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Gala apple production benefits from high shading levels and water limitation, under exclusion netting

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

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8 ABSTRACT. The application of exclusion nets is gaining interest for apple modern production, since it can
9 limit the use of pesticides. From the physiological point of view, information related to final fruit harvest is
10 missing. This two-year study compared a classical anti-hail net (A, 20% shading) with an exclusion net (E,
11 40% shading), and their effects on Gala apple trees, under two irrigation treatments each. Physiology,
12 production and quality parameters were tested. In both years, midday stem water potentials and leaf gas
13 exchanges were unaffected. The higher shading properties of E created a more favourable microclimate for
14 the trees, allowing them to improve marketable fruit weight, compared to the A net. Fruit quality was
15 influenced by different shading and water treatments, visual red colour especially in 2021; however, the
16 other quality traits did not have similar trends over the two years. A remarkable commercial impact was
17 gained, since higher shading provided by exclusion netting lowered water requirements. Fruit productivity
18 was sustained or, even elevated, under water limitations when exclusion netting was used. These results
19 are promising in the view of the increasing demand for sustainability in fruit production.

20

21 1.Introduction

22 Successful fruit production requires management strategies that minimize biotic and abiotic
23 stresses. The augmenting union of hailstorms, heat waves, water limitation, along with the altered cycle of
24 pests and diseases (endemic and nonnative), are posing challenges to plant performances and productivity.
25 Netting systems are a solution to protect fruit tree crops, indeed they have become necessary when
26 planning the planting of an orchard. The most classic version is the anti-hail netting system installed on
27 concrete posts (Castellano et al., 2008), which is, however, useless, when excluding insect pests is also a
28 target. In the last decade, France and Italy have seen an increase in the use of individually wrapped tree
29 rows, to exclude codling moth, *Cydia pomonella*, (Kelderer et al., 2010; Romet et al., 2010; Alaphilippe et
30 al., 2016) and, more recently, the brown marmorated stink bug, *Halyomorpha halys* (Candian et al., 2018,
31 2021). In Washington State, an increasing use of full block net enclosures is being adopted (Mupambi et al.,
32 2019) to protect the crop from sunburn, wind and hail damages. In Italy, this modernized kind of netting

33 protection is also starting to be adopted. Being a complete physical barrier, exclusion netting appears
34 promising, as it can greatly decrease the use of pesticides (Romet et al., 2010; Sauphanor et al., 2012;
35 Marshall and Beers, 2021). In fact, many studies report positive results of exclusion netting on some fruit
36 natural insect communities, enemies and diseases (Chouinard et al., 2017; Candian et al., 2018, 2020; Pajač
37 Živković et al., 2019, 2018; Marshall and Beers, 2021, 2022). Moreover, studies focused on issues with
38 pollination (Normandeau Bonneau et al., 2020), fruit set and seed number (Elsysy et al., 2020),
39 demonstrate an increasing interest in this protection management. However, these studies refer to single
40 row covers.

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

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

54

55 2. Materials and methods

56 2.1. Study site

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

65 regularly present during the fruit growing season. Full bloom (more than 50% open flowers on trees) was
66 recorded on 10 and 12 April 2020 and 2021, respectively.

67 2.2. Net treatments, weather conditions and irrigation

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

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

80 Both orchard sectors (A, E) received two different irrigation restitutions, during both years. A control
81 irrigation, based on the reference evapotranspiration (E_{t_0}) calculated by the Hargreaves-Samani equation,
82 was adopted in A. This corresponded to the volume suggested by the public irrigation scheduling service
83 IRRIFRAME (www.irriframe.it), combining local weather parameters with the orchard characteristics, and
84 represented the control (A100) in this study; this restitution was applied to half of the trees in A. A 30%
85 reduction of this volume was applied to the second half of A, resulting in the A70 treatment. In E, a
86 restitution equal to 70% of A100 was applied to half of the trees, while a further 70% reduction of this level
87 (i.e., 49% of A100) was applied to the other half of the trees. Hence, irrigation treatments were named as
88 follows:

- 89 - A100: anti-hail net control irrigation (100% E_{t_0} under the anti-hail net)
- 90 - A70: anti-hail net restricted irrigation (70% E_{t_0} under the anti-hail net)
- 91 - E70: exclusion net control irrigation (70% E_{t_0} under the anti-hail net)
- 92 - E50: exclusion net restricted irrigation (49% E_{t_0} under the anti-hail net)

93 The resulting four treatments were organized on a split plot complete randomized design, where each
94 thesis was repeated 3 times, with 8 trees for each repetition; of these 8, 2 trees were marked and were
95 tested for physiological parameters. The external rows were excluded from the trial and served as a guard.
96 An ad-hoc automated drip irrigation system was installed, where emitters were distant 0.5 m with a flow

97 rate of 2.0 L per hour. The IRRIFRAME platform communicated via a “web-API” (application programming
98 interface) and sent information to the irrigation controller. This unit controlled 3 sectors, corresponding to
99 control irrigation, 70% and 50%, respectively. Since flow rate was the same, irrigation treatments were
100 managed with different lengths of application that corrected the E_t volume based on the treatment
101 previously described.

102 2.3. Midday Stem Water Potential and Leaf Gas Exchanges

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

107 Ψ_s was performed with a Scholander pressure chamber (Model 3005, Soil Moisture Equipment Corp., Santa
108 Barbara, CA, USA), following recommendations of [Turner and Long \(1980\)](#). For each measured tree, a leaf
109 close to the trunk was wrapped in a black envelope, coated with aluminum foil, as to isolate it; the
110 procedure was done at least 1 hour prior to measurements. As for leaf gas exchanges, a portable infra-red
111 gas analyzer (LI-COR 6400, Lincoln, NE, USA) was used, connected to a leaf fluorometer chamber, which had
112 a LED light source. This allowed to set the right photosynthetic active radiation (PAR) for each net
113 treatment. Measurements were performed according to [Boini et al. \(2021\)](#), setting the reference CO_2 at
114 400 ppm and the flow rate at $300 \mu\text{mol mol}^{-1}$.

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

116 2.4. Yield determinants and fruit quality

117 Harvest occurred on the same date for all treatments, during the two-year experiment; on 5 August
118 2020 (117 days after full bloom) and on 9 August 2021 (119 days after full bloom). For each treatment, all 6
119 trees were harvested, plus an extra 12 in 2020 and an extra 3 in 2021. Crop load (fruit tree^{-1}) and total yield
120 (kg tree^{-1}) were first determined, then, for each tree, all fruit were measured with a digital caliper
121 (Mitutoyo, Kanagawa, Japan) attached to an external memory (www.hkconsulting.it), as to obtain
122 marketable yield (kg tree^{-1}), where fruit were above 65 mm diameter. This procedure allowed to obtain the
123 weight of each single fruit, applying the following conversion equation:

$$124 \text{ Fresh weight} = 0.0003 * \text{Diameter}^{3.0992}$$

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

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

137 2.5. Statistical analysis

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

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

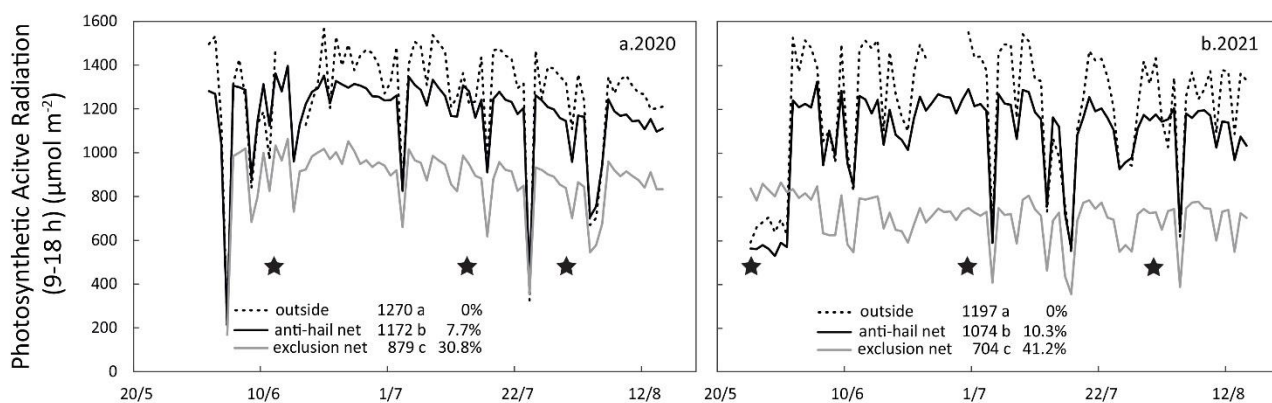
147 These analyses were performed for the mean seasonal value of Ψ_s and of midday A_n and g_s , total and
148 marketable yield, average marketable fruit weight and fruit quality traits. Class size distribution possible
149 differences were tested with a correspondence multivariate analysis, followed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

151

152 3. Results

153 3.1. Net treatments, weather, and irrigation

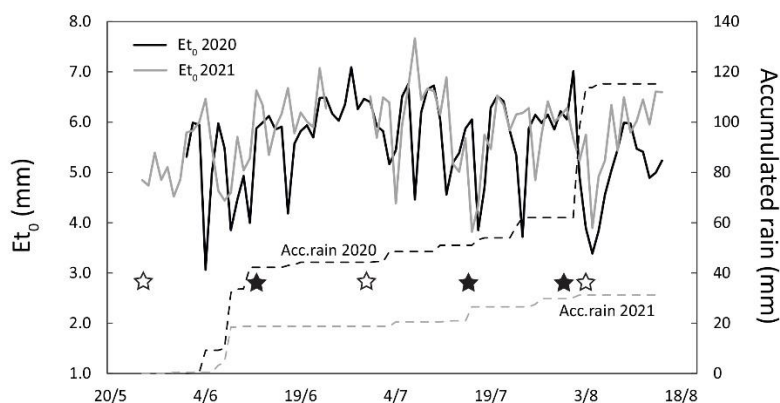
154 From the average PAR values, between 9-18 hours, for each year, the obtained shading percentage
155 was not exactly the same as the declared one (Figure 1). The anti-hail net shaded around 8-10%, while the
156 exclusion net shaded around 30-40%. All the same, the two net treatments were indeed significantly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



159

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

164 Average E_{t0} demand was the same, between the two growing seasons (around 5.6 mm), although the
 165 amount of rainfall was significantly higher in 2020 (115 vs 31 mm) (Figure 2). Irrigation final restitutions are
 166 reported in Table 1.



167

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

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

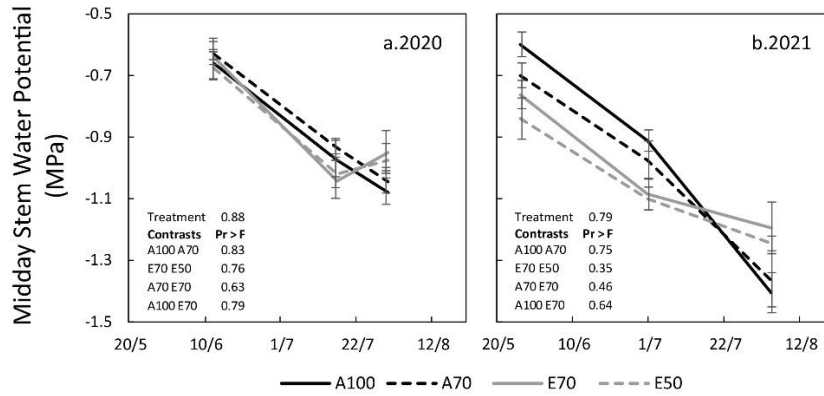
Net treatments	Irrigation treatments	Total accumulated irrigation (mm)	
		2020	2021
Anti-hail net	A100	143 100%	269 100%
	A70	112 78.4%	188 70.0%
Exclusion net	E70	112 78.4%	188 70.0%
	E50	74 52.1%	135 50.2%

172

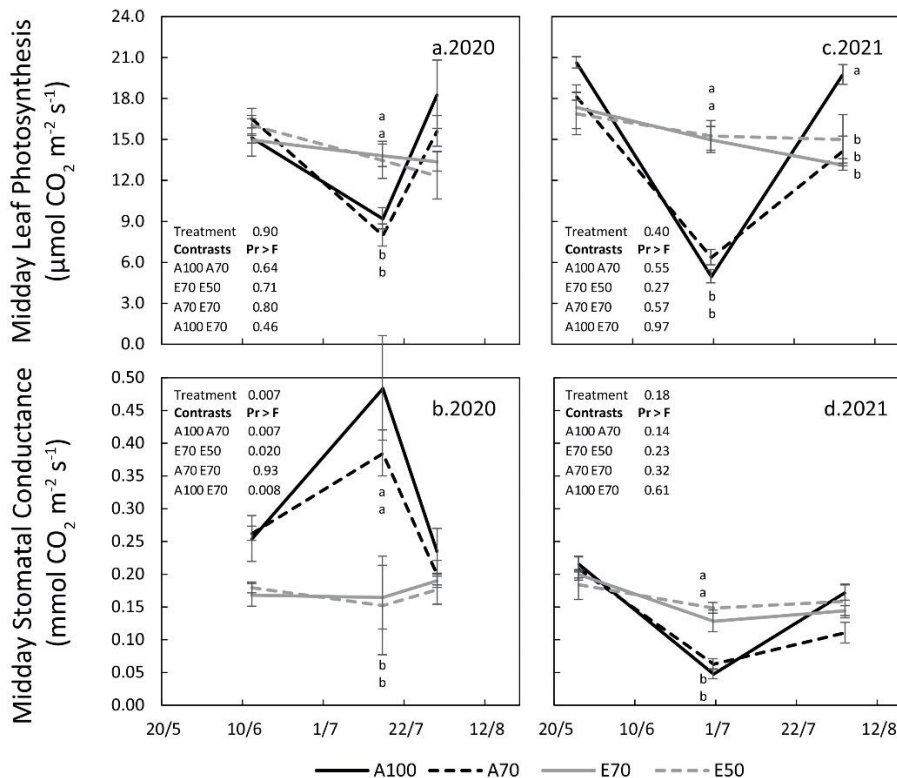
173 3.2. Midday Stem Water Potential and Leaf Gas Exchanges

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

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



179
 180 *Figure 3. Seasonal patterns of midday stem water potential throughout 2020 (a) and 2021 (b), for each treatment,*
 181 *represented by the mean value of 4 trees. For each day of measurement, the presence of different letters represents*
 182 *significant differences at 95%, according to an SNK test. Vertical bars represent standard error values. For each year,*
 183 *the effect of the treatment and linear contrast F values are shown and refer to the mean midday seasonal value of Ψ_s ;*
 184 *values below 0.05 are considered significant.*



185
 186 *Figure 4. Seasonal patterns of midday leaf photosynthesis and stomatal conductance, throughout 2020 (a,b) and 2021*
 187 *(c,d), for each treatment, represented by the mean value of 4 trees. For each day of measurement, the presence of*
 188 *different letters represents significant differences at 95%, according to an SNK test. Vertical bars represent standard*
 189 *error values. For each year, the effect of the treatment and linear contrast F values are shown and refer to the mean*
 190 *midday seasonal value of A_n or g_s ; values below 0.05 are considered significant.*

191

192 3.3. Yield determinants and fruit quality

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

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

Treatments	Crop Load (fruit tree ⁻¹)					
	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

198

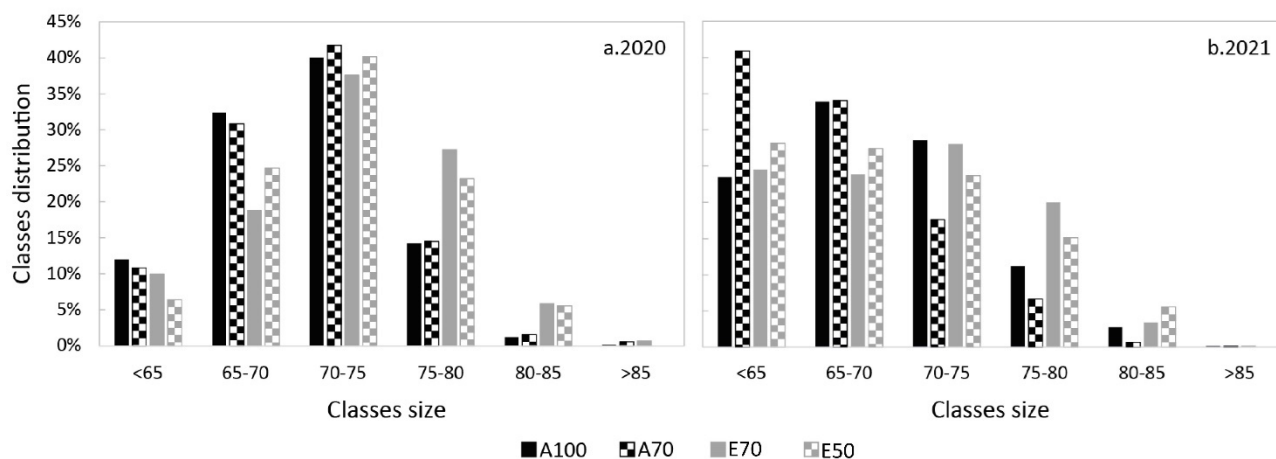
199 Total yield in year 2020 was not affected by net, nor by irrigation treatments, whereas an effect of shading
200 in 2021 was strong enough to induce differences between E70 and A trees (Table 3). For marketable yield
201 the effect of irrigation was strong only in 2020, while the shading effect was stronger in 2021 (3 kg extra
202 under the exclusion net). The average marketable fruit weight gives a better insight on treatment effects in
203 the two seasons: in 2020, all treatments were different from each other, with A fruit weighing around 15-
204 20 grams less than E fruit; in 2021, significant differences were present only between the nets, A fruit
205 weighing around 15 grams less than E fruit, excluding irrigation treatments (Table 3).

206 *Table 3. Total and marketable yields and average marketable fruit weight, measured at harvest, during years 2020 and*
207 *2021, followed by standard error and letters, indicating statistical significance at 95% when different, according to a*
208 *SNK test. In the lower part of the table, linear contrast F values for each year are shown; values below 0.05 are*
209 *considered significant.*

Treatments	Total yield (kg tree ⁻¹)						Marketable yield (kg tree ⁻¹)				Average marketable fruit weight (g fruit ⁻¹)							
	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		

210

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



216

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

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

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

Treatments	Ripeness (I _{AD})				Visual colour (%)							
	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					
Treatments	Soluble solid content (°Brix)				Firmness (kg cm ⁻²)							
	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		

225

226

227 4. Discussion

228 Many studies have previously reported how decreasing incoming light can be beneficial for apple
229 production (Brito et al., 2021; Boini et al., 2021; Lopez et al., 2021; Serra et al., 2020). This two-year study
230 further confirms how cutting even up to 40% sunlight does not negatively influence tree physiological
231 performances, in areas where moderately intense sunlight occurs, like the Po Valley of Italy. Having an
232 average between 700 and 800 $\mu\text{mol m}^{-2}\text{s}^{-1}$ during the day is not detrimental to apple leaf CO_2 assimilation
233 (Cheng et al., 2000, 2001) and to final yield, in fact E trees produced the same amount, if not significantly
234 higher quantities of marketable yield (Table 3, Figure 5). Trees were able to maintain the same water
235 status, with 50% less irrigation in both years (Figure 3), as has been previously shown in studies combining
236 shade and deficit irrigation (Boini et al., 2021; Lopez et al., 2021). Consequently, leaf gas exchanges were
237 not negatively affected and could be considered the same as those with 100% irrigation. Stomatal density
238 may have been affected, as has been found in the literature (Eckstein et al., 1996; Kim et al., 2011),
239 however significantly impacting g_s only in 2020 (Figure 4b). Although air temperature and relative humidity
240 did not significantly vary between net treatments (data not shown), having two different shading
241 percentages generated different microclimates; it follows that Et_0 would be different in the two orchard
242 sectors. The higher shading properties of the exclusion net certainly created a microclimate with more
243 favorable conditions for the trees. The plants, while receiving less light, could cope with less water, since
244 their Et_0 was lower. As assumed in light-and-shade related studies, less incoming solar energy might reduce
245 tree photo-oxidative stress, reducing the need to activate the protective biochemistry that is known to
246 utilize photosynthates (Aro et al., 1993; Takahashi and Murata, 2008; Losciale et al., 2010; Demmig-Adams
247 et al., 2014; Tikkanen et al., 2014; Marchin et al., 2017). In the case of E trees, the produced carbohydrates
248 were probably sent to fruit sinks, allowing cell expansion at greater rates, and ensuring bigger sizes (Table
249 3, Figure 5).

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

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

258 Ripeness was significantly different only in 2021, anticipated under E net, plus, there were strong
259 differences between the two E-irrigation treatments, where the “control”, E70, was the ripest ($P > F =$
260 0.017, Table 4). The same trend appeared in 2020, however without significant differences (Table 4). From
261 the shading point of view, these results are in contrast with those in the literature. In fact, shaded or more
262 shaded fruit appear to reduce ethylene synthesis (Klein et al., 2001), although those fruit were growing on
263 non-shaded trees, therefore different “populations” of fruit could be found on the same tree, due to the
264 different light microclimate that can occur in a canopy free of covers; making comparisons with the current
265 trial would be inappropriate. Other works state a delayed maturation of apples under nets, with shading
266 power ranging from 7% to 18%, (Bosco et al., 2015; Chouinard et al., 2019). On the other hand, another
267 multiple year study shows a tendency of earlier maturation of ‘Gala’ apples, under high levels of shading
268 (up to 50%, Boini et al., 2021), in line with what was found in this trial. Such similarities can be explained by
269 the fact that both works were conducted in the same farm, on the same kind of soil and variety (Gala),
270 although the orchards were different in many traits, including row orientation (N-S in this trial, and E-W in
271 Boini et al., 2021). In climatic conditions and environments like the Po Valley, Gala might anticipate
272 ripening, if cultivated under high levels of shading (above 40%). Apple appears to be sensitive to water
273 deficit, with effects on a hastened ripening (Ebel et al., 1993; Mpelasoka et al., 2001; Mpelasoka and
274 Behboudian, 2002; Ripoll et al., 2014; Boini et al., 2021) explained by a stress-induced increase in ethylene,
275 governed by associated genes (Apelbaum and Yang, 1981), however, this was not the case for our study
276 (Table 4). Another possible conclusion would be that a 30% reduction of E_0 is not penalizing internal
277 ethylene concentrations that influence fruit ripening processes.

278 Visual colour was strongly influenced only in 2021 (Table 4) by shading, which, regardless of irrigation,
279 decreased the % of colored surface of fruit. A possible explanation can be given by the influence of the two
280 nets on temperature ranges during day and night (supplementary material), which were lower under the
281 exclusion net, during 11 days before harvest, leading to a lower number of accumulated hours below 20 °C
282 in 2021, compared to 2020. It is clear that a decrease in orchard temperature in the pre-harvest period
283 improves the color of apple fruit (Iglesias et al., 2002, 2005). In fact, other studies focusing on anthocyanin
284 synthesis and fruit skin colour obtained positive results when temperatures were below 20 °C (Lin-Wang et

285 al., 2011; Honda et al., 2014). To improve peel visual colour under exclusion netting, a solution could be a
286 delay of the harvest date; this would allow further accumulation of hours below 20°C and augment
287 anthocyanin synthesis. Probably for early ripening red varieties, further mitigation strategies should be
288 implemented to improve fruit skin coloration, such as evaporative cooling (Iglesias et al., 2002, 2005),
289 under exclusion nets.

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

300 Fruit firmness was influenced only in 2021. The general picture shows higher values for A70 trees, which
301 can be explained by the higher number of smaller fruit (Figure 5b); a result of higher cellular density (Ebel
302 et al., 1993). However, when comparing treatments in pairs, more shading decreases significantly fruit
303 firmness (A70 vs E70; A100 vs E70; Table 4) and less water leads to significant differences, even under
304 higher shading levels (E70 vs E50, Table 4). This last consideration is valid throughout the literature, with
305 the overall statement that water deficit increases fruit firmness (Mpelasoka et al., 2000, 2001; Ripoll et al.,
306 2014; Boini et al., 2021).

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

314

315 5. Conclusion

316 Exclusion netting generated higher shading, nonetheless apple crop physiology was unaffected.
317 Shading maintained water status and leaf gas exchanges at an optimal level, which was positive for apple
318 production, even when irrigation was limited to 50% of E_t restitution. Although exclusion netting requires

319 higher initial investment costs, it can be highly beneficial for water saving purposes, without compromising
320 final yield and fruit quality. This strategy can be applied to pome fruit crops, or those crops that are
321 characterized by certain metabolisms, when it comes to fruit growth.

322 Full canopy netting may be tested in areas where the average E_{t0} is high during the growing season and is
323 forecast to increase in the future. From the commercial and practical points of view, the growers and the
324 environment would highly benefit from this solution.

325

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329

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