

Article

Variation in Avian Predation Potential on Insect Pests Across Time and Space Within a Small-Scale Agricultural Field: Implications for Applied Biocontrol

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Simple Summary

Birds are an important group of natural predators of insects. As such, leveraging natural bird populations to remove insect pests from crops is a potentially powerful strategy to increase agricultural yields. However, it remains unknown how birds' predation behaviors and intensity may vary within agricultural settings. We demonstrated that in small agricultural fields, putative bird predation potential on insects can be substantial. This predation potential is relatively uniform across space. We also show that bird predation potential on insects can vary throughout the year. These data support the role for birds as potential biocontrol agents, at least in smaller fields, and point to promising avenues of research to further investigate the nuances of such predation behaviors and how birds may best be leveraged to improve crop yields.

Abstract

To feed a growing population, humanity will need to see an increased global agricultural output in crop production. One key strategy for achieving this goal is to reduce herbivory by insect pests, which is one of the leading causes of crop loss. Although there have been many strategies for combating insect herbivores, biological control may be the most sustainable in the long term. Birds in particular are potentially powerful biocontrol agents, but how avian predation varies within individual agricultural settings remains largely unknown. Here, we analyzed temporal and spatial variations in putative avian predation potential on insect pests in a small-scale agricultural setting. Our results show that the spatial distribution of predation potential is nearly uniform across a small field, indicating that birds with their vagility may be particularly well suited for applying constant, uniform coverage, at least across smaller landscapes. We also found that predation potential by birds varied significantly between seasons, with the fall showing the highest rate of predation. We discuss the applications of our findings for further studies investigating the biocontrol potential of natural bird populations and for leveraging such avian predation to help improve food production systems.

Keywords: biocontrol; birds; predation; herbivory; agriculture; agroecosystems



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1. Introduction

Over the next several decades, food production must increase to sustainably feed a growing human population [1,2]. Sands et al. [3] projected that by 2050, humanity will see

an increase of ~50% in world crop calories as the population grows. One method to increase total crop production is to reduce crop loss. Although there are many factors contributing to crop loss, one of the major sources is insect herbivores [4]. Exacerbating this problem, projections indicate that losses due to insect herbivory will only increase with increasing annual temperatures; Deutsch et al. [5] estimated a 10–25% increased grain crop loss due to herbivory per degree of global mean surface warming. Thus, mitigating crop losses due to insect pests is a vital strategy for ultimately feeding an increasing global population.

A number of anti-herbivore strategies have been employed to reduce crop losses to insect pests. These include planting strategies, sanitation measures, physical barriers, physical traps, and various forms of direct removal [6]. Notable among these are genetically modified crops, such as those transformed with insecticidal genes from *Bacillus thuringiensis*, i.e., “Bt crops” [7]. However, gene flow from transgenic plants has the potential to shape the population dynamics of neighboring cultivated and wild populations [8]. Additionally, transgenic crop lines have historically been the subject of controversial litigation [9].

The most common strategy has been the use of pesticides. The mid-20th century saw the advent of widespread use of pesticides in agricultural settings [10], which corresponded with increases in total agricultural productivity [11,12]. However, increases in pesticide use have had severe negative effects on the environment and global human health [13]. These include runoff and contamination, potentially harming off-target species, including humans [14,15]. Furthermore, the costs and benefits of pesticide use may be suboptimal due to over- or underutilization in different global regions [16]. Still, despite the severe drawbacks, pesticides remain an attractive solution to farmers worldwide [17].

One alternative promising strategy for reducing crop loss to pests is biological control, henceforth “biocontrol” [18]. This includes the use of insect predators [19], fungi [20], bacteria [21], and even viruses [22] to combat insect pests on crops. Historically, classical biocontrol measures introduced non-native enemies of exotic insect herbivores [23]. However, such direct interventions can pose significant risks to human, animal, plant, and environmental health [24], and thus have been largely phased out [23]. Conversely, biocontrol measures that leverage native natural enemies have been suggested as a more ecologically friendly alternative [25]. These natural enemy populations can be actively recruited to agricultural plots, for example through the use of semiochemicals [26,27], or by cultivating appropriate natural habitats within agroecosystems [28].

In particular, combatting insect pests by leveraging birds as biocontrol agents is a promising solution to mitigating crop loss. Insects are an important part of birds’ diets, with 50% of bird species being predominantly insectivorous, and at least 75% of bird species consuming them at least occasionally [29]. For example, it is estimated that insectivorous birds consume 400–500 million metric tons of insect biomass annually [30]. Furthermore, birds have an innately high capacity for individual movement, making them particularly well-equipped for potential insect control in large-scale agriculture [31]. Indeed, it has been shown that birds contribute substantially to reducing the number of crop pests and reducing crop damage [32,33]. Furthermore, bird predation on insect pests may be particularly important in temperate growing zones [34], where a significant amount of the world’s crops are grown [35].

While birds have increasingly been shown to provide a promising contribution to reducing insect pest levels, the details of how this predation can vary locally within individual fields remains unknown. Such variation would be important for informing how to best leverage birds as biocontrol agents in the future. Specifically, we aimed to quantify the temporal and spatial variation in bird predation potential using clay insect models within a single agricultural field. We hypothesized that bird predation potential would be higher around the field perimeter compared to the field interior, since the field perimeter is

closer to surrounding natural habitat, e.g., forest habitat, which harbors most of the natural avian biodiversity [36]. We also hypothesized that predation potential would be highest in the spring. This is when protein requirements are often greatest due to the nutritional demands of breeding, and when insect prey are emerging [37].

2. Materials and Methods

2.1. Field Setup

We placed experimental setups at 14 transects in a small corn field (total area $\sim 0.14 \text{ km}^2$) adjacent to the DeSales University campus in eastern Pennsylvania, USA ($40^\circ 32' 19'' \text{ N}$, $75^\circ 22' 44'' \text{ W}$). This corn field was located near a larger suburban area and was surrounded first by a grassy walking path, and then by a forest edge (Figure 1).

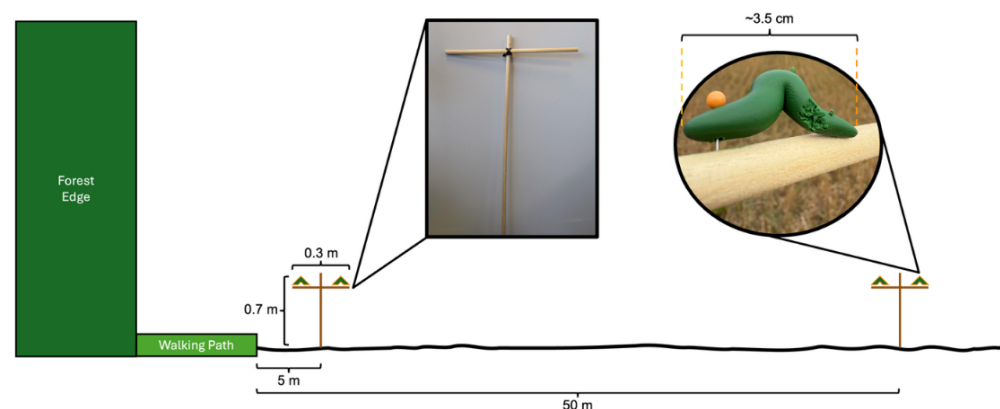


Figure 1. Experimental setup illustrating a single transect with artificial perches at 5 m (left) and 50 m (right) from the field edge. Photographs depict an artificial perch (left photo) and an example of typical avian attack marks on an artificial clay caterpillar (right photo).

Each transect was perpendicular to the walking path and extended into the field for 50 m. All transects were spaced relatively uniformly around the forested edge of the field, specifically such that there was at least a distance of 50 m between any two transects (Figure 2). Along each transect, we anchored two artificial perches (Figure 1). One artificial perch was positioned at a distance of 5 m into the field, i.e., from the walking path, and a second wooden perch was positioned further at a distance of 50 m into the field. Artificial perches were constructed from wooden dowels (diameter 0.95 cm). These artificial perches closely mimicked the remaining corn stubble present in the field during all experiments [38], minimizing potential attraction or avoidance of birds due to basic exploratory behavior toward or away from novel objects [39]. A vertical wooden dowel was hammered into the ground (total above-ground height 0.7 m) and a horizontal crossbar (crossbar length 0.3 m) was secured with two small black zip-ties at 2.5 cm below the top of the vertical dowel. To measure predation rates by birds, we placed 2 artificial caterpillars at either ends of the crossbar (Figure 1). Caterpillars were shaped out of green clay (Sculpey III, Leaf Green, Polyform Product Company, Elk Grove Village, IL, USA) following previous studies done in the same geographic region [40–43]. We molded 2.5 g of clay into 5 cm lengths and bent the caterpillar into an inchworm-like shape (scrunched length $\sim 3.5 \text{ cm}$). We pinned these caterpillars to the crossbar using small, orange, round-headed pins to resemble the head capsule of the insects [40]. Each caterpillar was pinned 2.5 cm from the end of the crossbar, with the orange pin “head” facing inward toward the vertical dowel. Similarly constructed artificial clay caterpillars have been widely used to quantify bird predation rates [40–44].

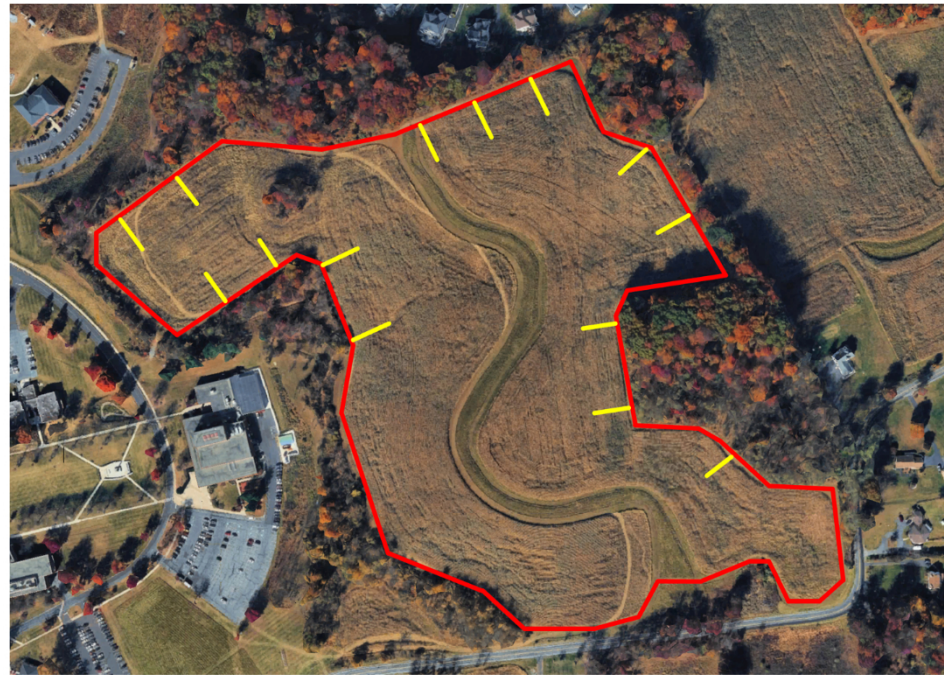


Figure 2. Experimental site illustrating the small agricultural field with the walking path perimeter highlighted in red and the locations of our 14 transects highlighted in yellow.

2.2. Data Collection

Identical experimental setups using the same 14 transects were deployed during three separate seasons: fall (12 November 2024), spring (22 April 2025), and summer (2 September 2025). The last corn harvest in this field occurred in October 2024 and the field contained corn stubble that closely mimicked our artificial perches during all experiments. No crops were actively sowed or growing during any of our experiments. Each artificial perch was checked daily for the following 10 days (13 November 2024–22 November 2024, 23 April 2025–2 May 2025, and 3 September 2025–12 September 2025). All data were collected between 800 h and 1200 h Eastern Standard Time (EST). In order to quantify whether the distance from the forest perimeter influenced predation rates on artificial caterpillars, we recorded whether either of the two caterpillars on a given artificial perch showed signs of predation, i.e., peck marks (Figure 1). If the caterpillars were predated upon or otherwise damaged, we reformed and smoothed the clay back into its original shape. If the caterpillar was irreparable or missing, we replaced it with a new caterpillar. In total, there were 168 caterpillars deployed over the course of our experiment (2 caterpillars/perch $\times$ 2 perches/transect $\times$ 14 transects/season $\times$ 3 seasons).

2.3. Statistical Analysis

We fit a logistic mixed-effects model for our dependent variable of whether an artificial perch was predated upon on a given day (Y/N) using the R package *lme4* (ver. 2.0-1) [45]. In our model, we included fixed effects of distance (5 m vs. 50 m), season (autumn, spring, and summer), and experiment day (1–10) to account for repeated measures. We also included the interaction effects of distance $\times$ season and distance $\times$ experiment day. Lastly, we included a random effect of site ID (1–14) to reflect the sampling design. However, the estimated variance of this term was effectively zero, indicating negligible variation among transects. Still, we retained this random effect to reflect the hierarchical and repeated sampling structure of our experimental design. Initially, we also added fixed effects of daily average temperature and precipitation to control for short-term weather changes.

Weather data were collected from the nearby Allentown Lehigh Valley International Airport weather station (40°38'59" N, 75°26'52" W) [46]. However, these variables did not improve model fit and were therefore excluded ($\Delta\text{AIC} = 2.13$, $\chi^2 = 1.867$, $p = 0.393$). Additionally, to evaluate whether the effect of experiment day was linear, we fit two models with either a linear or quadratic term for experiment day. The best fit supported model included a linear term for experiment day over a quadratic term ($\Delta\text{AIC} = 1.98$, $\chi^2 = 0.020$, $p = 0.888$). We analyzed our final model with a type-II ANOVA using the R package *car* (ver. 3.1-5) [47]. Post hoc comparisons of resulting estimated marginal means were performed with Tukey's adjustment for multiple comparisons. All data and R-code are publicly available [48].

3. Results

Overall, we found appreciable levels of bird predation (Table 1, Figure 3). On average, we found a 5.5% overall predation rate on our models. In particular, there was a significant effect of season (Table 2). In comparing the estimated marginal means, there was a ~2.4-fold higher odds of predation in the fall compared to both spring and summer (log-odds difference = 0.861 for both contrasts, Tukey-adjusted $p = 0.062$ for both contrasts). In contrast, there was no significant effect of distance on the number of predation events (Table 2), with perches located at 5 m and 50 m into the field experiencing similar levels of predation events (Table 3, Figure 3). Interestingly, there was also a significant effect of experimental day (Table 2), where the number of predation events significantly decreased, on average, over the course of each 10-day data collection period (Table 3, Figure 3). For example, compared to our average predation rate of 5.5%, we found a 17.9% overall predation rate on day 1 and 0% overall predation rate on day 10. No interaction effects were significant (Table 2).

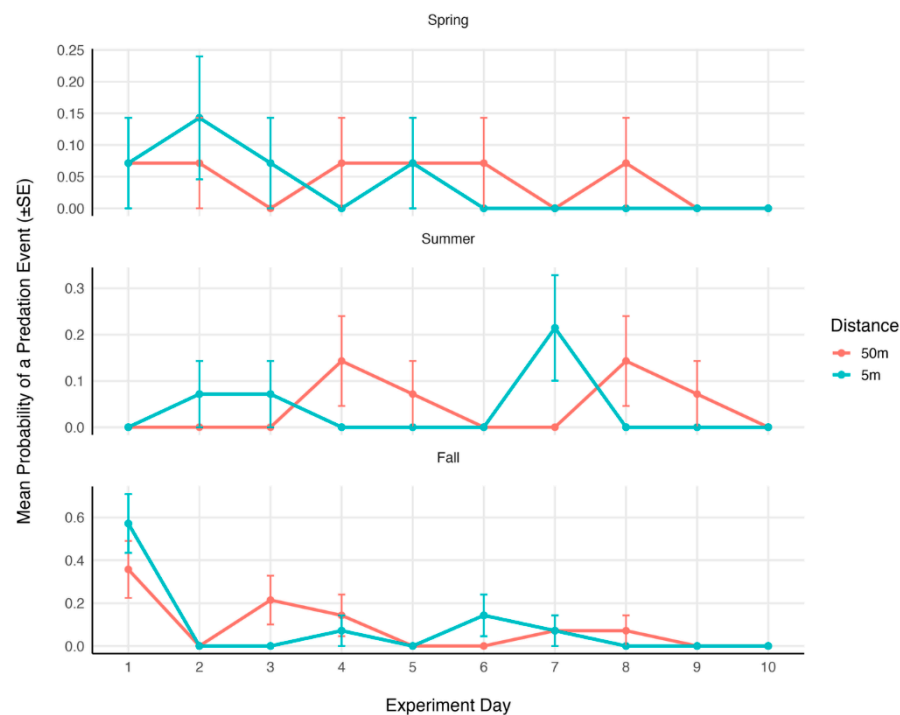


Figure 3. Time-series predation data for spring (top), summer (middle), and fall (bottom). Blue lines indicate data for artificial perches at 5 m into the field and red lines indicate data for artificial perches at 50 m into the field. Points indicate the average probability of a predation event and vertical bars indicate standard error.

Table 1. Raw predation counts by season and distance treatment. The total predation targets per season per distance treatment reflect the 14 perches that were assessed for predation over each 10-day collection period.

Season	Distance	Total Predation Targets	Total Predation Events
fall	5 m	140	12
fall	50 m	140	12
spring	5 m	140	5
spring	50 m	140	6
summer	5 m	140	5
summer	50 m	140	6

Table 2. Analysis of variance (type-II tests) of a logistic mixed-effects model for predation events by the fixed effects of distance, season, experiment day, distance $\times$ season, and distance $\times$ experiment day, and a random effect of site ID. Significant effects are marked with an asterisk.

Predictor	χ^2	df	p-Value
distance	0.065	1	0.799
season	7.597	2	0.022 *
experiment day	15.807	1	<0.001 *
distance $\times$ season	0.130	2	0.937
distance $\times$ experiment day	2.022	1	0.155

Table 3. Logistic mixed-effects model results for predation events showing fixed-effects coefficients (β), standard errors, odds ratios, and 95% confidence intervals for odds ratios.

Predictor	β	Standard Error	Odds Ratio	95% CI
summer (vs. spring)	~0	0.654	~1	[0.278, 3.601]
fall (vs. spring)	0.973	0.558	2.646	[0.886, 7.905]
50 m (vs. 5 m)	−0.470	0.775	0.625	[0.137, 2.857]
experiment day	−0.355	0.099	0.701	[0.578, 0.851]
summer $\times$ 50 m	~0	0.883	~1	[0.177, 5.640]
fall $\times$ 50 m	−0.224	0.762	0.799	[0.180, 3.559]
50 m $\times$ experiment day	0.180	0.126	1.197	[0.934, 1.534]

4. Discussion

We found a significant effect of season on putative bird predation on clay caterpillar models, but not in the direction we hypothesized. The number of bird attacks on our clay models was higher during the fall season (November) compared to the spring (April–May) or summer (early September). Thus, crops that may not be harvested until later in the fall, i.e., corn, soybeans, cabbage, etc. [49], may benefit most from bird predation activity. While no crops were concurrently being cultivated during the course of our experiment, crop identity could be a significant factor in recruiting avian predators. Indeed, it has been shown that the effectiveness of bird predation on preventing damage across different crop species may vary [50]. Thus, while we found a 5.5% overall predation rate on our clay caterpillars, with daily average predation rates ranging from 0% to 17.9%, we did not actually measure biocontrol directly, and the efficacy of birds as biocontrol agents may be

variable across different regions depending on the primary crops being cultivated and the local species present. Future work during active growing seasons will be important to expand upon the results presented here.

Relatedly, a historically important strategy to increase yield and reduce losses to herbivory is intercropping, where different crop species are sown in close proximity [51]. Intercropping has additionally been shown to increase the species richness of birds [52]. Assessing the exact contribution of bird diversity in reducing insect herbivory within mixed crop fields would further reinforce the benefits of intercropping.

One likely reason for seasonal differences could be the shifts in avian community composition, for example due to the movement of migratory species across different seasons. Alternatively, the higher predation potential we found in the fall may be an annual result of several months of forming an acute search image for caterpillars generally, i.e., it has been shown that preference for and capture of specific types of prey by birds increases with recent experience and repeated exposure [53,54]. Compounding this effect, hatch-year birds born earlier in the spring and summer would have had time to learn and develop improved foraging behaviors by fall [55]. Relatedly, lower predation potential during the summer may be a function of high general abundance of food, such that the proportional number of attacks on our artificial setups was lower. While all of these explanations could be consistent with our data, they nevertheless remain speculative without concrete bird community or insect abundance data. Future studies incorporating concrete bird and insect community data will be necessary to distinguish between these potential mechanisms.

Although we did not find support for our hypothesis that insect predation potential by birds differs between the perimeter and the interior of the field, these null results may reflect the nature of our specific experimental site. The relative habitat uniformity of the post-harvest field may have promoted uniform foraging, and such patterns may differ in more structurally complex, actively growing crops. Alternatively, these results may reflect the overall size of our specific experimental site. Our field was relatively small (total area $\sim 0.14 \text{ km}^2$) compared to the average field size in the larger United States (0.193 km^2) [56]. This means that the energy cost of movement by birds throughout our entire field site may have been trivial, resulting in relatively complete predation coverage. This may not necessarily hold true for a majority of larger industrial farm plots, which can reach over 10 km^2 [56]. Therefore, even though we did not find any substantial spatial effect in our small experimental field, this may only be true at least up to 50 m into a field's interior, and future work will be required to investigate whether any such spatial differences exist in larger fields. Quantifying such variation in larger fields may be potentially important for judiciously applying other pest management strategies, e.g., pesticides may be most useful in the middle of large fields where bird predation is lowest.

The mean number of avian attacks on our clay caterpillars decreased over the course of each 10-day experimental period. This could be caused by birds gaining experience with the experimental setups, i.e., learning that the clay caterpillars are inedible. From these results, we suggest that future researchers using this method to quantify avian predation consider the effects of experience and learning over the course of their experiments. Data may best be collected while the local bird population is still naïve. This effect of experience has been previously shown to possibly be context- or habitat-specific [43] and should be approached mindfully. Still, these results could also be reflective of local changes in community composition, but our data do not allow us to distinguish this. Future work incorporating bird surveys and investigations into the ontogeny of predation behaviors toward clay caterpillars will be necessary to disentangle these possibilities.

There are several limitations to our study. Most importantly, our experiments were conducted post-harvest, with no actively sowed or growing crops, which could limit the

applied significance of our findings. However, this fact does maintain constant conditions under which we could isolate our spatial and seasonal variables without additional confounding effects (i.e., crop identity, growing stage, etc.). Our study also took place in Pennsylvania, USA, a temperate region, and seasonal shifts in the composition of the local avian community could explain some of the variation in predation potential. Regional differences in climate, primary crops, and avian communities could produce variable results in other locations.

Additionally, we did not video record any of the attacks. We assumed from the size and structure of the attack marks that they were made by birds, but there is the possibility that non-avian predators contributed to the number of attacks scored (insects, mammals, etc.). Thus, while we scored attacks we deemed visually typical for avian predators (Figure 1), the individual identities of presumed bird predators were unknown. There may have been species-specific effects or repeat attackers that we were unable to quantify in our analyses. We also chose to use green clay caterpillar models (Figure 1). It has previously been shown that the color choice of the caterpillar model may affect rates of bird predation [34]. We chose green caterpillars following successful similar studies done in the same geographic location [40–43]. However, using other colors may have been more attractive to birds [34] or have recruited different bird species, which could have influenced our results. Additionally, these attacks on clay models are specifically assessing attack risk, not absolute biocontrol efficiency. However, previous studies do report that the use of clay caterpillar models probably underestimates true levels of avian predation on living insects [57,58]. Overall, the use of clay prey models provides a useful standardized measure of predation risk, although further studies directly comparing model attacks with those on live prey in agroecosystems are needed to determine how well these measures predict actual levels of avian biocontrol.

Our experimental windows most likely do not completely cover major life history events of many species. For example, our spring sampling window (23 April 2025–2 May 2025) does not extend very far into the month of May, which is the breeding season for many birds in Pennsylvania. Thus, the protein demands in birds and the dietary changes to accommodate them [37] may have occurred after our spring testing period. Our summer sampling window (3 September 2025–12 September 2025) presumably occurred after most nesting concluded. Lastly, our fall sampling window (13 November 2024–22 November 2024) most likely misses fall migration events of many species. Thus, our study may not accurately capture all acute changes in avian diets or community composition. Indeed, birds are well known to alter their diets seasonally, such as from high-protein diets (e.g., insects) during breeding to high-carbohydrate diets (e.g., fruits and seeds) during migration [59]. Future studies at a greater temporal breadth and which attempt to identify the species that most contribute to predation in agroecosystems could further indicate where and when bird biocontrol may be most effective.

For small-scale agricultural fields, our results suggest that predation by birds can be relatively uniform throughout the field. Thus, taking a landscape perspective in cultivating appropriate habitats to foster a healthy local bird population [60] may be an effective way to improve crop yields. Perimeters consisting of trees and shrubs around fields have historically been used as windbreaks [61], but these have also recently been shown to increase bird foraging activity [62–64]. Interestingly, there is also some evidence that the exact species identity of neighboring plants can either positively or negatively influence bird visitation rates to focal plants [65], which could be further examined in agricultural contexts. Fostering an attractive habitat within the agricultural field itself outside of the growing season may also help maintain local bird populations, for example, leaving corn stubble on fields after harvest [38]. Another strategy is to construct nesting boxes around

agricultural areas to increase the local bird population. Olmos-Moya et al. [66] found that the deployment of nest boxes increased the consumption of prey by 43% around vineyards.

Further, the benefits of bird biocontrol efforts may be highly dependent on the crop of interest. While insectivorous birds may help improve crop yields by reducing herbivore damage, frugivorous bird species may actually contribute to losses. For instance, in Californian agricultural landscapes, bird service was found to be equal to bird disservice; while birds suppressed pest damage on berries by 3.8%, 3.2% of berries were additionally damaged by birds [67]. Furthermore, while insectivorous birds may prey on crop pests, they may also consume insect predators of those same pests, effectively reducing other non-avian forms of biocontrol. Grass et al. [68] reported that the presence of Eurasian Tree Sparrows (*Passer montanus*) reduced predatory hoverfly (Syrphidae) and ladybird beetle (Coccinellidae) populations, ultimately increasing the number of aphid pests on cereal crops.

5. Conclusions

Our findings reinforce that birds seem to contribute to vital ecosystem services by playing an important role in biocontrol for agricultural systems. However, this effect may be context dependent. We show that avian predation potential varies across seasons, but seems to be relatively uniform across field topography, at least in smaller fields. These findings suggest that avian predators as a source of biocontrol may best be leveraged by considering known temporal patterns and local habitat management in smaller fields. Cultivating appropriate habitats to support natural bird communities may be a promising future strategy for promoting biocontrol by birds and reducing crop loss to herbivory. Future work in larger field systems and in species-specific contexts, both specific crop species and specific bird species, will be crucial for our understanding of avian foraging patterns and applied biocontrol. For example, biocontrol by birds on different insect pests may differ between host plants and the biocontrol benefits of specific bird species should be weighed against potential disservices such as frugivory or predation on beneficial arthropods. In conclusion, incorporating avian predation into larger strategies of biocontrol and overall integrated management frameworks is a promising avenue for a growing and sustainable global food production system.

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