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Jean-Charles Bouvier, Thomas Boivin, Claire Lavigne. Single-row exclusion nets: an alternative pest control method with no detectable impact on breeding bird assemblages in orchards bordered by hedgerows. *Agronomy for Sustainable Development*, 2022, 42 (2), pp.23. 10.1007/s13593-021-00743-7. hal-03612503

HAL Id: hal-03612503

<https://hal.inrae.fr/hal-03612503v1>

Submitted on 20 Mar 2023

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Single-row exclusion nets: an alternative pest control method with no detectable impact on breeding bird assemblages in orchards bordered by hedgerows

Jean-Charles Bouvier¹ · Thomas Boivin² · Claire Lavigne¹

Accepted: 8 November 2021 / Published online: 14 March 2022
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Abstract

Agricultural intensification has led to dramatic declines in bird populations. In particular, the acknowledged role of synthetic pesticides on direct bird intoxication or food resource depletion urges us to seek alternative crop protection methods. Pest exclusion netting systems have recently gained popularity among fruit growers as an efficient means of reducing pest attacks, allowing their transition to organic farming. Single-row exclusion nets, which only cover fruit trees and leave uncovered both the inter-row grassy strips and the hedges, are increasingly being used in apple orchards of Southern Europe. However, net-induced effects on wildlife remain unknown. This study is the first to assess the impacts of single-row exclusion nets on breeding bird communities. We hypothesized that the exclusion net effects would be weaker than those associated with synthetic pesticide use, except for bird species that forage in the tree canopy. We monitored breeding bird abundance, and species richness in 46 commercial apple orchards managed using integrated pest management (IPM) or organic standards with or without exclusion nets. We counted 705 birds belonging to 32 different species. Total bird abundance, the number of observed species, and the Chao1 estimate of species richness were influenced by orchard management strategy. Breeding bird assemblages in organic orchards were as numerous and diverse in both the presence and absence of exclusion nets. In contrast, both bird abundance and species richness were significantly decreased in IPM orchards. The abundance and species richness of bird assemblages and the abundance of a few individual species also increased with the number of hedgerows bordering the orchards. Our results demonstrate that single-row netting systems for organic farming represent an effective pest control strategy with no significant impact on bird communities and highlight the importance of hedgerows along the orchards' edges.

Keywords Bird diversity · Crop management · *Cydia pomonella* · Hedgerow · Organic · Pesticide

1 Introduction

Over the last decades, the processes of agricultural intensification, e.g., increased mechanization and pesticide use, expanded monocultures, and associated suppression of hedgerows, have been well associated with a dramatic global decline of breeding and wintering bird populations inhabiting farmed habitats (Donald et al. 2001; EBCC 2020; Geiger et al. 2010; Tscharnke et al. 2005). The main mechanisms

of population declines shared by bird species involve the loss of breeding and foraging habitats through an overall reduction in landscape heterogeneity and the loss of food resources through mechanization and changes in farming activity timing (Donald et al. 2001; Stanton et al. 2018). In addition, the increased use of agrochemicals also has significant indirect effects on bird populations by reducing arthropod biomass and abundance and direct effects by altering bird reproductive success from both lethal and sub-lethal effects of exposure to pesticides (Bouvier et al. 2005; Genghini et al. 2006; Parsons et al. 2010). In this regard, the compatibility of bird conservation with agricultural land use is traditionally questioned (Balmford et al. 2012), and birds constitute relevant bio-indicators of the environmental impact of agricultural practices (Furness and Greenwood, 1983; Morelli et al. 2014; Ormerod and Watkinson 2000). Therefore, identifying the drivers of bird species abundance

✉ Jean-Charles Bouvier
jean-charles.bouvier@inrae.fr

¹ INRAE, UR 1115, Plantes et Systèmes de culture Horticoles, 84000 Avignon, France

² INRAE, UR 629, Ecologie des Forêts Méditerranéennes, 84000 Avignon, France

in farmed landscapes is critical for assessing the bird population's response to human-driven changes in their habitats and counteracting adverse effects of agricultural practices on wildlife (Balmford et al. 2012; Brambilla et al. 2015).

Pome fruit orchards represented nearly 44% of the total fruit cultivated area in Europe in 2017 (Eurostat 2019). Across Europe, agricultural intensification has converted traditional fruit orchards with high natural value (Cooper et al. 2007; Myczko et al. 2013) into intensively managed, low-stem tree plantations that constitute more simplified habitats essentially managed to meet high production criteria (Simon et al. 2010). Commercial orchards display an overall structural homogeneity but still combine woody elements and herbaceous vegetation between tree rows that can benefit bird species associated with forest edges and open woodland (Bouvier et al. 2020; Myczko et al. 2013; Rime et al. 2020; Simon et al. 2010). Crop protection programs against pests in orchards mainly rely on synthetic (integrated pest management (IPM) farming) or natural (organic farming) pesticides (FAO 2009). The few studies on the impact of crop protection strategy on bird communities in orchards concur that these communities are predominantly affected by agrochemicals. Indeed, species abundance and diversity are generally significantly lower in IPM orchards than organic ones (Bouvier et al. 2011; Genghini et al. 2006; Katayama 2016; Wiacek and Polak 2008). Synthetic pesticides were also negatively associated with bird reproductive success (Bishop et al. 2000; Bouvier et al. 2016; Fluetsch and Sparling 1994) and functional diversity through an attenuated representation of insectivorous species in the communities (Bouvier et al. 2011; Genghini et al. 2006; Katayama 2016; Wiacek and Polak 2008).

In fruit orchards, the combination of ever-increasing pest pressures on crops (e.g., pesticide resistances and life cycles favored by climate change) and deleterious effects of pesticides on biodiversity led to the implementation of pheromone-based behavior disruptors (mating disruption) and physical barriers (netting) to complement pest management (Chouinard et al. 2016; Simon et al. 2010). Pest exclusion nets have been developed as a non-aggressive barrier preventing pest access to crops and potentially disturbing the behavior of certain pest species (Alaphilippe et al. 2016). Netting systems are widely used to protect crops against frugivorous bats and birds, hail, wind, frost, and sunburn (Lloyd et al. 2005). Their efficiency has driven the global expansion of their use against a broad range of insect pests of horticultural and fruit crops, including Lepidoptera, Diptera, and Hemiptera (Chouinard et al. 2017; Marshall and Beers 2016), among which *Rhagoletis cerasi* (Brand et al. 2013) and psyllas (Romet et al. 2010).

Currently, full block or single-row pest exclusion netting systems exist (Chouinard et al. 2016). Full block netting systems cover entire orchards with anti-hail nets and

with or without side walls, thus shielding the soil in the enclosed area. On the other hand, single-row nets are a novel exclusion netting system that covers the fruit tree rows and does not cover the soil surrounding the trees, grassy inter-row strips and hedges (Fig. 1). As exclusion nets gradually gained interest in overcoming fruit production issues in organic and IPM farming (Granatstein et al. 2016; Marliac et al. 2015), clarifying their impact on the abundance of farmland bird species is increasingly needed since they add an extra level of complexity to the birds' natural environment. For example, anti-hail nets have been reported to reduce breeding bird species densities by limiting access to and movements within and between orchards (Brambilla et al. 2013, 2015). However, to our knowledge, no work has assessed whether single-row exclusion nets, which only cover the orchard canopy, affect bird assemblages.

Here we investigate the response of bird abundance and species richness to single-row exclusion nets in apple orchards for the first time. We conducted this study in southeastern France, where pome fruit orchards cover approximately 10,000 ha, which corresponds to a quarter of the pome fruit producing area in France, the fourth largest apple producing country in Europe (Agreste 2019). We specifically assessed the response of bird assemblages to the implementation of the single-row exclusion net (Sévérac and Romet, 2008) in organic apple orchards. This exclusion device is one of the most widely used and effective exclusion systems against the codling moth (*Cydia pomonella*, Tortricidae), a major insect pest of pome fruit worldwide, with about 350 ha in Italy and 2,000 ha in Southern France (Alaphilippe et al. 2016; Sauphanor et al. 2012). In Southeastern France, such netting systems facilitate fruit growers' conversion to organic farming (e.g., from 2,976 ha in 2012 to 5,309 ha in



Fig. 1 Organic apple orchard covered with single-row exclusion nets in southeastern France (photograph by Jean-Charles Bouvier, INRAE).

2020 in the study area; source Agence Bio, <https://www.agencebio.org/>). We used an approach combining observations of bird assemblages in apple orchards, including their associated hedgerows, and assessments of landscape features surrounding each orchard within a 1 km² buffer. The apple orchards were exposed to three management strategies, IPM, organic without single-row exclusion net, and organic with single-row exclusion net farming.

This approach aimed to identify critical drivers of bird abundance and species richness among diverse components of orchards and their surroundings. We specifically investigated if *C. pomonella* single-row exclusion nets reduced abundance and species richness in bird assemblages in organic orchards and the extent of this reduction compared to IPM farming. We further questioned whether some bird species would be particularly affected, assuming that the abundance of those species that forage in trees would experience a more significant reduction.

2 Methods

2.1 Study orchards

The study was located in southeastern France between Bollène in the north (44°16'52"N, 4°44'58"E) and Beaucaire in the south (43°48'29"N, 4°38'39"E). It is a low altitude area of approximately 100 km × 20 km along the southern ends of the Rhone and Durance valleys. Main crops were orchards, diverse vegetables, and vineyards. Orchards were mainly grown with apple trees and managed following IPM standards. Fieldwork was carried out in 2015 in 46 commercial apple orchards consistently exposed to a wide range of diseases (*Venturia inaequalis* and *Podosphaera leucotricha*) and insects (*C. pomonella*, *Dysaphis plantaginea*, *Eriosoma lanigerum*, *Zeuzera pyrina*). Regardless of the pest management strategy, apple crops were subjected to recurrent phytosanitary treatments from March to October; however, the pesticide types differed among strategies. Among the studied orchards, 19 were under IPM, 13 were under organic pest management (ORG), and 14 were under organic pest management and covered with *C. pomonella* single-row exclusion nets (ORGnet). The orchards were selected, as much as possible, such that the three orchard types were distributed regularly over the study area and that orchards were at least 500 m from each other. This criterion, however, was only partly possible given the difficulty of finding organic orchards covered with exclusion nets (Fig. 2). On average, IPM orchards were managed with 27.3 ± 6.3 annual treatments (see Supplementary material S1). These treatments included mineral fungicides (0.6 ± 1.3 copper and 3.6 ± 2.4 sulfur), synthetic fungicides (10.8 ± 0.7), biological (1.6 ± 0.3) and synthetic insecticides (8.8 ± 2.5), including neurotoxic broad-spectrum insecticides (6.2 ± 2.4), and

herbicides (1.9 ± 0.1) sprayed only at the base of apple trees. Pesticide use reduction in these orchards was based on a targeted timing of spraying based on advice from extension services, a moderate use of biological insecticides, and the display of pheromone-based mating disruption against *C. pomonella*. ORG orchards were not equipped with *C. pomonella* single-row exclusion nets and were managed with 30.0 ± 4.6 annual treatments (Supplementary material S1). These treatments included two mineral fungicides (10.6 ± 3.9 copper and 6.0 ± 1.8 sulfur), biological insecticides (13.2 ± 1.9) including a selective granulosis virus against *C. pomonella* (6.4 ± 1.6), and mating disruption. ORGnet orchards were provided with *C. pomonella* single-row exclusion nets and were managed with 21.8 ± 9.7 annual treatments on average (Supplementary material S1). These treatments included two mineral fungicides (7.2 ± 3.2 copper and 9.2 ± 8.5 sulfur) and biological insecticides (5.4 ± 1.1). Mating disruption was not employed. The white polyethylene *C. pomonella* single-row exclusion nets (2.2 × 5.4 mm mesh size) independently covered each tree row. They draped over the tree and were secured around the tree approximately 0.5 m above the ground and below the tree canopy. They were installed before the first *C. pomonella* ovipositions on the apple trees, which occurred from mid to late April until harvest.

ORG, ORGnet, and IPM orchards had similar structures due to their common origin, i.e., the conversion of some conventional orchards to organic or IPM management, without modification of the ancestral farm structure. Orchards had an average area of 1.25 ± 0.14 ha, a plantation density of approximately 1,500 trees/ha distributed throughout an average of 16.8 ± 1.6 rows. Their inter-rows were all grown with grass to facilitate the passage of agricultural machinery and prevent soil compaction and erosion. All but two orchards were bordered by single-row hedgerows (mainly polar or cypress, sometimes complemented by bushy vegetation) for protection against the prevailing north wind. The number of hedgerows did not differ among management strategies (IPM = 2.26 ± 0.24, ORG = 2.31 ± 0.27, ORGnet = 2.86 ± 0.27, glm with Poisson distribution: $P = 0.54$).

2.2 Bird data

Birds were recorded in each orchard using the observation transect method. Transects were performed in the morning for 5 h after sunrise during birds' dawn peak activity on days without rain or wind (Bibby et al. 2000; Bouvier et al. 2020). We identified and counted birds within orchards and their surrounding hedgerows by walking regularly on the periphery and then on the middle row of each orchard. We recorded all birds heard and seen except flyovers with the assistance of binoculars (Leica 10 × 42 BN). Because the orchards had a small area and an elongated shape, all recorded birds were

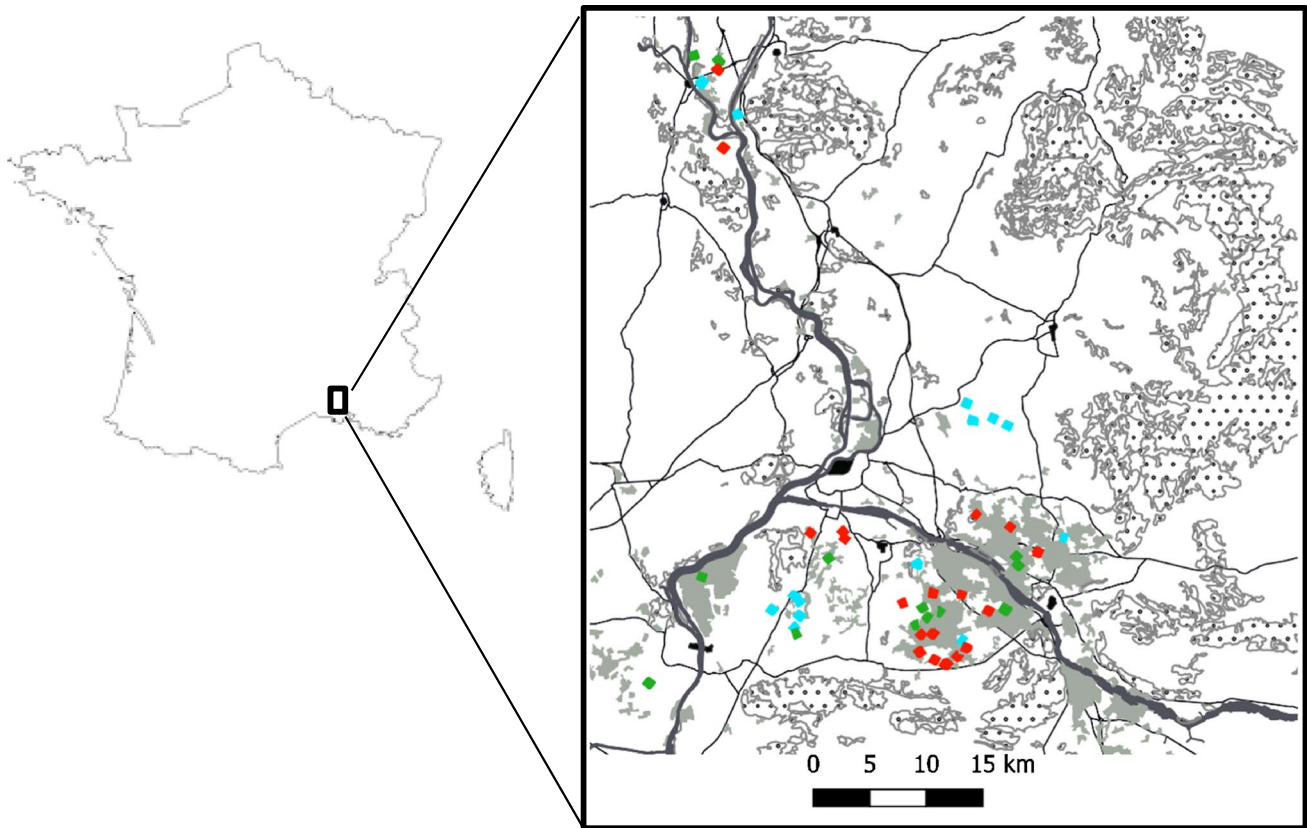


Fig. 2 Map of the study area. Colored dots represent the locations of the 46 study orchards: in red, integrated pest management orchards (IPM); in green, organic orchards without nets (ORG); in blue, organic orchards with nets (ORGnet). Orchards are represented

as grey areas and forests as dotted areas. These land covers were retrieved from CORINE Land Cover 2012 (<https://www.statistiques.developpement-durable.gouv.fr/corine-land-cover-0>) as an illustration. More detailed mapping was used for the analyses (see text).

within a 50 m distance from the observer. The length of the transects varied among the orchards with a mean \pm standard error (SE) of 645 ± 30 m. This value was strongly correlated with the orchard area (Spearman $r = 0.76$, $P = 8.9 \times 10^{-10}$). All orchards were surveyed twice, in mid-April and at the end of May, to cover the whole breeding period. Indeed, sedentary species that inhabit the area throughout the year breed earlier than migratory species. The counts were made after *C. pomonella* single-row exclusion nets were closed. The duration of each survey was approximately 20 min per ha. The same experienced ornithologist (JCB) performed all surveys to exclude between-observer variation and ensure that bird detectability did not vary between orchards (Bibby et al. 2000).

2.3 Landscape features description

We assessed landscape characteristics in the surrounding of each orchard within a 1 km^2 buffer zone. For this purpose, the studied orchards were mapped using a Geographic Information System (ArcGis V. 10.3). Orchards, arable crops, wooded areas, open semi-natural areas (e.g., meadows,

fallow land and low bush), and built areas within the buffer zones were manually digitalized based on aerial photographs (BD ORTHO® IGN 2014) and field surveys. All hedges were further digitalized as polygons assuming a 4-m width from field observations. From these features, we calculated the buffer zone areas covered with tree-based land covers (orchards and wooded areas) (*Land_trees*), hedges (*Land_hedge*), and open land covers (arable crops and open semi-natural areas, *Land_open*). Since *Land_trees* and *Land_open* were strongly correlated (Spearman $r = -0.77$, $P = 1.2 \times 10^{-9}$) and *Land_hedge* was less correlated with *Land_trees* (Spearman $r = 0.35$, $P = 0.02$) than *Land_open* (Spearman $r = -0.55$, $P = 6.6 \times 10^{-5}$), only *Land_hedge* and *Land_trees* were kept for further landscape description. These two landscape descriptors varied among buffer zones with a mean \pm SE of 3.6 ± 0.2 ha for *Land_hedge* and 34.2 ± 1.9 ha for *Land_trees*. The spatial structure of orchards also varied among buffer zones. The average area of individual orchards in buffers was $0.96 \pm 8 \times 10^{-2}$ ha (mean \pm SE) and was positively correlated both with the area of monitored orchards (Spearman $r = 0.42$, $P = 3.9 \times 10^{-3}$) and transect length ($r = 0.37$, $P = 1.1 \times 10^{-2}$).

2.4 Statistical analyses

Data were analyzed using the R.3.6.3 software (R Core team 2018).

2.4.1 Bird assemblages

For each bird species and orchard, the highest of the two counts was used as an abundance estimate (Chiron et al. 2014; Filippi-Codaccioni et al. 2008; Julliard and Jiguet 2002). The number of observed bird species was used as a proxy of bird species richness at the community level, and community evenness was calculated from species abundance. Moreover, low species detectability may result in underestimating species richness. We thus calculated the improved Chao1 index of species richness (Chao and Chiu 2016) using the SpadeR R package (Chao et al. 2016) for 45 out of the 46 orchards. The number of observed species was too low for calculating this index for one orchard. We further calculated the estimated community coverage to assess if some species were undetected during the surveys (SpadeR, Chao et al. 2016).

2.4.2 Effect of management strategy on bird assemblages

Factors affecting bird abundance were investigated with generalized linear models including management strategy (*Management*), the number of hedgerows (*Orch_hedge*), landscape characteristics (*Land_trees*, *Land_hedge*), and transect length (*Transect*), as independent variables (R package lme4, Bates et al. 2015). Transect length was included in all models to account for differences in sampled areas. All quantitative independent variables were scaled. Variance inflation factors were below 2 for all models, indicating low levels of multicollinearity (Zuur et al. 2010). Model residuals were inspected for dispersion using a quantile–quantile (QQ) plot of standardized residuals and for uniformity and outliers using a plot of residual versus predicted values. Associated statistical tests were also performed with the DHARMA R package (Hartig, 2019). Following analyses of residuals, a negative binomial distribution of data and a log link function were selected.

Factors affecting the number of observed species and the improved Chao1 index estimations of species richness were investigated with models including the same independent variables. Following the same analysis of residuals as above, we assumed a Poisson distribution of data (log link function) for the number of observed species and a Gaussian distribution for the square-rooted Chao1 index. Variance inflation factors were also all below 2.

Specific associations between the abundance of individual bird species and the same independent variables were assessed for frequent species (i.e., species present in at least

10 orchards). We assumed a Poisson distribution of the data (log link function) and checked the adequacy of variance inflation factors and residuals as above.

The significance of independent variables was assessed based on Chi-square likelihood-ratio tests for generalized linear models and F-tests for linear models (function Anova in car R package, Fox and Weisberg 2019). Pairwise comparisons between management strategies were carried out using post hoc Tukey tests (multcomp R package, Hothorn et al. 2008).

3 Results

3.1 Bird assemblages

3.1.1 Overview

We counted 705 birds belonging to 32 different species, that were all native species. Over the whole data set, the improved Chao1 index of species richness was very close to the total number of observed species (mean [95% confidence interval]: 32 [32, 34.38]). The coverage estimate for the entire dataset, i.e., the estimated fraction of the entire population of individuals in the community that belonged to the species represented in the sample, was 1. This is consistent with the low estimated number of undetected species.

Of these 32 species, 23 were observed in IPM orchards, 26 in ORG orchards, and 31 in ORGnet orchards (Table 1). Overall, 25 species (78% of the species) were songbirds. Fourteen of these are insectivorous, four are omnivorous, three are granivorous, and four feed on both arthropods and seeds or fruits at this time of year (Table 1). Eight of these songbird species forage almost exclusively in the trees: *Certhia brachydactyla*, *Cyanistes caeruleus*, *Dendrocopos major*, *Hippolais polyglotta*, *Oriolus oriolus*, *Parus major*, *Sylvia atricapilla*, and *Curruca melanocephala* (Table 1). The most frequent species were *P. major*, *Erithacus rubecula*, *Turdus merula*, and *Pica pica* (Table 1). Notably, six species were of conservation concern (*Falco tinnunculus*, *Serinus serinus*, *Passer montanus*, *Coracias garrulus*, *Chloris chloris*, *Carduelis carduelis*), being either threatened in France or with a declining population trend at the global level (Table 1).

3.1.2 Birds per orchard

The number of birds per orchard ranged from 2 to 30, and there were on average 15.3 ± 1.1 (mean \pm SE) birds per orchard. The number of observed species per orchard varied from 1 to 14, with an average of 7.8 ± 0.5 . The improved Chao1 estimation of species richness was higher than the number of observed species, ranging from

Table 1 Abundance of bird species in orchards in southeastern France in spring. The table provides the abundance (mean \pm standard error) of bird species and the number of orchards where they were observed in spring 2015, differentiating integrated pest management orchards (IPM), organic orchards without nets (ORG), and organic orchards covered with single-row exclusion nets (ORGnet). The

total number of orchards is provided in the rightmost column. Species in bold were analyzed individually. Gr granivores, I insectivores, O omnivores, P birds of prey; ¹bird species of conservation concern; ²birds foraging mainly in trees; ³birds foraging mainly on the ground. For each species, different letters indicate significant differences among treatments.

Orchard types		IPM		ORG		ORGnet		Total
Number of orchards		18		14		14		46
Species	Spring diet							
<i>Carduelis carduelis</i> ¹	Gr	0.58 \pm 0.31	b (4)	1.62 \pm 0.46	a (8)	0.86 \pm 0.38	ab (6)	18
<i>Certhia brachydactyla</i> ²	I	0.11 \pm 0.07	(2)	0.15 \pm 0.15	(1)	0.64 \pm 0.23	(6)	9
<i>Cettia cetti</i> ³	I	0.05 \pm 0.05	(1)	0.31 \pm 0.13	(4)	0.21 \pm 0.21	(1)	6
<i>Chloris chloris</i> ¹	Gr	0.26 \pm 0.13	(4)	0	(0)	0.50 \pm 0.25	(4)	8
<i>Coloeus monedula</i> ³	O	0	(0)	0	(0)	0.64 \pm 0.44	(2)	2
<i>Columba palumbus</i> ³	Gr	0.42 \pm 0.18	a (5)	0.85 \pm 0.32	a (7)	0.79 \pm 0.30	a (7)	19
<i>Coracias garrulus</i> ^{1,3}	I	0.11 \pm 0.11	(1)	0	(0)	0.36 \pm 0.29	(2)	3
<i>Corvus corone</i> ³	O	0.42 \pm 0.16	a (6)	0.54 \pm 0.18	a (6)	0.36 \pm 0.17	a (4)	16
<i>Curruca melanocephala</i> ²	I	0.16 \pm 0.12	b (2)	0.69 \pm 0.33	a (4)	0.43 \pm 0.17	ab (5)	11
<i>Cyanistes caeruleus</i> ²	I	0.11 \pm 0.11	(1)	0.23 \pm 0.17	(2)	0.14 \pm 0.14	(1)	4
<i>Dendrocopos major</i> ²	I	0.16 \pm 0.09	(3)	0.08 \pm 0.08	(1)	0.07 \pm 0.07	(1)	5
<i>Emberiza cirius</i> ³	Gr, I	0.37 \pm 0.16	a (5)	0.46 \pm 0.22	a (4)	0.71 \pm 0.30	a (6)	15
<i>Erithacus rubecula</i> ³	I	1.53 \pm 0.27	a (15)	1.23 \pm 0.26	a (9)	1.07 \pm 0.38	a (7)	31
<i>Falco tinnunculus</i> ^{1,3}	P	0.21 \pm 0.12	(3)	0.23 \pm 0.17	(2)	0.14 \pm 0.10	(2)	7
<i>Fringilla coelebs</i> ³	Gr, I	0	(0)	0	(0)	0.14 \pm 0.14	(1)	1
<i>Garrulus glandarius</i> ³	O	0.63 \pm 0.22	a (6)	0.92 \pm 0.47	a (5)	0.57 \pm 0.23	a (5)	16
<i>Hippolais polyglotta</i> ²	I	0	(0)	0.15 \pm 0.15	(1)	0.21 \pm 0.15	(2)	3
<i>Luscinia megarhynchos</i> ³	I	0.16 \pm 0.12	a (2)	0.54 \pm 0.31	a (4)	0.36 \pm 0.17	a (4)	10
<i>Oriolus oriolus</i> ²	I	0.05 \pm 0.05	(1)	0	(0)	0.07 \pm 0.07	(1)	2
<i>Parus major</i> ²	I	2.63 \pm 0.41	ab (15)	3.69 \pm 0.61	a (13)	2.14 \pm 0.35	b (12)	40
<i>Passer domesticus</i> ³	Gr, I	0	(0)	0.15 \pm 0.15	(1)	0	(0)	1
<i>Passer montanus</i> ^{1,3}	Gr, I	0.11 \pm 0.11	(1)	0.15 \pm 0.10	(2)	0.14 \pm 0.14	(1)	4
<i>Phoenicurus ochruros</i> ³	I	0	(0)	0	(0)	0.21 \pm 0.15	(2)	2
<i>Pica pica</i> ³	O	0.42 \pm 0.14	b (7)	1.23 \pm 0.30	a (9)	1.93 \pm 0.41	a (11)	27
<i>Picus viridis</i> ³	I	0.26 \pm 0.13	a (4)	0.31 \pm 0.13	a (4)	0.50 \pm 0.17	a (6)	14
<i>Serinus serinus</i> ^{1,3}	Gr	0.42 \pm 0.23	b (4)	1.38 \pm 0.42	a (8)	1.79 \pm 0.60	ab (8)	20
<i>Streptopelia decaocto</i> ³	Gr	0.16 \pm 0.12	(2)	0.23 \pm 0.17	(2)	0.21 \pm 0.11	(3)	7
<i>Streptopelia turtur</i> ³	Gr	0.05 \pm 0.05	(1)	0	(0)	0.07 \pm 0.07	(1)	2
<i>Sturnus vulgaris</i> ³	I	0	(0)	0.54 \pm 0.33	(3)	0.43 \pm 0.20	(4)	7
<i>Sylvia atricapilla</i> ²	I	0.42 \pm 0.22	b (4)	2 \pm 0.59	a (8)	1.29 \pm 0.42	a (7)	20
<i>Troglodytes troglodytes</i> ³	I	0	(0)	0.08 \pm 0.08	(1)	0.07 \pm 0.07	(1)	2
<i>Turdus merula</i> ³	I	0.79 \pm 0.21	a (10)	1.38 \pm 0.47	a (9)	1.14 \pm 0.36	a (8)	27

1 to 31.12 with an average of 12.02 ± 1.06 . As expected, bird abundance and the number of observed species per orchard were positively correlated (Spearman $r = 0.91$, $P < 2.2 \times 10^{-16}$), as were the number of observed species and estimated species richness (Spearman $r = 0.92$, $P < 2.2 \times 10^{-16}$).

The evenness of the observed bird assemblages varied little, ranging from 0.83 to 1 with an average of 0.93 ± 0.005 (mean \pm SE). It was not correlated with bird abundance

(Spearman $r = -0.22$, $P = 0.13$) nor with the number of observed species (Spearman $r = -0.049$, $P = 0.75$).

3.2 Factors affecting bird assemblages in orchards

3.2.1 Bird abundance per orchard

Bird abundance per orchard depended on the pest management strategy (Table 2). It was lower in IPM orchards

Table 2 Analysis of the variation in bird abundance, number of observed species and improved Chao1 estimate of species richness in orchards as a function of orchard management (Management), number of hedgerows bordering the orchard (*Orch_hedge*), landscape area

with woods and orchards (*Land_trees*), landscape area with hedgerows (*Land_hedge*), and transect length (*Transect*). df Degrees of freedom, LR Chisq likelihood ratio Chi-square statistic, Sum Sq sum of squares. *P* values < 0.05 are in bold.

	Abundance			Number of species			i-Chao1 estimate			
	df	LR Chisq	<i>P</i> value	df	LR Chisq	<i>P</i> value	df	Sum Sq	<i>F</i>	<i>P</i> value
Management	2	18.45	9.84×10^{-5}	2	13.87	9.7×10^{-4}	2	3.25	5.385	8.7×10^{-3}
<i>Orch_hedge</i>	1	5.74	0.017	1	10.42	1.2×10^{-3}	1	2.25	7.463	9.5×10^{-3}
<i>Land_trees</i>	1	0.31	0.577	1	0.45	0.502	1	0.30	0.987	0.327
<i>Land_hedge</i>	1	0.22	0.639	1	0.07	0.790	1	5.6×10^{-3}	0.019	0.892
<i>Transect</i>	1	0.80	0.371	1	5.00	0.025	1	2.05	6.790	0.013
Residuals							38	11.46		

(mean \pm SE: 10.58 ± 1.08) than in organic orchards with *C. pomonella* single-row exclusion nets (18.21 ± 1.74 , $P = 3.7 \times 10^{-4}$) or without (19.15 ± 2.24 , $P < 1 \times 10^{-4}$). Abundance did not differ significantly between the two organic management strategies ($P = 0.95$) (Fig. 3a). Interestingly, we found that bird abundance increased with the number of hedgerows surrounding the orchards ($P = 1.7 \times 10^{-2}$) (Tables 2 and 3, Fig. 3). Bird abundance did not depend on transect length or the two landscape variables (i.e., *Land_hedge* and *Land_trees*) (Tables 2 and 3).

3.2.2 Bird species richness per orchard

As with abundance, the number of observed species depended on management strategy and was higher in the two types of organic orchards (mean \pm SE: 9.08 ± 1.02 and 9.35 ± 0.90 for ORG and ORGnet orchards respectively) than in the IPM orchards (5.74 ± 0.59 , $P = 1.5 \times 10^{-3}$

and $P = 1.7 \times 10^{-2}$ for differences with ORG and ORGnet orchards, respectively) (Tables 2 and 3, Fig. 3b). The number of observed species also increased with the number of hedgerows surrounding orchards (Tables 2 and 3, Fig. 4). Surprisingly, it decreased with increasing transect length (Tables 2 and 3). It did not depend on the two landscape variables.

The results based on the improved Chao1 index estimations of species richness were similar to those of the number of observed species (Tables 2 and 3).

3.2.3 Abundance of frequent species

Fourteen out of the 32 species were present in more than 10 orchards (Table 1). Among these, six exhibited different abundances depending on orchard management (*C. carduelis*, *P. major*, *P. pica*, *S. serinus*, *S. atricapilla*, *C. melanocephala*) (Table 4). Except for *P. major*, they all showed a

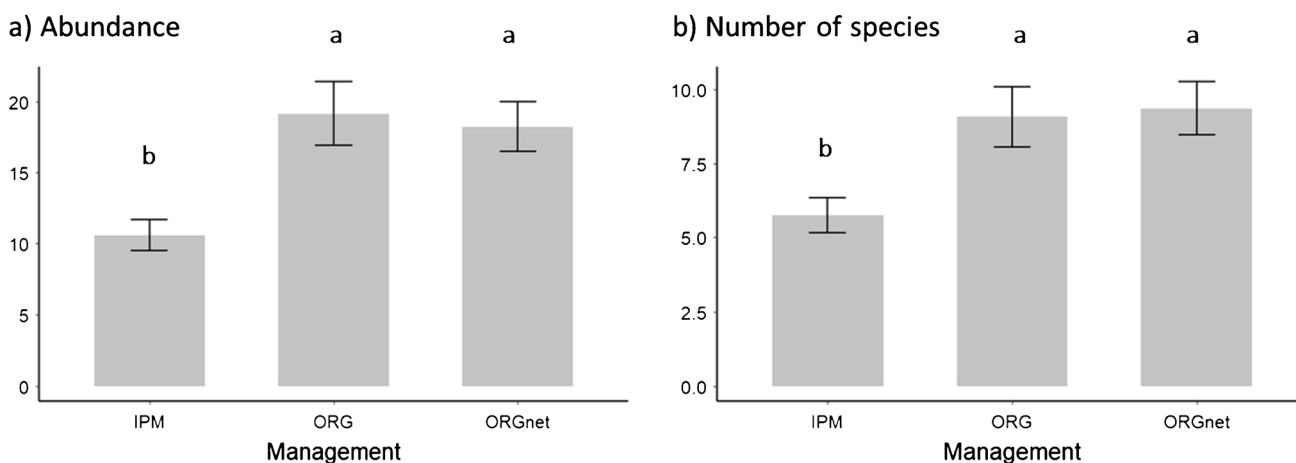


Fig. 3 Bird abundance (a) and the number of observed bird species (b) per orchard as a function of the orchard management strategy. IPM, integrated pest management; ORG, organic; ORGnet, organic with *C. pomonella* single-row exclusion nets. Error bars represent

standard errors. Mean values with the same letter are not significantly different ($P < 0.05$) based on pairwise comparisons using post hoc Tukey tests (see Material and Methods).

Table 3 Parameter estimates (\pm standard error—SE) in models analyzing the variation in bird abundance, number of observed species and improved Chao1 estimate of species richness. Independent variables are Management (Manag.), number of hedgerows bordering the orchard (*Orch_hedge*), landscape area with woods and orchards

	Abundance			Number of species			i-Chao1 estimate		
	Estimate \pm SE	z value	P value	Estimate \pm SE	z value	P value	Estimate \pm SE	t value	P value
(Intercept)	2.522 \pm 0.218	11.587	$< 2 \times 10^{-16}$	1.739 \pm 0.201	8.630	$< 2 \times 10^{-16}$	1.952 \pm 0.312	6.257	3×10^{-7}
Manag. ORG	0.049 \pm 0.166	0.297	0.766	0.026 \pm 0.148	0.174	0.862	-0.038 \pm 0.241	-0.159	0.874
Manag. IPM	-0.554 \pm 0.172	-3.214	1.3×10^{-3}	-0.443 \pm 0.161	-2.746	6.0×10^{-3}	-0.620 \pm 0.234	-2.654	0.012
<i>Orch_hedge</i>	0.152 \pm 0.061	2.469	0.014	0.179 \pm 0.056	3.210	1.3×10^{-3}	0.245 \pm 0.090	2.732	9.5×10^{-3}
<i>Land_trees</i>	0.039 \pm 0.068	0.574	0.566	0.042 \pm 0.062	0.672	0.502	0.093 \pm 0.094	0.993	0.327
<i>Land_hedge</i>	0.031 \pm 0.065	0.471	0.637	-0.016 \pm 0.059	-0.265	0.791	0.013 \pm 0.093	0.137	0.892
<i>Transect</i>	-0.053 \pm 0.062	-0.859	0.390	-0.129 \pm 0.058	-2.222	0.026	-0.225 \pm 0.086	-2.606	0.013

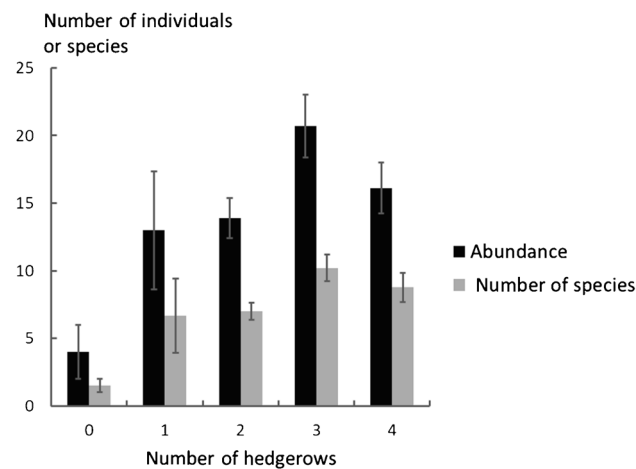


Fig. 4 Bird abundance and number of observed species per orchard as a function of the number of hedgerows surrounding the orchard. Error bars represent standard errors. The two variables increased significantly with the number of hedgerows (see Table 2 for statistical analysis).

similar pattern with the lowest abundance in IPM orchards and the highest abundance in ORG orchards. Abundance in the ORGnet orchards was similar to that in ORG orchards only (*P. pica* and *S. atricapilla*) or similar to both that in ORG and IPM orchards (*C. carduelis*, *C. melanocephala*, and *S. serinus*). For *P. major*, we found a distinct pattern of lowest abundance in ORGnet orchards and highest in ORG orchards; IPM orchards were intermediate (Table 1).

Local or landscape elements also affected some bird species (Table 4, Supplementary material S2). The abundance of five species (*E. rubecula*, *Luscinia megarhynchos*, *S. serinus*, *S. atricapilla*, *C. melanocephala*) increased with the number of hedgerows surrounding the orchards,

(*Land_trees*), landscape area with hedgerows (*Land_hedge*), and transect length (*Transect*). Estimates are provided for the ORG (organic without nets) and IPM (integrated pest management) management strategies. ORGnet is the reference management strategy. Estimates that significantly differ from 0 (P value < 0.05) are in bold.

and the abundance of *C. carduelis* and *T. merula* increased with the landscape area covered with hedgerows. *Garrulus glandarius* abundance increased with the area covered with tree-based land covers (orchards and forests). Lastly, the abundance of three species varied with transect length increasing for *S. serinus* and decreasing for *L. megarhynchos* and *S. atricapilla*.

4 Discussion

4.1 Diversity of bird assemblages in southeastern France apple orchards

Apple orchards are both intensively managed agroecosystems and important breeding sites for birds worldwide (southern Europe (Bouvier et al. 2011; Brambilla et al. 2015; Genghini et al. 2006); central Europe (Chmielewski 2019); Asia (Katayama 2016); USA (Mangan et al. 2017; Rime et al. 2020)). We recorded in this study a total of 32 bird species, which corresponds to 10% of the total avifauna breeding in France (Issa and Muller 2015) and noticeably supports the use of apple orchards by numerous breeding birds in this area.

Among these 32 species, six are currently listed on the Red List of Threatened Species in France (IUCN France et al. 2016), and 26 are common species that usually represent valuable indicators for early detection of changes in population trends (Gregory et al. 2005; O'Brien et al. 2011). Furthermore, bird assemblages involved a wide range of feeding guilds, including insectivores (53%), omnivores and mixed-diet (seeds and arthropods) species (25%), and granivores (19%). The diversity and abundance levels of the bird assemblage were similar to previous assessments in the same geographical area before the *C. pomonella* single-row exclusion nets were installed (Bouvier et al. 2011). These results

Table 4 Analysis of the variation in individual bird abundance as a function of orchard management (Management), number of hedgerows bordering the orchard (*Orch_hedge*), landscape area with woods and orchards (*Land_trees*), landscape area with hedgerows (*Land_**hedge*), and transect length (*Transect*). df degrees of freedom, LR Chisq likelihood ratio Chi-square statistic; ^abird species of conservation concern; ^bbirds mainly foraging in trees. *P* values < 0.05 are in bold. Effect estimates are provided in Table S2.

df	Management		<i>Orch_hedge</i>		<i>Land_trees</i>		<i>Land_hedge</i>		<i>Transect</i>	
	LR Chisq	<i>P</i> value	LR Chisq	<i>P</i> value	LR Chisq	<i>P</i> value	LR Chisq	<i>P</i> value	LR Chisq	<i>P</i> value
<i>Carduelis carduelis</i> ^a	9.235	9.9 × 10⁻³	0.448	0.503	0.503	0.478	6.481	0.011	3.683	0.055
<i>Columba palumbus</i>	2.597	0.273	0.00857	0.9262	1.456	0.228	0.868	0.352	1.8 × 10 ⁻³	0.966
<i>Corvus corone</i>	1.373	0.503	0.012	0.912	2.239	0.135	0.075	0.784	0.375	0.540
<i>Curruca melanocephala</i> ^b	7.357	0.025	8.297	4.0 × 10⁻³	0.808	0.369	0.630	0.427	0.697	0.404
<i>Emberiza cirrus</i>	1.048	0.592	0.057	0.811	2.899	0.089	3.484	0.062	0.433	0.511
<i>Erithacus rubecula</i>	0.671	0.715	4.008	0.045	< 10 ⁻⁴	0.997	1.695	0.193	0.718	0.397
<i>Garrulus glandarius</i>	1.324	0.516	< 10 ⁻⁴	0.999	3.967	0.046	0.509	0.475	0.393	0.531
<i>Luscinia megarhynchos</i>	4.764	0.092	6.225	0.013	0.481	0.488	1.550	0.213	12.346	4.4 × 10⁻⁴
<i>Parus major</i> ^b	6.668	0.036	0.025	0.874	0.042	0.837	1.235	0.266	2.528	0.112
<i>Pica pica</i>	10.199	6.1 × 10⁻³	1.359	0.244	0.0038	0.951	0.233	0.630	0.006	0.938
<i>Picus viridis</i>	1.129	0.569	0.044	0.835	0.255	0.614	0.061	0.805	1.283	0.257
<i>Serinus serinus</i> ^a	8.619	0.013	7.746	5.4 × 10⁻³	0.0015	0.969	0.017	0.896	4.826	0.028
<i>Sylvia atricapilla</i> ^b	19.577	6.0 × 10⁻⁵	5.739	0.017	0.187	0.666	2.721	0.099	7.361	6.7 × 10⁻³
<i>Turdus merula</i>	4.025	0.134	0.559	0.455	0.011	0.917	4.374	0.037	2.009	0.156

are also consistent with the structure of bird assemblages described in the few studies carried out in apple orchards in other European countries (Genghini et al. 2006; Wiacek and Polak 2008). Modern low-stem orchards are a simplified habitat compared to traditional orchards, but, in the study area, they retain some structural complexity: rows of the tree crop alternate with diverse herbaceous inter-row vegetation, and there were in all but two orchards; one or more bordering windbreak hedgerows comprised of high stem trees and bushy vegetation (Bouvier et al. 2020). This complexity, together with the temporal stability of the woody vegetation, may explain the ability of orchards to host birds with various ecological requirements (Simon et al. 2010). In this context, disentangling how the usual and the new pest management strategies in apple orchards may interfere with bird communities addresses significant issues about the compatibility of bird conservation and agricultural land use.

4.2 No effects of single-row pest exclusion nets on bird assemblages and importance of hedgerows

One central finding of this study is that the total abundance and estimated and observed species richness of breeding birds were not affected by *C. pomonella* single-row exclusion nets in organic orchards. This observation suggests that the exclusion of potential nesting and foraging sites in apple tree canopies had no significant effect on birds of apple orchards at the community level and we also found that

individual species abundance was similar between organic orchards with and without single-row exclusion nets, except in the very particular case of *P. major*. However, this effect on *P. major* is not relevant for this study due to the implementation of nest boxes for this species in 14 of the 19 IPM orchards and five of the 13 organic orchards without exclusion nets for an ongoing ecotoxicological study.

The absence of exclusion net-induced effects on the bird communities was unexpected. In the spring, birds may frequent apple orchards to search for food, in the herbaceous layer, on the ground, or, especially for insects, in the tree foliage (Rime et al. 2020). They may also use apple trees as a support for their nests. However, such nests rarely occur in the study area because of human interventions throughout the fruit production season (e.g., recurrent spraying and thinning). Our results may indicate that birds that forage on the ground, which represented 69% of the observed species (Table 1), were not deterred from their food source, even when single-row exclusion nets covered the trees. Indeed, a very particular feature of the studied single-row exclusion nets was that they allow birds to enter the orchard and access inter-rows from the sides and above. This netting system is distinct from anti-hail nets with mesh sidewalls that encase the whole orchard, precluding bird access to the inter-rows.

Moreover, grassed inter-rows were mown in the spring to facilitate access to trees for manual fruit thinning. Low inter-row vegetation provides an accessible food source for ground-dwelling birds (Rime et al. 2020). The lack of effect of the single-row exclusion nets was less expected

for species such as *T. merula*, *G. glandarius*, *P. pica*, *Picus viridis*, and *C. carduelis* that we occasionally observed nesting in apple trees (pers. obs.) and for the eight species known to forage in the tree foliage (Table 1). These bird species are frequently seen in apple trees (pers. obs.), and birds regularly attack artificial sentinel caterpillars in orchards (Martínez-Sastre et al., 2020; Rey Benayas et al., 2017). It is thus likely that birds built their nests and foraged in the hedgerows at the edge of the orchards when apple trees were made unavailable by single-row exclusion nets.

Such a hypothesis likely concurs with a second salient feature of our analysis since we showed a significantly positive effect of the number of hedgerows around orchards on both total bird abundance and species richness. Furthermore, the abundance of five species increased with the number of local hedgerows, and the abundance of two species increased with the area of hedgerows in the landscape. Of these species, *S. atricapilla* and *C. melanocephala* are known to feed in the foliage of trees and shrubs; two (*S. serinus* and *C. carduelis*) are known to nest in evergreen trees such as cypresses that make up the majority of hedgerows in the study area; three others nest in bushy vegetation (*E. rubecula*, *L. megarhynchos*, *T. merula*). Numerous studies have shown that the presence of hedgerows positively influences bird abundance and species richness in agricultural landscapes, particularly in grasslands and wheat and alfalfa fields during the breeding season and winter (Batory et al. 2010; Hinsley and Bellamy 2000; Kross et al. 2016). In addition, semi-natural elements such as hedgerows and bushy vegetation were also found to be important for birds in apple orchards at a local scale in the winter (Bouvier et al. 2020) and at a landscape scale during the breeding season (Assandri et al. 2017; Morelli et al. 2014).

The unexpected result that bird species richness (approximated by the number of observed species and by the Chao1 estimate of species richness) decreased with increasing transect length may also indirectly relate to the importance of hedgerows, and more generally to landscape heterogeneity, for birds. Transect length was indeed positively correlated with both the area of the surveyed orchards and the average area of orchards within the 1 km² landscape. Thus, this negative effect may be an indirect indication that bird species richness would be higher in landscapes with higher configurational complexity (i.e., smaller fields, more extensive edge lengths), as observed in arable crops (e.g., Fahrig et al. 2015; Sirami et al. 2019). However, this possibility requires further investigation as a reduced plot area may also be related to a higher heterogeneity of crops or crop management practices and more diversity in hedgerow management in the study area. In any case, our results provide further evidence that the essential role of semi-natural elements

for avian biodiversity is not exclusive to open landscapes and that the maintenance of vegetally diversified hedgerows is essential in agricultural landscapes mainly grown with orchards.

4.3 Negative effects of pesticide use on bird assemblages in apple orchards

By comparing the responses of bird assemblages to different pest management strategies in apple orchards, we confirmed the negative effect of synthetic pesticides on both bird abundance and species richness. These findings are consistent with other studies in apple orchards worldwide. Organic farming is associated with more diversified and abundant bird communities than farming that relies predominantly on synthetic pesticide use (Barbaro et al. 2021; Brambilla et al. 2015; Chmielewski 2019; Genghini et al. 2006; Katayama 2016; Wiacek and Polak 2008). We found that bird abundance and the observed number of species were about 1.5 times greater in organic than in IPM orchards (Fig. 3a and b) and similar trends were observed for five out of 13 individual species (Table 1). The influence of agricultural management strategies on bird populations has been widely investigated in annual crops (e.g., Navedo et al. 2015; Ponce et al. 2014). However, it has been less documented in perennial crops such as fruit orchards, although this question has recently gained interest (see e.g., Bouvier et al. 2011; Brambilla et al. 2015; Katayama 2016; Rey 2011; Rime et al. 2020). There is a continuous need to fill this gap because both management strategies and habitat structures strongly differ between annual and perennial crops, influencing bird responses to agricultural practices (Bruggisser et al. 2010). In both annual and perennial crops, negative associations between bird communities and pesticide use generally result from the direct (toxicity on birds) or indirect (food limitation) effects of pesticides (Bouvier et al. 2005; Genghini et al. 2006; Parsons et al. 2010). In our study system, synthetic pesticides sprayed in IPM orchards included pyrethroids, carbamates, neonicotinoids, and organophosphorus neurotoxic insecticides (Supplementary material S1). These insecticides are known to reduce bird insect prey (Mueller-Beilschmidt 1990) and affect bird nervous central system and behavior (Li et al. 2020; Smith et al. 1986), which possibly leads to population decline (Genghini et al. 2002; Walker 2003). Insecticides were also sprayed in organic orchards, but they might have affected food availability to a lesser extent due to their narrower spectrum than those sprayed in IPM. There is overall evidence that organic farming is far more beneficial to arthropod diversity and abundance than conventional farming (Bengtsson et al. 2005; Stein-Bachinger et al. 2021), including apple orchards (Dib et al. 2016).

5 Conclusion

This study provides the first assessment of the impact of an increasingly used pest exclusion technique on birds breeding in pome fruit orchards, one of the most extensive perennial crops worldwide. Single-row pest exclusion nets are a management option aimed at reducing pesticide use in such crops. We showed that restricting access to trees only but leaving grassed areas and hedgerows free did not alter bird abundance and species richness. This observation contrasts with full block netting systems spread over the whole orchard, preventing access to the diverse orchard components that birds require for nesting and feeding. Our results indicate that birds may find alternative resources in the hedgerow vegetation when excluded from apple tree canopies. In this sense, hedgerows are beneficial and recommended in intensively managed agroecosystems. Provided that pome fruit growers are continuously encouraged to integrate hedgerows as a critical component of their production systems, single-row netting systems represent a viable alternative to chemical pest control, thereby reducing the environmental impacts of crop management strategies.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s13593-021-00743-7>.

Acknowledgements We thank the technical advisors for their cooperation, particularly the GRCEA de Basse Durance team and Guilhem Séverac of the Chambre d'Agriculture de Vaucluse, and the orchard owners for access to the orchards. We also thank the two anonymous reviewers for their helpful comments.

Authors' contributions All authors contributed to the study's conception and design. Jean-Charles Bouvier contributed to data collection, literature review, writing, and funding acquisition. Claire Lavigne contributed to the data analysis, literature review, and writing. Thomas Boivin contributed to the literature review and writing.

Funding Partial financial support was received from the Scientific Direction Environment of INRAE and the Research Division Plant Health and Environment (Exclu project).

Availability of data and material The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interests The authors declare no competing interests.

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