# How Moderate Water Stress Can Affect Water Use Efficiency Indices in Potato

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**Abstract:** Since water is increasingly becoming an expensive and limited resource, it is necessary to improve crop water use efficiency (WUE) to save water while maintaining high yields. The objective of this research was to evaluate the effects of moderate water stress compared to well-watered conditions (supplying 50 or 100% of the maximum evapotranspiration (ETm)) on dry aboveground biomass yield (AB-Y), dry whole biomass yield (WB), tuber yield, irrigation WUE, and WUE at early harvest (E-TY, E-IWUE, E-YWUE), and at final harvest (F-TY, F-IWUE, F-YWUE), on WUE for dry aboveground biomass (AB-WUE) and for dry whole biomass (WB-WUE), on sink/source ratio and dry matter content of tubers in two potato cultivars—Sieglinde and Spunta, in two planting dates (early and late). Moderate water stress, compared to well-watered conditions, resulted in a small decrease in E-TY (−14%) and F-TY (−11%), but a high increase in E-IWUE (+69%) and F-IWUE (+78%), making savings in irrigation water of roughly 380 or 600 m$^3$ per crop cycle in relation to early or final harvest. Moderate water stress improved in Sieglinde IWUE, YWUE, and WB-WUE at final harvest, whereas Spunta appeared more appropriate for early harvest. In the late planting date, the crop used water better compared to the early planting, resulting in a greater increase in IWUE (+77 vs. +66%) and an, albeit, slight increase in the WUE. It would, therefore, be convenient to apply the moderate water stress in the late planting, saving a further 100 m$^3$ of irrigation water. The highest yield, IWUE, and YWUE were reached when moderate water stress was applied in both planting dates on cv. Spunta for early harvest and on cv. Sieglinde for final harvest. It was possible to increase WUE indices and save water, not only by water management, but also by choosing opportune planting dates and cultivars.

**Keywords:** potato; water stress; water saving; water use efficiency; tuber yield; planting date; cultivar

## 1. Introduction

In the Mediterranean basin, water is becoming an increasingly expensive (and ever less available) resource due to increased population growth, and competing demands from industry and urban development [1]. The changing climate, with a gradual but continuous increase in temperatures and evapotranspiratory demand of crops, which tends to generate an increase of irrigation water requirements in the Mediterranean region, adds further complexity to water management. Consequently, as the main consumer of freshwater, agriculture is currently faced with the challenge of new approaches to water resource management that can ensure the protection of water resources and their integrity [2]. The water scarcity and the incremental increase in irrigation costs have led to a growing interest in improving the productivity of water use in crop production [3]. The efficiency of the use of the available water, namely the proportion of available water directed towards plant transpiration, is often <50% [4]. Consequently, such a proportion gives room for potential improvements of crop water use efficiency (WUE). WUE may be generically defined as the ratio between the crop

yield achieved and the water used, referring to the total water use including rainfall, or just to the irrigation water use (Irrigation Water Use Efficiency—IWUE) [5]. Among open-field vegetables in the Mediterranean basin, potato plays an important role, occupying an overall area of a little less than one million ha and producing about 25 Mt of tubers [6]. It is largely grown in a winter–spring cycle for "early" potatoes production, which are highly appreciated and mainly exported to northern European countries, with considerable profit [7]. The shallow and sparse root system of the potato plant makes it vulnerable to water deficits [8]. An appropriate irrigation is therefore necessary to achieve desirable yield and quality [9,10]. Nonetheless, over-irrigation with excessive water inputs (up to 250–300 mm per crop season) in some cases are common, also due to inefficient irrigation methods (furrow, macro-sprinklers), resulting in a large waste of irrigation water [10]. The introduction of efficient irrigation technologies, such as micro and trickle irrigation systems, has been suggested [11]. In view of the considerable susceptibility of potato to drought, and the decrease in water resources, farmers are being challenged to save water without sacrificing yield or quality. The real challenge is to establish how to reduce current excessive irrigation supplies by maintaining or even increasing crop productivity while saving irrigation water and, therefore, increasing the IWUE [12]. Deficit irrigation—the deliberate and systematic under-irrigation of crops [13] is one way of optimizing WUE to achieve higher crop yields per unit of irrigation water [14]. Therefore, investigating how improving WUE could lead to water saving in irrigation requires considering different factors: (a) the contribution of rainfall to satisfy crop water requirements, (b) the management and technologies of irrigation, (c) the agronomic practices, (d) the adaptability of the crop variety to the environment, and (e) the water use efficiency of the crop and variety under consideration [5]. Several researches have been carried out in the Mediterranean area on potatoes to study WUE response to different irrigation methods or to the application of soil water deficit at different crop stages [10,15–18] and to a combination of the water regime with fertilization [19–23]. However, information concerning the effects on WUE deriving from moderate water deficit throughout the whole growing season, which is quite common during the winter–spring potato cycle in the Mediterranean basin, with very few exceptions [15,24], is lacking. Yet it would be very important to ascertain whether a moderate water deficit can allow saving water without compromising yields. In the Mediterranean environment, knowledge on the effect of moderate water deficit on WUE indices deriving from different cultivars is lacking, as is the effect of different planting dates, which changing rainfall and temperature conditions can play a key role on water stress and water saving and, therefore, on WUE indices. The objective of this work was to evaluate the effects of moderate water deficit on (a) tuber yield at early and final harvest, (b) dry aboveground biomass, (c) irrigation water use efficiency (IWUE), (d) water use efficiency (WUE) for tuber yield, (e) (WUE) for aboveground biomass and (f) (WUE) for whole biomass, (g) source/sink ratio (h) tubers' dry matter content of two potato cultivars in two planting dates.

## 2. Materials and Methods

### 2.1. Experimental Design, Plant Material, and Management Practices

Experiments were conducted during 1999 at our experimental field, in Sicily (South Italy), in an area used for potato cultivation. The climate is semi-arid Mediterranean, with mild winters, and commonly rainless springs; frost occurrence is virtually unknown (two events in 30 years). During the potato crop season for early production (from January to May), the mean maximum day temperatures and the mean minimum night temperatures of the 30 year period 1977–2006 were, respectively, 15.4 and 7.1 °C in January, 16.2 and 7.6 °C in February, 17.7 and 8.8 °C in March, 20.2 and 10.9 °C in April, 24.3 and 14.4 °C in May. Rainfall over the same period averages about 180 mm. The soil type is Calcixerollic Xerochrepts (USDA, Soil Taxonomy), moderately deep, with the following characteristics: clay 30%, silt 25%, sand 45%, organic matter 2.0%, pH 8.4, total nitrogen 0.18% assimilable $P_2O_5$ 78 kg ha$^{-1}$, exchangeable $K_2O$ 337 kg ha$^{-1}$. The field capacity at −0.03 MPa was 0.26 g g$^{-1}$ dry weight, the wilting point at −1.5 MPa was 0.13 g g$^{-1}$ dry weight and bulk density was 1.2 g cm$^{-3}$.

The experiment was conducted on potato (*Solanum tuberosum* L.) in a randomized split-split-plot design with three replications, including two planting dates (5 and 30 January 1999), subsequently called I and II planting date, respectively, as main plots, moderate water deficit compared to well-watered (50% and 100% of the maximum evapotranspiration (ETm), respectively) as sub-plots and two cultivars (Sieglinde and Spunta) as sub-sub-plots. The two cultivars used in this research are widely cultivated in the Mediterranean region and were chosen because they differ markedly for morphological, biological, physiological, and productive traits [25]. The two planting dates were chosen since they are usually utilized by farmers in the Mediterranean basin for early production. Information about management practices adopted has already been reported [26]. Tubers harvest was carried out in two steps: (i) early harvest, when mass tubers reached about 80% (at 96 and 89 days after planting (DAP) in the I and II planting dates, respectively), and (ii) final harvest, when mass tubers reached 100% (at 115 and 105 DAP in the I and II planting, respectively) [27]. The early harvest was chosen since when the selling price of potatoes was high; farmers commonly harvest the tubers before their mass reaches 100%.

## 2.2. Irrigation Treatments

The crop was irrigated supplying 50 or 100% of the maximum evapotranspiration (ETm). ETm (net of rain) was calculated using the following formula:

$$ETm = \sum_0^n E \times Kc \times Kp \qquad (1)$$

Where: $n$ = the number of days since the last watering; E = the daily evaporation from an unscreened class A Pan situated about 100 m from the crop; Kc = crop coefficient, which varied from 0.45 to 1.15 in relation to the phase of the crop's biological cycle; Kp = pan correction coefficient, which is 0.8 in the Mediterranean area [28]. Drip irrigation was applied when the accumulated daily evaporation reached 40 mm, which corresponded to 50–60% of available soil water content (measured gravimetrically twice each planting date) at 0.30 m depth in the plots irrigated with 100% ETm. Analogical water meters were used to measure the volume of irrigation water applied in each treatment. Drip lines were placed along rows with pressure compensating drippers spaced at 0.30 m (0.70 × 0.30). Following the above formula, five irrigations (20 March; 6, 18, and 29 April, and 9 May 1999) were performed in the I planting date, and four in the II one (27 March; 10 and 22 April, and 3 May 1999). The amount of irrigation water supplied to plots receiving 100% of ETm was 70 and 80 mm in the I and II planting date, respectively, until early harvest, and 130 and 110 mm in the I and II planting dates, respectively, until final harvest (Table 1).

**Table 1.** Total water intercepted by the crop (water supplied by irrigation and rainfall) and seasonal evapotranspiration (ET) in relation to planting date, irrigation rate, and harvest time.

| Planting Date | Irrigation Rate (% ETm) | Harvest Time | Irrigation (mm) | Rainfall (mm) | Total (mm) | Seasonal ET (mm) |
|---|---|---|---|---|---|---|
| I | 50 | early | 35 | 174 | 209 | 2200 |
| | | late | 65 | 206 | 271 | 2850 |
| | 100 | early | 70 | 174 | 244 | 2550 |
| | | late | 130 | 206 | 336 | 3490 |
| II | 50 | early | 40 | 144 | 184 | 1930 |
| | | late | 55 | 159 | 214 | 2180 |
| | 100 | early | 80 | 144 | 224 | 2330 |
| | | late | 110 | 159 | 269 | 2730 |

ET = seasonal evapotranspiration; ETm = maximum evapotranspiration.

### 2.3. Data Collection and Calculations

For each planting date growing degree days (GDD) were calculated throughout the season using the following formula [29]:

$$GDD = [(T_{max} + T_{min})/2] - T_{base} \qquad (2)$$

where $T_{max}$, and $T_{min}$ are daily maximum and minimum air temperature, respectively, and $T_{base}$ is the temperature below which the crop growth does not progress; $T_{base}$ in potato is 7 °C.

To identify the main growth stages [27] in seven destructive samplings in the I planting date, and in six in the II planting date, five whole plants per subplot and replications were harvested and separated into aboveground biomass, roots, and tubers. Leaf area was measured by a LI-3100C area meter (Li-COR Inc., Lincoln, Nebraska, USA). All parts of plants were weighed. Samples of about 50 g of aboveground biomass, tubers, and roots were oven-dried at 65 °C until constant weight and weighed to determine dry matter content of several parts. At both early harvest and final harvest 30 plants from central rows of each sub-sub-plot were collected; the tubers were counted and weighed to determine fresh total yield (YT). YT was determined in both planting dates at early harvest (E-TY) and at final harvest (F-TY). Dry matter content of tubers was determined on a representative sample at final harvest by drying in a thermoventilated oven at 65 °C until constant weight.

The following were calculated [30]:

$$LAI = [(LA_2 + LA_1)/2](1/GA) \qquad (3)$$

where LAI is leaf area index, $LA_2$ and $LA_1$ are leaf area at time 2 ($t_2$) and time 1 ($t_1$), respectively, GA ground area covered by the crop. The aboveground dry biomass yield (ABY) was measured by dry matter accumulation of stems + leaves at the maximum LAI value, which occur at 84 DAP and 76 DAP in the I and II planting times, respectively. Whole dry biomass yield (WBY) was obtained by adding dry aboveground biomass yield and dry root yield at 84 and 76 DAP in the I and II planting time, respectively and dry tuber yield at final harvest. Sink/source ratio is the ratio of dry tuber yield measured at final harvest and aboveground dry biomass yield; it gives an indication on the transfer efficiency of carbohydrates from the leaves to the tubers. From each subplot, the seasonal crop evapotranspiration (ET, $m^3$) was estimated by the soil water balance equation:

$$ET = P + I + CR - Dp - R \pm \Delta S \qquad (4)$$

where P is precipitation; I the depth of irrigation water applied; CR, capillary rise; Dp, deep percolation, R the run-off and $\Delta S$, the change in soil moisture content, with all terms expressed in $m^3$. The amount of water obtained from capillary rise was negligible. Deep percolation was assumed negligible because field capacity was medium-high (29%), rainfall was distributed regularly throughout the season, and irrigation water was supplied by controlled drip system. Runoff was assumed equal to zero because the soil was flat. Soil moisture was measured at planting and at final tuber harvest by taking a soil sample in the 0.2–0.3 m depth interval (along the maximum root development of the potato roots) using the gravimetric method for each subplot. Soil samples were weighed, dried in an oven (for 24 h at 105 °C), and then reweighed. As CR, Dp and R were negligible, ET was calculated as:

$$ET = P + I \pm \Delta S \qquad (5)$$

Values of seasonal ET are reported in Table 1. Irrigation Water Use Efficiency (IWUE, kg FWm$^{-3}$), was calculated as follows:

$$IWUE = YT/I \qquad (6)$$

where YT is the actual fresh tuber yield achieved (kg), and I is the total amount of irrigation expressed in $m^3$. IWUE was determined both at early harvest (E-IWUE) and at final harvest (F-IWUE) in both planting dates.

Yield Water Use Efficiency (YWUE, kg FW m$^{-3}$), was calculated as follows:

$$YWUE = YT/ET \tag{7}$$

where YT is the actual fresh tuber yield achieved (kg), ET as in (4). YWUE was determined both at early harvest (E-YWUE) and at final harvest (F-YWUE) in both planting dates.

Aboveground dry biomass Water Use Efficiency (AB-WUE, kg DW m$^{-3}$), as:

$$AB\text{-}WUE = ABY/ET \tag{8}$$

where ABY is the dry above-ground biomass yield (kg), ET as in (4).

Whole dry biomass Water Use Efficiency (WB-WUE, kg DW m$^{-3}$), as:

$$WB\text{-}WUE = T/ET \tag{9}$$

where WB is the total dry biomass yield (kg), ET as in (4).

### 2.4. Meteorological Data

The following meteorological variables were recorded daily throughout the crop growing season: air temperature and rainfall, using a data logger (CR21, Campbell Scientific, Logan, UT, USA) located approximately 20 m from the experimental field; maximum and minimum 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.

### 2.5. Data Analysis

All data were subjected to Bartlett's test for homogeneity of variance and then analyzed using 3-way ANOVA (planting date × irrigation regime × cultivar). Means were compared by a Least Significant Difference (LSD) test, when the F-test was significant. Costat (version 6.311, CoHort, USA, 1998–2005) was used. Table 2 shows the statistical significance from the analysis of variance for all studied variables. The percentage values relating to tuber dry matter content were previously arcsine transformed before ANOVA.

**Table 2.** *F* values resulting from analysis of variance for all studied variables.

| | Planting Date (P) | Irrigation Rate (I) | Cultivar (C) | (P) × (I) | (P) × (C) | (I) × (C) | (P) × (I) × (C) |
|---|---|---|---|---|---|---|---|
| Degree of freedom | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| AB-Y [a] (kg DW ha$^{-1}$) | 502 *** | 68 *** | 115 *** | 2 NS | 3 NS | 5 NS | 54 *** |
| WB-Y [b] (kg DW ha$^{-1}$) | 9 NS | 182 *** | 609 *** | 4 NS | 107 *** | 45 *** | 8 NS |
| E-TY [c] (kg FW ha$^{-1}$) | 46 *** | 918 *** | 926 *** | 26 *** | 52 *** | 24 *** | 0.4 NS |
| F-TY [d] (kg FW ha$^{-1}$) | 2 NS | 207 *** | 1347 *** | 3 NS | 120 *** | 74 *** | 0.1 NS |
| E-IWUE [e] (kg FW m$^{-3}$) | 726 *** | 6545 *** | 2099 *** | 6 NS | 196 *** | 1657 *** | 633 *** |
| F-IWUE (kg FW m$^{-3}$) | 524 *** | 7201 *** | 1170 *** | 19 *** | 284 *** | 23 *** | 27 *** |
| E-WUE [f] (kg FW m$^{-3}$) | 92 *** | 5 NS | 1582 *** | 67 *** | 175 *** | 1187 *** | 768 *** |
| F-WUE (kg FW m$^{-3}$) | 1346 *** | 221 *** | 1926 *** | 2 NS | 350 *** | 30 *** | 2 NS |
| AB-WUE (kg DW m$^{-3}$) | 1310 *** | 50 *** | 96 *** | 6 NS | 13 ** | 14 ** | 51 *** |
| WB-WUE (kg DW m$^{-3}$) | 1767 *** | 308 *** | 782 *** | 4 NS | 239 *** | 17 *** | 18 *** |
| Sink/source | 340 *** | 1 NS | 3 NS | 1 NS | 17 ** | 13 ** | 17 ** |
| Tuber dry matter (%) | 8067 *** | 4630 *** | 20582 *** | 4 NS | 210 *** | 5145 *** | 5 NS |

[a] AB-Y = Above-ground Biomass yield; [b] WB-Y = Whole Biomass yield; [c] E-TY = Tuber yield at early harvest (at 96 and 89 DAP in the I and II planting date); [d] F-TY = Tuber yield at final harvest (at 115 and 105 DAP in the I and II planting date); [e] IWUE = Irrigation Water Use Efficiency; [f] WUE = Water Use Efficiency; FW = Fresh Weight; DW = Dry Weight; **, *** indicate significant at $P \leq 0.001$, 0.01; NS = Not Significant.

## 3. Results

### 3.1. Temperature and Rainfall

The ten-day course of the minimum and maximum temperatures and rainfall recorded during the trial are shown in the Figure 1. It is possible to note an increase in the minimum and maximum temperatures starting from the first ten days of March until the final harvest. The crop cycles length (interval emergency–final harvest) following the two planting dates underwent different maximum and minimum temperatures. In particular, in the II planting date compared to the I planting average minimum temperatures (7.0 vs. 6.2 °C) and average maximum temperatures (19.1 vs. 17.8 °C) were higher. The accumulated GDD at early harvest were 567 and 573 in the I and II planting dates, respectively, and at final harvest 712 and 743 in the I and II planting dates, respectively (data not shown). Rainfall although fairly regular, was lower in the II planting date compared to the I (144 vs. 174 mm, respectively, for early harvest and 159 vs. 206 mm for final harvest) (Table 1). The particular climatic conditions (intermittent rain and only moderate levels of irradiance and temperature), typical of the extra-seasonal crop cycle, alleviated the effects of supplying 50% ETm, which, therefore, generated only a moderate water deficit.
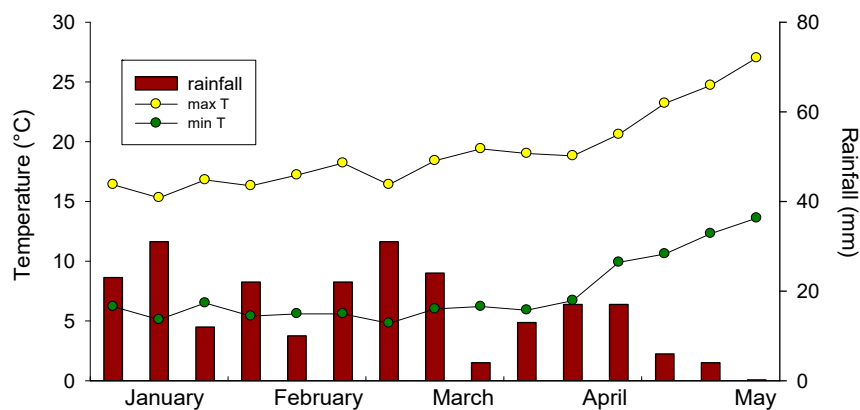


**Figure 1.** Average ten-day trend of maximum and minimum air temperatures and ten-day total rainfall during the trial.

### 3.2. Aboveground and Whole Dry Biomass Yield

Moderate water stress induced by the supply of 50% ETm reduced aboveground dry biomass yield, but the differences from the well-watered plots (supply of 100% of ETm) were only significant in Spunta in the I planting date (985 vs. 1171 kg ha$^{-1}$ DW) and in Sieglinde in the II planting date (1109 vs. 1414 kg ha$^{-1}$ DW) (Table 3).

Spunta showed a higher aboveground dry biomass yield in both planting dates than Sieglinde. Irrespective of irrigation regime and cultivar, the aboveground dry biomass was higher in the II planting than in the I planting date (Table 3). Moderate water stress resulted in a bigger reduction of the whole dry biomass yield in Spunta (−13%) than in Sieglinde (−5%) compared to well-watered situations; however, whole dry biomass yield of Spunta was higher than that of Sieglinde by about 15% in moderate water stress conditions, but was higher by 24% in well-watered conditions (Table 4). The whole dry biomass yield differences between the two cultivars (in favor of Spunta), were 11% in the I planting date and 29% in the II planting date (Table 4).

**Table 3.** Aboveground dry biomass yield (AB-Y), Irrigation Water Use Efficiency at early harvest (E-IWUE) and final harvest (F-IWUE) and Sink/source as affected by interaction 'planting date × irrigation rate × cultivar'.

| Planting Date | Irrigation Rate (% ETm) | Cultivar | AB-Y (kg DW ha$^{-1}$) | E-IWUE (kg FW m$^{-3}$) | F-IWUE (kg FW m$^{-3}$) | Sink/Source |
|---|---|---|---|---|---|---|
| I | 50 | Spunta | 985 | 75.2 | 47.4 | 5.88 |
| | | Sieglinde | 923 | 60.0 | 41.3 | 6.07 |
| | 100 | Spunta | 1171 | 43.4 | 27.6 | 5.68 |
| | | Sieglinde | 952 | 38.1 | 21.3 | 5.95 |
| II | 50 | Spunta | 1457 | 78.3 | 59.6 | 4.14 |
| | | Sieglinde | 1109 | 37.9 | 42.6 | 4.31 |
| | 100 | Spunta | 1458 | 31.9 | 35.1 | 4.82 |
| | | Sieglinde | 1414 | 33.9 | 23.0 | 3.58 |
| LSD interaction $P \leq 0.01$ | | | 82.1 | 1.7 | 1.3 | 0.54 |

LSD = Least Significant Difference.

**Table 4.** Whole dry biomass yield (WB-Y), tuber yield at early harvest (E-TY) and at final harvest (F-TY) and Water Use Efficiency for tuber at final harvest (F-YWUE) as affected by interaction 'Planting date × cultivar' and 'Irrigation rate × cultivar'.

| | | WB-Y (kg DW ha$^{-1}$) | E-TY (kg FW ha$^{-1}$) | F-TY (kg FW ha$^{-1}$) | F-YWUE (kg FW m$^{-3}$) |
|---|---|---|---|---|---|
| Planting date | | | | | |
| I | Spunta | 7286 | 28346 | 33386 | 10.54 |
| | Sieglinde | 6555 | 23848 | 27275 | 8.70 |
| II | Spunta | 7961 | 28436 | 35700 | 14.59 |
| | Sieglinde | 6180 | 21124 | 24371 | 10.00 |
| LSD interaction $P \leq 0.01$ | | 188.6 | 718.6 | 882.1 | 0.27 |
| I. rate (% ETm) | | | | | |
| 50 | Spunta | 7109 | 28831 | 31813 | 12.91 |
| | Sieglinde | 6195 | 18076 | 25133 | 10.10 |
| 100 | Spunta | 8138 | 27951 | 37273 | 12.22 |
| | Sieglinde | 6540 | 26896 | 26513 | 8.61 |
| LSD interaction $P \leq 0.01$ | | 188.6 | 718.6 | 882.1 | 0.27 |

### 3.3. Tuber Yield

Moderate water stress, irrespective of planting date, caused a decrease in tuber yield at early harvest of 26% in Sieglinde, but no effect in Spunta; this meant that yield differences between the two cultivars (in favor of Spunta) were significant and evident (59%) only in moderate water stress conditions (Table 4). Moderate water stress compared to well-watered conditions also resulted in a greater reduction of tuber yield at early harvest in the II planting date than in the I planting date (24% vs. 17%) (data not shown). The delay in the planting date led to a significant reduction in the tuber yield at early harvest in Sieglinde, but had no effect in Spunta (Table 4). Moderate water stress also caused a decrease in tuber yield at final harvest, which was irrespective of planting date, of 15% in Spunta, but only 5% in Sieglinde. However, compared to Sieglinde, Spunta showed at final harvest higher tuber yield both in moderate stress conditions (+27%) and in well-watered conditions (+41%). Irrespective of water conditions, the delay in the planting date from I to II led to an increase in the tuber yield at final harvest in Spunta (+7%) and a reduction in Sieglinde of (−11%) (Table 4).

### 3.4. Irrigation Water Use Efficiency (IWUE)

Moderate water stress caused an increase in irrigation water use efficiency at early harvest (E-IWUE) of about 73% in Spunta in I planting date, and about double in the II planting date, whereas in Sieglinde it caused an increase of 57% in the I planting date and only 12% in the II planting date

(Table 3). Moderate water stress also caused an increase in irrigation water use efficiency at final harvest (F-IWUE) of about 70% in Spunta and 90% in Sieglinde in both planting dates. In both planting dates, the highest F-IWUE was found in Spunta under moderate water stress, the lowest in Sieglinde in no stress conditions.

### 3.5. Water Use Efficiency (WUE)

Water Use Efficiency was calculated on tuber yield at early and final harvest (E-YWUE and F-YWUE), on aboveground dry biomass yield (AB-WUE), and on whole biomass yield (WB-WUE). Moderate water stress did not affect E-YWUE in the I planting date, whereas in the II planting date it caused an increase +47% in Spunta and a decrease (−32%) in Sieglinde. The highest E-YWUE was found in Spunta supplied with 50% ETm (12.0 and 16.2 kg m$^{-3}$ in the I and II planting date, respectively), the lowest in Sieglinde supplied with 50% ETm (9.5 and 7.9 kg m$^{-3}$ in the I and II planting date, respectively) (Table 5). Moderate water stress caused an increase of F-YWUE of 17% in Sieglinde, instead no significant effect was found in Spunta (Table 4). Irrespective of water conditions, going from the I to II planting date F-YWUE increased by 47% in Spunta and by 21% in Sieglinde. Spunta, therefore, showed a higher yield water use efficiency than Sieglinde and this difference in favor of Spunta was 21% in the I planting date, but was 47% in the II one. Moderate water stress led to a significant increase in AB-WUE in Sieglinde in the I planting date (0.33 vs. 0.27 kg DW m$^{-3}$), and in Spunta in the II one (0.67 vs. 0.53 kg DW m$^{-3}$) (Table 5). In all water conditions and cultivars, AB-WUE increased markedly from the I to II planting dates in almost double increments. Moderate water deficit resulted in a significant increase in WB-WUE in Sieglinde in both planting dates (2.29 vs. 1.89 kg DW m$^{-3}$ in I planting date and 2.70 vs. 2.37 kg DW m$^{-3}$ in II planting date), but it had no effect on Spunta (Table 4). The delay in the planting date (from I to II) led to a sharp increase of WB-WUE in all regimes and cultivars (Table 5); regardless of the irrigation regime, the increase was more marked in Spunta than in Sieglinde (48% vs. 24%). The differences between Spunta and Sieglinde, though always in favor of Spunta, were small and about 10% in the I planting date and equal to 31% in the II one.

**Table 5.** Water Use Efficiency for tuber at early harvest (E-YWUE), for aboveground biomass (AB-WUE) and for Whole Biomass (WB-WUE) as affected by interaction 'planting date × irrigation rate × cultivar'.

| Planting Date | Irrigation Rate (% ETm) | Cultivar | E-YWUE (kg FW m$^{-3}$) | AB-WUE (kg DW m$^{-3}$) | WB-WUE (kg DW m$^{-3}$) |
|---|---|---|---|---|---|
| I | 50 | Spunta | 12.0 | 0.34 | 2.36 |
| | | Sieglinde | 9.5 | 0.33 | 2.29 |
| | 100 | Spunta | 11.9 | 0.34 | 2.24 |
| | | Sieglinde | 10.5 | 0.27 | 1.89 |
| II | 50 | Spunta | 16.2 | 0.67 | 3.43 |
| | | Sieglinde | 7.9 | 0.51 | 2.70 |
| | 100 | Spunta | 11.0 | 0.53 | 3.10 |
| | | Sieglinde | 11.6 | 0.52 | 2.37 |
| LSD interaction $P \leq 0.01$ | | | 0.4 | 0.03 | 0.09 |

### 3.6. Sink/Source

Sink/source ratio was unaffected by water stress and cultivar in the I planting date. In the II planting date, moderate water stress caused a decrease (−16%) in the sink/source ratio in Spunta whereas an increase in Sieglinde (+20%) (Table 3). The delay in the planting date from I to II resulted in an important decrease in sink/source, more marked in Sieglinde than in Spunta.

### 3.7. Tuber Dry Matter Content

Moderate water deficit compared to 100% ETm resulted in a higher increase of tuber dry matter content in Sieglinde (21.2% vs. 19.5%) than in Spunta (18.7% vs. 18.1%). Regardless of other factors studied Spunta showed a lower dry matter content than Sieglinde (18.4% vs. 20.4%) (data not shown).

## 4. Discussion

In our experiment moderate water stress induced by the supply of 50% ETm, compared to well-irrigated conditions led to a tuber yield decrease of only 14% at early harvest and 11% at final harvest, similarly to what was found in previous research in the same area [19,20,31] and in comparable environments [15,17,18,21,32]. The water deficit, as also demonstrated by an increase in diffusive leaf resistance and a reduction in photosynthetic rate found in previous work [26], occurred only in the last part of the cycle due to the simultaneous increase in temperatures and decrease in rainfall. This is a phase in which the effects of water stress on the growth and development of tubers are modest and less important for the reduction of yields compared to other periods [10]. Moderate water stress compared to well-watered conditions, greatly increased the IWUE by about 71% or 77% if tubers were harvested at early or at final harvest, respectively. These results are in agreement with the findings of several authors [15,18,22,33,34]. In previous studies conducted in the same environment [20] passing from 100% to 50% of ETm, IWUE increased by about 55%. The increase in IWUE values found in this experiment is of great interest since it was associated with acceptable tuber yields (about 23 t ha$^{-1}$ at early harvest and 29 t ha$^{-1}$ at final harvest). Thus, growers inducing moderate water stress could save irrigation water by about 380 m$^3$ ha$^{-1}$ in early harvest or 600 m$^3$ ha$^{-1}$ in final harvest without sacrificing yield. The IWUE values obtained in this research in moderate water stress conditions (from 41.3 to 59.6 kg m$^{-3}$) and in well-irrigated treatment (from 21.3 to 35.1 kg m$^{-3}$) were greater than those found in the same environment [19] (from 23 to 30 kg m$^{-3}$ supplying 50% of ETm and from 16 to 19.5 kg m$^{-3}$ supplying 100% of ETm) and also higher than the values found in Turkey [15], supplying 33 or 66% of ETm compared to 100% of ETm (about 31 vs. 10 kg m$^{-3}$). This can be attributed to the weather conditions during the crop season and in particular to the regular distribution of rainfall, as well as to the adequate and uniform distribution of irrigation water. Moderate water stress compared to well-watered conditions slightly increased aboveground biomass WUE, tuber production WUE at both early and final harvest and, consequently, whole biomass WUE. The values of aboveground biomass WUE found in the I planting date (about 0.30 kg DW m$^{-3}$) are in line with results of a previous research [20]. The values of WUE for tubers production at final harvest, equal on average to 11.5 kg m$^{-3}$ (moderate water stress) and 10.4 kg m$^{-3}$ (well-watered), are in perfect line with what was found in previous researches in the same environment [20], supplying 50 and 100% ETm, and with what was found in Portugal [24], supplying 60% and 120% ET. The values of WUE tubers are higher than the values found in Turkey [15] supplying 33 or 66% ETm compared to 100% (about 10.3 vs. 6.7 kg m$^{-3}$). In the literature, the WUE of potatoes varied between 12 and 25 kg m$^{-3}$ in temperate climates [35,36], 10–13 kg m$^{-3}$ in sub-humid climates [37], 9–13 kg m$^{-3}$ in hot and dry environments [32,38]. The two planting dates, although not very far apart, altered the response of plants to moderate water stress. In fact, in the II planting date, plants were able to better exploit irrigation water in conditions of moderate stress compared to the I one, resulting in a greater increase of IWUE (+77 vs. +66%). In addition, regardless of irrigation regime, plants in the II planting date also showed a better use of the overall water (irrigation plus rain) as indicated by the highest values of the WUE indices: aboveground biomass WUE (0.55 vs. 0.31 kg DW m$^{-3}$), WUE for tuber production (12.6 vs. 9.4 kg FW m$^{-3}$), and whole biomass WUE (2.9 vs. 2.2 kg DW m$^{-3}$). This is probably because the plants had less water available from both irrigation (110 vs. 130 mm) and rain (159 vs. 206 mm) and because the lesser rain in the II planting date occurred in the period in which it is most necessary, namely during the tuber bulking [28,39]. In Tunisia [40] were found different values of WUE for tuber production in relation to the potato planting time (6–8 winter, 8–9 autumn, 11–14 spring planting). In a warm tropical environment for three potato cultivars that were grown in winter and summer, were found, respectively, values of 10–16 and 3–5 kg m$^{-3}$ of WUE [41]. The cultivars responded to moderate water stress differently in relation to harvest time. In both planting dates, at early harvest can be seen that Spunta under moderate water stress compared to well-watered conditions managed to make better use of irrigation water than Sieglinde without significant influences on the yields, which were significantly reduced in Sieglinde (−21% in the I planting and −33% in the II planting). At final

harvest, on the other hand, Sieglinde, in conditions of moderate stress, uses the water better than Spunta, showing greater increases in IWUE and WUE tubers and without reducing the yield which instead were significantly reduced in Spunta (–14% in the I and –15% in II). This is because, compared to Spunta, Sieglinde is less vigorous, develops smaller canopy and roots size and is therefore less able to exploit soil water content. However, in the last part of the cycle it seems that Sieglinde was able to adjust better to conditions of moderate water deficit than Spunta, making better use of the lower availability of water. The superior response of Sieglinde to water deficit may be due to its ability to maintain turgor more effectively via an increase in cell solute concentration (osmotic adjustment) [26]. We found that tuber dry matter content of Sieglinde was increased significantly by supplying 50% ETm compared to 100% ETm. This is in agreement with a number of authors [39,42] who reported that the tolerant potato cultivar adjusted to the water stress with more dry matter distributed to tubers compared to other organs of the crop. When deciding on moderate water stress to save water, it is important to choose the right cultivar, namely Spunta or Spunta-type for an early harvest or Sieglinde or Sieglinde-type for a late harvest.

## 5. Conclusions

Research aimed at studying the effects of moderate water stress on WUE indices to establish whether a moderate water deficit can allow saving water without compromising yields has substantially highlighted that:

(1) supplying 50% of the ETm induced only moderate water deficits, so it compared to well-watered conditions reduced the yield slightly but increased the IWUE considerably, saving irrigation water (650 m$^3$ ha$^{-1}$ in the I planting and 550 m$^3$ ha$^{-1}$ in the II planting);

(2) the moderate water stress had a lesser effect in the II planting date, in which the plants made better use of the water than in the I planting, allowing further improvements in WUE and saving irrigation water;

(3) in both planting dates Spunta appeared more suitable to moderate water deficit for early harvest while Sieglinde for final harvest.

Overall, our findings suggest it was possible to increase IWUE, WUE, and save water, not only by water management, but also by choosing opportune planting dates and cultivars. The breeding or selection of genotypes, which could be more efficient in water use, may represent an important strategy and a long-term solution to the problem of water scarcity.

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