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Complete List of Authors:	Candian, Valentina; Università degli Studi di Torino, Dipartimento di Scienze Agrarie, Forestali e Alimentari (DISAFA) Pansa, Marco; Università degli Studi di Torino, Dipartimento di Scienze Agrarie, Forestali e Alimentari (DISAFA) Santoro, Karin; Università degli Studi di Torino, Dipartimento di Scienze Agrarie, Forestali e Alimentari (DISAFA) Spadaro, Davide; Università degli Studi di Torino, Dipartimento di Scienze Agrarie, Forestali e Alimentari (DISAFA) Tavella, Luciana; Università degli Studi di Torino, Dipartimento di Scienze Agrarie, Forestali e Alimentari (DISAFA) TEDESCHI, Rosemarie; Università degli Studi di Torino, Dipartimento di Scienze Agrarie, Forestali e Alimentari (DISAFA)
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4 1 **Photoselective exclusion netting in apple orchards: effectiveness against pests**
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10 3 **Effectiveness of photoselective exclusion nets in apple orchards**

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13 4 Valentina Candian, Marco G Pansa, Karin Santoro, Davide Spadaro, Luciana Tavella, Rosemarie
14
15 5 Tedeschi

16
17
18 6 Dipartimento di Scienze Agrarie, Forestali e Alimentari (DISAFA), University of Torino, Largo
19
20 7 Paolo Braccini 2, 10095 Grugliasco (TO), ITALY

21
22
23
24 8 Corresponding author

25
26 9 Rosemarie Tedeschi

27
28
29 10 E-mail: rosemarie.tedeschi@unito.it

30
31 11 Phone number: +39 011 6708675

32
33 12 Fax: +39 011 2368675

34
35
36 13 Co-authors' email address

37
38 14 Valentina Candian: valentina.candian@unito.it

39
40 15 Marco G Pansa: marco.pansa@unito.it

41
42 16 Karin Santoro: santorokarin@gmail.com

43
44 17 Davide Spadaro: davide.spadaro@unito.it

45
46 18 Luciana Tavella: luciana.tavella@unito.it

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50 19 Author Contribution Statement

51
52 20 DS, LT and RT conceived and designed research. VC, MGP, KS conducted experiments. VC, KS
53
54 and DS analysed data. VC wrote the manuscript. All authors assisted in the follow up of the work,
55
56
57 22 read and approved the manuscript.

23 Abstract

24 BACKGROUND: Frequent pesticide treatments in fruit orchards increase hazards for workers,
25 consumers and environment. Moreover, their indiscriminate and excessive use often induces
26 resistance in pests. In the last few years, physical exclusion strategies have been proposed as an
27 alternative for the control of insect pests. The goal of this study was to evaluate the effectiveness of
28 an anti-hail photoselective net in protecting apples against key and emerging pests as well as the
29 impact on beneficial arthropods, fungal diseases and fruit quality.

30 RESULTS: In netted plots, a significant reduction of pest populations [i.e. fruit moths,
31 *Halyomorpha halys* (Stål) and *Drosophila suzukii* (Matsumura)] was recorded in comparison with
32 un-netted controls. Moreover, the damage on fruits caused by *H. halys* was reduced up to 62%
33 compared with insecticidal treatments. The net did not negatively affect the abundance of predators
34 and the incidence of postharvest rots. In addition, the incidence of bitter pit on apple was reduced
35 up to 52%. Furthermore, the fruit quality was unaffected by the net coverage (both at harvest and
36 after 4 months of storage).

37 CONCLUSION: The anti-hail photoselective pearl net proved to be a promising exclusion system
38 that can prevent the attack of more than one insect pest at a time, allowing a strong reduction of
39 insecticide treatments and the relative costs. At the same time, the net did not negatively influenced
40 the presence of predators, the incidence of fungi disease and the fruit quality.

41 **Keywords:** fruit moths, *Halyomorpha halys*, fruit damage, predators, bitter pit.

43 1. Introduction

44 In the past, crop protection was mainly based on the use of synthetic pesticides to prevent or limit
45 pest damage.¹ In particular, in fruit orchards the application of several pesticides has been required

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3 46 to ensure the quality of the fruits, which is a key point for commercialization. Nowadays, it is well
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5 47 established that pesticides increase hazards for workers, consumers and environment. The
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7 48 indiscriminate and excessive use induces both resistance in the treated populations² and pest
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10 49 outbreaks.³
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12 50 Over the last few years, there has been an increasing interest in the development of alternative
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14 51 control strategies in order to reduce environmental impact. For apple orchards, microbiological
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17 52 insecticides⁴ and sex-pheromone-mediated mating disruption technologies⁵ were developed against
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19 53 tortrix moths. Although these methods are widely implemented, they often target a single key pest,
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21 54 and insecticides are still needed under high pest densities⁶ and to contain other pests.⁷ As an
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24 55 alternative, exclusion nets, known as the Alt'Carpo system, have been successfully designed and
25
26 56 applied in apple orchards against *Cydia pomonella* L. (Lepidoptera: Tortricidae) in France since the
27
28 57 early 2000s⁸ allowing a significant reduction in insecticide inputs. More recently, the nets have been
29
30 58 revalued as a multi-target strategy,^{9,10} in particular in relation to the introduction of exotic pests
32
33 59 such as *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae).^{11,12} Indeed, the chemical
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35 60 management required to control this invasive pest disrupts the established integrated pest
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37 61 management (IPM) programmes for many crops, especially for fruit orchards. The aim of this study
38
39 62 was to assess the effectiveness of the exclusion nets in apple orchards in a multi-target approach by
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42 63 monitoring different pest populations, their damage on fruits, and their possible impact on natural
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44 64 enemies, in particular predators. Moreover, the effects on fruit quality as well as on postharvest
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46 65 diseases and bitter pit were evaluated at harvest and after the storage period.
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50 66 **2. Materials and methods**

51 52 67 2.1 Experimental sites

53 68 Field trials were carried out in 2 apple orchards equipped with an anti-hail net system and located in
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55 69 Cervignasco (cv. Baigent Brookfield[®], area: 3.9 ha, age: 13 YR) and in Revello (cv. Galaval*, area:
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3 70 1.1 ha, age: 3 YR), in the province of Cuneo (NW Italy), in 2016 and 2017. Trials were arranged in
4
5 71 a randomized complete block design with 3 replicates for each of the following treatments: 1)
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7 72 netted plots (N); 2) un-netted control plots (C); 3) un-netted plots treated with insecticides following
8
9 73 the farmer schedule (I). Un-netted insecticide-treated plots were included to evaluate the
10
11 74 effectiveness of the net in comparison with the insecticide treatments in reducing pest fruit damage
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14 75 at harvest.

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17 76 In each orchard, 9 plots of 20 neighbouring trees on the row were selected. The 3 netted plots were
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19 77 covered by the pearl anti-hail photoselective net Tenax Iridium (mesh 2.4×4.8 mm) [AGRINTECH
20
21 78 S.r.l., Eboli (SA), Italy] set up hooking their upper side to the anti-hail net support and fixing the
22
23 79 lower side to the ground with metal pegs. The net was placed at the petal fall (mid-May) and
24
25 80 removed after harvesting, at the end of the trials (mid-October). A knock-down treatment with the
26
27 81 pyrethroid deltamethrin (Decis® Jet, Bayer CropScience AG, Monheim am Rhein, Germany, 120
28
29 82 mL hL⁻¹) was performed immediately after the net closing to eliminate pest populations. Later in the
30
31 83 trials, no insecticides were applied in netted plots and un-netted control plots, while fungicides were
32
33 84 applied in the same way in netted plots (directly through the net coverage) and in both un-netted
34
35 85 plots, including control and insecticide-treated plots. The schedule of all pesticide treatments is
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37 86 reported in Table 1.

41 42 43 87 2.2 Insect monitoring

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45 88 Every 10 days from the net setting-up until the harvest, pest populations [i.e. fruit moths, *H. halys*,
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47 89 *Drosophila suzukii* (Matsumura) (Diptera: Drosophilidae) and aphids] and beneficial arthropods
48
49 90 were monitored by traps and visual inspections.

51 52 53 91 2.2.1 Fruit moths

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55 92 Fruit moths were sampled using sticky delta traps (CSALOMON®, Budapest, Hungary). In each
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57 93 orchard, a trap for *C. pomonella* and another one for *Grapholita molesta* (Busck) (Lepidoptera:
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3 94 Tortricidae) baited with sex pheromones (CSALOMON[®], Budapest, Hungary) were placed in each
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5 95 netted and un-netted control plot. Moreover, traps for *C. pomonella* were baited with the feeding
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7
8 96 attractant CSALOMON[®] “BISEX” (CSALOMON[®], Budapest, Hungary) in order to collect also
9
10 97 females of this species as well as other moths. Sex pheromones and feeding attractants were
11
12 98 replaced every 4 weeks to ensure their consistent effectiveness. Caught adults were transferred to
13
14
15 99 the laboratory for the species identification by analysis of morphological features and, when
16
17 100 necessary, of the aedeagus shape following dichotomous keys [Gilligan TM and Epstein ME
18
19 101 (http://idtools.org/id/leps/tortai/Fact_Sheet_Index.htm)], and counted.
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22 102 2.2.2 *Halyomorpha halys*

23
24 103 The abundance of *H. halys* was monitored through DEAD-INN[™] Stink Bug Traps (AgBio,
25
26 104 Westminster, CO, USA) (high 121.92 cm), baited with the Xtra Combo lure provided with the trap
27
28
29 105 as described in Candian *et al.*¹² In each orchard, a trap was placed in a netted plot and an un-netted
30
31 106 control plot from mid-June in 2016 and from mid-May in 2017, until the end of the harvest time.
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34 107 The lure was changed every 4 weeks according to manufacturer’s instructions. The specimens
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36 108 collected into the traps during each survey were identified and counted. Moreover, in each netted
37
38 109 and un-netted control plot, 5 branches of 3 randomly selected trees were shaken on a beating tray
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40 110 (1×1 m) to assess the presence and the abundance of the pest during the growing season.
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43 111 2.2.3 *Drosophila suzukii*

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46 112 Although at the moment *D. suzukii* is not a key pest in apple orchards, the abundance of this pest
47
48 113 was monitored during the trials. A trap filled with the feeding attractive Droskidrink (74.5% apple
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50 114 vinegar, 25% red wine and sugar) [Prantil, Priò di Vervò (TN), Italy] was hung in each netted and
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52
53 115 un-netted control plot at 1.50 m from the ground. It consisted in a transparent plastic bottle filled
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55 116 with 250 mL of Droskidrink and a drop of soap as surfactant. The bottle was closed, and 4
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58 117 symmetrical holes were applied in its upper part in order to allow the insect entrance. At each
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118 survey, the collected *D. suzukii* adults were determined [Vlach J
119 (http://liebegg.ch/upload/cms/user/150730_Identifikation2.pdf)] and counted, and the attractive
120 solution was replaced with new Droskidrink.

121 2.2.4 Other arthropods

122 Other arthropods including aphids and beneficials were monitored every 10 days during the trials.
123 Aphid population levels were sampled by visual inspection of 30 shoots (10 shoots from 3 trees) in
124 each netted and un-netted control plot. The abundance of beneficial arthropods was evaluated
125 thanks to sticky traps. A Glutor YELLOW (25×20 cm) [BIOGARD® Division, Cesena (FC), Italy]
126 sticky trap was placed in each netted and un-netted control plot. The collected specimens were
127 examined under a stereomicroscope for their identification, and at the same time, the predators were
128 separated and counted.

129 Moreover, in 2017, after harvesting, a knock-down treatment with the pyrethroid deltamethrin
130 (Decis® Jet, Bayer CropScience AG, Monheim am Rhein, Germany, 120 mL hL⁻¹) was applied on a
131 tree per plot in all the treatments (N, C, I) to assess the arthropod fauna, as described in Candian *et*
132 *al.*¹² After 3 h and a final beating of the canopy, all the arthropods killed were collected on a nylon
133 tarpaulin (3×2 m) lying under the tree canopy. The collected specimens were examined and sorted
134 in the following clusters: 1) total catches, 2) predators.

135 2.3 Evaluation of fruit damage caused by pests

136 The damage on fruits caused by tortrix moths and *H. halys* was evaluated along the growing season
137 and at harvest. Since the net setting-up, 30 fruits in each netted and un-netted control plot (10 fruits
138 on 3 randomly selected trees) were visually inspected every 10 days to evaluate the damage during
139 the growing season. Overall, 270 and 300 apples per replicate were checked in 2016 and 2017,
140 respectively.

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3 141 At harvest, apples were sampled in all the 3 treatments (N, C, I). Fruits were picked in 3 dates in
4
5 142 2016 and 2 dates in 2017. Overall, 510 apples in 2016 and 480 apples in 2017 were picked in each
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8 143 treatment (N, C and I), with 8,910 fruits totally harvested in each apple orchard in the 2 years. The
9
10 144 number of fruits damaged by tortrix moths and *H. halys* was recorded. In particular, the damage
11
12 145 caused by *H. halys* was identified according to Acebes-Doria *et al.*¹³

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16 146 2.4 Evaluation of postharvest rots and bitter pit

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18 147 In both years, samples of harvested fruits were selected to evaluate the incidence of postharvest
19
20 148 diseases and bitter pit after the storage period. For each netted, un-netted control and un-netted
21
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23 149 insecticide treated plot, 150 apples were collected in 3 plastic boxes (50 fruits per box) for a total of
24
25 150 2,700 apples (900 per treatment) per orchard. Apples were stored in normal atmosphere (0°C, 98%
26
27 151 RH) for 4 months. The incidence of postharvest rots and bitter pit was evaluated after storage and
28
29
30 152 after further 14-day of shelf life at 15°C. Fungal isolation was performed from fruit showing disease
31
32 153 symptoms. Pathogens were isolated by transferring small pieces of symptomatic fruit tissues,¹⁴
33
34 154 previously washed in 1% sodium hypochlorite and rinsed in sterile deionized water, onto potato
35
36 155 dextrose agar (PDA, Merck, Darmstadt, Germany) plates amended with 25 mg L⁻¹ streptomycin
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38 156 sulfate (Merck). A 7-day-old culture was used for observation of the fungal structures under optical
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41 157 microscope.

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45 158 2.5 Fruit quality parameters

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3 165 was pushed into the flesh tissue to a depth of 9 mm. The total soluble solids (TSS) were measured
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6 166 on fresh prepared juice with a DBR 95 digital refractometer (XS Instruments, Carpi, Italy).
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8 167 Titratable acidity was determined by titrating to an end point of pH 8.0 with 0.1N NaOH. For each
9
10 168 sample, 10 mL of pressed juice were diluted with 40 mL of distilled water. Titratable acidity was
11
12 169 calculated as percent malic acid.¹⁵
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15 170 2.6 Statistical analyses

17
18 171 The statistical analyses were performed using SPSS v24.0 [SPSS Inc., Chicago, IL, USA] and
19
20 172 outcomes were considered significant at $P < 0.05$. Captures of fruit moths, *D. suzukii* and other
21
22 173 beneficial arthropods effected with traps were compared using a *t*-test for two independent samples.
23
24 174 The numbers of damaged fruits per treatment and orchard at harvest were compared using a
25
26 175 generalized linear mixed model (GLMM; random effect: plot; fixed effects: treatment, block,
27
28 176 picking date) with a binary distribution and logit link and Bonferroni correction. The data on
29
30 177 arthropods collected by the knock-down treatments and on the incidence of postharvest rots, bitter
31
32 178 pit and fruit quality were checked for homogeneity of variance (Levene test) and normality
33
34 179 (Shapiro-Wilk test), and compared using a one-way ANOVA. In the case of significant differences,
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36 180 the means for the arthropods were separated by Tukey's test, while the others were separated by
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38 181 Duncan's multiple range test.
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44 182 3. Results

45 183 3.1 Populations and damage of fruit moths

46
47 184 Low catches of Tortricidae by traps were recorded in both apple orchards. In Baigent Brookfield®,
48
49 185 *C. pomonella* was never trapped in both years. In 2016, 1 and 13 *G. molesta* were totally collected
50
51 186 in netted plots and in un-netted control plots, respectively; in the following year, 2 *G. molesta* were
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53 187 collected in netted plots and 11 in un-netted control plots. In Galaval*, only 1 *C. pomonella* and 2
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3 188 *G. molesta* were recorded in un-netted control plots in 2016, while only 2 *C. pomonella* were
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5 189 collected in un-netted control plots and no *G. molesta* was trapped in 2017. By contrast, high
6
7 infestations of *Synanthedon myopaeformis* (Borkhausen) (Lepidoptera: Sesiidae) were observed in
8 190
9 traps for *C. pomonella* in both orchards, especially in 2017. In Baigent Brookfield[®], 2 and 38
10 191
11 specimens were collected in netted plots and in un-netted control plots, respectively, in 2016, while
12 192
13 18 and 111 specimens were trapped in netted plots and in un-netted control plots, respectively, in
14 193
15 2017. In Galaval*, 4 specimens were recorded in netted plots in both years, while 71 and 108
16 194
17 specimens were trapped in un-netted control plots in 2016 and in 2017, respectively. In order to
18 195
19 evaluate the efficacy of the net, all adults of *C. pomonella*, *G. molesta* and *S. myopaeformis* caught
20 196
21 with traps were grouped before the statistical analysis. Significant differences between the 2
22 197
23 treatments (N and C) were observed both in 2016 (Baigent Brookfield[®]: $t = -7.224$, $P = 0.002$;
24 198
25 Galaval*: $t = -6.515$, $P = 0.003$) and in 2017 (Galaval* $t = -5.550$, $P = 0.005$) with always a lower
26 199
27 number of catches under net (Table 2).
28 200
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33 201 Damage on fruits caused by Tortricidae was never observed in the apple orchards all along the
34
35 202 growing season but 4, 6 and 6 fruits damaged by *C. pomonella* were recorded in 2017 at harvest in
36
37 Galaval* in netted, control and un-netted insecticide-treated plots, respectively.
38 203
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40

41 204 3.2 Population and damage of *Halyomorpha halys*

42
43 205 *Halyomorpha halys* was collected by traps but never by using the beating tray. In netted plots, only
44
45 2 nymphs of *H. halys* were caught in Baigent Brookfield[®] in 2017 at the end of July, otherwise no
46 206
47 catches were recorded in both cultivars (Fig. 1). In un-netted control plots, a variable population
48 207
49 density was observed between the years. In 2016, only 3 adults and 1 nymph in Baigent
50 208
51 Brookfield[®] and 3 adults in Galaval* were totally collected by the traps (Fig. 1). By contrast, in
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53 2017, *H. halys* was detected along all the growing season, with peaks of catches close to the fruit
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3 211 ripening. Overall, 42 nymphs and 23 adults were caught in Baigent Brookfield[®], while 180 nymphs
4
5 212 and 18 adults were trapped in Galaval* (Fig. 1).

7
8 213 In 2016, during the growing season, a low number of damaged fruits was recorded. In Galaval*, no
9
10 214 and only one damaged fruit were found in netted and un-netted control plots, respectively. In
11
12 215 Baigent Brookfield[®], 3 damaged fruits (0.4%) were observed in netted plots and 4 (0.5%) in un-
13
14 216 netted control plots. In 2017, a higher number of damaged fruits was recorded. In Baigent
15
16 217 Brookfield[®], 25 (2.8%) and 21 (2.3%) damaged fruits were found in netted and in un-netted control
17
18 218 plots respectively, while in Galaval*, 12 (1.2%) and 17 (1.7%) damaged fruits were observed in
19
20 219 netted plots and in un-netted control plots, respectively.

23
24 220 The damage on fruits at harvest is reported in Table 3. Significant differences between the 3
25
26 221 treatments (N, C, I) were only observed in 2017, both in Baigent Brookfield[®] ($F = 9.117$, $P =$
27
28 222 0.006), where damage rate was similar in netted and insecticide-treated plots, and in Galaval* ($F =$
29
30 223 9.462 , $P = 0.005$), where damage rate was lower in netted plots (Table 3). Significant differences
31
32 224 between the picking dates were found both in Baigent Brookfield[®] (2017: $F = 5.022$, $P = 0.049$) and
33
34 225 in Galaval* (2016: $F = 5.933$, $P = 0.012$; 2017: $F = 6.444$, $P = 0.029$) with a significantly lower
35
36 226 damage in the second picking date in Baigent Brookfield[®] and in the first picking date in Galaval*.
37
38 227 No interactions between the treatments and the picking dates were recorded in any orchard.
39
40 228 Moreover, the block effect was analysed in order to assess if the damage by *H. halys* was higher on
41
42 229 the borders or in the middle of the orchards. Significant differences for the block effect were
43
44 230 recorded only in Baigent Brookfield[®] in 2017 ($F = 10.749$, $P = 0.003$) with a higher concentration
45
46 231 of the damage along the borders.

52 232 3.3 Population of *Drosophila suzukii*

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55 233 *Drosophila suzukii* was collected starting from June in 2016 and from May in 2017. Abundant
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57 234 catches were recorded in 2016 when 118 *D. suzukii* were totally collected in netted plots and 631 in
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3 235 un-netted control plots in Baigent Brookfield[®], while in Galaval* 117 and 394 specimens were
4
5 236 trapped in netted plots and un-netted control plots, respectively. Significant differences between the
6
7
8 237 2 treatments (N and C) were recorded in both cultivars with always a lower number of *D. suzukii*
9
10 238 collected in netted plots (Baigent Brookfield[®]: $t = 7.071$, $P = 0.002$; Galaval*: $t = 0.561$, $P = 0.025$)
11
12 239 (Table 2).

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14
15 240 In 2017, catches well below than the previous year were recorded. In Baigent Brookfield[®], 21
16
17 241 specimens were totally collected in netted plots and 111 in un-netted control plots, while 50
18
19 242 specimens were trapped in netted plots and 147 un-netted control plots in Galaval*. The number of
20
21 243 *D. suzukii* was always significantly lower in netted plots in both cultivars (Baigent Brookfield[®]: $t =$
22
23
24 244 4.472 , $P = 0.011$; Galaval*: $t = 6.364$, $P = 0.003$) (Table 2).

25 26 27 245 3.4 Other arthropods

28
29 246 *Aphis pomi* De Geer (Hemiptera: Aphididae) and *Eriosoma lanigerum* (Hausmann) (Hemiptera:
30
31 247 Aphididae) were recorded in both orchards in 2016, but colonies were mainly composed by *E.*
32
33 248 *lanigerum* in Baigent Brookfield[®] and by *A. pomi* in Galaval*. Overall, 20 infested shoots (10 for
34
35
36 249 each aphid species) in netted plots and 5 infested shoots in un-netted control plots (one by *A. pomi*
37
38 250 and 4 by *E. lanigerum*) were observed in Baigent Brookfield[®]. In Galaval*, only 4 infested shoots
39
40 251 by *A. pomi* in netted plots and 38 infested shoots in un-netted control plots (35 by *A. pomi* and 3 by
41
42
43 252 *E. lanigerum*) were recorded, respectively. In 2017, only *A. pomi* was observed in both orchards
44
45 253 with 56 infested shoots in netted plots and 107 in un-netted control plots in Baigent Brookfield[®],
46
47 254 while 23 in netted plots and 81 in un-netted control plots were sampled in Galaval*. Significant
48
49
50 255 differences between the 2 treatments (N and C) were found only in Galaval* (2016: $t = 2.909$, $P =$
51
52 256 0.044 ; 2017: $t = 5.469$, $P = 0.005$) with a lower number of aphids recorded in netted plots.

53
54 257 Predators collected by sticky traps belonged to Aranaeidae (Araneae), Anthocoridae (Hemiptera)
55
56 258 [only in Baigent Brookfield[®] in 2016], Hemerobiidae [except in Galaval* in 2017] and Chrysopidae
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58
59 259 (Neuroptera), Staphylinidae and Coccinellidae (Coleoptera), Syrphidae (Diptera). These predators
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3 260 were together grouped and statistically analysed. Higher catches were always obtained in un-netted
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5 261 control plots but significant differences between the 2 treatments (N and C) were recorded only in
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7
8 262 Galaval* in 2016 ($t = 6.993$, $P = 0.002$) and in Baigent Brookfield® in 2017 ($t = 4.628$, $P = 0.010$)
9
10 263 (Table 2).

11
12 264 In the final knock-down treatment, all the specimens killed by the insecticide were considered in the
13
14 265 cluster total catches. Specimens belonging to Aranaeidae (Araneae); Acarina; Forficulidae
15
16
17 266 (Dermaptera); Psocoptera; Thripidae (Thysanoptera); Anthocoridae, Nabidae, Tingidae, Coreidae,
18
19 267 Lygeidae, Pentatomidae, Cicadellidae and Aphidoidea (Hemiptera); Hemerobiidae and Chrysopidae
20
21 268 (Neuroptera); Staphylinidae and Coccinellidae, Chrysomelidae and Curculionidae (Coleoptera);
22
23
24 269 Syrphidae and Drosophilidae (Diptera); Lepidoptera; and Hymenoptera were collected. Significant
25
26 270 differences between the 3 treatments (N, C, and I) were not recorded for this cluster in both
27
28 271 orchards. Moreover, Aranaeidae (Araneae); *Allothrombium fuliginosum* (Hermann) (Acarina);
29
30 272 Forficulidae (Dermaptera); Anthocoridae and Nabidae (Hemiptera); Hemerobiidae and Chrysopidae
31
32 273 (Neuroptera); Staphylinidae and Coccinellidae (Coleoptera); Syrphidae (Diptera) were grouped in
33
34
35 274 predators, but no significant differences between the 3 treatments (N, C, and I) were recorded.
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37

38 275 3.5 Evaluation of postharvest rots and bitter pit

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41 276 During the trials, the incidence of postharvest rots was not significantly different between the 3
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43 277 treatments in either cultivar of apple (Table 4). The main postharvest pathogens isolated from
44
45 278 diseased apples at the end of storage were counted. On Galaval*, *Botrytis cinerea* Persoon (92%)
46
47
48 279 was the major pathogen isolated, followed by low levels of *Alternaria* spp. and *Penicillium*
49
50 280 *expansum* Link. In Baigent Brookfield®, the main pathogens isolated were *B. cinerea* (77%),
51
52 281 *Alternaria* spp. (15%) and *P. expansum* (8%). Moreover, the incidence of bitter pit was significantly
53
54
55 282 reduced in netted plots in Galaval* both in 2016 (4-month storage: $F = 3.928$, $df = 2$, $P = 0.042$; 14-
56
57 283 day storage: $F = 8.034$, $df = 2$, $P = 0.004$) and in 2017 (14-day storage: $F = 6.012$, $df = 2$, $P =$
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59
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1
2
3 284 0.012) (Table 5). No differences between the 3 treatments (N, C, and I) were recorded in Baigent
4
5 285 Brookfield® (Table 5).

9 286 3.6 Fruit quality parameters

11 287 The fruit quality evaluated on fruits sampled at the first picking date in 2017 at harvest and after 4-
12
13 month storage was not affected by the presence of photoselective net. Differences between the the 3
14 288
15 treatments (N, C, and I) were not statistically significant except for the firmness in Baigent
16 289
17 Brookfield® (harvest: $F = 7.412$, $df = 2$, $P = 0.023$) and for the total soluble solid in Galaval*
18 290
19 (harvest: $F = 6.432$, $df = 2$, $P = 0.006$; 4-month storage: $F = 8.034$, $df = 2$, $P = 0.013$) (Table 6).
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24 292 4. Discussion

26 293 The growing attention to food safety and environmental protection, the increasing occurrence of
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28 294 resistance in insects as well as the introduction of exotic pests require the implementation of new
29
30 295 methods for crop protection in accordance with IPM principles. In this scenario, exclusion netting
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32 represents a valid multi-purpose system against several key and emerging apple pests. The impact
33 296
34 of insect exclusion nets is not only confined to being an actual physical barrier against the in-out
35 297
36 movement of insects from the orchard but they also interfere with their behaviour. The nets indeed
37 298
38 hamper the flight of male moths during their approach towards the females reducing mating
39
40 299 success, and may interfere by causing a visual disturbance to the searching males.^{16, 17} Even if *C.*
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42 300 *pomonella* and *G. molesta* were not very abundant in the surveyed orchards, our trials confirmed the
43
44 301 effectiveness of the nets against these moths¹⁸ as well as against *S. myopaeformis* collected thanks
45
46 302 to the feeding attractant added in the *C. pomonella* pheromone traps. In our trials, the number of
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48 damaged fruits was too low to assess the effectiveness of the used net in containing *C. pomonella*
49 303
50 damage, as reported by other anti-hail nets.⁸
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55 306 Particularly interesting are the results obtained against *H. halys* whose density has increased
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57 worrisomely in NW Italy in the last years.¹⁹ The net always prevented the entry of the adults while
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3 308 only 2 nymphs were collected under the net, allowing a reduction of fruit damage, in particular in
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5 309 2017, in comparison not only to the un-netted control plots, but also, in Galaval*, to the un-netted
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7
8 310 plots treated with insecticides. *Halyomorpha halys* is a perimeter-driven threat²⁰ and, as expected,
9
10 311 the damage was higher on netted and un-netted trees closer to the edges. Moreover, the highest
11
12 312 damage rate was observed in the netted and un-netted control plots where the pheromone trap was
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14
15 313 placed, confirming the fact that adults aggregate around a pheromone source within a radius of ca.
16
17 314 2.5 m without contacting the source.²¹

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19 315 Although previous research reported that only nets with a mesh thinner than 1 mm² are effective in
20
21 316 excluding *D. suzukii*,^{22, 23} satisfactory results in reducing *D. suzukii* populations, and generally the
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23
24 317 Drosophilidae abundance (data not shown), were recorded under the net in our trials, in which a
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26 318 2.4×4.8 mm net was used. This may be due more to the optical properties of the photoselective net
27
28 319 than to its physical activity. In fact, it was shown that the light reflected by the photoselective nets
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30
31 320 may cause an optical disruption and as a consequence, negatively affect the pest in distant host
32
33 321 finding and landing.²⁴

34
35 322 The influence of the exclusion nets on aphid populations is quite controversial and seems mainly
36
37 323 related to the species,^{25,10} to the microclimate under the nets and to the preclusion of natural
38
39
40 324 enemies²⁶ as well as to the exclusion system (single row or single-plot).²⁷ In our trials, a low
41
42 325 number of infested shoots was observed under the net, except in Baigent Brookfield® in 2016 when
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45 326 colonies were mainly composed by *E. lanigerum*. As already observed, the net favours the
46
47 327 development of this aphid species²⁸ while no clear effect of the nets has been yet demonstrated for
48
49 328 *A. pomi*.²⁹

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51 329 As observed by other authors,^{25,30,31} a significant lower number of predators was collected by sticky
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54 330 traps under the net, in both orchards, during the growing seasons. Generally, the net mesh was large
55
56 331 enough to allow tiny beneficial insects to pass through (mainly Anthocoridae, Staphylinidae and
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58 332 Coccinellidae). Larger size insects, such as Hemerobiidae, Chrysopidae and Syrphidae, were
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3 333 collected only in the first weeks after the net setting-up probably following the hatching of eggs laid
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5 334 on the plants covered with the net before the installation. However, the results obtained with the
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8 335 final knock-down treatments (here referred only to 2017, but 2016 data are available in Candian *et*
9
10 336 *al.*¹²) showed that the net did not negatively influence the abundance of predators. These contrasting
11
12 337 results may be due to different aspects, such as the timing of the survey and the impact of the net on
13
14 338 the visual cues of predators. The disrupting insect fly orientation, visual detection, and colour
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16
17 339 perception might reduce the attractiveness of yellow sticky traps and render this monitoring
18
19 340 technique ineffective,³² as already observed in Candian *et al.*¹²
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21 341 The mesh size is a very critical factor not only for the exclusion effectiveness, but also for the
22
23 342 consequences on the microclimate occurring under the net. Despite the expectations, under the pearl
24
25
26 343 net the temperature and the relative humidity were similar to the ones recorded outside net (data not
27
28 344 shown). Therefore, the pearl photoselective net did not favour the development of fungal pathogens.
29
30 345 Neither significant differences were found in the incidence of apple scab in the field (data not
31
32 346 shown), nor in the incidence of postharvest rots. The main agents of postharvest rots isolated were
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34 347 *B. cinerea*, *Alternaria* spp. and *P. expansum*, which are the most common postharvest pathogens on
35
36 348 apple in northern Italy.³³ High relative humidity could be conducive to the occurrence of russetting
37
38 349 and other physiological disorders in apples during postharvest.³⁴ Apples subjected to cold storage
39
40 350 after harvest revealed an interesting effect of the nets on bitter pit. For both cultivars, and in
41
42 351 particular for Galaval*, the presence of the nets reduced the incidence of bitter pit, as previously
43
44 352 observed on Gala and Fuji apples grown under white net.³⁵ Various papers show that the influence
45
46 353 of protective shade netting on the incidence of bitter pit varies depending on cultivar, net colour,
47
48 354 shading percentage, net mesh size and timing of deployment relative to full bloom.^{36,37}
49
50
51 355 Finally, the fruit quality was not affected by the net coverage as already reported by several
52
53 356 authors.³⁸⁻⁴⁰ A lower level of total soluble solids in Galaval* apples grown under net is comparable
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55 357 with the previously reported reduction of total soluble solids in ‘Gala’ apples, but not in ‘Fuji’
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358 apples grown under whiteshade net.³⁵ Actually, in some cases, the pearl photosensitive net was also
359 able to enhance some nutraceutical properties of the fruits.¹²

360 Overall, photosensitive exclusion nets are able to preserve apple production and quality with a
361 strong reduction of insecticide treatments, in our trials up to 7 less. This aspect is particularly
362 important in the case of invasive pests with typical severe outbreaks. For instance, in the case of *H.*
363 *halys*, the use of frequent and broad spectrum insecticides are required to reduce fruit injury,^{41,42} but
364 this prejudices the principles of IPM. On the contrary, exclusion nets allow obtaining apples
365 without insecticidal residues as confirmed by a multiresidual analysis performed on fruits at harvest
366 (data not shown). Moreover, the use of exclusion nets can even have an added value considering the
367 reduction of costs associated with insecticide use: in our trials, the omission of 7 insecticidal
368 treatments in the netted plots gave rise to a saving up to 1,050 € ha⁻¹ (ca. 150 € ha⁻¹ per treatment).
369 In terms of costs, in orchards in which an anti-hail net system is already present, a single plot
370 exclusion-net system is more feasible, entailing a 2,300 € ha⁻¹.¹² The reduction of insecticide costs,
371 associated with possible public contributions to the growers can easily amortize in few years the
372 upfront fixed costs of nets setting up.

373 5. Conclusion

374 The pearl photosensitive exclusion net proved to be effective in controlling more than one apple
375 pest species at a time and their damage on fruits, and in reducing the occurrence of some
376 physiological disorders and diseases. Moreover, in some cases, it has been more effective than
377 chemical treatments representing a great-value alternative for the management of pests not
378 effectively controlled by insecticide treatments and in organic farming. It can be a great resource as
379 an environment-friendly strategy for a healthier fruit production in face of climate change issues,
380 which are favouring the increasing occurrence of invasive exotic pests.

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4
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8 384 ENV/HR/000580 project “Low pesticide IPM in sustainable and safe fruit production”.

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44 498 *halys* (Stål) (Hemiptera: Pentatomidae) mortality and injury in apple and peach orchards.
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8. Tables

Table 1. Insecticidal and fungicidal treatments applied in the orchards from the net setting-up until harvest in 2016 and 2017.

Cultivar	Target	Treatment					
		Applied on	Active ingredient	Trade name	Year	No.	
Baigent	<i>Aculus schlechtendali</i>	I	Abamectin	Zoro® 1,9 EV	2017	1	
Brookfield®	<i>Cydia pomonella</i>	I	Chlorpyrifos	Terial® 75 WG	2016	2	
			Chlorpyrifos methyl	Reldan™ LO	2016	1	
			Etofenprox	Trebon® STAR	2016	1	
			Etofenprox	Trebon® UP	2017	1	
			Phosmet	Spada® 50 WG	2017	2	
	<i>Halyomorpha halys</i>	I	Chlorpyrifos methyl	Reldan™ LO	2017	1	
	<i>Synanthedon myopaeformis</i>	I	Chlorpyrifos	Terial® 75 WG	2017	1	
	Tortricidae	I	Methoxyfenozide	Intrepid™	2017	1	
	Heart-rot	N, C, I		Pyraclostrobin-boscalid	Bellis®	2016	2
				Pyraclostrobin-boscalid	Bellis®	2017	1
	Postharvest rots	N, C, I		Captan	Merpan® 80 WDG	2016	1
				Captan	Santhane® WG	2017	1
				Fludioxonil	Geoxe®	2017	1
<i>Venturia inaequalis</i>	N, C, I		Dodine	Syllit 355 SC	2016	1	
			Dithianon	Delan® 70 WG	2016	1	
			Dodine	Syllit 355 SC	2017	3	
			Fluazinam	Banjo®	2017	1	
Galaval*	<i>Anthonomus pomorum</i>	I		Spada® 50 WG	2017	1	
				<i>C. pomonella</i>	I		Chlorpyrifos methyl
	Etofenprox	Trebon® UP	2016	1			
	Chlorpyrifos methyl	Runner® LO	2017	2			
	Etofenprox	Trebon® UP	2017	1			
	Methoxyfenozide	Prodigy®	2017	2			
	<i>Podosphaera leucotricha</i>	N, C, I		Sulfur	Tiovit® Jet	2016	1
				Sulfur	Thiopron®	2017	1
Postharvest rots	N, C, I		Captan	Merpan® 80 WDG	2017	1	
<i>Venturia inaequalis</i>	N, C, I		Captan	Captan arvesta 80 WG	2016	2	
			Sulfur	Thiopron®	2016	1	

Treatment: N = netted plots, C = un-netted control plots, I = un-netted plots treated with insecticides.

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505 **Table 2.** Percentage of Tortricidae + Sesiidae and *Drosophila suzukii* per trap on the total catches (mean \pm SE), and
506 total number of predators per sticky trap (mean \pm SE) in the apple orchards. For each cultivar, means followed by
507 different letters are significantly different (*t*-test, $P < 0.05$).

Cultivar	Treatment	Tortricidae + Sesiidae (%)		<i>Drosophila suzukii</i> (%)		Predators (no.)	
		2016	2017	2016	2017	2016	2017
Baigent	N	1.85 \pm 1.07 b	4.70 \pm 0.80	5.30 \pm 2.00 b	5.30 \pm 1.90 b	74.67 \pm 27.51	2.33 \pm 0.88 b
Brookfield [®]	C	31.48 \pm 3.21 a	28.60 \pm 11.10	28.10 \pm 2.20 a	28.80 \pm 4.30 a	137.00 \pm 9.45	15.33 \pm 2.66 a
Galaval*	N	1.71 \pm 1.71 b	1.20 \pm 0.30 b	7.60 \pm 0.90 b	8.50 \pm 1.80 b	7.00 \pm 1.00 b	0.66 \pm 0.66
	C	31.62 \pm 2.26 a	32.10 \pm 8.00 a	25.70 \pm 4.10 a	24.90 \pm 2.80 a	67.33 \pm 8.56 a	7.00 \pm 3.05

508 Treatment: N = netted plots, C = un-netted control plots.

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3 510 **Table 3.** Percentages of apples damaged by *Halyomorpha halys* (mean \pm SE) on fruits sampled at harvest in 2016 (no. =
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5 511 510 fruits per repetition) and in 2017 (no. = 480 fruits per repetition). For each cultivar, means followed by different
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7 512 letters are significantly different (GLMM, Bonferroni correction, $P < 0.05$).

Cultivar	Treatment	Damaged apples	
		2016	2017
Baigent Brookfield®	N	5.8 \pm 1.4	1.9 \pm 0.8 b
	C	7.1 \pm 1.6	7.7 \pm 2.1 a
	I	5.5 \pm 1.4	1.2 \pm 0.7 b
Galaval*	N	4.3 \pm 1.3	6.3 \pm 1.4 b
	C	9.0 \pm 1.9	17.7 \pm 2.3 a
	I	7.4 \pm 1.7	16.4 \pm 2.4 a

17 513 Treatment: N = netted plots, C = un-netted control plots, I = un-netted plots treated with insecticides.

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Table 4. Incidence of postharvest fungal diseases (mean % \pm SE) in apples harvested in 2016 and 2017 after 4-month storage and after additional 14-day in shelf life. For each cultivar, means followed by different letters are significantly different (Duncan's multiple range test, $P < 0.05$).

Cultivar	Treatment	2016		2017	
		4-month storage	14-day shelf life	4-month storage	14-day shelf life
Baigent	N	2.00 \pm 0.86	11.11 \pm 6.28	4.67 \pm 1.73	13.55 \pm 2.43
Brookfield [®]	C	1.11 \pm 0.44	8.89 \pm 0.87	4.28 \pm 1.22	14.78 \pm 2.58
	I	0.89 \pm 0.28	6.56 \pm 0.63	2.83 \pm 1.13	12.05 \pm 1.68
Galaval*	N	2.22 \pm 0.92 b	13.97 \pm 4.14	1.35 \pm 0.44	7.42 \pm 1.95
	C	4.25 \pm 1.06 ab	17.07 \pm 4.22	2.85 \pm 0.62	14.42 \pm 3.29
	I	7.34 \pm 1.44 a	24.91 \pm 2.28	6.00 \pm 3.51	30.92 \pm 12.55

Treatment: N = netted plots, C = un-netted control plots, I = un-netted plots treated with insecticides.

Percent rotten apples = (no. of infected apples/total no. of apples) \times 100.

Table 5. Incidence of bitter pit (mean % \pm SE) in apples harvested in 2016 and 2017 after 4-month storage and after additional 14-day in shelf life. For each cultivar, means followed by different letters are significantly different (Duncan's multiple range test, $P < 0.05$).

Cultivar	Treatment	2016		2017	
		4-month storage	14-day shelf life	4-month storage	14-day shelf life
Baigent	N	14.67 \pm 3.71	14.89 \pm 4.44	1.78 \pm 0.66	3.57 \pm 1.12
Brookfield [®]	C	9.56 \pm 1.39	10.44 \pm 4.02	1.78 \pm 0.71	3.85 \pm 1.22
	I	6.22 \pm 2.14	8.22 \pm 2.69	0.52 \pm 0.52	1.53 \pm 0.78
Galaval*	N	27.29 \pm 2.64 ab	32.25 \pm 2.91 b	11.03 \pm 2.90	19.45 \pm 3.36 b
	C	33.21 \pm 5.29 a	42.37 \pm 6.45 ab	16.07 \pm 3.59	32.85 \pm 3.80 a
	I	24.91 \pm 2.28 b	55.20 \pm 3.99 a	22.18 \pm 5.54	40.45 \pm 4.06 a

Treatment: N = netted plots, C = un-netted control plots, I = un-netted plots treated with insecticides.

Percent apples with bitter rot = (no. of diseased apples/total no. of apples) \times 100.

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3 527 **Table 6.** Firmness, total soluble solids and titratable acidity (mean \pm SE) recorded on fruits at the first picking date
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5 528 in 2017 at harvest and after 4-month storage. For each cultivar, means followed by different letters are
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7 529 significantly different (Duncan's multiple range test, $P < 0.05$).

Cultivar	Treatment	Firmness (g cm ⁻²)		Total soluble solids (°Brix)		Titratable acidity (% malic acid)	
		Harvest	4-month storage	Harvest	4-month storage	Harvest	4-month storage
Baigent	N	7.63 \pm 0.23 a	6.33 \pm 0.21	13.83 \pm 0.16	14.37 \pm 0.19	0.27 \pm 0.03	0.28 \pm 0.02
Brookfield®	C	7.41 \pm 0.16 b	6.54 \pm 0.12	13.88 \pm 0.13	13.80 \pm 0.17	0.27 \pm 0.03	0.27 \pm 0.02
	I	7.50 \pm 0.09 ab	6.15 \pm 0.15	13.55 \pm 0.19	13.46 \pm 0.23	0.27 \pm 0.01	0.26 \pm 0.03
Galaval*	N	8.28 \pm 0.36	6.39 \pm 0.33	12.38 \pm 0.11 c	12.53 \pm 0.14 b	0.32 \pm 0.01	0.30 \pm 0.03
	C	8.01 \pm 0.34	6.57 \pm 0.37	13.43 \pm 0.21 b	13.51 \pm 0.16 a	0.30 \pm 0.03	0.28 \pm 0.02
	I	7.81 \pm 0.31	6.27 \pm 0.23	13.71 \pm 0.13 a	13.35 \pm 0.11 a	0.34 \pm 0.03	0.28 \pm 0.02

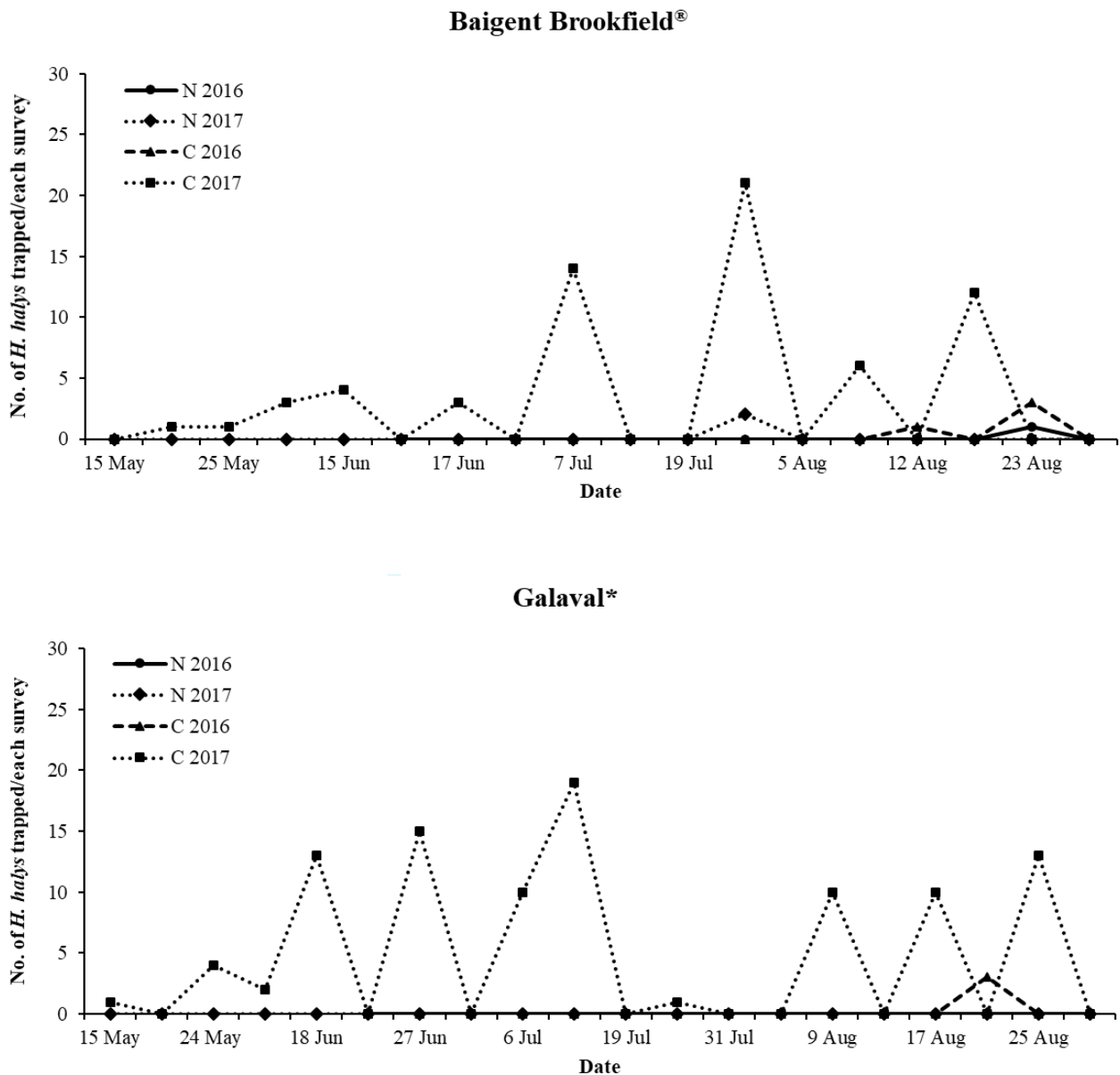
19 530 Treatment: N = netted plots, C = un-netted control plots, I = un-netted plots treated with insecticides.

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4 532 **9. Figure Legends**

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6 533 Figure 1. Total number of *Halyomopa halys* collected by traps in the cultivars Baigent Brookfield®
7 534 and Galaval* in treatments N (netted plots) and C (un-netted control plots) in 2016 and in 2017.

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3 **Figure 1.** Total number of *Halyomorpha halys* collected by traps in the cultivars Baigent
4 Brookfield® and Galaval* in treatments N (netted trees) and C (un-netted control trees) in 2016 and
5 in 2017.