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Influence of Irrigation Frequency on Radicchio (*Cichorium Intybus* L.) Yield

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Abstract: Red chicory (radicchio) plants produce leafy heads that are of great commercial interest and they require a proper irrigation technique to achieve satisfactory productivity. The use of mini-sprinklers with high-frequency irrigation schedules may increase radicchio productivity, provide better growing conditions due to timely intervention, and save water, but so far little research has been carried out on this topic. This experiment aims at evaluating the effect of two mini-sprinkler irrigation schedules (high- and low-frequency) on radicchio yield and growing conditions over a 5-year cultivation period. Marketable radicchio head production was on average 12% greater with the high-frequency schedule (26.5 t ha^{-1}) than with the low-frequency schedule (23.6 t ha^{-1}), mainly due to greater head weight. The number of underweight, pre-flowering, rotten, and missing plants was significantly different between the two schedules when these variables were considered separately, but the overall number of marketable plants was greater in the high-frequency schedule during certain years. In general, the high-frequency schedule permitted to increase both radicchio yield and to reduce irrigation water use on average by 14% (−24 mm in volume), improving the irrigation water productivity by 19% (from 0.18 t mm^{-1} of the low-frequency schedule to 0.22 t mm^{-1} of the high-frequency schedule). Reducing the irrigation interval permits a timely adaptation to the weather course and improves radicchio growing conditions, presenting itself as a valid strategy that could be adopted by the farmers, upon appropriate consideration of energy and management costs.

Keywords: sprinkler irrigation; irrigation scheduling; crop production

1. Introduction

Chicory (*Cichorium intybus* L.) is a plant of the Asteraceae family, grown in Europe and North America for the production of beverages from the roots and for the production of leafy heads used as vegetables, usually processed post-harvest through "forcing" [1,2].

Plants of the group *rubifolium* (red chicory or radicchio) are one of the most important horticultural products grown in northeastern Italy, with almost 8500 ha cultivated and a harvested production of about 280,000 tons per year [3,4]. In the Veneto region, some varieties, obtained in the course of time due to selective processes operated by the growers, are protected by the European laws that restrict cultivation area and method in order to obtain the PGI (protected geographical indication) trademark recognized by the European Union. Farmers selling under this mark can get a higher price, up to 2000 euros per ton of marketable heads. The PGI area includes 24 districts and the cultivated varieties are "rosso di Chioggia", "rosso di Verona", "variegato di Castelfranco", and "rosso di Treviso".

Radicchio is of great commercial interest due to its culinary features and nutritional qualities, including antioxidant properties [5,6], but it is still among the less known species which need attention from research bodies [7]. It should also be considered that radicchio cultivation is gaining increasing attention and showing profitability in other areas of the world, like Chile [8,9], Argentina [10], and Iowa (USA) [11].

Along with fertilization [12], irrigation of radicchio is paramount to achieve satisfactory productivity [13,14]. Irrigation is carried out in several ways depending on water availability and technological advancement of the farm, going from furrow irrigation [10] to sprinkler techniques [15] or drip irrigation [16].

In Italy, the most common irrigation system uses gun sprinklers with 28–40 mm diameter nozzles operating at 5–8 bars of pressure. These sprinklers are capable of supplying large volumes of water to large areas in a limited amount of time and also require low-frequency scheduling. The field layout of this irrigation system fails to ensure uniform water distribution and the application rate tends to exceed the infiltration capacity of the soil so that significant surface runoff is common in the final phases of irrigation, decreasing the water use efficiency. Besides, the impact of large droplets on the ground can damage plants after transplantation and create a surface crust that may hinder radicchio growth and reduce the number of harvestable heads [15].

Radicchio adapts well to different soil conditions, but in heavier soils (fine-textured soils), it may encounter problems due to water logging, which is also related to the frequent and abundant irrigation required by this crop [17] and to the consequent difficulties in carrying out soil tillage and other operations [18].

The adoption of mini-sprinkler irrigation allows a more uniform distribution of the water with lower runoff wastes leading to a higher water use efficiency and also permitting easier management of irrigation and other crop operations [15]. Its use is increasing in radicchio cultivation, but little is known about the effect of irrigation scheduling on the yield and the amount of marketable and non-marketable yields. It is clear, however, that properly scheduling the irrigation may result in a large increase in radicchio yield [19] and, in theory, by decreasing the irrigation frequency, it would be possible to better take advantage of any rainfall events and as a result, reduce the total irrigation volumes.

In Southern Europe, in light of the recent concerns about water scarcity under climate change, proper management of water for irrigation should be considered of primary importance [20]. For all these reasons, a field experiment was set up in a commercial farm in the Veneto region to study the effects of two sprinkler irrigation schedules (low-frequency irrigation and high-frequency irrigation) on radicchio "rosso di Treviso" production.

2. Materials and Methods

2.1. Experimental Site

The trial took place from 2013 to 2017 in a 6.4 ha horticultural farm in Mirano (45°30′34.5″ N, 12°06′09.0″ E), in the district of Venice in northeastern Italy. The experiment tested the effects of two irrigation schedules on the yield performances under five years of cultivation. Unluckily, in 2014, radicchio was not harvested due to an extremely heavy rainfall event after transplantation. The variety cultivated was "rosso di Treviso" PGI. Figure 1 shows the position of the experimental field within the Italian territory and within the municipalities in which the cultivation of radicchio "rosso di Treviso" is protected by the PGI trademark. The trademark was registered through the European regulation [21], and the list of the municipalities involved in the cultivation can be found in the website of the Italian Ministry of Agriculture [22].

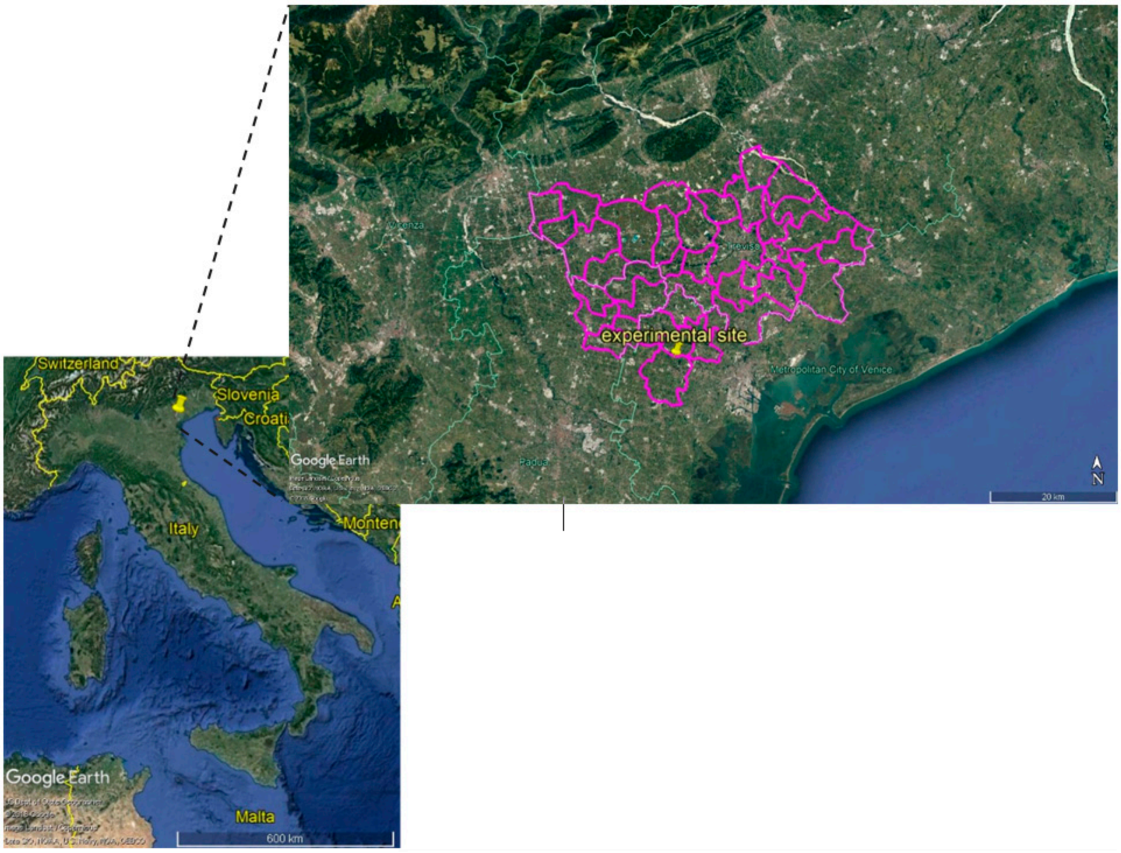

Figure 1. Location of the experimental site (yellow pin) within the municipalities (violet boundaries) where the cultivation of radicchio "rosso di Treviso" is recognized by the protected geographical indication (PGI) trademark. The map was created using Google Earth Pro [23].

The soil texture was silty loam with an organic matter content of 1.8%, pH 8, and cation-exchange capacity (CEC) of 16 meq/100 g. The saturated hydraulic conductivity was 11.5 mm h^{-1} and the total available water capacity (AWC) was 220 mm m^{-1}. The AWC of the top soil layer, having a thickness of 0.30 m in which the most plant roots are distributed, was 66 mm. The main soil characteristics of the first uniform soil layer are reported in Table 1.

Table 1. Characteristics of the soil of the experimental site (values refer to 0–45 cm depth).

Parameter	Unit	Value
Clay, sand, silt	%	19.0, 24.0, 57.0
Organic matter	%	1.8
Available water capacity	mm m^{-1}	220
Saturated hydraulic conductivity	mm h^{-1}	11.5

Meteorological data were collected from the nearby weather station of the Regional Environmental Protection Agency (ARPAV—Agenzia Regionale per la Protezione Ambientale del Veneto) and rainfall data were recorded by a rain gauge placed on the experimental site. Weather data characterizing the growing period were graphically analyzed and interpreted. Evapotranspiration during the cropping period was estimated with reference to locally calibrated evapotranspiration [24] and average radicchio-specific crop coefficient [17].

2.2. Agronomic and Irrigation Management

Seedlings of radicchio were transplanted on seedbeds during the first half of August each year, and harvested at the end of October or the beginning of November. Seedbeds, 15 cm high, were prepared according to [18], to provide the most favorable conditions for plants growth. Plant spacing was 0.6 m between the rows and 0.26 m in the row, for a total of 6.41 plants m^{-2}. During the experiment, the following crop rotation was adopted: radicchio was followed by green manure (leguminous and crucifer mixture) and cabbage. A nitrogen fertilizer at 100 kg N ha^{-1} in the form of ammonium nitrate was applied before transplanting. Phosphorus and potassium content in the soil was sufficient to support radicchio growth, so that no additional fertilizer was applied.

Two irrigation treatments were tested, planned in order to not fall below the wilting point with any of the schedules, considering the crop evapotranspiration of the previous days: (i) a low-frequency irrigation schedule, with water application about every four days and (ii) a high-frequency irrigation schedule, with irrigation about every two days. In the latter, the number of irrigations could be half or less with respect to the other treatment depending on the rainfall events, reducing the irrigation water needs. Consequently, irrigation water volumes could also decrease. The irrigation volumes were measured considering the flow rate of the irrigation system and the operating hours. The irrigation water productivity (IWP, kg m^{-3}) was calculated as the ratio between crop yield and irrigation volume, while water productivity (WP, kg m^{-3}) was calculated as the ratio between crop yield and the sum of rainfall and irrigation volumes.

In both treatments, the irrigation system (Figure 2) was low-volume mini-sprinklers on stand, "Super10" (NaanDanJain Irrigation Ltd., Israel), with a nominal flow rate of 530 L h^{-1} at 3.5 bar, placed in a triangular layout about 10 m apart. The system was powered by a 4 kW electric pump that pumped water from the nearby irrigation district canal. The water was filtered through a 120 mesh screen to avoid any system clogging.

Figure 2. Mini-sprinkler irrigation on the seedbeds during the first stages of radicchio growth.

2.3. Harvest, Data Collection, and Analysis

The field where the experiment took place was 130 m long and 30 m wide. The field was divided by the long side into two main plots where the irrigation treatments were applied. Each plot was half the size of the entire field, and multiple lines of mini-sprinklers were installed in each plot. Seven sample areas per each plot were set to measure radicchio response to irrigation at the end of the growing period. The following responses were monitored: (i) total weight of marketable plants per sample area, (ii) average weight of marketable plants, (iii) number of marketable plants, (iv) number of underweight plants, (v) number of pre-flowering plants, (vi) number of rotten plants, and (vii) number of missing plants (plants under the categories from iv to vii were considered non-marketable). The size of each sample area was of 3.74 m^2, equivalent to the surface potentially covered by 24 plants. The sample areas were spaced in such a way that each area was covered by different sprinklers, to provide independent observations. After the harvest, the chicory heads of each parcel were cleaned and prepared according to the standard practices used for heads assigned to be sold: the outer leaves were removed and a portion of the taproot was cut; then they were counted and weighted singularly (Figure 3).

Figure 3. Radicchio heads prepared before the counting and weighting.

Different approaches were used to analyze data on radicchio productivity (weights, marketable plants per hectare, IWP, and WP) and count data on radicchio quality and growth (number of underweight, pre-flowering, rotten, and missing plants). Productivity data was analyzed with pairwise two-tailed independent *t*-test between irrigation frequencies within each year, with Bonferroni correction for multiple comparisons. Assumptions of normality and homoscedasticity were visually checked, revealing satisfactory conditions to run the analysis. Count data were used to further investigate the effect of irrigation frequency on radicchio quality and growth. Raw data from each sample area, with no subsequent calculations or transformation, were used for visual (count plots) and statistical analyses. The statistical approach accounted for the specific count data distribution, according to [25]. For each variable, a generalized linear model of the Poisson family was built and a zero-inflation term was added to account for the presence of several 0 values. The zero-inflated Poisson model was built with the package glmmTMB [26] of the R software [27]. Considering the characteristics of the counts obtained and the aim of the experiment, year was used as a factor to model the zero-inflation, while the irrigation system was used as a factor for the count part of the model. The model provided a better fit than the simple Poisson model or negative binomial (lower Akaike Information Criterion (AIC) score). Residuals were checked both visually and with statistical tests for uniformity and the presence of outliers and overdispersion using the DHARMa package [28] of the R software [27], satisfying model assumptions. An analysis of deviance was used to spot significant differences between irrigation schedules. Overall, this procedure provided both a satisfactory fit to the real data and a conceptually sound explanation of the observations.

3. Result

3.1. Annual Radicchio Production, Weather, and Irrigation Frequency

Rainfall and minimum and maximum temperature were recorded during the cropping season of each year (Figure 4). The year 2016 was particularly rainy, with a peak event of 70 mm in October and characterized by 214 mm of rainfall during the cropping period. Temperatures were lower than in the other years, and a more pronounced temperature drop was recorded in October and November. Rainfall was more homogeneously distributed during the cropping period of 2013 (152 mm), 2015 (183 mm), and 2017 (218 mm).

Irrigation volumes differed in each year (Table 2), with the high-frequency schedule providing lower water volumes due to a better timely adaptation to rainfall pattern and crop evapotranspiration. This reflected on radicchio production, influencing the overall yield as well as average head weight and number of marketable plants (Figure 5). Overall, the low-frequency schedule marketable yield averaged 23.6 t ha^{-1}, while the high-frequency schedule averaged 26.5 t ha^{-1} (12% more). Significantly greater productivity of the high-frequency schedule was recorded in 2013 and 2016. Average head weight was 0.44 kg with the low-frequency schedule and 0.46 kg with the high-frequency schedule (6% more, on average). Significantly greater head weight was reported for the high-frequency schedule in 2016, consistent with the greater productivity that was recorded in the same year. It should be noted that the volumes of water applied in 2016 showed the greatest differences between the two treatments (Table 2).

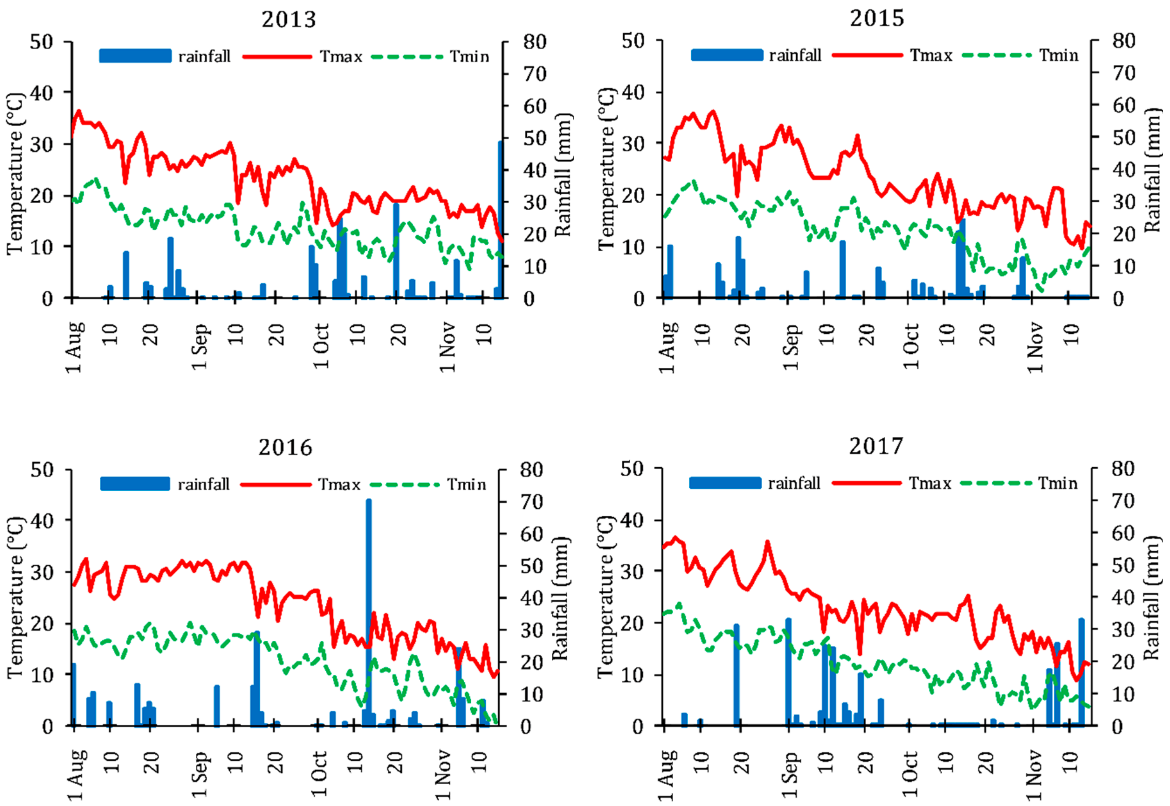

Figure 4. Rainfall and maximum and minimum temperature (1 August–15 November) during the growing period for 2013, 2015, 2016, and 2017.

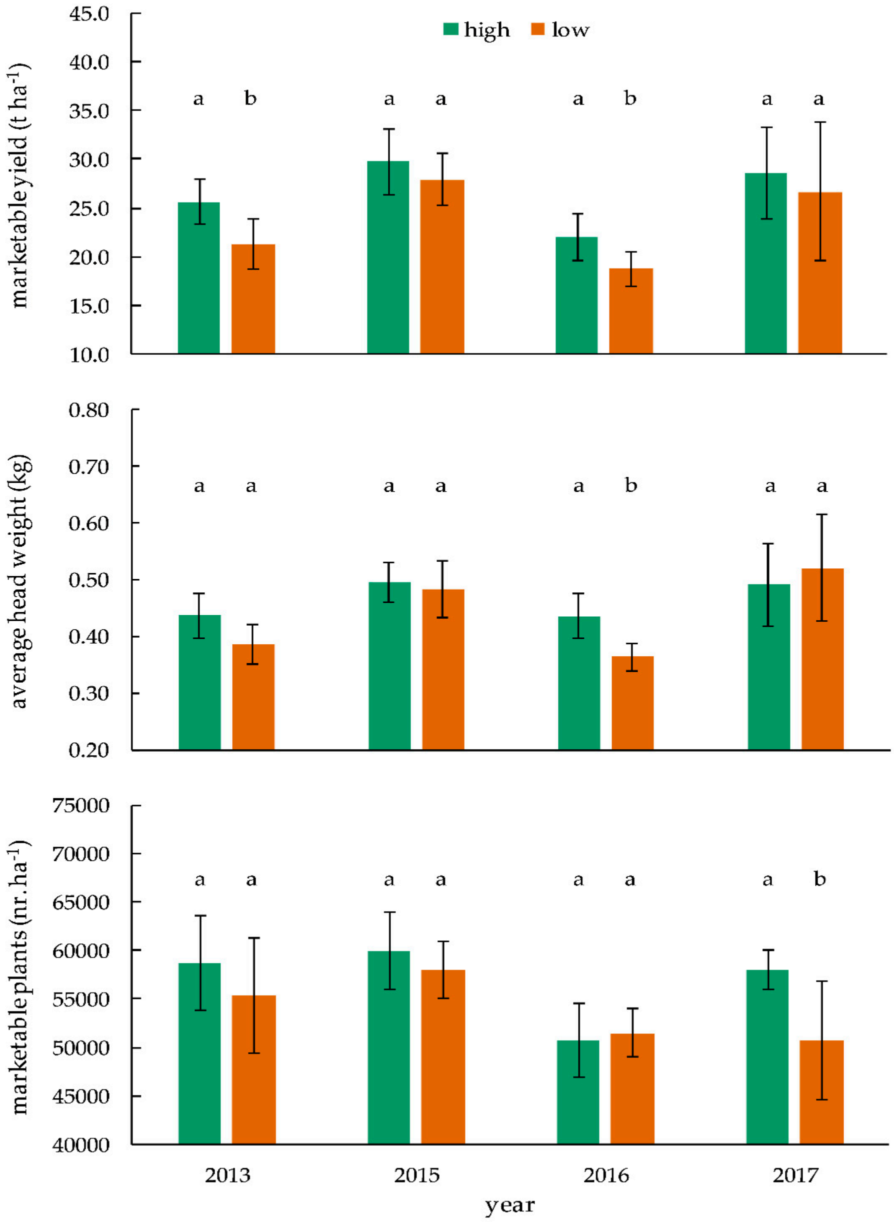

Figure 5. Yield factors measured per each year and irrigation frequency (average ± SD). Different letters indicate significant differences within the same year (pairwise independent *t*-test).

Table 2. Basic water characterization of the cropping period.

Year	Planting Date	Harvest Date	Rainfall (mm)	ETc (mm)	High-Frequency Irrigation Volume (mm)	Low-Frequency Irrigation Volume (mm)
2013	6 Aug. 2013	15 Oct. 2013	152	130	85	86
2015	4 Aug. 2015	14 Nov. 2015	183	163	125	126
2016	2 Aug. 2016	3 Nov. 2016	214	178	151	175
2017	6 Aug. 2017	10 Nov. 2017	218	166	153	170

As mentioned previously, 2016 was the year with the second greatest rainfall volume, with the highest evapotranspiration and with the greatest fluctuation of temperatures during the cropping period. In this situation, the high-frequency schedule proved to be the most efficient by increasing radicchio production and saving water due to better timing of irrigation in accordance with the weather trend.

Overall, the number of marketable plants was estimated to be 53,896 plants ha^{-1} for the low-frequency schedule, and 56,853 plants ha^{-1} for the high-frequency schedule (on average, 5% more). In 2017, the number of plants was significantly greater in the high-frequency schedule, but this was not reflected by significantly greater productivity. Indeed, 2017 was the only year when the average head weight was greater for the low-frequency schedule (even if the difference was not statistically significant), and compared to the other years, a greater variability was found in the factors determining the yield. It could be hypothesized that the lower number of marketable plants of the low-frequency schedule was partially offset by an increase in plant weight, considering that the marketable plants may have also had more room for growth due to the high number of missing plants (which will be further discussed in Section 3.2).

Finally, it is also worth noting that in 2013, even if a significantly greater production was reported in the high-frequency schedule, no statistical differences between the treatments were found for the average head weight and the number of marketable plants. This suggests once again that neither the head weight nor the number of marketable plants are individually and fully responsible for radicchio productive response.

The relationship of radicchio marketable yield with average head weight and the number of marketable plants was quantitatively investigated and visually represented, using data from all the sample areas. As shown in Figure 6, radicchio final yield was strictly positively related to average head weight ($p < 0.001$, $R^2 = 0.78$), while the positive relationship with the number of marketable plants was looser but still significant ($p < 0.001$, $R^2 = 0.41$), in accordance with the results presented in Figure 5 and previously discussed.

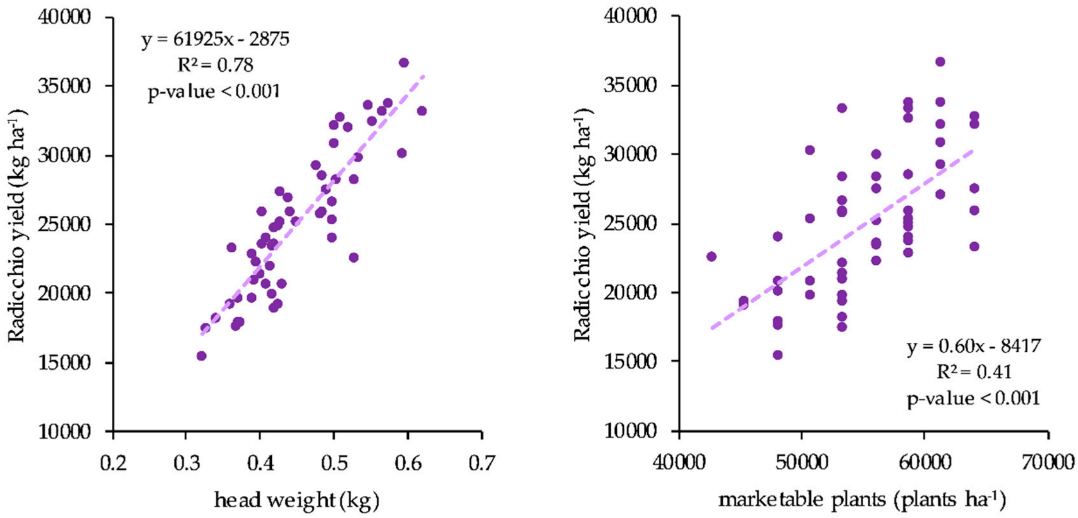

Figure 6. Relationship of radicchio yield with average head weight and the number of marketable plants. Data from all the sample areas are included.

3.2. Plant Quality: Underweight, Pre-Flowering, Rotten, and Missing Plants

The effect of irrigation schedule on the number of underweight, pre-flowering, rotten, and missing plants (Table 3), calculated from the analysis of the zero-inflated Poisson count models, was non-significant for all the quality variables considered. It is also interesting to notice that in several years the counts of the variables were 0 in many sample areas, often for both the irrigation treatments (Figure 7).

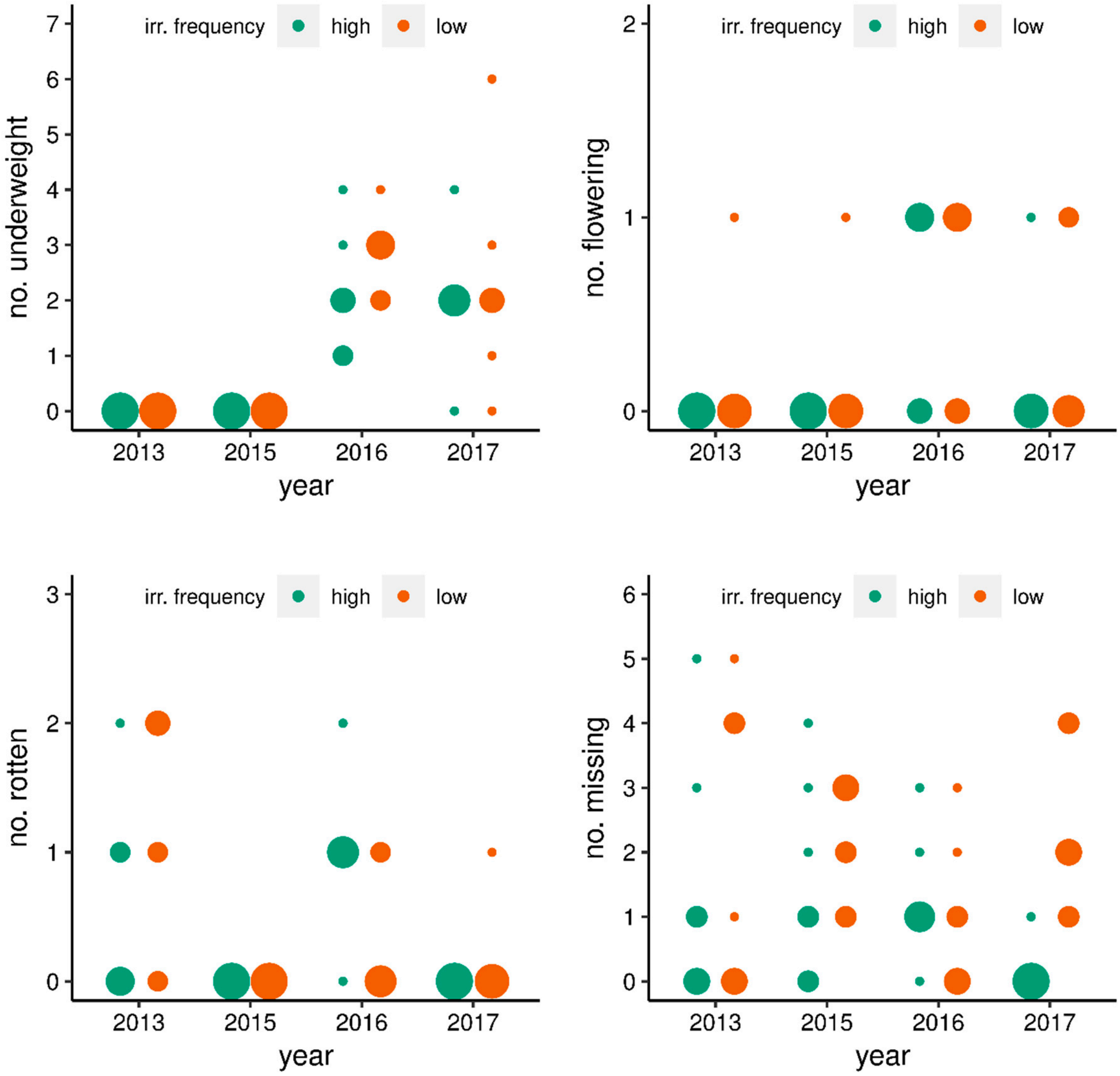

Figure 7. Count plots of the number of underweight, pre-flowering, rotten, and missing plants per year and irrigation frequency. Counts of each of the seven sample areas were considered (the dot size indicates the frequency with which the value was detected, ranging from 1 to 7 times).

Table 3. Analysis of deviance *p*-values of the count part of the models.

Counts	Irrigation Frequency *p*-Values
Underweight plants	0.376
Pre-flowering plants	0.576
Rotten plants	0.883
Missing plants	0.077

The effect of the year factor (rainfall and temperatures) in determining the number of underweight, pre-flowering, rotten, and missing plants was considered in the modeling structure (the zero-inflation part). Considering the amount of null counts, it can be inferred that the weather often provided growing conditions that were satisfactory enough to not put radicchio quality under excessive stress. In fact, the number of pre-flowering and rotten plants was limited compared to the number of underweight and missing plants, suggesting that radicchio growth was more heavily influenced than the quality of the plant. This is in agreement with the findings of [15], who reported that rain and irrigation droplets may impair radicchio growth in silty soils. In this regard, it is worthwhile to notice that, even though no significant differences were found between the two treatments, the amount of missing plants was generally greater with the low-frequency schedule (with a *p*-value of 0.07, approaching the commonly accepted threshold). The difference was more marked in 2017, when the overall number of marketable plants was significantly lower in the low-frequency schedule, as highlighted in Section 3.1. The authors of [15] also reported that higher volumes of water supplied with longer irrigation intervals may negatively impact radicchio growth, further substantiating our findings.

3.3. Irrigation Water Productivity

The efficiency of each irrigation schedule was summarized per each year using the irrigation water productivity (IWP) index. Results are reported in Table 4.

Table 4. Irrigation water productivity (IWP) and water productivity (WP) per irrigation schedule per year (average ± SD). Different letters indicate significant differences within the same year (pairwise independent *t*-test).

Year	IWP (kg m^{-3})		WP (kg m^{-3})	
	High-Frequency Schedule	Low-Frequency Schedule	High-Frequency Schedule	Low-Frequency Schedule
2013	30.1 ± 2.7 a	24.7 ± 3.0 b	10.8 ± 1.0 a	8.9 ± 1.1 b
2015	23.8 ± 2.8 a	22.2 ± 2.1 a	9.7 ± 1.1 a	9 ± 0.8 a
2016	14.6 ± 1.6 a	10.7 ± 1.0 a	6 ± 0.7 a	4.8 ± 0.5 a
2017	18.7 ± 3.1 a	15.7 ± 4.2 a	7.7 ± 1.3 a	6.9 ± 1.8 a

The irrigation water productivity was greater with the high-frequency schedule than with the low-frequency schedule during each year of the experiment. On average, the IWP was 21.8 kg m^{-3} with the high-frequency schedule and 18.3 kg m^{-3} with the low-frequency schedule, indicating that increasing the frequency of irrigation increased the productivity of irrigation water by 19%. Considering also the amount of water provided by the rainfall (WP index), the productivity per unit of water volume averaged at 7.4 kg m^{-3} with the low-frequency schedule and 8.5 kg m^{-3} with the high-frequency schedule (+15%). When the contribution of rainfall was considered, the difference between the irrigation schedules was less pronounced, since rainfall water contributed to the water needs. Significantly greater IWP and WP were found in the high-frequency schedule in 2013 (when an increase in radicchio yield was also reported, as highlighted in Section 3.1). In general, IWP obtained for the mini-sprinklers in this experiment was comparable with the average value (21.5 kg m^{-3}) obtained in a previous study in a nearby location [15]. While the previous study demonstrated that the IWP of radicchio "rosso di Treviso" was greater with mini-sprinklers than with the irrigation gun (that showed an average IWP of 7.4 kg m^{-3}), with this study, we also testified that increasing the number of mini-sprinkler irrigations per season can further increase the irrigation water productivity (with the strength of the effect that depends on the weather trend).

4. Conclusions

This work reports the findings of multiple years of experimentation on radicchio yield (2013–2017) in a commercial farm in the PGI area in northeastern Italy.

The experiment analyzed the response of radicchio to two mini-sprinkler irrigation schedules (low- and high-frequency) on marketable yield and on the number of non-marketable plants (flowering, rotten, underweight, and missing plants). Overall, radicchio marketable yield was 12% greater in the high-frequency irrigation schedule. In 2013 and 2016, radicchio production was significantly greater in the high-frequency schedule (20% and 18% more, respectively). The average weight per plant was 6% greater in the high-frequency schedule, with a significant difference in 2016 (20% more, on average). The number of underweight, pre-flowering, rotten, and missing plants was not significantly influenced by irrigation frequency when considered individually, but the number of marketable plants per hectare as a whole was 5% greater in the high-frequency treatment, with a significant difference in 2017 (14% more, on average). The number of underweight and missing plants was generally greater than that of rotten and pre-flowering plants, suggesting that rainfall and irrigation may adversely impair radicchio growth in silty soils. Overall, it is important to stress that the high-frequency irrigation increased radicchio yield by using less water for irrigation, saving up to 24 mm (−14%) in certain years, due to better timing of the irrigation intervals in accordance with the rainfall pattern. Reducing the irrigation interval improved the irrigation water productivity (on average, by 19%) and the overall water productivity (on average, by 15%). In conclusion, increasing the irrigation frequency may be a useful method to increase productivity and save water, but the choice of the irrigation schedule by the farmer should also consider energy consumptions and management costs.

Author Contributions: Conceptualization, L.B.; data curation, L.B.; investigation, L.B.; methodology, L.B. and M.T.; validation, L.B. and M.T.; formal analysis, M.T.; writing—original draft, L.B. and M.T; writing—review and editing, L.B. and M.T.; supervision, L.B.

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

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