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Eco-Physiological and Productive Response of Deficit Irrigated Potatoes

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Abstract: A comprehensive study on both the eco-physiological and productive response of potatoes to dynamic deficit irrigation is lacking. Therefore, the aim was to study, over two growing seasons and on two potato cultivars—Arinda and Timate, the effects of five irrigation regimes (I0–dry control, I1—irrigated control, I2—supply 100% of the maximum evapotranspiration—ETm from tuber initiation up to 50% of tuber growth and 0% ETm from 50% to the end of tuber growth, I3—supply 100% of ETm from tuber initiation up to 50% of tuber growth and 50% ETm from 50% to the end of tuber growth, I4—supply 100% of ETm from tuber initiation up to 50% of tuber growth and 75% ETm from 50% to the end of tuber growth) simultaneously on the crop physiology (via chlorophyll fluorescence and leaf gas exchange traits), above-ground biomass yield, tuber yield and its components, irrigation water use efficiency (IWUE), source/sink ratio and tubers' dry matter content. Regardless of cultivars and seasons, in I3 and I4 for eco-physiological and productive traits, values comparable with I1 were found. Compared to I1, I2 reduced tuber yield by about 18% but increased the IWUE by about 110%, saving a high amount of irrigation water (about 1500 m^3 ha^{-1} per season). Arinda appeared more susceptible than Timate to water deficit in the second part of tuber growth, namely I2, from an eco-physiological point of view, but no differences between cultivars were found from a productive point of view. It was possible to effectively apply dynamic deficit irrigation to save irrigation water without compromising yields strongly.

Keywords: *Solanum tuberosum*; irrigation regime; leaf gas exchanges; chlorophyll fluorescence; yield; IWUE

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1. Introduction

The potato (*Solanum tuberosum* L.) plays an important role among open-field vegetables in the Mediterranean basin, occupying an overall area of about three million ha and producing 28 Mt of tubers [1]. There it is largely grown in a winter–spring cycle for "early" potato production, which is highly appreciated and mainly exported to northern European countries, with considerable profit [2,3]. Adequate water management is essential to achieve high yields because early potatoes, like the common one, are also particularly sensitive to water stress [4]. A continuous and adequate water supply is required from tuber initiation until near maturity to obtain high yields, good grades, and quality [4–9]. Considering that in the Mediterranean basin, as well as in some areas throughout the world, water is becoming ever less available and an increasingly expensive resource [10], farmers should adopt irrigation strategies, such as Deficit irrigation (DI), in order to save the water resources and increase Irrigation Water Use Efficiency (IWUE) [11]. In DI, the crop is under-irrigated throughout the whole growing season (Static Deficit irrigation—SDI) or only at a particular growth stage (Dynamic Deficit Irrigation—DDI) [12]. In particular, DDI consists in supplying water throughout growth stages sensitive to water scarcity (critical stages), that in potatoes is tuber bulking, while water deficit is applied during less sensitive growth stages, such as early vegetative growth and late tuber bulking [13]. Research conducted on the DDI of potatoes in semi-arid Mediterranean environments [7,14–17] has highlighted the validity of this strategy for saving irrigation water accompanied by an increase in IWUE. The effects of moderate water deficits at different phenophases were studied, for example, applying 90% ETc from planting to tuber initiation—75% ETc from tuber initiation to the beginning of flowering—50% ETc from the beginning of flowering to final harvest [14] or applying for one week 50% ETc at vegetative growth or at tuber bulking or at ripening [7]. Other studies performed with strong water deficit-0% ETm, applied only for two weeks at tuber bulking (at 75 days after planting) or at tuber ripening (at 90 days after planting) [15] or for a long time throughout the growing season [17]. In particular, the latter research [17] studied the effects of water deficit in the first part of tuber growth (from tuber initiation up to 50% of tuber growth) or in the second part (from 50% of tuber growth to the end of tuber growth), otherwise supplying the 100% of ETm in the second part or in the first part of tuber growth, respectively. It was found that the water deficit applied in the first part of tuber growth led to similar yields to dry control, confirming what has already been found by other authors on the great sensitivity of potato crops to water deficit during tuber bulking. In contrast, applying water deficit in the second part of tuber growth allows comparable tuber yields compared to irrigation throughout the whole cycle, using roughly half the irrigation water and so making savings of irrigation water of about 77 mm for the growing season. These results require further confirmation. They encourage further research on the response of the crop to different levels of water supply in the second part of tuber growth, which appeared to be the least sensitive to water deficit. Such knowledge is essential to fully understand the response in production terms of the crop to water availability, which could assist growers in solving current practical problems in irrigation scheduling of the crop. Moreover, as is known, water deficit decreases photosynthesis [6,18–21] by stomatal closer [22]. The decrease in photosynthetic rate reduces the production of photo-assimilates and, therefore, plant growth through the modification of several parameters such as foliar area, total dry mass, and distribution of photo-assimilates within the plants [23–25]. With severe water deficit, in addition to the stomatal limitation of photosynthesis, the presence of non-stomatal limitations that can be measured by chlorophyll fluorescence has been reported [26]. In potatoes under SDI, the eco-physiological response for both gas exchanges [6,20,27,28] and chlorophyll fluorescence [19,29–31] has been well studied. However, the eco-physiological response of the crop to the DDI has never been investigated; this knowledge would be important because it was hypothesized that the effect of variable deficit (the crop is subject to sudden changes in the availability of water in the soil) could be different from the static one. Moreover, it is well known that potato cultivars may respond differently to water deficit, so it could be important to evaluate the effects of DDI on the eco-physiological growth and productive behavior of cultivars that are spreading in the Mediterranean cultivation area and which until now have not been evaluated in this sense. In addition, there are no comprehensive studies on several aspects, from ecophysiology to crop growth and yield of the potato crop in relation to DDI. In taking all these issues into consideration, the present research investigated under field conditions the effects of DDI on (a) eco-physiological response (leaf gas exchange and chlorophyll fluorescence), (b) above-ground biomass yield, (c) tuber yield and yield components, (d) IWUE, (e) source/sink ratio and (f) tubers' dry matter content in two potato cultivars. The research was conducted in two seasons to explore possible changes in rainfall and temperature conditions that could play a key role in water deficit.

2. Materials and Methods

2.1. Site, Climate and Soil

Field experiments were conducted during two growing seasons on the coastal plain south of Siracusa (37°03′ N, 15° 18′ E, 15 m a.s.l.), Sicily, South Italy, which is a typical area for early potato cultivation. The climate is semi-arid Mediterranean, with mild winters, and commonly rainless springs. During the potato crop season for early production (from January to May), the monthly average temperatures of the 30-year period 1977–2006 were 11.2 °C in January, 11.9 °C in February, 13.2 °C in March, 15.5 °C in April, and 19.3 °C in May. Rainfall over the same period averaged about 180 mm. The soil type is Calcixerollic Xerochrepts [32]. A layer of 0.25 m thick (from −0.05 to −0.30 m), where more or less 90% of potato active roots are located, was considered for the soil analysis. The analysis made before the start of the trials indicated the following characteristics: clay 30%, silt 25%, sand 45%, organic matter 2.0%, pH 8.4, total nitrogen 1.8‰, assimilable P_2O_5 78 kg ha^{-1}, and exchangeable K_2O 337 kg ha^{-1}. The field capacity at −0.03 MPa was 0.29 g g^{-1} dry weight, the wilting point at −1.5 MPa was 0.11 g g^{-1} dry weight, and bulk density was 1.2 g cm^{-3}. All analyses were performed according to procedures approved by the Italian Society of Soil Science [33].

2.2. Experimental Design, Plant Material and Management Practices

In the two growing seasons, hereafter referred to as Season I and II, the experiment was conducted on potatoes using a randomized split-plot design with three replications, including five irrigation regimes as main plots and two cultivars (Arinda and Timate) as sub-plots. The five irrigation regimes were: irrigation only at plant emergence—dry control (I0), irrigation along the whole cycle supplying 100% ETm—irrigated control (I1), irrigation from tuber initiation up to 50% of tuber growth, supplying 100% ETm and 0% ETm from 50% of tuber growth to the end of tuber growth (I2), irrigation from tuber initiation up to 50% of tuber growth supplying 100% ETm and from 50% of tuber growth to the end of tuber growth supplying 50% ETm (I3), and irrigation from tuber initiation up to 50% of tuber growth supplying 100% ETm and from 50% of tuber growth to the end of tuber growth supplying 75% ETm (I4). The irrigation regime I2 is the same as that already studied in previous work [17] and was chosen to confirm or not previous results. Arinda and Timate have been chosen because they are widespread in the Mediterranean region for early potato production [34]. Arinda (Vulkano × AR 74-78-1) is an early ware potato with large tubers. The plants produce a moderate number of tall, erect, and vigorous stems. It has a very high yield in tubers that have a medium-low percentage of dry matter and cooking type AB, according to the European Association for Potato Research (EAPR). Timate (Elvira × SVP AM 66-42) is a medium-early ware potato tolerant to abiotic stresses with medium-large tubers. Plants produce numerous stems of medium height, semi-erect and moderately vigorous. The yield is high, and the tubers have a fairly high dry matter content, and cooking type B. Virus-free whole seed tubers imported from North European countries were planted in January in both growing seasons, 0.3 m apart, in rows separated from each another by 0.7 m (equivalent to a planting density of 4.76 plants m^{-2}). In both growing seasons, the experimental unit size was 4.2 × 3.0 m, with 60 plants, and the width of borders between irrigation treatments was 2 m. All plants emerged 40 days after planting (DAP) in Season I and 43 (DAP) in Season II. In both seasons, all plots received 100, 50, and 150 kg ha^{-1} of N, P_2O_5 and K_2O, which coincides with the crop uptake determined in a previous study [35]; phosphorus (as superphosphate) and potassium (as potassium sulfate) was applied at planting, whereas 50% of nitrogen (as ammonium sulfate) was supplied at complete emergence and the remaining 50% three weeks after as top dressing. Standard crop management was applied, involving post-emergence weeding with linuron and pest control when needed. Tubers were harvested when 80% of leaves were dry at 88 days after plant emergence (DAE) in Season I and 96 DAE in Season II.

2.3. Irrigation Treatments

All plots, including the unirrigated control (I0), received one irrigation of 30 mm when all the plants emerged. Irrigation in I1, I3 and I4 in accordance with different % ETm supply as described in 2.2 was carried out from tuber initiation which occurred on 24 March (26 DAE) and on 5 April (32 DAE), respectively, in Season I and II, to the end of tuber growth, which occurred on 17 May (80 DAE) in Season I and on 3 June (90 DAE) in Season II, respectively. In I2, irrigation was applied from tuber initiation up to 50% of tuber growth, which was reached at 51 DAE and 60 DAE in Seasons I and II, respectively. In order to record the main growth stages of tuber formation and growth (initiation, 50% of tuber growth and 100% of tuber growth) [36], in both seasons, observations were carried out by digging gently and removing the soil from the tubers carefully on three plants per sub-sub-plot and replicate approximately every ten days from 40 DAE to 90 DAE.

The maximum potato evapotranspiration (ETm) was calculated using the following formula:

$$\mathrm{ETm} = \sum_{0}^{n} \mathrm{E} \cdot \mathrm{Kc} \cdot \mathrm{Kp} \quad (1)$$

where: n = the number of days since the last watering; E = daily evaporation from an unscreened class A Pan placed about 100 m from the crop and mesh covered to prevent animals from drinking the water; Kc = crop coefficient, which varied from 0.45 to 1.15 in relation to the phase of the crop's biological cycle [37]; Kp = pan coefficient, which was taken to be 0.8 in our conditions using the criteria set out by Doorembos and Kassam [37]. Water was applied by drip irrigation when the accumulated daily evaporation corrected for rain reached about 30 mm, which corresponded to 50–60% of available soil water content at 0.30 m depth in the plots irrigated with 100% ETm. Drip lines were collocated along the rows with pressure-compensating drippers spaced at 0.30 m (0.70 × 0.30). Only rainfall exceeding 5 mm within 25 h was considered effective and included in the calculation. Analogical water meters were used to measure the volume of irrigation water applied in each treatment. The total water supplied and the number of irrigations for each irrigation water regime in the two growing seasons is reported in Table 1. The downward flux below the root zone and runoff were assumed to be negligible because the soil was flat, and the irrigation water was supplied by a drip system. Consequently, different treatment responses were due only to the differing amounts of water supplied by irrigation.

Table 1. Total water applied and number of irrigations in the studied irrigation treatments.

Season	Water Applied (mm)		Number of Irrigations	
	I	II	I	II
I0 (dry control) = Irrigation only at plant emergence	30	30	1	1
I1 (irrigated control) = supply of 100% ETm along the whole cycle	272	228	1 + 9	1 + 8
I2 = supply of 100% ETm up to 50% of tuber growth and of 0% ETm from 50% to the end of tuber growth	102	100	1 + 5	1 + 5
I3 = supply of 100% ETm up to 50% of tuber growth and of 50% ETm from 50% to the end of tuber growth	178	158	1 + 9	1 + 8
I4 = supply of 100% ETm up to 50% of tuber growth and of 75% ETm from 50% to the end of tuber growth	224	193	1 + 9	1 + 8

2.4. Data Collection and Calculations

2.4.1. Eco-Physiological Traits

Chlorophyll (Chl) fluorescence parameters were recorded in the field with a continuous excitation portable fluorimeter (Fim1500, Analytical Development Company BioScientific, Herts, UK). It uses 650 nm radiation to provide the saturating pulse and detects at wavelengths above 730 nm. Measurements were made on leaflets of fully expanded leaves of the upper canopy after a 20 min dark adaptation period. Dark adaptation time was the time needed to obtain a steady value of Fv/Fm. Leaf clips were applied to four potato plants randomly sampled in the center of each sub-plot previously marked for the purpose. All measurements were made from the tip of the youngest fully expanded leaf (usually the third or fourth leaf from the apex). Measurements were made with saturation irradiance up to 3000 µmol m^{-2} s^{-1}. The main Chl fluorescence parameters (initial fluorescence—F0, maximum fluorescence—Fm, variable fluorescence—Fv and Fv/Fm) were recorded. F0 represents the basal emission of Chl fluorescence when redox components of photosystems are fully oxidized; Fm is obtained at the fully saturating irradiance for the plant when the electron acceptor QA is fully reduced; Fv is obtained by subtracting F0 from Fm and reflects the reduction at a given time of the primary electron acceptor, which, in the oxidized state, quenches fluorescence [29]; Fv/Fm is a useful ratio expressing the photochemical efficiency of photosystem II, which also exhibits a high degree of correlation with the quantum yield of net photosynthesis [38]. Chl fluorescence measurements were carried out at 50 and 57 days after emergence (DAE) in Season I and at 67, 71, and 83 DAE in Season II. Three daily measurements were taken on each date between 10:30 and 13:30 h (local solar time). The mean values of the three daily measurements are reported and discussed. Photosynthetic rate, diffusive leaf resistance and stomatal conductance were measured with a Licor LI-6200 Portable Photosynthesis system (LI-Cor Inc., Lincoln, Nebraska, USA) using a 250 cm^3 chamber in the closed-circuit mode. At the start of measurements, the CO_2 concentration in the air immediately surrounding the plant was 350 ± 20 mL L^{-1}. All measurements were made from the tip of the youngest fully expanded leaf (usually the third or fourth leaf from the apex) and were taken in duplicate on the same leaves of four plants per sub-plot used for Chl fluorescence measurements. Measurements were carried out only in Season I at 50 and 57 days after emergence (DAE) in days typically clear and sunny characterized by a PAR < 1900 mmol photons m^{-2} s^{-1}. Air temperatures ranged between 19 and 28 °C during the period of measurements. On each date, three daily measurements were conducted between 10:30 and 13:30 h (local solar time); the mean values of the three daily measurements were reported and discussed.

2.4.2. Above-Ground Biomass, Tuber Yield and Yield Components

Four destructive samplings (five whole plants/subplot) at 50, 59, 70, and 79 DAE in Season I and at 59, 68, 75, and 85 DAE in Season II were carried out. Plants were collected by removing an undisturbed soil sample, approximately 0.25 m deep, with a radius of 0.15 m. Plants were individually separated into above-ground biomass (stems + leaves), roots and tubers. Leaf area was measured by an LI-3100C area meter (Li-COR Inc., Lincoln, NE, USA). Samples of about 100 g of stem + leaves were oven-dried at 70 °C until reaching an invariable dry weight. The following was calculated [39]:

$$LAI = [(LA2 + LA1)/2]\ (1/GA) \tag{2}$$

where LAI is the leaf area index, LA2 and LA1 are leaf area at time 2 (t2) and time 1 (t1), respectively, and GA ground area is covered by the crop.

The above-ground dry biomass yield was measured by dry matter accumulation of stem + leaves at the maximum LAI value, which occurred at 70 DAE and 75 DAE in Seasons I and II, respectively.

Tubers harvest was carried out manually at 88 and 96 DAE in Seasons I and II, respectively, on the remaining plants of each subplot.

Tubers were classified as marketable (unitary weight > 20 g) and unmarketable (unitary weight < 20 g, or deformed, green, and diseased), counted and weighed separately. Marketable tubers were used to determine marketable tuber yield (MTY), the number of tubers per plant (NTP), and mean tuber weight (MTW).

Marketable tubers were also distributed, based on transverse diameter, in three size classes: <40 mm, 40–60 mm, and >60 mm. Then, the percentage incidence of each size class on the overall marketable production was calculated as caliber tubers (CT).

Unmarketable tuber (UT) was determined as the % weight of unmarketable tubers of the total yield (marketable + unmarketable tubers).

2.4.3. Irrigation Water Use Efficiency

Irrigation Water Use Efficiency (IWUE, kg FW m^{-3}) was calculated as follows:

$$IWUE = YT/I \tag{3}$$

where YT is the marketable fresh tuber yield achieved (kg), and I is the total amount of irrigation water applied and expressed in m^3.

2.4.4. Source/Sink Ratio and Tubers Dry Matter

The source/sink ratio was calculated as the ratio of above-ground dry biomass weight at maximum LAI (achieved at 70 DAE in Season I and 75 DAE in Season II) to the dry tuber weight measured at the end of the cycle. On a representative sample of marketable tubers per sub-plot, the dry matter of marketable fresh potato tubers was determined after being dried at 65 °C and until a constant weight was achieved [40].

2.5. Meteorological Measurements

The meteorological variables were recorded daily throughout the growing seasons, using a data logger (CR21, Campbell Scientific, Logan, UT, USA) located approximately 20 m from the experimental field; temperatures were measured by the SHN multiple sensor and rainfall by the R102 sensor (ETG, Florence, Italy). Daily evaporation was measured from a class-A pan.

2.6. Data Analysis

Given the normality of distributions [41] and the homogeneity of variances [42], the data were generally subjected to a three-way analysis of variance (ANOVA) based on a factorial combination of five irrigation regimes x two cultivars x two seasons. By contrast, for the data of photosynthesis rate, leaf resistance, stomatal conductance, and chlorophyll fluorescence parameters, ANOVA was performed separately per season (since the considered measurement dates did not intercept the same phenological phases in both seasons) and was based on a factorial combination of five irrigation regimes x two cultivars x two measurement dates in Season I and factorial combination of five irrigation regimes x two cultivars x three measurement dates in Season II. Means were separated by a least significant difference (LSD) test when the *F*-test was significant. All percentage values (%) were subjected to Bliss transformation [43] prior to ANOVA; however, untransformed data (thus expressed as %) for these traits were reported and discussed. All calculations and analyses were performed using CoStat® version 6.003 (CoHort Software, Monterey, CA, USA). Collected data were submitted to multiple correlation analyses in order to define the relationship among variables.

2.7. Weather Conditions

The maximum and minimum temperatures during the growing Season II were lower than Season I and the 30-year (1977–2006) average. In particular, differences between the two seasons for maximum temperatures reached 1.1 °C in January, 4.2 °C in February, 4.3 °C in March and 3.1 °C in April and for minimum temperatures, 2.5 °C in January, 0.7 in February and April and 2.0 in March. The volume of rainfall from January to June in Season I (130 mm) was lower than the 30-year mean (180 mm), whereas it was higher (420 mm) during Season II and was concentrated for about 60% in January and February, and for 40% in April (Figure 1).

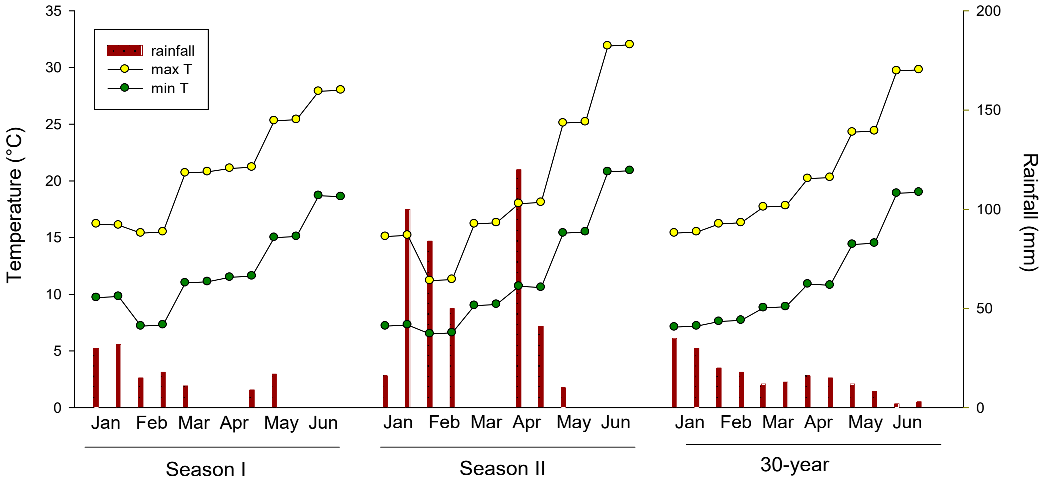

Figure 1. Average fifteen-day trend of maximum and minimum air temperatures and the fifteen-day total rainfall during the trial throughout Season I and Season II, and 30-year (1977–2006) climatic trend.

3. Results

3.1. Eco-Physiological Traits

Statistical significance from ANOVA for Chlorophyll fluorescence parameters is reported in Table 2. In Season I, chlorophyll fluorescence parameters were affected only by the cultivar and by the interaction "cultivar x measurement date". Indeed, regardless of irrigation regimes, passing from the 1st to 2nd measurement date, there were significant decreases for Fm (2229 vs. 2476), Fv (1482 vs. 1758) and Fv/Fm (0.66 vs. 0.70) in Arinda, and for F0 (592 vs. 676) in Timate (data not shown). Instead, in Season II, all chlorophyll fluorescence parameters, with the exception of F0, were affected by the interactions "irrigation regimes × cultivar" and "irrigation regimes × measurement date" (Table 2). Regarding the "irrigation regimes × cultivar" interaction, in Arinda, I1, I3 and I4 maximized the Fm, Fv and Fv/Fm (2070, 1417 and 0.69, respectively), whereas I2 showed intermediate Fm, Fv and Fv/Fm values between I0 and the other irrigation regimes. In Timate, the differences between the irrigation regimes were not unique and sometimes not significant (Table 3).

Table 2. Summary of statistical significance from analysis of variance (ANOVA) for the eco-physiological traits.

Variable	Source of Variation	d.f.	Season I	d.f.	Season II
F0	Irrigation regime (I)	4	NS	4	***
	Cultivar (C)	1	***	1	***
	Date of measurement (D)	1	NS	2	***
	I × C	4	NS	4	NS
	I × D	4	NS	8	NS
	C × D	1	**	2	NS
Fm	Irrigation regime (I)	4	NS	4	***
	Cultivar (C)	1	***	1	NS
	Date of measurement (D)	1	***	2	***
	I × C	4	NS	4	***
	I × D	4	NS	8	***
	C × D	1	**	2	***
Fv	Irrigation regime (I)	4	NS	4	***
	Cultivar (C)	1	***	1	**
	Date of measurement (D)	1	NS	2	***
	I × C	4	NS	4	***
	I × D	4	NS	8	***
	C × D	1	***	2	***

Table 2. *Cont.*

Variable	Source of Variation	d.f.	Season I	d.f.	Season II
Fv/Fm	Irrigation regime (I)	4	NS	4	***
	Cultivar (C)	1	***	1	***
	Date of measurement (D)	1	NS	2	NS
	I × C	4	NS	4	***
	I × D	4	NS	8	***
	C × D	1	***	2	***
PR (μmol CO_2 m^{-2} s^{-1})	Irrigation regime (I)	4	***		
	Cultivar (C)	1	NS		
	Date of measurement (D)	1	**		-
	I × C	4	**		
	I × D	4	***		
	C × D	1	NS		
LR (s cm^{-1})	Irrigation regime (I)	4	***		
	Cultivar (C)	1	NS		
	Date of measurement (D)	1	***		-
	I × C	4	***		
	I × D	4	***		
	C × D	1	**		
SC (cm s^{-1})	Irrigation regime (I)	4	***		
	Cultivar (C)	1	NS		
	Date of measurement (D)	1	***		-
	I × C	4	NS		
	I × D	4	NS		
	C × D	1	NS		

PR: Photosynthetic rate; LR: Leaf resistance; SC: Stomatal conductance; d.f. = degree of freedom; NS, Not Significant, ** and *** significant at $p < 0.01$ and 0.001, respectively.

Table 3. Fm, Fv and Fv/Fm (Season II), Photosynthetic rate and Leaf resistance (Season I) as affected by the interaction "irrigation regime × cultivar".

	Fm		Fv		Fv/Fm		PR		LR	
Cultivar	**Arinda**	**Timate**	**Arinda**	**Timate**	**Arinda**	**Timate**	**Arinda**	**Timate**	**Arinda**	**Timate**
I regimes										
I0	1772 ± 211	2037 ± 32	939 ± 15	1462 ± 25	0.51 ± 0.04	0.71 ± 0.06	4.3 ± 0.3	4.9 ± 0.4	1.69 ± 0.4	1.99 ± 0.3
I1	2119 ± 24	1834 ± 25	1530 ± 22	1352 ± 21	0.70 ± 0.07	0.73 ± 0.05	12.7 ± 0.9	12.6 ± 0.8	0.52 ± 0.1	0.44 ± 0.1
I2	1713 ± 20	1821 ± 27	1036 ± 17	1340 ± 20	0.59 ± 0.05	0.73 ± 0.08	9.7 ± 0.8	12.2 ± 0.7	1.29 ± 0.3	0.86 ± 0.2
I3	2035 ± 30	1961 ± 28	1398 ± 19	1417 ± 23	0.66 ± 0.05	0.72 ± 0.07	13.2 ± 0.9	13.5 ± 1.0	0.84 ± 0.2	0.61 ± 0.1
I4	2068 ± 28	1713 ± 23	1417 ± 20	1237 ± 18	0.68 ± 0.06	0.70 ± 0.05	13.1 ± 1.0	12.5 ± 0.9	0.50 ± 0.1	0.48 ± 0.1
LSD int. $p \leq 0.01$	125		160		0.05		1.9		0.24	

Data are mean ± standard deviation (n = 9 and 6 in Season II and I, respectively). PR: Photosynthetic rate (μmol CO_2 m^{-2} s^{-1}); LR: Leaf resistance (s cm^{-1}). I0 (dry control) = irrigation only at plant emergence; I1 (irrigated control) = supply of 100% ETm along the whole cycle; I2 = supply of 100% ETm up to 50% of tuber growth and of 0% ETm from 50% to the end of tuber growth; I3 = supply of 100% ETm up to 50% of tuber growth and of 50% ETm from 50% to the end of tuber growth; I4 = supply of 100% ETm up to 50% of tuber growth and of 75% ETm from 50% to the end of tuber growth. LSD = Least Significant Difference.

Regardless of the other factors, Timate showed, compared to Arinda, significantly lower F0 values and higher Fm, Fv and Fv/Fm values (Table 4).

With regard to interaction "irrigation regimes x measurement date", it emerged that both Fm and Fv were almost constant from the 1st to the 2nd measurement date in all irrigation regimes, but at the 3rd measurement date they underwent a reduction, particularly evident in I2 (Figure 2).

Fv/Fm did not change significantly in the three measurement dates in I1, I3, and I4, whereas in I0 and I2, it increased from the 1st to the 2nd measurement date, then decreased significantly by the 3rd measurement date (Figure 2).

Table 4. Eco-physiological traits as affected by the main factors in Seasons I and II.

	F0	Fm	Fv	Fv/Fm	F0	Fm	Fv	Fv/Fm	PR	LR	SC
Season	I				II				I		
I regimes											
I0	674 ± 8 a	2393 ± 20 ab	1703 ± 22 ab	0.71 ± 0.04 a	703 ± 14 a	1904 ± 30 a	1201 ± 13 b	0.61 ± 0.09 c	4.57 ± 1.4 d	1.84 ± 0.9 a	0.33 ± 0.1 b
I1	671 ± 9 a	2542 ± 21 a	1875 ± 27 a	0.73 ± 0.06 a	537 ± 16 b	1977 ± 25 a	1441 ± 14 a	0.72 ± 0.15 a	12.14 ± 3.4 bc	0.48 ± 0.6 c	1.11 ± 0.4 a
I2	681 ± 8 a	2395 ± 20 ab	1711 ± 26 ab	0.70 ± 0.04 a	579 ± 12 b	1767 ± 24 b	1188 ± 19 b	0.66 ± 0.11 b	11.00 ± 1.9 c	1.07 ± 0.7 b	0.53 ± 0.2 b
I3	702 ± 8 a	2485 ± 21 a	1788 ± 21 ab	0.71 ± 0.05 a	590 ± 17 b	1998 ± 33 a	1407 ± 13 a	0.69 ± 0.10 ab	12.87 ± 2.9 ab	0.66 ± 0.4 c	0.95 ± 0.3 a
I4	700 ± 8 a	2331 ± 20 b	1642 ± 23 b	0.69 ± 0.04 a	561 ± 16 b	1890 ± 29 a	1328 ± 14 a	0.69 ± 0.11 ab	13.82 ± 3.7 a	0.55 ± 0.5 c	1.16 ± 0.5 a
Cultivar											
Arinda	737 ± 8 a	2353 ± 19 b	1620 ± 22 b	0.68 ± 0.05 b	677 ± 13 a	1873 ± 25 b	1264 ± 10 b	0.63 ± 0.08 b	10.61 ± 2.1 a	0.97 ± 0.6 a	0.77 ± 0.4 a
Timate	634 ± 7 b	2506 ± 20 a	1867 ± 25 a	0.74 ± 0.07 a	512 ± 11 b	1941 ± 29 a	1362 ± 22 a	0.72 ± 0.14 a	11.14 ± 2.2 a	0.88 ± 0.5 a	0.87 ± 0.5 a
D Measurement											
I	700 ± 8 a	2493 ± 21 a	1791 ± 26 a	0.71 ± 0.06 a	653 ± 12 a	2023 ± 33 a	1370 ± 21 a	0.68 ± 0.13 b	10.24 ± 2.6 b	0.71 ± 0.7 b	0.97 ± 0.3 a
II	671 ± 7 a	2365 ± 21 b	1696 ± 21 b	0.71 ± 0.05 a	591 ± 13 b	2048 ± 34 a	1457 ± 14 a	0.70 ± 0.12 a	11.51 ± 3.1 a	1.13 ± 0.9 a	0.66 ± 0.2 b
III					538 ± 11 c	1650 ± 25 b	1112 ± 17 b	0.65 ± 0.11 b			

Data are mean ± standard deviation (n = 12 and 18 for irrigation regimes, respectively, in Season I and II; n = 30 and 45 for cultivar, respectively, in Season I and II; n = 30 for date of measurement). PR: Photosynthetic rate (μmol CO_2 m^{-2} s^{-1}); LR: Leaf resistance (s cm^{-1}); SC: Stomatal conductance (cm s^{-1}); I0 (dry control) = irrigation only at plant emergence; I1 (irrigated control) = supply of 100% ETm along whole cycle; I2 = supply of 100% ETm up to 50% of tuber growth and of 0% ETm from 50% to the end of tuber growth; I3 = supply of 100% ETm up to 50% of tuber growth and of 50% ETm from 50% to the end of tuber growth; I4 = supply of 100% ETm up to 50% of tuber growth and of 75% ETm from 50% to the end of tuber growth. Different letters within each column's factor indicate significance at Fisher's protected least significant difference test ($p < 0.01$).

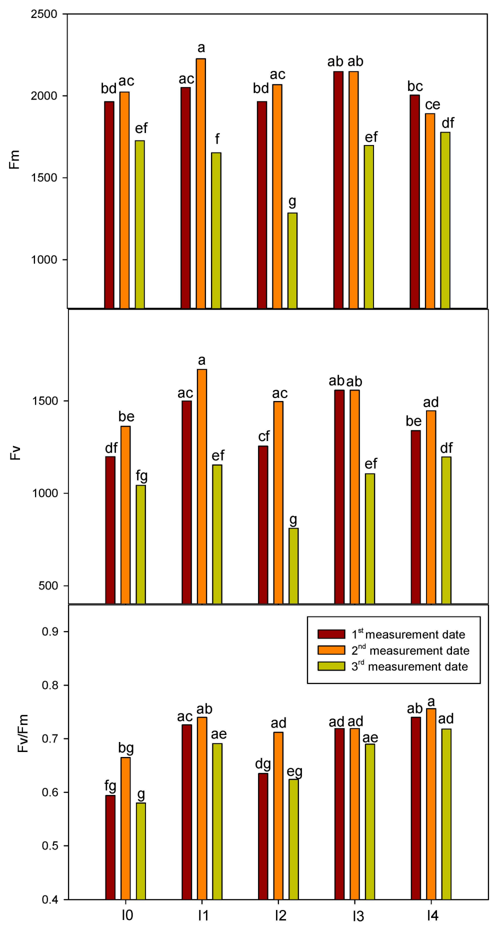

Figure 2. Fm, Fv and Fv/Fm as affected by the "irrigation regime × measurement dates" interaction in Season II. Different letters for each parameter indicate significant differences at $p \leq 0.01$.

The photosynthetic rate (PR), diffusive leaf resistance (LR), and stomatal conductance (SC), measured only in Season I, were significantly affected by irrigation regimes and measurement date but not by the cultivar (Table 2). However, PR and LR were cultivar-dependent, as demonstrated by the significance of the interaction "irrigation regime x cultivar" and were affected by the interaction "irrigation regime x measurement date" (Table 2). The PR in Arinda and Timate reached the lowest value in I0 (4.3 and 4.9 µmol CO_2 m^{-2} s^{-1}, respectively); in Arinda, it increased significantly in I2 (+125%) and in I1, I3 and I4 indifferently with an increase on the average of the 3 irrigation regimes compared to I0 of about 200%; in Timate irrigation regimes I1, I2, I3 and I4, indifferently among them showed a significant increase compared to I0 dry control of about 159% (Table 3). It should be noted, however, that the two cultivars showed values not dissimilar to each other in all irrigation regimes, with the exception of I2, in which PR was significantly lower in Arinda than in Timate (9.7 vs. 12.2 µmol CO_2 m^{-2} s^{-1}). In both Arinda and Timate, LR reached the highest value in I0 (1.69 and 1.99 s cm^{-1}, respectively) and was lowered significantly and progressively in I2, I3 and I4, showing in the latter comparable values to I1. However, it should be highlighted that Arinda in I2 showed a value significantly higher than Timate (1.29 vs. 0.86 s cm^{-1}), while for the other irrigation regimes, the differences were not significant (Table 3).

With regard to interaction "irrigation regimes x measurement dates", PR from the 1st to the 2nd measurement date decreased significantly in I0 (5.8 vs. 3.3 µmol CO_2 m^{-2} s^{-1}), increased significantly in I1, I3 and I4 (on average 14.4 vs. 11.5 µmol CO_2 m^{-2} s^{-1}), but remained constant and equal to 11.0 µmol CO_2 m^{-2} s^{-1} in I2 (Figure 3). LR increased significantly and markedly from the 1st to the 2nd measurement date in I0 (from 1.11 to 2.57 s cm^{-1}) and in I2 (from 0.77 to 1.38 s cm^{-1}), while it remained almost constant in the other irrigation regimes (Figure 3).

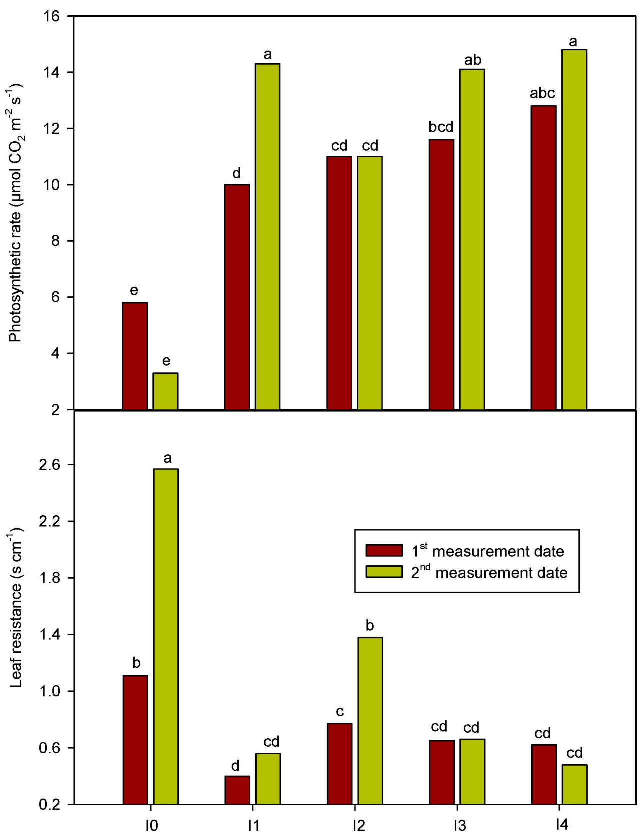

Figure 3. Photosynthetic rate and leaf resistance as affected by "irrigation regime × measurement dates" interaction in Season I. Different letters for each parameter indicate significant differences at $p \leq 0.01$.

SC showed the highest values (about 1 cm s^{-1}) indifferently in I1, I3 and I4 and the lowest indifferently in I1, I3 and I4 in I0 and I2 (on average 0.43 cm s^{-1}). Moreover, it was significantly lower on the 2nd measurement date compared to the 1st one (0.66 vs. 0.97 cm s^{-1}) (Table 3).

3.2. Above-Ground Biomass Yield, Tuber Yield and Yield Components

The statistical significance from ANOVA for above-ground biomass yield, tuber yield and yield components is reported in Table 5.

Table 5. Summary of statistical significance from ANOVA for Above-ground Biomass Yield (ABY), Marketable tuber yield (MTY), Number of tubers (NTP), Mean Tuber Weight (MTW), caliber tubers (CT), unmarketable tubers (UT), Irrigation Water Use Efficiency (IWUE), source/sink and tuber dry matter.

	Source of Variation					
Variable	**Irrigation Regime (I)**	**Cultivar (C)**	**Season (S)**	**I × C**	**I × S**	**C × S**
Degree of freedom	4	1	1	4	4	1
ABY (t DW ha^{-1})	***	NS	***	NS	***	NS
MTY (t FW ha^{-1})	***	***	***	NS	***	NS
NTP (N $plant^{-1}$)	NS	NS	NS	NS	NS	NS
MTW (g)	***	***	***	NS	***	NS
CT < 40 mm (%)	***	**	NS	NS	NS	NS
CT 40–60 mm (%)	***	NS	***	NS	***	NS
CT > 60 mm (%)	***	NS	***	NS	***	NS
UT (%)	***	**	NS	NS	NS	NS
IWUE (kg FW m^{-3})	***	***	**	NS	NS	NS
Source/sink	***	NS	NS	NS	***	NS
Tuber Dry matter (%)	***	***	NS	NS	NS	NS

DW = Dry Weight; FW = Fresh Weight; NS, not significant, ** and *** indicate significant at $p < 0.01$ and 0.001, respectively.

ABY was significantly affected by irrigation regime, season and their interaction, but not by cultivar (Table 6). Indeed, in Season I, the highest values of ABY were found in I1 and I4 indifferently (about 2.63 t DW ha^{-1}), the lowest in I0 and I2 indifferently (about 0.89 t DW ha^{-1}), intermediate values in I3 (1.60 t DW ha^{-1}); in Season II were not found significant differences among irrigation regimes (Table 7). In both seasons, the lowest MTY was found in the I0-dry control (about 19.8 t ha^{-1}). However, the effects of irrigation regimes were different between the two seasons. In Season I, the highest value, equal to roughly 47.9 t ha^{-1}, was recorded in I1; lower values but not significantly different from I1 were found indifferently in I3 and I4, whereas I2 lowered tuber yield in comparison to I1 of about 25%.

In Season II, MTY not differed significantly among irrigation regimes and was equal to roughly 28.4 t ha^{-1} (Table 7). Regardless of irrigation regimes, Arinda yielded more than Timate (35.6 vs. 28.5 t ha^{-1} on the average of the two seasons) (Table 6). The significant effects of irrigation regimes on MTY were due exclusively to the MTW because the differences in NTP were not significant (Tables 5 and 6). In both seasons, the lowest MTW was found in I0 (about 71 g). In Season I, the highest MTW was recorded indifferently in I1, and I4 (roughly 157 g), whereas I3 showed an intermediate value. In Season II, I1, I3 and I4 indifferently increased compared to dry control MTW to roughly 40%, whereas I2 increased MTW by 25%, although this difference did not reach statistical significance (Table 7). Arinda produced tubers with significantly higher MTW than Timate (125 vs. 102 g) on the average of the other factors (Table 6). The distribution of marketable tubers into the three-dimensional classes was significantly affected by irrigation regimes and by interaction “irrigation regime x season” (only for CT 40–60 mm and CT > 60 mm). CT < 40 mm was 10% in I0 and was lowered by I1, I2, I3, and I4 with no significant differences between them, giving, on average, a value of 4% (Table 6). In Season I, CT 40–60 mm showed the highest value in I0 (87%), the lowest in I1, I3 and I4 without significant differences between them (roughly 56%), and was intermediate (70%) in I2 (Table 7). On the contrary, the lowest CT > 60 mm was found in I0 (2%), the highest in I1, I3, and I4 indifferently (about 40%) and the intermediate value (27%) in I2. In Season II, the highest value (about 95%) was found in CT 40–60 mm without significant differences among irrigation regimes, whereas no tubers > 60 mm were found (Table 7). The unmarketable tubers (UT) were influenced by the irrigation regime and cultivar but not by their interaction (Table 5). The highest UT was recorded in I0 and I2 (6% on average of the two irrigation regimes); significantly lower values (about 2%) were recorded without distinction in I1, I3 and I4. Regardless of other factors, Timate showed a higher UT than Arinda (5% vs. 3%) (Table 6).

Table 6. Above-ground Biomass Yield (ABY, t DW ha^{-1}), Marketable tuber yield ((MTY, t FW ha^{-1}), Number of tubers (NTP, N plant^{-1}), Mean Tuber Weight (MTW, g), caliber tubers (CT, %), unmarketable tubers (UT, %), Irrigation Water Use Efficiency (IWUE, kg FW m^{-3}), source/sink ratio and tuber dry matter (DM, %) as affected by the main factors.

	ABY	MTY	NTP	MTW	CT < 40	CT40–60	CT > 60	UT	IWUE	Source/Sink	DM
Iregime											
I0	1.02 ± 00.5 c	19.8 ± 0.6 c	6.3 ± 0.9 a	71 ± 2 c	10 ± 0.8 a	89 ± 4 a	1 ± 0 c	7 ± 1.0 a	65.9 ± 2.5 a	0.22 ± 0.02 b	21.2 ± 2.2 a
I1	2.05 ± 00.9 a	37.8 ± 1.0 a	6.6 ± 0.6 a	129 ± 4 a	3 ± 0.1 b	76 ± 1 b	21 ± 1.2 a	2 ± 0.1 b	14.9 ± 0.5 c	0.27 ± 0.03 a	18.3 ± 1.9 c
I2	1.07 ± 00.4 c	31.1 ± 1.1 b	6.5 ± 0.8 a	110 ± 2 b	4 ± 0.2 b	82 ± 2 b	14 ± 0.8 b	5 ± 0.5 a	30.8 ± 1.1 b	0.18 ± 0.02 b	19.2 ± 1.8 bc
I3	1.57 ± 00.5 b	35.8 ± 1.5 ab	6.6 ± 0.7 a	1233 ab	3 ± 0.11 b	79 ± 3 b	18 ± 0.9 ab	2 ± 0.3 b	21.1 ± 0.8 c	0.21 ± 0.03 b	19.7 ± 1.9 b
I4	1.98 ± 00.8 a	35.8 ± 1.3 ab	6.2 ± 0.8 a	133 ± 3 a	3 ± 0.1 b	76 ± 3 b	21 ± 1.0 a	2 ± 0.2 b	17.0 ± 0.7 c	0.28 ± 0.04 a	18.3 ± 1.8 c
Cultivar											
Arinda	1.61 ± 00.6 a	35.6 ± 1.5 a	6.5 ± 1.1 a	125 ± 2 a	4 ± 0.22 b	81 ± 4 a	15 ± 0.8 a	3 ± 0.4 b	33.5 ± 1.3 a	0.24 ± 0.02 a	18.3 ± 1.7 b
Timate	1.47 ± 00.7 a	28.5 ± 0.9 b	6.4 ± 1.21.0 a	102 ± 3 b	5 ± 0.4 a	80 ± 3 a	15 ± 0.9 a	5 ± 0.6 a	26.4 ± 1.0 b	0.23 ± 0.01 a	20.4 ± 2.1 a
D Measurement											
I	1.73 ± 00.8 a	37.9 ± 1.4 a	6.7 ± 1.2 a	129 ± 3 a	4 ± 0.22 a	66 ± 2 b	30 ± 1.5 a	3 ± 0.5 a	32.5 ± 1.4 a	0.22 ± 0.02 a	19.2 ± 2.1 a
II	1.35 ± 00.4 b	26.2 ± 0.8 b	6.3 ± 1.1 a	98 ± 3 b	5 ± 0.3 a	95 ± 5 a	0 ± 0 b	4 ± 0.6 a	27.3 ± 1.3 b	0.25 ± 0.03 a	19.5 ± 2.2 a

Data are mean ± standard deviation (n = 12 for irrigation regime; n = 30 for cultivar and date of measurement). I0 (dry control) = Irrigation only at plant emergence; I1 (irrigated control) = supply of 100% ETm along the whole cycle; I2 = supply of 100% ETm up to 50% of tuber growth and of 0% ETm from 50% to the end of tuber growth; I3 = supply of 100% ETm up to 50% of tuber growth and of 50% ETm from 50% to the end of tuber growth; I4 = supply of 100% ETm up to 50% of tuber growth and of 75% ETm from 50% to the end of tuber growth. Different letters within each column's factor indicate significance at Fisher's protected least significant difference test ($p < 0.01$).

Table 7. Above-ground Biomass Yield (ABY, t DW ha^{-1}), Marketable tuber yield (MTY, t FW ha^{-1}), Mean Tuber Weight (MTW, g), caliber tubers (CT, %) and source/sink ratio as affected by interaction "irrigation regime × season".

	ABY		MTY		MTW		CT 40–60		CT > 60 mm		Source/Sink	
	I	II	I	II	I	II	I	II	I	II	I	II
I regime												
I0	0.96 ± 0.08	1.09 ± 0.09	20.1 ± 1.3	19.5 ± 1.0	67 ± 3	76 ± 3	87 ± 3	90 ± 4	2 ± 1	0	0.19 ± 0.02	0.24 ± 0.02
I1	2.76 ± 0.23	1.34 ± 0.15	47.9 ± 2.2	27.8 ± 1.6	155 ± 7	104 ± 6	55 ± 2	97 ± 3	43 ± 2	0	0.30 ± 0.03	0.24 ± 0.02
I2	0.83 ± 0.08	1.32 ± 0.14	35.9 ± 1.7	26.4 ± 1.1	124 ± 3	95 ± 4	70 ± 4	95 ± 3	27 ± 2	0	0.13 ± 0.02	0.25 ± 0.03
I3	1.60 ± 0.16	1.54 ± 0.17	42.7 ± 1.8	28.9 ± 1.5	141 ± 4	106 ± 5	61 ± 2	97 ± 3	36 ± 3	0	0.18 ± 0.02	0.24 ± 0.03
I4	2.51 ± 0.25	1.46 ± 0.13	43.1 ± 2.1	28.5 ± 1.2	159 ± 5	107 ± 4	56 ± 2	96 ± 3	42 ± 2	0	0.31 ± 0.03	0.26 ± 0.02
LSD int. $p \leq 0.01$	0.43		6.2		24		8		7		0.10	

Data are mean ± standard deviation (n = 6). DW = Dry Weight; FW = Fresh Weight; I0 (dry control) = Irrigation only at plant emergence; I1 (irrigated control) = supply of 100% ETm along the whole cycle; I2 = supply of 100% ETm up to 50% of tuber growth and of 0% ETm from 50% to the end of tuber growth; I3 = supply of 100% ETm up to 50% of tuber growth and of 50% ETm from 50% to the end of tuber growth; I4 = supply of 100% ETm up to 50% of tuber growth and of 75% ETm from 50% to the end of tuber growth. LSD = Least Significant Difference.

3.3. IWUE

IWUE was significantly influenced by irrigation regime, cultivar and season (Table 5). Regardless of the other factors, the highest value was recorded in the plots irrigated only at the plant emergence (I0) (about 66 kg m^{-3}), and the lowest value in I1, I3, and I4 without significant differences between them (roughly 18 kg m^{-3}); intermediate values were found in the regime I2 with an increase of about 74% compared to I1, I3, and I4. Regardless of irrigation regimes, IWUE was about 34 kg m^{-3} in Arinda and 26 kg m^{-3} in Timate and was higher in Season I than in Season II (32 vs. 27 kg m^{-3}) (Table 6).

3.4. Source/Sink and Tuber Dry Matter

The source/sink ratio was influenced by the irrigation regime and the interaction "irrigation regime x season". In Season I, the highest value (0.30) was found indifferently in I1 and I4. Significantly lower values were found in I0, I2 and I3; in Season II, values of about 0.25 without significant differences between irrigation regimes were found (Table 7). Tuber dry matter content was influenced only by the irrigation regime and cultivar (Table 5). Regardless of the season and cultivar, the highest dry matter content of tubers was recorded in the plots irrigated only at plant emergence (I0) (21.2%), I1 and I4 showed the lowest value (18.3%); intermediate values were recorded in I2 and I3 (about 19.5%) (Table 6). Regardless of the irrigation regime, Timate showed a higher dry matter content than Arinda (20.4% vs. 18.3%) (Table 6).

3.5. Relationships among Eco-Physiological and Productive Traits

The mean photosynthetic rate averaged across irrigation regimes, cultivar and measurement dates was positively correlated with ABY (r = 0.54 **) and MTY (r = 0.70 ***), and negatively with IWUE (r = −0.84 ***); LC was positively correlated with ABY (r = 0.78 ***) and MTY (r = 0.61 ***) and negatively with IWUE (r = −0.70 ***); LR was negatively correlated with ABY (r = −0.72 ***) and MTY (r = −0.71 ***) and positively with IWUE (r = 0.83 ***); F0, Fm, Fv were positively correlated with MTY (r = 0.34 **, r = 0.45 ***, r = 0.37 **, in the order) whereas Fv/Fm was negatively correlated with IWUE (r = −0.342 **).

4. Discussion

Water is becoming ever less available and an increasingly expensive resource in semi-arid areas, so it is crucial to adopt irrigation strategies, such as Deficit Irrigation, to save water resources and maintain high yields. This is particularly important for early potato crop that requires a significant amount of water to meet the yield and qualitative standard levels demanded by the fresh markets and which, at the same time, is very sensitive to water deficit. The study demonstrates that there was a significant effect of different irrigation regimes originating from Dynamic Deficit Irrigation on eco-physiological response, above-ground biomass yield, tuber yield and yield components, IWUE, source/sink ratio and tubers dry matter content. In both growing seasons, as was logical to expect, the lowest marketable tuber yield was found in I0-dry control; the yield was increased by the application of water irrigation to different extents in relation to irrigation regimes and seasons. In Season I, the dynamic regimes involving water supply with 100% ETm in the first part of tuber growth and water supply with 50% ETm (I3) or 75% ETm (I4) in the second part of tuber growth gave tuber yields statistically comparable to irrigation regime which presupposed the application of 100% throughout the growing season (I1). In addition, these irrigation regimes have made it possible to save 94 mm (equal to 940 m^3 ha^{-1}) of water (I3) and 48 mm (equal to 480 m^3 ha^{-1}) (I4) compared to the well-irrigated control (I1). Minimum yield reduction was also found by other authors using similar dynamic irrigation regimes, such as applying 90% ETc up tuber initiation and then 65% up to tuber harvest (irrigation regime similar to I4 under study) [44] or applying 90% ETc from planting to tuber initiation—75% ETc from tuber initiation to the beginning of flowering—50% ETc from the beginning of flowering to final harvest (irrigation regime similar to I3 under study [14]. The irrigation regime involving water supply with 100% ETm in the first part of tuber growth and strong water deficit (0% ETm) in the second part of tuber growth (I2) lowered tuber yield by 25% in comparison to the application of 100% throughout the growing season (I1) with a saving of irrigation water of 170 mm (equal to 1700 m^3 ha^{-1}).

In previous research carried out in the same environment, the irrigation regime I2 had resulted in a similar water saving, but yield reduction was only 3% compared to fully irrigated [17]. Other studies performed with similar irrigation regimes, i.e., water deficit-0% ETm applied for two weeks at tuber bulking (at 75 days after planting) or at tuber ripening (at 90 days after planting) gave, compared to fully irrigated control, yield reductions of 12% or of 42%, respectively [15]. The differences in response to water deficit applied are attributable both to the utilization of different cultivars and to climatic conditions during field trials, especially levels of irradiance and temperature, such as to lead to different levels of water deficit. In Season II, however, were not found significant differences among regimes involving water supply (I1, I2, I3 and I4) which determined, compared to dry control (I0), an increase of marketable tuber yield by an average of only 47%. This indicates that using the I2 irrigation regime, it is possible to save 128 mm (equal to 1280 m^3 ha^{-1}) of irrigation water compared to I1. The lack of differences among irrigation regimes in Season II could be attributed to high rainfall in April (160 mm), coinciding approximately with the second part of tuber growth that allowed a satisfaction of the water requirements of the plants by smoothing out the differences in water supply between irrigation regimes. It is presumable that for the same reason, in Season II, no differences between irrigation regimes for above-ground dry biomass yield were found. Instead, in Season I in dry control (I0) and in I2 were found the lowest values of above-ground dry biomass yield; this was to be expected because, in potato crops, the decrease in the leaf size is the first morphological manifestation of water stress [20,23]; a consequence of the reduction of leaf size is a less light interception, ultimately leading to reduced dry matter accumulation in tubers [45]. As it was logical to expect, in I1 and I4, the highest values of above-ground dry biomass were found, whereas, in I3, intermediate values were found. Surprisingly, however, tuber yield in I3 was comparable to I1 and I4 due to better efficiency of assimilating translocation from leaves to tubers, as demonstrated by the low values of source/sink ratio found in plants subjected to this irrigation regime. Overall, regardless of irrigation regimes, Season II found above-ground dry biomass and marketable tuber yields significantly lower than in Season I. This observed year-to-year variation is attributable mainly to the least favorable meteorological conditions to which the crop was subjected throughout the field trials in Season II, such as lower maximum and minimum temperatures in the months of February, March and April compared to Season I, together with the high precipitation in April. A daily mean temperature of 15–18 °C is generally considered an optimal temperature for potato growth; the growth rate declines nearly linearly to zero when either the average temperature decreases to 5 °C or increases to 28 °C from this optimum [46]. Irrigation regimes influenced not only the quantity but also the quality of the production. In fact, I1, I3, and I4 indifferently lowered the unmarketable production compared to irrigation regimes involving strong water deficit (namely I0 and I2). It is well known that several tuber physiological disorders, including secondary growth, growth cracks and misshapen tubers, are associated with water stress and/or wide variations in soil moisture content [9]. Tuber's dry matter content, which is one of the characteristics of potato tuber in determining harvest quality, showed the highest value in I0, the lowest in I1 and I4, and intermediate values in I2 and I3, confirming the thesis already seen that essentially it depends on the total amount of water applied and is not linked to the stage in which stress occurs [17]. The cultivars showed a similar productive response to irrigation regimes. Regardless of irrigation regimes and seasons, Arinda yielded more than Timate due to higher mean tuber weights, and consequently, having applied the same amount of irrigation water, it showed a higher IWUE. This suggests that Arinda is better able to exploit favorable soil water content than Timate.

One of the objectives of the present research was also to study, via Chl fluorescence and via gas exchange traits, the eco-physiological response of the potato crop to dynamic deficit irrigation and to detect relationships, if any, between eco-physiological and productive traits. The analysis of the chlorophyll fluorescence results showed that in Season II, Fv/Fm ratio showed the highest values in the irrigated control (I1) and comparable values in I3 and I4; the lowest value was found in I0-dry control, highlighting that damage to light reaction systems to PSII in photosynthetic mechanisms under drought stress occurred [17]. In the I2 irrigation regime, intermediate values of Fv/Fm were found, meaning that even if the plants have been well irrigated up to 50% of tuber growth, the water deficit occurred in the second part affected the photosystem, according to Jefferies [29]. The damage to the photosystem appears to be gradual. It is noted that throughout measurements dates (at 67, 71 and 83 DAE) for Fv/Fm in regimes involving severe stress (I0-dry, but also I2), the bell is noted, so if plants do not show physiological symptoms up to the 2nd measurement date, then at the 3rd measurement date the damage it is evident. In Season I, instead, the differences between the irrigation regimes in all chlorophyll fluorescence parameters were small and not significant, attributable to the fact that the chlorophyll fluorescence measurements were made quite early (at 50 and 57 DAE) when the plants were not yet suffering the effects of water stress. The Chl fluorescence measurements times, namely 50 and 57 days after emergence (DAE) in Season I and at 67, 71, and 83 DAE in Season II, did not intercept the same crop phenological phases in both growing seasons. However, on the average of measurement dates, in Season II found that Fv/Fm values were lower than in Season I (0.67 vs. 0.71), attributable to lower mean temperatures throughout the monitoring period experienced by plants in Season II. The response via gas exchange parameters (even if detected only in Season I) to irrigation regimes has highlighted that in the dry control -I0, as was logical to expect, the lowest values of photosynthetic rate and stomatal conductance and the highest of stomatal resistance were found. As it has been widely reported in drought stress conditions, potato plants close their stomata to avoid further water loss, resulting in a decrease in stomatal conductance and a decline in the availability of internal CO_2 (Ci) and inhibition of ribulose-1, 5-bisphosphate carboxylase/oxygenase enzyme activity and ATP synthesis lead to a decrease of net photosynthetic rate under drought stress [44,47]. Correlation analysis confirms that eco-physiological parameters (mean photosynthetic rate and stomatal conductance) were significantly and positively associated with average above-ground biomass and tuber yield. It has been widely reported that moisture stress in potatoes determines a decline in photosynthesis per unit leaf area [48], resulting in a reduction of leaf area and stem elongation. Leaf resistance was significantly and negatively associated with average above-ground biomass and tuber yield, as was to be expected because leaf resistance has a negative regression with photosynthesis [6]. In the irrigated control (I1) were noted the highest stomatal conductance and photosynthetic rate and lowest stomatal resistance; values of stomatal conductance, photosynthetic rate and stomatal resistance comparable to I1 were also found in I3 and in I4. When a supply of 50% ETm is applied throughout the whole cycle (Static deficit irrigation), a reduction was found in photosynthetic and leaf conductance [27,28]. Supplying100% of ETm in the first part of tuber growth (most sensitive part to water deficit) and supplying 50 or 75% of ETm in the second part of tuber growth (irrigation regimes I3 and I4) did not cause water stress to the plant and therefore did not affect gas exchange. Instead, in the irrigation regime, I2 values of photosynthetic rate, leaf conductance and diffusive stomatal resistance intermediate between I0 and well-irrigated treatments (I1, I3 and I4) were found, indicating that the plants were affected by the sudden interruption of water. With regard to the studied cultivars, Arinda and Timate showed photosynthetic rate and diffusive leaf resistance values not dissimilar to each other in all irrigation regimes, with the exception of I2, in which in Arinda were found significantly lower values for photosynthetic rate and higher value for leaf resistance than in Timate. Arinda also showed in I2 values comparable to I0 -dry control for Fm, Fv and Fv/Fm, while in Timate, the differences among the irrigation regimes for these traits were not unique. All this confirms the tolerance of Timate to water deficit and suggests a certain sensitivity of Arinda to the sudden water stress. However, Arinda would be preferable to Timate due to its earliness and better quality characteristics of the tubers. Moreover, regardless of irrigation regimes in both seasons, Timate showed compared to Arinda minor F0, major Fv and Fv/Fm. These traits, namely Fv/Fm, Fv, and F0, have proven to be reliable Chl fluorescence parameters for the definition of genotypic differences in potatoes [49]. In view of this, it is considered appropriate in future research to evaluate the behavior of potato cultivars currently grown, as well as to deepen the possible interactions of irrigation regimes with other agronomic practices (e.g., N fertilization) both on eco-physiological and productive response.

5. Conclusions

This study provided comprehensive data on both eco-physiological and productive responses of potato crops under dynamic deficit irrigation with the aim of investigating whether it is possible to reduce the irrigation water applied without implications on the aforementioned characteristics. The results of the research highlighted that by supplying 100% ETm in the first part of tuber growth and 50% ETm in the second part of tuber growth, the eco-physiological values are comparable with irrigated control and up 82 mm, equal to 820 m^3 ha^{-1}, of irrigation water can be saved without significant reductions in tuber yield. Moreover, by reducing the supply of the second part to 0% ETm, the eco-physiological traits show intermediate values between irrigated control and dry control, and it is possible to achieve water saving up to 150 mm, equal to 1500 m^3 ha^{-1}, by accepting a reduction in tuber yield of about 18%. Arinda seemed more susceptible than Timate, both in terms of gas exchange and chlorophyll fluorescence, to strong water deficit in the second part of tuber growth, whereas from a productive point of view, no differences between cultivars were found. Overall, our findings demonstrated that it is possible to effectively apply dynamic deficit irrigation in potato crops to save irrigation water without strongly compromising yields by choosing an appropriate irrigation regime in relation to the availability of irrigation water.

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References

1. Faostat. FAO Statistical Database. Production. Crops. Rome, Italy. 2020. Available online: http://faostat.fao.org (accessed on 30 October 2021).
2. Scavo, A.; Mauromicale, G.; Ierna, A. Genotype × environment interactions of potato tuber quality characteristics by AMMI and GGE biplot analysis. *Sci. Hortic.* **2023**, *310*, 111750. [CrossRef]
3. Lombardo, S.; Lo Monaco, A.; Pandino, G.; Parisi, B.; Mauromicale, G. The phenology, yield and tuber composition of 'early' crop potatoes: A comparison between organic and conventional cultivation systems. *Renew. Agric. Food Syst.* **2013**, *28*, 50–58. [CrossRef]
4. Ierna, A.; Mauromicale, G. How moderate water stress can affect water use efficiency indices in potato. *Agronomy* **2020**, *10*, 1034. [CrossRef]
5. Foti, S.; Mauromicale, G.; Ierna, A. Response of Seed-Grown Globe Artichoke to Different Levels of Nitrogen Fertilization and Water Supplies. *Acta Hort.* **2005**, *681*, 237–242. [CrossRef]
6. Ierna, A.; Mauromicale, G. Physiological and growth response to moderate water deficit of off-season potatoes in a Mediterranean environment. *Agric. Water Manag.* **2006**, *82*, 193–209. [CrossRef]
7. Fabeiro, C.; Martin de santa Olalla, F.; De Juan, J.A. Yield and size of deficit irrigated potatoes. *Agric. Water Manag.* **2001**, *48*, 255–266. [CrossRef]
8. Onder, S.; Caliskan, M.E.; Onder, D.; Caliskan, S. Different irrigation methods and water stress effects on potato yield and yield components. *Agric. Water Manag.* **2005**, *73*, 73–86. [CrossRef]
9. Ierna, A.; Mauromicale, G. How irrigation water saving strategy can affect tuber growth and nutritional composition of potato. *Sci. Hortic.* **2022**, *299*, 111034. [CrossRef]

10. Mastrorilli, M.; Zucaro, R. Towards sustainable use of water in rainfed and irrigated cropping systems: Review of some technical and policy issues. *AIMS Agric. Food* **2016**, *1*, 294–314. [CrossRef]
11. English, M.J.; Musick, J.T.; Murty, V.V.N. Deficit irrigation. In *Management of Farm Irrigation Systems*; Hoffman, G.J., Soloman, K.H., Eds.; American Society of Agricultural Engineers: St. Joseph, MI, USA, 1990; pp. 631–663.
12. Geerts, S.; Raes, D. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agric. Water Manag.* **2009**, *96*, 1275–1284. [CrossRef]
13. Shock, C.C.; Pereira, A.B.; Eldredge, E.P. Irrigation best management practices for potato. *Am. J. Potato Res.* **2007**, *84*, 2937. [CrossRef]
14. Ahmadi, S.H.; Agharezaee, M.; Kamgar-Haghighi, A.A.; Sepaskhah, A.R. Effects of dynamic and static deficit and partial root zone drying irrigation strategies on yield, tuber sizes distribution, and water productivity of two field grown potato cultivars. *Agric. Water Manag.* **2014**, *134*, 126–136. [CrossRef]
15. Karam, F.; Amacha, N.; Fahed, S.; EL Asmar, T.; Domınguez, A. Response of potato to full and deficit irrigation under semiarid climate: Agronomic and economic implications. *Agric. Water Manag.* **2014**, *142*, 144151. [CrossRef]
16. Kifle, M.; Gebretsadikan, T.G. Yield and water use efficiency of furrow irrigated potato under regulated deficit irrigation, Atsibi-Wemberta, North Ethiopia. *Agric. Water Manag.* **2016**, *170*, 133–139. [CrossRef]
17. Ierna, A.; Mauromicale, G. Tuber yield and irrigation water productivity in early potatoes as affected by irrigation regime. *Agric. Water Manag.* **2012**, *115*, 276–284. [CrossRef]
18. Moorby, J.; Munns, R.; Walcott, J. Effect of water deficit on photosynthesis and tuber metabolism in potatoes. *Aust. J. Plant Physiol.* **1975**, *2*, 323–333. [CrossRef]
19. Schapendonk, A.H.C.M.; Spitters, J.J.; Groot, P.J. Effects of water stress on photosynthesis and chlorophyll fluorescence of five potato cultivars. *Potato Res.* **1989**, *32*, 17–32. [CrossRef]
20. Liu, F.; Shahnazari, A.; Andersen, M.N.; Jacobsen, S.E.; Jensen, C.R. Effects of deficit irrigation (DI) and partial root drying (PRD) on gas exchange, biomass partitioning, and water use efficiency in potato. *Sci. Hortic.* **2006**, *109*, 113–117. [CrossRef]
21. Ramirez, D.A.; Yactayo, W.; Rens, R.L.; Rolando, J.J.; Palacios, S.; De Mendiburu, F.; Mares, V.; Barreda, C.; Loayza, H.; Monneveux, P.; et al. Defining biological thresholds associated to plant water status for monitoring waterrestriction effects: Stomatal conductance and photosynthesis recovery as key indicators in potato. *Agric. Water Manag.* **2016**, *177*, 369–378. [CrossRef]
22. Liu, F.; Jensen, C.R.; Shahanzari, A.; Andersen, M.N.; Jacobsen, S.E. ABA-regulated stomatal control and photosynthetic water use efficiency of potato (*Solanum tuberosum* L.) during progressive soil drying. *Plant Sci.* **2005**, *168*, 831–836. [CrossRef]
23. Lahlou, O.; Ouattar, S.; Ledent, J.F. The effect of drought and cultivar on growth parameters, yield, and yield components of potato. *Agronomie* **2003**, *23*, 257–268. [CrossRef]
24. Tourneux, C.; Devaux, A.; Camacho, M.; Mamani, P.; Ledent, J.F. Effect of water shortage on six potato genotypes in the highlands of Bolivia II: Water relations, physiological parameters. *Agronomie* **2003**, *23*, 181–190. [CrossRef]
25. Xu, Z.; Zhou, G.; Shimizu, H. Plant responses to drought and rewatering. *Plant Signal Behav.* **2010**, *5*, 649–654. [CrossRef] [PubMed]
26. Krause, G.H.; Weis, E. Chlorophyll fluorescence and photosynthesis: The basics. *Annu. Rev. Plant Physiol. Plant Mol. Biol.* **1991**, *42*, 313–349. [CrossRef]
27. El-Abedin, T.K.Z.; Mattar, M.A.; Al-Ghobari, H.M.; Alazba, A.A. Water-saving irrigation strategies in potato fields: Effects on physiological characteristics and water use in arid region. *Agronomy* **2019**, *9*, 172. [CrossRef]
28. Zhang, P.; Yang, X.; Manevski, K.; Li, S.; Wei, Z.; Andersen, M.N.; Liu, F. Physiological and Growth Responses of Potato (*Solanum tuberosum* L.) to Air Temperature and Relative Humidity under Soil Water Deficits. *Plants* **2022**, *11*, 1126. [CrossRef]
29. Jefferies, R.A. Effects of drought on chlorophyll fluorescence in potato (*Solanum tuberosum* L.). I. Plant water status and the kinetics of chlorophyll fluorescence. *Potato Res.* **1992**, *35*, 25–34. [CrossRef]
30. Jefferies, R.A.; Mackerron, D.K.L. Response of potato genotypes to drought. II. Leaf area index, growth and yield. *Ann. Appl. Biol.* **1993**, *122*, 105–112. [CrossRef]
31. Basu, P.S.; Sharma, A.; Sukumaran, N.P. Changes in net photosynthetic rate and chlorophyll fluorescence in potato leaves induced by water stress. *Photosynthetica* **1998**, *35*, 13–19. [CrossRef]
32. Soil Survey Staff. *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys*, 2nd ed.; U.S. Gov. Print. Office: Washington, DC, USA, 1999.
33. Italian Society of Soil Science. *Metodi Normalizzati di Analisi del Suolo*; Edagricole: Bologna, Italy, 1985.
34. Ierna, A.; Pellegrino, A.; Di Silvestro, I.; Buccheri, M. Sensory and physico-chemical characteristics of minimally processed "early" potato tubers as affected by anti-browning treatments and cultivar. *Acta Hortic.* **2016**, *1141*, 229–236. [CrossRef]
35. Ierna, A.; Mauromicale, G. Sustainable and profitable nitrogen fertilization management of potato. *Agronomy* **2019**, *9*, 582. [CrossRef]
36. Hack, H.; Gal, H.; Klemke, T.H.; Klose, R.; Meier, U.; Stauss, R.; Witzenberger, A. The BBCH scale for phenological growth stages of potato (*Solanum tuberosum* L.). In *Growth Stages of Mono- and Dicotyledonous Plants BBCH Monograph*, 2nd ed.; Meier, U., Ed.; Federal Biological Research Centre for Agriculture and Forestry: Berlin/Braunschweig, Germany, 2001; pp. 7–16.
37. Doorenbos, J.; Kassam, A.H. Yield Response to Water. In *Irrigation and Drainage Paper No. 33*; FAO: Rome, Italy, 1979.
38. Kitajima, M.; Butler, W.L. Quenching of fluorescence and primary photochemistry in chloroplasts by dibromothymoquinone. *Biochim. Biophys. Acta* **1975**, *376*, 105–115. [CrossRef] [PubMed]

39. Gardner, F.P.; Pearce, R.B.; Mitchell, R.L. *Physiology of Crop Plants*; Iowa State University Press: Iowa City, IA, USA, 1985.
40. AOAC. Official Methods of Analysis. Association of Official Analytical Chemists. 2010. Available online: http://www.aoac.org/ (accessed on 26 January 2018).
41. Shapiro, S.S.; Wilk, M.B. Analysis of variance test for normality (complete samples). *Biometrika* **1965**, *52*, 591–611. [CrossRef]
42. Levene, H. Robust tests for equality of variances. In *Contributions to Probability and Statistics*; Olkin, I., Ghurye, S.G., Hoeding, W., Madow, W.G., Mann, H.B., Eds.; Stanford University Press: Stanford, CA, USA, 1960; pp. 278–292.
43. Snedecor, G.W.; Cochran, W.G. *Statistical Methods*, 8th ed.; Iowa State University Press Publishing: Ames, IA, USA, 1989; p. 503.
44. Ahmadi, S.H.; Andersen, M.N.; Plauborg, F.; Poulsen, R.T.; Jensen, C.R.; Sepaskhah, A.R.; Hansen, S. Effects of irrigation strategies and soils on field grown potatoes: Yield and water productivity. *Agric. Water Manag.* **2010**, *97*, 1923–1930. [CrossRef]
45. Deblonde, P.M.K.; Ledent, J.F. Effects of moderate drought conditions on crop growth parameters and earliness of six potato cultivars under field conditions. *Agronomie* **2000**, *20*, 595–608. [CrossRef]
46. Struik, P.C. Chapter 18—Responses of the potato plant to temperature. In *Potato Biology and Biotechnology*; Vreugdenhil, D., Bradshaw, J., Gebhardt, C., Govers, F., Mackerron, D.K.L., Taylor, M.A., Ross, H.A., Eds.; Elsevier Science, B.V.: Amsterdam, The Netherlands, 2007; pp. 367–393.
47. Dulai, S.; Molnar, I.; Pronay, J.; Csernak, A.; Tarnai, R.; Molnarlang, M. Effects of drought on photosynthetic parameters and heat stability of PSII in wheat and in Aegilops species originating from dry habitats. *Acta Biol. Szeged.* **2006**, *50*, 11–17.
48. Vos, J.; Groenwold, J. Characteristics of photosynthesis and conductance of potato canopies and the effects of cultivar and transient drought. *Field Crops Res.* **1989**, *20*, 237–250. [CrossRef]
49. Ierna, A. Characterization of potato genotypes by chlorophyll fluorescence during plant aging in a Mediterranean environment. *Photosynthetica* **2007**, *45*, 568–575. [CrossRef]