The Ecosystem Service Values of Birds to U.S. Corn and Soybeans: A National Scale Analysis

Nabin Bhandari[a] and Ruiqing Miao[a]

[a] Department of Agricultural Economics and Rural Sociology, Auburn University, USA

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Abstract: Valuing the agro-ecosystem services of birds can quantify the economic contribution of biodiversity and inform agricultural and conservation policies. Yet, no large-scale, generalizable study has assessed the contribution of birds to crop yields. Using county-level panel data for breeding birds in the United States over 1997-2014, we estimate the effects of grassland bird, insectivorous bird, and endangered bird biodiversity on corn and soybean yields in the presence of neonicotinoid use. We find that the yield effects vary by bird group: grassland birds contribute positively to corn and soybean yields, insectivorous birds contribute negatively, and endangered birds show no statistically significant effect. Neonicotinoid use diminishes both the beneficial and detrimental influences of birds on crop yields. When evaluated at sample means, grassland birds contribute to 11.52% of corn yield (an economic value of $9.3 billion per year), while their contribution to soybean yield is statistically insignificant. Neonicotinoid use contributes to 3.82% of corn yield and 7.02% of soybean yield, corresponding to annual economic values of $3.1 billion and $4.1 billion, respectively. Were grassland birds to become extinct, neonicotinoid use would need to increase by 219.43% to maintain current corn yield. Conversely, if neonicotinoid use were banned, then a 32.93% increase in grassland bird population could offset the resulting reduction in corn yield.

Keywords: bird abundance, crop yields, ecosystem services, neonicotinoids, species evenness, species richness

JEL codes: Q15, Q18, Q57

1. INTRODUCTION

The relationship between humans and birds is significantly influenced by people's evaluation of birds' ecosystem services, particularly agro-ecosystem services. For example, in China, sparrows were once viewed as pests in the 1950s because they were believed to damage crops, and such a perception caused a significant population reduction in sparrows during that period (Chen and Wang, 2021). Valuing the agro-ecosystem services of birds quantifies the economic contribution of biodiversity and informs agricultural and conservation policies. However, an objective and comprehensive evaluation of birds' agro-ecosystem services can be challenging (Wenny et al., 2011). Current evaluations are mainly based on field experiments whereby scientists compare crop yields between plots with and without bird exposure (Garfinkel et al., 2020; Garfinkel et al., 2022; Garcia et al., 2023). Inferences from these experiments conducted in a few small fields, however, may not reflect birds' comprehensive agro-ecosystem services at the national-scale, leaving an important research gap. The purpose of this article is to fill this gap by conducting a national scale analysis of birds' impact on corn and soybean yields based on U.S. county-level birds and crop yield data.

Because national scale field experiments that involve randomly manipulating bird populations or altering birds' access to crop fields are infeasible, the valuation of agro-ecosystem services of birds on such scale requires non-experimental settings (Frank, 2024; Larsen et al., 2024). In this study, we use U.S. county-level data for birds and crop yields over 1997-2014 to statistically quantify the agro-ecosystem service of birds, offering nation-level perspectives that complement the localized insights derived from field experiments. Specifically, by using fixed effects models and the instrumental variable approach to address endogeneity issues in the econometric analysis, we quantify the impact of bird biodiversity on crop yields while controlling for other factors that may also affect crop yields, such as chemical uses, genetically engineered (GE) adoption, and weather. Following previous studies (e.g., Li et al., 2020; Chen and Khanna, 2024), we use three measures of biodiversity which include (1) species abundance (i.e., the number of bird count), (2) species richness (i.e., the number of distinct bird species), and (3) species evenness (measured by the Shannon index of diversity, to be discussed below). We focus on three bird groups: grassland birds, insectivorous birds, and endangered birds. Grassland and insectivorous birds are of interest because their habitat or forage area may overlap with crop fields (Mineau and Whiteside, 2013; Li et al., 2020; Washuck et al., 2022). Endangered birds are considered because their impact on crop yields remains underexplored (Groner et al., 2023).

Moreover, due to the large impact of neonicotinoid use on crop yields and bird diversity (Hurley and Mitchell, 2016; Li et al., 2020), we also examine how the neonicotinoid use moderates birds' agro-ecological service in determining crop yields.[1] We quantify the extent to which birds can serve as viable substitutes for neonicotinoid use. If birds and neonicotinoid substitute each other, then public policies that support one of them may impede the effect of the other. The European Union has implemented a ban on certain neonicotinoid pesticides (European Union, 2024). Similarly, the United State Environmental Protection

[1] About two-thirds of total pesticides used in the U.S. is applied to corn and soybean fields (see Table S1 in the online Supporting Information (SI)) (Fernandez-Cornejo et al., 2014) and previous studies (e.g., Lu et al., 2012) have found that pesticides decrease ecosystem service of birds on crops. Among various pesticide groups, neonicotinoid use has grown exponentially and has raised concerns about negative impacts on the environment and non-target organisms, including birds (Hallmann et al., 2014; Forister et al., 2016, DiBartolomeis et al., 2019; Frank and Tooekr, 2020; Jones, 2020; Rigal et al., 2023; Molenaar et al., 2024; Yan et al., 2024). In addition, more than 1,000 pesticide-active ingredients are registered for use in the U.S. These different pesticides ingredients have different orders of magnitude in potency to target and non-target organisms (Douglas et al., 2020; Deynze et al., 2024). Therefore, it is challenging to obtain a reasonable aggregated measure of total pesticide use. This is another reason we consider neonicotinoids in our study, instead of seeking to construct an aggregate measure of general pesticide use.

Agency (USEPA) has implemented restrictions on the use of neonicotinoid use such as limiting neonicotinoid applications to blooming crops (USEPA, 2020). The State of New York in the U.S. bans the use of neonic-treated seeds for corn, soybeans, and wheat starting in 2029 (Axelson, 2024). Our study contributes to the debate around neonicotinoid ban by seeking to quantify the intricate relationships among birds, pesticides, and crop yields.

We find that the effect of birds on crop yields differs across bird groups, and that these effects are weakened by the level of neonicotinoid use. When neonicotinoid use level is low (e.g., at the 10th percentile of our sample), both grassland bird abundance and species richness have positive and statistically significant effect on corn yield whereas insectivorous bird abundance, species richness, and species evenness have negative and statistically significant effect on corn yield. When evaluated at the sample mean or median of neonicotinoid use, however, only grassland bird abundance has positive and statistically significant impact on corn yield. This finding implies that grassland birds and neonicotinoids are substitutes while insectivorous birds and neonicotinoids are complements. When evaluated at the sample mean of neonicotinoid use, the elasticity of corn yield with respect to grassland bird abundance is 0.1152, which indicates that, everything else equal, had grassland bird population not declined by 53% in the past few decades (Rosenberg et al., 2019), the corn yield would have been 6.1% higher than the current level in the U.S. We do not find evidence that the abundance, species richness, or species evenness of endangered birds has statistically significant impact on corn yield, regardless of the levels of neonicotinoid uses.

The bird-neonicotinoid-yield relationship for soybeans is similar to that for corn but is generally less pronounced. When neonicotinoid use level is low (e.g., the 10th percentile of our sample), grassland bird biodiversity (i.e., abundance, species richness, or species evenness) has a positive and statistically significant effect on soybean yield. As neonicotinoid use increases (e.g., to mean or median), however, such an effect becomes smaller and often statistically insignificant. Similar finding holds for endangered bird abundance and species richness. Biodiversity of insectivorous birds and species evenness of endangered birds have no statistically significant impact on soybean yields regardless of the level of neonicotinoid use, even though their point estimates are typically negative.

Our counterfactual analysis shows that if grassland birds were to become extinct, then there would be an 11.52% decrease in the corn yield, translating into an economic loss of $9.3 billion per year (in 2023 dollars). To offset this negative yield effect, the neonicotinoid use should be increased by 219.43%. On the other hand, a ban on neonicotinoid use would decrease corn yield by 3.82%, causing about $3.1 billion loss per year. We estimate that everything else equal, increasing grassland birds' abundance by 32.93% would be sufficient to offset this corn yield reduction caused by the neonicotinoid ban. Considering the 53% of reduction in grassland bird abundance in the past few decades (Rosenberg et al., 2019), our estimates suggest that if grassland bird abundance had not declined, then the U.S. would not have to use neonicotinoids to reach current corn yield level. In the case of soybeans, the ban on neonicotinoid use would decrease soybean yield by 7.02%, resulting in about $4.1 billion loss per year. To offset this soybean yield reduction, about 120.9% increase in grassland birds' abundance would be needed.

Our contributions to existing literature are threefold. First, by conducting a national-level analysis, our study complements existing studies that investigate the impact of birds on crops based on small-field experiments. These studies suggest that effect of birds on crop yields can be positive, negative, or neutral depending on the type of crops and birds in question (e.g., Karp et al. 2013; Garfinkel et al. 2020; Garfinkel et al., 2022; Campos et al., 2023; Mayne et al., 2023). For instance, Garfinkel et al. (2020, 2022) find that birds suppress pests in corn fields and boost corn yield while having no effect on soybean yield. Pejchar et al. (2018), Garfinkel et al. (2020), and Garcia et al. (2023) find that some birds can damage crops by preying on beneficial predatory arthropods or by spreading pathogens that develop into plant disease. A few other field-experiment-based studies evaluate the service or disservice of birds in terms of crop physical damage or crop pest density, but they do not consider birds' effect on crop yields (e.g., Van Bael et al., 2007; Koh, 2008; Whelan et al., 2015). To the best of our knowledge, the present study is the first national level analysis to investigate the impact of birds on U.S. corn and soybean yields.

Second, although the impact of agricultural intensification on bird biodiversity is well documented (e.g., Hallmann et al., 2014; Li et al., 2020; Cole et al., 2021; Noack et al., 2021; and Strobl, 2021), the reverse direction—the impact of bird diversity on agricultural production—remains underexplored. Our study addresses this research gap by providing empirical evidence on the influence of bird biodiversity on crop yields in the U.S. By focusing on the bird-crop relationship, our study also adds onto the literature of quantifying the agro-ecological services of wildlife (e.g., Losey and Vaughan (2006) on insects and Boyles et al. (2024) on bats). Our estimates about the annual economic costs associated with hypothetical grassland bird extinction and a neonicotinoid ban will assist policymakers in assessing the value of ecological service of birds on corn and soybean yields as well as the value of neonicotinoid use, enabling them to evaluate the trade-offs between a neonicotinoid ban and bird conservation policies.

Finally, while the negative consequences of chemical pesticides on biodiversity and human health have been intensively scrutinized (e.g., Jones, 2020; Calzada et al., 2023; Fletcher et al., 2024), quantifying how pesticide uses (e.g., neonicotinoids in our study) moderate the ecological services of biological pest control agents such as birds on crop yields is lacking. Some previous studies (e.g., Hurley and Mitchell, 2017; Garfinkel et al., 2022; Mayne et al., 2023) have focused on how birds, or separately, neonicotinoids will contribute to crop yields based on small field experiments or econometric analysis. However, how birds and neonicotinoids interact with each other in determining crop yield has received little attention. Our study fills this research gap as well. We find that neonicotinoid use weakens the positive effect of grassland birds and endangered birds on corn and soybean yields. This finding suggests that reducing neonicotinoid uses could potentially increase the agro-ecosystem service of these birds, thereby promoting sustainable pest management practices.

The subsequent sections of this article are organized as follows. Section 2 presents a conceptual framework to illustrate how birds may provide ecosystem service or disservice to a crop by influencing the pest pressure and to show the possible relationship between birds and pesticide use. Section 3 describes the empirical model of our study. Section 4 describes the data and variables, and Section 5 presents the results. Section 6 provides a thorough discussion of the insights derived from these results. Section 7 concludes.

2. CONCEPTUAL FRAMEWORK

In this section, we present a stylized conceptual framework to illustrate how birds may provide ecosystem service or disservice to a crop by influencing the pest pressure, which has effects on crop yields.[2] We assume that there are two types of insects associated with crops: pest insects and beneficial insects. Pest insects (e.g., white grubs, cutworms) cause crop damage while beneficial insects (e.g., lacewings and seven-spotted ladybird beetles) prey on pest insects and

[2] For simplicity we only consider the effects of birds through the pest-control channel. Because corn is wind-pollinated and soybean is self-pollinated (Bannert and Stamp, 2007; Vogler et al., 2009; Kim et al., 2021), we do not consider the pollination effect of birds.

thus reduce crop damage. Although there are many types of birds, here we categorize them into two groups (i.e., service group and disservice group) based on their diets, which determine a group's impact on crop yields. For instance, if a bird mainly feeds on pest insects, then it is categorized into the service group. If a bird mainly feeds on crop grain, beneficial insects, or even birds in the service group, then it is included in the disservice group. We present the possible food chain of these two groups of birds and two types of insects in Figure 1 to demonstrate the relationship between birds and crop yields.

Let y^c denote the yield of crop c $\in \{\text{corn}, \text{soybean}\}$ and Q_p^c denote the quantity of pesticide used for crop c. Furthermore, Q_{PI}^c and Q_{BI}^c denote the abundance of pest insects and beneficial insects in the field of crop *c,* respectively. *Let* Q_B^c represent the number of birds visiting the field and *X* represents the vectors of other co-variates that affect the yield of crop *c*, such as climatic variables and non-pesticide input uses. The abundance of pest insects, Q_{PI}^c, is a function of Q_B^c, Q_{BI}^c, and Q_p^c. Therefore, we have:

$$Q_{PI}^c = h(Q_B^c, Q_{BI}^c, Q_p^c). \tag{1}$$

The yield function of crop *c* can be written as,

$$y^c = f^c(Q_{PI}^c, X). \tag{2}$$

The marginal impact of birds on crop yield can be shown in the following equation as,

$$\frac{\partial y^c}{\partial Q_B^c} = \frac{\partial f^c(\cdot)}{\partial h(\cdot)} \cdot \frac{\partial h(\cdot)}{\partial Q_B^c}, \tag{3}$$

where the first term in the right-hand side of equation (3), $\frac{\partial f^c(\cdot)}{\partial h(\cdot)}$, the marginal impact of pest pressure $h(Q_B^c, Q_{BI}^c, Q_p^c)$ on crop yield y^c, is expected to be negative. The second term, $\frac{\partial h(\cdot)}{\partial Q_B^c}$, is the marginal impact of birds Q_B^c on pest pressure $h(Q_B^c, Q_{BI}^c\ Q_p^c)$, which can be positive or negative depending on the types of birds (service birds or disservice birds).

To determine whether birds and pesticide use are substitutes or complements in affecting crop yield, we examine the impact of pesticide use on the marginal ecological (dis)service of birds, which can be written as,

$$\frac{\partial^2 y^c}{\partial Q_B^c \partial Q_p^c} = \underbrace{\frac{\partial f^c(\cdot)}{\partial h(\cdot)} \cdot \frac{\partial^2 h(\cdot)}{\partial Q_B^c \partial Q_p^c}}_{(a)} + \underbrace{\frac{\partial^2 f^c(\cdot)}{\partial h^2(\cdot)} \cdot \frac{\partial h(\cdot)}{\partial Q_p^c} \cdot \frac{\partial h(\cdot)}{\partial Q_B^c}}_{(b)}. \tag{4}$$

When $\frac{\partial^2 y^c}{\partial Q_B^c \partial Q_p^c} \leq 0$, indicating that pesticide use decreases the marginal impact of birds on crop yield, then we define that birds and pesticide use are substitutes; when $\frac{\partial^2 y^c}{\partial Q_B^c \partial Q_p^c} > 0$, we categorize them as complements.[3]

In equation (4), term (a) indicates how pesticide use affects the marginal impact of birds on crop yield through affecting the marginal impact of birds on pest pressure, which is reflected by $\frac{\partial^2 h(\cdot)}{\partial Q_B^c \partial Q_p^c}$ · Term (b) represents how pesticide use affects the marginal impact of birds on crop yield through affecting the marginal impact of pest pressure on crop yield, measured by $\frac{\partial^2 f^c(\cdot)}{\partial h^2(\cdot)} \cdot \frac{\partial h(\cdot)}{\partial Q_p^c}$. Although the relationship between pest density and crop yield varies from crop to crop and from one pest species to another within the same crop, we assume that the relationship between pest pressure and crop yield is concave downward with yield decreasing at an increasing rate as pest pressure intensifies (Pedigo, 2025). This implies that the signs of both $\frac{\partial f^c(\cdot)}{\partial h(\cdot)}$ and $\frac{\partial^2 f^c(\cdot)}{\partial h^2(\cdot)}$ are negative in equation (4). The last two items in term (b), $\frac{\partial h(\cdot)}{\partial Q_p^c}$ and $\frac{\partial h(\cdot)}{\partial Q_B^c}$, capture the marginal effect of pesticide use and birds on pest pressure,

[3] This definition of substitutability between pesticides and birds is analogous to that in Moscona and Sastry (2023) where the authors define the substitutability between technology and climate (see their Definition 1).

respectively. The former is expected to be negative and the latter can be either positive (for disservice birds) or negative (for service birds).

In the case of service birds, term (b) is negative because all three items in this term are negative. The sign of term (a), however, is determined by the sign of $\frac{\partial^2 h(\cdot)}{\partial Q_B^c \partial Q_p^c}$ · If $\frac{\partial^2 h(\cdot)}{\partial Q_B^c \partial Q_p^c} > 0$ then term (a) is negative, implying that $\frac{\partial^2 y^c}{\partial Q_p^c \partial Q_B^c}$ is negative and that pesticide use and service birds are substitutes. On the other hand, if $\frac{\partial^2 h(\cdot)}{\partial Q_B^c \partial Q_p^c} < 0$ then term (a) is positive. In this case, the sign of $\frac{\partial^2 y^c}{\partial Q_p^c \partial Q_B^c}$ is undetermined and depends on the magnitude of terms (a) and (b). Without knowing further specifications of the yield and pest pressure functions, we cannot decide whether pesticide use and service birds are substitutes or complements. This leaves the relationship between birds and pesticides an empirical question.

For disservice birds, item $\frac{\partial^2 h(\cdot)}{\partial Q_B^c \partial Q_p^c}$ is likely to be negative because the increase in pesticide use would potentially limit the impact of disservice birds on pest pressure (in the extreme, pesticide use is so intensive that disservice birds no longer impact pest pressure). Thus, the term (a) is likely to be positive. Because term (b) is positive for disservice birds, the sign of $\frac{\partial^2 h(\cdot)}{\partial Q_B^c \partial Q_p^c}$ is positive as well, indicating that pesticide use and disservice birds are complements. Table 1 summarizes the impact of service birds, disservice birds, and pesticide on crop pest and presents the possible relationship between pesticides and birds in determining crop yield.

3. EMPIRICAL MODEL

Based on the conceptual framework discussed above, we seek to estimate the effect of birds' biodiversity on corn and soybean yields in the U.S. By following Li et al. (2020), we consider three measures of bird diversity (abundance, richness, and evenness) of grassland and insectivorous birds. Furthermore, to explore the agro-ecosystem services of endangered bird species, we also include this group of birds in our analysis. Another key control variable included in the empirical model is neonicotinoid use. In addition, because fertilizer accounts for a large share of the total crop production cost (39% for corn and 21% for soybeans (Economic Research Service (ERS), the U.S. Department of Agriculture (USDA), 2024)), fertilizer prices may affect county-level crop yields through affecting farmers' input-use or crop-choice decisions, or both (Miao et al., 2016). Genetically engineered (GE) varieties reduce yield losses caused by certain crop pests, thereby allowing crops to reach their yield potential (Fernandez-Cornejo et al., 2014). Therefore, we control for both fertilizer price index and adoption rate of GE varieties in our regression model. Other control variables include weather and time trend, as the former is crucial for crop production and the latter represents technological advances. Finally, since data for pest pressure are not available to us, we control for crop damage duration in addition to temperature and precipitation, which could partially approximate the pest pressure in a county (Diffenbaugh et al., 2008; Crossley et al., 2023).[4]

The regression model for each crop yield and each bird diversity measure is specified as follows:

$$y_{it}^{c}=\beta_0+\beta_1 B_{it}+\beta_2 P_{it}+\beta_3 B_{it}\times P_{it}+\boldsymbol{\beta}_4\boldsymbol{F}_{it}+s_i+u_{it}\ , \quad (5)$$

where y represents crop yield per acre (in logarithmic form), subscripts i and t respectively stand for county and year, and superscript c stands for crop (corn or soybeans). In addition, B is one of the bird biodiversity measures (i.e., abundance, species richness, and species

[4] Crop damage duration is defined as the number of the days with extreme heat associated with crop loss in a county for a given year (Center for Emergency Management and Homeland Security, 2022).

evenness); P is the quantity of neonicotinoid use; $\boldsymbol{F}$ is a vector of controls including weather variables, crop damage duration, GMO adoption rate, fertilizer price, and time trends. Finally, s is the county fixed effects and u is the error term. The error term is clustered at the county level to allow for arbitrary serial correlation within a county. The construction of these variables is discussed below in the Data and Variables section. In addition to crop yield, bird diversity measures and neonicotinoid use are in the natural logarithmic form as well. We conduct the regression analysis separately for each biodiversity measure of each bird group by using equation (5).

It is likely that the following three variables in model (5) are endogenous: bird diversity measure, neonicotinoid use, and fertilizer price. Bird population and bird diversity may be influenced by crop yields of a county (Chen and Khanna, 2024), causing the simultaneity issue. Neonicotinoid use can be endogenous because some unobserved time varying factors that may affect both crop yield and neonicotinoid use, such as local pest outbreaks and farming practice, cannot be controlled by fixed effects. Furthermore, following Miao et al. (2016) and Li et al. (2019), we treat lagged fertilizer price as an endogenous variable because unobserved, time-varying confounders may affect both crop yield and fertilizer applications, which in turn may influence fertilizer prices.

We employ a fixed-effect instrumental variable (FE-IV) approach to address the aforementioned endogeneity issues. The FE-IV approach is appropriate because it can address the endogeneity issues of explanatory variables by removing the fixed effects such as the county-level geographical and soil characteristics that may be correlated with some explanatory variables as well as by instrumenting endogenous variables using instrumental variables. Specifically, we use the one-year lagged value of bird diversity measure as an IV for the current period bird diversity measure. The lagged bird diversity affects the current year's bird diversity through bird population dynamics but is unlikely to directly affect the current year crop yield once we control for input use, weather, crop damage duration, time trend, and some other variables. In addition, we use the pesticide price index as an IV for neonicotinoid use. We believe that pesticide price is a valid instrument because it directly correlates with neonicotinoid use (Bocker and Finger, 2017) but does not directly affect crop yield. One might be concerned that the pesticide price index may influence corn and soybean yields by affecting farmers' crop choices, as crop rotation and mixed cropping are common tools to manage insect pests (Fernandez-Cornejo and Jans, 1999). However, pesticide expenditure accounts for only 5-15% of the total production costs (ERS, 2024). Therefore, we believe that pesticide prices should not be a major driver of changes in crop farming patterns which may have an impact on crop yields.

Following Miao et al. (2016) and Li et al. (2019), we use the natural gas price index as an IV for the fertilizer price index for two reasons. First, natural gas is one of the major inputs for manufacturing synthetic fertilizers (Huang, 2007). Therefore, natural gas prices are highly correlated with fertilizer prices. Second, gasoline, diesel, and electricity are primary direct energy sources for different farm operational practices rather than natural gas (Marshall et al., 2015), and worldwide geopolitical and economic events determine the price of these energy sources (U.S. Energy Information Administration (USEIA), 2016). One may argue that 43% of electricity in U.S. is generated from natural gas (USEIA, 2023) and that electricity price may influence crop yield by affecting farm management such as irrigation. Since electricity cost only accounts for about 3% of a farm's total costs (ERS, 2024), we believe the link through which the price of natural gas affects the price of electricity and then affect crop acreage would be weak and negligible.

4. DATA AND VARIABLES

Our analysis focuses on corn and soybean producing counties in the United States, with a temporal framework over 1997-2014. Our data start from 1997 because the number of bird survey routes maintained by the North American Breeding Bird Survey increased substantially after 1997, providing more observations. Moreover, the use of neonicotinoids was limited before the mid-1990s. We have limited our sample to 2014 because the United States Geological Survey (USGS) ceased reporting neonicotinoid use after 2014 (USGS, 2023). In the remaining part of this section, we describe the key variables in detail. The summary statistics of the variables are presented in Tables S2 and S3 in the online Supporting Information (SI).

Yield data. We obtain the county-level data for corn and soybean yields from the National Agricultural Statistics Services (NASS) of the U.S. Department of Agriculture (USDA). Substantial inter-county variability in the corn and soybean yields exists. The range of corn yield is from 4.5 to 246 bushels per acre, whereas that of soybean is 0.7 to 69.3 bushels per acre. Maps (a) and (b) in Figure 2 present the average yield for corn and soybean over our sample period, respectively.

Bird data. We obtain bird counts by species over 1997-2014 from the North American Breeding Bird Survey (BBS) maintained by the Eastern Ecological Science Center of the USGS. The Breeding Bird Survey data have become a primary source of large-scale, long-term bird population data and have been widely used in the literature (e.g., Rosenberg et al., 2019; Li et al., 2020; Chen and Khanna, 2024; Engist et al., 2024). Starting in 1966, the BBS provides an annual count of more than 700 North American bird species at thousands of observation routes. Every year, during the breeding season (around June), bird observation data are collected along the selected survey routes in the U.S. and Canada. A survey route spans about 24.5 miles long, with stops at approximately half-mile intervals. Participants skilled in avian identification conduct a 3-minute count at each observation stop, recording all birds seen or heard within a 400-meter radius. There are over 4,100 survey routes in the U.S. and Canada (Carroll et al., 2023).[5] Since not all routes are sampled every year, our panel dataset is unbalanced. Following Spiller and Randy (2019) and Li et al. (2020), we identified 29 grassland bird species and 42 insectivore bird species. We also identified 43 endangered bird species based on the information provided by the U.S. Fish and Wildlife Service (2024). The names of these species are listed in Table S4 in the online SI.

Following the procedure of Li et al. (2020), based on the data for birds observed on each route, we calculate the bird population abundance (measured by total bird counts), species richness (measured by the number of distinct species), and species evenness (measured by Shannon diversity index) for a bird group (i.e., grassland birds, insectivorous birds, or endangered birds) at the county-level. If a route spans more than one county, then we allocate the bird population counts of the route to a county based on the proportion of the route located in that county.[6] Shannon diversity index of a county is calculated as

$$-\sum_{i=1}^{S} p_i * \log(p_i), \tag{6}$$

where p_i is the ratio of species i's population (denoted by $Population_i$) to the total bird population of a bird group within a county in a year. Mathematically, p_i can be calculated by

[5] See Figure S1 in the online SI for the geographical distribution of these survey routes in the contiguous United States.
[6] First, we allocate the count of each bird species along each route to a county based on the proportion of the route within the county. Then, we aggregate the bird counts of a species across all routes within the county to obtain total number of birds of that species within the county in a year. The population abundance of a bird group in the county and year is the sum of total number of birds of all species within that group in that county and year. The species richness of a bird group for a county and year is the number of distinct species in a bird group within that county and year.

using $p_i = Population_i / \sum_{i=1}^{S} Population_i$, where S is the total number of species in a bird group within a county for a given year. Maps (c) to (e) of Figure 2 show the county-level average bird count over the sample period for the three bird groups considered in this study.

Pesticide data. County-level neonicotinoid use data for corn and soybeans are obtained from the USGS Pesticide National Synthesis Project. Furthermore, for every county (excluding those in California), the pesticide data include values of active ingredients under two scenarios (namely, EPest-low and EPest-high) to address the missing data problem in pesticide-crop combinations. The two scenarios differ in the way of treating the missing values (USGS, 2023): Under the EPest-low scenario, the missing values are set to be zero, while under the EPest-high scenario, the missing values are extrapolated from the non-missing values of neighboring crop reporting districts. California uses extrapolation techniques and reports the same values for EPest-low as that of Epest-high. Following Li et al. (2020) and Chen and Khanna (2024), we use the EPest-high values for our analysis because there are fewer missing observations under that scenario, and we include Acetamiprid, Clothianidin, Dinotefuran, Imidacloprid, Thiacloprid, and Thiamethoxam as neonicotinoid pesticides. Map (f) of Figure 2 shows the county-level average neonicotinoid use over the sample period.

Weather data. The data for temperature and precipitation are obtained from the Terrestrial Hydrology Research Group at Princeton University. Existing literature suggests that the relationship between temperature and yield is non-linear (Schlenker and Roberts, 2009). To capture such a nonlinear relationship, we use the concept of growing degree days (GDD), reflecting the amount of time that the temperature falls in an interval on a specific day. Following Schlenker and Roberts (2009), we define the growing season as March to August and obtain growing degrees days (GDD) based on the data for daily maximum and minimum temperatures. The lower and upper thresholds of the GDD for corn are set to be 8°C and 29°C, respectively. For soybeans, these two thresholds are 8°C and 30°C, respectively. Furthermore, we define the GDD between the two thresholds as normal GDD, and GDD above the upper threshold as overheat GDD. Precipitation is measured as the total accumulation over the growing season. Following Schlenker and Roberts (2009), we include both linear and quadratic terms of precipitation.

Other variables. We obtain the GE variety adoption rate at the state-year level from the ERS of the USDA. Since the adoption data before 2000 are missing in our sample and the adoption rate during that period was low, we approximate GE adoption rate before 2000 as zero. The details of the GE adoption rate for corn and soybeans are presented in Tables S5 and S6 in the online SI. Similarly, we obtain the crop damage duration (in days) information from the Center for Emergency Management and Homeland Security (2022). We obtain the national-level fertilizer price index from the ERS of the USDA. Because farmers generally purchase fertilizer in the fall prior to spring planting, we use one-year lagged fertilizer price index in our analysis. The annual natural gas price index and annual pesticide price index are obtained from the U.S. Energy Information Administration and the NASS, respectively (USEIA, 2024; NASS, 2024). All prices are in 2011 dollars.

5. RESULTS

We estimate two different models for each crop (i.e., corn and soybean): the fixed effect (FE) model and the FE-IV model. The former assumes that all the variables are exogenous, and the latter considers the endogeneity issues discussed above. We include FE models along with our preferred models (i.e., FE-IV) to show the importance of addressing the endogeneity issue. For the key variables, the regression results for corn yield based on equation (5) are presented in Tables 2-4, each of which focuses on a bird biodiversity measurement. We present the full set of results of corn yield in Tables S7-S9 in the online SI. The corresponding full set of results for soybean yield are in Tables S10-S12 in the online SI.

We use Kleibergne and Paap (2006) *rk* statistics to test for under identification for our models with FE-IV. The test results show that all our preferred models are identified. We use two tests for weak identification: Cragg-Donald *F* Wald statistic and Kleibergen-Paap Wald rk *F* statistic. Our results show that regression models with instrumental variables pass the weak identification test, indicating that instrumental variables are strongly correlated with the endogenous variables. The overidentification test does not apply here because we have the same number of instruments as the number of endogenous variables.

5.1 Determinants of corn yield

Tables 2-4 show that the results from the FE models are quite different from the FE-IV models for each bird group. For instance, in model 1(a) of Table 2 where the endogeneity issue is ignored, the coefficient of grassland bird abundance is negative (-0.005) and statistically insignificant. However, when the endogeneity issue is addressed (see model 1(b) in the same table), the coefficient of grassland bird abundance is positive and statistically significant at 1% significance level.

From model 1(b) in Table 2 we can see that the coefficients of grassland bird abundance (log-transformed) and neonicotinoid use (log-transformed) are both positive and statistically significant at 1% significance level. Furthermore, the coefficient of the interaction term between grassland bird abundance and neonicotinoid use is negative and statistically significant at 1% significance level, indicating a substitutive relationship between grassland bird abundance and neonicotinoid use in determining corn yield. In other words, neonicotinoid and grassland bird decrease each other's marginal impact on corn yield. When evaluated at the sample mean of the log-transformed neonicotinoid use, the estimated elasticity of corn yield with respect to grassland bird abundance is 0.1152 and is statistically significant at 1% level.[7]

Results from model 2(b) of Table 2 show that the coefficient of insectivorous bird abundance is negative and statistically significant. For neonicotinoid use, the coefficient is positive but not statistically significant at conventional significance levels: with a *p*-value of 0.12, it suggests a weak effect. In contrast to the results from model 1(b), the coefficient of the interaction term between insectivorous bird abundance and neonicotinoid use here is positive and statistically significant, indicating that the marginal impact of neonicotinoid is greater when the insectivorous birds are more abundant. One possible reason for this complementary relationship may be due to insectivorous birds' foraging behaviors: they might mainly prey on beneficial insects that feed on insect pests (see Figure 1) (Jimenez-Albarral et al., 2025) and thus increase the pest pressure. In this case, the same amount of pesticide use may eliminate more pests than in the case where pest pressure is not increased, resulting in greater impact on crop yield. Based on results from model 2(b), when evaluated at the sample means, the estimated elasticity of corn yield with respect to insectivorous bird abundance is -0.016 but it is statistically insignificant (p=0.183).

Results of model 3(b) show that neither the coefficient of endangered bird abundance nor the interaction term is statistically significant, suggesting an insignificant effect of endangered bird abundance on corn yield. One probable reason for the insignificant effect

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[7] Calculated by using 0.116-0.00018×4.55, where 0.116 is the coefficient of log-transformed grassland bird abundance, -0.00018 is the coefficient of the interaction term between log-transformed grassland bird abundance and log-transformed neonicotinoid use, and 4.55 is the sample mean of log-transformed neonicotinoid use. Using the log-transformed sample mean of neonicotinoid levels in the calculation yields quite close elasticity value: 0.1149.

may be because the endangered bird species group includes a mix of grassland bird species and insectivorous bird species, and their effects on corn yield cancel each other.

Table 3 presents the impact of grassland, insectivorous, and endangered bird species richness on corn yield. By comparing the results from the FE-IV models in Table 3 with those in Table 2, we can see that the signs and significance of the coefficients in Table 3 are largely the same as those of the corresponding coefficients in Table 2. For instance, similar to the results under model 1(b) in Table 2, results of model 4(b) in Table 3 show that the coefficient of grassland bird species richness is positive while the coefficient of the interaction term is negative, and both are statistically significant. For insectivorous birds (see model 5(b) in Table 3), the coefficient of species richness is negative whereas the coefficient of the interaction term is positive; both are statistically significant. These results indicate that grassland and insectivorous bird species richness may act as a substitute for and a complement to neonicotinoid use, respectively, in determining corn yield. Because the signs of the coefficients of model 6(b) (for endangered birds) are the same as those of the corresponding coefficient in model 4(b) (for grassland bird), endangered bird species richness is a substitute for neonicotinoid use in determining corn yield. In sum, similar to what we find about the relationship between bird abundance and neonicotinoid use from Table 2, results in Table 3 show that neonicotinoid use decreases the beneficial impact of grassland birds and endangered birds, as well as the detrimental impact of insectivorous birds, on corn yield.

Based on the coefficient estimates under model 4(b) in Table 3, when evaluated at the sample means, the elasticity of corn yield with respect to grassland bird species richness is small (0.0006) and statistically insignificant.[8] Following the same procedure, based on the results from model 5(b) we can calculate that when evaluated at sample means, the elasticity of corn yield with respect to insectivorous bird species richness is -0.07, with a *p*-value at 0.07, indicating a slight detrimental effect of insectivorous birds species richness on corn yield. Similarly, we find that when evaluated at the sample means, the elasticity of corn yield with respect to endangered bird species richness is -0.03 and statistically insignificant.

Table 4 presents the impact of grassland, insectivorous, and endangered bird species evenness on corn yield. The signs and significance of the coefficients in this table follow the same pattern as those in Tables 2 and 3, indicating that the impact of species evenness on corn yield is similar to that of bird abundance and species richness, and that the relationship between species evenness and neonicotinoid use mirrors the relationship between bird abundance (or species richness) and neonicotinoid use. Based on models 7(b) and 9(b), when evaluated at the sample means, the elasticity of corn yield with respect to grassland bird and endangered bird species evenness is statistically insignificant. However, when evaluated at the sample means, the elasticity of corn yield with respect to insectivorous bird species evenness is negative (-0.18) and statistically significant at the 10% level (model 8(b)).

The estimates of all other coefficients in the corn yield models under the three measures of bird biodiversity are presented in Supplementary Tables S7 to S9 in the online SI. As expected, corn yield responds negatively to the fertilizer price index in most of our preferred regression models. The coefficient of crop-damaging duration is negative and

[8] Calculated by using 0.147-0.0322×4.55, where 0.147 is the coefficient of log-transformed grassland bird species richness, -0.0322 is the coefficient of the interaction term between log-transformed grassland bird species richness and log-transformed neonicotinoid use, and and 4.55 is the sample mean of log-transformed neonicotinoid use.

statistically significant at the 1% significance level across all FE-IV models. The sign and statistical significance level of the estimates of climate variables are robust across all regressions, and the results are consistent with previous studies focused on climate-crop relationships (Lobell and Field, 2007; Schlenker and Roberts, 2009; Miao et al., 2016; Malikov et al., 2020).

5.2 Beyond sample means

In the analysis described above, we evaluate the elasticity of corn yield with respect to bird diversity measures at the sample means. To further illustrate the impact of neonicotinoid use in determining the agro-ecological service values of birds on corn yield, we also evaluate the elasticity of corn yield with respect to bird biodiversity at various levels of neonicotinoid use. The results are presented in Figure 3.

Graph (a) in Figure 3 shows that the elasticity of corn yield with respect to grassland bird abundance is quite insensitive to the levels of neonicotinoid use, with a value around 0.12 presenting a slight downward trend as neonicotinoid use increases. This is because the coefficient of the interaction term between grassland bird abundance and neonicotinoid use is extremely small (-0.00018, see model 1(b) in Table 2). Graph (b) displays a clear downward trend of the corn yield elasticity with respect to grassland bird species richness as neonicotinoid use increases, with the elasticity being positive and statistically significant when evaluated at low levels of neonicotinoid use (e.g., the 10^{th} percentile). Graph (c) follows the same trend as that in Graph (b), but the yield elasticity with respect to grassland bird species evenness is statistically insignificant in most cases of neonicotinoid uses. Graphs (d), (e), and (f) in Figure 3 show that when the level of neonicotinoid use is low (e.g., at the 10^{th} percentile), the corn yield elasticity with respect to each measure of insectivorous bird biodiversity is negative and statistically significant. As neonicotinoid use increases, however, the elasticity become less negative and statistically insignificant. Graphs (g), (h), and (i) show the same pattern as that displayed in Graphs (a), (b), and (c), although none of the yield elasticities with respect to the measures of endangered bird biodiversity is statistically significant.

In sum, Figure 3 shows that when neonicotinoid use is low, both the beneficial impact of grassland birds and the detrimental impact of insectivorous birds on corn yield are more pronounced than when neonicotinoid use is high. In other words, as a pest control agent, neonicotinoids reduce the extent to which corn yield is affected by birds' ecosystem services or disservices.

5.3 Soybean yield and additional results

Due to space limitation, the detailed regression results for soybean yield are presented in Tables S10 to S12 in the online SI. Here we only briefly summarize the major results of soybean yield models and some additional results.

The signs of the soybean yield model coefficients in Tables S10 to S12 in the SI follow the same pattern as those of the corn yield model coefficients in Tables 2 to 4, indicating that the relationship between bird biodiversity and neonicotinoid use for soybean production is the same as that for corn production. Particularly, across all the soybean yield models, we find the substitutive relationship between grassland birds and neonicotinoid use. So is the relationship between endangered birds and neonicotinoid use. In contrast, insectivorous birds have a complementary relationship with neonicotinoid use. When evaluated at the sample mean of neonicotinoid use, all three diversity measures (i.e., abundance, species richness, and species abundance) of grassland, insectivorous, and endangered birds have no statistically significant impact on soybean yield, except the species richness of grassland birds (with an elasticity of 0.075 at 5% significance level).

In addition to evaluating the elasticities at sample means, similar to corn yield, we also evaluate the elasticity of soybean yield at various levels of neonicotinoid use. The results are presented in Figure 4. Graphs (a) to (c) show that when evaluated at a low level of neonicotinoid use (e.g., the 10th percentile), the elasticities of soybean yield with respect to grassland bird abundance, species richness, and species evenness are positive and statistically significant. These elasticities decrease and eventually become negative as the levels of neonicotinoid use increase. Note that they are statistically insignificant when the neonicotinoid use levels are around the median but generally become statistically significant with negative point estimates when the neonicotinoid use reaches the 90th percentile. The relationship between neonicotinoid uses and soybean yield elasticities with respect to endangered bird biodiversity measures follow the similar pattern as that regarding grassland birds (see Graphs (g) to (i)). These findings provide evidence that neonicotinoids use impede agro-ecosystem services provided by grassland birds and endangered birds. In contrast, the elasticities of soybean yield with respect to insectivorous bird biodiversity measures increase as neonicotinoid uses increase, although in most cases these elasticities are statistically insignificant across all neonicotinoids use levels (see Graphs (d) to (f)).

Based on field experiments, Garfinkel et al. (2020, 2022) find that birds increase pest in soybean field due to intraguild predation, although the net effect on soybean yield was not statistically different from zero. Our national level analysis suggests that at lower levels of neonicotinoid use (e.g., the 10th percentile) both grassland birds (abundance, species richness, and species evenness) and endangered birds (abundance and species richness) increase soybean yield whereas insectivorous bird richness decreases soybean yield. The present study thus illustrates the moderating effect of pesticides on birds in determining soybean yields and shows that different bird groups have different impact on soybean yields. The impact of other variables on soybean yield is as expected and is presented in Tables S10-S12 in the online SI.

Moreover, Tables S13-S18 in the online SI present the corn and soybean yield regression results by only using counties east of the 100th Meridian. These counties account for over 90% of total corn production and more than 95% of total soybean production in the United States. We perform this sub-sample analysis to see if results still hold on major corn and soybean producing counties. The results from these sub-sample analysis show that the coefficients of estimates of the variables under the sub-dataset are similar in magnitude and statistical significance to those under the full dataset.

6. COUNTERFACTUAL ANALYSES

Based on results from model 1(b) of Table 2 for corn yield and from model 10(b) of Table S10 in the SI for soybean yield, we conduct counterfactual analyses to further evaluate the agro-ecoservice value provided by grassland birds on corn and soybean yields. We consider two separate counterfactual scenarios: Scenario I, an extinction of grassland birds, and Scenario II, a ban on neonicotinoid use. Scenario I is relevant because existing research suggests that bird population is declining (Brennan and Kuvlesky, 2005; Rosenberg et al., 2019). For example, Rosenberg et al. (2019) estimate that over 1970-2019, the net decrease in bird population was around 3 billion in the U.S., a 29% reduction. Grassland birds have experienced faster declines, with a 53% decrease in their population from 1970 to 2019 (With et al., 2008; Rosenberg et al., 2019). In addition, birds from 12 families have suffered the most, contributing 90% of cumulative bird loss in the same time framework (1970 to 2019) (Rosenberg et al., 2019). Scenario II is relevant because EU has banned some neonicotinoids and the State of New York in the U.S. has already enacted regulation regarding the ban of neonicotinoid use (Axelson, 2024; European Union, 2024).

Under Scenario I, our estimates reveal that if grassland birds were to become extinct, then everything else being equal, corn yield would decrease by 11.52% (see Table 5).[9] Note that when evaluated at the sample means, the impact of grassland bird abundance on soybean yield is not statistically different from zero. Assuming a national average corn yield at 177.3 bu./acre, corn acreage at 94,641,000 acres, and price at $4.8/bu., the annual economic loss from this yield reduction is estimated to be $9.3 billion.[10] In addition, our estimates show that if grassland birds were to become extinct, we would need to increase neonicotinoid use by 219.43% compared to the current use rate to offset the yield reduction.[11] However, this is unlikely a sustainable approach to maintain yield because many studies have documented the health and environmental consequences associated with the use of agricultural pesticides (e.g., Eng et al., 2019; Taylor, 2021; Pena and Dixon, 2021; Calzada et al. 2023; Sasikala et al. 2023; Skidmore et al. 2023; Kaur et al., 2024), showing that increasing pesticide use to control insect pests is not a socially, ecologically, or economically sustainable approach. For instance, inappropriate pesticide use can decrease farm profits by eliminating natural enemies of crop pests (e.g., the grassland birds and ladybird beetles) thereby decreasing the ecological biocontrol service (Lu et al., 2012). Moreover, when crop pests are continuously exposed to pesticides, pests become pesticide resistant, thereby demanding increased quantity of pesticide

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[9] Here 11.52% is calculated by using $(0.116-0.0001847\times4.55)\times100$, where 0.116 is the estimate of the coefficient of log of grassland bird abundance in Table 2 , -0.0001847 is the estimate of the coefficient of the interaction term between log of grassland bird abundance and log of neonicotinoid use, 4.55 is the sample mean of neonicotinoid use, and 100 represents the case when 100% of grassland birds disappear (i.e., an extinction).
[10] Average national corn yield, total acres under corn, and average price of corn of year 2023 are obtained from the NASS of the USDA.
[11] Calculated by using $11.52/0.052$, where 11.52 is the decrease in corn yield (in %) if grassland birds were to become extinct and 0.052 is the coefficient of neonicotinoid use in Model 1(b) of Table 2.

use to prevent crop loss from crop pest (Brattsten et al., 1986; Waterfield and Zilberman, 2012; Wu et al., 2018; Sargent et al., 2023; Stokstad, 2024).[12]

Under Scenario II (a neonicotinoid ban), holding everything else equal, there would be a 3.82% and 7.02% decrease in corn and soybean yields, respectively (see Table 5 and Tables S19-S20 in the online SI for details). The economic cost of neonicotinoid ban is estimated to be $3.1 billion and $4.1 billion annually for corn and soybeans, respectively.[13] We estimate that increasing grassland birds abundance by 32.93% is sufficient to offset the corn yield reduction caused by the ban.[14] Given that grassland bird abundance has declined by more than 53% in the U.S., our finding suggests that had the grassland bird population not declined, the U.S. corn yield would have not needed to rely on neonicotinoids to reach today's level. For soybean yields, were there a ban on neonicotinoid use, then about 120.9% increase in grassland birds' abundance would be needed to offset the decrease in soybean yield caused by the ban.

Further, we map the drop in corn yield and corn production in each county under Scenario I and Scenario II (Figure 5). We also map the percentage and the absolute amount of neonicotinoid use that would need to be increased to offset the corn yield drop if grassland birds were to become extinct. Similarly, we map the required increases in the percentage and absolute number of grassland birds needed to offset the corn yield loss if neonicotinoids were

[12] One example is cotton bollworm outbreaks in China. In the 1970s, Chinese farmers extensively used insecticides to control cotton bollworm. However, by the early 1990s, the pest had developed resistance to pesticides, leading to severe outbreaks.
[13] For corn, we use the same figures as we assumed to calculate economic cost of grassland birds' disappearance. For soybeans, we use a national soybean yield average at 50.6 bu./acre, soybean acreage at 82,356,000 acres, and price at $14.1/bu. obtained from the NASS.
[14] Calculated by using $(1/0.116)\times 3.82$, where 0.116 is the coefficient of grassland bird abundance in model 1(b) of Table 2 and 3.82 is the decrease in corn yield (in %) if there were a ban on the neonicotinoid use (see Table S19 in the online SI).

banned. Figure 5 shows that under Scenario I (i.e., grassland bird extinction), the percentage reduction in corn yield is smaller in the Midwest than that in the non-Midwestern regions (see Graph (a)). In absolute terms, the largest corn yield reductions under Scenario I would occur in the Midwest, central Great Plains, and part of California and Arizona (see Graph (b)). Due to high yield and large acreage of corn in the Midwest, reduction in corn production would mainly occur in the Midwest under Scenario I (see Graph (c)). To offset the yield reduction caused by grassland bird extinction under Scenario I, the largest percentage increases in neonicotinoid use would occur in the western part of the Great Plains (see Graph (d)), while the largest absolute amount of increases would occur in California and the Midwest (see Graph (e)).

Under Scenario II (a neonicotinoid ban), the eastern region of the United States would experience the largest percentage reduction in corn yield. However, due to high yield and large acreage, the absolute amount of yield and production reduction would still occur in the Midwest (see Graphs (g) and (h)). To offset the yield reduction caused by the neonicotinoid ban, relatively smaller percentage increase in grassland bird abundance is required in the western part of the US than that required in the eastern part of the US (see Graph (i)). However, as grassland birds are more abundant in the Great Plains, the smaller percentage in the Great Plains actually implies larger absolute amount of grassland bird increase (see Graph (j)).

Farmers tend to substitute natural inputs with technical inputs when the service provided by natural inputs declines. For example, in U.S. counties affected by the white-nose syndrome, insecticide use has increased by 31.1% after a decline in the abundance of bats (Frank, 2024). Although technical substitutes (e.g. pesticides) can be used to control insect pests, they are poor proxies for functioning ecosystems (Larsen et al., 2024). The findings of our study contribute to our understanding of the Integrated Pest Management (IPM), which prioritizes the functioning of agro-ecosystems. Specifically, the IPM combines various control methods (e.g., physical, biological, chemical) to manage pests sustainably by minimizing risk to people, property, and the environment (USEPA, 2024). From the beginning of the IPM's inception, the focus of the IPM was on the use of arthropods as bio-control agents for crop pests (Stenberg, 2017). However, the use and the importance of bird-mediated pest suppression services is less widely acknowledged than that of arthropods (Sekercioglu, 2006; Garcia et al., 2020). Moreover, our national-level analysis complements field-level experiments, which suggest that some species (e.g., grassland birds) of birds can enhance crop yields. We recommend the incorporation of grassland birds in the IPM. Building grassland birds nest boxes is one of the practical and cost-effective tools for enhancing grassland birds (Diaz-Siefer, 2022; Garcia et al., 2020), which may increase corn yields without incurring the social and economic costs associated with neonicotinoid use.

Based on our findings that neonicotinoids reduce the ecological service provided by grassland birds and endangered birds on corn and soybean yields, we provide evidence supporting pesticide use regulation, particularly in areas where grassland and endangered birds are abundant. Furthermore, our findings suggesting endangered birds' agro-ecological service to soybeans at low levels of neonicotinoid may help policymakers and farmers perceive protecting endangered bird species as an opportunity to enhance agriculture production through birds' ecological services rather than solely a regulatory challenge (Melstrom, 2020).

Finally, our results show that insectivorous birds negatively impact corn and soybean yields, which suggests the complexity of food web and ecological dynamics in agricultural systems. For areas where insectivorous birds dominate, implementing new technologies to deter birds from fields and adopting approaches that seek to balance ecosystems, such as protecting the natural predators of insectivorous birds like big hawks and other animals, can be potential steps to increase corn and soybean yields without resorting to pesticide uses.

7. CONCLUSION

This article presents a national-scale analysis on how bird biodiversity may affect corn and soybean yields in the United States and how this yield effect is moderated by neonicotinoid uses. Its counterfactual analyses quantify the agro-ecosystem service value provided by grassland birds and the economic value of neonicotinoid uses. We find that the yield effect differs across bird groups, with grassland birds providing a service, insectivorous birds a disservice, and endangered birds neither a service nor disservice to corn and soybean yields when evaluated at sample means. The use of neonicotinoids weakens both the agro-ecosystem service and disservice provided by birds. We estimate that the extinction of grassland birds would cause 11.52% of corn yield reduction, an annual economic loss of $9.3 billion to corn producers. To offset this 11.52% corn yield reduction, a 219.43% increase in neonicotinoid use would be required, holding everything else constant. We also estimate that a ban on neonicotinoid uses would reduce corn and soybean yields by 3.82% and 7.02%, respectively. The annual economic cost of such a ban is about $3.1 billion and $4.1 billion for corn and soybeans, respectively. To offset the corn yield reduction caused by the ban, increasing grassland birds' abundance by 32.93% would suffice. To offset the soybean yield reduction caused by the ban, however, the required increase in grassland bird abundance is estimated to be 120.9%.

This article focuses on the impact of three bird groups (grassland, insectivorous, and endangered) on corn and soybean yields. The impact of these bird groups on other crops, such as fruits and vegetables is likely to be different due to their different growth pattern, pest pressure, and habitat requirements. By exploring how birds affect other crops, future research could extend the present study and deepen our understanding of the agro-ecosystem service provided by birds. In addition, because the reporting of neonicotinoids uses ceased after 2014, we could not explore current trends of interacting relation between bird population structure and neonicotinoid use in determining crop yields. To address this limitation, recent data on neonicotinoid applications should be made publicly available, which would enable future research to explore the evolving relationships among birds, neonicotinoid use, and crop yields, and to provide timely policy-relevant insights.

The agro-ecosystem involves numerous intricate interactions, and the relationship among crop yields, birds, and pesticides is dynamic and far more complicated than what we have measured and modeled in the present study. Furthermore, the emerging agricultural technologies (including novel pesticides) will offer new pathways to enhance agriculture productivity while safeguarding biodiversity. For example, the adoption of precision agriculture and the employment of artificial intelligence have gained momentum in commercial farming. These new technologies are expected to have a profound impact on the yield-bird-pesticide relationship, which can be a prolific area for future research.

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Table 1. The direct and interaction effects of birds and pesticides on pest pressure and crop yield

Terms in Eq. (4)	Signs of terms		
	Service bird		Disservice bird
	Case I	Case II	
$\frac{\partial f^c(\cdot)}{\partial h(\cdot)}$	< 0	< 0	< 0
$\frac{\partial^2 h(\cdot)}{\partial Q_p^c \partial Q_B^c}$	> 0	< 0	< 0
Term (a)	**< 0**	**> 0**	**> 0**
$\frac{\partial^2 f^c(\cdot)}{\partial h^2(\cdot)}$	< 0	< 0	< 0
$\frac{\partial h(\cdot)}{\partial Q_p^c}$	< 0	< 0	< 0
$\frac{\partial h(\cdot)}{\partial Q_B^c}$	< 0	< 0	> 0
Term (b)	**< 0**	**< 0**	**> 0**
$\frac{\partial^2 y^c}{\partial Q_B^c \partial Q_p^c}$	< 0	Undetermined	> 0
Relationship between pesticides and bird	Substitutability	Undetermined	Complementarity

Note: In Case I we assume $\frac{\partial^2 f^c(\cdot)}{\partial h^2(\cdot)} < 0$ and in Case II we assume $\frac{\partial^2 f^c(\cdot)}{\partial h^2(\cdot)} > 0$ for service bird in equation (4).

Table 2. Impact of grassland, insectivorous, and endangered bird abundance on corn yield (dependent variable: log of corn yield)

	Grassland birds		Insectivorous birds		Endangered birds	
	FE	FE-IV	FE	FE-IV	FE	FE-IV
Variables	1(a)	1(b)	2(a)	2(b)	3(a)	3(b)
Abundance (log)	-0.005 (0.004)	0.116*** (0.244)	-0.01*** (0.003)	-0.0466*** (0.0132)	-0.0049 (0.0040)	-0.0133 (0.0143)
Neonicotinoid Use (kg) (log)	-0.0025** (0.001)	0.0525*** (0.007)	-0.0099*** (0.003)	0.0130+ (0.0081784)	-0.0052* (0.0024)	0.0474*** (0.0088)
Bird Abundance (log) × Neonicotinoid Use (kg) log	-0.000007** (0.000003)	-0.00018*** (0.00002)	0.0014** (0.0028)	0.0068*** (0.0023)	0.0004 (0.0006)	-0.0009 (0.0015)
Number of Observations	15,061	14,792	18,579	15,228	18,377	15,042
Number of Counties	1,557	1,440	1,618	1,471	1,605	1,464
Kleibergen-Paap *rk* LM value and statistic		134 *p<0.001*		540 *p<0.001*		514.24 *p*<0.001
Cragg-Donald Wald *F* statistic		65.311		137		*133*
Kleibergen-Paap *rk* Wald *F* statistic		34.57		150		143

Notes: ***, **, *, and + denote 1%, 5%, 10%, and 12% significance level, respectively. Robust standard errors are in parenthesis. The full set of results are in Table S7 in the online SI. Models 1(a), 2(a), and 3(a) treat all the explanatory variables as exogenous whereas models 1(b), 2(b), and 3(b) address the endogeneity issues of the explanatory variables. The instrumental variables used are, for model 1(b): one-year lag of grassland bird abundance, current-year pesticide price index, and one-year lag of natural gas price index; for model 2(b): one-year lag of insectivorous bird abundance, current-year pesticide price index, and one-year lag of natural gas price index; for model 3(b): one-year lag of endangered bird abundance, current-year pesticide price index, and one-year lag of natural gas price index.

Table 3. Impact of grassland, insectivorous, and endangered bird species richness on corn yield (dependent variable: log of corn yield)

	Grassland birds		Insectivorous birds		Endangered birds	
	FE	FE-IV	FE	FE-IV	FE	FE-IV
Variables	4(a)	4(b)	5(a)	5(b)	6(a)	6(b)
Species Richness (log)	0.0172**	0.147***	- 0.0275 **	-0.1616***	-0.0050	0.0722
	(0.0082)	(0.0414)	(0.0102)	(0.0426)	(0.0080)	(0.0575)
Neonicotinoid Use (kg) (log)	0.0043***	0.086201***	-0.0126942***	0.0014	-0.0046*	0.0767994***
	(0.0024)	(0.0096966)	(0.0033484)	(0.0083)	(0.0022)	(0.01170)
Birds Species Richness (log)	-0.0047***	-0.0322***	0.0045921***	0.0202075***	0.0007	-0.022651***
×Neonicotinoid Use (kg) (log)	(0.0012)	(0.003277)	(0.0015764)	(0.0035608)	(0.0013)	(0.0054)
Number of Observations	15,061	14,792	18,579	15,228	18,377	15,042
Number of Counties	1,557	1,440	1,618	1,471	1,605	1,464
Kleibergen-Paap *rk* LM statistic		220		263		109.5
		p<0.001		*p<0.001*		*p<0.001*
Cragg-Donald Wald *F* statistic)		118		124.774		48.749
Kleibergen-Paap *rk* Wald *F* statistic		60		74		29

Notes: ***, **, and * denote 1%, 5%, and 10% significance level, respectively. Robust standard errors are in parenthesis. The full results are in Table S8 in the online SI. Models 4(a), 5(a), and 6(a) treat all the explanatory variables as exogenous whereas models 4(b), 5(b), and 6(b) address the endogeneity issues of the explanatory variables. The instrumental variables used are, for model 4(b): one-year lag of grassland bird species richness, current-year pesticide price index, and one-year lag of natural gas price index; for model 5(b): one-year lag of insectivorous bird species richness, current-year pesticide price index, and one-year lag of natural gas price index; for model 6(b): one-year lag of endangered bird species richness, current-year pesticide price index, and one-year lag of natural gas price index.

Table 4. Impact of grassland, insectivorous, and endangered bird species evenness on corn yield (dependent variable: log of corn yield)

	Grassland birds		Insectivorous birds		Endangered birds	
	FE	FE-IV	FE	FE-IV	FE	FE-IV
Variables	7(a)	7(b)	8(a)	8(b)	9(a)	9(b)
Species Evenness (log)	0.0294** (0.0122)	0.0612 (0.0627)	0.0027 (0.0097)	-0.2633 *** (0.1005)	-0.0009 (0.0077)	0.0215 (0.0510)
Neonicotinoid Use (kg) (log)	0.0007 (0.0012)	0.0426 *** (0.0063187)	-0.0038*** (0.0010)	0.0408 *** (0.0056)	-0.0036*** (0.0010)	0.0440*** (0.0064)
Birds Species Evenness (log) ×Neonicotinoid Use (kg) (log)	-0.0042** (0.0019)	- 0.0233242 *** (0.0052539)	0.0015 (0.0016)	0.0186609 *** (0.0048)	0.0023266* (0.0013)	-0.0032*** (0.0047)
Number of Observations	15,061	14,792	18,511	15,076	17,547	14,201
Number of Counties	1,557	1,440	1,699	1,461	1,565	1,405
Kleibergen-Paap *rk* LM statistic		105 *p<0.001*		45 *p<0.001*		101.6 *p<0.001*
Cragg-Donald Wald *F* statistic)		73.86		25		62.54
Kleibergen-Paap *rk* Wald *F* statistic		28		12		27.55

Notes: ***, **, and * denote 1%, 5%, and 10% significance level, respectively. Robust standard errors are in parenthesis. The full results are in Table S9 in the online SI. Models 7(a), 8(a), and 9(a) treat all the explanatory variables as exogenous whereas models 7(b), 8(b), and 9(b) address the endogeneity issues of the explanatory variables. The instrumental variables used are, for model 7(b): one-year lag of grassland bird species evenness, current-year pesticide price index, and one-year lag of natural gas price index; for model 8(b): one-year lag of insectivorous bird species evenness, current-year pesticide price index, and one-year lag of natural gas price index; for model 9(b): one-year lag of endangered bird species evenness, current-year pesticide price index, and one-year lag of natural gas price index.

Table 5: Impact of grassland bird extinction or neonicotinoid ban on corn and soybean yields

Scenario	I. Grassland Bird Extinction		II. Neonicotinoid Ban	
	Corn	Soybean	Corn	Soybean
Yield Reduction	11.52% CI: [6.70%, 16.30%]	-1.4% CI: [-0.78%, 3.7%]	3.82% CI: [2.89%, 4.64%]	7.02% CI: [5.70%, 8.4%]
Additional neonicotinoid use required to maintain yield	219.43% CI: [127.60%, 310.50%]	No change	-	-
Additional grassland birds required to maintain yield	-	-	32.93% CI: [24.90%, 40.70%]	120.87% CI: [99.35%, 180.34%]

Notes: The values in square brackets show the 95% confidence intervals. "No change" indicates statistically insignificant effect of grassland bird abundance on soybean yield when evaluated at sample means. The details of calculation are presented in Tables S19 and S20 in the online SI.

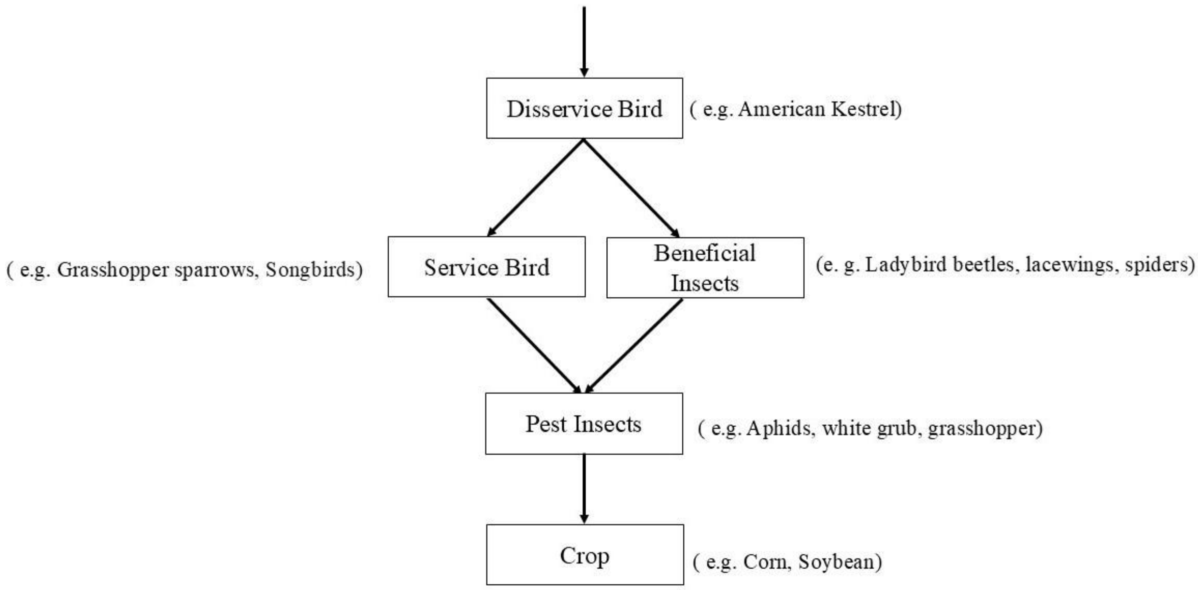


Figure 1. The potential service or disservice of birds on crops based on their foraging behavior

Note: The arrows indicate forage relationships. For instance, American Kestrel feeds on service bird species (e.g., song birds) and some beneficial insects (lacewings) that prey on crop insect pests.

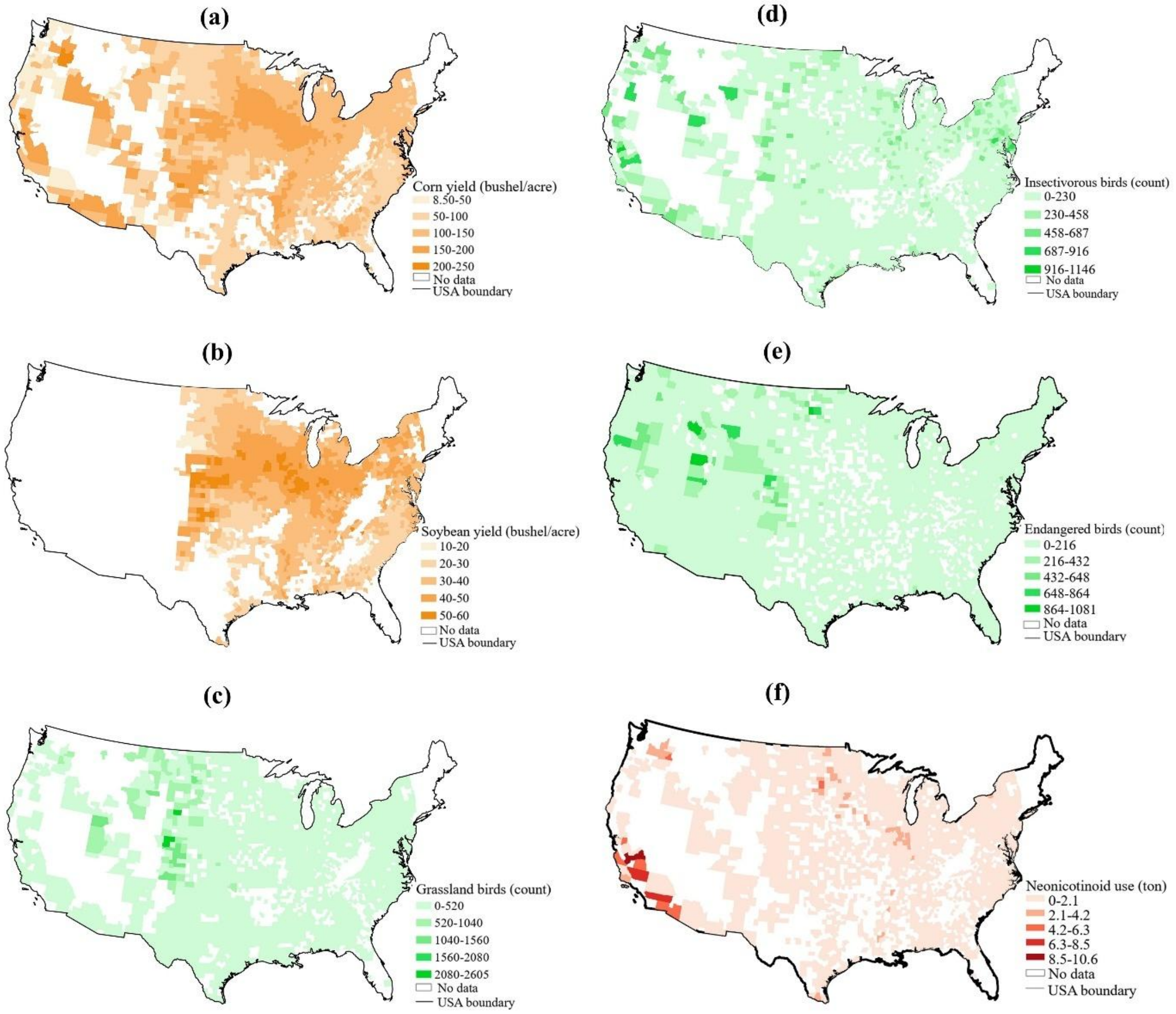
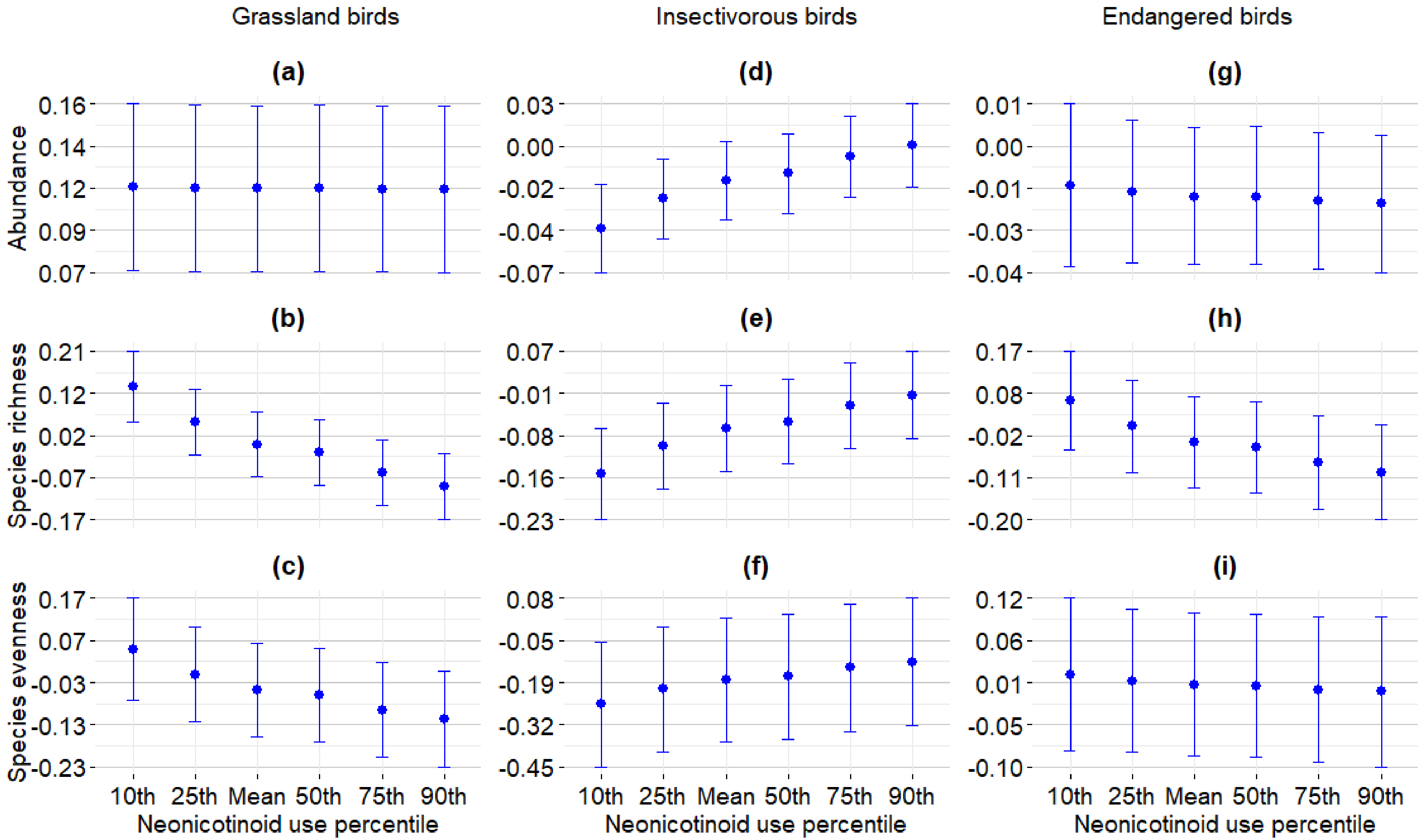


Figure 2. County-level corn and soybean yields, abundance of three bird species, and neonicotinoid use averaged over sample period (1997-2014)

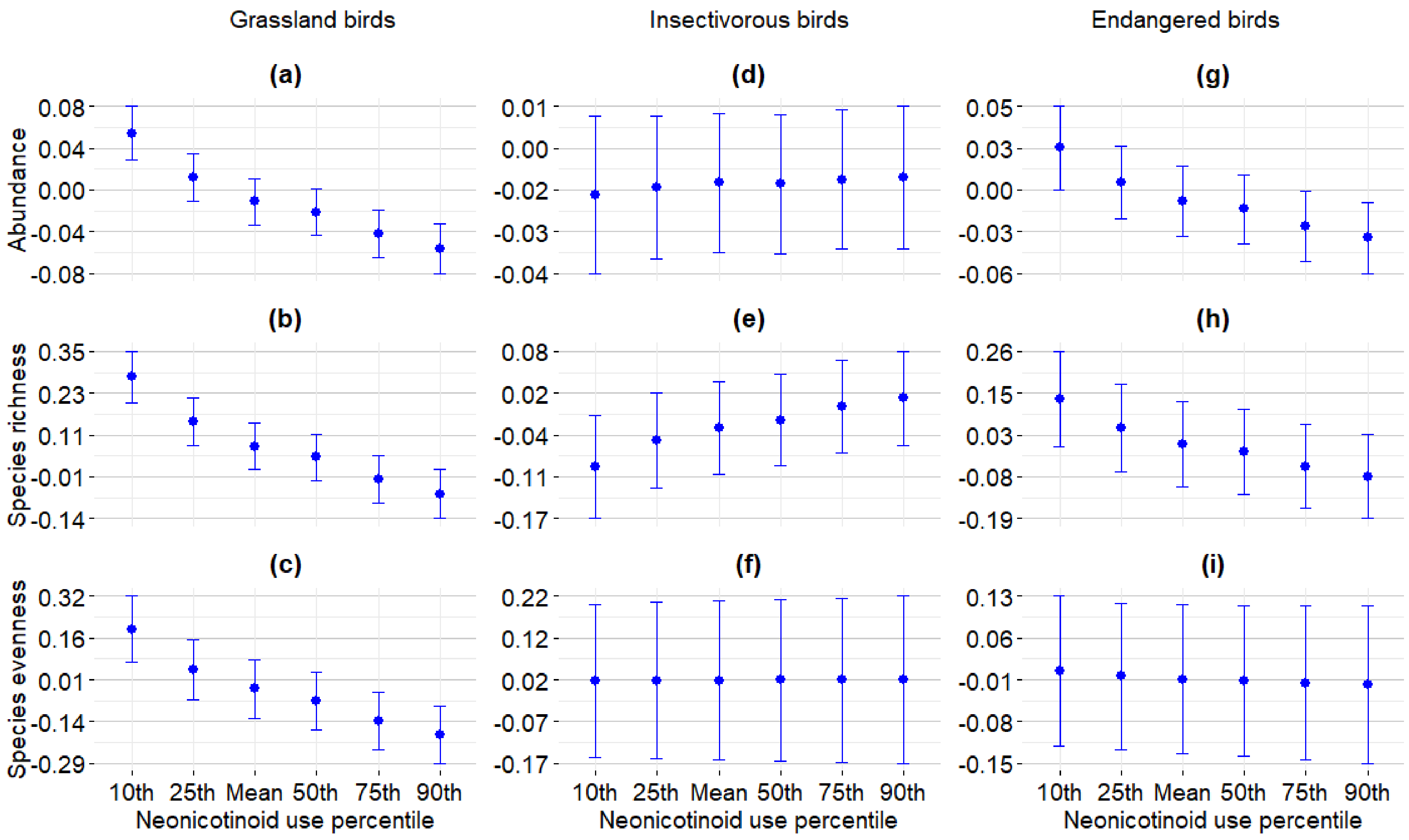
Notes: Maps (a) and (b) represent the average corn and soybean yield, respectively. Maps (c), (d), and (e) represent the average abundance of grassland birds, insectivorous birds, and endangered birds considered in this study. Finally, Map (f) represents the average neonicotinoid use.



Grassland birds
Insectivorous birds
Endangered birds
(a)
(d)
(g)
(b)
(e)
(h)
(c)
(f)
(i)
Abundance
Species richness
Species evenness
0.16
0.14
0.12
0.09
0.07
0.03
0.00
-0.02
-0.04
-0.07
0.01
0.00
-0.01
-0.03
-0.04
0.21
0.12
0.02
-0.07
-0.17
0.07
-0.01
-0.08
-0.16
-0.23
0.17
0.08
-0.02
-0.11
-0.20
0.17
0.07
-0.03
-0.13
-0.23
0.08
-0.05
-0.19
-0.32
-0.45
0.12
0.06
0.01
-0.05
-0.10
10th 25th Mean 50th 75th 90th
Neonicotinoid use percentile

Figure 3. Corn yield elasticity with respect to bird diversity measures when neonicotinoid use varies

Notes: Graphs (a), (b), and (c) represent the corn yield elasticity with respect to grassland birds abundance, species richness, and species evenness, respectively. Similarly, Graphs (d), (e), and (f) represent corn yield elasticity with respect to insectivorous birds abundance, species richness, and species evenness, respectively. Finally, Graphs (g), (h), and (i) represent the corn yield elasticity with respect to endangered birds abundance, species richness, and species evenness, respectively. The x-axis represents the neonicotinoid use at different percentile values and the mean value. The whiskers represent the 95% confidence intervals (CI) and the dots represent the point estimates of corn yield elasticity. In our sample the mean is smaller than the median.



Grassland birds
Insectivorous birds
Endangered birds
(a)
(d)
(g)
(b)
(e)
(h)
(c)
(f)
(i)
Abundance
Species richness
Species evenness
0.08
0.04
0.00
-0.04
-0.08
0.01
-0.02
-0.03
-0.04
0.05
0.03
-0.06
0.35
0.23
0.11
-0.01
-0.14
0.02
-0.11
-0.17
0.26
0.15
-0.08
-0.19
0.32
0.16
-0.29
0.22
0.12
-0.07
0.13
0.06
-0.15
10th
25th
Mean
50th
75th
90th
Neonicotinoid use percentile

Figure 4. Soybean yield elasticity with respect to bird diversity measures when neonicotinoid use varies
Notes: Graphs (a), (b), and (c) represent the soybean yield elasticity with respect to grassland bird abundance, species richness, and species evenness, respectively. Similarly, Graphs (d), (e), and (f) represent soybean yield elasticity with respect to insectivorous bird abundance, species richness, and species evenness, respectively. Finally, Graphs (g), (h), and (i) represent the soybean yield elasticity with respect to endangered bird abundance, species richness, and species evenness, respectively. The x-axis represents the neonicotinoid use at different percentile values and the mean value. The whiskers represent the 95% confidence intervals (CI) and the dots represent the point estimates of soybean yield elasticity. In our sample the mean is smaller than the median.

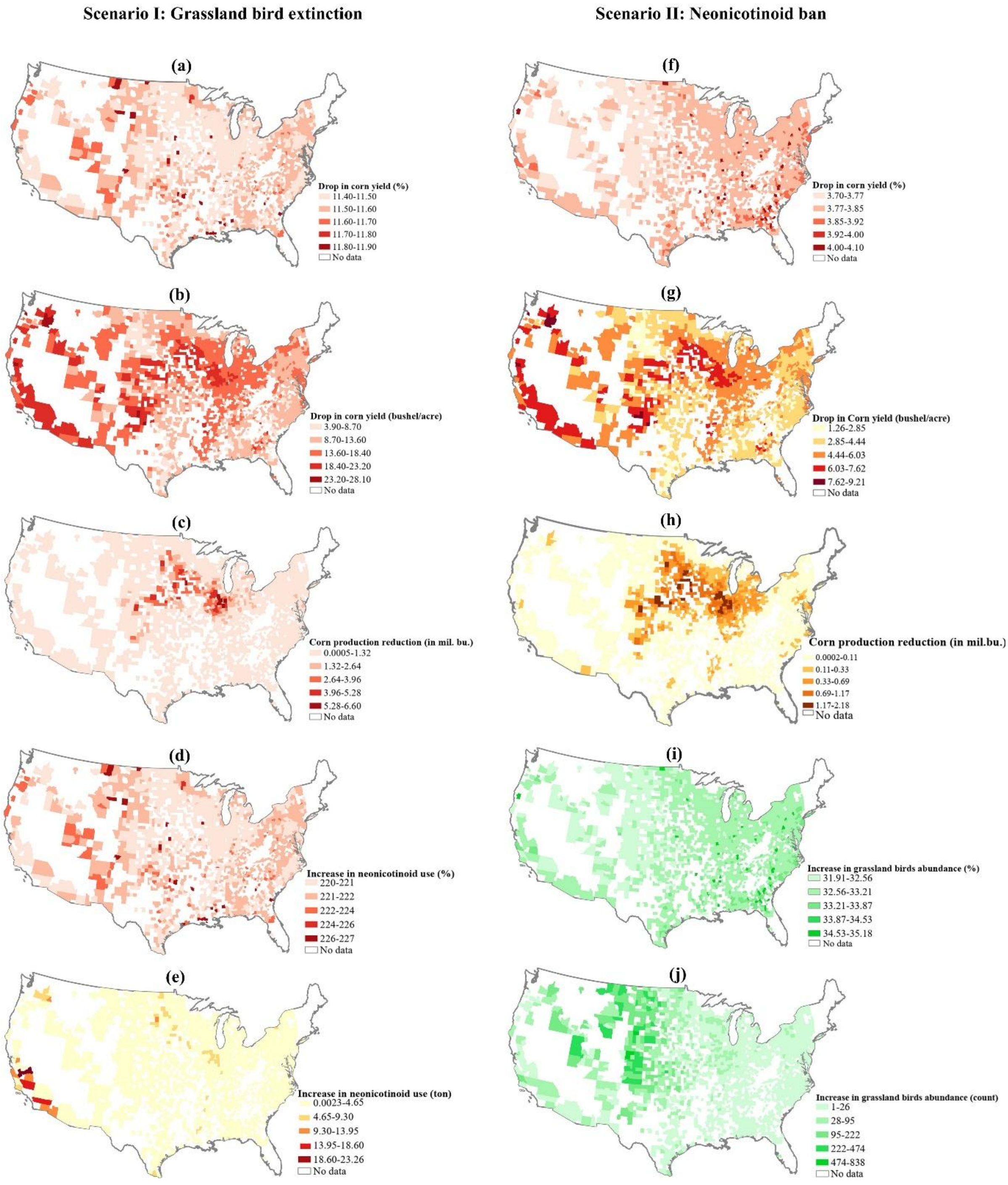


Figure 5. Impact of grassland bird extinction and neonicotinoid ban on U.S. corn production
Notes: Maps in the left column depict the impact of grassland bird extinction (scenario I) whereas maps in the right column depict the impact of neonicotinoid ban (scenario II). Maps (a) and (b) represent the county-level corn yield reduction in percentage and in bushel per acre, respectively, under scenario I. Map (c) represents the decrease in total corn production (in million bushels) in a county. Maps (d) and (e) represent the percentage increase and the absolute amount increase in neonicotinoid use that would be needed to offset the corn yield reduction when grassland birds were to become extinct. In the left column, Map (f) and Map (g) represent the county-level corn yield reduction in percentage and in bushel per acre,

respectively, under a neonicotinoid ban. Map (h) represents the decrease in total corn production (in million bushels) in a county. Maps (i) and (j) show respectively the required percentage increase and the absolute amount increase in grassland bird abundance to offset the yield reduction caused by the ban.

Supplementary Information (SI) for

The Ecosystem Service Values of Birds to U.S. Corn and Soybeans: A National Scale Analysis

Supplementary Table S1: Pesticide use by Crop in year 2008 in the United States

Crop	Million pounds (active ingredients)
Corn	203.73
Soybeans	111.96
Potatoes	52.53
Cotton	37.56
Wheat	23.31
Sorghum	14.17
Oranges	13.12
Peanuts	10.32
Tomatoes	9.70
Grapes	7.90
Rice	7.58
Apples	7.28
Sugarcane	4.01
Other Crops	12.95
Total	516.11

Source: Fernandez-Cornejo et al. (2014).

Supplementary Table S2: Summary statistics of dataset for corn yield

Variable	Unit	Mean	Std. dev	Min	Max
Corn yield	Bushel/acre	125	37.55044	4.5	246
Grassland birds					
Population	Count	91.393	196.621	0.000	3,873.000
Species Richness	Species	4.458	3.057	0.000	19.000
Shannon Index		0.935	0.601	0.000	2.312
Insectivorous Birds					
Population	Count	131.899	140.323	0.000	2,156.000
Species Richness	Species	8.384	3.068	0.000	19.000
Shannon Index		1.416	0.473	0.000	2.469
Endangered Birds					
Population	Count	59.866	95.365	0.000	3,043.000
Species Richness	Species	4.045	1.805	0.000	12.000
Shannon Index		1.130	0.547	0.000	3.114
Other Explanatory Variables					
Neonicotinoid use	kg	539.811	1,129.339	0.000	33,880.700
Fertilizer price index (one year lag)		57.069	27.489	31.900	119.200
Crop damage duration	Days	1.194	9.380	0.000	351.000
GE adoption rate	Percentage	48.222	33.490	0.000	97.000
Normal GDD (1,000)	Degree Celcius	2.162	0.455	1.059	3.464
Overheat GDD (1,00)	Degree Celcius	0.597	0.665	0.000	7.131
Precipitation (100)	cm	5.797	1.919	0.027	14.541
Precipitation square (100)	cmsq.	37.284	22.676	0.001	211.439
Instrumental Variables					
pesticide price index (log)		4.502	0.101	4.408	4.696
Lag gas price index		186.238	81.044	83.930	355.820
Lag Grassland abundance (log)	Count	3.439	1.591	0.000	8.242
Lag Insectivore abundance (log)	Count	4.431	1.137	0.000	7.676
Lag Endangered abundance (log)	Count	3.481	1.223	0.000	8.021
Lag grassland richness (log)	Species	1.324	0.728	0.000	2.944
Lag Insectivore richness (log)	Species	2.073	0.443	0.000	2.944
Lag Endangered richness (log)	Species	1.325	0.485	0.000	2.485
Lag grassland Shannon index (log)		0.054	0.482	-3.573	0.838
Lag Insectivore Shannon index (log)		0.311	0.364	-2.278	0.894
Lag Endangered Shannon index (log)		0.106	0.473	-3.491	1.136

Supplementary Table S3: Summary statistics for a dataset for soybean yield

Variable	Unit	Mean	Std. dev	Min	Max
Soybean yield	Bushel/acre	38.12127	10.49415	0.7	69.3
Grassland birds					
Population	Count	61.4366	93.62164	1	1231
Species Richness	Species	4.52907	2.801666	1	18
Shannon Index		0.9982444	0.5810829	0	2.29383
Insectivorous Birds					
Population	Count	139.1159	135.8703	0	2390
Species Richness	Species	8.863173	2.760259	0	17
Shannon Index		1.453194	0.4398255	0	2.443709
Endangered Birds					
Population	Count	55.47976	74.9558	0	1799
Species Richness	Species	4.33745	1.696934	0	12
Shannon Index		1.230762	0.5151995	0	3.472375
Other Explanatory Variables					
Neonicotinoid use	kg	675.7348	1134.087	0.1	11743.3
Fertilizer price index (one year lag)		60.9124	28.20233	31.9	119.2
Crop damage duration	Days	1.070564	8.664348	0	351
GE adoption rate	Percentage	75.53966	27.70207	0	99
Normal GDD (1,000)	Degree celcius	2.187013	0.4305565	1.059332	3.522829
Overheat GDD (1,00)	Degree celcius	0.3260611	0.3748966	0	3.563107
Precipitation (100)	cm	6.225857	1.604361	1.245882	13.91526
Precipitation square (100)	cmsq.	6.225857	1.604361	1.245882	13.91526
Instrumental Variables					
pesticide price index (log)		4.502	0.101	4.408	4.696
Lag gas price index		187.1718	80.71191	83.93	355.82
Lag Grassland abundance (log)	Count	3.285629	1.43215	0	7.231287
Lag Insectivore abundance (log)	Count	4.496567	1.05382	0	7.779048
Lag Endangered abundance (log)	Count	3.486	1.121	0.000	7.437
Lag grassland richness (log)	Species	1.296233	0.7127132	0	2.890372
Lag Insectivore richness (log)	Species	2.119995	0.392045	0	2.833213
Lag Endangered richness (log)	Species	1.393	0.441	0.000	2.485
Lag grassland Shannon index (log)		0.0514319	0.4897224	-2.51969	0.8302231
Lag Insectivore Shannon index (log)		0.3263467	0.3532785	-2.27839	0.8935168
Lag Endangered Shannon index (log)		0.162	0.428	-2.532	1.245

Supplementary Table S4. Bird groups included in this Study

a. Insectivorous bird species (42 species)

AOU	English Name
4650	Acadian Flycatcher
4661	Alder Flycatcher
4540	Ash-throated Flycatcher
6160	Bank Swallow
6130	Barn Swallow
4220	Black Swift
4480	Cassin's Kingbird
6121	Cave Swallow
4230	Chimney Swift
4160	Chuck-will's-widow
6120	Cliff Swallow
4200	Common Nighthawk
4180	Common Poorwill
4640	Cordilleran Flycatcher
4690	Dusky Flycatcher
4440	Eastern Kingbird
4560	Eastern Phoebe
4171	Eastern Whip-poor-will
4610	Eastern Wood-Pewee
4730	Eurasian Skylark
6883	Eurasian Tree Sparrow
4930	European Starling
4691	Gray Flycatcher
4520	Great Crested Flycatcher
4680	Hammond's Flycatcher
4670	Least Flycatcher
4210	Lesser Nighthawk
6170	Northern Rough-winged Swallow
4590	Olive-sided Flycatcher
4641	Pacific-slope Flycatcher
6110	Purple Martin
4570	Say's Phoebe
4430	Scissor-tailed Flycatcher
6140	Tree Swallow
4447	unid. Cassin's Kingbird / Western Kingbird
4689	unid. Hammond's Flycatcher / Dusky Flycatcher
4240	Vaux's Swift
6150	Violet-green Swallow

AOU	English Name
4620	Western Wood-Pewee
4250	White-throated Swift
4660	Willow Flycatcher
4630	Yellow-bellied Flycatcher

b. Grassland birds (29 species)

AOU	English Name
2610	Upland sandpiper
2640	Long_billed Curlew
2810	Mountain Plover
2881	Gray Partridge
3050	Greater prairie-chicken
3080	Sharp-tailed Grouse
3091	Ring-necked pheasant
3310	Northern harrier
3480	Ferruginous hawk
3650	Barn Owl
3670	Short-eared owl
4740	Horned lark
4940	Bobolink
5010	Eastern Meadowlark
5011	Western Meadowlark
5380	Chestnut-collared Longspur
5390	McCown's Longspur
5400	Vesper Sparrow
5420	Savannah Sparrow
5450	Baird's Sparrow
5460	Grasshopper Sparrow
5470	Henslow's Sparrow
5480	Le Conte's Sparrow
5760	Botteri's Sparrow
5780	Cassin's Sparrow
6040	Dickcissel
6050	Lark Bunting
7000	Sprague's Pipit
7240	Sedge Wren

c. Endangered Birds (43 species)

AOU	English Name
2210	American Coot
3590	Aplomado Falcon
3520	Bald Eagle
6330	Bell's Vireo
2160	Black Rail
2260	Black-necked Stilt
3430	Broad-winged Hawk
1260	Brown Pelican
3240	California Condor
7530	California Gnatcatcher
1720	Canada Goose
2190	Common Gallinule
4790	Florida Scrub-Jay
6660	Golden-cheeked Warbler
5460	Grasshopper Sparrow
3050	Greater Prairie-Chicken
1710	Greater White-fronted Goose
4740	Horned Lark
6700	Kirtland's Warbler
740	Least Tern
6220	Loggerhead Shrike
230	Marbled Murrelet
1331	Mexican Duck
2890	Northern Bobwhite
3560	Peregrine Falcon
2770	Piping Plover
2340	Red Knot
3950	Red-cockaded Woodpecker
2111	Ridgway's Rail
720	Roseate Tern
2060	Sandhill Crane
5500	Seaside Sparrow
3320	Sharp-shinned Hawk
3300	Snail Kite
2780	Snowy Plover
5810	Song Sparrow
4665	unid. Alder Flycatcher / Willow Flycatcher
3451	unid. Buteo hawk
2040	Whooping Crane
4660	Willow Flycatcher
1880	Wood Stork
3870	Yellow-billed Cuckoo
4970	Yellow-headed Blackbird

Notes: Earlier called as McCown's Longspur─a grassland bird, is now called as the thick-billed longspur (Science, 2020). The list of grassland birds and insectivorous birds is obtained from Li et al. (2020), and Spiller and Dettmers (2019). Readers can explore https://www.pwrc.usgs.gov/bbs/specieslist.html for a complete BBS species list. The endangered species are collected from the United States Fish and wildlife service, available at https://www.fws.gov/program/endangered-species/species.

Supplementary Table S5. Genetically Engineered (GE) Crop Adoption Rate in the U.S. (2000-2014): Corn

	Year														
State	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Illinois	17	16	22	28	33	36	55	74	80	84	82	86	85	89	91
Indiana	11	12	13	16	21	26	40	59	78	79	83	85	84	85	88
Iowa	30	32	41	45	54	60	64	78	84	86	90	90	91	91	95
Kansas	33	38	43	47	54	63	68	82	90	91	90	92	90	91	95
Michigan	12	17	22	35	33	40	44	60	72	75	80	87	86	90	93
Minnesota	37	36	44	53	63	66	73	86	88	88	92	93	88	91	93
Missouri	28	32	34	42	49	55	59	62	70	77	79	85	86	92	93
Nebraska	34	34	46	52	60	69	76	79	86	91	91	93	91	93	96
North Dakota	NA	NA	NA	NA	NA	75	83	88	89	93	93	97	96	94	96
Ohio	9	11	9	9	13	18	26	41	66	67	71	74	76	85	86
South Dakota	48	47	66	75	79	83	86	93	95	96	95	96	94	96	97
Texas	NA	NA	NA	NA	NA	72	77	79	78	84	85	88	85	89	91
Winsconsin	18	18	26	32	38	46	50	64	75	77	80	86	86	84	92
Other state	17	20	27	36	46	44	55	67	74	78	82	86	85	88	91
United States	25	26	34	40	47	52	61	73	80	85	86	88	88	90	93

Notes: For years 2000, 2001, 2002, 2003, and 2004 we have missing values in the source data for states Texas and North Dakota. So, we use the adaptation rate as of "Other states" as mentioned in our source data for both states. We use 17%, 20%, 27%, 36%, and 46 % for years 2000, 2001, 2002, 2003, and 2004, respectively. For states other than explicitly mentioned in the table above, we use the GMO adoption rate as that of other states. For example, Alabama is not explicitly mentioned in the table. Therefore, we consider GMO adoption rate of Alabama in the year 2000 to be 17%. Data source: https://www.ers.usda.gov/data-products/adoption-of-genetically-engineered-crops-in-the-u-s/.

Supplementary Table S6. Genetically Engineered (GE) Crop Adoption Rate in the U.S. (2000-2014): Soyabean

	Year														
State	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Arkansas	43	60	68	84	92	92	92	92	94	94	96	95	94	97	99
Illinois	44	64	71	77	81	81	87	88	87	90	89	92	90	92	91
Indiana	63	78	83	88	87	89	92	94	96	94	95	96	93	90	92
Iowa	59	73	75	84	89	91	91	94	95	94	96	97	97	93	97
Kansas	66	80	83	87	87	90	85	92	95	94	95	96	94	93	94
Michigan	50	59	72	73	75	76	81	87	84	83	85	91	91	90	91
Minnesota	46	63	71	79	82	83	88	92	91	92	93	95	91	93	94
Mississippi	48	63	80	89	93	96	96	96	97	94	98	98	95	98	99
Missouri	62	69	72	83	87	89	93	91	92	89	94	91	91	90	91
Nebraska	72	76	85	86	92	91	90	96	97	96	94	97	95	96	95
North Dakota	22	49	61	74	82	89	90	92	94	94	94	94	98	94	96
Ohio	48	64	73	74	76	77	82	87	89	83	86	85	86	89	90
South Dakota	68	80	89	91	95	95	93	97	97	98	98	98	98	97	97
Wisconsin	51	63	78	84	82	84	85	88	90	85	88	91	92	89	95
Other State	54	64	70	76	82	84	86	86	87	87	90	92	93	92	94
United State	54	68	75	81	85	87	89	91	92	91	93	94	93	93	94

Note: For states other than explicitly mentioned in the table, we use the other state adoption rate as we did for corn. Data source is https://www.ers.usda.gov/data-products/adoption-of-genetically-engineered-crops-in-the-u-s/.

Supplementary Table S7. Impact of grassland, insectivorous, and endangered bird abundance on corn yield (dependent variable: log of corn yield)

	Grassland		Insectivorous		Endangered	
	FE	FE-IV	FE	FE-IV	FE	FE-IV
Variables	1(a)	1(b)	2(a)	2(b)	3(a)	3(b)
Abundance (log)	-0.005	0.116***	-0.01***	-0.0466478***	-0.004893	-0.0133
	(0.004)	(0.244)	(0.003)	(0.0131843)	(0.0039363)	(0.0143035)
Neonicotinoid Use (kg) (log)	-0.0025**	0.0525***	-0.0099***	0.012696+	-0.00519*	0.0473995***
	(0.001)	(0.007)	(0.003)	(0.0081784)	(0.0024196)	(0.0087982)
Bird Abundance (log)	-0.000007**	-0.0001847***	0.001435**	0.0068339***	0.0004381	-0.000853
×Neonicotinoid Use (kg) (log)	(0.000003)	(0.0000262)	(0.0028216)	(0.002305)	(0.0005899)	(0.0014548)
GE Adoption Rate (%)	0.0005**	0.00005	0.0006***	0.000152	0.0006396***	0.0002356
	(0.0002)	(0.0002799)	(0.002)	(0.0002488)	(0.0002067)	(0.0002529)
Normal GDD (1,000)	0.143***	0.113***	0.123***	0.0990721***	0.129152***	0.1053617***
	(0.023)	(0.027)	(0.0183)	(0.0247811)	(0.0184859)	(0.0251581)
Overheat GDD (100)	-0.509***	-0.489***	-0.487***	-0.4922216***	-0.49152***	-0.496236***
	(0.018)	(0.015)	(0.0117)	(.0138874)	(0.0117254)	(0.0139391)
Precipitation (100)	0.044***	0.0466***	0.043542***	0.0542095***	0.0422697***	0.0542629***
	(0.009)	(0.0096)	(0.0072214)	(0.0085128)	(0.0072824)	(0.0086748)
Square Precipitation (100)	-0.003***	-0.00273***	-0.0028092***	-0.0032545***	-0.002728***	-0.003289***
	(0.001)	(0.00069)	(0.0005215)	(0.0006106)	(0.0005258)	(0.000623)
Linear time trend	0.019***	-0.0026***	0.0168465***	-0.006768	0.0164219***	-0.007564
	(0.003)	(0.0050046)	(0.0020996)	(0.0047237)	(0.0021211)	(0.0047634)
Quadratic time trend	-0.0002*	0.0003496***	-0.0000233	0.0004167 ***	-0.000014	0.0004152***
	(0.0001)	(0.0001393)	(0.0000714)	(0.0001292)	(0.000072)	(0.0001291)
Crop damaging duration (Days)	-0.0009***	-0.0010***	-0.0008413***	-0.0012236***	-0.000839***	-0.001232***
	(0.0002)	(0.00024)	(0.0001752)	(0.0002458)	(0.0001658)	(0.0002431)
Fertilizer price index (lag)	-0.0007***	-.00087***	-0.0008383***	-.0010417***	-0.000835***	-0.001065***
	(0.0001)	(.00017)	(0.0001106)	(.0001497)	(0.0001114)	(0.0001519)

Number of Observations	15,061	14,792	18,579	15,228	18,377	15,042
Number of Counties	1,557	1,440	1,618	1,471	1,605	1,464
Kleibergen-Paap *rk* LM statistic		134 *p<0.001*		540 *p<0.001*		514.24 *p<0.001*
Cragg-Donald Wald *F* statistic)		65.311		137		133
Kleibergen-Paap *rk* Wald *F* statistic		34.57		150		143

Notes: ***, **, *, and + denote 1%, 5%, 10%, and 12% significance level, respectively. Robust standard errors are in parenthesis. Models 1(a), 2(a), and 3(a) treat all the explanatory variables as exogenous whereas models 1(b), 2(b), and 3(b) address the endogeneity issues of the explanatory variables. The instrumental variables used are, for model 1(b): one-year lag of grassland bird abundance, current-year pesticide price index, and one-year lag of natural gas price index; for model 2(b): one-year lag of insectivorous bird abundance, current-year pesticide price index, and one-year lag of natural gas price index; for model 3(b): one-year lag of endangered bird abundance, current-year pesticide price index, and one-year lag of natural gas price index.

Supplementary Table S8. Impact of grassland, insectivorous, and endangered bird species richness on corn yield (dependent variable: log of corn yield)

	Grassland		Insectivorous		Endangered	
	FE	FE-IV	FE	FE-IV	FE	FE-IV
Variables	4(a)	4(b)	5(a)	5(b)	6(a)	6(b)
Species Richness (log)	0.0172** (0.0082)	0.147*** (0.0414)	- 0.0275 ** (0.0102)	-0.161648*** (0.0426379)	-0.0050007 (0.0080285)	0.0721784 (0.0574904)
Neonicotinoid Use (kg) (log)	0.0042732*** (0.002363)	0.086201*** (0.0096966)	-0.0126942*** (0.0033484)	0.0014039 (0.0082733)	-0.004612* (0.0021925)	0.0767994*** (0.0116902)
Bird species Richness (log) ×Neonicotinoid Use (kg) (log)	-0.0047319*** (0.0012007)	-0.0322215*** (0.003277)	0.0045921*** (0.0015764)	0.0202075*** (0.0035608)	0.0007128 (0.0013445)	-0.022651*** (0.0053704)
GE Adoption Rate (%)	0.0004955** (0.0002054)	-0.0000545 (0.0002509)	0.0005812*** (0.0001999)	0.0001574 (0.0002496)	0.000639*** (0.0002068)	0.0002514 (0.0002627)
Normal GDD (1,000)	0.1268513*** (0.0186488)	0.0825884*** (0.0254856)	0.1233943*** (0.0207839)	0.1027421*** (0.0247019)	0.129256*** (0.0184732)	0.1042287*** (0.0252069)
Overheat GDD (100)	-0.4875031*** (0.0119077)	-0.4848681*** (0.0142472)	- 0.487123*** (0.0155861)	-0.492638*** (0.0138634)	-0.49144*** (0.0117282)	-0.492456*** (0.0139778)
Precipitation (100)	0.043286*** (0.0073258)	0.0463013*** (0.0085506)	0.0436572*** (0.0082302)	0.0543328*** (0.0085158)	0.042204*** (0.0072829)	0.0537851*** (0.0088302)
Square Precipitation (100)	-0.0027786*** (0.0005305)	-.0026666*** (0.0006187)	-0.0028145*** (0.0006027)	- 0.0032594*** (0.0006135)	-0.00272*** (0.0005258)	-0.003226*** (0.0006319)
Linear time trend	0.0168542*** (0.0021236)	-0.0035475 (0.0044777)	0.0167946*** (0.0020214)	- 0.0066388 (0.0046964)	0.0164785 (0.0021254)	-0.008297* (0.0048849)
Quadratic time trend	-.000047 (.0000723)	0.0002945** (0.000124)	-0.0000232 (0.000067)	0.0004085*** (0.0001284)	-0.0000153 (0.0000721)	0.0004147*** (0.0001334)
Crop damaging duration (Days)	-0.0007743*** (0.0001581)	-0.0009617*** (0.0002038)	-0.0008404*** (0.0001852)	-0.0011859*** (0.0002446)	-0.00084*** (0.0001657)	-0.001263*** (0.0002468)
Fertilizer price index (lag)	-0.0007806*** (0.000112)	-0.0007918 (0.0001484)	-0.0008364*** (0.0001078)	-0.001032*** (0.00015)	-0.00083*** (0.0001113)	-0.000998*** (0.0001541)
Number of Observations	15,061	14,792	18,579	15,228	18,377	15,042

Number of Counties	1,589	1,440	1,709	1,471	1,605	1,464
Kleibergen-Paap *rk* LM statistic		220 p<0.001		263 p<0.001		109.5 p<0.001
Cragg-Donald Wald *F* statistic)		118		124.774		*48.749*
Kleibergen-Paap *rk* Wald *F* statistic		60		74		29

Notes: ***, **, and * denote 1%, 5%, and 10% significance level, respectively. Robust standard errors are in parenthesis. Models 4(a), 5(a), and 6(a) treat all the explanatory variables as exogenous whereas models 4(b), 5(b), and 6(b) address the endogeneity issues of the explanatory variables. The instrumental variables used are, for model 4(b): one-year lag of grassland bird species richness, current-year pesticide price index, and one-year lag of natural gas price index; for model 5(b): one-year lag of insectivorous bird species richness, current-year pesticide price index, and one-year lag of natural gas price index; for model 6(b): one-year lag of endangered bird species richness, current-year pesticide price index, and one-year lag of natural gas price index.

Supplementary Table S9. Impact of grassland, insectivorous, and endangered bird species evenness (dependent variable: log of corn yield)

	Grassland		Insectivorous		Endangered	
	FE	FE-IV	FE	FE-IV	FE	FE-IV
Variables	7(a)	7(b)	8(a)	8(b)	9 (a)	9 (b)
Species Evenness (log)	0.0293981**	0.0612498	0.0026735	-0.2632953 ***	-0.000888	0.0215131
	(0.0122218)	(0.0626817)	(0.0096939)	(0.1005289)	(0.007718)	(0.0509595)
Neonicotinoid Use (kg) (log)	0.0006577	0.0425681 ***	-0.0038052***	0.0407954 ***	-0.0036***	0.0444083***
	(0.0012303)	(0.0063187)	(0.0010433)	(0.0059929)	(0.0010545)	(0.0064157)
Birds Evenness (log)	-0.0041832**	- 0.0233242 ***	0.0015064	0.0186609 ***	0.0023266*	-0.003174***
×Neonicotinoid Use (kg) (log)	(0.0019343)	(0.0052539)	(0.0015742)	(0.0047627)	(0.0012662)	(0.00471)
GE Adoption Rate (%)	0.0006002**	0.0003921	0.0006008	0.0002611	0.0006788***	0.0002858
	(0.004)	(0.0002544)	(0.0002002)	(0.000256)	(0.0002093)	(0.0002573)
Normal GDD (1,000)	0.129159***	0.0892189***	0.1219812 ***	0.1048668 ***	0.1286087***	0.104194***
	(0.0223055)	(0.0271791)	(0.0208991)	(0.0250798)	(0.0189266)	(0.0258951)
Overheat GDD (100)	-0.4707283***	-0.4640415***	-0.4880571***	-0.4895553***	-0.499356***	-0.503563***
	(0.0177632)	(0.0167143)	(0.0156925)	(0.0141616)	(0.0121986)	(0.0146692)
Precipitation (100)	0.0497655***	0.0562015***	0.0431505 ***	0.0536025 ***	0.0370403***	0.047511***
	(0.0095146)	(0.009674)	(0.0082217)	(0.0087369)	(0.0074837)	(0.0089519)
Square Precipitation (100)	-0.0032652***	-0.0034385***	- 0.0027879 ***	-0.0032062 ***	-0.002363***	-0.002807***
	(0.0007126)	(0.0007141)	(0.0006014)	(0.0006268)	(0.000542)	(0.0006463)
Linear time trend	0.0127853***	-0.0136744***	0.0006014	-0.0072593	0.0161252***	-0.008108*
	(0.0022051)	(0.0050861)	(0.0020213)	(0.0048318)	(0.00216)	(0.0049864)
Quadratic time trend	-0.0000307	0.0004909***	-0.000025	0.0004015***	-0.00002	0.0004364***
	(0.0000736)	(.0001406)	(0.0000764)	(0.0001308)	(0.0000731)	(0.0001372)
Crop damaging duration (Days)	-0.0007153***	-0.0009323***	-0.0008455	-0.001252***	-0.000867***	-0.001218***
	(0.0001534)	(0.0001922)	(0.0001841)	(0.0002589)	(0.0001694)	(0.0002379)
Fertilizer price index (lag)	-0.0006014***	-0.0007279***	-0.0008415	-0.0010664	-0.000838***	-0.00105***
	(0.0001146)	(0.0001568)	(0.0001081)	(0.0001562)	(0.0001122)	(0.0001556)
Number of Observations	15,061	14,792	18,579	15,228	18,377	15,042
Number of Counties	1,589	1,440	1,709	1,471	1,605	1,464
Kleibergen-Paap *rk* LM statistic		105		45		101.6
		p<0.001		p<0.001		P<0.001

Cragg-Donald Wald *F* statistic)	73.86	25	62.54
Kleibergen-Paap *rk* Wald *F* statistic	28	12	27.55

Notes: ***, **, and *denote 1%, 5%, and 10% significance level, respectively. Robust standard errors are in parenthesis. Models 7(a), 8(a), and 9(a) treat all the explanatory variables as exogenous whereas models 7(b), 8(b), and 9(b) address the endogeneity issues of the explanatory variables. The instrumental variables used are, for model 7(b): one-year lag of grassland bird species evenness, current-year pesticide price index, and one-year lag of natural gas price index; for model 8(b): one-year lag of insectivorous bird species evenness, current-year pesticide price index, and one-year lag of natural gas price index; for model 9(b): one-year lag of endangered bird species evenness, current-year pesticide price index, and one-year lag of natural gas price index.

Supplementary Table S10. Impact of grassland, insectivorous, and endangered bird abundance on soybean yield (dependent variable: log of soybean yield)

Variables	Grassland		Insectivorous		Endangered	
	FE	FE-IV	FE	FE-IV	FE	FE-IV
	10(a)	10(b)	11(a)	11(b)	12(a)	12(b)
Abundance (log)	0.010623*** (0.0039521)	0.0580791*** (0.0135063)	0.0044438 (0.004204)	-0.017839 (0.0136846)	0.002903 (0.0039468)	0.0305138* (0.0147274)
Neonicotinoid Use (kg) (log)	0.0183868*** (0.0022184)	0.1208542*** (0.0107516)	0.0070187* (0.0027069)	0.0678597*** (0.0087646)	0.0113552*** (0.0022546)	0.1036853*** (0.0100913)
Birds Abundance (log) ×Neonicotinoid Use (kg) (log)	-0.0035214*** (0.0005124)	-0.0155587*** (0.0014566)	-0.0005589 (0.0005534)	0.0007997 (0.0012631)	-0.001915*** (0.00055)	-0.0085539*** (0.0014453)
GE Adoption Rate (%)	0.0016986*** (0.0002021)	0.0040576*** (0.0003893)	0.0016913*** (0.0001997)	0.0043831*** (0.0004044)	0.0016945*** (0.0002008)	0.0044219*** (0.0004131)
Normal GDD (1,000)	0.4479153*** (0.0191041)	0.5419585*** (0.0248219)	0.4467735*** (0.0188412)	0.5645336*** (0.0246397)	0.448552*** (0.0190199)	0.5626938*** (0.0250762)
Overheat GDD (100)	-0.5547875*** (0.0123311)	-0.5491312*** (0.0156763)	-0.5527287*** (0.0122455)	-0.5472513*** (0.0157783)	-0.554833*** (0.0123672)	-0.5494996*** (0.0159806)
Precipitation (100)	0.1078881*** (0.0077027)	0.1344908*** (0.0087632)	0.1111964*** (0.0076391)	0.146289*** (0.0088252)	0.1101314*** (0.0076781)	0.1437419*** (0.0090046)
Square Precipitation (100)	-0.0063273*** (0.0005407)	-0.0075814*** (0.0006119)	-0.0065794*** (0.0005363)	-0.0084552*** (0.0006119)	-0.006516*** (0.0005395)	-0.0082758*** (0.0006251)
Linear time trend	-0.0341341*** (0.004093)	-0.1129879*** (0.0113359)	-0.03276*** (0.0040402)	-0.1216241*** (0.0117287)	-0.032813*** (0.0040698)	-0.1230247*** (0.0119981)
Quadratic time trend	0.0016412*** (0.0001402)	0.003752*** (0.0003309)	0.0016274*** (0.0001387)	0.004035 (0.0003449)	0.001625*** (0.0001397)	0.0040522*** (0.0003505)
Crop damaging duration (Days)	-0.0004314 (0.0002899)	-0.0002448 (0.0003387)	-0.000587* (0.0003317)	-0.0006691* (0.0003623)	-0.0005175* (0.0002977)	-0.0006034* (0.0003629)
Fertilizer price index (lag)	0.001266*** (0.0001193)	0.0015596*** (0.0001864)	0.0012546*** (0.0001174)	0.0016016*** (0.0001859)	0.0012364 (0.0001184)	0.0015986*** (0.0001898)

Number of Observations	15,023	12,471	15,374	12,778	15,202	12,614
Number of Counties	1,288	1,168	1,312	1,186	1,305	1,180
Kleibergen-Paap *rk* LM statistic		440 *p<0.001*		404 *p<0.001*		386 *p<0.001*
Cragg-Donald Wald *F* statistic)		112.183		103		99.835
Kleibergen-Paap *rk* Wald *F* statistic		121.273		110		105.365

Notes: ***, **, and * denote 1%, 5%, and 10% significance levels, respectively. Robust standard errors are in parenthesis. Models 10(a), 11(a), and 12(a) treat all the explanatory variables as exogenous whereas models 10(b), 11(b), and 12(b) address the endogeneity issues of the explanatory variables. The instrumental variables used are, for model 10(b): one-year lag of grassland bird abundance, current-year pesticide price index, and one-year lag of natural gas price index; for model 11(b): one-year lag of insectivorous bird abundance, current-year pesticide price index, and one-year lag of natural gas price index; for model 12(b): one-year lag of endangered bird abundance, current-year pesticide price index, and one-year lag of natural gas price index.

Supplementary Table S11. Impact of grassland, insectivorous, and endangered bird species richness on soybean yield (dependent variable: log of soybean yield)

Variables	Grassland		Insectivorous		Endangered	
	FE	FE-IV	FE	FE-IV	FE	FE-IV
	13 (a)	13 (b)	14 (a)	14 (b)	15 (a)	15 (b)
Species Richness (log)	0.0566179*** (0.0079577)	0.2992342*** (0.0391522)	-0.0109339 (0.0096846)	-0.1000528** (0.0414575)	0.0112564 (0.0086068)	0.146413** (0.0670774)
Neonicotinoid Use (kg) (log)	0.0239115*** (0.0022597)	0.1335823*** (0.0110098)	0.004117 (0.0028283)	0.0404598*** (0.0076893)	0.0094257*** (0.0023025)	0.1146845*** (0.0118538)
Birds Species Richness (log) ×Neonicotinoid Use (kg) (log)	-0.0113901*** (0.0011413)	-0.0479911*** (0.0035631)	0.0002129 (0.0013642)	0.0147485*** (0.0036615)	-0.0034501** (0.0013676)	-0.0295049*** (0.0050889)
GE Adoption Rate (%)	0.0017157*** (0.0002009)	0.0038271*** (0.0003743)	0.0017023*** (0.0001999)	0.0043823*** (0.0004036)	0.0016872*** (0.0002009)	0.0043291*** (0.000424)
Normal GDD (1,000)	0.4450867*** (0.0190486)	0.5218779*** (0.0245734)	0.447467*** (0.0188277)	0.5634057*** (0.0244939)	0.4494071*** (0.0190002)	0.5627042*** (0.0250383)
Overheat GDD (100)	-0.553462*** (0.0123105)	-0.5471152*** (0.0158582)	-0.5529996*** (0.0122403)	-0.5474688*** (0.0157279)	-0.554419*** (0.012375)	-0.5454127*** (0.0161808)
Precipitation (100)	0.1061969*** (0.0077)	0.1250638*** (0.0086718)	0.111312*** (0.0076411)	0.1473225*** (0.0088637)	0.109913*** (0.0076747)	0.1426887*** (0.009029)
Square Precipitation (100)	-0.0061932*** (0.0005405)	-0.0069538*** (0.0006086)	-0.0065872*** (0.0005363)	-0.008511*** (0.0006137)	-0.006495*** (0.0005391)	-0.008174*** (0.000624)
Linear time trend	-0.0350513*** (0.0040804)	-0.1063405*** (0.0109817)	-0.0329036*** (0.0040472)	-0.1215712*** (0.0116862)	-0.03276*** (0.0040671)	-0.1216301*** (0.0123579)
Quadratic time trend	0.0016611*** (0.0001397)	0.0035719*** (0.0003192)	0.0016308*** (0.0001389)	0.004038*** (0.000344)	0.001627*** (0.0001396)	0.0040098*** (0.0003579)
Drought damaging duration (Days)	-0.0004372^{+} (0.0002876)	-0.0002733 (0.0003279)	-0.0005719* (0.0003304)	-0.0006153* (0.0003566)	-0.0005274* (0.000296)	-0.0006718* (0.0003645)
Fertilizer price index (lag)	0.0012579 (0.0001195)	0.0015126*** (0.0001861)	0.0012579*** (0.0001173)	0.0016076*** (0.0001856)	0.001241*** (0.0001183)	0.0016327*** (0.0001902)

Number of Observations	15,023	12,471	15,374	12,778	15,202	12,614
Number of Counties	1,288	1,168	1,312	1,186	1,305	1,180
Kleibergen-Paap *rk* LM statistic		431 $p<0.001$		382 p<0.001		86.959 p<0.001
Cragg-Donald Wald *F* statistic)		116		101		38.57
Kleibergen-Paap *rk* Wald F statistic		118		104		23

Notes: ***, **, and * denote 1%, 5%, and 10% significance levels, respectively. Robust standard errors are in parenthesis. Models 13(a), 14(a), and 15(a) treat all the explanatory variables as exogenous whereas models 13(b), 14(b), and 15(b) address the endogeneity issues of the explanatory variables. The instrumental variables used are, for model 13(b): one-year lag of grassland bird species richness, current-year pesticide price index, and one-year lag of natural gas price index; for model 14(b): one-year lag of insectivorous bird species richness, current-year pesticide price index, and one-year lag of natural gas price index; for model 15(b): one-year lag of endangered bird species richness, current-year pesticide price index, and one-year lag of natural gas price index.

Supplementary Table S12. Impact of grassland, insectivorous, and endangered bird species evenness (dependent variable: log of soybean yield)

Variables	Grassland		Insectivorous		Endangered	
	FE 16 (a)	FE-IV 16 (b)	FE 17 (a)	FE-IV 17 (b)	FE 18 (a)	FE-IV 18 (b)
Species Evenness (log)	0.0869375***	0.2213644***	-0.0188075**	-0.1791766*	0.002903	0.0305138**
	(0.0115174)	(0.0625109)	(0.0093074)	(0.1000422)	(0.0039468)	(0.0147274)
Neonicotinoid Use (kg) (log)	0.011072***	0.0740806***	0.0002171***	0.0621161***	0.011355***	0.1036853***
	(0.0012373)	(0.0069381)	(0.0010719)	(0.0062235)	(0.0022546)	(0.0100913)
Species Evenness (log)	-0.014493***	-0.0536891***	-0.0001689	0.0316687***	-0.001915***	-0.008554***
×Neonicotinoid Use (kg) (log)	(0.0016664)	(0.0049393)	(0.0013586)	(0.0051309)	(0.0005499)	(0.0014453)
GE Adoption Rate (%)	0.0010542***	0.0039068***	0.0012867***	0.0041694***	0.0016945***	0.0044219***
	(0.00023)	(0.0004135)	(0.0002171)	(0.0003927)	(0.0002008)	(0.0004131)
Normal GDD (1,000)	0.4779161***	0.5716853***	0.4382794***	0.5646698***	0.448552***	0.5626938***
	(0.0205276)	(0.0258002)	(0.019157)	(0.0246761)	(0.0190199)	(0.0250762)
Overheat GDD (100)	-0.55675***	0.5443088***	-0.5505663***	-0.5509341***	-0.554833***	-0.549499***
	(0.0141401)	(0.0179289)	(0.0124276)	(0.0159917)	(0.0123672)	(0.0159806)
Precipitation (100)	0.0947038***	0.1192409***	0.1122422***	0.1468254***	0.1101314***	0.1437419***
	(0.008539)	(0.0094618)	(0.0076989)	(0.0090732)	(0.0076781)	(0.0090046)
Square Precipitation (100)	-0.005389***	0.0067059***	-0.0065975***	-0.0085186***	-0.006516***	-0.008276***
	(0.0006108)	(0.0006789)	(0.0005397)	(0.0006308)	(0.0005395)	(0.0006251)
Linear time trend	-0.035932***	0.1175994***	-0.0307298***	-0.1156381***	-0.032813***	-0.123025***
	(0.004414)	(0.0124149)	(0.0041022)	(0.0113923)	(0.0040698)	(0.0119981)
Quadratic time trend	0.0023725***	0.0038059***	0.002126***	0.0038383***	0.0016249***	0.0040522***
	(0.0001667)	(0.0003659)	(0.0001591)	(0.0003333)	(0.0001397)	(0.0003505)
Crop damaging duration (Days)	-0.0003825	0.0003787	-0.0005859*	-0.0006168*	-0.0005175*	-0.0006034*

	(0.0002764)	(0.0003388)	(0.0003269)	(0.0003638)	(0.0002977)	(0.0003629)
Fertilizer price index (lag)	0.0031591*** (0.0002708)	0.0016503*** (0.0002018)	0.0025634*** (0.0002567)	0.0015417*** (0.0001854)	0.0012364*** (0.0001184)	0.0015986*** (0.0001898)
Number of Observations	12,571	10,297	15,248	12,654	15,202	12,614
Number of Counties	1,121	1,011	1,305	1,179	1,305	1,180
Kleibergen-Paap *rk* LM statistic		121 *p*=0.00		40 *p=0.00*		386 *p=0.00*
Cragg-Donald Wald *F* statistic)		80		20.69		99.84
Kleibergen-Paap *rk* Wald F statistic		34		10.28		105.4

Notes: ***, **, and * denote 1%, 5%, and 10% significance level, respectively. Robust standard errors are in parenthesis. Models 16(a), 17(a), and 18(a) treat all the explanatory variables as exogenous whereas models 16(b), 17(b), and 18(b) address the endogeneity issues of the explanatory variables. The instrumental variables used are, for model 16(b): one-year lag of grassland bird species evenness, current-year pesticide price index, and one-year lag of natural gas price index; for model 17(b): one-year lag of insectivorous bird species evenness, current-year pesticide price index, and one-year lag of natural gas price index; for model 18(b): one-year lag of endangered bird species evenness, current-year pesticide price index, and one-year lag of natural gas price index.

Supplementary Table S13. Impact of grassland, insectivorous, and endangered bird abundance on corn yield when only eastern counties are included in the analysis (dependent variable: log of corn yield)

Variables	Grassland FE-IV 19 (a)	Insectivorous FE-IV 19(b)	Endangered FE-IV 19 (c)
Abundance (log)	0.1029002***	-0.0421699***	-0.0161986
	(0.0225352)	(0.0133393)	(0.0143507)
Neonicotinoid Use (kg) (log)	0.0495348***	0.0100292	0.0404591***
	(0.0072326)	(0.0081096)	(0.0087291)
Bird Abundance (log) ×Neonicotinoid Use (kg) (log)	-0.0002779***	0.0063398***	-0.0002645
	(0.0000384)	(0.0013148)	(0.0014902)
GE Adoption Rate (%)	0.0002565	0.0002257	0.0003203
	(0.0002786)	(0.0002536)	(0.0002578)
Normal GDD (1,000)	0.0725044***	0.0657809***	0.0728615***
	(0.0278141)	(0.0256376)	(0.0260408)
Overheat GDD (100)	-0.5102745***	-0.5161108***	-0.5206971***
	(0.0155513)	(0.0147275)	(0.0147482)
Precipitation (100)	0.061098***	0.0715673***	0.071648***
	(0.0101752)	(0.0094826)	(0.0147482)
Square Precipitation (100)	-0.0039515***	-0.0046953***	-0.0047445***
	(0.0007271)	(0.0006725)	(0.0006843)
Linear time trend	-0.001944	-0.0064677	-0.0073332
	(0.0048548)	(0.0047539)	(0.0047681)
Quadratic time trend	0.0003393***	0.0004746***	0.0004783***
	(0.000137)	(0.0001328)	(0.000132)
Crop damaging duration (Days)	-0.0023724***	-0.0027914***	-0.0031924***
	(0.0005617)	(0.000562)	(0.0005681)
Fertilizer price index (lag)	-0.0008464***	-0.001017***	-0.0010607***
	(0.000165)	(0.0001519)	(0.0001542)
Number of Observations	13,429	13,868	13,699
Number of Counties	1,259	1,290	1,284
Kleibergen-Paap *rk* LM statistic	197.25 *p<0.001*	588.583 *p<0.001*	555 *p<0.001*
Cragg-Donald Wald *F* statistic)	71.776	152	146
Kleibergen-Paap *rk* Wald F statistic	51.275	169	159

Notes: ***, **, and * denotes 1%, 5%, and 10% significance levels, respectively. Robust standard errors are in parenthesis. The instrumental variables used are, for model 19(a): one-year lag of grassland bird abundance, current-year pesticide price index, and one-year lag of natural gas price index; for model 19(b): one-year lag of insectivorous bird abundance, current-year pesticide price index, and one-year lag of natural gas price index; for model 19 (c): one-year lag of endangered bird abundance, current-year pesticide price index, and one-year lag of natural gas price index.

Supplementary Table S14. Impact of grassland, insectivorous, and endangered bird species richness on corn yield when only eastern counties are included in samples (dependent variable: log of corn yield)

Variables	Grassland FE-IV 20(a)	Insectivorous FE-IV 20(b)	Endangered FE-IV 20(c)
Species Richness (log)	0.1343172***	-0.1642433***	0.0536522
	(0.041213)	(0.0436771)	(0.0583111)
Neonicotinoid Use (kg) (log)	0.0791313***	-0.0014468	0.0713788***
	(0.0095198)	(0.0081624)	(0.0113068)
Bird Species Richness (log)	-0.0306198***	0.0190493***	-0.0219232***
×Neonicotinoid Use (kg) (log)	(0.0033577)	(0.003807)	(0.0053645)
GE Adoption Rate (%)	0.0000179	0.0002345	0.0003183
	(0.0002563)	(0.0002546)	(0.0002685)
Normal GDD (1,000)	0.0500392***	0.0685509***	0.071675***
	(0.0265011)	(0.0255538)	(0.0260834)
Overheat GDD (100)	-0.5096741***	-0.5164686***	-0.5173411***
	(0.0151444)	(0.0146936)	(0.0147951)
Precipitation (100)	0.0627139***	0.0713745***	0.0713611***
	(0.0095268)	(0.0095027)	(0.0097996)
Square Precipitation (100)	-0.5096741***	-0.0046793***	-0.0046972***
	(0.0095268)	(0.0006743)	(0.0006947)
Linear time trend	-0.0032937	-0.0062352	-0.0076856
	(0.0045188)	(0.0047204)	(0.004888)
Quadratic time trend	0.0003455***	0.0004629***	0.0004593***
	(0.0001278)	(0.000132)	(0.0001369)
Crop damaging duration (Days)	-0.0024943***	-0.0027149***	-0.0032564***
	(0.0005461)	(0.0005618)	(0.0005722)
Fertilizer price index (lag)	-0.0007884***	-0.0010079***	-0.0010043***
	(0.0001517)	(0.0001519)	(0.0001568)
Number of Observations	13,429	13,868	13,699
Number of Counties	1,259	1,290	1,284
Kleibergen-Paap *rk* LM statistic	215 *p<0.001*	588.583 *p<0.001*	109.6 *p<0.001*
Cragg-Donald Wald *F* statistic	119	152	48.5
Kleibergen-Paap *rk* Wald *F* statistic	59	169	29

Notes: ***, **, and * denotes 1%, 5%, and 10% significance levels, respectively. Robust standard errors are in parenthesis. The instrumental variables used are, for model 20(a): one-year lag of grassland bird richness, current-year pesticide price index, and one-year lag of natural gas price index; for model 20(b): one-year lag of insectivorous bird species richness, current-year pesticide price index, and one-year lag of natural gas price index; for model 20(c): one-year lag of endangered bird species richness, current-year pesticide price index, and one-year lag of natural gas price index.

Supplementary Table S15. Impact of grassland, insectivorous, and endangered bird species evenness on corn yield when only eastern counties are included in samples (dependent variable: log of corn yield)

Variables	Grassland FE-IV 21(a)	Insectivorous FE-IV 21 (b)	Endangered FE-IV 21(c)
Species Evenness (log)	0.0652907	-0.323788***	0.0230528
	(0.066077)	(0.1033269)	(0.058208)
Neonicotinoid Use (kg) (log)	0.0363131***	0.036243***	0.0409266***
	(0.0058044)	(0.0056167)	(0.0061207)
Species Evenness (log)	-0.0234366***	0.0148718***	-0.0063128
×Neonicotinoid Use (kg) (log)	(0.00529)	(0.0051473)	(0.0052426)
GE Adoption Rate (%)	0.0004627*	0.0004033	0.0003647
	(0.0002597)	(0.0002697)	(0.000263)
Normal GDD (1,000)	0.0629312**	0.0728334***	0.0764302***
	(0.028324)	(0.026166)	(0.0267435)
Overheat GDD (100)	-0.4987447***	-0.5130055***	-0.5302598***
	(0.0181392)	(0.0150335)	(0.0155618)
Precipitation (100)	0.0814527***	0.0689356***	0.0653976***
	(0.0109913)	(0.0097788)	(0.009916)
Square Precipitation (100)	-0.0055469***	-0.0045076***	-0.0043041***
	(0.0007976)	(0.0006937)	(0.0007076)
Linear time trend	-0.0120022*	-0.006845	-0.0081458***
	(0.0050815)	(0.0049231)	(0.005008)
Quadratic time trend	0.0005142***	0.0004602***	0.0005004***
	(0.0001459)	(0.0001362)	(0.0001415)
Drought damaging Duration (Days)	-0.0024139***	-0.0029321***	-0.0032235***
	(0.000586)	(0.0005719)	(0.000599)
Fertilizer price index (lag)	-0.0006754***	-0.0010558	-0.0010394***
	(0.0001604)	(0.0001598)	(0.0001584)
Number of Observations	10,783	13,753	12,936
Number of Counties	1,042	1,283	1,230
Kleibergen-Paap *rk* LM statistic	93	48	89
	p<001	*p<001*	*p<001*
Cragg-Donald Wald *F* statistic)	63	26	47
Kleibergen-Paap *rk* Wald *F* statistic	24.5	12	23

Notes: ***, **, and * denote 1%, 5%, and 10% significance level, respectively. Robust standard errors are in parenthesis. The instrumental variables used are, for model 21(a): one-year lag of grassland bird species evenness, current-year pesticide price index, and one-year lag of natural gas price index; for model 21(b): one-year lag of insectivorous bird species evenness, current-year pesticide price index, and one-year lag of natural gas price index; for model 21(c): one-year lag of endangered bird species evenness, current-year pesticide price index, and one-year lag of natural gas price index.

Supplementary Table S16. Impact of grassland, insectivorous, and endangered bird abundance on soybean yield when only eastern counties are included in samples (dependent variable: log of soybean yield)

Variables	Grassland FE-IV 22(a)	Insectivorous FE-IV 22 (b)	Endangered FE-IV 22 (c)
Abundance (log)	0.0603531***	-0.0145479	0.0340881**
	(0.0133435)	(0.0134564)	(0.0145929)
Neonicotinoid Use (kg) (log)	0.1176397***	0.066744***	0.1017758***
	(0.0107263)	(0.0087659)	(0.0100368)
Bird Abundance (log) ×Neonicotinoid Use (kg) (log)	-0.0156474***	0.0004312	-0.008939***
	(0.0014669)	(0.0012597)	(0.001437)
GE Adoption Rate (%)	0.0037814***	0.0037814***	0.0041424***
	(0.0003899)	(0.0003899)	(0.0004143)
Normal GDD (1,000)	0.5313597***	0.5313597***	0.5535004***
	(0.024652)	(0.024652)	(0.0248919)
Overheat GDD (100)	-0.5534926***	-0.5534926***	-0.5544862***
	(0.0158688)	(0.0158688)	(0.0161441)
Precipitation (100)	0.1374152***	0.1374152***	0.147575***
	(0.0088037)	(0.0088037)	(0.0090484)
Square Precipitation (100)	-0.0078727***	-0.0078727***	-0.0086323***
	(0.0006136)	(0.0006136)	(0.0006267)
Linear time trend	-0.105454***	-0.105454***	-0.115358***
	(0.0112781)	(0.0112781)	(0.0119469)
Quadratic time trend	0.0035357***	0.0035357***	0.0038298***
	(0.0003294)	(0.0003294)	(0.0003492)
Drought damaging duration (Days)	-0.0015444***	-0.0015444***	-0.0019508***
	(0.0005103)	(0.0005103)	(0.0005159)
Fertilizer price index (lag)	0.0014352***	0.0014352***	0.0014701***
	(0.0001852)	(0.0001852)	(0.0001883)
Number of Observations	12,267	12,574	12,410
Number of Counties	1,131	1,149	1,143
Kleibergen-Paap *rk* LM statistic	434.6	396	380
	p<0.001	*p<0.001*	*p<0.001*
Cragg-Donald Wald *F* statistic)	111	102	99
Kleibergen-Paap *rk* Wald *F* statistic	120	109	104

Notes: ***, **, and * denote 1%, 5%, and 10% significance levels, respectively. Robust standard errors are in parenthesis. The instrumental variables used are, for model 22(a): one-year lag of grassland bird abundance, current-year pesticide price index, and one-year lag of natural gas price index; for model 22(b): one-year lag of insectivorous bird abundance, current-year pesticide price index, and one-year lag of natural gas price index; for model 22(c): one-year lag of endangered bird abundance, current-year pesticide price index, and one-year lag of natural gas price index.

Supplementary Table S17. Impact of grassland, insectivorous, and endangered bird species richness on soybean yield when only eastern counties are included in samples (dependent variable: log of soybean yield)

Variables	Grassland FE-IV 23(a)	Insectivorous FE-IV 23(b)	Endangered FE-IV 23(c)
Species Richness (log)	0.2970658*** (0.0388454)	-0.08449** (0.0408627)	0.1490851** (0.065)
Neonicotinoid Use (kg) (log)	0.1301603*** (0.011)	0.038968*** (0.007706)	0.1114756*** (0.0118313)
Bird Species Richness (log) ×Neonicotinoid Use (kg) (log)	-0.047793*** (0.003576)	0.0141077*** (0.0036752)	-0.0293689*** (0.0050422)
GE Adoption Rate (%)	0.0035604*** (0.0003754)	0.0041284*** (0.0004068)	0.0040475*** (0.0004244)
Normal GDD (1,000)	0.5131462*** (0.0244293)	0.5538332*** (0.0243106)	0.5542287*** (0.024866)
Overheat GDD (100)	-0.5526089*** (0.0160489)	-0.551717*** (0.015931)	-0.5511592*** (0.0163352)
Precipitation (100)	0.1282981*** (0.0087272)	0.1515593*** (0.0089207)	0.1470048*** (0.0090734)
Square Precipitation (100)	-0.0072653*** (0.0006112)	-0.0088899*** (0.0006162)	-0.0085639*** (0.0006254)
Linear time trend	-0.0992043*** (0.0109478)	-0.1148427*** (0.0117025)	-0.1140554*** (0.0122728)
Quadratic time trend	0.0033639*** (0.0003183)	0.0038441*** (0.0003447)	0.00379*** (0.0003546)
Crop damaging duration (Days)	-0.001479*** (0.0005084)	-0.0019084*** (0.0005248)	-0.0019838*** (0.0005169)
Fertilizer price index (lag)	0.0013874*** (0.0001851)	0.0014884*** (0.0001847)	0.0014987*** (0.0001885)
Number of Observations	12,267	12,574	12,410
Number of Counties	1,131	1,149	1,143
Kleibergen-Paap *rk* LM statistic	423.677 *p<0.001*	379.8 *p<0.001*	90 *p<0.001*
Cragg-Donald Wald *F* statistic)	115	100	40
Kleibergen-Paap *rk* Wald *F* statistic	116	104	24

Notes: ***, **, and * denote 1%, 5%, and 10% significance levels, respectively. Robust standard errors are in parenthesis. The instrumental variables used are, for model 23(a): one-year lag of grassland bird species richness, current-year pesticide price index, and one-year lag of natural gas price index; for model 23(b): one-year lag of insectivorous bird species richness, current-year pesticide price index, and one-year lag of natural gas price index; for model 23(c): one-year lag of endangered bird species richness, current-year pesticide price index, and one-year lag of natural gas price index.

Supplementary Table S18. Impact of grassland, insectivorous, and endangered bird species evenness on soybean yield when only eastern counties are included in samples (dependent variable: log of soybean yield)

Variables	Grassland FE-IV 24(a)	Insectivorous FE-IV 24(b)	Endangered FE-IV 24(c)
Species Evenness (log)	0.2248136***	-0.147725	0.0022361
	(0.0619221)	(0.09795)	(0.063315)
Neonicotinoid Use (kg) (log)	0.0710738***	0.0598838***	0.0717632***
	(0.0069171)	(0.0062261)	(0.007066)
Species Evenness (log) ×Neonicotinoid Use (kg) (log)	-0.0539612***	0.031509***	-0.003311
	(0.0049178)	(0.0051417)	(0.0049622)
GE Adoption Rate (%)	0.0035997***	0.0039621***	0.0040742***
	(0.0004167)	(0.0003967)	(0.0004138)
Normal GDD (1,000)	0.5624861***	0.5552637***	0.5600871***
	(0.0256392)	(0.0245283)	(0.0252211)
Overheat GDD (100)	-0.550932***	-0.5535483***	-0.5617352***
	(0.0182906)	(0.0161951)	(0.0165424)
Precipitation (100)	0.1232844***	0.1508345***	0.1462222***
	(0.0095045)	(0.0091458)	(0.0092624)
Square Precipitation (100)	-0.0071009***	-0.0088736***	-0.0085067***
	(0.00068)	(0.000635)	(0.0006451)
Linear time trend	-0.1091658***	-0.1105033***	-0.1179605***
	(0.0124288)	(0.0114302)	(0.0119463)
Quadratic time trend	0.0035572***	0.0036905***	0.0039374***
	(0.0003665)	(0.0003346)	(0.0003533)
Crop damaging duration (Days)	-0.0017194***	-0.0018983***	-0.0020522***
	(0.0005336)	(0.0005251)	(0.0005442)
Fertilizer price index (lag)	0.0015007***	0.0014461***	0.0014875***
	(0.000201)	(0.0001847)	(0.0001907)
Number of Observations	10,093	12,460	11,779
Number of Counties	974	1,144	1,099
Kleibergen-Paap *rk* LM statistic	120	42	66.64
	p<0.001	*p<0.001*	*p<0.001*
Cragg-Donald Wald *F* statistic)	79	21	34
Kleibergen-Paap *rk* Wald *F* statistic	34	10.5	17

Notes: ***, **, and * denote 1%, 5%, and 10% significance levels, respectively. Robust standard errors are in parenthesis. The instrumental variables used are, for model 24(a): one-year lag of grassland bird species richness, current-year pesticide price index, and one-year lag of natural gas price index; for model 24(b): one-year lag of insectivorous bird species richness, current-year pesticide price index, and one-year lag of natural gas price index; for model 24(c): one-year lag of endangered bird species richness, current-year pesticide price index, and one-year lag of natural gas price index.

Supplementary Table S19: Impact of extinction of grassland birds and neonicotinoid ban on corn yield based on model 1(b) of Table 2.

Scenario	Extinction of Grassland Birds	Ban on Neonicotinoids
Yield Reduction	11.52% CI: [6.70%, 16.30%]	3.82% CI: [2.89%, 4.64%]
Additional neonicotinoid use required to maintain yield	219.43% CI: [127.6%, 310.5%]	-
Additional grassland birds required to maintain yield	-	32.93% CI: [24.9%, 40.00%]

Note: The value in square brackets shows the 95% confidence interval.

a) **If all grassland birds extinct, everything else equal, then decrease in corn yield**: Calculated by using (0.116-0.0001847×4.55)×100, where 0.116 is the coefficient of log of grassland bird abundance, -0.0001847 is the coefficient of the interaction term between log of grassland bird abundance and log of neonicotinoid use, 4.55 is the sample mean of log of neonicotinoid use, and 100 represents the case when all the grassland birds disappear.

b) **If neonicotinoid is banned, everything else equal, then the decrease in corn yield**: 5.2%-1.38%=3.82%. In this approximation, 5.2% is calculated by using (0.0525-0.0001847×3.34) ×100 where 0.0525 is the coefficient of log of neonicotinoid use, 0.0001847 is the coefficient of the interaction term between log of grassland bird abundance and log of neonicotinoid use, 3.34 is the sample mean of log of grassland bird abundance, and 100 represents the case when there is no use of neonicotinoid (neonicotinoid ban). Similarly, 1.38% is calculated by using (0.116-0.0001847×4.55)×12, where 0.116 is the coefficient of log of grassland bird abundance, -0.0001847 is the coefficient of the interaction between log of grassland bird abundance and log of neonicotinoid use, 4.55 is the sample mean of log of neonicotinoid use, and 12 is the annual percentage of grassland birds that would have been saved if there were a neonicotinoid ban. Li et al. (2020) has estimated about 12% annual rate of reduction of the grassland birds due to the use of neonicotinoid use.

c) **Additional neonicotinoid use required to maintain corn yield, when all the grassland birds are gone, everything else is equal**: If all the grassland birds are gone, then the decrease in corn yield is by 11.52%. Since 0.0525% increase in corn yield requires a 1% increase in the neonicotinoids. So, to increase the corn yield by 11.52% (corn yield contributed by grassland birds) the % needed to increase in neonicotinoids = 11.52⁄0.0525=219.43.

d) **Additional grassland birds required to maintain corn yield, when neonicotinoids are banned**: Calculated by using (1⁄0.116×3.82), where 0.116 is the yield % increased by 1% increase in grassland bird abundance. So, to increase the corn yield by 3.82% (this is the decrease in corn yield when we ban the neonicotinoids) there should be 32.93% increase in grassland bird abundance.

Supplementary Table S20: Impact of extinction of grassland birds and ban on neonicotinoids on soybean yield (Based on model 10(b) of Table S10.

Scenario	Extinction of Grassland Birds	Ban on Neonicotinoids
Yield Reduction	1.4% CI: [-0.7%, 3.7%]	7.02% CI: [5.70%, 8.4%]
Additional neonicotinoid use required to maintain yield	No change	-
Additional grassland birds required to maintain yield	-	120.87% CI: [99.35%,180.34%]

Notes: The value in square brackets shows the 95% confidence interval. “No change” indicates statistically insignificant effect of grassland bird abundance on soybean yield when evaluated at sample means.

If all grassland birds disappear, everything else equal, then decrease in soybean yield: Calculated by using (0.0580791-0.0155587×4.68) ×100, where 0.0580791 is the coefficient of log of grassland bird abundance, -0.0155587 is the coefficient of the interaction term between log of grassland bird abundance and log of neonicotinoid use, 4.68 is the sample mean of log of neonicotinoid use, and 100 represents the case when all the grassland birds extinct. But this is not statistically significant (p=0.19).

If neonicotinoid is banned, everything else equal, then decrease in soybean yield: 7.02%, calculated by using (0.1208542-0.0155587×3.25)×100. Here 0.1208542 is the coefficient of log of neonicotinoid use, 0.0155587 is the coefficient of the interaction term between log of grassland bird abundance and log of neonicotinoid use, 3.25 is the sample mean of log of grassland bird abundance, and 100 represents the case when there is no use of neonicotinoid (neonicotinoid ban).

Additional neonicotinoids use required to maintain soybean yield, when all the grassland birds are gone: When evaluated at sample means**,** grassland bird abundance has no statistically significant impact on soybean yield. There is no need to increase the neonicotinoid use to maintain the soybean yield.

Additional grassland birds required to maintain soybean yield, when neonicotinoids use are banned: When analyzed at sample means of neonicotinoid use (log), the impact of grassland birds on soybean yield is insignificant. However, when evaluated at the lower value of neonicotinoid use, grassland birds have significant impact on soybean yield. From Table S10, when neonicotinoid is banned, 1% increase in grassland birds is associated with 0.0580791% increase in soybean yield. So, to increase the soybean yield by 7.02% (decrease in soybean yield when there is neonicotinoid ban) increase in grassland birds equals 120.87%, calculated by using $1/0.0580791 \times 7.02$.

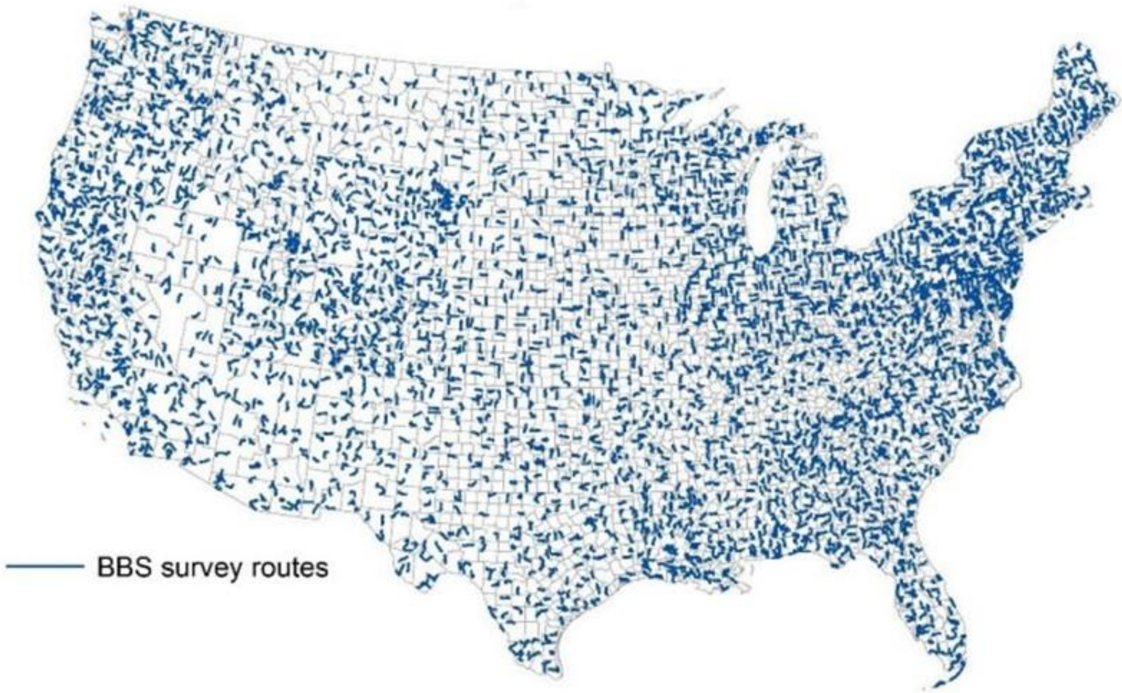


Figure S1. North American Breeding Bird Survey Routes in the Contiguous United States

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