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This is the submitted version (pre peer-review, preprint) of the following publication:

Published Version:
Gala apple production benefits from high shading levels and water limitation, under exclusion netting / A.Boini; G.Bortolotti; G.D.Perulli; M.Venturi; A.Bonora; L.Manfrini; L.Corelli Grappadelli. - In: SCIENTIA HORTICULTURAE. - ISSN 0304-4238. - ELETTRONICO. - 310:15 February 2023(2023), pp. 111756.1-111756.8. [10.1016/j.scienta.2022.111756]

This version is available at: https://hdl.handle.net/11585/909473 since: 2022-12-12

Published:

DOI: http://doi.org/10.1016/j.scienta.2022.111756

GALA APPLE PRODUCTION BENEFITS FROM HIGH SHADING LEVELS AND WATER LIMITATION, UNDER EXCLUSION NETTING.

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ABSTRACT. The application of exclusion nets is gaining interest for apple modern production, since it can limit the use of pesticides. From the physiological point of view, information related to final fruit harvest is missing. This two-year study compared a classical anti-hail net (A, 20% shading) with an exclusion net (E, 40% shading), and their effects on Gala apple trees, under two irrigation treatments each. Physiology, production and quality parameters were tested. In both years, midday stem water potentials and leaf gas exchanges were unaffected. The higher shading properties of E created a more favourable microclimate for the trees, allowing them to improve marketable fruit weight, compared to the A net. Fruit quality was influenced by different shading and water treatments, visual red colour especially in 2021; however, the other quality traits did not have similar trends over the two years. A remarkable commercial impact was gained, since higher shading provided by exclusion netting lowered water requirements. Fruit productivity was sustained or, even elevated, under water limitations when exclusion netting was used. These results are promising in the view of the increasing demand for sustainability in fruit production.

1.Introduction

Successful fruit production requires management strategies that minimize biotic and abiotic stresses. The augmenting union of hailstorms, heat waves, water limitation, along with the altered cycle of pests and diseases (endemic and nonnative), are posing challenges to plant performances and productivity. Netting systems are a solution to protect fruit tree crops, indeed they have become necessary when planning the planting of an orchard. The most classic version is the anti-hail netting system installed on concrete posts (Castellano et al., 2008), which is, however, useless, when excluding insect pests is also a target. In the last decade, France and Italy have seen an increase in the use of individually wrapped tree rows, to exclude codling moth, *Cydia pomonella*, (Kelderer et al., 2010; Romet et al., 2010; Alaphilippe et al., 2016) and, more recently, the brown marmorated stink bug, *Halyomorpha halys* (Candian et al., 2018, 2021). In Washington State, an increasing use of full block net enclosures is being adopted (Mupambi et al., 2019) to protect the crop from sunburn, wind and hail damages. In Italy, this modernized kind of netting protection is also starting to be adopted. Being a complete physical barrier, exclusion netting appears promising, as it can greatly decrease the use of pesticides (Romet et al., 2010; Sauphanor et al., 2012; Marshall and Beers, 2021). In fact, many studies report positive results of exclusion netting on some fruit natural insect communities, enemies and diseases (Chouinard et al., 2017; Candian et al., 2018, 2020; Pajač Živković et al., 2019, 2018; Marshall and Beers, 2021, 2022). Moreover, studies focused on issues with pollination (Normandeau Bonneau et al., 2020), fruit set and seed number (Elsysy et al., 2020), demonstrate an increasing interest in this protection management. However, these studies refer to single row covers.

Specific research on orchards completely enclosed with one single block of net, i.e., full canopy netting (Rigden, 2008), is still scarce (Marshall and Beers, 2021). The few related studies have shown that exclusion netting influences the microclimate only in terms of light and wind intensity, inside an entirely enclosed orchard (Kalcsits et al., 2017; Mupambi et al., 2018; Marshall and Beers, 2021). Lower light levels are known to decrease crop coefficient (Girona et al., 2011; Boini et al., 2018) and, as a consequence, plant water requirements (Green et al., 2003; Lopez et al., 2018; Mahmood et al., 2018; Boini et al., 2021). Thus, nets in general have demonstrated to be beneficial for saving water purposes (Nicolás et al., 2004; Boini et al., 2019). Since there is a growing commercial interest in the use of full canopy netting, knowledge on the microclimate effects, plus the influence on tree physiology and water status, with repercussions on final yield, over multiple years, is required. To date, ad-hoc studies do not appear in the literature.

The following work reports one of a series, dedicated to testing combined orchard management strategies; the aim is to push modern fruit production to be more sustainable, with the main ambition to decrease irrigation volumes to the possible extent.

2. Materials and methods

2.1. Study site

The trial was conducted during 2020 and 2021 at the experiment farm of the University of Bologna, located in Cadriano (Bologna, Italy) (44°30′N; 10°36′E, 27m elevation), in a Gala Buckeye apple orchard grafted on M9-Pajam2. The orchard was planted in 2014 in a silty clay loam soil and consists of 10 rows. Trees were trained as slender spindle, spaced 1x3.3m, with a North-South orientation. Since its inception, integrated production management protocols were followed and trees were irrigated as needed; the orchard was covered with a standard anti-hail net (A) (20% shading, as stated by the manufacturer; Valente srl, Campodarsego, PD, Italy), which is deployed each Spring, after fruit set is complete, and rolled-up post-harvest, in the Fall. This practice is common in the majority of Northern Italy, where hailstorms are regularly present during the fruit growing season. Full bloom (more than 50% open flowers on trees) was recorded on 10 and 12 April 2020 and 2021, respectively.

2.2. Net treatments, weather conditions and irrigation

In May 2020, the orchard was divided in two sectors (5 rows each): one remained covered with A, while the other was covered with a white exclusion netting system (E), deployed over the entire block, including access space inside the cover. Both nets had an English-turn weaving system and were of the same material (polymethyl methacrylate) with different wefts: the black net was around 10x5mm, while the white exclusion net was approximately 3x4mm, in order to repel *Cydia pomonella* and the increasingly threatening *Halyomorpha halys*. The latter was integrated with a rain-proof cover placed over each row, as a protection against rain (1 meter on both East and West sides), consisting of a double layer of the same net, with extremely dense links (<1mm). The overall shading percentage of the exclusion net was stated to be around 50%, a desired level of light intensity reduction.

In both orchard sectors and outside the orchard, three weather stations were installed, which registered on an hourly basis the environmental parameters: air temperature [°C], relative humidity [%], rain [mm], solar radiation [W m^{-2}].

Both orchard sectors (A, E) received two different irrigation restitutions, during both years. A control irrigation, based on the reference evapotranspiration (Et_0) calculated by the Hargreaves-Samani equation, was adopted in A. This corresponded to the volume suggested by the public irrigation scheduling service IRRIFRAME (www.irriframe.it), combining local weather parameters with the orchard characteristics, and represented the control (A100) in this study; this restitution was applied to half of the trees in A. A 30% reduction of this volume was applied to the second half of A, resulting in the A70 treatment. In E, a restitution equal to 70% of A100 was applied to half of the trees, while a further 70% reduction of this level (i.e., 49% of A100) was applied to the other half of the trees. Hence, irrigation treatments were named as follows:

- A100: anti-hail net control irrigation (100% Et_0 under the anti-hail net)
- A70: anti-hail net restricted irrigation (70% Et_0 under the anti-hail net)
- E70: exclusion net control irrigation (70% Et_0 under the anti-hail net)
- E50: exclusion net restricted irrigation (49% Et_0 under the anti-hail net)

The resulting four treatments were organized on a split plot complete randomized design, where each thesis was repeated 3 times, with 8 trees for each repetition; of these 8, 2 trees were marked and were tested for physiological parameters. The external rows were excluded from the trial and served as a guard. An ad-hoc automated drip irrigation system was installed, where emitters were distant 0.5 m with a flow rate of 2.0 L per hour. The IRRIFRAME platform communicated via a "web-API" (application programming interface) and sent information to the irrigation controller. This unit controlled 3 sectors, corresponding to control irrigation, 70%s and 50%, respectively. Since flow rate was the same, irrigation treatments were managed with different lengths of application that corrected the Et_0 volume based on the treatment previously described.

2.3. Midday Stem Water Potential and Leaf Gas Exchanges

During the two experimental years, midday stem water potential (Ψ_s) and midday leaf gas exchanges (leaf photosynthesis [A_n] and stomatal conductance [g_s]) were measured on a monthly basis, from the onset of irrigation treatments until harvest. Both physiological parameters were measured simultaneously, at solar noon (±30 min) within one hour time, on cloudless days.

Ψ_s was performed with a Scholander pressure chamber (Model 3005, Soil Moisture Equipment Corp., Santa Barbara, CA, USA), following recommendations of Turner and Long (1980). For each measured tree, a leaf close to the trunk was wrapped in a black envelope, coated with aluminum foil, as to isolate it; the procedure was done at least 1 hour prior to measurements. As for leaf gas exchanges, a portable infra-red gas analyzer (LI-COR 6400, Lincoln, NE, USA) was used, connected to a leaf fluorometer chamber, which had a LED light source. This allowed to set the right photosynthetic active radiation (PAR) for each net treatment. Measurements were performed according to Boini et al. (2021), setting the reference CO_2 at 400 ppm and the flow rate at 300 µmol mol^{-1}.

Measurement dates were: 12 June, 16 July, 30 July, in 2020; 26 May, 30 June, 03 August, in 2021.

2.4. Yield determinants and fruit quality

Harvest occurred on the same date for all treatments, during the two-year experiment; on 5 August 2020 (117 days after full bloom) and on 9 August 2021 (119 days after full bloom). For each treatment, all 6 trees were harvested, plus an extra 12 in 2020 and an extra 3 in 2021. Crop load (fruit $tree^{-1}$) and total yield (kg $tree^{-1}$) were first determined, then, for each tree, all fruit were measured with a digital caliper (Mitutoyo, Kanagawa, Japan) attached to an external memory (www.hkconsulting.it), as to obtain marketable yield (kg $tree^{-1}$), where fruit were above 65 mm diameter. This procedure allowed to obtain the weight of each single fruit, applying the following conversion equation:

$$\text{Fresh weight} = 0.0003 * \text{Diameter}^{3.0992}$$

Such equation has a regression coefficient (R^2) of 0.99 and was derived from fruit diameter and weight data of about 300 fruits from several Gala apple orchards in the growing area. Having all fruit calipers, these could be divided at 5 mm intervals and size class distribution was generated.

On the same harvest dates, fruit quality parameters were determined. In 2020, 18 fruit per replication were collected, while in 2021, 20 fruit per replication. These were tested for: I - individual fruit coloration (percentage of red-colored surface from visual observation); II - individual fruit ripeness (chlorophyll degradation index, measured with a DA-meter 53500 [Turoni, Forlì, Italy] on exposed and non-exposed fruit sides); III - individual fruit flesh firmness (determined with a PCE-PTR 200 penetrometer [PCE Instruments, Meschede, Germany], using an 11 mm diameter tip after removing the fruit peel from opposite sides [exposed and non-exposed to the sun] and calculating the mean value of the two outputs); IV - soluble solid content (refractive index of the juice [°Brix] for each fruit, measured with a HI 96811 digital refractometer [Hanna, Woonsocket, RI, USA]).

2.5. Statistical analysis

Values of PAR for the external, anti-hail and exclusion nets, during the trial, were subjected to an ANOVA analysis to characterize the environmental shade conditions of each experimental year. For each year, an ANOVA was used to test for differences in crop load; since no significant differences were found between treatments, ANOVAs and simple linear contrasts followed. A SNK test was used to separate the mean values. For each year, linear contrasts were performed to compare possible differences between:

- irrigation treatments, under the anti-hail net (A100 A70);
- irrigation treatments, under the exclusion net (E70 E50);
- the same amount of irrigation, under different net treatments (A70 E70);
- control irrigation treatments, under different net treatments (A100 E70).

These analyses were performed for the mean seasonal value of Ψ_s and of midday A_n and g_s, total and marketable yield, average marketable fruit weight and fruit quality traits. Class size distribution possible differences were tested with a correspondence multivariate analysis, followed by a cluster analysis, with a Chi-square test (Greenacre, 2007).

3. Results

3.1. Net treatments, weather, and irrigation

From the average PAR values, between 9-18 hours, for each year, the obtained shading percentage was not exactly the same as the declared one (Figure 1). The anti-hail net shaded around 8-10%, while the exclusion net shaded around 30-40%. All the same, the two net treatments were indeed significantly different, in both years. In year 2021, both nets tended to increase their shading power; a plausible explanation can be given from dust and dirt settling from rain events, in the previous season.

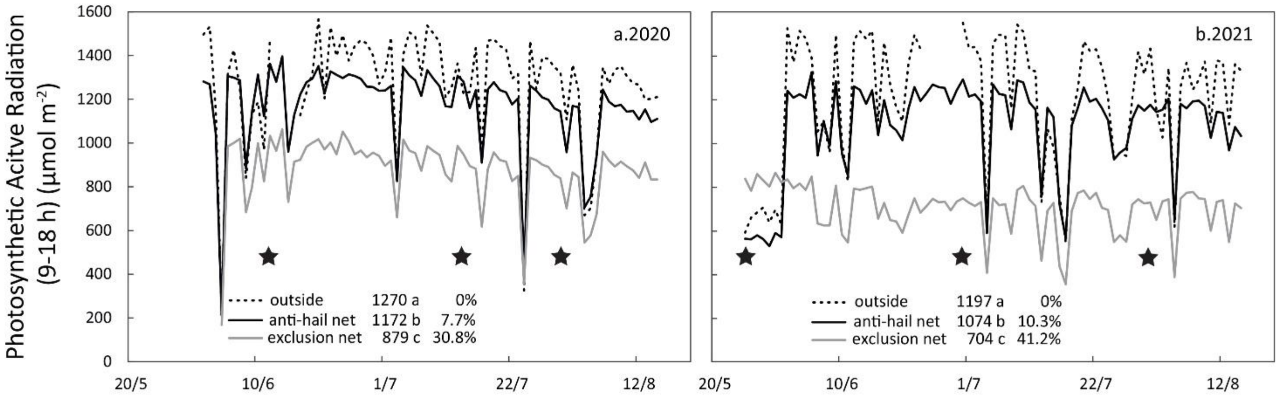

Figure 1. Seasonal patterns of PAR availability between 9:00 and 18:00 hours of the outside reference and of the two net treatments, with average daily values, followed by letters representing significant differences at $p < 0.05$, from the end of May until mid-August, for 2020 (a) and 2021 seasons (b). Percentages reflect the level of shading in the various environments. Black stars represent the dates of midday physiological measurements.

Average Et_0 demand was the same, between the two growing seasons (around 5.6 mm), although the amount of rainfall was significantly higher in 2020 (115 vs 31 mm) (Figure 2). Irrigation final restitutions are reported in Table 1.

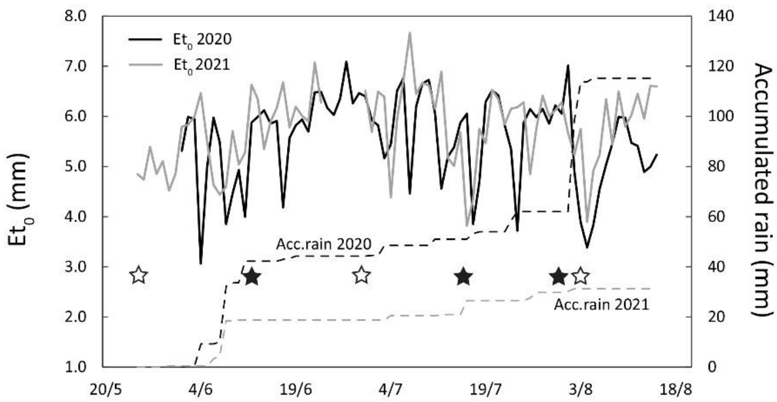

Figure 2. Seasonal patterns of reference evapotranspiration and accumulated rainfall, from the end of May until mid-August for 2020 and 2021 seasons. Midday physiological measurements dates are represented by black (2020) and white (2021) stars.

Table 1. Total irrigation for each year, for each irrigation treatment.

		Total accumulated irrigation (mm)			
Net treatments	**Irrigation treatments**	**2020**		**2021**	
Anti-hail net	A100	143	100%	269	100%
	A70	112	78.4%	188	70.0%
Exclusion net	E70	112	78.4%	188	70.0%
	E50	74	52.1%	135	50.2%

3.2. Midday Stem Water Potential and Leaf Gas Exchanges

Ψ_s did not seem to be influenced by shading, nor irrigation restrictions. In fact, all four treatments move parallel until July, after which the E trees tend to rise above the A trees, in the pre-harvest period

(Figure 3). As for midday leaf gas exchanges, these do not appear to be affected as well; on average, A trees tend to decrease (except for g_s in 2020, Figure 4b), then rise in the pre-harvest period, while E trees only have a very slight decrease.

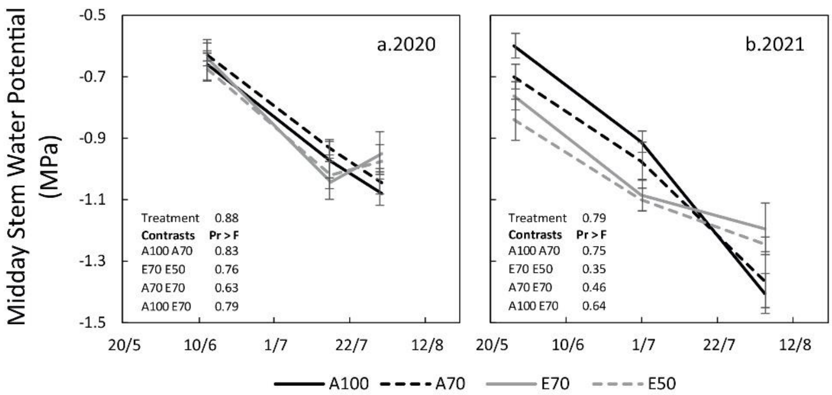

Figure 3. Seasonal patterns of midday stem water potential throughout 2020 (a) and 2021 (b), for each treatment, represented by the mean value of 4 trees. For each day of measurement, the presence of different letters represents significant differences at 95%, according to an SNK test. Vertical bars represent standard error values. For each year, the effect of the treatment and linear contrast F values are shown and refer to the mean midday seasonal value of Ψ_s; values below 0.05 are considered significant.

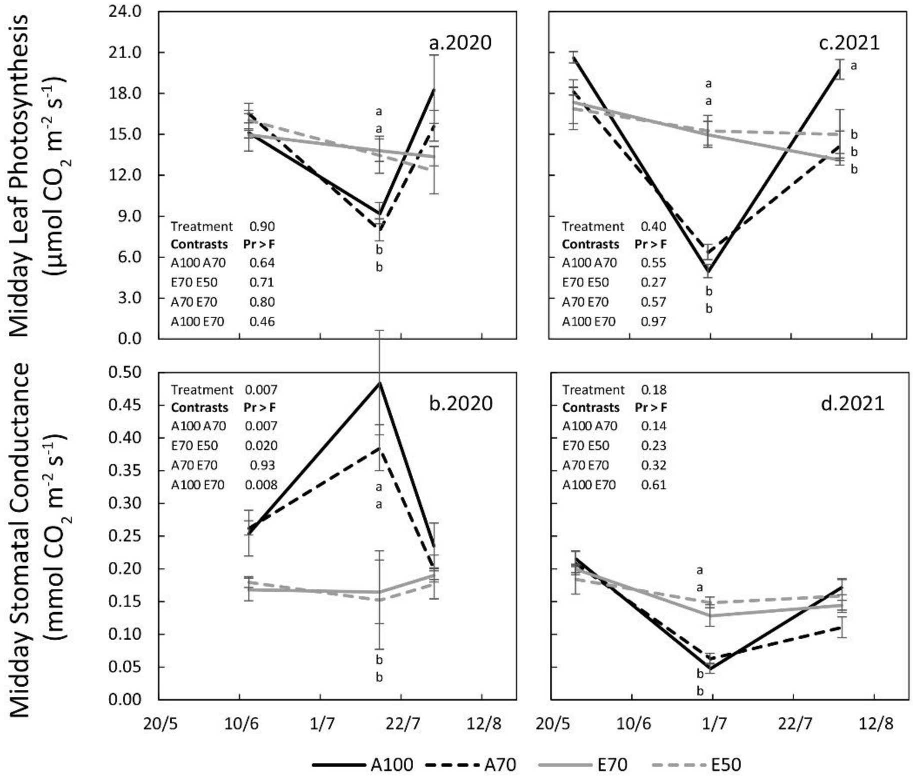

Figure 4. Seasonal patterns of midday leaf photosynthesis and stomatal conductance, throughout 2020 (a,b) and 2021 (c,d), for each treatment, represented by the mean value of 4 trees. For each day of measurement, the presence of different letters represents significant differences at 95%, according to an SNK test. Vertical bars represent standard error values. For each year, the effect of the treatment and linear contrast F values are shown and refer to the mean midday seasonal value of A_n or g_s; values below 0.05 are considered significant.

3.3. Yield determinants and fruit quality

Crop load was the same among treatments in both years, ranging from 56 to 77 fruit tree^{-1}, in 2020, and from 61 to 91 fruit tree^{-1}, in 2021 (Table 2).

Table 2. Crop load determined at harvest (quantity of fruit per tree). Each output represents the mean value of 18 trees in 2020 and 9 trees in 2021, followed by standard error and letters, indicating statistical significance at 95% when different, according to a SNK test.

	Crop Load (fruit tree^{-1})					
Treatments	**2020**	**±SE**		**2021**	**±SE**	
A100	77	9	a	61	6	a
A70	75	8	a	67	12	a
E70	56	6	a	83	10	a
E50	71	7	a	90	10	a

Total yield in year 2020 was not affected by net, nor by irrigation treatments, whereas an effect of shading in 2021 was strong enough to induce differences between E70 and A trees (Table 3). For marketable yield the effect of irrigation was strong only in 2020, while the shading effect was stronger in 2021 (3 kg extra under the exclusion net). The average marketable fruit weight gives a better insight on treatment effects in the two seasons: in 2020, all treatments were different from each other, with A fruit weighing around 15-20 grams less than E fruit; in 2021, significant differences were present only between the nets, A fruit weighing around 15 grams less than E fruit, excluding irrigation treatments (Table 3).

Table 3. Total and marketable yields and average marketable fruit weight, measured at harvest, during years 2020 and 2021, followed by standard error and letters, indicating statistical significance at 95% when different, according to a SNK test. In the lower part of the table, linear contrast F values for each year are shown; values below 0.05 are considered significant.

	Total yield (kg tree^{-1})						Marketable yield (kg tree^{-1})						Average marketable fruit weight (g fruit^{-1})					
Treatments	**2020**	**±SE**		**2021**	**±SE**		**2020**	**±SE**		**2021**	**±SE**		**2020**	**±SE**		**2021**	**±SE**	
A100	12.3	1.32	a	8.66	0.71	a	11.3	1.27	a	7.63	0.58	b	166	1.02	d	158	1.85	b
A70	11.8	1.07	a	8.66	1.35	a	11.6	1.05	a	6.28	0.97	b	170	1.09	c	159	1.51	b
E70	9.51	0.77	a	11.5	1.03	a	9.45	0.63	a	10.7	0.86	a	185	1.38	a	174	1.44	a
E50	11.5	0.69	a	12.7	1.10	a	12.5	0.83	a	10.3	0.89	a	181	1.17	b	172	1.62	a
Treatment	0.2187			0.02			0.1846			0.0016			<.0001			<.0001		
L. contrasts	**Pr > F**			**Pr > F**			**Pr > F**			**Pr > F**			**Pr > F**			**Pr > F**		
A100 A70	0.71			0.99			0.84			0.26			0.01			0.71		
E70 E50	0.17			0.46			0.03			0.77			0.53			0.23		
A70 E70	0.82			0.012			0.53			0.0018			<.0001			<.0001		
A100 E70	0.55			0.012			0.41			0.03			<.0001			<.0001		

Size class distribution follows a normal distribution in 2020 (Figure 5a), with a higher presence of the 70-75 size and no significant differences between treatments. In 2021 only A100 shows a normal distribution, while the other treatments appear to be one-tailed distributions, trending towards lower sizes, in the 65-70 range (Figure 5b); the A70 treatment is significantly different from the rest of the treatments, having more than 40% of fruit below 65 mm. Both E treatments show more fruit in the larger sizes.

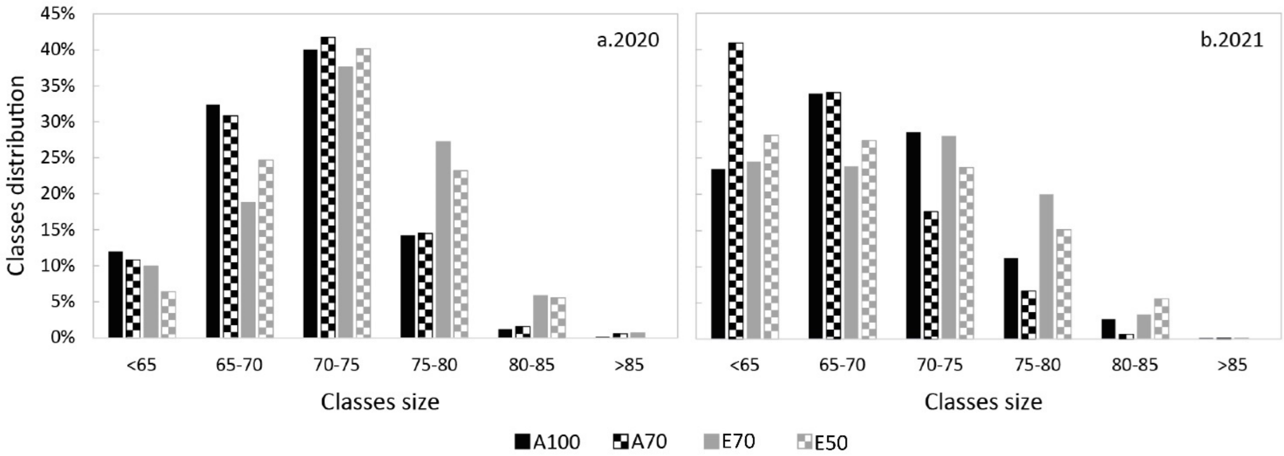

Figure 5. Size class distribution values for each irrigation treatment, of fruit diameters ranging from <65 mm to >85 mm, in years 2020 (a) and 2021 (b).

Fruit quality results are shown in Table 4, presenting slightly different trends between years. In 2020, only soluble solid content was influenced by both net and irrigation treatments. The various parameters were influenced in 2021, by net treatments, except for SSC.

Table 4. Fruit quality traits, during 2020 and 2021, followed by standard error and letters, indicating statistical significance at 95% when different, according to a SNK test. In the lower part of the table, linear contrast F values for each year are shown; values below 0.05 are considered significant.

	Ripeness (I_{AD})						**Visual colour (%)**					
Treatments	**2020**	**±SE**		**2021**	**±SE**		**2020**	**±SE**		**2021**	**±SE**	
A100	1.07	0.03	a	0.89	0.03	ab	86	1.9	a	74	1.5	a
A70	1.04	0.04	a	0.96	0.03	a	80	2.3	a	71	1.5	a
E70	1.01	0.03	a	0.83	0.03	b	80	2.1	a	66	1.5	b
E50	1.03	0.03	a	0.86	0.03	b	81	2.1	a	64	1.4	b
Treatment	0.69			0.017			0.18			<.0001		
L. contrasts	**Pr > F**			**Pr > F**			**Pr > F**			**Pr > F**		
A100 A70	0.54			0.54			0.06			<.0001		
E70 E50	0.74			0.0024			0.79			0.02		
A70 E70	0.82			0.017			0.80			0.0005		
A100 E70	0.40			0.07			0.10			0.15		

	Soluble solid content (°Brix)						**Firmness (kg cm^{-2})**					
Treatments	**2020**	**±SE**		**2021**	**±SE**		**2020**	**±SE**		**2021**	**±SE**	
A100	11.2	0.14	c	11.1	0.12	a	8.49	0.10	a	9.73	0.12	b

A70	11.6	0.15	b	11.0	0.09	a	8.68	0.15	a	10.1	0.12	a
E70	11.9	0.11	ab	10.8	0.09	a	8.66	0.10	a	9.46	0.09	b
E50	12.2	0.09	a	11.0	0.10	a	8.58	0.11	a	9.52	0.10	b
Treatment	<.0001			0.19			0.65			0.0002		
L. contrasts	**Pr > F**			**Pr > F**			**Pr > F**			**Pr > F**		
A100 A70	0.014			0.48			0.26			0.16		
E70 E50	0.13			0.06			0.61			<.0001		
A70 E70	0.0017			0.51			0.54			0.0003		
A100 E70	<.0001			0.96			0.60			0.02		

4. Discussion

Many studies have previously reported how decreasing incoming light can be beneficial for apple production (Brito et al., 2021; Boini et al., 2021; Lopez et al., 2021; Serra et al., 2020). This two-year study further confirms how cutting even up to 40% sunlight does not negatively influence tree physiological performances, in areas where moderately intense sunlight occurs, like the Po Valley of Italy. Having an average between 700 and 800 µmol $m^{-2}s^{-1}$ during the day is not detrimental to apple leaf CO_2 assimilation (Cheng et al., 2000, 2001) and to final yield, in fact E trees produced the same amount, if not significantly higher quantities of marketable yield (Table 3, Figure 5). Trees were able to maintain the same water status, with 50% less irrigation in both years (Figure 3), as has been previously shown in studies combining shade and deficit irrigation (Boini et al., 2021; Lopez et al., 2021). Consequently, leaf gas exchanges were not negatively affected and could be considered the same as those with 100% irrigation. Stomatal density may have been affected, as has been found in the literature (Eckstein et al., 1996; Kim et al., 2011), however significantly impacting g_s only in 2020 (Figure 4b). Although air temperature and relative humidity did not significantly vary between net treatments (data not shown), having two different shading percentages generated different microclimates; it follows that Et_0 would be different in the two orchard sectors. The higher shading properties of the exclusion net certainly created a microclimate with more favorable conditions for the trees. The plants, while receiving less light, could cope with less water, since their Et_0 was lower. As assumed in light-and-shade related studies, less incoming solar energy might reduce tree photo-oxidative stress, reducing the need to activate the protective biochemistry that is known to utilize photosynthates (Aro et al., 1993; Takahashi and Murata, 2008; Losciale et al., 2010; Demmig-Adams et al., 2014; Tikkanen et al., 2014; Marchin et al., 2017). In the case of E trees, the produced carbohydrates were probably sent to fruit sinks, allowing cell expansion at greater rates, and ensuring bigger sizes (Table 3, Figure 5).

Another factor possibly influencing the response of trees under the E net is the mesh colour; white filters are known to have a high power of diffusing incoming radiation (Basile et al., 2012, Shahak, 2014, Kalcsits et al., 2017), coupled to spectral neutrality regarding light transmission (Boini et al., 2022). Maintaining sunlight spectral quality and improving its penetration within E trees might explain why, in E trees, marketable yield, average fruit weight and size distribution classes were the same if not improved (Table 3, Figure 5).

Fruit quality was influenced by light and water restriction, however trends were not always the same over the two years.

Ripeness was significantly different only in 2021, anticipated under E net, plus, there were strong differences between the two E-irrigation treatments, where the "control", E70, was the ripest (Pr>F = 0.017, Table 4). The same trend appeared in 2020, however without significant differences (Table 4). From the shading point of view, these results are in contrast with those in the literature. In fact, shaded or more shaded fruit appear to reduce ethylene synthesis (Klein et al., 2001), although those fruit were growing on non-shaded trees, therefore different "populations" of fruit could be found on the same tree, due to the different light microclimate that can occur in a canopy free of covers; making comparisons with the current trial would be inappropriate. Other works state a delayed maturation of apples under nets, with shading power ranging from 7% to 18%, (Bosco et al., 2015; Chouinard et al., 2019). On the other hand, another multiple year study shows a tendency of earlier maturation of 'Gala' apples, under high levels of shading (up to 50%, Boini et al., 2021), in line with what was found in this trial. Such similarities can be explained by the fact that both works were conducted in the same farm, on the same kind of soil and variety (Gala), although the orchards were different in many traits, including row orientation (N-S in this trial, and E-W in Boini et al., 2021). In climatic conditions and environments like the Po Valley, Gala might anticipate ripening, if cultivated under high levels of shading (above 40%). Apple appears to be sensitive to water deficit, with effects on a hastened ripening (Ebel et al., 1993; Mpelasoka et al., 2001; Mpelasoka and Behboudian, 2002; Ripoll et al., 2014; Boini et al., 2021) explained by a stress-induced increase in ethylene, governed by associated genes (Apelbaum and Yang, 1981), however, this was not the case for our study (Table 4). Another possible conclusion would be that a 30% reduction of Et_0 is not penalizing internal ethylene concentrations that influence fruit ripening processes.

Visual colour was strongly influenced only in 2021 (Table 4) by shading, which, regardless of irrigation, decreased the % of colored surface of fruit. A possible explanation can be given by the influence of the two nets on temperature ranges during day and night (supplementary material), which were lower under the exclusion net, during 11 days before harvest, leading to a lower number of accumulated hours below 20 °C in 2021, compared to 2020. It is clear that a decrease in orchard temperature in the pre-harvest period improves the color of apple fruit (Iglesias et al., 2002, 2005). In fact, other studies focusing on anthocyanin synthesis and fruit skin colour obtained positive results when temperatures were below 20 °C (Lin-Wang et al., 2011; Honda et al., 2014). To improve peel visual colour under exclusion netting, a solution could be a delay of the harvest date; this would allow further accumulation of hours below 20°C and augment anthocyanin synthesis. Probably for early ripening red varieties, further mitigation strategies should be implemented to improve fruit skin coloration, such as evaporative cooling (Iglesias et al., 2002, 2005), under exclusion nets.

Soluble solid content was significantly different only in 2020, once again showing that conditions in 2021 may have been more extreme across the board, due to warmer and drier conditions. In 2020, lower contents were found in A100, then in A70, with E50 having the highest content and E70 intermediate (Table 4). Although the difference was in terms of only 1 °Brix, both shading and irrigation had strong effects. E trees improved the amount of their fruit soluble solids, probably thanks to their unaffected leaf photosynthesis (Figure 4a); the light scattering properties of the E net might have helped less exposed leaves to be more efficient, hence more leaves contributed to carbohydrates supply to the fruit. Under the anti-hail net, less irrigated trees had higher soluble solids, as has been previously stated in the literature (Mpelasoka et al., 2000, 2001; Ripoll et al., 2014; Boini et al., 2021), indicating that a general moderate stress can be positive for certain quality traits.

Fruit firmness was influenced only in 2021. The general picture shows higher values for A70 trees, which can be explained by the higher number of smaller fruit (Figure 5b); a result of higher cellular density (Ebel et al., 1993). However, when comparing treatments in pairs, more shading decreases significantly fruit firmness (A70 vs E70; A100 vs E70; Table 4) and less water leads to significant differences, even under higher shading levels (E70 vs E50, Table 4). This last consideration is valid throughout the literature, with the overall statement that water deficit increases fruit firmness (Mpelasoka et al., 2000, 2001; Ripoll et al., 2014; Boini et al., 2021).

These considerations may not be true for other varieties, in other climatic areas. As previously stated (Widmer, 2001; Stampar et al., 2002; Boini et al., 2022), the interaction of climatic conditions, orchard age and management, planting system, crop load, variety and not to mention the repercussion of possible late frosts during blooming stage, create a series of responses that can easily surpass the effect of shading, alone. Other species would not benefit from shading, for water saving purposes, such as peach and nectarine crops (George et al., 1996), unless further management practices would be implemented, such as reflective mulching (Layne et al., 2001; Costa et al., 2003; Morandi et al., 2012).

5. Conclusion

Exclusion netting generated higher shading, nonetheless apple crop physiology was unaffected. Shading maintained water status and leaf gas exchanges at an optimal level, which was positive for apple production, even when irrigation was limited to 50% of Et_0 restitution. Although exclusion netting requires higher initial investment costs, it can be highly beneficial for water saving purposes, without compromising final yield and fruit quality. This strategy can be applied to pome fruit crops, or those crops that are characterized by certain metabolisms, when it comes to fruit growth.

Full canopy netting may be tested in areas where the average Et_0 is high during the growing season and is forecast to increase in the future. From the commercial and practical points of view, the growers and the environment would highly benefit from this solution.

6. Acknowledgments

This study was supported by the “S3O – Smart, Specialized, Sustainable Orchard” project, funded from the Emilia-Romagna Region POR-FESR programs 2014/2020.

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