



Water retention potentials of Italian soils and physiological responses of potted golden kiwifruit

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ABSTRACT

Correct water management of golden kiwifruit vines, besides being essential for reaching high yield and fruit quality, is also fundamental to keep plants healthy and avoid useless water loss. The objectives of this trial were to: 1) assess the water retention curve in typical soils for the kiwifruit production in Italy; 2) evaluate the response of potted Zezy002 plants to the variation of soil moisture, in term of leaf gas exchange and stem water potential. Plants grown on each soil were divided into two groups: 3 plants were irrigated maintaining soil water at field capacity (control); 4 plants were subjected to water stress as follows: irrigation rate was reduced 50 % of the evapotranspiration rate for one week, then irrigation was suspended. Two days after water suspension, 2 of the 4 stressed plants were irrigated as for the control plants (recovery), the other 2 vines were not irrigated (stress). Each pot was provided with a chalk potentiometric probe so that soil matric potential was constantly monitored. During the experiment leaf gas exchange and stem water potential were daily measured. After irrigation stop, a decrease of net photosynthesis, transpiration and stomatal conductance were observed, on the other hand, intercellular CO₂ concentration showed the opposite trend. Specific behavior has been detected for the two loam soils tested (here labelled as “sand-clay-silt” and “silt” soils). At wilting point, established when plant photosynthetic activity stopped, soil matric potential, measured by chalk probes, ranged between -1.8 and -2.0 MPa in all soils with the exception of “sandy-clay-silt”, where it was -0.49 MPa. Soil matric potential at field water capacity ranged between -20 and -50 kPa in all soils with the exception of “silt” soil (-140 kPa). This peculiar behavior will be likely due to specific pore size distribution or poor-connected pores, however further investigations are needed.

1. Introduction

Kiwifruit Zezy002 (*A. chinensis* var. *chinensis*) is an excellent fruit crop in term of yield and quality and the correct water management is a powerful tool to achieve both high vine yield, fruit quality at harvest and after storage.

The Mediterranean region is characterised by dry summers, with high temperatures and little or no precipitations, consequently irrigation is used to compensate for inadequate rainfall for most cultivated plants, avoiding restriction of physiological processes induced by drought stress (Flexas et al., 2004). Long-term models predict a decrease of natural water resources for the Mediterranean agriculture as a consequence of changing climate (Katerji et al., 2006; Swann, 2018); consequently,

plants (especially those sensitive to water shortage) could suffer from drought alone or in combination with other typical climatic parameters such as high irradiance, elevated air temperatures, and high leaf-to-air vapor pressure deficit. Kiwifruit plants are, among fruit trees cultivated in Italy, those with higher need of water, mainly due to their high vegetative growth and leaf surface.

Water deficit negatively affects plant growth since it adversely influences several physiological and biochemical responses. Inhibition of photosynthesis is one of the primary response of drought stress and is the consequence of stomatal closure, chlorophyll degradation, and impairment of photochemical apparatus (Bohnert and Jensen, 1996) with final reduction of carbohydrate synthesis (Miller et al., 1998). If water becomes a limiting factor, fruit weight and dry matter (DM) concentration

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at harvest are reduced (Judd et al., 1989; Prendergast et al., 1987).

Soil water availability (WA), the difference between the water at field capacity (FWC) and at wilting point (WP), can be estimated through soil matric potential (Ψ_m), as a percentage of water on soil dry weight, as stem water potential (Ψ_w), carbon fixation, etc. Since soil texture affects the soil holding capacity and the availability of water for root uptake, to define the correct irrigation plan, soil water content should be determined according to soil properties. So far, it is not clear the response of Zezy002 to a reduction of soil water availability, and what is the soil moisture threshold, below which, leaf carbon (C) assimilation, and consequently fruit size and yield are reduced. Previous studies on Hayward (Xiloyannis et al., 1999) evidenced that water use efficiency increases with the decrease of leaf transpiration; however, fruit size responds negatively to water stress (Miller et al., 1998).

The objectives of this trial were to: 1) assess differences in soil moisture and soil Ψ_m of some of the typical soils of the Italian kiwifruit industry; 2) observe the effect of soil moisture reduction on potted Zezy002 plant in term of leaf gas exchange and stem Ψ_w .

2. Material and methods

2.1. Plants material and treatments

The study was carried out at the experimental station of the Department of Agricultural and Food Science of the University of Bologna (44°32'57"N 11°24'43"E), in the north side of the metropolitan area of the city, on 35, 4-year-old, potted Zezy002 (*A. chinensis* var. *chinensis*) plants, grafted on *A. chinensis* var. *deliciosa*. Plants were trained to "pergoletta" with a 0.5-m long cordon holding 4–5 shoots. During the experiment, air temperature was monitored with a digital temperature and humidity data logger (EL-USB-2 Lascar, Wiltshire, UK; Fig. 1).

The pots were filled with 5 different soils, collected from different kiwifruit growing areas in Italy and characterized by different texture (from loamy sand to clay; Schoeneberger et al., 2012 - Table 1): loamy sand (Calabria - 38° 25' 55.934" N, 16° 2' 35.153" E; labelled in this paper as "sand"), loam (Basilicata - 40° 15' 35.820" N, 16° 42' 1.260" E; here a "sand-clay-silt"), loam (Emilia-Romagna - 44° 32' 54.359" N, 11° 23' 13.913" E; here as "silt"), clay (Lazio - 41° 26' 42.374" N, 12° 48' 19.012" E; here as "clay-silt") and clay (Lazio - 41° 32' 43.951" N, 12° 49' 52.165" E; here as "clay"). In this paper soils were labelled in this paper

according to their clay content ("clay">"clay-silt">"sandy-clay-silt">"silt">"sand"; Table 1)

According to the soil, the vines were divided into 5 groups of 7 plants each. At the beginning of the growing season plants were fertilized twice for a total amount (in g plant⁻¹) of 1.7 nitrogen (N); 0.8 phosphorus (P); 1.25 potassium (K) and 0.02 iron (Fe).

Before bud burst, a chalk potentiometric probe was installed in each pot. The probe consists in pair of highly corrosion-resistant electrodes that are embedded within chalk; electric current is applied to the probes to obtain an electrical circuit. The lower the humidity of the chalk (in equilibrium with soil moisture) the higher the resistance, that is thus inversely correlated to soil water content. The sensors constantly monitored soil Ψ_m ; data were collected every 15 min and transmitted to a cloud-based web platform provided by Ifarming srl (Imola, Bo, Italy), a company specializing in precision farming technologies. According to soil Ψ_m , irrigation started at the beginning of May, in order to maintain soils at FWC that was established by watering the pots until soil saturation, and then waiting 1 h to allow the water in excess to drain outside the pot. At this point gravimetric force equals soil adhesion and cohesion forces.

Starting from July 13th, plants from each soil were divided into two groups: 3 plants were irrigated as described above to maintain soil at FWC (control); 4 plants were gradually stressed by reducing the irrigation rate to 50 % of the evapotranspiration (ET) as measured the previous day by weight. Pot weight was recorded by a digital scale (Scale House, PM-30, DINI ARGEO S.r.l., Modena, Italy). On July 23rd, in pots receiving 50 % ET, irrigation was suspended (stress); while control pots were manually irrigated by returning the water lost the day before and measured by weight. On July 25th, two of the four stressed plants were irrigated as for the control plants (recovery) to assess the recovery capacity and any eventual damages suffered during stress; the other 2 plants were not irrigated.

2.2. Plants and soil measurements

Every day, from July 21st to July 28th, leaf gas exchange was measured on one well light-exposed leaf per plant using an open circuit gas exchange system equipped with a led-light source (LI-6400, LI-COR, Lincoln, Nebraska, USA). In detail, leaf net photosynthesis rate (P_n), stomatal conductance (g_s), intercellular CO₂ concentration (C_i), and transpiration rate (E) were measured. Light intensity, inside the

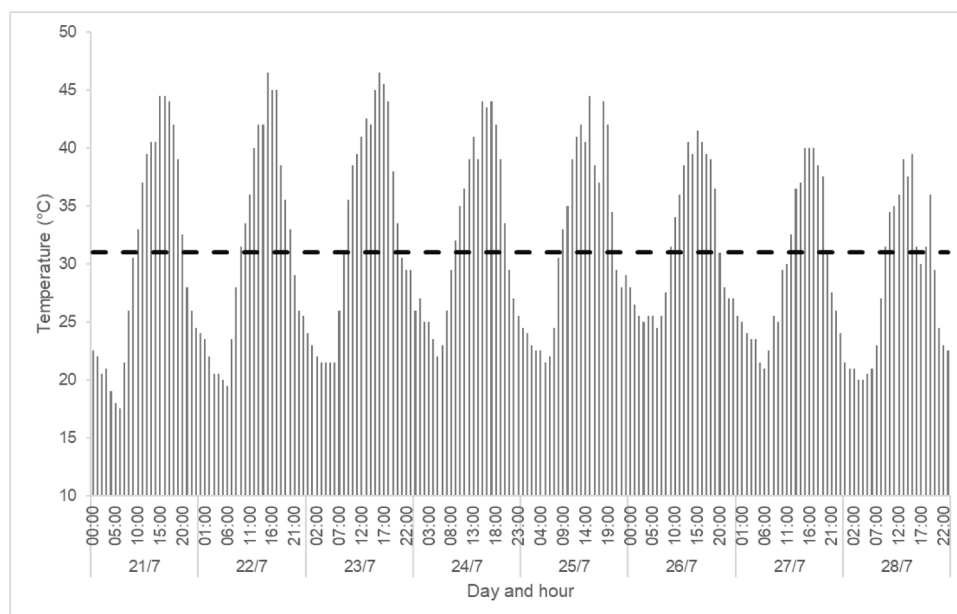


Fig. 1. Daily air temperature (°C) during the experiment. Dotted line is the average air temperature.

Table 1
Selected characteristics of the soils used in the experiment.

Characteristic	unit	sand	sand-clay-silt	silt	clay-silt	clay
Sand	g kg ⁻¹	820	620	340	300	400
Silt	g kg ⁻¹	100	120	420	280	170
Clay	g kg ⁻¹	80	260	240	420	430
Bulk density	g cm ⁻³	1.22	1.24	1.27	0.948	0.934
pH		6.5	7.7	8.2	7.0	7.2
Lime	g CaCO ₃ kg ⁻¹	0	traces	120	traces	0
Active lime	g CaCO ₃ kg ⁻¹	–	–	45	0	–
Organic matter	g kg ⁻¹	21.5	10.1	20.2	25.5	14.7
CEC	cmol(+) kg ⁻¹	6.5	15.4	22	20.5	21.7
EC	mS cm ⁻¹	0.08	0.32	–	0.22	0.17
N total	g kg ⁻¹	1.31	0.7	1.25	1.53	0.93
P available	mg kg ⁻¹	25	59	25	20	10
K exchangeable	mg kg ⁻¹	68	184	182	199	661
Mg exchangeable	mg kg ⁻¹	94	420	125	440	760
Ca exchangeable	mg kg ⁻¹	780	2200	4096	3150	2600
Fe available	mg kg ⁻¹	119	14	12	35	34
Mn available	mg kg ⁻¹	5	6.4	2.8	60	51.6
Zn available	mg kg ⁻¹	0.7	1.2	2.4	2.4	2.8
Cu available	mg kg ⁻¹	2.2	1.7	2.7	4	5

CEC = cation exchange capacity; EC = electrical conductivity; N = nitrogen, P = phosphorous, K = potassium, Mg = magnesium, Ca = calcium, Fe = iron, Mn = manganese, Zn = zinc; Cu = copper.

chamber, was maintained at the natural photosynthetic active radiation level experienced by the leaves immediately before the measurements.

From July 22nd to July 26th, stem Ψ_w was measured with a pressure chamber, on one leaf per plant, previously wrapped in aluminum foil

and closed into a plastic bag, at least one hour before excision, to allow leaf and soil moisture equilibration (Naor et al., 1995; Turner, 1988). Pressure was gently applied using a pump-up pressure chamber (PMS Instrument Company, Albany, OR, USA).

Abscised leaves and fruits dropped as a consequence of stress were daily collected and weighted.

Every day (from July 22nd to July 26th), a soil sample was collected with an auger, fresh and dry weight measured to evaluate soil moisture (w:w).

Soil Ψ_w was constantly measured by chalk potentiometric probes as described in 2.1.

2.3. Statistical analysis

All data were statistically analysed as in a complete randomized experimental design; when analysis of variance showed effects statistically significant ($P \leq 0.05$), means were separated by Student Newman-Keuls (SNK) test. Leaf gas exchange data were also analysed, using the R statistical software, according to the canonical discriminant analysis (CDA), that is a dimension-reduction technique related to principal component analysis and canonical correlation and it finds linear combinations of the quantitative variables that provide maximal separation between classes or groups. Pearson correlation coefficient was employed to estimate the linear relationship between soil parameters and plant physiological plant responses.

The data are presented in 2 ways in order to meet the objectives of the experiment: 1) evaluate the effect of water stress on plants; 2) compare the response of different soils to drought stress.

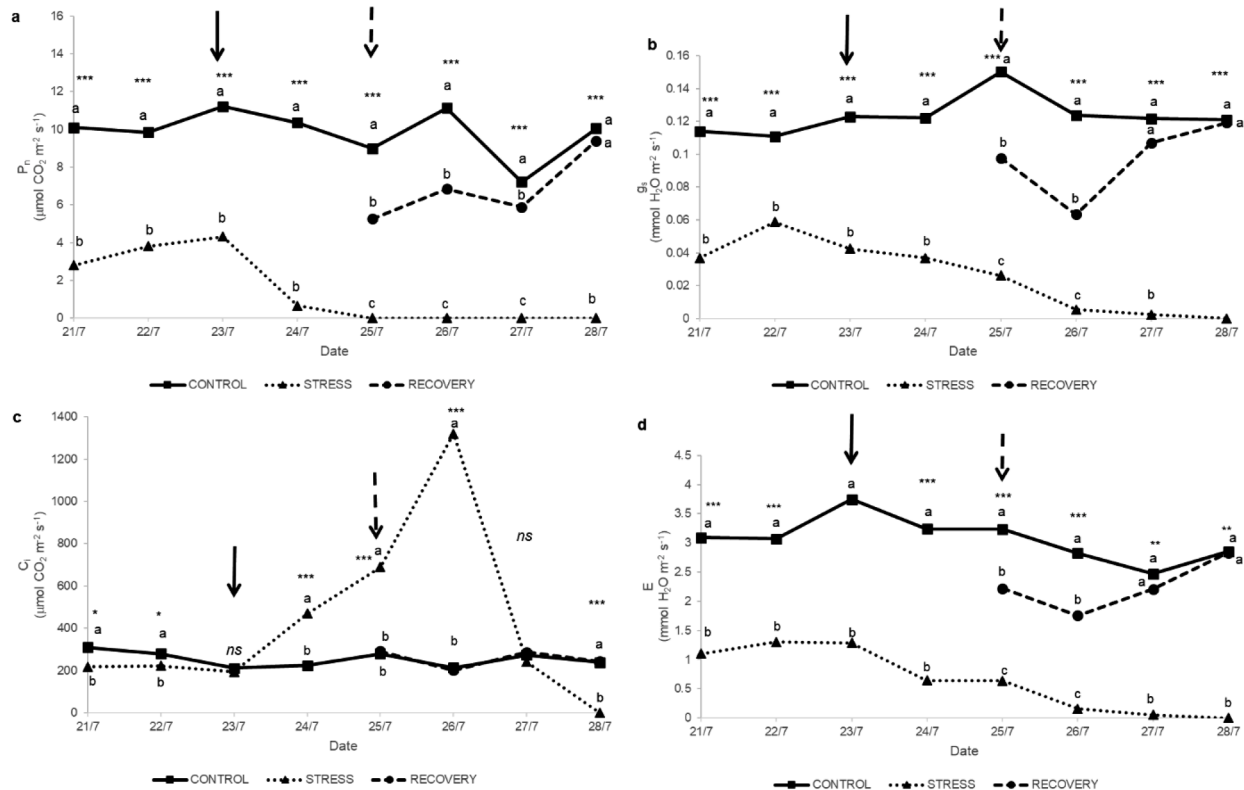


Fig. 2. Effect of water stress on net photosynthesis (P_n ; a), stomatal conductance (g_s ; b), intercellular CO_2 concentration (C_i ; c) and leaf evapotranspiration (E; d) of Zezy002 plants, during the experiment. Full arrow indicates the first day of water suspension; dotted arrow the day of re-watering. Each point is the average of 15 plants for control and 10 plants for stress and recovery. ns, *, **, ***: effect not significant or significant at $P \leq 0.05$, $P \leq 0.01$ and $P \leq 0.001$, respectively. Values followed by the same letter are not statistically different according to Student Neuman Keul test ($P \leq 0.05$).

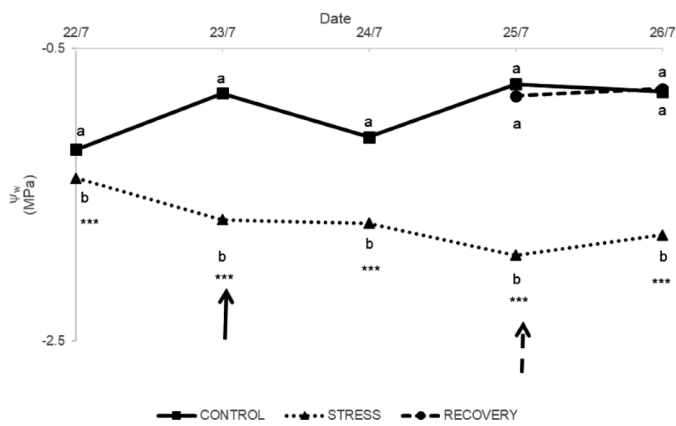


Fig. 3. Effect of water stress on stem water potential (stem Ψ_w) of Zezy002 plants, during the experiment. Full arrow indicates the first day of water suspension; dotted arrow the day of re-watering. Each point is the average of 15 plants for control and 10 plants for stress and recovery. ***: effect significant at $P \leq 0.001$. Values followed by the same letter are not statistically different according to Student Neuman Keul test ($P \leq 0.05$).

3. Results

3.1. Evaluation of the effects of water stress on plant response

After one week of water reduction (50 % ET), P_n decreased significantly in all soils, to become, on average close to zero two days after the suspension of irrigation (Fig. 2a). When water was re-applied (recovery plants), P_n immediately increased to intermediate values, higher than stress and lower than control, until July 28th (4 days after re-watering), when the values became similar to control plants (Fig. 2a). As for P_n , the reduction of water supply by 50 % ET induced a decrease of stomatal conductance in comparison to control leaves (Fig. 2b). Recovery plants showed an increase of g_s immediately after the re-start of the irrigation, reaching the same values of control plants the third day after water re-supply (Fig. 2b). Intercellular CO_2 concentration showed constant and lower values in both control and recovery plants than stress ones (Fig. 2c). The latter showed an increase of C_i that peaked on July 26th and a sharp decrease afterwards, with values that became lower than control and recovery plants on July 28th (Fig. 2c). Leaf transpiration significantly decreased as a response of water reduction and subsequent suspension, in comparison to control plants (Fig. 2d). When water was re-supplied, the values of leaf transpiration increased, reaching the values of control plants on July 27th (Fig. 2d).

Stem Ψ_w was significantly lower in stress in comparison to control

plants at all sampling days; after re-watering, stem Ψ_w increased immediately (recovery plants) reaching values similar to control (Fig. 3).

Soil moisture, measured as a percentage (w:w) of soil dry weight, was lower in stress than in control pots; re-watering induced a significant increase of soil moisture that reached the value of control the same day (Fig. 4a). Water supply interruption quickly promoted a decrease of soil Ψ_m to levels of WP; after the re-watering, soil Ψ_m showed an increase that reached the same values of the control on July 28th (Fig. 4b). Matric potential of well-watered soil (control) always showed values near the FWC (-30 kPa).

The DCA carried out on leaf gas exchanges from July 21st to July 28th, clearly separated plants in relation to water availability; stress plants were positioned in the opposite side of control and recovery that were separated as well, but on the same side of the graph (Fig. 5). Intercellular CO_2 concentration characterized the group of stress plants, while P_n , g_s and E mainly represented control plants; stem water potential (SWP) was intermediate between recovery and control plants (Fig. 5).

3.2. Plant physiology and soil hydraulic characteristics in response to water supply: comparison of the different soils

Net photosynthesis was not significantly influenced by the type of soil in control plants, with the only exception of the values measured on July 28th when plants grown in clay-silt soil showed the highest values (Fig. 6). On July 21st, in stress plants, silt soils induced higher values than clay-silt, while the other soils showed intermediate values; on July 24th, plants in silt soil showed the highest values (Fig. 6). The suspension of irrigation induced a decrease of C fixation that became zero on July 24th for all soils, except for silt soil that became zero one day later, on July 25th (Fig. 6). In recovery plants, an effect of soil on net photosynthesis was observed only on July 28th, with higher P_n values induced by silt soils in comparison to sand and clay ones; clay-silt and sand-clay-silt showed intermediate values (Fig. 6).

The type of soil affected stomatal conductance with a trend similar to that observed for P_n ; in stress conditions the values almost zeroed on July 27th for all soils but silt and sand-clay-silt ones, that showed complete stomatal closure one day later (data reported in supplemental material-fig. S1).

Leaf intercellular CO_2 concentration of control plants in general showed few differences among soils. In fact, only on July 22nd and 27th plants grown in clay-silt soil showed higher values than in the other soils (Fig. 7). stress plants grown on clay-silt soil presented the highest values on July 21st, while those on silt soil showed the lowest C_i on July 25th (Fig. 7). The values reached zero on July 27th for all soils with the

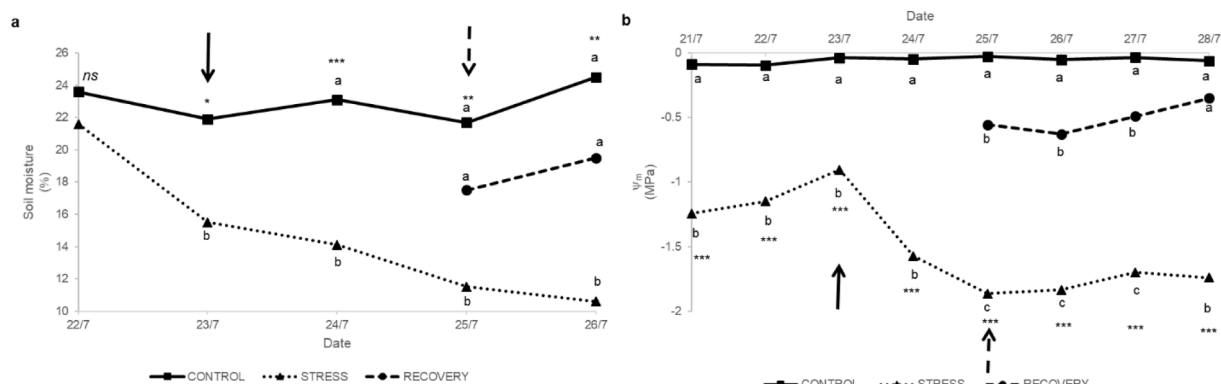


Fig. 4. Effect of water stress on soil moisture (a) and soil matric potential (soil Ψ_m ; b) during the experiment. Full arrow indicates the first day of water suspension; dotted arrow the day of re-watering. Each point is the average of 15 plants for control and 10 plants for stress and recovery. ns, *, **, ***: effect not significant or significant at $P \leq 0.05$, $P \leq 0.01$ and $P \leq 0.001$, respectively. Values followed by the same letter are not statistically different according to Student Neuman Keul test ($P \leq 0.05$).

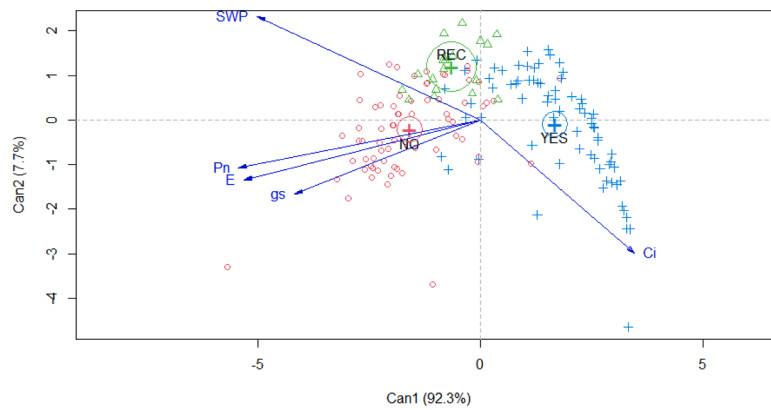


Fig. 5. Discriminant canonical analysis on leaf gas exchanges in relation to stress. All data from July 21st to July 28th were included; only exception are data of stem water potential that were collected from July 22nd to July 26th. Arrows represent the direction of each parameter analyzed. NO = control plants; REC = recovery plants; YES = stress plants. P_n = net photosynthesis; g_s = stomatal conductance; C_i = intercellular CO₂ concentration; E = leaf transpiration; SWP = stem water potential.

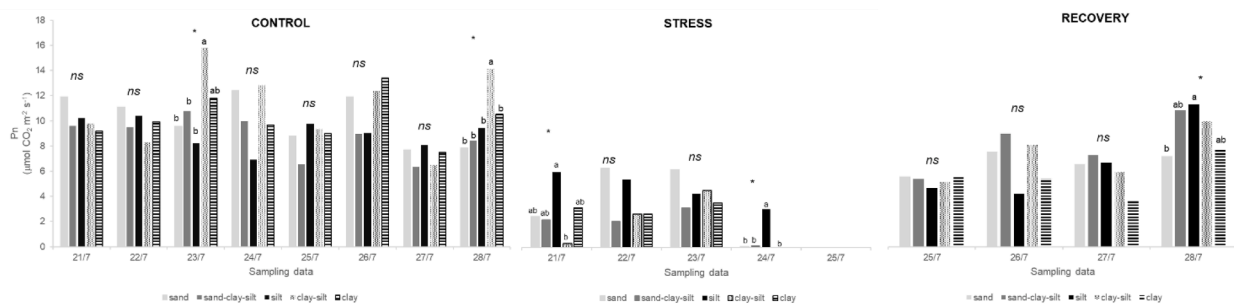


Fig. 6. Effect of soil type on net photosynthesis (P_n) in control, stress and recovery plants. On July 21st and 22nd, each bar is the average of 7 plants; from July 23rd, each bar is the average of 3 plants for control and 2 plants for stress and recovery. ns, *: effect not significant or significant at P ≤ 0.05, respectively. Values followed by the same letter are not statistically different according to Student Neuman Keul test (P ≤ 0.05).

exclusion of silt and sandy-clay-silt that zeroed the following day (Fig. 7). The C_i values of recovery plants did not evidence any differences among soils (Fig. 7).

On July 26th, control plants grown in clay-silt soil showed an E higher than in silt and sandy-clay-silt soils, while the other soils promoted intermediate values (Fig. 8); on July 28th, clay-silt soil induced a higher E value compared to the other soils (Fig. 8). On July 21st, stress plants grown in silt soil showed a higher E than those in clay-silt; while on July 25th, the value was higher than in the other soils (Fig. 8). Leaf E zeroed on July 27th in plants in sand-clay-silt, clay and clay-silt soils, and the day after in silty and sandy soils (Fig. 8). In recovery plants, leaf evapotranspiration was not significantly influenced by the type of soil (Fig. 8).

On July 23rd, in control plants, stem Ψ_w was lower in silt than in the

other soils, while on July 24th in stress plants, stem Ψ_w was higher in silt than in the other soils (Fig. 9). No differences were observed in other dates and in recovery soils (Fig. 9).

Soil moisture was affected by soil type and it showed a decreasing trend from the finest to the coarser soil (Fig. 10). In detail, on July 22nd and 25th, in control conditions, clay and clay-silt soils evidenced higher moisture than the other soils; on July 23rd, clay soil showed a moisture similar to clay-silt and higher than the other soils; while on July 26th, clay soil induced the highest values, followed by clay-silt that was higher than sand and sandy-clay-silt, but similar to silt one (Fig. 10). On July 22nd, silt soil evidenced a moisture higher than sand and sandy-clay-silt while on July 23rd, 24th and 26th the values of these soils were intermediate (Fig. 10). On July 21st, 25th and 26th in stress conditions, we observed values of soil moisture similar in clay, clay-silt and silt soils and

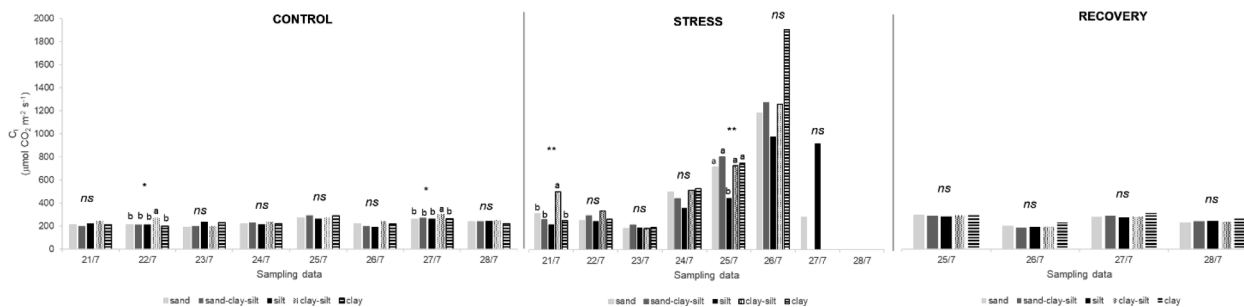


Fig. 7. Effect of soil type on intercellular CO₂ concentration (C_i) in control, stress and recovery plants. On July 21st and 22nd, each bar is the average of 7 plants; from July 23rd, each bar is the average of 3 plants for control and 2 plants for stress and recovery. ns, * and **: effect not significant or significant at P ≤ 0.05 and P ≤ 0.01, respectively. Values followed by the same letter are not statistically different according to Student Neuman Keul test (P ≤ 0.05).

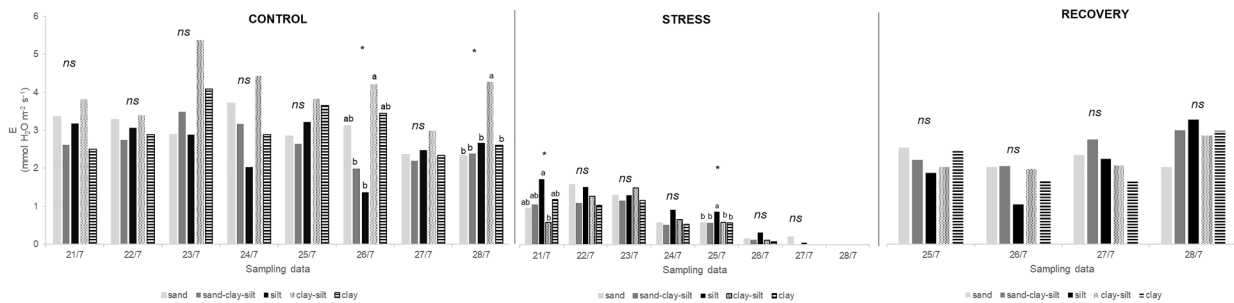


Fig. 8. Effect of soil type on leaf evapotranspiration (E) in control, stress and recovery plants. On July 21st and 22nd, each bar is the average of 7 plants; from July 23rd, each bar is the average of 3 plants for control and 2 plants for stress and recovery. ns, *: effect not significant or significant at $P \leq 0.05$, respectively. Values followed by the same letter are not statistically different according to Student Neuman Keul test ($P \leq 0.05$).

higher than sandy-clay-silt and sand ones. On July 22nd and 23rd, the highest moisture was measured in clay soil, followed by clay-silt, silt, sandy-clay-silty and sand (Fig. 10). After recovery, on July 25th, clay and clay-silt soils evidenced the highest moisture, followed by silt and sandy-clay-silt that were similar and higher than sand soil (Fig. 10). On July 26th, the highest moisture was observed in clay and clay-silt soils, followed by silt, sandy-clay-silt and sand (Fig. 10).

On July 22nd, 23rd, 24th, 25th and 26th silt soil showed the lowest Ψ_m in control conditions; no significant differences were observed in other days (Fig. 11). In stress condition, clay, clay-silt and sandy soils evidenced a decrease of Ψ_m in comparison to silt (on July 21st and 22nd) and sandy-clay-silt soils (on July 22nd); on July 24th, 25th and 26th sandy-clay-silt soil showed the highest values, while no significant differences were observed in the other sampling dates (Fig. 11). As a consequence of water re-supply, on July 25th, sand and clay-silt soils showed similar values, but higher than clay and similar to silt and sandy-clay-silt; on July 26th and 27th no differences among soils were observed, while on July 28th clay, clay-silty and sandy soils showed similar values, higher than silt and sandy-clay-silt (Fig. 11).

Soil matric potential at FWC (measured on control soils as the means of all the data collected in the experiment) ranged between -0.05 to -0.02 MPa in all soils with the exception of silt (-0.14 MPa). The estimated WP ranged between -1.8 and -1.9 MPa in all soils with the exception of sand-clay-silt where it was -0.49 MPa (Table 2).

Soil Ψ_m and stem Ψ_w were correlated to leaf gas exchange parameters showing positive correlation with P_n , g_s , E and stem Ψ_w and negative with C_i , with the exclusion of July 23th and 27th when no correlation was observed and July 28th, when a positive correlation between soil Ψ_w and C_i was observed (Table 3). Soil moisture was positively correlated to P_n , g_s , E and stem Ψ_w starting from July 23rd, the correlation with C_i was not significant on July 22nd, 23rd and 24th and negative on July 25th and 26th (Table 3).

Soil Ψ_m was positively correlated to soil moisture in all soils (Fig. 12).

Fruit drop started in clay soil on July 25th (three days after water suspension); the following day also plants grown in clay-silt and sandy-clay-silt evidenced fruit drop that was higher in the former than the latter (Table 4). Five days of water suspension promoted a fruit drop more dramatic in sand, clay and clay-silt soils than in sandy-clay-silt,

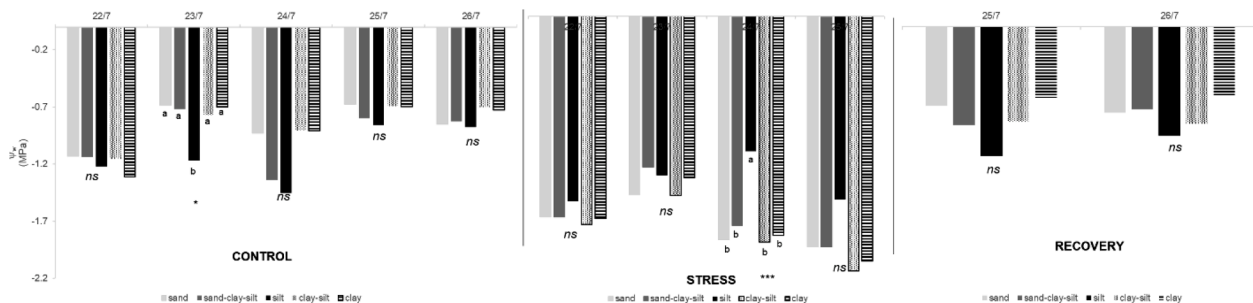


Fig. 9. Effect of soil type on stem water potential (stem Ψ_w) in control, stress and recovery plants. On July 22nd, each bar is the average of 7 plants; from July 23rd, each bar is the average of 3 plants for control and 2 plants for stress and recovery. ns, *, ***: effect not significant or significant at $P \leq 0.05$ and $P \leq 0.001$, respectively. Values followed by the same letter are not statistically different according to Student Neuman Keul test ($P \leq 0.05$).

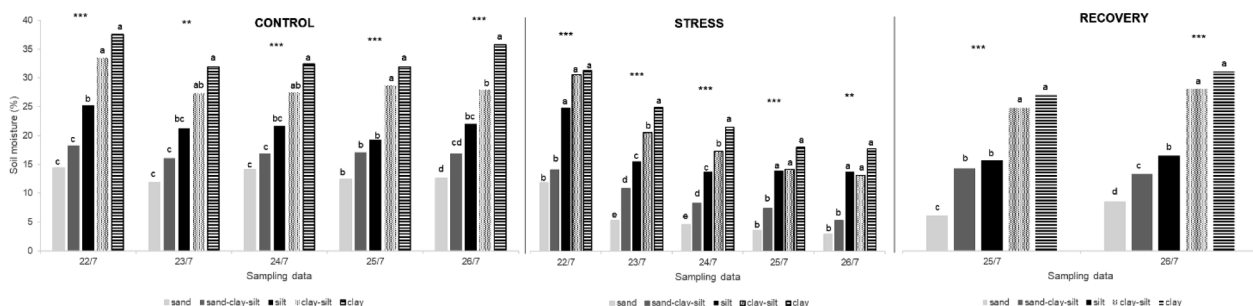


Fig. 10. Effect of soil type on soil moisture in control, stress and recovery plants. On July 22nd, each bar is the average of 7 plants; from July 23rd, each bar is the average of 3 plants for control and 2 plants for stress and recovery. ns, **, ***: effect not significant or significant at $P \leq 0.01$ and $P \leq 0.001$, respectively. Values followed by the same letter are not statistically different according to Student Neuman Keul test ($P \leq 0.05$).

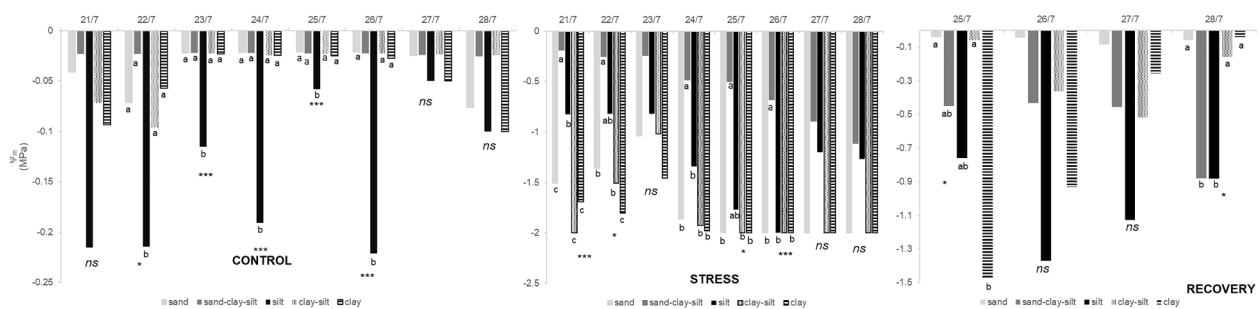


Fig. 11. Effect of soil type on soil water potential (soil Ψ_m) in control, stress and recovery plants. On July 21st and 22nd each bar is the average of 7 plants; from July 23rd, each bar is the average of 3 plants for control and 2 plants for stress and recovery. ns, *, **, ***: effect not significant or significant at $P \leq 0.05$, $P \leq 0.01$ and $P \leq 0.001$, respectively. Values followed by the same letter are not statistically different according to Student Neuman Keul test ($P \leq 0.05$).

Table 2

Soil matric potential (Ψ_m) at field capacity (FWC), wilting point (WP), and at plant death.

SOIL	FWC (-MPa)	WP (-MPa)	Plant death (-MPa)
Sand	0.037	1.87	2.00
Sand-clay-silt	0.023	0.49	0.68
Silt	0.145	1.77	2.00
Clay-silt	0.050	1.98	2.00
Clay	0.039	1.93	2.00
Replicates	$n = 56^*$	$n = 4$	$n = 2$

* : number of observations 7 by 8 dates = 56.

while silt soil did not show any fruit abscission until July 29th (Table 4).

Leaves abscission in stress plants started, in clay soil, one day after total water suspension (July 24th, Table 5). On July 26th all soils but silt induced a similar leaf fall, while on July 27th plants in clay, clay-silt and sand soil evidenced a higher leaf fall than silt, while sandy-clay-silt showed intermediate values (Table 4).

On July 28th and 29th only plants in silt soils showed some leaf fall (Table 5).

4. Discussion

During the experiment the reduction of photosynthesis was coupled with reduced g_s and E indicating that stomatal closure is the primary cause of reduced photosynthesis as also previously evidenced on potted *A. chinensis* plants (Mills et al., 2009). Our results are also in line with previous findings on *A. deliciosa* (Chartzoulakis et al., al.,1995; Gucci et al., 1992), since stomatal closure occurred as a results of low soil water availability and reduction of stem Ψ_w . If stomatal closure were the only reason for reduction in P_n , C_i would be depleted in water-stressed leaves; however, this was not the case, suggesting, as previously observed in *A. deliciosa* potted plants (Chartzoulakis et al., 1993), that, besides the stomatal response, also the biochemical properties of the photosynthetic apparatus in the mesophyll are impaired with a consequent decrease of C fixation in chloroplasts.

From the present experiment we observed a fast reaction of kiwifruit trees to water suspension and water re-supplied (recovery plants), that indicate a high susceptibility of plants to soil moisture, exacerbated by the low unit of soil of the pot and the high water request of the species (ET rates accounted for 5–7 l 100 kg⁻¹ dry soil day⁻¹). Moreover, from our results *A. chinensis* appears to have good stomatal control, since plants were able to reduce transpiration if exposed to water stress. The recovery of physiological parameters as soon as water was re-supplied strengthened this hypothesis and excluded, for short period of drought stress, permanent damages to photosynthetic apparatus. In a field experiment on *A. deliciosa*, Montanaro et al. (2007) observed a rapid relief from water deficit, with plants recovering 85 % of P_n five days after re-watering, and 98 % of P_n a week later. According to Flexas et al.

(2004), the rate of recovery depends not only on the severity of the stress, but also on a complex interaction of leaf age, light intensity and number of consecutive drying cycles. In field conditions we do not expect such severe symptoms since the root system explores larger soil volumes and consequently is able to better face a reduction of water availability.

The severe drought stress induced leaf and fruit drop; while, leaf symptoms started 48 h after the stress was imposed, fruit drop was delayed compared to the beginning of the stress and became more intense 4 days after total water suspension. According to Judd et al. (1989), as a consequence of drought stress, fruit growth ceases, and wilting of leaves and shoots occur as soon as stress is imposed. These authors did not observe fruits drop even under severe and prolonged water stress and, upon re-watering, leaf and fruit turgor was regained within 24 h, similarly to what we observed.

One of the most commonly water status parameter used to assess water stress intensity is stem Ψ_w (Flexas et al., 2004); indeed, according to our data we observed a positive correlation between stem Ψ_w and leaf gas exchange, indicating that leaf water potential could be easily used to identify the stress. According to the present experiment with values

Table 3

Pearson correlation of soil matric potential (soil Ψ_m), soil moisture (SM) and stem water potential (stem Ψ_w) with leaf net photosynthesis rate (P_n), stomatal conductance (g_s), intercellular CO₂ concentration (C_i), and leaf transpiration rate (E).

	P_n	g_s	C_i	E	stem Ψ_w
July 21 st					
soil Ψ_m	0.67 ***	0.62 ***	-0.57 ***	0.63 ***	-
July 22 nd					
SM	ns	ns	ns	ns	ns
soil Ψ_m	0.62 ***	0.44 *	-0.50 **	0.60 ***	0.68 ***
stem Ψ_w	0.70 ***	0.52 **	-0.50 **	0.76 ***	-
July 23 rd					
SM	0.39 *	ns	ns	0.48 **	0.38 *
soil Ψ_m	0.57 ***	0.54 ***	ns	0.54 **	0.70 ***
stem Ψ_w	0.76 ***	0.60 ***	ns	0.70 ***	-
July 24 th					
SM	0.45 *	0.37 *	ns	0.48 **	ns
soil Ψ_m	0.82 ***	0.53 **	-0.78 ***	0.64 ***	0.63 ***
stem Ψ_w	0.68 ***	0.59 ***	-0.61 ***	0.64 ***	-
July 25 th					
SM	0.45 **	0.52 **	-0.47 **	0.56 ***	0.45 **
soil Ψ_m	0.73 ***	0.74 ***	-0.79 ***	0.74 ***	0.82 ***
stem Ψ_w	0.79 ***	0.80 ***	-0.94 ***	0.81 ***	-
July 26 th					
SM	0.58 ***	0.60 ***	-0.39 *	0.59 ***	ns
soil Ψ_m	0.87 ***	0.76 ***	-0.68 ***	0.75 ***	0.59 **
stem Ψ_w	0.74 ***	0.54 *	-0.67 **	0.60 **	-
July 27 th					
soil Ψ_m	0.76 ***	0.73 *	ns	0.78 ***	-
July 28 th					
soil Ψ_m	0.78 ***	0.75 *	0.88 ***	0.77 **	-

ns, *, **, ***: effect not significant, significant at $P \leq 0.05$, $P \leq 0.01$ and $P \leq 0.001$, respectively.

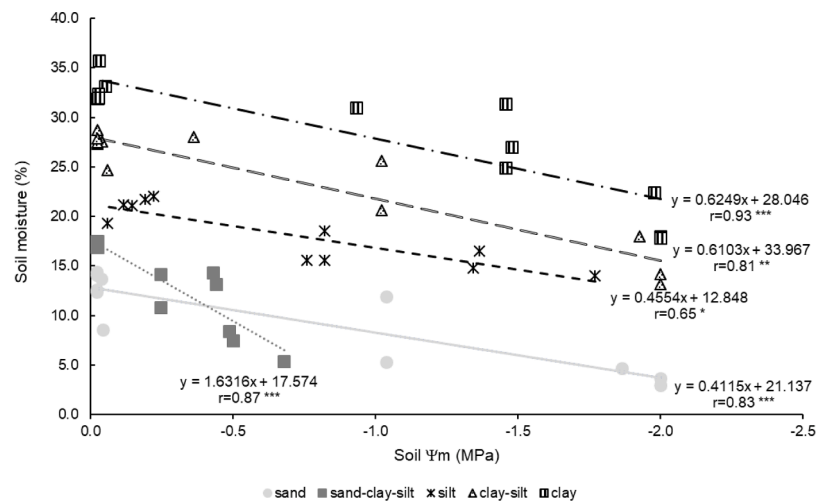


Fig. 12. Correlation between soil moisture and soil matric potential (Ψ_m) in different soils. *, **, ***: effect significant at $P \leq 0.05$, $P \leq 0.01$ and $P \leq 0.001$, respectively. r = Pearson correlation coefficient.

Table 4

Effect of soil on abscised fruits dry weight (g plant^{-1}) in stress plants.

SOIL	July 25 th	July 26 th	July 27 th	July 29 th
Sand	0 b	0 c	39.8 a	0 b
Sand-clay-silt	0 b	5.51 b	29.1 b	0 b
Silt	0 b	0 c	0 b	27.4 a
Clay-silt	0 b	27.9 a	36.1 a	0 b
Clay	3.59 a	0 c	44.3 a	0 b
Significance	***	***	*	***

*, ***, effect significant at $P \leq 0.05$ and $P \leq 0.001$, respectively. Values followed by the same letter are not statistically different according to Student Neuman Keul test ($P \leq 0.05$).

Table 5

Effect of soil on abscised leaves dry weight (g plant^{-1}) in stress plants, between parenthesis the percentage of fallen leaves is reported.

SOIL	July 24 th	July 26 th	July 27 th	July 28 th	July 29 th
Sand	0 b	14.0 (17) a	66.8 (83)a	0 b	0 b
Sand-clay-silt	0 b	16.5 (32) a	35.6 (68) ab	0 b	0 b
Silt	0 b	0 b	14.8 (19) b	10.6 (14) a	51.1 (67) a
Clay-silt	0 b	28.3 (30) a	65.8 (70) a	0 b	0 b
Clay	35.6 (33) a	20.4 (19) a	51.3 (48) a	0 b	0 b
Significance	***	*	*	*	***

*, ***, effect significant at $P \leq 0.05$ and $P \leq 0.001$, respectively. Values followed by the same letter are not statistically different according to Student Neuman Keul test ($P \leq 0.05$).

below -1 MPa, P_n is severely impaired. Lawlor and Cornic (2002) proposed C_i as a reference parameter; however, there are questions about its reliability related to patchy stomatal closure, as found in apple leaves (Buckley et al., 1997) and the increase of the relative importance of cuticular transpiration when stomata are closing, such as in drying grape leaves (Boyer et al., 1997). Flexas et al. (2004), proposed g_s as the indicator for the intensity of water stress suggesting that photosynthetic metabolism is substantially resistant to water stress until g_s is below $0.10\text{--}0.15 \text{ mol H}_2\text{O m}^{-2} \text{ s}^{-1}$. In the present experiment, we could define values of stomatal conductance of $0.06 \text{ mol H}_2\text{O m}^{-2} \text{ s}^{-1}$ as the threshold of plant survivorship. Arbitrarily we considered the wilting point the day in which C fixation was equal to 0, and plant death the day

in which leaf transpiration rate was equal to 0. This is because plants with no photosynthesis can recover from drought stress, while once leaf transpiration stops, plants cannot recover.

Soils differed from each other mainly in the texture composition and OM, that may have affected the plant susceptibility to the drought stress, however, it's difficult to explain the response of sandy clay silt soil, where leaf C assimilation stopped at a soil Ψ_m of -0.5 MPa, that was almost 4-fold higher than the other soils. This response cannot be in relation to bulk density, that was similar to those found in sand soil. However, differences in pore size distribution could occur between sand-clay-silt and sand soils due to the different amount in sand and clay particles (e.g., Fiès, 1992). In sand soil in fact more than 80 % of particles belonged to a one particle size class (i.e., sand) and thus a quite homogeneous pore size distribution was expected. In sand-clay-silt soil the contrasting presence of sand and clay particles could have produced an heterogeneous pore size distribution decreasing air-water flow, due to the decreasing diameter of water-occupied pores and decreasing pore connections (Chen et al., 2022). In addition, the volcanic origin of soils from Lazio (clay-silt and clay) could be partially responsible for the results obtained.

Silt soil showed a slower response to water addition, in comparison to the other soils, as it took a couple of days to decrease its Ψ_m , and on July 28th, the soil Ψ_m was still at a drought stress level (-0.88 MPa). According to Dexter and Czyż (2000), we suppose that it could be due to poor-connected pores of larger diameter, as rapid water infiltration requires well-connected large pores.

Correlation between soil Ψ_m and moisture (% w:w) was significant for all soils. According to our data, the use of probes seems to be an efficient tool to precisely identify soil water availability in any type of soil and consequently their use should be routinely inserted in water management of orchards. Probes could be used to identify the wilting point (defined when plant photosynthetic activity stops) that was close to -1.8 MPa for all the soils. The value observed in sandy-clay-silt (-0.5 MPa) was much higher than the values reported in literature and, as discussed above, it could be due a heterogeneous pore size distribution due to the contrasting particle size distribution in sandy-clay-silt soil. However, it is well known that in sandy-coarse textures the potentiometric probes can suffer from the low contact between soil and chalk surface, even if in sand soil we did not find it. Further investigations thus need in order to understand the performance of probes in sand-rich soils.

5. Conclusions

Our plants were grown in pots and the trial was performed during a

hot week (average temperature 31°C, with peak of 46°C) that exacerbated plant responses to a severe water limitation. Although the rapidity of drought stress symptoms and recovery observed in this trial may not be observed in field, these data give an idea on the promptness of golden kiwifruit plants to respond to variation of soil moisture. From our data, it appears that soil water availability must be kept at optimal level, since it regulates plant C fixation. In particular stem water potential (Ψ_w) can be used to check the water status of kiwifruit plants, in our experimental conditions it should be kept higher than -0.8 MPa, since values lower than this threshold may compromise the final kiwifruit fruit size at harvest. When soil moisture probes are used, it is recommendable to calibrate them before their employment, since their accuracy can change according to soil texture and structure. Finally the time of probe reaction to soil water addition can be used as a tool to assess soil structure and porosity, the longer the reaction time the poorer the soil structure.

CRedit authorship contribution statement

Elena Baldi: Writing – original draft, Investigation, Formal analysis, Data curation. **Maurizio Quartieri:** Methodology, Investigation. **Giacomo Chiarelli:** Investigation. **Greta Nicla Larocca:** Investigation. **Marco Mastroleo:** Validation. **Evangelos Xylogiannis:** Validation. **Gloria Falsone:** Writing – review & editing, Validation, Data curation. **Moreno Toselli:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation.

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.

Data availability

Data will be made available on request.

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Supplementary materials

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