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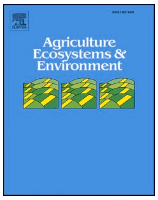

Crop-specific effectiveness of birds as agents of pest control

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ABSTRACT

Ecosystem services provided by the natural enemies of agricultural pests can increase crop yield in low intensity agricultural systems. However, these services are highly variable, and trade-offs may exist between harmful and beneficial species. An increasing proportion of New England farms have adopted farming practices that retain extensive native vegetation, and prior research has shown these practices support native bird populations. To determine the pest control services provided by birds on low-intensity New England farms, we compared pest populations and leaf damage on crops where birds were excluded to those where they were not. We found that pest abundance was higher on brassica and cucurbit crops within exclosures than on control plants without exclosures, suggesting the presence of birds reduced pest numbers on these crops. In contrast, pest numbers were lower on solanaceous crops within exclosures, suggesting birds may be consuming other natural enemies of pests on these crops. Leaf damage was also lower where birds were present in all three crop types, though not significantly so in brassica crops. Our results show that growers in can improve natural biological control of brassica and cucurbit crop pests by enhancing bird communities near these crops, while effects may be less predictable in solanaceous crops.

1. Introduction

Currently 40% of the world's land area is used for agricultural production (McLaughlin, 2011), and the intensification of farming practices on those lands has been one of the major contributors to global wildlife declines (Tscharntke et al., 2005). High intensity farming practices generally include high chemical inputs (e.g., pesticides and herbicides), large farm size, low crop diversity, and greater mechanization (Donald et al., 2001; Sánchez-Bayo and Wyckhuys, 2019; Stanton et al., 2018; Tscharntke et al., 2005). These high intensity farming practices have been show to lead to sharp wildlife declines (Sánchez-Bayo and Wyckhuys, 2019; Stanton et al., 2018). By contrast, when agricultural landscapes are less intensively managed, native wildlife populations can persist (Tscharntke et al., 2005).

The presence of native wildlife in turn has been shown to promote farm productivity through ecosystem services such as pollination and pest control (Classen et al., 2014; Garibaldi et al., 2018; Gonthier et al., 2019; Johnson et al., 2010; Kremen et al., 2007; Lundin et al., 2013; Martínez-Salinas et al., 2022; Sutter and Albrecht, 2016; Tscharntke et al., 2005). Referred to by many names (e.g., ecological intensification, agroecology, diversified farming systems), managing farmlands to accentuate ecosystem services allows growers to maintain yields while supporting wildlife populations (Bommarco et al., 2013; Kremen, 2015; Kremen et al., 2012; Tittonell, 2014). In tropical cacao and coffee, for example, intensively managed plantations support less biodiversity than do lower intensity agroforestry designs (De Beenhouwer et al., 2013). Ecosystem services in coffee and cacao agroforestry are also significantly higher than on more intensive systems (Chain-Guadarrama et al., 2019; De Beenhouwer et al., 2013; Meylan et al., 2017). A 2019 review found that a variety of low intensity practices (e.g., reduced tillage, intercropping, organic production), resulted in improved biodiversity and ecosystem services, and though many resulted in short-term yield losses, the long-term effects on yield and farm profitability were generally positive (Rosa-Schleich et al., 2019). Based on a relatively conservative estimate of ecosystem service benefits from protected natural areas, Garibaldi et al. (2020) showed that 13% of a farming landscape can be taken out of production without reducing total productivity.

In many low intensity farming landscapes birds have been identified as both important agents of insect pest control (Boesing et al., 2017; Chain-Guadarrama et al., 2019; De Beenhouwer et al., 2013; Díaz-Siefer et al., 2021; Johnson et al., 2010; Karp et al., 2014, 2013; Kellermann et al., 2008; Kirk et al., 1996; Lindell et al., 2018; Maas et al., 2019,

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2016; Martínez-Salinas et al., 2016; Milligan et al., 2016; Perfecto et al., 2004), as well as disruptors of other ecosystem services (Garcia et al., 2021; Martin et al., 2013), and direct pests of crops (Anderson et al., 2013; Borkhataria et al., 2012; Pejchar et al., 2018). While a number of studies have demonstrated the benefits of farmland habitat conservation for bird populations (Brofsky, 2020; Heath et al., 2017; Hiron et al., 2015; Muñoz-Sáez et al., 2017; Santana et al., 2017), and their positive impacts on tropical coffee and cacao production has been relatively well documented (Chain-Guadarrama et al., 2019; Classen et al., 2014; De Beenhouwer et al., 2013; Martínez-Salinas et al., 2022; Meylan et al., 2017), their impacts in temperate agriculture are less understood (Boesing et al., 2017; Lindell et al., 2018). For example, several studies have documented that more abundant and diverse bird populations lead to improved pest reductions (Gonthier et al., 2019; Jedlicka et al., 2011), while even more have documented pest reduction by existing bird populations without linking it to abundance and diversity (Garfinkel et al., 2020; Hooks et al., 2003; Linden et al., 2019; Mols and Visser, 2007; Ndang'ang'a et al., 2013; Tremblay et al., 2001). In contrast, other studies have either shown that birds indirectly increase pest populations by suppressing pest natural enemies (Garfinkel et al., 2020; Martin et al., 2013) or have failed to detect any statistically significant effect of birds on pests (Garfinkel and Johnson, 2015; Lemessa et al., 2015).

In the northeastern USA consumers, growers, and retailers support the use of alternative pest control methods to pesticides when economically viable (Anderson, 1993; Anderson et al., 1996; Hollingsworth et al., 1993; Martinez et al., 2010). Farms in this region are becoming smaller, in contrast to national trends, and are increasingly implementing practices such as Integrated Pest Management (IPM) techniques to control pests with fewer pesticides (USDA, 2017). These adoptions, particularly reductions in pesticides, have the potential to benefit native wildlife, and recent work has shown that low intensity farms can harbor rich bird communities (Brofsky, 2020). The presence of avian insectivores present on these farms thus raises the possibility that agroecological practices that promote avian habitat could result in additional pest control services (Garfinkel et al., 2020) as they do in other systems. Therefore, in our study we explore the positive and negative roles of birds in these low intensity diversified farms to determine the impact of birds in terms of regulating pest abundances and preventing crop damage by deploying exclosures around selected crop species on farms. This information will allow stakeholders to make a more informed decision about whether and how to implement habitat conservation to enhance pest control services by native birds.

2. Methods

2.1. Study area

Field experiments were conducted on nine diversified farms in Franklin and Hampshire County, Massachusetts, USA. These counties account for 26% of Massachusetts's cropland and 24% of the value of the state's agricultural production (USDA, 2017). Average farm size was 13.7 ha (SD 15.6, range 0.4 – 48.6). Experiments were conducted in 18 fields during the summers of 2019 and 2020. We selected low intensity small farms that engaged in direct-to-consumer sales (e.g., farm stands, farmer's market, or Community Supported Agriculture [CSA]) and produced a variety of fruit and vegetable crops. Agricultural practices varied across farms, but all included some combination of low intensity farming practices, (e.g., organic management, reduced tillage, cover cropping, reduced pesticide use) that have been associated with greater biodiversity and ecosystem services (Rosa-Schleich et al., 2019). A map showing the locations of each farm in western Massachusetts is presented in Appendix A (Fig. 1A). Typical of small farms in the region, the agricultural fields we studied are integrated into a landscape featuring forest, additional farmland, human development, and water bodies. Although farms such as these encompass habitats that support birds, such as fallow areas, hedgerows and scattered trees (Brofsky, 2022), the practice of retaining these natural vegetation features on these low intensity farms is incidental and not directed intentionally at bird conservation.

2.2. Field Methods

Birds were excluded from crops during the growing season to determine their role in insect pest suppression due to predation. Exclosures were constructed to eliminate bird predation on crops by suspending 25.4 mm synthetic mesh bird netting over either a PVC frame or four metal garden stakes (dimensions: 1–1.5 m width × 1–3 m length × 1–1.5 m height). Mesh size was selected to exclude all bird species while still allowing access by insects. Similar sized mesh has been used to exclude birds and not insects in previous research (Bollinger and Caslick, 1984; Garfinkel et al., 2020; Karp et al., 2013; Martínez-Salinas et al., 2022; Perfecto et al., 2004), and the largest of the crop pests we were interested in (see below for a complete list) had a wingspan of ~4 cm wingspan and were observed entering and exiting exclosures in the field. Pest numbers and leaf damage within each exclosures (no bird activity) were compared to those within a control plot (where bird activity was allowed). Exclosures encompassed between 3 and 24 plants, depending on crop type and row configuration, and only included a single crop species. Control plots were situated immediately adjacent to exclosure plots, within the same row or a neighboring row, and encompassed an equal number of plants as within the paired exclosure. Exclosures were deployed as near as possible to the date plants sprouted or were transplanted to the field and left for 2–12 weeks, depending on crop type and harvest schedules (which was accounted for in our analyses). The number of exclosures established in each field was dependent on crop availability. Farms involved in this study rotated crops regularly across multiple fields and often had a given crop type in only one location at a time. Surveys of pest abundance and damage were conducted approximately every two weeks, from initial exclosure installation until exclosure removal. Surveys were conducted immediately before initial exclosure installation, but these surveys were not included in analyses. No surveys were conducted after growers had fully harvested the crop.

Surveys were conducted on three crop types: the genus *Brassica* (crop variants: collards, kale, cabbage, Chinese cabbage, broccoli, cauliflower, kohlrabi, Brussels sprouts), the family Cucurbitaceae (crop variants: summer squash, winter squash, melons, cucumbers), and the species *Solanum melongena* (crop variant: eggplant). Except where otherwise noted, pest surveys included full-plant searches for specific pest species on all plants in an exclosure plot and its paired control plot. On brassica plants, the total number of individuals of *Pieris rapae* (imported cabbageworm, ICW), *Plutella xylostella* (diamondback moth, DBM), and *Trichoplusia ni* (cabbage looper, CL) were counted separately. On Cucurbitaceae, the number of *Acalymma vittatum* (striped cucumber beetle, StCB) adults, and *Anasa tristis* (squash bug, SqB) adults (Sqb_A), nymphs (SqB_N), and egg masses (SqB_E) were counted separately. In eggplant, the total number of *Leptinotarsa decemlineata* (Colorado Potato Beetle, CPB) adults (CPB_A), larvae (CPB_L), and egg masses (CPB_E) on the entire plant were counted, along with the number of aphids (superfamily Aphidoidea, Aph) on three arbitrarily selected leaves. Leaf damage was estimated using a protocol similar to Schwenk et al. (2010) on a maximum of three arbitrarily selected leaves per plant within a plot, distributed evenly across plants. A transparent square grid of points 2 cm apart was superimposed over each leaf, and at each point within the outline of the leaf we noted whether the leaf was damaged or undamaged, resulting in binary data. In total, 487 unique brassica plants across 23 plots, 144 cucurbit plants across 14 plots, and 243 unique eggplant plants across 15 plots were surveyed. This experimental design produced nested and temporally correlated data, which was accounted for in our statistical methods (Appendix B, Table B1).

2.3. Statistical analysis

Generalized linear mixed models (GLMMs) were used to model pest populations and leaf damage, with each pest species modeled separately. Significance of the exclosure treatment was determined using a chi-square test of the best fit model with and without exclosure status as a predictor. For pest abundance models, Poisson and negative binomial error distributions with and without zero-inflation were considered to model pest counts, while leaf damage models used binomial error distributions to model binary data. Predictors considered for pest abundance models included: 1) fixed effects: exclosure status (exstat), day of year (DOY), days since exclosure start (days), time, temperature, crop variant (e.g., kale vs broccoli), and the interaction between DOY and days 2) random effects: exclosure ID (EXID), farm, and observer 3) zero-inflation parameters: DOY, days, and their interaction, and 4) AR-1 autocorrelation: assessment number by exclosure ID (to identify each individual count within a given exclosure and its paired control). For leaf damage models, the predictors considered were: 1) fixed effects: exstat, DOY, days, crop variant, total leaf area, and the interaction between DOY and days 2) random effects: EXID, farmer, observer, plant ID, and a unique ID for each individual plant assessment 3) AR-1 autocorrelation: assessment number by exclosure ID and plant ID separately. Details in the appendices further illustrate model structure (Table B2) and of predictor variables (Table B3). Because binary observations were made at each point of the leaf damage assessment grid, the random effects allow for correlation at the level of exclosure, plant, and leaf. All continuous predictors (DOY, days, time, temperature, leaf area) were standardized by subtracting the mean value and then dividing by the standard deviation before all analyses. Results are presented in original, unstandardized units, but all tests were performed on standardized data. Best fit GLMMs were selected by comparing fitted models for all combinations of plausible predictors, and in all cases the response variables were either pest population size or amount of damage. Model fit was evaluated using AICc. AICc was also used to determine whether a zero-inflation or autocorrelation parameter improved model fit. Models showing collinearity between predictors (variance inflation factor > 2) were rejected. The simulated residuals of all models were visually assessed in DHARMa (Hartig, 2021) to confirm that no patterns existed.

Standardized effect sizes (Cohen's *d*) were also calculated according to Sullivan and Feinn (2012) for the effect of exclosure treatment on each response variable. Although this calculation does not account for the nested experimental design with repeated measures employed in this study, no method for reporting single component standardized effect sizes currently exists for this data structure (Rights and Sterba, 2019). Readers are encouraged to consider Cohen's *d* along with the raw model coefficients. In addition to standardized effect sizes, we report unstandardized effect sizes (model coefficients) as recommended by Pek and Flora (2018). All analyses were performed in R (Team, 2021) using packages glmmTMB (Brooks et al., 2017), MUMIn (Barton, 2020), DHARMa (Hartig, 2021), emmeans (Lenth, 2021), and tidyverse (Wickham et al., 2019).

3. Results

3.1. Pest abundance

In total, pest abundance data was collected from 18 fields located at nine farms. At each farm an average of 5.78 (± 0.76) paired avian exclosure treatments were established. For crops in the genus *Brassica* (collards, kale, cabbage, Chinese cabbage, broccoli, cauliflower, kohlrabi, Brussels sprouts), an average of 2.22 (± 0.15) surveys were conducted during the two growing seasons starting on May 29 and ending on August 19. For crops in the family Cucurbitaceae (summer squash, winter squash, melons, cucumbers) an average of 3.0 (± 0.68) surveys were conducted during the two growing seasons starting on May 29 and ending on July 30. For species in the family *Solanaceae* (eggplant) an average of 3.73 (± 1.16) surveys were conducted during the two growing seasons starting on May 27 and ending on August 19. Exclosures were left up for an average of 32.1 (± 2.11), 42.4 (± 2.32), and 54.2 (± 4.09) days for brassicas, cucurbits, and eggplant respectively.

We found that excluding birds from crops had a significant effect on abundance of several insect pest species. For example, bird predation significantly reduced the abundances of imported cabbageworm, diamondback moth, squash bug adult, squash bug nymph, and squash bug egg masses (Table 1, Fig. 1). In contrast, Colorado potato beetle larval abundance was significantly lower inside exclosures than in control plots (Table 1, Fig. 1). No significant difference in abundance was observed in the populations of cabbage loopers, striped cucumber beetles, Colorado potato beetle adults, Colorado potato beetle egg masses, or aphids (Table 1, Fig. 1). For pests that differed significantly between exclosures and controls, bird predation reduced squash bug nymph abundance the most (−74%) and imported cabbageworm the least (−33%; Table 1). Colorado potato beetle larval abundance was decreased 59% by the exclosure treatment. Cohen's *d* for all pest species was in the range considered small (≤0.2; Table 1). Based on our conversations with farmers, our field observations, and consultations with the University of Massachusetts Agricultural Extension, the pest species we included in our analyses comprised the species responsible for the majority of leaf damage on the crops considered in our study.

3.2. Leaf Damage

Cucurbit and solanaceous crops experienced significantly higher leaf damage inside exclosures than in control plots (−42% and −12%, respectively; Table 1; Fig. 1). Leaf damage was slightly higher within exclosures for brassicas (−15%; Table 1), although this latter result was not significant at an alpha level of 0.05. It is worth noting that the residuals in all three leaf damage models were underdispersed, so these p-values may be conservative (Paul and Plackett, 1978). The effect sizes (Cohen's *d*) for all three crop types were small (≤0.2; Table 1).

4. Discussion

We found that bird predation has disparate effects on different species of crop pests. While the abundance of imported cabbageworms, diamondback moths, and squash bugs were all reduced by predation pressure from birds, the abundance of Colorado potato beetle larvae were more abundant where birds were present. These types of differing effects of bird predation between different crop types have been reported in previous research in other crops (Garfinkel et al., 2020). We also observed a trend that birds had a beneficial effect on leaf damage in all crop types surveyed, though this effect was not significant in brassicas. Our results provide further evidence that insect pest control by birds can be beneficial to farmers.

To our knowledge, this is the first time that significant positive impacts of birds on brassica crops have been quantified in North American agriculture. Here we found that brassica pests (imported cabbageworm, diamondback moth) were reduced in our system by approximately one third as a result of bird predation. In a tropical setting, Hooks et al. (2003) similarly determined that birds were the primary driver of natural pest control of caterpillars on brassicas, and that the pest control provided by avian predators increased brassica mass at harvest time. However, this is in contrast to the study by Martin et al. (2013), who found that birds either increased or had minimal impact on brassica pest abundance and damage in a temperate setting as a result of consuming other natural enemies. Garfinkel and Johnson (2015) also demonstrated that birds remove caterpillars from brassicas but failed to detect a significant effect on pest abundance or, as in our study, herbivory. Though no significant relationship was found in our study, we saw a trend suggesting cabbage looper abundance is also reduced by bird predation. The relative rarity of cabbage loopers in our study (36 individuals across 985 plant surveys) likely limited our ability to detect an effect, but with

Table 1
Model estimates for the effect of exclosure (birds excluded vs birds present) on pest abundance per plant and percent damage on arbitrarily selected leaves. Pest abundance and leaf damage were measured on plants where birds were excluded and not excluded during the summers of 2019 and 2020 on nine farms in western Massachusetts, USA. Model coefficients reported as individuals/plant for all pest abundance estimates except aphids which are reported as individuals/three leaves, and proportion damaged for leaf damage estimates.

Pest Abundance	Treatment	Model Coeff.[a]	Cohen's *d*	SE[b]	LCL[b]	UCL[b]	χ^2	p-value
Imported cabbageworm	Excluded	0.086	-0.12	0.027	0.047	0.16		
	Present	0.058		0.018	0.031	0.11	7.23	0.007[c]
Cabbage looper	Excluded	0.019	-0.060	0.0080	0.0087	0.044		
	Present	0.014		0.0061	0.0062	0.033	0.81	0.37
Diamondback moth[d]	Excluded	0.39	-0.17	0.13	0.20	0.75		
	Present	0.25		0.085	0.13	0.49	13.4	< 0.001[c]
Striped cucumber beetle	Excluded	1.64	-0.15	0.30	1.15	2.34		
	Present	1.42		0.26	0.99	2.03	1.39	0.24
Squash bug adults	Excluded	0.42	-0.24	0.12	0.24	0.73		
	Present	0.21		0.064	0.11	0.38	11.6	< 0.001[c]
Squash bug nymphs	Excluded	3.90	-0.26	2.67	1.01	15.0		
	Present	1.03		0.71	0.27	3.98	27.2	< 0.001[c]
Squash bug egg masses	Excluded	0.73	-0.18	0.35	0.29	1.85		
	Present	0.46		0.22	0.18	1.16	21.2	< 0.001[c]
Colorado Potato Beetle Adults	Excluded	0.0088	0.011	0.0084	0.0013	0.056		
	Present	0.0085		0.0082	0.0013	0.056	0.034	0.85
Colorado Potato Beetle Larvae	Excluded	0.0011	0.068	0.0031	< 0.0001	0.32		
	Present	0.0017		0.0050	< 0.0001	0.50	5.61	0.002[c]
Colorado Potato Beetle Eggs	Excluded	0.023	0.080	0.013	0.0081	0.067		
	Present	0.033		0.017	0.011	0.092	3.10	0.08
Aphids	Excluded	0.20	-0.038	0.078	0.090	0.42		
	Present	0.20		0.078	0.091	0.43	0.0049	0.94
Leaf damage								
Brassicas	Excluded	0.023	-0.082	0.0026	0.019	0.029		
	Present	0.020		0.0022	0.016	0.025	2.31	0.13
Cucurbits	Excluded	0.024	-0.21	0.0050	0.016	0.036		
	Present	0.019		0.0030	0.0090	0.021	9.74	0.002[c]
Solanaceae	Excluded	0.063	-0.096	0.018	0.036	0.11		
	Present	0.055		0.016	0.031	0.096	3.83	0.05[c]

LCI = lower 95% confidence level, UCI = upper 95% confidence level.

[a] Model coefficients reported on the response scale.

[b] SE = standard error,

[c] Indicates a significant result

[d] Chinese cabbage removed from coefficient averaging due to zero variance (0 DBM found on all Chinese cabbage);

a larger sample size a significant effect might be found. It should be noted that, in the case of cabbage looper and imported cabbageworm, it is possible that our estimates are an underestimate of the true pest suppression by birds. Adults of both species have a wingspan larger than the mesh size used for exclosures, and though adult imported cabbageworms (the larger species) were observed entering and exiting exclosures, it is possible this mesh was a partial barrier, resulting in fewer egg depositions inside exclosures. On a related note, although the used of exclosures to assess pest damage on crops is widespread, it is conceivable the mesh itself could have caused damage to crops or affected plant growth or development in some other way. Given the popularity of this approach, examining these incidental effects may be a fruitful topic for future study.

In addition, this is the first time to our knowledge that bird suppression of any cucurbit pests has been quantified – though bird predation of squash bugs has been previously observed. (Decker and Yeargan, 2008). This is an area that warrants further study, as pest herbivory can have significant negative effects on cucurbit productivity (Barber et al., 2012). It is important to note that though pest abundance and leaf damage were increased within exclosures, average pest levels across the study were lower than commonly suggested thresholds for pesticide treatment under both treatments (Campbell-Nelson et al., 2020). The lack of effect on striped cucumber beetle may be due to aposematism, as Luperini beetle species that feed on cucurbits are known to deter bird predators through the buildup of toxic cucurbitacins (Nishida et al., 1992).

4.1. *The conundrum of Colorado potato beetles*

Our results for Colorado potato beetles present several seemingly contradictory findings that warrant further discussion. The lack of reduction in numbers of Colorado potato beetle adults by birds may be explained by the toxicity of this pest which chemically discourages bird predation (Daloze et al., 1986; Hough-Goldstein et al., 1993). In a related study in this system, Mayne (2022) found DNA from known arthropod natural enemies of Colorado potato beetle in bird fecal samples. Therefore, it is plausible that the arthropod natural enemies provide greater pest-suppression services than birds do for Colorado potato beetles, and that bird predation upon these species causes an overall increase in the numbers of Colorado potato beetle larvae. An alternative hypothesis could be that Colorado potato beetle larvae were less abundant in exclosures due to obstructed movement of adults through exclosure mesh. However, we observed similar levels of Colorado potato beetle adults between treatments, and adults were often observed moving between plants and through mesh. It is important to note, however, that we did not directly detect any predation of Colorado potato beetle eggs because we counted total egg masses, not individual eggs, so partial predation of an egg mass would not have been detected. We believe that our conclusions about Colorado potato beetle larvae can be extended to other solanaceous crops where Colorado potato beetle is a major pest (e.g., potatoes). Finally, while our results indicated that Colorado potato beetle abundance was not reduced in the control treatment where bird activity was allowed, we also observed that excluding birds resulted in increased leaf damage for eggplants. We are unable to account for this inconsistency.

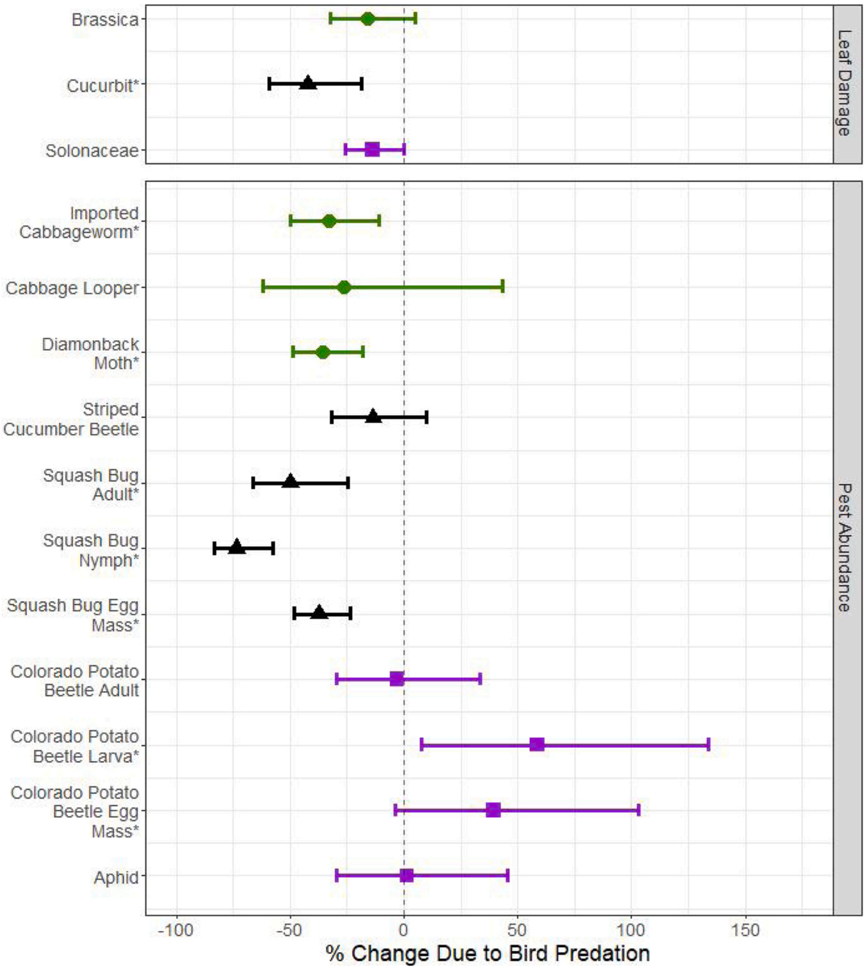

Fig. 1. The percent change in pest abundance and leaf damage due to bird predation on nine Western Massachusetts farms is shown for brassicas (●), curcubits (▲) and solaneaceous crops (■). Points indicate the estimated mean change in pest abundance or leaf damage when birds are present, compared to when they are excluded. Brackets show the 95% confidence interval of the mean estimates.

4.2. *Effect size and overall interpretation*

Lastly, it is important to consider the overall effect size of our findings. Calculated Cohen's *d* values showed that the effect size of the exclosure treatment was small (≤0.2) for all pest abundance and leaf damage response variables. However, Cohen's *d* should be considered an approximation of the effect size because it does not account for the nested, repeated sampling design of our exclosure experiment. Unfortunately, no single component measure of standardized effect size currently exists for complex data structures like those presented here (Rights and Sterba, 2019). We therefore encourage readers to consider the unstandardized model coefficients in addition to the Cohen's *d* values when comparing effect sizes (both are presented in Table 1).

4.3. *Variable responses in low intensity agriculture*

The variable responses to bird predation shown here demonstrate our lack of understanding of the specific trophic interactions between pests and predators in agricultural systems. The divergent responses to bird predation between our study and Martin et al. (2013) show that even when considering the same crops and pest species, results are not necessarily generalizable across ecological communities. Pest suppression (or release) is dependent on the ecological interactions of multiple potential predators, which may vary with factors such as landscape characteristics and ecological interactions (Kremen et al., 2007; Martin et al., 2013). We therefore caution about generalizing our results beyond the agroecological context of low intensity farms in the northeastern USA.

5. Conclusions

Our results show that on many diversified farms such as those studied here, a farm-wide approach to birds can have disparate impacts on different crop species. While in all crops we studied the ensuing effect on crop damage was either significantly positive or nonsignificant, it remains a possibility that birds could release pests in some crops, causing increased damage. In this case, farmers have a number of potential management practices to maximize bird-mediated pest control by boosting bird populations in chosen locations where they will be beneficial (e.g., brassicas, cucurbits). These practices operate on the assumption that bird predation is highest near suitable nesting habitat, which appears to be true in multiple agricultural systems (Garfinkel and Johnson, 2015; Gras et al., 2016; Linden et al., 2019; Milligan et al., 2016). Firstly, growers can maintain natural habitat on field margins to increase abundance of all birds (Heath et al., 2017) or specific species (Brofsky, 2020) and promote their associated ecosystem services. In addition to natural habitat, nest boxes can be used to enhance insectivorous bird abundance and predation in desired locations (Jedlicka et al., 2014, 2011; Mols and Visser, 2007; Rey Benayas et al., 2017), for example in fields planted with brassica or cucurbit crops. Providing perches for insectivorous birds may also increase some insectivorous birds' use of fields as foraging habitat (Puckett et al., 2009), allowing farmers to enhance biocontrol by native birds. Farmers can also adjust their row configurations to place crops where birds are beneficial (i.e., brassicas, cucurbits) closer to natural habitat than those where they are detrimental. Further research into how pest predation changes as distance to habitat, a nest box, or a perch, increases will help refine these management techniques. Knowledge of which bird species provide greater pest control benefits (see Mayne, 2022) can also help inform management techniques. Many of the farms we worked with already maintain natural vegetation on field edges and configure their fields to enhance ecosystem services. We hope this and other studies on the agroecological benefits from avian conservation continue to promote such practices and improve their efficacy.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2023.108395.

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