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Vegetable Crops Grown under High Soil Water Availability in Mediterranean Greenhouses

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Received: 16 March 2020; Accepted: 10 April 2020; Published: 14 April 2020

Abstract: The soil water availability of six vegetable crop cycles, irrigated with water of 0.4 dS m^{-1} electrical conductivity, was modified by varying the irrigation frequency in typical Mediterranean greenhouses at SE Spain. The soil matric water potential (SMP) in the middle of the loamy soil layer where most roots usually grow was maintained between −10 and −20 kPa (H), −20 and −30 kPa (C), and −30 and −50 kPa (L) for the crops grown under high, conventional and low soil water availability, respectively, while the total irrigation water applied was similar for the three treatments. The high soil water availability (H) did not improve the fresh weight of total, marketable and first class fruits, or the shoot biomass and partitioning. The irrigation frequency did not affect the total root biomass at the end of the autumn–winter cucumber, but the crop under L distributed its root biomass more homogenously throughout the soil profile than the crop under H. Regulating the soil water availability (maintaining the SMP higher than or close to the level at which crop water stress may occur) over the cycle as a function of crop conditions or farmers' requirements appears to be a useful management practice for controlling soil root distribution or shoot partitioning.

Keywords: crop evapotranspiration; crop yield; irrigation frequency; root biomass; soil matric potential; water deficit

1. Introduction

Greenhouse agricultural systems have expanded worldwide, especially in areas with mild winter climates, such as the Mediterranean basin. One of the largest greenhouse areas in the world is located on the SE Spanish Mediterranean coast, where fruit-vegetable crops are usually grown in low-cost structures covered with plastic film, without active climate control systems and with *enarenado* (sand-mulched) soils [1]. In this and other Mediterranean greenhouse areas, crops are intensive and heavily fertigated, the irrigation water is usually scarce and the quality of surface and groundwater sources is deteriorating [2–4]. Consequently, there is increasing pressure to optimise irrigation management.

Steps to improve the irrigation water efficiency in Mediterranean greenhouses have included: determining water requirements of greenhouse crops using the K_c–ET_0 method adapted to Mediterranean greenhouses [5,6]; development of a simple computer programme for estimating daily irrigation crop water requirements [7]; and analysis of on-farm irrigation performance [8]. In most Mediterranean greenhouses from the SE Spanish coast, the conventional recommendation regarding irrigation frequency of soil-grown vegetable crops is to maintain the soil matric water potential (SMP) in the middle of the soil layer where most roots usually grow above or equal to −20 or −30 kPa, depending on soil texture (i.e., to keep the soil water status slightly over or around field capacity). This recommendation is in line with numerous studies aimed to establish the optimum SMP threshold for crop irrigation, although they were carried out under open field conditions [9–11]. In greenhouse crops, water deficit has been found when they have been grown with SMP values below −58 kPa for pepper, −35 kPa for melon and −38 to −58 kPa for tomato [12]. However, the use of high irrigation frequencies to maintain a high soil water availability (SMP values higher than –20 kPa) around the roots of high-value greenhouse crops has been recurrently proposed or questioned [13], and various high-frequency irrigation systems have been implemented and commercially distributed in the region over recent decades without thorough experimental evaluation. Moreover, a recent study, carried out in a typical greenhouse on the SE Spanish Mediterranean coast with a silty loam soil [14], is supporting the use of high irrigation frequencies in soil-grown greenhouse crops: a higher biomass production and fruit yield was found in a zucchini crop irrigated at SMP of −10 kPa, compared to that irrigated when the SMP was −25 kPa. A higher soil water availability can theoretically facilitate crop water uptake and improve soil nutrient availability [15], especially under water stress conditions, but the responses of plant species to water stress or availability significantly depend on the intensity and duration of stress and their stages of development [16–19].

Irrigation scheduling and methods can affect root distribution, and water and nutrient availability within the soil. Under drip-irrigation systems, roots grow preferentially around the wetted emitter area and are concentrated within the upper part of the soil profile [20,21], but this pattern of root growth and distribution is usually affected by the frequency and rate of irrigation. A higher irrigation frequency or a lower water application rate modified the soil root distribution and, consequently, the plant water uptake across the soil profile [15].

This work was aimed at analysing the agronomical effects, including the soil root distribution, of modifying the level of soil water availability by using various irrigation frequencies in some of the main soil-grown vegetable crops of a representative Mediterranean greenhouse area.

2. Materials and Methods

2.1. Site and Experiments

Six soil-grown crop cycles were assessed in six experiments (autumn–winter cycles of zucchini, green bean and cucumber, and spring cycles of watermelon, melon and cucumber), conducted from 2000 to 2002 at *Las Palmerillas* research station (36°47.6′ N, 2°43.3′ W and 155 m elevation), Cajamar Foundation, Almería, Spain. Experiments were carried out in two typical Parral greenhouses: low-cost structures covered with plastic films (0.2 mm-thick thermal polyethylene sheet), without heating, naturally ventilated and with artificially layered soils with top gravel-sand mulches, known as *enarenado* [1], of similar water retention characteristics. The soils consisted of the naturally-occurring, gravelly sandy-loam soil covered with a 0.3 m layer of imported loamy soil, and, finally, a top 0.1 m mulch layer, mostly composed of fine gravel and coarse sand particles. The upper limit of drained water content (field capacity) of the imported soil was 0.31 m^3 m^{-3} and the lower limit (wilting point) was 0.11 m^3 m^{-3} [7]. The irrigation water of about 0.4 dS m^{-1} electrical conductivity (EC) contained 0.6 mmol L^{-1} of calcium, 1.2 of magnesium, 0.3 of sulphate, 0.6 of sodium and 0.6 of chloride. The irrigation water mixed with fertilizers was supplied through a surface drip system (90% distribution uniformity). One greenhouse had four drainage lysimeters (8 m^2 of ground surface) located on the southern side. The soil profile in these lysimeters reproduced the aforementioned soil to a depth of 0.6 m. Most of the root growth from soil-grown greenhouse crops usually occurs within the imported soil layer [5]. Green bean and melon crops were grown in the greenhouse with lysimeters, while cucumber, zucchini and watermelon crops were grown in the greenhouse without lysimeters.

Two irrigation treatments were compared at each experiment: conventional (C) versus high soil irrigation water availability (H). Moreover, in the two cucumber cycles an additional low soil water availability (L) treatment was included. In the C treatments, crops were irrigated when the soil water matric potential (SMP) in the middle of the imported soil was about −25 kPa (between −20 and −30 kPa). These values are usually recommended for irrigation in the area. In the H treatments, crops were irrigated when the SMP was between −10 and −20 kPa, while the L treatments were irrigated when the SMP was between −30 and −50 kPa. Treatments were arranged in a randomised complete-block design with four replications. One-way analysis of variance (ANOVA) was used to test for statistical differences among irrigation treatments. When differences were significant ($p < 0.05$), Tukey's honestly significant difference procedure was used for mean comparisons. The experimental plot per replicate and treatment was 48 m^2 (9 m length and 5 m width) for zucchini, watermelon and cucumber, and 54 m^2 (9 m length and 6 m width) for green bean and melon crops. For each irrigation treatment, the total amount of water applied, determined from daily estimates of crop evapotranspiration (ET_c, mm d^{-1}) using the K_c−ET_0 method [22], was practically the same. The greenhouse reference evapotranspiration (ET_0, mm d^{-1}) was computed with a locally calibrated radiation method [6]. This requires greenhouse daily solar radiation data, determined from outdoor solar radiation and the daily greenhouse transmission coefficient to solar radiation. The latter was determined monthly from measurements of solar radiation outside and inside the greenhouse. Crop coefficients (K_c) at the key crop growth stages were obtained from [5,23]. Daily values of K_c from sowing/planting to effective full cover were determined as a function of the thermal time inside the greenhouse. The frequency and rate of irrigation varied depending on treatment, crop and greenhouse evaporative demand. The irrigation rate usually ranged between 1 and 4 mm, while the irrigation frequency normally ranged between daily and every 4 days, except for the cucumber crops under L treatment, which were irrigated every 5 days during part of the winter period, and the cucumber crops under H treatment, which were irrigated twice a day for short periods at the beginning (autumn cycle) and the end (spring) of their cycles.

Local practices of crop management were applied. Variety, planting and harvest schedules, and plant spacing for all the studied crops are presented in Table 1.

Table 1. Crop, variety, date of sowing (S) or transplanting (T) and end of the cycle, and plant spacing of greenhouse experiments. Almería, Spain.

Crop Cycles	Cultivar	Sowing/Transplanting	End of Cycle	Plant Spacing
Autumn–winter cycles				
Zucchini (*Cucurbita pepo* L.)	Cónsul	29/08/2000 (S)	22/01/2001	1.5 m × 0.75 m
Cucumber (*Cucumis sativus* L.)	Borja	05/09/2001 (T)	09/01/2002	1.5 m × 0.5 m
Green bean (*Phaseolus vulgaris* L.)	Donna	12/09/2001 (S)	04/01/2002	2.0 m × 0.5 m
Spring cycles				
Watermelon (*Citrullus lanatus* L.)	Reina de Corazones	16/02/2001 (T)	18/05/2001	4.5 m × 1.0 m
Melon (*Cucumis melo* L.)	Aitana	22/02/2001 (T)	26/05/2001	2.0 m × 0.5 m
Cucumber (*Cucumis sativus* L.)	Borja	8/02/2002 (T)	19/06/2002	2.0 m × 0.5 m

2.2. Measurements

The air temperature inside the experimental greenhouses was daily measured (H08-032-08, HOBO, Onset Compute Corp, Bourne, MA, USA). The solar radiation was measured with pyranometers inside the greenhouses (at 2.5 m aboveground; H08-008-04, HOBO) and outdoors (at 1.5 m aboveground; CM21, Kipp & Zonen, Delft, Netherlands).

The soil matric potential (SMP, kPa) was measured with manual tensiometers (Irrometer, Riverside, California, USA) installed at 0.12 and 0.27 m below the gravel-sand mulch layer and near the plant (four tensiometers per treatment and depth). Measurements were taken at about 9 h each working day, just before irrigating. A Time Domain Reflectometry (TDR) system (TRASE 6005X1, Soil Moisture Corp. Santa Barbara, CA, USA) was fortnightly used to measure the volumetric soil water content (VWC) in the crops grown in the greenhouse with lysimeters. TDR probes were installed in three soil locations in line with the plant (at 0.1, 0.25 and 0.45 m from the drip line) within each of the two lysimeters per irrigation treatment. The VWC was measured at 0–45 cm below the upper gravel-sand layer. Drainage from lysimeters was collected and measured at about 9 h each working day. Representative sub-samples of lysimeter drainage solutions were collected each day from each lysimeter, and analysed for EC (Conductimeter Basic 30, Crison Instruments SA, Barcelona, Spain), pH (pH Meter GLP 21, Crison Instruments SA) and contents of $NO3^-$, K^+ and Ca^{2+} [24]. The irrigation water applied per treatment was periodically measured with a water meter.

Crop dry biomass and partitioning at the end of the cycles, and marketable and non-marketable yield throughout the cycles were determined in plants within an area of 6 (green bean, melon and cucumber), 9 (zucchini) and 18 m^2 (watermelon). The harvest index was determined as the ratio of generative-to-total shoot biomass (HI, g g^{-1}). A 2 m^2 area of plants was also collected at three different stages of the green bean and melon cycles to measure leaf area index (LAI) with an electronic planimeter (AM7626, Delta T Devices LTD, Cambridge, England). Moreover, a detailed growth study was conducted throughout the two cucumbers crops. The number, length and diameter of internodes, and the maximum height and width of leaves was fortnightly measured in two plants per replication. Simultaneously, cucumber leaves were sampled at each cucumber cycle and their maximum height (L, m), maximum width (W, m) and area (A, m^2) were measured. For the latter, the electronic planimeter was used. A close potential relationship between A and W leaf values was found for the autumn–winter ($A = 0.4333\ W^{2.12}$; N = 35; $R^2 = 0.99$) and for the spring ($A = 0.2683\ W^{2.28}$; N = 27; $R^2 = 0.99$) cucumber cycle. These relationships were used to determine LAI values throughout both cycles.

At the end of the harvesting period in the autumn–winter cucumber cycle, 16 soil profiles were opened using the trench profile method [25] to characterise root growth and distribution across the soil profile in the cucumber under high (H) and low (L) soil water availability treatments. After removing the upper gravel-sand layer, eight profiles were opened per treatment, four of them just where the emitter and plant were located (P1) and the other four in the middle of two adjacent plants (P2), always perpendicular to the plant rows. Each profile consisted of a 1.5 m wide by 0.4 m deep smoothed vertical trench, which was washed with water, removing approximately 10 mm of soil in order to expose the roots [20]. A 0.3 m high metal grid (0.1 m × 0.1 m) was laid against the trench wall of the imported soil layer. The roots in each grid area were counted, cut, dried and weighed, and biomass root density (g cm^{-3}) was determined. Some roots were also observed in the upper gravel-sand layer of the soil profile, but they could not be measured with the trench profile method.

A dataset of this work is deposited in the Mendeley data repository [26].

3. Results

3.1. Water Use

At each of the six studied crop cycles, the total irrigation water applied was similar for all the irrigation treatments (Table 2).

Table 2. Total irrigation water supply (mm) to the greenhouse vegetable crops grown under high (H), conventional (C) and low (L) soil water availability treatments.

Irrigation Treatments	Zucchini	Autumn Winter Cucumber	Green Bean	Watermelon	Melon	Spring Cucumber
H	177	171	114	114	156	210
C	178	159	105	108	144	216
L	-	159	-	-	-	206

In the green bean and melon crops, the total irrigation water supplied was close to the corresponding estimates of the seasonal cumulative ET_c values (Tables 2 and 3). The total volume of drainage collected from lysimeters was slightly higher in the H than in the C irrigation treatment in the green bean crop and opposite occurred in the melon crop (Table 3), but most of it occurred during early crop stages in both treatments and crops [8,12]. The mean seasonal pH of the collected drainage was similar for the C and H treatments, while the mean seasonal EC was slightly higher in the crops under the C treatment (Table 3). The total amounts of nitrate, potassium and calcium collected in the drainage were relatively similar for both treatments in the green bean crop, while they were higher in the C than in the H treatment in the melon cycle (Table 3). Both crops presented a relatively high pH value in the drainage (Table 3) due to the high $CaCO_3$ content of this soil.

Table 3. Crop evapotranspiration (ET_c, mm), and drainage volume (mm) and composition of green bean and melon crops grown under high (H) and conventional (C) soil water availability treatments. Mean seasonal values of electrical conductivity (EC, dS m^{-1}) and pH, and cumulative seasonal values (g m^{-2}) of nitrates (NO_3^-), potassium (K^+) and calcium (Ca^{2+}) collected in the drainage. The drainage was collected from drainage lysimeters.

Crops	Irrigation Treatments	ETc	Drainage					
			Volume	EC	pH	NO_3^-	K^+	Ca^{2+}
Green bean	H	105	16.7 ± 14.7	3.5 ± 0.2	8.1 ± 0.1	13.5 ± 5.1	7.2 ± 1.6	4.9 ± 1.3
	C	100	8.2 ± 1.0	4.0 ± 0.6	8.0 ± 0.1	13.8 ± 6.8	8.6 ± 6.8	7.3 ± 5.3
Melon	H	142	24.6 ± 4.5	2.6 ± 0.1	8.2 ± 0.1	16.8 ± 3.6	5.9 ± 0.3	5.5 ± 1.4
	C	130	33.6 ± 1.4	3.0 ± 0.4	8.2 ± 0.0	26.8 ± 0.6	13.6 ± 1.0	7.9 ± 0.6

3.2. Soil Matric Potential

The SMP averaged for measurements taken before irrigation at 0.12 and 0.27 m depth below the gravel-sand mulch layer was, in general, within the pre-set values for each treatment and crop (Figure 1): between −10 and −20 kPa for the H treatment; between −20 and −30 kPa for the C treatment; and between −30 and −50 kPa for the L treatment. Values of SMP were outside these ranges for short crop periods, particularly at the end of the melon and watermelon crops, when the soil water availability was gradually lowered in both irrigation frequencies, which is a common local practice aimed at increasing fruit quality [27], and at the beginning of the cycles since local greenhouse growers usually apply a large irrigation just before the next transplanting/sowing for salt leaching and soil profile wetting (8).

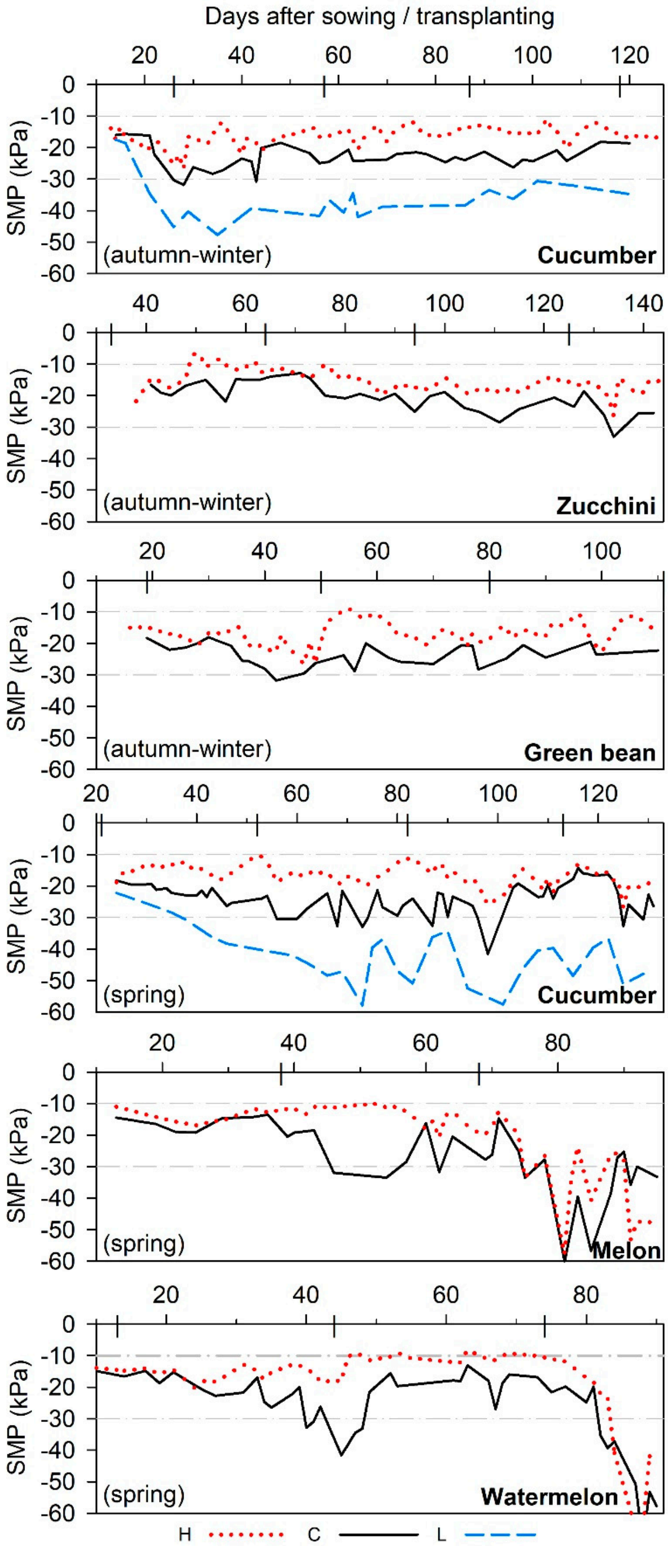

Figure 1. Seasonal evolution of the soil matric potential (SMP) measured before the irrigation in autumn–winter and spring cucumbers, autumn–winter zucchini and green bean, and spring melon and watermelon cycles of crops grown under high (H), conventional (C) and low (L) soil water availability. Mean values of measurements taken at 0.12 and 0.27 m below the gravel-sand layer and near the plant.

3.3. Shoot Growth, Biomass and Allocation

No differences in LAI values were observed between the C and H treatments for green bean and melon crops. However, the cucumber under L treatment presented significantly lower LAI values ($p < 0.05$) than those measured in the cucumber under C or H treatments throughout most of the autumn–winter cycle and at end of the spring cycle (Figure 2).

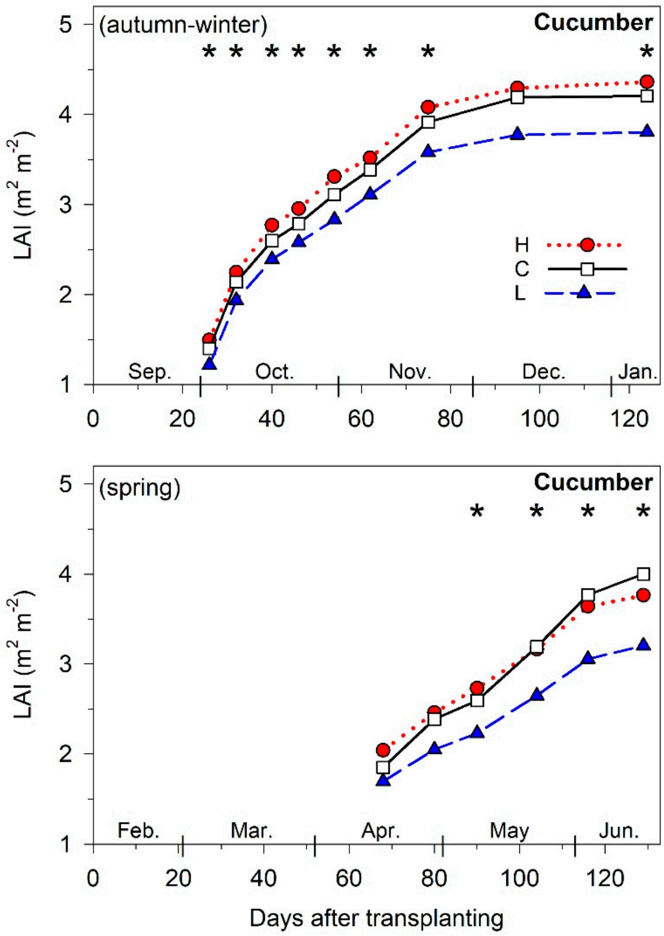

Figure 2. Seasonal evolution of leaf area index values (LAI) of autumn–winter and spring cucumber crop cycles grown under high (H), conventional (C) and low (L) soil water availability. *: Dates when significant differences between irrigation treatments were found ($p < 0.05$).

Shoot biomass (dry matter) and its partitioning at the end of the cycles are shown in Table 4. In two (zucchini and green been) of the three autumn–winter crop cycles studied, the total shoot biomass was significantly lower ($p < 0.05$) under the H than under the C treatment, which was mostly due to a significantly lower vegetative biomass. On the other hand, no significant differences in total shoot biomass between irrigation treatments were found for any spring crop cycle, although values were always slightly higher in the H treatment. Moreover, the vegetative biomass of the watermelon crop was significantly higher in the H treatment.

Table 4. Vegetative, generative and total shoot biomass, and crop harvest index (HI) of autumn–winter and spring cycles of greenhouse vegetable crops under high (H), conventional (C) and low (L) soil water availability treatments.

Crops	Treatments	Shoot Biomass (g m^{-2})			HI (g g^{-1})
		Vegetative	Generative	Total	
Autumn–winter cycles					
Zucchini	H	365 b *	358	723 b	0.50
	C	503 a	382	885 a	0.43
Green bean	H	395 b	197	592 b	0.34 a
	C	457 a	208	665 a	0.31 b
Cucumber	H	352	302	654	0.46
	C	341	333	674	0.50
	L	331	330	664	0.50
Spring cycles					
Melon	H	356	805	1161	0.69
	C	338	688	1026	0.67
Watermelon	H	244 a	735	979	0.75
	C	210 b	705	915	0.77
Cucumber	H	314	479	793	0.63
	C	310	467	778	0.60
	L	287	487	774	0.63

*: Irrigation treatment values within a column followed by different letters are significantly different ($p < 0.05$).

3.4. Root Biomass and Distribution

No significant differences were found between L and H treatments for the total cucumber root biomass near the plant position or between two adjacent plants (Table 5), but the total root biomass was much higher near the emitter and plant position than between two adjacent plants in both irrigation treatments (Table 5), and the pattern of root biomass distribution throughout the soil profile also differed between these two soil positions (Figure 3).

Table 5. Total root biomass (g m^{-2}) of an autumn–winter cucumber crop grown under two soil water availability treatments (H: High soil water availability; L: low soil water availability) for two soil positions, and weighted averages using fitted relationships.

Treatments	Near the Plant (P1)	Between Plants (P2)	Weighted Average
H	18.5 ± 5.2 a *	9.3 ± 4.1 a	11.9 ± 5.5 a
L	22.8 ± 7.2 a	6.2 ± 3.0 a	10.9 ± 5.4 a

*: Values within a column followed by the same letter are not significantly different ($p < 0.05$).

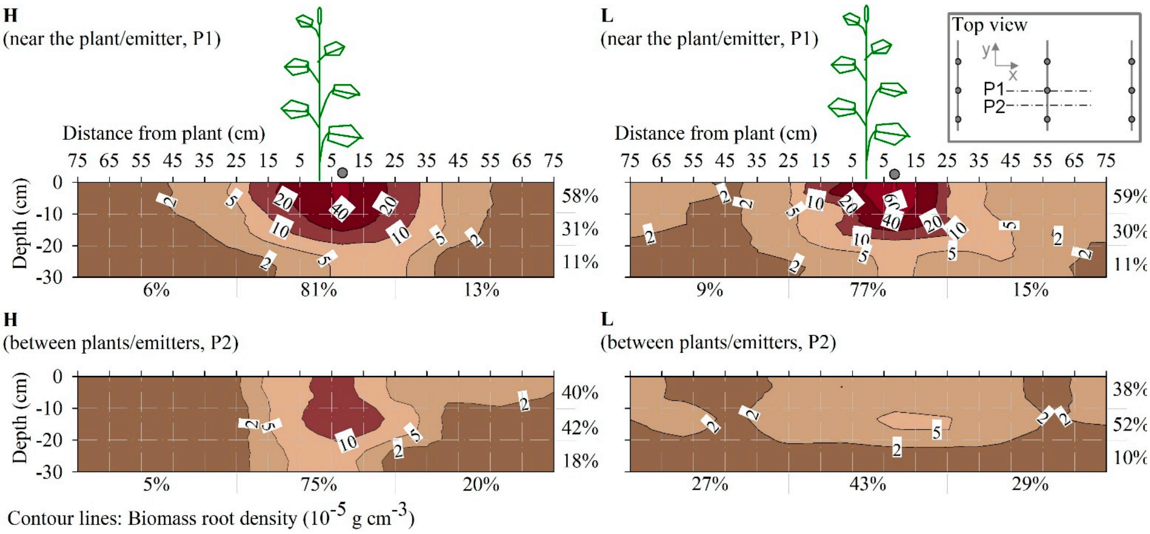

Figure 3. Root biomass distribution across soil profiles perpendicular to plant rows near the emitter and the plant (P1), and between two adjacent plants (P2) at the end of an autumn–winter cucumber crop cycle grown under high (H) and low (L) soil water availability. Contour lines represent mean biomass root density values (10^{-5} g cm^{-3}). Percentage values represent the root biomass of the zone relative to the total biomass, i.e., root biomass distribution in depth (in the upper 0.1 m, between 0.1 m and 0.2 m, and between 0.2 m and 0.3 m depth) and root biomass distribution within the soil profile (in the left, central and right part of the profile); •: Emitter.

The pattern of root biomass distribution across the trench (perpendicular to plant rows) clearly differed between the L and H irrigation treatments (Figure 3). The H treatment presented a greater concentration of roots in the soil around the plant and the emitter (the zone wetted by the point-source emitter) than the L treatment: i.e., the cucumber under L treatment distributed its root biomass more homogenously throughout the soil profile than the cucumber under the H treatment. Despite this, most roots in L and H treatments were located about 0.30 m from both sides of the emitter and the plant. On the other hand, the root biomass decreased with depth similarly in both treatments, and more than half of the root biomass was located in the 0.1 m-thick upper part of the imported soil layer. Moreover, some roots were observed in the upper part of the original soil in the two irrigation treatments and soil positions studied (data not shown), but their quantities were much lower than those measured in the lower part of the imported soil. The distribution of cucumber root biomass (RDM) along the axis perpendicular to the plant rows (×) fitted to $RDM_{\times}/RDM_{\times=0} = 1.04EXP[-5.14\times]$ ($R^2 = 0.98$) for H and to $RDM_{\times}/RDM_{\times=0} = 0.97EXP[-8.52\times]$ ($R^2 = 0.99$) for L. These relationships were used to determine the weighted average root biomass (Table 5).

3.5. Crop Yield

No significant differences between irrigation treatments were found for the total and marketable yield in any of the studied crop cycles (Table 6). Moreover, no significant differences between irrigation treatments were found for the fresh weight of first or second class fruits, or for the yield components of marketable fruits. However, in two of the three autumn–winter crop cycles studied the marketable fresh fruit weight of the crops under the H treatment was between 10% and 11% lower than that of the crops under the C treatment (Table 6).

Table 6. Fresh weight of total, marketable, first and second class fruits (g m^{-2}), and yield components of marketable fruits: fruits number and mean fruit weight (g). Autumn–winter and spring cycles of greenhouse vegetable crops under high (H), conventional (C) and low (L) soil water availability treatments.

Crops	Soil Water Availability	Fresh Fruit Weight				Yield Components	
		Total	Marketable	First Class	Second Class	Fruits m^{-2}	Fruit Weight
Autumn–winter cycles							
Zucchini	**H**	5925	5282	3741	1541	24.6	215
	C	6619	5903	4177	1726	25.1	236
Green bean	**H**	2713	2601	2085	516	-	-
	C	2714	2619	2145	475	-	-
Cucumber	**H**	7924	6409	4635	1774	15.1	425
	C	8567	7189	5169	2019	17.0	422
	L	8725	7281	5219	2062	16.9	431
Spring cycles							
Melon	**H**	8016	6561	2514	4047	5.6	1179
	C	7256	5453	2055	3398	4.5	1204
Watermelon	**H**	9625	9281	9244	36	1.5	6308
	C	10,057	9817	9472	344	1.7	5765
Cucumber	**H**	11,598	7495	5334	2161	15.3	491
	C	11,721	7723	5432	2292	15.6	493
	L	10,901	7340	5140	2200	14.8	498

Values within a column followed by different letters are significantly different ($p < 0.05$).

4. Discussion

A high soil water availability throughout the whole crop cycle, which can theoretically facilitate water and soil nutrient availability and uptake [15], did not improve the biomass, yield or the physical fruit quality of high-value Mediterranean greenhouse crops irrigated with water of low salinity (EC of 0.4 dS m^{-1}). Vegetable crops grown under high (between SMP values of −10 and −20 kPa, Figure 1), conventional (between −20 and −30 kPa) and low (between −30 and −50 kPa) soil water availability (irrigated with practically the same total amount of water, Table 2) did not present significant differences for the total and marketable yield, the fresh weight of first or second class fruits, or the yield components of marketable fruits (Table 6). This response could be mainly attributable to the relatively high soil water availability observed in all the irrigation treatments (Figure 1), since SMP values were generally higher than (H and C treatments) or close to (L treatment) those values at which water stress may occur [12,27]. Therefore, fruit-vegetable greenhouse crops can be irrigated under a relatively wide range of SMP values without significantly affecting their yields. This finding can be relevant for implementing new precise automatic irrigation scheduling technologies [28], which appears to be the best way of optimising water and nutrient use in soil-grown Mediterranean greenhouse crops. These results are still of great agronomical interest since there is an urgent need of improving the irrigation water use in many Mediterranean greenhouse areas due to increasing problems of water scarcity, and water and soil pollution and salinization [3,4]. Moreover, in the same area and greenhouse system, [14] recently found a higher yield and aerial biomass in a zucchini crop irrigated when the SMP reached −10 kPa, compared to that irrigated when the SMP reached −25 kPa or −40 kPa. The result of this study [14] appears be conflicting with the results of our work (although experiments are not fully comparable) and with previous studies, mostly carried out under open field conditions [9–11] and some under greenhouse conditions [12]. In the six experiments presented in our work, irrigated with water of low salinity (EC of 0.4 dS m^{-1}), different soil water availability treatments were induced by modifying the irrigation frequency, but the total amount of irrigation water supplied was similar for all the treatments (Table 2). In the zucchini experiment [14], irrigated with moderate saline water (1.4 dS m^{-1}), the total water supply was substantially greater in the crop irrigated when the SMP reached −10 kPa (390 mm) than in those irrigated when the SMP reached −25 kPa (315 mm) or −40 kPa (272 mm). The irrigation of the zucchini crop with moderate saline water may have led to soil salt accumulation, particularly in the treatments less frequently irrigated (C and L), which might have affected the soil water availability for the crop. However, this hypothesis can not be contrasted since measurements of soil water osmotic potential or soil solution EC are not available in this study. Therefore, further and more detailed research is required to optimise the irrigation water use (irrigation frequency and rate) in soil-grown greenhouse crops irrigated with moderate saline waters since the water quality of many greenhouse Mediterranean areas is deteriorating [3,4].

The low soil water availability treatment did not significantly affect shoot biomass of cucumber crops (Table 4), but it produced smaller leaves (data not shown) reducing LAI values significantly (Figure 2) throughout most of the autumn–winter and spring cycles [15,19,29]. Despite the lower LAI values, fruit yield and physical fruit quality of the cucumber grown under low soil water availability were not significantly affected (Table 6). The cucumber crops grown under low soil water availability frequently presented SMP values slightly lower than −40 kPa. These values might cause mild water stress [12,27], but not so severe as to clearly inhibit stomata conductance and photosynthesis per unit leaf area or to increase root dry matter production [30,31]. However, they may reduce leaf growth and its role as a sink for assimilates [17,19]. Thus, for high-value greenhouse crops, such as cucumber (about 12 € m^{-3} of water-productivity [8]), maintaining low soil water availability throughout the whole crop cycle may prove risky, especially during periods of high evaporative demand (spring cycles), and it may, therefore, be unadvisable over the whole crop cycle in commercial Mediterranean greenhouses.

The irrigation treatment of low soil water availability did not affect root biomass at the end of the autumn–winter cucumber cycle (Table 5), but it modified the root distribution across the soil profile. Roots grew preferentially around the wetted emitter area and were concentrated within the upper part of the soil profile in the crops under both irrigation treatments, high and low soil water availability (Figure 3), which coincided with previous results from [20,21]. However, this pattern of root growth was less accentuated for the cucumber under low soil water availability, which showed a more homogeneous root distribution throughout the soil profile (Figure 3). Although high-value greenhouse crops usually receive abundant water and nutrients [32], a more homogeneous root distribution may be of interest in commercial greenhouses whether water or nutrient crop requirements are not properly supplied or when soil characteristics might hamper crop water and nutrient uptake.

On the other hand, growing vegetable crops under high soil water availability does not appear to be the best management practice for autumn–winter vegetable cycles in commercial Mediterranean greenhouses. The total shoot and vegetative biomass was significantly lower under high than under conventional soil water availability in two (zucchini and green been) of the three autumn–winter cycles studied (Table 4), although the marketable fresh fruit weight was not affected (Table 6). In crops grown at the end of the autumn and winter periods, the greenhouse evaporative demand under the non-controlled climatic conditions of most Mediterranean greenhouses is usually low but variable [5,6]. Under these circumstances, the probability of periods with excessive water content limiting the root oxygen supply or enhancing the proliferation of some soil diseases might be greater in crops grown with high irrigation frequency, but further research is required to elucidate this hypothesis.

In substrate-grown greenhouse crops, regulating the level of water availability by varying the irrigation frequency is a usual practice for growing well-balanced plants and other management purposes [32]. In soil-grown greenhouse crops, regulating the soil water availability without affecting plant photosynthesis by varying the irrigation frequency throughout the crop cycle can be useful for: (i) producing fruit vegetable plants with a better equilibrium between vegetative (source strength) and generative (sink strength) parts [16], or enhancing fruit quality [27]; (ii) modifying the soil root distribution in order to increase the potential root access to water and nutrients and to improve the use of these scarce resources; and (iii) controlling or minimising salt accumulation in the root zone. The latter might become of great interest since the irrigation water quality of many greenhouse Mediterranean areas is deteriorating [3,4]. Farmers, by varying the irrigation frequency, can maintain relatively low soil water availability when the plant vegetative growth is too vigorous or increase the soil volume explored by the roots, or can maintain relatively high soil water availability over periods under stressful climate conditions, such as periods of hot and dry winds.

5. Conclusions

Soil-grown fruit vegetables crops in Mediterranean greenhouses can be properly irrigated with waters of low salinity by using irrigation frequencies that maintain the SMP in the root zone higher than −20 to −30 kPa. A high soil water availability (maintaining the SMP higher o equal to −15 kPa) did not improve crop biomass, yield or physical fruit quality, compared to the conventional soil water availability (maintaining the SMP between −20 and −30 kPa). The total irrigation water applied was similar for both treatments. Regulating the soil water availability over the cycle of these crops without affecting their photosynthesis rate by varying the irrigation frequency may be a useful practice for controlling soil root distribution or shoot partitioning. The level of soil water availability did not affect the total root biomass of an autumn–winter cucumber crop, but the low soil water availability treatment led to a more homogeneous cucumber root biomass distribution across the soil profile.

Author Contributions: Conceptualization, S.B. and M.D.F.; Data curation, A.M.G. and F.J.C.-C.; Formal analysis, A.M.G. and F.J.C.-C.; Funding acquisition, S.B. and M.D.F.; Investigation, A.M.G. and M.D.F.; Methodology, S.B. and M.D.F.; Project administration, S.B. and M.D.F.; Resources, M.D.F.; Supervision, S.B. and M.D.F.; Visualization, S.B. and F.J.C.-C.; Writing—original draft, S.B. and A.M.G.; Writing—review & editing, S.B., M.D.F. and F.J.C.-C. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by a research grant from Cajamar Caja Rural and the University of Almería.

Acknowledgments: Authors would like to thank R.S. "Las Palmerillas" Cajamar Foundation for the technical support.

Conflicts of Interest: The authors declare no conflict of interest.

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