWP). The phenological stages were defined after direct observations, following the classification proposed for citrus by Limón de la Oliva et al. (1972). The periods of the phenological phases, and thus the timing of the irrigation treatments were:

with diversified irrigation treatments were:

-Phase I of fruit growth corresponding to flowering-fruit set: from March 20 to July 3 in 1995 and from April 1 to July 1 in 1996;

-Phase II of fruit growth corresponding to the initial fruit enlargement phase: from July 4 to August 7 in 1995 and from July 2 to 28 in 1996;

-Phase III of fruit growth corresponding to the final growth and maturation: from August 8 in 1995 and from July 29 in 1996 until harvesting.

All the treatments were irrigated every five, four and two days per week in winter, spring-autumn and summer, respectively. The experimental design included randomized blocks with three replications per treatment. Further details about the distribution and the replicates of the applied treatments can be found in Ginestar and Castel (1996), González-Altozano and Castel, (1999) and González-Altozano and Castel (2000).

2.3 Measurements of soil and tree water status

The soil water content was monitored with a Trase TDR system (Soil Moisture Equipment Corp.) and probes installed at distances of 0.2 m and 0.4 m from the emitters. TDR stainless steel rods, 0.47 m length, were installed in one tree per each plot, thus three trees per treatment were monitored. Measurements of soil water content and leaf water potential were contextually acquired, in days without irrigation, every 7 days in 1995, and every 1 or 2 weeks in 1996.

The tree water status was quantified by pre-dawn leaf (PLWP, MPa) and midday stem (MSWP, MPa) water potential, measured with a Scholander chamber (Soil Moisture Equip. Corp.), following the recommendations of Turner (1981). For each determination, five mature leaves on two representative trees per treatment were used. Leaves exposed to North-West were used for the pre-dawn measurements and to South for the midday measurements. Two hours before the measurement of MSWP, the leaves were covered with silver foils and inserted in plastic bags.

For each treatment, the water stress integral ($S_{MSWP,}$ MPa per day) in each period of deficit irrigation and for the whole year were calculated by using the measurements of MSWP. The water stress integral was computed from the midday stem water potential as (Myers, 1988):

$$S_{MSWP} = \left[\sum_{i=0}^{i=i}\left(\text{MSWP}_{i,i+1} - c\right)n\right] \quad (1)$$

where $MSWP_{i,i+1}$ is the average midday water potential measured in the time interval *i,i+1*, *c* is the maximum predawn leaf water potential measured during the study period in the control treatment, which resulted of -0.8 MPa, and *n* is the number of days of the period.

2.4 Yield determination

The yield was determined at the time of commercial harvest at the end of each season, which took place around mid-December. The average fruit weight was obtained by counting the number of fruits in 15 boxes per each experimental plot (about 20 kg/box), which were randomly selected and previously weighed with a resolution of 20 g. Fruit of low commercial value, e.g. off-season and fruit with creasing were left on the trees and picked and counted later.

3. Results

3.1. Agrometeorological characteristics and lysimeter-based crop evapotranspiration

The dynamic of daily standard meteorological variables during the two experimental years is presented in Figure 2. During the fruit growth stage I (flowering and fruit set phases), precipitation and crop water evapotranspiration (ET_{lys}) in 1995 resulted lower than in 1996. During the phenological stage II (initial phases of fruit enlargement) there were more scarce precipitations and greater evaporative demand (ET_0) compared to the phase I. The stage III (final phases of fruit enlargement and maturation), occurring in both years at the end of summer, in 1995 was characterized by higher precipitations and lower ET_0. The maximum daily evapotranspiration in the lysimeter, ET_{lys}, was registered around the beginning of stage III.

The cumulated precipitation during the fruit growth cycle in 1996 was higher of about 130 mm compared to 1995. The rainfall events were rare in stage II, and mainly concentrated during stage III.

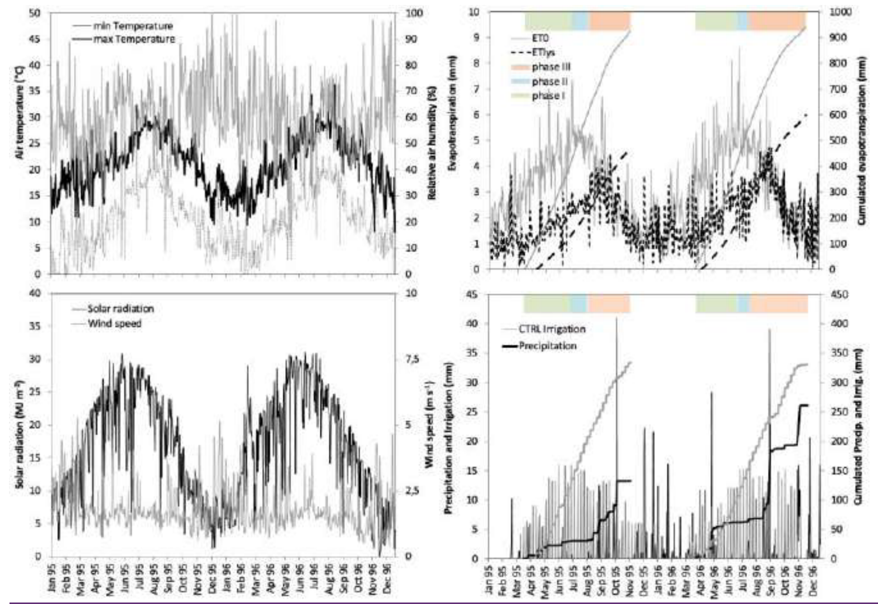

Figure 2a - d - Daily values measured in 1995 and 1996 of (a) minimum and maximum air temperature, and average relative air humidity; (b) global solar radiation, and wind at 2.0 m above the soil surface, v; (c) reference, ET_0, lysimeter evapotranspiration, ET_{lys}, and their cumulated values; (d) precipitation, P, irrigation, I, and their cumulated values.

3.2 Eco-physiological crop response to soil water deficit

Figure 3 shows the average soil water content (SWC) as a function of the indicators of plant water status, represented by the pre-dawn leaf (PLWP) and midday steam (MSWP) water potentials, for the control (CTRL) and the deficit irrigation (DI) treatments.

For the higher values of soil water content, both the indicators resulted around a constant value, corresponding to about -0.4 MPa and -1.0 MPa in terms of PLWP and MSWP, respectively; for soil water content below a certain threshold, the values of leaf/stem water potential started to sharply decrease. Similarly to what observed by Ballester et al. (2011) for the same citrus spp., this pattern was more accentuated in the 25% DI than in the 50% DI treatments.
Despite the dispersion of data makes difficult to identify a clear threshold of SWC, it is plausible to assume a value of SWC around 20%, below which both the PLWP and MSWP decline at decreasing SWC, whose lower limit resulted of about 10%. According to Pellegrino et al. (2006), this lower limit of soil water status can be considered close to the wilting point. Therefore, assuming these thresholds of SWC and a soil field capacity of 0.27 $cm^3\ cm^{-3}$, the investigated soil is characterized by a depletion of 70 mm m^{-1}, and a depletion factor (p) value of 0.41. As expected, the lowest PLWP and MSWP values were reached in the 25% treatments, due to the lower amount of water applied with irrigation. Regarding the 25% DI, the lowest values of SWC, PLWP and MSWP were registered when the timing stress was applied in the stages II and III of fruit growth.

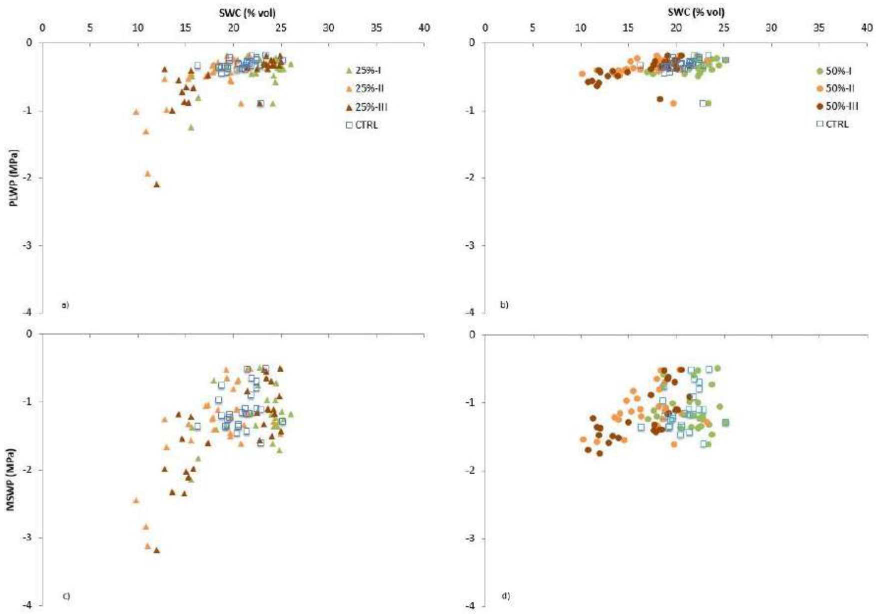

Figure 3a-d - Experimental values of Predawn (PLWP) and Midday (MLWP) Leaf Water Potential as a function of soil water content, SWC

Therefore, the intensity and timing of DI treatments affected the crop water status, which was well represented by the plant and soil water status indicators, and their relationship.
The different crop response, particularly evident when considering the dispersion of MSWP (Fig. 3c-d) for any fixed SWC, could be associated to the quite high spatial variability of soil water content associated to the microirrigation system, as well as to the different evaporative demand.

The largest dispersion of the measured variables was observed during the periods of water deficit application. This dispersion could be due to the partial wetting of the root system, with the wetted volume becoming smaller at decreasing water doses (increasing water stress levels), as well as to the three-dimensional soil moisture gradients around the water emission points characterizing the localized irrigation system. To support these hypotheses, Guswa et al. (2004) observed that for similar values of average soil water contents, in the treatments characterized by higher water stress levels (lower irrigation doses for a fixed frequency) the root volume in which the water is readily available is more limited and consequently root water uptake is lower.

3.2. Water stress integral and effects due to irrigation variables

The water stress integral (S_{MSWP}) approach is used to assess the relationship between crop water status and the total water supplied by precipitation and/or irrigation. At the same time, S_{MSWP} was related to the average irrigation dose, *Id*, supplied in each watering event. The S_{MSWP} was calculated based on the values of MSWP potential measured during the three fruit growth stages. As discussed above, the computation of S_{MSWP} started on the first of June, because no data were available before that date. The *c* value in eq. (1), which was assumed as the maximum leaf water potential measured in the control treatment was -0.8 MPa.

For all the treatments, table 1 shows the cumulated water stress integral during each of the three fruit growth stages in which the different irrigation treatments were applied in 1995 and 1996. As expected, the cumulated water stress integral was higher for the 25% DI treatments in both the experimental years, due to the lower amount of water supplied. The 25%-III treatment presented the highest S_{MSWP} value, which was higher in 1996 compared to 1995. This confirms the sensitivity of Clementina de Nules variety to water deficit applied during the stage III of crop growth, as previously observed by González-Altozano and Castel (1999) and Ballester et al. (2011). In both the experimental years, the second-highest S_{MSWP} was observed in the 25%-II treatment, due to the scarce precipitation and high atmospheric evaporative demand characterizing both the summer periods. As expected, the control treatment was associated with the smallest S_{MSWP}.

Table 1 – Summary of water stress integral, precipitation, total irrigation amount, average irrigation doses and its variability applied during the three stages of fruit growth in 1995 and 1996. The symbols μ *and* CV *represent the mean and the coefficient of variation of irrigation doses*

		Water Stress Integral, S_{MSWP}	Precipitation, *P*	Irrigation total, *I*	Irrigation doses, *Id* μ	CV
Treatment	year	[MPa]	[mm]	[mm]	[mm]	[-]
25%-I	1995	65.8	109.9	202.3	8.8	0.5
	1996	100.4	257.5	253.9	7.8	0.8
25%-II	1995	79.0	109.9	197.9	8.6	0.6
	1996	105.2	206.5	235.8	9.1	0.5

25%-III	1995	87.9	109.9	157.8	6.9	0.9
	1996	123.7	257.5	206.4	6.0	0.9
50%-I	1995	56.2	109.9	228.9	10.0	0.4
	1996	77.0	257.5	274.7	8.4	0.6
50%-II	1995	60.0	109.9	214.7	9.3	0.5
	1996	74.9	257.5	298.6	9.1	0.4
50%-III	1995	71.2	109.9	174.7	7.6	0.7
	1996	81.6	257.5	238.9	7.3	0.6
CTRL	1995	60.0	102.2	229.1	11.3	0.3
	1996	74.1	257.5	339.7	10.0	0.4

When considering the 50% DI treatments, slight differences with the CTRL were recognized in terms of S_{MSWP}, especially in 1995. As a result, the application of 50% DI treatments is likely to cause significant crop water stress only during irrigation seasons with low rainfall and high evaporative demand. Even for the 50% DI treatments, stage III of crop growth was the most sensitive to water stress.

Figure 4a-b shows the S_{MSWP} (MPa per day) of the DI treatments during the three fruit growth stages versus the total amount of water applied, e.g. precipitation and irrigation (mm), both in absolute (fig. 4a) and normalized (fig. 4b) terms. The normalization was obtained as the ratio between the variable obtained in DI treatment and the corresponding associated to the CTRL. The normalization procedure allowed excluding the effects deriving from the different atmospheric conditions registered in the two experimental years.

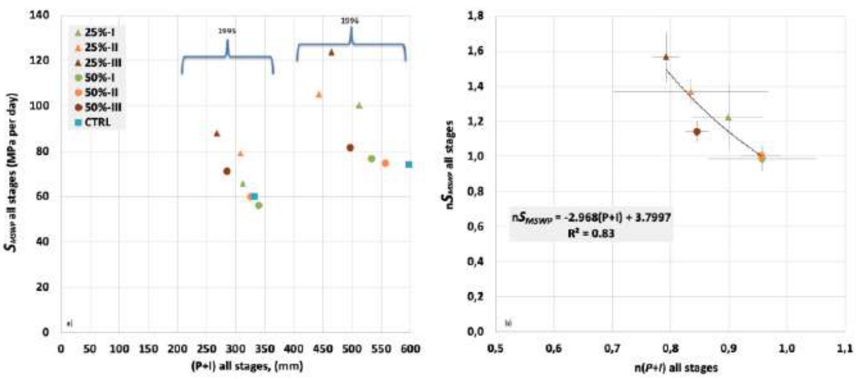

Figure 4a-b – Relationship between the water stress integral in all stages and the water supply (precipitation plus irrigation) in a) absolute and b) normalized terms

There is a trend between the S_{MSWP} for all stages and the total amount of water applied (P+I) in absolute terms for each experimental year. The values of S_{MSWP} decreased at increasing the amount of water applied. Moreover, a robust (R^2= 0.83) relationship between the normalized water stress integral, nS_{MSWP}, and the corresponding normalized water supplied, n(P+I), can be observed (Fig. 4b). The decreasing regression curve shows how the crop water stress becomes smaller as the water supplied regime of the DI treatments tend to the CTRL one. As observed in previous studies (García-Tejero et al., 2010; Goldhamer, 2012; Rallo et al., 2017), the S_{MSWP} can be used as an indicator to predict the seasonal amount of water, necessary to accomplish a desired level of stress.

Figure 5a-b illustrates the relationship between S_{MSWP} cumulated during the whole season (Fig. 5a) and stage II (Fig. 5b) of fruit growth, and the corresponding amount of irrigation applied during the same periods in both the experimental years. The relationships in Fig. 5b was compared with the relationship identified by Rallo et al. (2017) for an orange citrus orchard under DI applied during only the phase II fruit growth stage.

The value of S_{MSWP} decreased at increasing of the total irrigation, *I*, supplied, being the lowest values obtained for the control treatment (CTRL). Moreover, the 50%-I and 50%-II treatments showed values closed to the CTRL one.

As shown in Fig. 5b, the S_{MSWP} and the *I* obtained for the 25%-II and 50%-II are very close to the empirical relationship proposed by Rallo et al. (2017), confirming that during stage II of citrus fruit growth it is feasible to predict the amount of irrigation necessary to achieve the desired level of crop water stress.

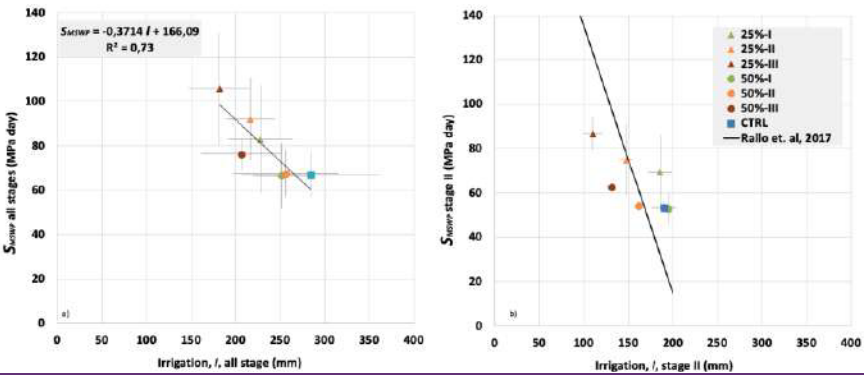

Figure 5a-b – Relationship between the water stress integral, S_{MSWP}, and the relative total amount of irrigation, I, applied during a) the whole year and b) the stage II of fruit growth. The model proposed by Rallo et al. (2017) is also reported in b)

Figure 6a-b shows the effects of the average irrigation doses applied in each watering, *Id*, on the S_{MSWP} observed during the whole period of water deficit application (Fig. 6a) and during the phase II of fruit growth (Fig. 6b). The analysis of the relationship in fig. 6a shows that S_{MSWP} also depends on the quantity of water applied in each watering, which could suggest the relevance of this irrigation management variable in the designing of the water saving strategies.

The relationship found between S_{MSWP} and *Id* under water deficit in the stage II of fruit growth (Fig. 6b) evidences a different regression curve that the one observed in Rallo et al. (2017). The different shape of the curves is probably due to the different methods used to determine the irrigation doses, *Id*, which were the lysimeter-based in this experiment, and according to the weather-based method in Rallo et al. (2017).

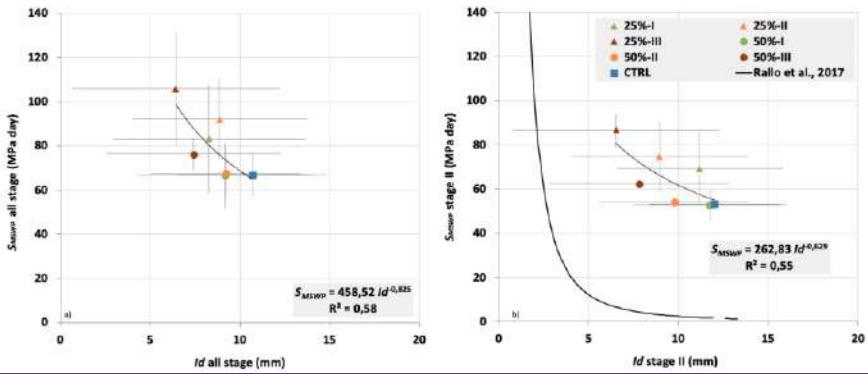

Figure 6a-b - Relationship between the S_{MSWP}, and average irrigation depth, Id, applied in each watering during a) the whole period of water deficit application and b) the phase II of fruit growth. The relationship from Rallo et al. (2017) is also displayed in b)

3.3. Effect of irrigation depth variability on crop water stress and crop yield

Figure 7a shows the relationship (R^2= 0.71) between the cumulated water stress integral, S_{MSWP}, in all the stages of fruit growth and the coefficient of variation of irrigation doses applied in each watering (CV-*Id*). The relationship confirms that the level of water stress increased with the irrigation doses variability. The most severe DI treatment (DI 25%-III) was characterized by the highest variability of CV-*Id*, whereas the control treatment was characterized by the lowest CV-*Id*. As referred, the irrigation depth was calculated based on the ET_{lys} and, thus, the *Id* depends on the atmospheric demand of the days included among consecutive watering: two, three or five days, respectively for summer, spring and autumn periods. Therefore, the irrigation volumes supplied during each irrigation event were different being based on the ET demand and the imposed reductions of irrigation volumes.

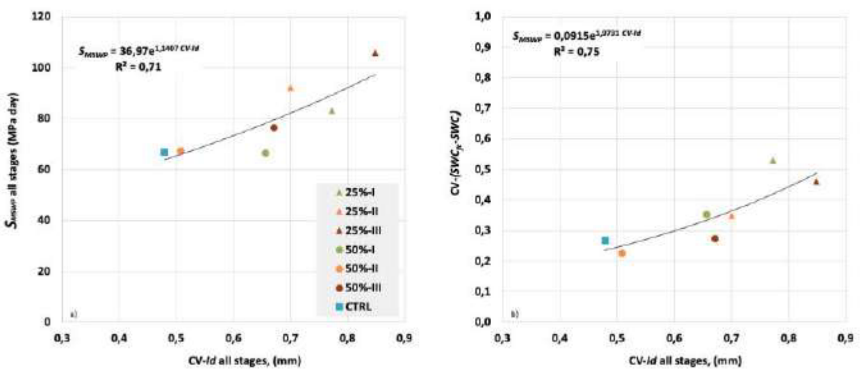

Figure 7a-b – Relationship between a) the water stress integral, S_{MSWP}, and b) the coefficient of variation of available soil water content, CV-*(SWC_{fc}-SWC_i), with the coefficient of variation of the irrigation depth,* CV-*Id*

As stated in section 3.2, the effect of *Id* variability on the cumulated water stress integral could be explained following the consideration of Guswa et al. (2004). As shown in figure 7a, the lowest variability of the supplied irrigation volume was associated to the control treatment, in which the highest irrigation doses (125% ET_{lys}) allowed to wet more homogeneously the crop root volume. Thus, crop water uptake was not affected by the soil water deficit conditions because a higher fraction of roots was moistened at soil water content close to the soil field capacity (SWC_{fc}), before starting the drying process.

On the other hand, in the DI treatments, the plant started to increase the cumulated stress originated from lower and more time-variable irrigation doses supplied in each event. The root system could have experimented soil water content quite lower than that corresponding to the field capacity, even after irrigation events, when part of the root system was differently moistened. The reasons behind this behavior are mainly due to the smaller water doses and the localized irrigation system, which generates high three-dimensional soil moisture gradients around the water emission points.

The crop water stress was consequent to the root water uptake lower than the maximum in a bigger fraction of the root volume, in which water was not readily available. Hence, the plant needed to extract water from further wet regions to compensate for the limitations occurring in the dry root volume. Therefore, the CV-*Id* depended on the magnitude of irrigation doses, because the higher quantity of water supply allowed moistening more uniformly wider fraction of the root zone, with more readily water available for the crop.

As observed, the CV-*Id* would influence the variability of the available soil water content (SWC_{fc}-SWC_i) in the root volume. For the different treatments, figure 7b shows the correlation between the coefficient of variation of the available soil water content, CV-(SWC_{fc}-SWC_i) and the CV-*Id* measured during all the fruit growth stages. The variability of the difference between the field capacity and the actual soil water content, CV-(SWC_{fc}-SWC_i) becomes higher as the CV-*Id* increases. Thus, this difference would become wider under the most severe treatment, in which the actual soil water contents are quite lower than the soil field capacity (SWC_{fc}).

The effect of irrigation depth variability, and consequently with the available water variability, on crop water stress could justify the yield decrease showed in figure 8. There is, in fact, a high correlation (R^2=0.74) between the crop yield and the observed CV-(SWC_{fc}-SWC_i).

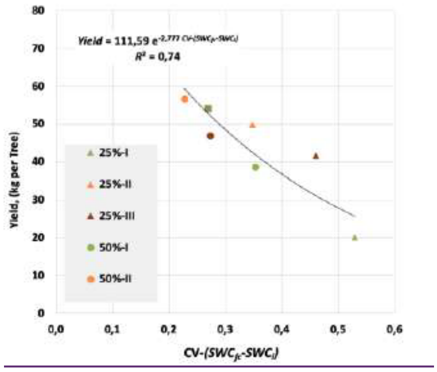

Figure 8 – Relationship between crop yield and the coefficient of variation of available soil water content, CV-*(SWC_{fc}-SWC_i), observed during the three stages of crop growth*

4. Discussion

The effects of deficit irrigation treatments on the woody perennial crops have been mainly studied by following the agronomic approach (Chai et al., 2016). However, investigating the impact of soil water deficit from an agro-hydrological point of view could help to deepen the understanding of the crop ecophysiological relationships with hydraulic and hydrological parameters of the agro-ecosystem. In this work, the relationships between the crop water status and soil water content under deficit irrigation treatments characterized by different timing and intensity have been investigated in a citrus orchard. The cumulated water stress in each of the three-fruit growth stage was correlated to parameters of irrigation management, such as the amount of water applied and the variability of the irrigation doses.

The relationship between measured predawn leaf and midday stem water potential with soil water content allowed identifying a threshold in terms of depletion factor, *p*, representing a basic parameter for a feed-back control (soil moisture-based) of irrigation scheduling. The depletion factor obtained in this study (*p*=0.41) was lower than that tabulated for citrus spp. in the FAO56 paper (Allen et al., 1998). In this sense, compared to other citrus spp. Clementina de Nules is characterized by a lower resistance to water stress, as stated in previous studies (González-Altozano and Castel, 1999; Ballester et al., 2011). Similar thresholds of soil moisture content have been reported for citrus spp. and woody perennial crops in Mediterranean areas by plotting leaf water potential with measurements of soil water content (Ginestar and Castel, 1996; Rallo and Provenzano, 2013 Agüero Alcaras et al., 2016; Rallo et al., 2017). In the same line, a previous study by Rallo et al. (2017) carried out in an orange orchard reported a threshold of soil depletion when MSWP started to decrease corresponding to a p-factor equal to 0.20; this value, lower than that obtained in this study, could have been due to the different soil texture, citrus spp., age, crop practices and irrigation management. Continuous and automatic measurements of soil water content have been suggested as accurate methods for the feedback control of irrigation in fruit trees (Agüero Alcaras et al., 2016; Gasque et al., 2016; Rallo et al., 2017; Vera et al., 2013 Vera et al., 2019; Domínguez-Niño et al., 2020). Therefore, the identified threshold of soil water status is useful to design accurate and easy site-specific irrigation scheduling protocol in Clementina de Nules.

The cumulated water stress index (S_{MSWP}) was used to assess the link between the crop water status in the three fruit growth stages and the total water supplied (precipitation plus irrigation) in the field. It was observed that the S_{MSWP} is an useful indicator for scheduling irrigation in citrus trees when a degree of soil water deficit is imposed, and for evaluating the effects of soil water deficit on the crop water status. Literature for citrus and woody perennial crops has reported strong correlations between indicators of crop water stress with actual evapotranspiration, trunk growth, volumetric soil water content, irrigation depth and crop yield (Ginestar and Castel., 1996a; Gasque et al., 2016; De la Rosa et al., 2016; Rallo et al., 2017; Gonzalez-Benecke and Dinger., 2018; Martinez-Gimeno et al., 2018). Specifically, Rallo et al. (2017) observed a robust relationship between the S_{MSWP} and irrigation depth in an orange orchard under deficit irrigation applied during stage II of crop growth. Overall, the response of the citrus crop to the imposed stress conditions varied in terms of timing and intensity (magnitude of the imposed deficit), confirming what already stated in previous studies on citrus orchards (Glodhammer, 2012, Ballester et al., 2014). Moreover, in line with the conclusions of Treeby et al. (2007), the crop response to the lower water supply depends on the timing and severity of the treatments, as well as on the species, soil type, and other site-specific factors.

Even the dispersion characterizing the soil moisture measurements and commonly associated to the drip-irrigated orchards, which was higher in the most severe DI treatments, has been observed in previous studies (Intrigliolo and Castel, 2004; Rallo et al., 2017). Nonetheless, to our knowledge, there are no studies that have related the effects produced on crop yield by the magnitude and variation of irrigation doses (*Id*). As evidenced by Guswa et al. (2004), higher the variability of soil water content, wider the fraction of the root zone not wetted up to the soil field capacity. This lag determines the lowering of the plateau of the water stress function and hence the increase of the crop stress level. This assumption was confirmed by the fact that the coefficient of variation of the irrigation doses (CV-*Id*) affects the crop stress level and, at the same time, influences the variability of the difference between the field capacity and the actual soil water content, CV-$(SWC_{fc}$-$SWC_i)$. Hence, the variability of the available water, CV-$(SWC_{fc}$-$SWC_{i,}$ due to the combined effect of the micro-irrigation system, its management and the adopted water-saving protocol, can have effects on crop yield.

5. Conclusions

The results achieved in this study reinforce the importance to consider, in woody perennial crops, the relationships between hydrological and hydraulic variables as indicators of irrigation management. The ecophysiological relationships evidence the significance of monitoring the soil-plant-atmosphere continuum to define accurate thresholds of allowable soil depletion for precise irrigation scheduling. A threshold in terms of depletion factor (*p*=0.41) was recognized for Clementina de Nules to design location-specific irrigation scheduling protocol.

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Large dispersion of MSWP measurements for any fixed SWC data was observed in the most severe deficit irrigation treatments (e.g. 25% DI), as a consequence of the localized irrigation system and the variability of the applied irrigation doses. At the same time, the tree water status was differently affected by the timing and the severity of applied stress conditions.

The cumulated water stress integral (S_{MSWP}) has been validated as an appropriate crop water status indicator for irrigation scheduling to predict specific levels of crop water stress. The S_{MSWP} was well correlated to the total amount of water supplied by precipitation and irrigation and the average irrigation doses applied on each watering event, confirming the significance of these hydraulic variables to design appropriate water-saving strategies. The normalized S_{MSWP} index, whose calculation allows accounting for the different atmospheric conditions observed during the two experimental years, was highly correlated to the normalized total amount of water supplied.

The variability of the irrigation doses (*CV-Id)* produced effects either on the crop water status and yield production. The relationship between the S_{MSWP} and the *CV-Id* showed that the deficit irrigation treatments characterized by the relatively higher variability of irrigation doses are associated with the higher crop stress levels observed on the crop. The lower and more time-variable irrigation doses in deficit treatments moistened wider fractions of the root zone with water not readily available for the crop. Thus, *CV-Id* influences the variability of the available soil water content in the root volume, CV-(SWC_{fc}-SWC_i), which affects the final performance in terms of crop yield.

Therefore, the accurate assessment of the impact of deficit irrigation on crop water status and agronomic performance has to consider variables of irrigation management, such as the irrigation amount and the variability of irrigation doses. When designing a drip irrigation system, it is also necessary to consider the fraction of the root volume to wet.

CRediT authorship contribution statement

Angela Puig-Sirera: Conceptualization, Methodology, Data curation, Writing - original draft. **Giuseppe Provenzano:** Validation, Writing - review & editing. **Pablo González-Altozano:** Investigation, Validation, Writing - review & editing. **Diego Intrigliolo:** Validation, Writing - review & editing. **Giovanni Rallo:** Conceptualization, Methodology, Data curation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The research was carried out in the frame of "Progetto OP-Illuminati Frutta-Rallo" (University of Pisa, 1048 MIPAF-Regione Toscana) and "ATMOSMART-dimostratore tecnologico" (University of Pisa).

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