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Salad Yields Under Agrivoltaics: A Field Test

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Abstract. Agrivoltaics is presented as a possible solution to the need for new sources of renewable energies, also responding to the increasing demand for feed/food and energy in a strongly efficient and sustainable manner. To this aim, agrivoltaics proposes to combine agricultural and renewable energy production on the same land using photovoltaic technology. The performance of this new production model strongly depends on the interaction between the two systems, agricultural and photovoltaic. In that sense, one of the most important aspects to consider are the effects of the shadows of the photovoltaic panels on the crop land. Overall, the experiment clearly indicated that a fourth cycle of escarole is possible under the PVs of agrivoltaics. Both fresh weight and size of the salad bowls were significantly increased by the shade provided by the PVs. Escarole appeared to be very tolerant to the shade and commercial yields were boosted, compared to full sun treatments, even under extended shade conditions. Such an effect can be likely explained by an overall amelioration of the water status in shaded plots. Therefore, a further study of the behavior of escarole under agrivoltaic conditions will be desirable.

Keywords: Agrivoltaics, Escarole, Agronomic Management, Food-Energy-Water Nexus

1. Introduction

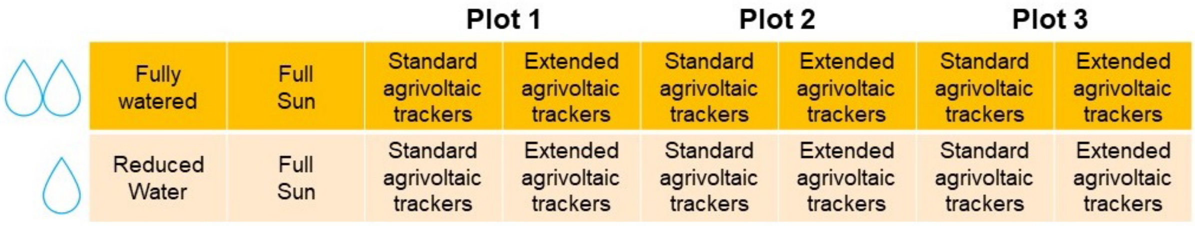
The growth of the world population creates remarkable challenges to satisfy the increasing demand for food and energy. FAO estimates that to sustain the growing population, while eradicating undernourishment, the food system, as a whole, must be able to double its current production by 2050 (FAO, 2018). This objective, that embeds a significant complexity, being related to social behaviors such as dietary regimes, food losses and wastes and poverty, is further complicated by the increase in the demand for renewable energy, that is, for a large part, produced on agricultural lands. Competition for croplands allocation is not a new issue (Johansson & Azar, 2004; Nonhebel, 2005) and the percentage of arable lands dedicated to bioenergy production or other industrial use has significantly increased in the last 20 years (Saleem, 2022), especially in the most fertile lands of the planet (Foley et al., 2011). The essence of this conflict stays in the alternative use of land, whether it is used to produce food or to produce energy. The advent of agrivoltaic plants capable of conjugate crops and energy production on the same land is a promising solution to this problem, enabling to simultaneously produce crops and generate renewable energy on the same land area (Sarr, Aminata et al., 2023). Plants require light to feed the photosynthetic machinery, but in many regions of the world the amount of light can be in excess and this, coupled with water limitations, may drive plant stress with a subsequent decrease of production. This relation cannot be generalized, as different plant species exhibit different light needs as comprehensively described by Amaducci and co-workers (Amaducci et al., 2018). Accordingly, they identified three categories of plants that i) benefit from shading, ii) are tolerant to shade and iii) are susceptible to shade. Shade-dependence of yield was assessed for several widely cultivated species. In this context high-value horticultural crops represent a special case, considering the shortness of the growth-cycle, the possibility to grow multiple cycles along a season, the high-water demand, and the fact that their selling price is tied to the fresh-weight rather than the dry-weight. In this study we tried to answer the question of a farmer specialized in ready-to-eat salad production who asked the question if it is possible to successfully close a fourth summer production cycle of escarole under agrivoltaics. His experience, in northern Italy, suggests that from June onwards, excessive radiation and high temperature loads in open fields cannot be further counterbalanced by irrigation finally causing a strong reduction in yields. For this, we investigated growth and yield of escarole (Cichorium endivia var. latifolium) subjected to shading and variable irrigation regimes under a sun-tracking bi-axial agrivoltaic system in Northern Italy from early June to the end of August 2022. The trial did not consider the effect of shading on the production of the previous spring-time cycles.

2. Materials and Methods

The experiment was made in the Agrovoltaico® plant of Borgo Virgilio (Mantova, Italy, 45°05’40’’N - 10°47’30’’E) which has been built by REM Tec srl and is operational since April 2011. The system occupies an area of approximately 15 ha of agricultural land, it has a nominal power of 2’150.4 kWp being made of 768 trackers and 7680 PV modules (Figure 1).

Figure 1. A view of the Agrovoltaico® plant in Borgo Virgilio, test with the escarole in progress.

The overall PV module area is 1.49 ha so the Ground Coverage Ratio (GCR) is 13%. Escarole seedlings were transplanted at trifoliate stage with 0.3 x 0.3 m row spacing. Three replicates were planted under “standard” agrivoltaic trackers (GCR=13%) and three replicates under “extended” agrivoltaics with a GCR of 41% (Figure 1). One large plot of 150 m^2 was also planted nearby the agrivoltaic plant to serve as “full sun” control. The plots were fully watered (with the irrigation protocol suggested by Romero-Gámez et al., 2014) by drip irrigation until 20.06.2022 when the irrigation was halved in half of the plot areas. Plants in each plot (both fully and partially irrigated) were randomly sampled four times during the growing season until the harvest. The experimental design is reported in figure 2 while the agronomic practices are reported in table 1.



		Plot 1		Plot 2		Plot 3	
Fully watered	Full Sun	Standard agrivoltaic trackers	Extended agrivoltaic trackers	Standard agrivoltaic trackers	Extended agrivoltaic trackers	Standard agrivoltaic trackers	Extended agrivoltaic trackers
Reduced Water	Full Sun	Standard agrivoltaic trackers	Extended agrivoltaic trackers	Standard agrivoltaic trackers	Extended agrivoltaic trackers	Standard agrivoltaic trackers	Extended agrivoltaic trackers

Figure 2. Escarole test scheme.

At each sampling, five plants per plot were randomly collected and the fresh biomass was determined by weighing individual plants. Maximum/minimum diameter and the total number of leaves in each clump were also determined soon after the harvest. Dry weight of individual clumps was determined after a drying period of 48 hours in an oven at 65°C. At final harvest, the size/weight of a larger number of plants was also determined by annotating their relative spatial position in the plot space. The data were statistically evaluated by ANOVA.

Table 1. Main management of crops.

Crop management	Data
Ploughing	June, 01
Harrowing	June, 02
Convexing of the soil	June, 06
Transplanting (trifoliate stage)	June, 06
Sampling and plants measurement	June, 28, July, 13, 28, August, 10
Harvest	August, 25

3. Results and Discussion

Escarole plants established well in all the replicated plots and at the first sampling date, 18 days after transplanting, differences in fresh and dry weight as well in dimensions were negligible among the different treatments. Those differences rapidly increased and became appreciable 28 days after transplanting, when the plots were sampled before irrigation levels were modified. Mean fresh weight of the plants grown under the standard and extended agrivoltaics were larger compared to that of plants grown under full-sun (Figure 3). The difference between full-sun and shaded plants further raised in the following sampling as shown in figure 3 where percent differences and statistical significance are indicated for both full and reduced watered treatments.

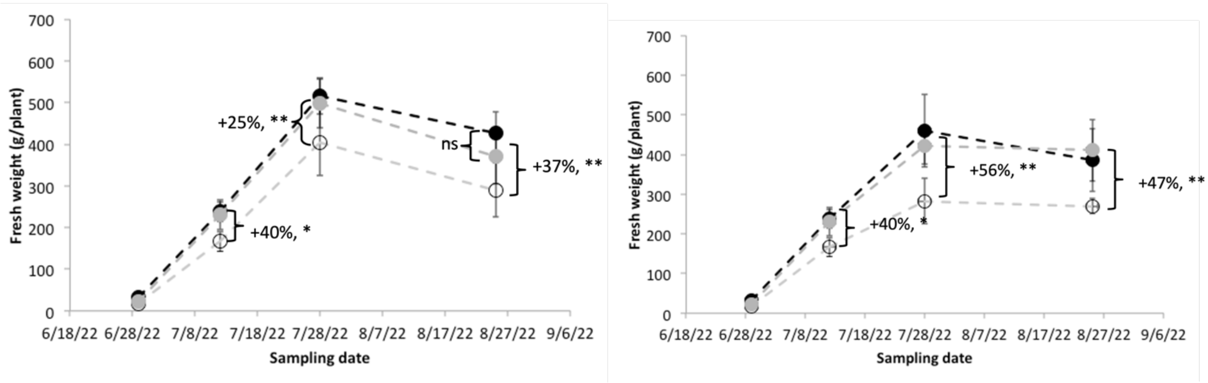


Figure 3. The time course of the mean fresh weight of escarole under fully (left) and partly irrigated (right) regimes. Black and grey dots&lines refer to the extended and standard PVs while the yellow dots&line refer to the full sun plots. Asterisks indicate statistically significant differences (within a variable) at $p < 0.05$ or <0.01. Bars indicate the standard error.

Clump dimensions (diameter and height) were well correlated to the fresh weight ($R^2 = 0.93$; $p < 0.05$ in fully watered, and $R^2 = 0.87$; $p < 0.05$ in reduced water), while the number of leaves per clump was comparable (fig. 4).

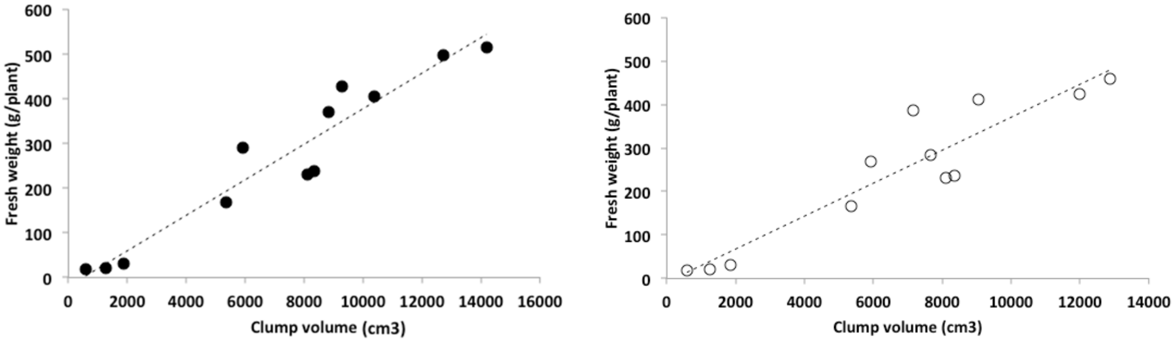


Figure 4. Correlation between volume (cm^3/plant) and fresh weight (gr/plant) in full-watered (left panel) and reduced-water (right panel) treatments.

The dry weight of plants grown under the sun or under the agrivoltaics was instead very similar (data not shown). According to Marrou et al., 2013, in a more structured experimental test, Lettuce yield was maintained through an improved Radiation Interception Efficiency (RIE) in the shade, while Radiation Conversion Efficiency (RCE) did not change significantly. The modification of the irrigation regime (50% on half of the plots) had a very limited effect on the fresh weight of plants grown under the agrivoltaics, irrespective of the "standard" and "extended" dimension of the PV panels. The effect on plants growing under full-sun was instead very large.

4. Conclusions

Overall, the experiment clearly indicated that yields of escarole under full-sun in a fourth growing cycle (June-August) were indeed severely limited as predicted by the experienced farmer that inspired the execution of this study. Shading nets are often used by farmers to reduce radiation load in salad cultivation but this implies additional production costs. The shading created by a sun-tracking agrivoltaic is indeed an interesting alternative, with a large intrinsic economic value linked to renewable energy production. Shading provided by agrivoltaics had a positive effect on growth and yield thus confirming that a fourth cycle of escarole is indeed possible. Such an effect can likely be explained by an overall amelioration of the water status in shaded plots as confirmed by the fact that yields under reduced water supply were larger in the extended than in the standard shade treatments. However, this study does not enable to conclude that the cumulative (4-cycles) salad yields achievable under the agrivoltaics are superior to those obtained under full-sun conditions when all the four growth cycles are considered together. It is likely that yields in the spring may be reduced by shading so that it remains difficult to ascertain the net advantage of enhanced yields in the last cycle. On the other hand, our result suggest that a possible solution would be that of cultivating salad as a second harvest crop in agrivoltaics, following a winter crop harvested in the late spring, such as for instance wheat or barley.

Data availability statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Author contributions

Conceptualization: Aldo Dal Prà, Lorenzo Genesio, Franco Miglietta. **Data curation:** Aldo Dal Prà, Lorenzo Genesio, Franco Miglietta. **Formal analysis:** Aldo Dal Prà. **Funding acquisition:** Lorenzo Genesio, Franco Miglietta. **Investigation:** Aldo Dal Prà, Lorenzo Genesio, Franco Miglietta, Federico Carotenuto, Silvia Baronti, Marco Moriondo, Antonino Greco, Nicola Morè, Laura Svanera, Alessandro Reboldi. **Methodology:** Aldo Dal Prà, Lorenzo Genesio, Franco Miglietta. **Project administration:** Lorenzo Genesio **Resources:** Lorenzo Genesio, Franco Miglietta. **Software:** Lorenzo Genesio, Franco Miglietta. **Writing – original draft:** Aldo Dal Prà, Lorenzo Genesio, Franco Miglietta.

Competing interests

The authors declare no conflict of interest.

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