

The impact of genetically modified crops on bird diversity

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Abstract

Biodiversity provides essential ecosystem services to agriculture, including pest control and pollination. Yet, global biodiversity is declining at an alarming rate, largely due to agricultural change. The introduction of genetically modified (GM) crops in the United States marked a major transformation of agricultural production: over 90% of US corn, soybean, and cotton areas are now planted with GM varieties. This shift in crop cultivation has significantly altered crop management practices, most notably the types and quantities of pesticides used. Despite the magnitude of these changes, the impact on biodiversity is still poorly understood. Here, we estimate the causal impact of GM crops on bird diversity in the United States. We combine bird observations from the North American Breeding Bird Survey with data on GM crop adoption. This allows us to compare bird communities through time in areas with high exposure to GM crops to otherwise similar areas with low exposure to GM crops. We find that insectivorous birds benefit from GM crop adoption and that this benefit is largest in cotton. In contrast, herbivorous birds weakly decrease with GM crop adoption. Thus, while GM crop adoption has a weakly positive effect on overall abundance and diversity of birds, the effect is heterogeneous across species groups, with potentially important consequences for bird community composition and associated ecosystem services in agricultural landscapes.

1 Main

Global biodiversity has declined alarmingly over the past decades. While the recent adoption of the Kunming-Montréal Global Biodiversity Framework exemplifies the increased attention this issue is receiving, biodiversity loss still continues at an unprecedented rate. With the consumption of agricultural products projected to increase dramatically over the coming decades, it is necessary to design agricultural systems that reconcile the increase in food demand with the conservation of biodiversity and the crucial ecosystem services it provides. Genetically modified (GM) crop varieties could constitute one component of such systems if GM crops lead to environmental benefits relative to equally intensive non-GM production. Yet, more than two decades after this new technology’s approval and rapid adoption, it is still unclear how GM crops affected biodiversity. Here, we contribute to this research by estimating the impact of GM crop adoption on bird diversity. Using methods from the causal inference literature, we show how GM crops may have affected different groups of bird species, and we suggest mechanisms that explain these heterogeneous effects.

Birds play an important role in agricultural pest control [13, 17, 3, 34, 18]. They are also one of the taxa that have been mostly negatively affected by agricultural production, especially those species dependent on agricultural land for food resources and habitat [29, 28, 16]. This loss of bird diversity is likely a sign that other animals and biodiversity in general are similarly affected because birds form an integral part of ecosystems and are an important indicator for overall ecosystem health [37, 15]. An important mechanism that links agricultural intensification to the decline of bird diversity is the increased use of pesticides [20]. The adoption of GM crops fundamentally changed pesticide use in agriculture [23, 19], with potentially important consequences for bird diversity and biodiversity in general. Despite a large number of field trials and laboratory studies initially demonstrating a limited immediate impact of GM crops on biodiversity [7], the impact of their large-scale adoption and consequent changes in crop management remains largely unknown.

GM crops were first approved and commercially introduced in the United States in 1996 as

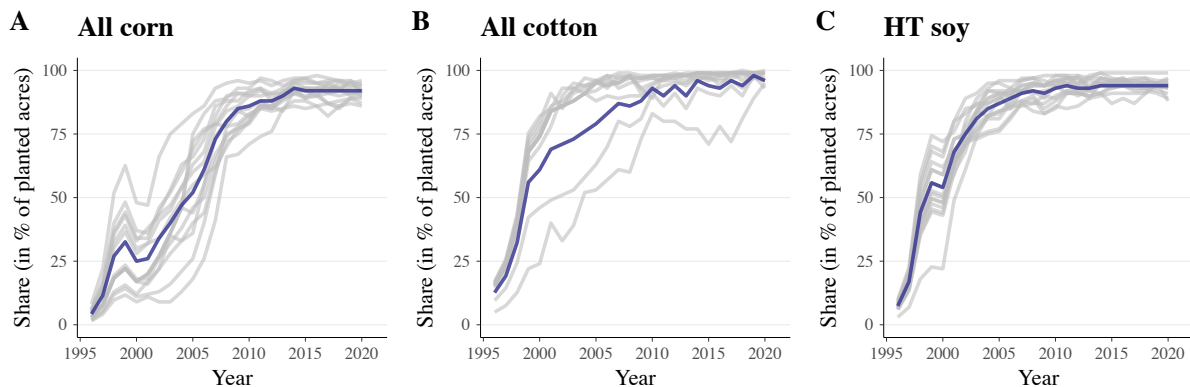


Figure 1: Adoption rates of GM (all traits combined) corn, cotton, and soy varieties as shares of planted acreage. The average adoption rate in the United States is in blue, and state-level adoption rates are in grey [35]. See Figure A1 in Appendix A for adoption rates of Bt, HT, and stacked varieties.

varieties of corn, cotton, and soy. In GM crops, desirable crop properties are not achieved through selective breeding but by directly inserting genes into the crop genome [27]. Farmers in the United States widely adopted GM varieties of corn, cotton, and soy within a few years of their development (Fig. 1) [40]. GM crops can have many different traits, but by far, the most common traits are herbicide tolerance and insect resistance [27]. Herbicide-tolerant (HT) crops contain a gene that makes the crop resistant to specific broad-spectrum herbicides. Insect-resistant Bt crops (so called because they contain a gene from *Bacillus thuringiensis*, a soil microbe) produce a toxin against the caterpillars of moths. These GM traits increase pest control efficiency by allowing the application of broad-spectrum herbicides without direct harm to the crop or by making the crop itself pest-resistant. Therefore, they affect the frequency, composition, and quantity of pesticide applications, which has implications for pesticide toxicity and general management practices, including crop rotations and conservation tillage. While corn and cotton are now grown mainly as stacked varieties, combining both HT and Bt traits, GM soy is so far only available as HT varieties in the United States.

Adding the herbicide tolerance to corn, soy, and cotton, which made them resistant to specific broad-spectrum herbicides (primarily glyphosate, glufosinate, 2,4-D, and more recently,

Dicamba), led to a significant increase in their use, but also to a concurrent decrease in the use of other herbicides [9]. This shift could have affected biodiversity if these specific herbicides were less or more toxic, dissolved into water less or more easily, and had a shorter or longer half-life than the herbicides they replaced [8]. Furthermore, a substitution in pesticide use is often accompanied by changes in the quantity of pesticides used. For example, the total amounts of herbicides applied increased on soybeans, remained unchanged on cotton, and decreased on corn after adopting GM varieties [9]. These changes may directly impact bird communities through changes in toxicity exposure, but they could also affect their food sources through increased weed control efficiency. This could reduce the diversity and abundance of wild plants and insects in the agricultural landscape, with potentially negative consequences for species on higher trophic levels.

The Bt trait in GM corn and cotton had substantial implications for insecticide use. In the first sixteen years after approval of GM crops, total insecticide use is estimated to have been reduced by 41 million kg on corn and 14 million kg on cotton [5]. While Bt crops produce proteins toxic to insects in amounts much larger than the quantity of applied insecticides, these proteins are located inside the cells and deter specific insects feeding on the crop, such as the corn rootworm [5]. Reduced insecticide use could benefit biodiversity if more non-targeted insects survive pest control interventions and if vertebrates are exposed to fewer toxins.

Changes in weed and insect control efficiency, coupled with potentially higher farm profits and negative spillovers of GM crops on non-GM crops [23], may have led to additional indirect changes in the agricultural landscape, including changes in crop rotations and crop diversity as well as tillage practices, with further implications for bird diversity and abundance. For example, previous studies have shown that crop diversity loss negatively impacts bird diversity [32]. While these indirect effects are plausible pathways of the effect of GM crops on bird diversity, we mainly focus on changes in pesticide use as a mechanism that links GM crop adoption to bird diversity.

The main objective of this paper is to estimate the causal impact of GM crop adoption on bird diversity in the United States. We are specifically interested in understanding the effect of GM relative to non-GM, holding all other variables, such as other agricultural technologies, constant. We combine data on GM crop adoption, crop production, and land cover to model GM crop adoption at high spatial resolution. To address concerns that farmers who adopt GM crops also differ from their non-adopting counterparts in other and potentially biodiversity-relevant dimensions, we combine state-level adoption rates with local baseline crop cover to predict local farmer-independent GM crop adoption. While this approach adds noise to our measure of GM crop adoption, it is independent of local farm characteristics and therefore avoids that farm characteristics correlated with GM crop adoption drive our results.¹

To compare changes in bird outcomes over time between areas exposed to GM crops and areas not exposed, we combine the GM crop adoption data with bird diversity data from the North American Breeding Bird Survey (BBS) [25] and then use Two-Way Fixed Effects models. These are regression models commonly used in economics, where dummy variables for each unit and time period (so-called fixed effects) control for unobserved confounding factors between observations and over time, leaving only time-varying differences in outcomes and GM crop exposure between treatment and control group to estimate the impact of GM crop adoption on bird diversity. While our statistical approach absorbs time-constant differences between observations and general fluctuations, it relies on the assumption of parallel trends. In other words, it assumes that conditional on fixed effects and controls, bird populations in areas with and without GM crop adoption would have followed similar trends in the absence of GM crop adoption. Due to the spatial separation between GM and non-GM areas, i.e. corn, soy, and cotton areas versus regions growing other crops (Figure 2), finding a valid control group is challenging, as the environmental conditions that lead farmers to grow different crops in different regions also impact the composition of bird populations.

¹Note that measurement error in the independent variable biases the estimate towards zero. Our estimates are, therefore, rather conservative.

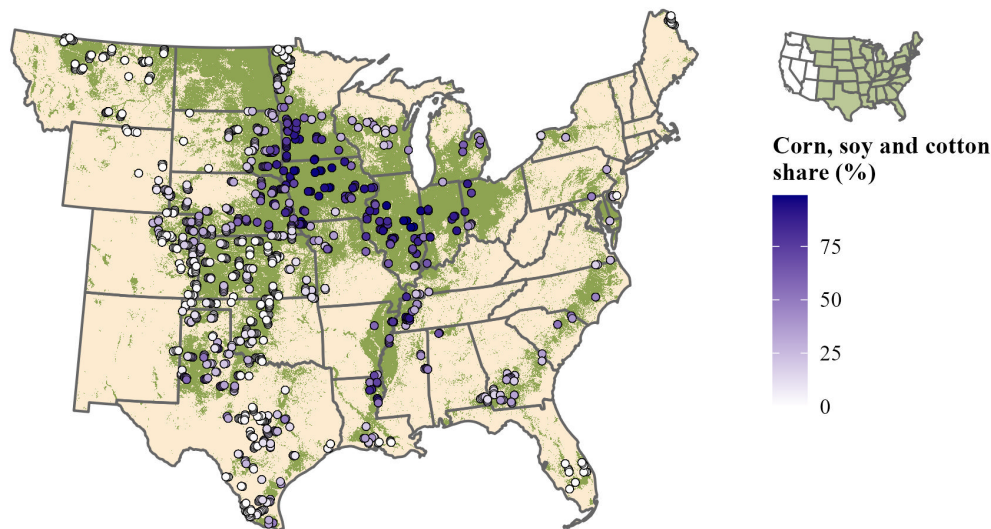


Figure 2: Distribution of corn, soy, and cotton exposure of BBS routes. The sample consists of routes in the Great Plains and Eastern Temperate Forests EPA Level I ecoregions (excluding North Dakota) surrounded by at least 25 % cropland in a 1 and 10 km buffer, and routes in cropland with <25% corn, soy and cotton matched 1:1 to routes in cropland with $\geq 25\%$ corn, soy and cotton share based on abundance of the 100 most common birds and the share of cropland surrounding a BBS route in a 1 km buffer. Cropland areas (based on ESA CCI-LC land cover data in 1992) in green.

We address this challenge in two steps: first, we filter our sample to only include BBS observation routes in agricultural regions in the Eastern Temperate Forest and Great Plains ecoregions (see Appendix B); second, we subsample the data to use comparable treated and control units using a matching algorithm. Specifically, we pair each route in counties with low exposure to corn, soy, and cotton to a route in counties with high exposure, based on the abundances of the 100 most common bird species in the region of interest over the ten years preceding GM crop introduction (1986-1995).

In our main analysis, we estimate the impact of the introduction of GM corn, soy, and cotton

varieties on overall (i.e. all birds in the sample) bird species richness, abundance (number of individual birds), and Shannon diversity. We then focus on the effect heterogeneity between different crops and groups of birds. Specifically, we estimate the impact of GM crop adoption on insectivorous birds (177 species with a diet consisting of $\geq 80\%$ insects according to the EltonTraits database, see Appendix C, Table C2 for a list of species) and herbivorous birds (65 species with a diet consisting of $\geq 80\%$ plants and/or grains, see Appendix C, Table C3 for a list of species. We exclude nectar-eating birds). We focus on these two groups of species because we expect that herbivorous birds might respond to the increased efficiency of weed control, while insectivorous birds may be affected by changes in insecticide use. We then explore the heterogeneous effect across GM crops and the potential mechanisms that link GM crop adoption to bird diversity.

2 Results

Overall, we find a positive and statistically significant impact of overall GM crops on total bird abundance. On routes surrounded entirely by cropland, GM crop adoption led to a 14.3% increase in abundance (coefficient and 95% confidence interval: 0.143 ± 0.108). As the average abundance at a BBS route with high exposure to GM crops is around 171 individuals (see Appendix D, Fig. D2), this corresponds to an increase of 24 birds per BBS route. The effect of GM crops on overall species richness is positive but noisy (0.221 ± 1.59), whereas the effect on Shannon diversity is indistinguishable from zero (0.001 ± 0.096) (Fig. 3 and Appendix E, Table E1).

The impact of GM crop adoption on insectivorous birds is positive and statistically significant (abundance 0.383 ± 0.251 , species richness 0.632 ± 0.545 , and Shannon diversity 0.130 ± 0.122). These coefficients are interpreted as high GM crop adoption leading to 38.3% higher insectivorous bird abundance and higher insectivorous bird richness by 0.632 species. Considering that the average insectivorous bird species richness is approximately 4.6 at a BBS

route in the sample, this effect is substantial (see Table D2 in Appendix D). It is important to note that this does not reflect absolute population changes, i.e., that overall insectivorous bird populations are increasing, but rather that these species are more abundant in high GM crop areas relative to low GM crop areas. Shannon diversity of insectivorous birds also increases with GM crop adoption, meaning that the population of insectivorous birds may have become more diverse in areas with high GM crop adoption. In contrast, the impacts of GM crop adoption on herbivorous bird richness and abundance are negative but only statistically significant for richness. There is also a positive but statistically insignificant effect on herbivorous bird Shannon diversity (species richness -0.304 ± 0.255 , abundance -0.141 ± 0.193 , and Shannon diversity 0.033 ± 0.105). These findings suggest that GM crop adoption affects bird diversity mainly through an increase in insectivorous birds and, to a lesser extent, through a decline in herbivorous birds.

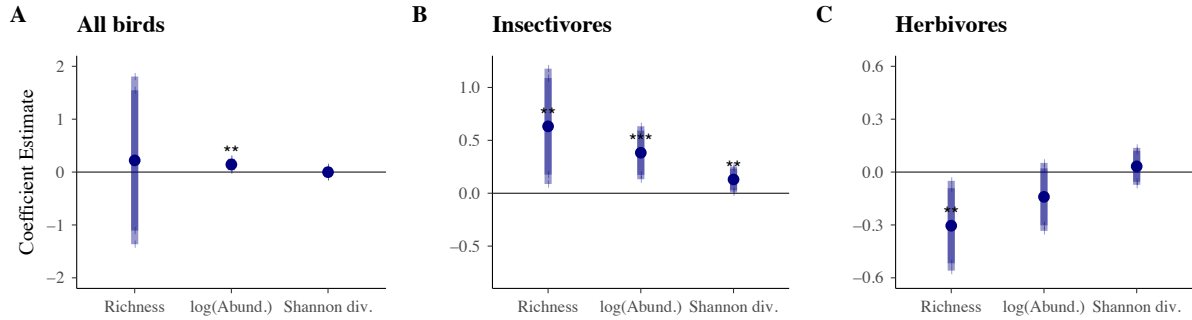


Figure 3: Overall effect of GM crops on all, insectivorous and herbivorous birds. Dark and light bars indicating 90% and 95% confidence intervals, respectively, and stars indicate p-values (* : $P < 0.1$, ** : $P < 0.05$, *** : $P < 0.01$).

The dynamic effects of GM crop adoption on bird diversity, i.e. how the impact of GM crops on biodiversity unfolds over time, align with these findings (see Appendix F, Table F1 for the average treatment effects calculated from the event study coefficients). Whereas the static effects are estimated using a model that provides a single coefficient of the average treatment effect (as presented in Fig. 3), we use an extension of the two-way fixed effects model that allows us to estimate an effect coefficient for each year separately. In the panels of Figure 4,

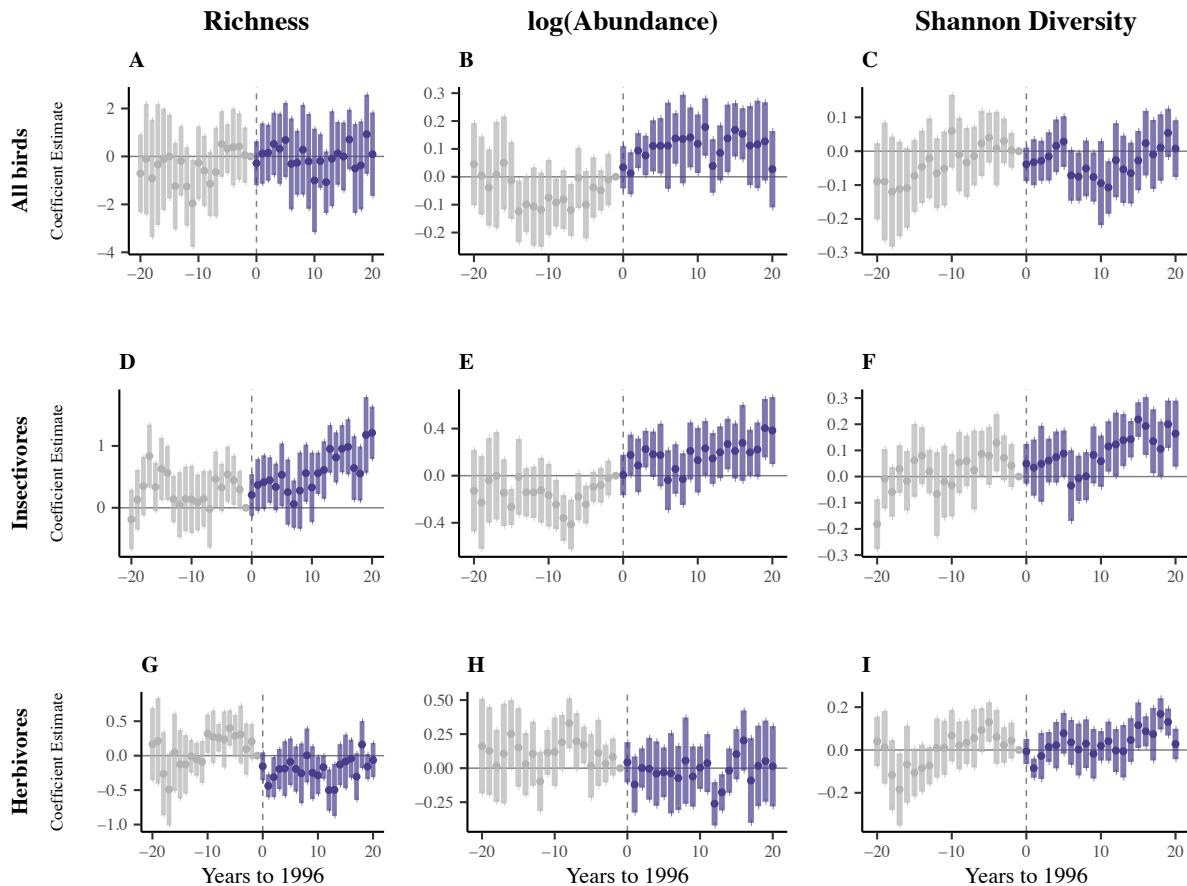


Figure 4: Dynamic overall effect of GM crops on all, insectivorous and herbivorous birds. Bars indicate 95% confidence intervals. Years to 1996 indicate years to and since the commercialization of GM corn, soy, and cotton varieties in 1996.

the points denote the relative difference between the treated group (bird observation in areas with high GM crop adoption) and the control group (bird observations in areas with low or no GM crop adoption) in each year. The lack of statistically significant pre-trends, i.e., that the bird populations changed similarly before GM crop adoption in treatment and control locations supports our assumption of parallel trends. For example, the coefficients for differences in bird abundance on GM vs. non GM routes prior to the introduction of GM crops in 1996 are mostly close to and not statistically different from zero (panel B in Fig. 4). After the introduction of GM crops in 1996, however, coefficients are distinctly positive (~ 0.10), implying that overall abundance in regions with a high share of GM crops increased by about 10% relative to regions with a low share. In addition, the effect

was gradual, which is consistent with our expectations, as GM crop adoption was gradual (Fig. 1), and bird populations may have responded slowly to changes in the agricultural landscape.

The dynamic effects on insectivorous bird richness, abundance, and Shannon diversity (Fig. 4) again correspond to the static effects presented in Fig. 3. All three insectivore metrics exhibit a gradually increasing positive effect of GM crops. The magnitudes of these effects are similar to the static framework, with an effect on species richness of 0.64 (an additional 0.64 species present, which corresponds to about a 14% increase relative to regions with a low share given the mean insectivorous bird richness of 4.615), an increase in abundance of 21%, and an increase in Shannon diversity by roughly 0.11 (Appendix F, Table F1). Finally, the effects on herbivorous birds in the dynamic framework are less clear, with no obvious effect apparent.

2.1 Heterogeneity of the results

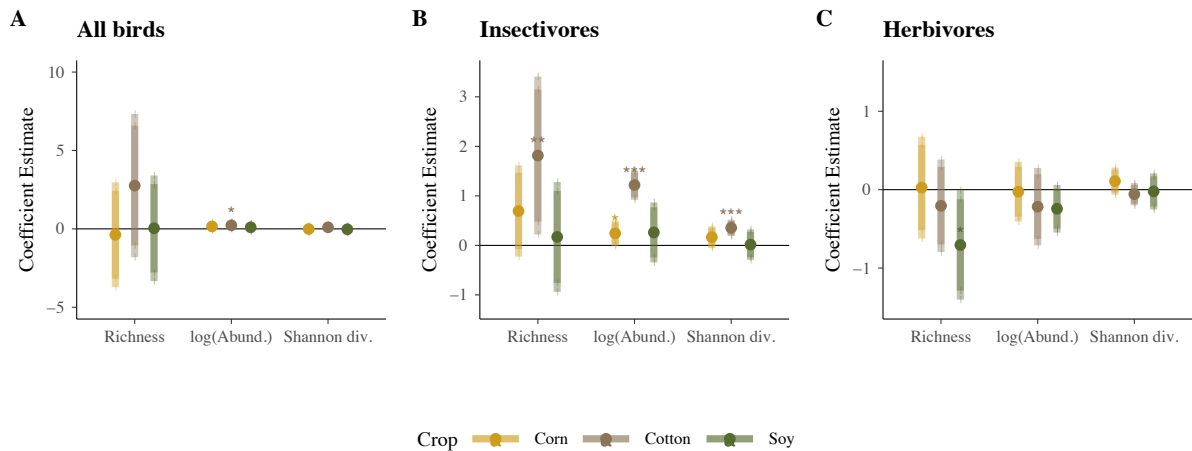


Figure 5: Effect of GM corn, soy, and cotton on all insectivorous and herbivorous birds. Dark and light bars indicating 90% and 95% confidence intervals respectively, and stars indicating p-values (* : $P < 0.1$, ** : $P < 0.05$, *** : $P < 0.01$).

Corn, soy, and cotton have different management requirements, which means the impacts of their respective GM varieties would likely also be different. Further, corn and cotton are

grown as varieties containing the Bt and HT traits, whereas GM soy is only cultivated as HT varieties. For that reason, we here present crop-specific estimates (see Figs. G1–G3 in Appendix G for the distribution of crop exposure in the study region). This analysis reveals a more nuanced picture of the overall effects (Fig. 5 and Appendix E, Table E2). The effect of GM corn is mixed across bird subsamples. It has no significant effect on overall abundance (0.158 ± 0.235), species richness (-0.376 ± 3.342), or Shannon diversity (-0.010 ± 0.217). The effect of corn on insectivorous bird richness is not statistically significant, while its effect on insectivorous bird abundance is positive but noisy (0.243 ± 0.260).

The overall positive effect of GM crops on insectivorous birds is largely driven by GM cotton. The effect of cotton on all three bird community metrics is positive, statistically significant, and large. According to these estimates, the introduction of GM cotton led to a 122% relative increase in insectivorous bird abundance (1.220 ± 0.297) and an additional 1.82 insectivore species (1.815 ± 1.594), as well as a relative increase in Shannon diversity (0.356 ± 0.166). The impact of GM cotton on herbivorous birds is overall negative but not statistically significant.

In contrast to cotton, GM soy generally had no impact on insectivorous birds or bird diversity. This finding is consistent with the relative absence of the Bt trait in soy, implying no or smaller changes in insecticide use. There is a positive effect of soy on overall bird abundance and a positive effect on insectivorous bird abundance, but neither are statistically significant (0.101 ± 0.257 and 0.262 ± 0.606 , respectively). There is also a negative effect on herbivorous bird richness (-0.705 ± 0.697). We discuss the dynamic effects in Appendix H.

We also estimate the effects of GM crop adoption on the abundance of the ten most common insectivorous and herbivorous species individually. The pattern of these effects confirms the results we find in the aggregate: the effect on insectivorous birds is positive, and the effect on herbivorous birds is largely ambiguous (see Appendix I).

Finally, we estimate several additional specifications and placebo tests to test the robustness of our results. First, three placebo tests with hypothetical treatment timing 15 years before

and 10 years after actual timing plus the entire timeline of available data (see Appendix J, K and L), and second, an additional test in which we replace our fixed 1992 baseline exposure to corn, soy and cotton with a time-varying exposure based on the USDA Agricultural Census 1978-2012 (see Appendix M). The tests are described in more detail in the Methods section.

2.2 Mechanisms

We investigate pesticide use as an underlying mechanism of our results. We show that changes in pesticide use are likely to be the main driver of the observed effect because pesticide toxicity was greatly reduced following the adoption of GM crops. We also show how GM crops affect small and large birds similarly to insectivorous and herbivorous birds, i.e., that small (predominantly insectivorous) birds react positively to GM crop adoption. At the same time, there is no or a weak negative effect on large (often herbivorous) birds, which means that both resource availability and direct toxicity are viable mechanisms (see Appendix N). We discuss these results and other potential mechanisms in Appendix O. We also present the results of the main estimation stratified by family. We focus on the 10 most common families in the region of interest, and show that of these, most families are positively or not affected by GM crops (see Appendix P, Fig. P1 and Fig. P2). Only Corvidae and Cardinalidae show a negative response to GM crops with varying levels of significance, while the rest are not significantly affected, or positively affected. Although Corvidae are generally large birds and Cardinalidae are at least partial herbivores, the patterns of diet and body weight among these families do not always clearly point to a specific mechanism. These results further underscore the complex pathways of GM crop impacts.

3 Discussion

The introduction of GM crops represented a major change in how crops are cultivated in the US and globally. So far, the impacts on biodiversity have been largely unclear. Here,

we evaluate the overall impact of GM crops on bird diversity. We report three main results:

- 1) GM crops in general had a positive effect on bird abundance and a more muted effect on richness and diversity.
- 2) The overall relationships are heterogeneous across species groups, with insectivorous birds increasing in abundance, richness, and Shannon diversity, while herbivorous birds generally have a slightly negative or no effect.
- 3) Major GM crops have differential effects on bird species, with GM cotton having a consistent, positive effect on insectivorous birds. In contrast, the impact of GM soy and corn on bird diversity and abundance is smaller and less precisely estimated.

Our findings suggest that the adoption of GM crops overall led to a reduction in bird decline, which could have important implications, because relatively small changes across a large geographic range can have substantial consequences for biodiversity. For example, Mineau [21] estimates that the use of granular carbofuran on corn alone killed 17-91 million songbirds per year. Yet we also find that richness and diversity are less impacted than abundance, which suggests that some species benefitted from GM crop adoption and increased in their abundance but that the effect is not proportional across the ecological community. Indeed, we find that insectivorous birds, in particular, benefit from GM crop adoption as they increase in richness, abundance, and Shannon diversity, while herbivorous birds show ambiguous responses across all three metrics. The differential effects across GM crops add another layer of complexity, but as corn, soy and cotton differ greatly in their management practices, this does not come as a surprise. Cotton, where we observe the largest impact of GM varieties, is known to be very pesticide intensive [9].

Our results align with the hypothesized benefits for insectivorous birds due to reduced non-target insect losses with Bt crops. Apart from indirect effects through resource availability, pesticides can also have direct negative effects on birds due to the toxicity of their active ingredients [24]. We show that in the period following GM crop adoption, pesticide bird toxicity has markedly decreased. This was due to an overall reduction of insecticide use related to the Bt trait (at least initially, before the large-scale adoption of neonicotinoids),

and a shift in herbicide use towards less toxic substances related to herbicide tolerance. As insectivorous birds are usually also smaller than herbivorous birds, they are more likely to be directly impacted by toxic pesticides. A reduction in pesticide toxicity would, therefore, benefit insectivorous/small-bodied birds more than herbivorous/larger-bodied birds, which is what we observe. Apart from changes in pesticide use and toxicity, GM crops may impact biodiversity through other pathways, including tillage practices [36, 4] and crop diversity [32]. These contrasting effects are not mutually exclusive and may interact in complex ways. For example, the common use of stacked varieties may decrease insecticide use, shift herbicide use, modify the toxicity of pest eradication efforts, and enable the spread of monocultures through improved weed and pest control. While we also look at crop diversity as a potential mechanism, we don't find direct evidence of it linking GM crops to bird diversity. While this study represents an effort to estimate the overall causal impact of GM adoption on bird diversity, there are several limitations. Importantly, we focus on common birds and cannot test the effect of GM crops on rare or threatened birds because they contribute little to the variance in the bird diversity sample and thus have only a minor influence on the estimate. In addition, we cannot fully isolate the underlying mechanisms. Detailed data on resource availability (e.g., insect abundance and plant diversity) are not generally available at the required scale. The trophic level is also not independent of other life history characteristics (like body size) that may influence susceptibility to pesticides in ways that are difficult to tease apart without detailed field data. Given the many co-occurring pathways by which GM may impact birds and other taxa and the simultaneous lack of national-scale data, local studies that include such information could fill this important gap. Furthermore, linking pesticide use practices directly to biodiversity is challenging due to a lack of detailed pesticide use data in most of the US and due to the complexity of pesticide toxicity impacts. These factors prevent us from establishing an unequivocal link between GM crops, pesticides, and bird diversity. Better, spatially, and temporally more refined pesticide data would improve the ability of researchers to pinpoint whether and how pesticide use, toxicity, and

278 technological improvements affect biodiversity.

279 There is evidence that the initial positive effect is dampened or even reversed by newer
280 developments in pesticide use that are not necessarily tied to GM crop technology, such as
281 the introduction of neonicotinoids and neonicotinoid seed treatments starting in 2004, which
282 are used in both GM and non-GM crops [31, 20, 10]. Previous studies find that neonicotinoids
283 have caused a large decline in bird abundance [20]. While they may have replaced chemicals
284 that could have been more directly toxic to birds and humans, their widespread preemptive
285 use as seed coatings instead of spray applications in response to pest outbreaks opened new
286 pathways of pesticide exposure and toxin accumulation [24]. In addition, neonicotinoid-
287 coated seeds are abundant on the soil surface following seed spills, especially for soybeans,
288 which could have further detrimental effects on herbivorous birds and wildlife when the seeds
289 are eaten [30], and could explain part of the effect of GM soy on herbivorous birds we here
290 observe. It has also been shown that neonicotinoids are extremely toxic to invertebrates,
291 including non-target insects, which could have further affected birds by negatively impacting
292 the resource availability of insectivorous birds [14, 11, 26].

293 Finally, the heterogeneous effects across crops and bird groups caution that GM crop adop-
294 tion may have unintended and negative consequences for some species and groups, which may
295 change ecological interactions and ecosystem services in unexpected ways. The longer-term
296 effects of GM crops could also look very different from what we have observed so far. For ex-
297 ample, because GM crops are associated with a strong reliance on individual herbicides, they
298 contribute to the development of herbicide-tolerant weeds, which could lead to higher levels
299 of pesticide use in the future. It should also be noted that the development of GM crops was
300 largely driven by agricultural corporations motivated by profit maximization, not by envi-
301 ronmental concerns. Nonetheless, technological progress in agriculture that is targeted at
302 improving conservation outcomes could potentially contribute to overall conservation goals.

4 Methods

4.1 Data

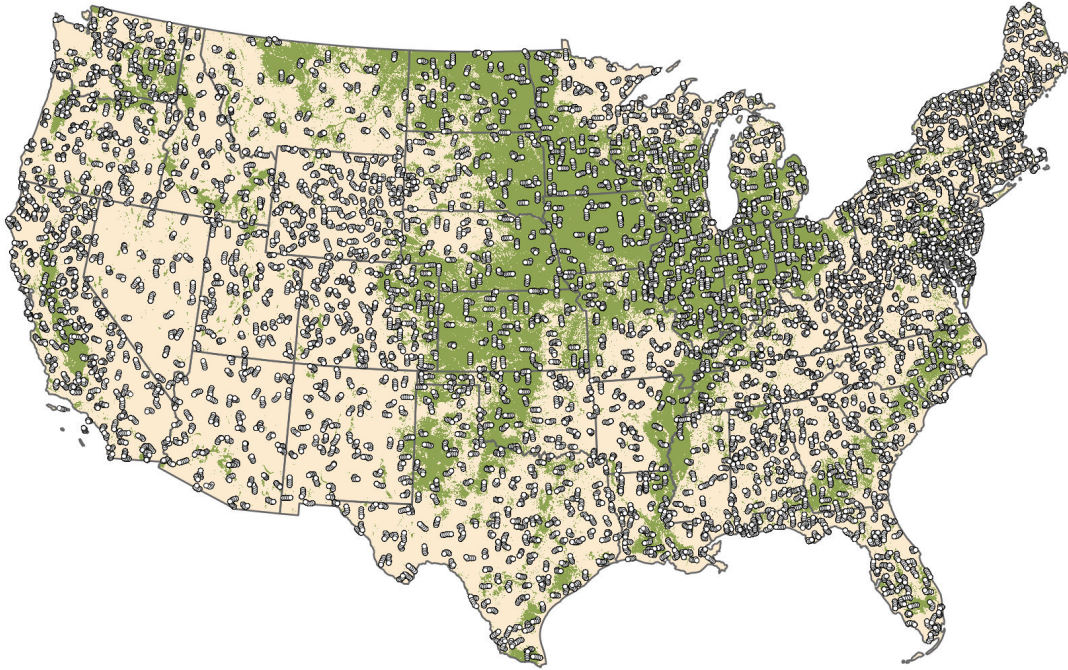


Figure 6: Distribution of BBS routes across the United States. Cropland is represented by green shading. Sub-routes are represented by white dots, while strings of five white dots represent complete BBS routes.

We use bird count data from the North American Breeding Bird Survey (BBS) across the United States [25] as our main dataset. From 1966 onwards, the BBS provides yearly counts of 740 North American bird species at thousands of observation routes. At each location, volunteers drive along the approximately 40km observation routes and stop 50 times, each time counting birds for three minutes. Counts are then compiled and made publicly available.

Counts are aggregated to sub-routes of 10 stops, so each route-year combination provides five sub-routes with individual bird counts. As most routes are digitized and available as vector files, we can allocate each bird count (sub-routes) to a specific geolocation and characterize its surroundings. A number of digitized routes greatly deviate in length from the 40km specification. To address this, we remove routes that fall into the top and bottom 10-percentile in length ($\geq 32'372$ m and $\leq 45'985$ m), leaving 3958 distinct routes (each consisting of five sub-routes), 2933 of which located in the contiguous United States. Fig. 6 presents the distribution of routes and sub-routes across the United States. Using ESA CCI-LC land cover data from 1992, we filter the dataset to only include routes surrounded by more than 25% cropland (as in land cover classes 10, 11, 12 and 20: cropland rainfed, cropland herbaceous cover, cropland tree or shrub cover and cropland irrigated or post-flooding, respectively) in both a 1 km buffer and a 10km donut buffer (which excludes the 1km buffer directly surrounding the route). Furthermore, we remove routes outside the Great Plains and Eastern Temperate Forest EPA Level I ecoregions, as bird communities and agriculture in the western United States are structurally different than in the center and east and, therefore, not fully comparable. Finally, we remove North Dakota from the sample, as a sharp increase in duck and geese numbers in 1993/1994, likely a result of a series of unusually wet years combined with a game bird breeding program (activities that are unrelated to GM crop adoption) contaminates the counterfactual (untreated) observations (see Appendix Q for bird population trends compared between low-GM share routes in North Dakota and the rest of the sample).²

Using USDA agricultural census data, we calculate the share of corn, soy, and cotton of overall crop acreage in 1992 for every county in the US. We then calculate the exposure of every bird observation route to corn, soy, and cotton based on the county where a BBS route is located. To predict the exposure of individual routes to GM crop adoption, we multiply the combined share of corn, soy, and cotton of overall cropland in 1992 (the last Agricultural

²“Overabundant resident Canada geese present a giant dilemma”, <https://www.grandforksherald.com/sports/overabundant-resident-canada-geese-present-a-giant-dilemma>, accessed 23.5.2023.

census before the onset of GM crop adoption) with the share of cropland surrounding a BBS
 route, as calculated by the number of ESA CCI-LC cropland pixels divided by the total
 number of pixels in a 1 km buffer. We repeat the same process for corn, soy, and cotton
 individually. We then multiply these crop shares with their respective state-level GM crop
 adoption rate provided by the USDA Economic Research Service (Fig. 1). To find the total
 exposure to GM crops, we add up the exposure to GM corn, soy, and cotton. For each
 sub-route, we obtain a measure of exposure to GM crops, combined and per crop, which are
 the treatment variables in our estimation. Although this measure is unrelated to local farm
 characteristics, it is also noisy. Our estimates are therefore potentially biased toward zero.
 As BBS routes in areas with a high share of corn, soy, and cotton are spatially separated
 from routes in areas with a low share of these crops, the concern might arise that the bird
 populations between the treatment and control groups are not comparable. We take several
 steps to ensure that the populations are similar enough to make a meaningful comparison.
 As described above, we limit the selection of routes in the sample to agricultural areas in the
 Great Plains and Eastern Temperate Forests EPA level 1 ecoregions (see Appendix B), which
 comprise most of the agricultural areas in the Eastern United States. Within these areas,
 agriculture is dominated by corn, soy, and cotton, and only a smaller proportion of cropland
 is planted with cereals and other non-GM crops. We leverage this imbalance in number of
 observations between treatment and control group, i.e. areas planted with corn, soy and
 cotton versus areas planted with other crops, to make the bird populations more similar.
 We match each BBS route segment surrounded by less than 25% corn, soy, and cotton to a
 route segment surrounded by more than 25% corn, soy, and cotton (without replacement) by
 minimizing the Euclidean distance between the mean abundances of the 100 most common
 birds in the sample over the period 1986-1995 and the share of cropland in a 1 km buffer
 surrounding the route. Table D1 and table D2 in Appendix D provide summary statistics
 of the dataset before and after matching. The number of routes in the matched dataset is
 more balanced between high and low corn, soy and cotton share, and most of the main bird

363 population indices are more similar. Fig. D4 in Appendix D presents mean abundances of
 364 the 10 most common bird species over the period 1986-1995 between areas with a high and
 365 low share of corn, soy and cotton. Of these, only the cliff Swallow and Western Meadowlark
 366 exhibit a markedly different mean abundance. In the unmatched sample, mean abundances
 367 of most birds are different (Fig. D2 in Appendix D). Table D3 in Appendix D presents the
 368 mean abundances and differences in percent between the high and low share of corn, soy,
 369 and cotton groups of the 50 most common bird species after matching, as well as the average
 370 abundance and difference across these species. All of these species are present in both groups
 371 and most of them in similar numbers. We also present the mean abundances of the 50 most
 372 common bird species before matching in the two regions, where the means of the two groups
 373 are further apart (1.09 species versus 0.06 species after matching, see Appendix D, Table D4).
 374 Finally, we present absolute standardized mean differences between treatment and control
 375 groups before and after matching of all 100 birds used in the matching procedure (Fig. D6
 376 in Appendix D). We see that after matching, abundance of all birds is more similar between
 377 the two groups after matching. While our statistical approach benefits from communities
 378 that are as similar as possible between treatment and control groups, it is sufficient that
 379 bird diversity observations in the two groups follow a similar trend in the absence of GM
 380 adoption. Time constant differences are absorbed by route fixed effects (binary variables for
 381 each route). Fig. 2 presents the locations and exposure of each BBS route segment to corn,
 382 soy, and cotton across the United States in the matched sample. Figs. G1-G3 in Appendix
 383 G present the exposure of each BBS route segment in the matched sample to corn, soy and
 384 cotton individually. In addition, to show that our results are not sensitive to the exact
 385 choice of the matching cutoff of 25% corn, soy and cotton, we also run the estimation using
 386 an alternative 50% cutoff with results that are largely unchanged (see Appendix R). We
 387 also present the main results when standardizing the abundances of the 100 birds used in the
 388 matching procedure, as opposed to bird abundances on the real scale as done in the main
 389 estimation. The results are also largely unchanged (see Appendix S).

For each BBS route segment, we calculate a number of bird population indices, which we then use as outcome variables in the estimation. We calculate species richness (the number of species observed at a specific route segment), abundance (the total number of individual birds observed at a specific route segment), and Shannon diversity (a diversity index incorporating both species richness and abundance) across all bird species in the sample. We log-transform abundance to de-emphasize extreme values (Appendix D, Fig. D5). Shannon diversity at route segment i is calculated as

$$\text{Shannon} = - \sum_{i=1}^S p_i \times \log(p_i) \quad (1)$$

where p_i is the proportion of species i , and S is the total number of species at a route segment. Using the EltonTraits database [39], we then create subsets of insectivorous as well as herbivorous by choosing only species whose diet consists of $\geq 80\%$ insects or plants and grains, respectively, and calculate the same three indices based on those subsets. We choose 80% as a cutoff to draw a sharp line between feeding guilds while still maintaining a relatively large number of bird species per subgroup (see Appendix C, Table C2 and C3 for a complete list of insectivorous and herbivorous species in the data).

The BBS data also provides temperature, weather type and wind speed data at the beginning and end of each observation period, which we use to control for weather on the day of the bird count.

4.2 Estimation strategy

We use Two-Way Fixed Effects (TWFE) models to estimate the impact of GM crops on bird populations. Here, we use the term fixed effects to refer to binary or dummy variables (i.e. individual intercepts). TWFE models are ordinary least squares (OLS) regression models that are applied to panel data (i.e. repeated observations over time of the same units), allowing us to compare the changes over time in bird populations in areas with high GM

crop adoption to the changes in areas with low GM crop adoption. To address concerns that GM adoption is correlated with farm characteristics that could also derive biodiversity changes independently of GM adoption, we predict GM crop adoption with the shares of corn, cotton, and soy before the introduction of GM crops in combination with state-level adoption rates. We first estimate the static (average) effect of GM crops (corn, soy and cotton combined) on bird populations using the specification

$$y_{it} = \beta \text{GMExposure}_{it} \times \text{CroplandShare}_{i,1992} + \gamma X_{it} + \delta_t + \eta_i + \lambda_o + \epsilon_{it} \quad (2)$$

where y_{it} are bird population indices at route segment i in year t , β is the coefficient of the effect of GM crop adoption, $\text{CroplandShare}_{i,1992}$ is the share of cropland surrounding each route segment in a 1km buffer in 1992, GMExposure_{it} is the exposure of route segment i to corn, soy, and cotton in 1992 in percent multiplied with the state-level adoption rates of their respective GM varieties in year t as in

$$\begin{aligned} \text{GMExposure}_{it} = & \text{GMCornAdoption}_{st} \times \text{CornShare}_{i,1992} + \text{GMSoyAdoption}_{st} \times \text{SoyShare}_{i,1992} \\ & + \text{GMCottonAdoption}_{st} \times \text{CottonShare}_{i,1992} \end{aligned} \quad (3)$$

X_{it} is a vector of weather controls. δ_t are year fixed effects (binary variables), serving as an individual intercept in the linear model for each year and thereby removing variation over time that is common to the entire sample. η_i are route segment fixed effects, introducing an individual intercept for each route segment, thereby removing time-averaged variation across routes and thus taking care of unobserved time-invariant differences between the route segments. Together, these two fixed effects leave only variation over time in bird outcomes that is specific to each route segment, allowing the model to estimate differences over time between routes exposed to GM crops and routes not exposed. The BBS data also provide an observer ID for each observation, so that we can include a fixed effect λ_o for

433 observers o , as different observers might have different observation abilities or characteristics.
 434 Finally, ϵ_{it} denotes the error term. In all specifications, we cluster standard errors by state
 435 and year, as treatment is assigned at the state and year level and errors might therefore
 436 be correlated at this level [1]. In a second specification, we then estimate the effect of GM
 437 varieties individually for corn, soy, and cotton:

$$\begin{aligned}
 y_{it} = & \beta_1 \text{GMCorn}_{st} \times \text{CornShare}_{i,1992} \times \text{CroplandShare}_{i,1992} \\
 & + \beta_2 \text{GMSoy}_{st} \times \text{SoyShare}_{i,1992} \times \text{CroplandShare}_{i,1992} \\
 & + \beta_3 \text{GMCotton}_{st} \times \text{CottonShare}_{i,1992} \times \text{CroplandShare}_{i,1992} \\
 & + \gamma X_{it} + \delta_t + \eta_i + \lambda_o + \epsilon_{it}
 \end{aligned} \tag{4}$$

438 where β_1 , β_2 and β_3 are the coefficients of the effect of GM corn, soy, and cotton varieties,
 439 GMCorn_{st} , GMCotton_{st} and GMSoy_{st} are the adoption rates of each GM crop variety in
 440 year t and state s , and $\text{CornShare}_{i,1992}$, $\text{SoyShare}_{i,1992}$ and $\text{CottonShare}_{i,1992}$ are the shares
 441 of each crop in the cropland surrounding BBS route i in 1992. We estimate the regression
 442 equation with OLS, as GM crop introduction was simultaneous across the United States,
 443 such that we are not concerned about biases from staggered adoption [6].

444 We then also estimate the dynamic effects of GM crop adoption on bird population using an
 445 event study design. The basic concept of the model remains the same as before. However,
 446 we now estimate a coefficient for each period individually. Periods are years relative to the
 447 year of GM adoption, i.e. the approval of GM crops in 1996. In this specification, we define
 448 the exposure of each route to GM crop adoption as the share of cropland multiplied by the

share of corn, soy, and cotton in 1992. This specification takes the form

$$\begin{aligned}
y_{it} = & \sum_{\tau=-31}^{-2} \beta_{\tau} \text{CornSoyCottonShare}_{i,1992} \times \text{CroplandShare}_{i,1992} \times 1(t = \tau) \\
& + \sum_{\tau=0}^{23} \beta_{\tau} \text{CornSoyCottonShare}_{i,1992} \times \text{CroplandShare}_{i,1992} \times 1(t = \tau) \\
& + \gamma X_{it} + \delta_t + \eta_i + \lambda_o + \epsilon_{it}
\end{aligned} \tag{5}$$

where β_{τ} are the coefficients of the effect of GM crops in each year from 31 years before the introduction of GM crops (in 1996) to 23 after, covering 1966 to 2019. β_{-1} is omitted and serves as a reference period to which the other years are compared. $\text{CornSoyCottonShare}_{i,1992}$ are the shares of corn, soy, and cotton in cropland surrounding a BBS route i in 1992 added up. $1(t = \tau)$ is an indicator function that takes the value 1 when an observation is in time τ and 0 otherwise. This specification provides us with a coefficient and standard errors of each year relative to the reference period -1, which can be seen in Fig. 4. Omitted period -1 does not have standard errors, as it serves as a reference point for the other coefficients, while each point before and after represents a coefficient estimate of a specific year comparing regions with high to regions with low corn, soy, and cotton, i.e. regions with high and low GM crop adoption. The bars indicate the 95% confidence intervals of each coefficient. As before, we include three kinds of fixed effects δ_t , η_i and λ_o , as well as a vector of weather controls X_{it} . Finally, we also estimate the exposure to GM crops individually for corn, cotton, and soy

463 using a fourth specification:

$$\begin{aligned}
y_{it} = & \sum_{\tau=-31}^{-2} \beta_{1\tau} \times \text{CornShare}_{i,1992} \times \text{CroplandShare}_{i,1992} \times 1(t = \tau) \\
& + \sum_{\tau=0}^{23} \beta_{1\tau} \times \text{CornShare}_{i,1992} \times \text{CroplandShare}_{i,1992} \times 1(t = \tau) \\
& \sum_{\tau=-31}^{-2} \beta_{2\tau} \times \text{SoyShare}_{i,1992} \times \text{CroplandShare}_{i,1992} \times 1(t = \tau) \\
& + \sum_{\tau=0}^{23} \beta_{2\tau} \times \text{SoyShare}_{i,1992} \times \text{CroplandShare}_{i,1992} \times 1(t = \tau) \\
& \sum_{\tau=-31}^{-2} \beta_{3\tau} \times \text{CottonShare}_{i,1992} \times \text{CroplandShare}_{i,1992} \times 1(t = \tau) \\
& + \sum_{\tau=0}^{23} \beta_{3\tau} \times \text{CottonShare}_{i,1992} \times \text{CroplandShare}_{i,1992} \times 1(t = \tau) \\
& + \gamma X_{it} + \delta_t + \eta_i + \lambda_o + \epsilon_{it}
\end{aligned} \tag{6}$$

464 where $\beta_{1\tau}$, $\beta_{2\tau}$ and $\beta_{3\tau}$ are the coefficients of the individual effects of corn, soy and cotton
465 GM varieties in period τ . While we estimate coefficients for every period, we only present the
466 time periods -20 to 20 in the results section, although we show the full timeline in Appendix
467 [L](#).

468 As we are dealing with count data, the concern could arise that OLS might not be a suitable
469 method for these estimations and that Poisson models would be more appropriate. To test
470 this, we first present the distribution of the residuals of the main regressions using equation
471 (2) as histograms and QQ-plots (Fig. [T1](#) and [T2](#) in Appendix [T](#)), which show that for
472 the most part (except when estimating the effect on abundance on herbivorous birds and
473 Shannon diversity of all birds) the errors are normally distributed, which means that OLS
474 is an appropriate choice. Nevertheless, we repeat the main estimations using a Poisson
475 model (see Fig. [U1](#) to [U6](#) in Appendix [U](#)). The results are qualitatively identical to the OLS
476 estimates; only the magnitude of the coefficients changes, which is to be expected when using
477 non-linear regression models.

4.3 Effects on individual species

We estimate the effect of GM crops on the abundance of a number of species individually. Based on the 100 most common bird species in our sample, we select the 10 most common species with a diet consisting of more than 80% insects, as well as the 10 species with a diet of more than 80% plants and grains, based on the EltonTraits database [39]. We use models (2) and (4) from above, using abundance of these individual species as outcomes y_{it} .

4.4 Pesticides as a mechanism

We test pesticide use (total quantity of insecticide and herbicide, as well as quantity of glyphosate active ingredient) and pesticide toxicity as a mechanism. We use state-level pesticide use data from the USGS Pesticide National Synthesis Project [33, 2, 38], covering the years 1992-2019 (although we exclude data post-2014 due to lack of coverage of neonicotinoid seed treatments). We use the low estimate of quantity of active ingredients used of each pesticide per state (which differs from the high estimate in that surveyed zero use of a pesticide is treated as absence of use, whereas in the high estimate, it is treated as unsurveyed and interpolated from neighboring surveys), separated by corn, soy, cotton and other crops. We add up all insecticides and herbicides to find the total quantity per state of each and also keep glyphosate individually due to its close association with HT crops.

To estimate the change in pesticide toxicity over time following GM crop adoption, we divide each individual pesticide by its bird LD50 toxicity value (see Appendix V for a full list of pesticides and associated LD50 values) to calculate a risk quotient. As a lower LD50 value indicates higher oral toxicity, putting LD50 into the denominator turns the pesticide amounts into a risk quotient that is higher for more toxic pesticides. We assign the mean LD50 value over all pesticides to compounds that don't have an associated LD50 value, as LD50 coverage is incomplete in our data (see Fig. V1 in Appendix V). We then divide the total use of insecticides, herbicides and glyphosate as well as insecticide and herbicide risk quotients by the total number of acres under cultivation of corn, soy, cotton and other crops

per state as provided by the USDA Census of Agriculture 1992-2017, with the missing years interpolated. This gives us an estimate of kg/acre active ingredients per state for these crops, as well as pesticide toxicity risk quotient/acre. Using county-level crop acreages from the USDA Census of Agriculture 1992-2017, we then multiply these values with the acres of each respective crop grown in a county to arrive at an estimate of county-level pesticide use and pesticide risk quotient over time. Based on the county each BBS observation route is located in, we match the insecticide, herbicide and glyphosate use as well as insecticide and herbicide toxicity risk quotient to the bird observations.

To test the impact of GM crops (combined and corn, soy and cotton individually) on pesticides, we filter the dataset to include only one observation per county and year and then use models (5) and (6) with insecticides, herbicides and glyphosate as outcomes y_{it} , effectively making it a county-level estimation, as both the crop composition and the pesticide data are on county-level. We run the same model with insecticide and herbicide toxicity risk quotient as an outcome.

To test the impact of pesticide toxicity on the estimated coefficient, we estimate the effect of GM crops on bird outcomes as in models (2) and (4), with insecticide and herbicide toxicity risk quotients separately added as an additional control. We then compare the coefficients of the models with and without pesticide controls.

We hypothesize that there are two potential pathways, through which changes in pesticide use and pesticide toxicity could influence bird population: changing resource availability (e.g. increased survivability of non-target insects) and direct toxicity of pesticides to birds. The evidence for the former lies in the distinct effects on feeding guilds, whereas we test the second pathway by splitting the sample of birds by body weight, as birds with smaller body mass are more susceptible to pesticide toxicity. We use body mass values provided in the EltonTraits database to filter out the top and bottom quartiles of birds in the sample by body mass ($\geq 395.2\text{g}$ and $<19.5\text{g}$), then calculate richness, abundance and Shannon diversity based on these birds and repeat the main estimation of GM crop impacts using

those outcomes.

We further explore these two pathways by splitting the sample by phylogenetic family. We choose the 10 most common families in the sample by first only considering families with at least 10 species, and second by choosing among those the families with the highest abundance (see Appendix P, Table P1 for the number of species per family in the sample, Table P3 for a complete list of species per family, Table P2 for abundance per family, and Table P4 for average diet and body mass per family). We match species to families using data from the Jetz-Elton database, the BBS species data and the NCBI taxonomy database [12].

4.5 Robustness checks

To support our claim that our approach captures a causal effect and not differential time trends in the treatment and the control group, we conduct placebo tests in which we move a hypothetical GM introduction further back in time, to 1981 (Fig. J1 to J4 in Appendix J), and forward to 2006 (Fig. K1 to K4 in Appendix K). In the first test, we subset the data to include only observations from before 1996, and then designate 1981 as the first “treatment year”. We repeat the matching as specified in the previous section, but now match our treatment and control groups based on average abundance of the 100 most common birds between 1971 and 1980. We then use model (5) and (6) to estimate the dynamic effects of “treatment”. We also run a similar test using only observations after 1996, in which we designate 2006 as the start of treatment in the same fashion and match our treatment and control groups based on common birds between 1996 and 2005. Because some of the plots make it look like there was an effect of this hypothetical treatment (e.g. the effect of placebo-GM cotton on insectivorous bird richness in Fig. J3), we also present the full timeline of the event study plots of the actual treatment (Fig. L2 to Fig. L4 in Appendix L). The two placebo tests are contained in those plots, if one were to assume treatment happened in period -15 (1981) or +10 (2006) and look at only the coefficients surrounding it. These plots show that, while there were fluctuations in the periods before and after, the effects after the

557 actual introduction of GM crops are more consistent and clear, especially for insectivorous
558 birds.

559 Finally, there is a concern that calculating GM treatment by multiplying exposure of BBS
560 routes to corn, soy and cotton in 1992 with yearly adoption rates could bias the results if crop
561 distribution would change a lot over time. We use constant baseline exposure because crop
562 and cropland expansion could itself be an outcome of GM crop adoption. However, to show
563 that this does not affect our results, we also present the results of our main estimation using
564 a GM treatment variable that is calculated based on varying crop shares over time from the
565 USDA Agricultural Censuses 1978-2012. Apart from changes in the level of significance, the
566 results remain essentially the same (Fig. [M1](#) and Fig. [M2](#) in Appendix [M](#)).



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6 Contributions

D.E. conceived the empirical strategy, assembled the data, ran the estimations, and wrote the manuscript. L.M.G. and A.L. provided feedback and advice on the empirical strategy and edited the manuscript. T.C. provided feedback on pesticide toxicity data, and advice on the mechanism section. F.N. provided funding, conceived the project idea and supervised the project, contributed to the empirical strategy, and edited the manuscript.

7 Data and code availability

A full replication package is available on figshare (link not available before submission) and at https://drive.google.com/drive/folders/1VPIE29xf8DQGAbjToEq_k7yR-GZ2uJ44?usp=sharing.

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A GM adoption rates

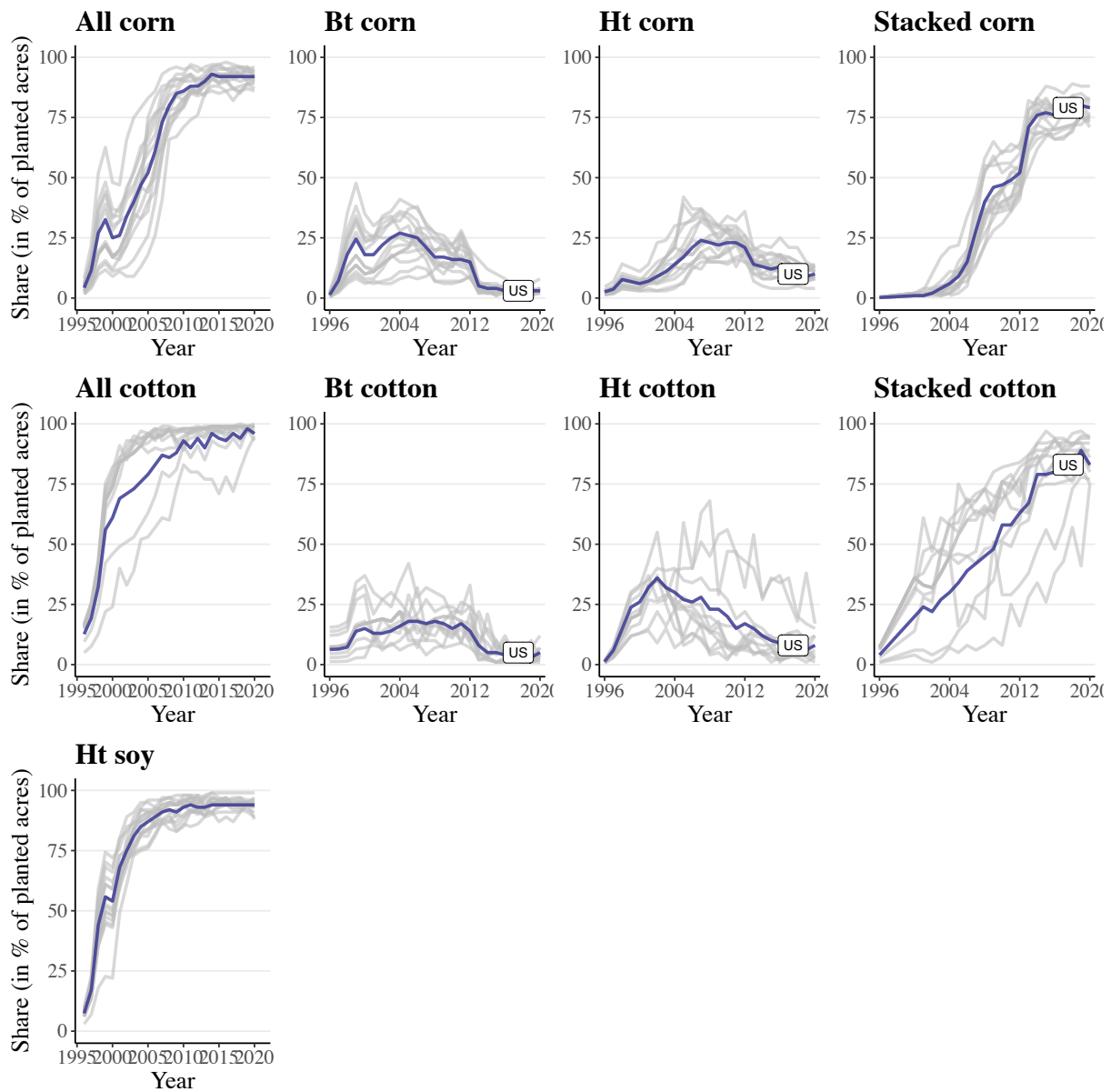


Figure A1: Adoption rates of all, Bt, HT and stacked GM corn and cotton and HT soy varieties as shares of planted acreage. The average adoption rate in the United States in blue, and state-level adoption rates in grey [35].

B Ecoregions

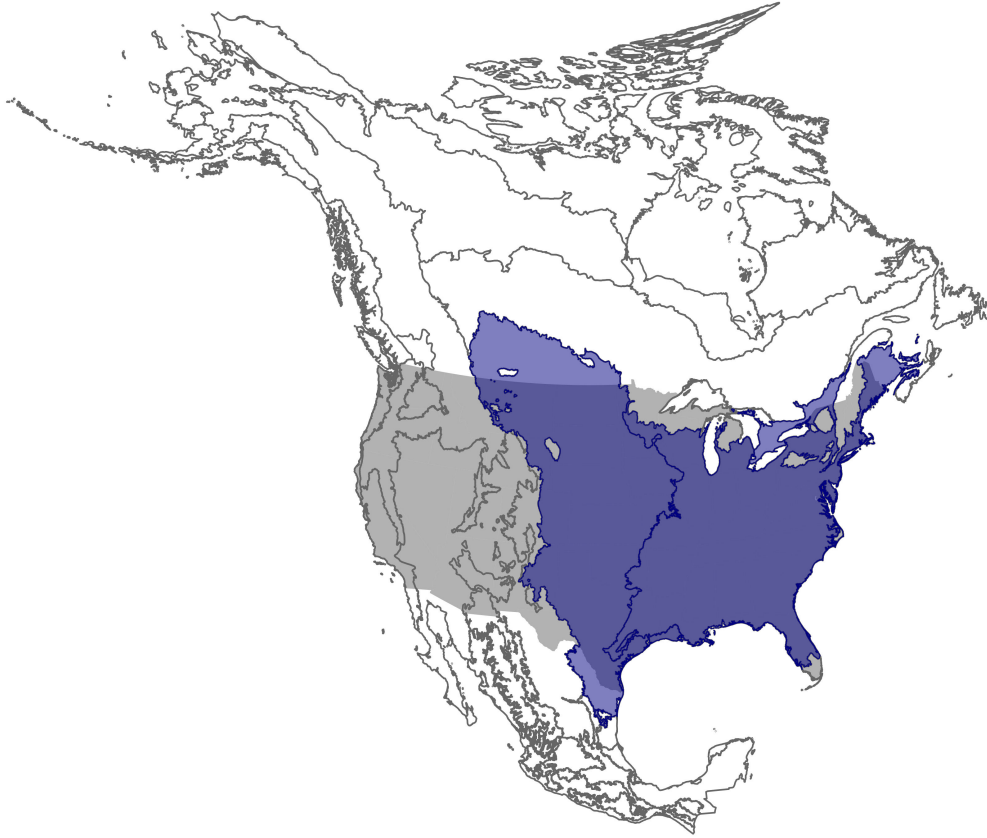


Figure B1: EPA level 1 North American Ecoregions, Great Plains and Eastern Temperate Forests regions highlighted in blue, the contiguous United States in grey.

C Birds in sample

Table C1: The 100 most common birds in the region of interest.

Species	Species
1 Red-winged Blackbird	51 Brewer's Blackbird
2 Mourning Dove	52 Field Sparrow
3 Western Meadowlark	53 Red-headed Woodpecker
4 House Sparrow	54 Orchard Oriole
5 Common Grackle	55 Chipping Sparrow
6 Horned Lark	56 Eastern Bluebird
7 Dickcissel	57 Yellow-headed Blackbird
8 European Starling	58 Franklin's Gull
9 Cliff Swallow	59 Eastern Towhee
10 Brown-headed Cowbird	60 Great Crested Flycatcher
11 Barn Swallow	61 (Yellow-shafted Flicker) Northern Flicker
12 Ring-necked Pheasant	62 Blue Grosbeak
13 American Robin	63 Tufted Titmouse
14 Northern Mockingbird	64 Yellow Warbler
15 Northern Bobwhite	65 Loggerhead Shrike
16 Lark Bunting	66 Eurasian Collared-Dove
17 Eastern Meadowlark	67 Bewick's Wren
18 Northern Cardinal	68 Pyrrhuloxia
19 American Crow	69 Chestnut-collared Longspur
20 Killdeer	70 Cave Swallow
21 Western Kingbird	71 Upland Sandpiper
22 Grasshopper Sparrow	72 House Finch
23 Common Yellowthroat	73 Red-tailed Hawk
24 Blue Jay	74 Gray Catbird
25 Eastern Kingbird	75 Northern Rough-winged Swallow
26 Cattle Egret	76 Warbling Vireo
27 Rock Pigeon	77 Carolina Chickadee
28 Great-tailed Grackle	78 Clay-colored Sparrow
29 Indigo Bunting	79 Bank Swallow
30 Lark Sparrow	80 Great Egret
31 Scissor-tailed Flycatcher	81 Golden-fronted Woodpecker
32 House Wren	82 Eastern Wood-Pewee
33 Song Sparrow	83 White Ibis
34 Savannah Sparrow	84 Eastern Phoebe
35 Vesper Sparrow	85 Black-billed Magpie
36 Brown Thrasher	86 Red-eyed Vireo
37 American Goldfinch	87 Swainson's Hawk
38 Baltimore Oriole	88 White-winged Dove
39 Turkey Vulture	89 Bullock's Oriole
40 Mallard	90 Blue-winged Teal
41 Bobolink	91 Yellow-breasted Chat
42 Purple Martin	92 Great Blue Heron
43 Cassin's Sparrow	93 Tree Swallow
44 Common Nighthawk	94 Black-capped Chickadee
45 Yellow-billed Cuckoo	95 Downy Woodpecker
46 Chimney Swift	96 Black Vulture
47 Red-bellied Woodpecker	97 Black-crested Titmouse
48 Canada Goose	98 American Kestrel
49 Painted Bunting	99 White-eyed Vireo
50 Carolina Wren	100 Boat-tailed Grackle

Table C2: Insectivorous birds in the BBS data (diet consisting of $\geq 80\%$ insects, according to EltonTraits database).

	Order	Family	Species	English
1	Accipitriformes	Accipitridae	Chondrohierax uncinatus	Hook-billed Kite
2	Accipitriformes	Accipitridae	Ictinia mississippiensis	Mississippi Kite
3	Accipitriformes	Accipitridae	Rostrhamus sociabilis	Snail Kite
4	Anseriformes	Anatidae	Aythya marila	Greater Scaup
5	Anseriformes	Anatidae	Bucephala islandica	Barrow's Goldeneye
6	Anseriformes	Anatidae	Clangula hyemalis	Long-tailed Duck
7	Anseriformes	Anatidae	Histrionicus histrionicus	Harlequin Duck
8	Anseriformes	Anatidae	Melanitta fusca	White-winged Scoter
9	Anseriformes	Anatidae	Melanitta perspicillata	Surf Scoter
10	Anseriformes	Anatidae	Somateria spectabilis	King Eider
11	Apodiformes	Apodidae	Aeronautes saxatalis	White-throated Swift
12	Apodiformes	Apodidae	Chaetura pelagica	Chimney Swift
13	Apodiformes	Apodidae	Chaetura vauxi	Vaux's Swift
14	Apodiformes	Apodidae	Cypseloides niger	Black swift
15	Caprimulgiformes	Caprimulgidae	Antrostomus vociferus	Eastern whip-poor-will
16	Caprimulgiformes	Caprimulgidae	Caprimulgus carolinensis	Chuck-will's-widow
17	Caprimulgiformes	Caprimulgidae	Chordeiles acutipennis	Lesser Nighthawk
18	Caprimulgiformes	Caprimulgidae	Chordeiles gundlachi	Antillean Nighthawk
19	Caprimulgiformes	Caprimulgidae	Chordeiles minor	Common Nighthawk
20	Caprimulgiformes	Caprimulgidae	Nyctidromus albigollis	Common Pauraque
21	Caprimulgiformes	Caprimulgidae	Phalaenoptilus nuttallii	Common Poorwill
22	Charadriiformes	Charadriidae	Anarhynchus nivosus	Snowy plover
23	Charadriiformes	Charadriidae	Charadrius hiaticula	Common Ringed Plover
24	Charadriiformes	Charadriidae	Charadrius melodus	Piping Plover
25	Charadriiformes	Charadriidae	Charadrius montanus	Mountain Plover
26	Charadriiformes	Charadriidae	Charadrius semipalmatus	Semipalmated Plover
27	Charadriiformes	Charadriidae	Charadrius vociferus	Killdeer
28	Charadriiformes	Charadriidae	Charadrius wilsonia	Wilson's Plover
29	Charadriiformes	Haematopodidae	Haematopus bachmani	Black Oystercatcher
30	Charadriiformes	Haematopodidae	Haematopus palliatus	American Oystercatcher
31	Charadriiformes	Laridae	Rhodostethia rosea	Ross's Gull
32	Charadriiformes	Recurvirostridae	Himantopus mexicanus	Black-necked Stilt
33	Charadriiformes	Recurvirostridae	Recurvirostra americana	American Avocet
34	Charadriiformes	Scolopacidae	Actitis macularia	Spotted Sandpiper
35	Charadriiformes	Scolopacidae	Aphriza virgata	Surfbird
36	Charadriiformes	Scolopacidae	Arenaria interpres	Ruddy Turnstone
37	Charadriiformes	Scolopacidae	Arenaria melanocephala	Black Turnstone
38	Charadriiformes	Scolopacidae	Calidris alpina	Dunlin
39	Charadriiformes	Scolopacidae	Calidris bairdii	Baird's Sandpiper
40	Charadriiformes	Scolopacidae	Calidris canutus	Red Knot
41	Charadriiformes	Scolopacidae	Calidris himantopus	Stilt Sandpiper
42	Charadriiformes	Scolopacidae	Calidris mauri	Western Sandpiper
43	Charadriiformes	Scolopacidae	Calidris melanotos	Pectoral Sandpiper
44	Charadriiformes	Scolopacidae	Calidris minutilla	Least Sandpiper
45	Charadriiformes	Scolopacidae	Calidris ptilocnemis	Rock Sandpiper
46	Charadriiformes	Scolopacidae	Calidris pusilla	Semipalmated Sandpiper
47	Charadriiformes	Scolopacidae	Catoptrophorus semipalmatus	Willet
48	Charadriiformes	Scolopacidae	Heteroscelus incanus	Wandering Tattler
49	Charadriiformes	Scolopacidae	Limosa fedoa	Marbled Godwit
50	Charadriiformes	Scolopacidae	Limosa haemastica	Hudsonian Godwit
51	Charadriiformes	Scolopacidae	Limosa lapponica	Bar-tailed Godwit
52	Charadriiformes	Scolopacidae	Numenius americanus	Long-billed Curlew
53	Charadriiformes	Scolopacidae	Phalaropus lobatus	Red-necked Phalarope
54	Charadriiformes	Scolopacidae	Scolopax minor	American Woodcock
55	Charadriiformes	Scolopacidae	Steganopus tricolor	Wilson's Phalarope
56	Charadriiformes	Scolopacidae	Tringa flavipes	Lesser Yellowlegs
57	Charadriiformes	Scolopacidae	Tringa melanoleuca	Greater Yellowlegs
58	Charadriiformes	Scolopacidae	Tringa solitaria	Solitary Sandpiper
59	Passeriformes	Cardinalidae	Piranga flava	Hepatic Tanager
60	Passeriformes	Cardinalidae	Piranga ludoviciana	Western Tanager

	Order	Family	Species	English
61	Passeriformes	Cardinalidae	<i>Piranga olivacea</i>	Scarlet Tanager
62	Passeriformes	Cardinalidae	<i>Piranga rubra</i>	Summer Tanager
63	Passeriformes	Cinclidae	<i>Cinclus mexicanus</i>	American Dipper
64	Passeriformes	Emberizidae	<i>Aimophila botterii</i>	Botteri's Sparrow
65	Passeriformes	Emberizidae	<i>Ammodramus caudacutus</i>	Saltmarsh Sparrow
66	Passeriformes	Emberizidae	<i>Ammodramus maritimus</i>	Seaside Sparrow
67	Passeriformes	Emberizidae	<i>Pipilo aberti</i>	Abert's Towhee
68	Passeriformes	Hirundinidae	<i>Hirundo rustica</i>	Barn Swallow
69	Passeriformes	Hirundinidae	<i>Petrochelidon fulva</i>	Cave Swallow
70	Passeriformes	Hirundinidae	<i>Petrochelidon pyrrhonota</i>	Cliff Swallow
71	Passeriformes	Hirundinidae	<i>Progne subis</i>	Purple Martin
72	Passeriformes	Hirundinidae	<i>Riparia riparia</i>	Bank Swallow
73	Passeriformes	Hirundinidae	<i>Stelgidopteryx serripennis</i>	Northern Rough-winged Swallow
74	Passeriformes	Hirundinidae	<i>Tachycineta bicolor</i>	Tree Swallow
75	Passeriformes	Hirundinidae	<i>Tachycineta thalassina</i>	Violet-green Swallow
76	Passeriformes	Icteridae	<i>Euphagus carolinus</i>	Rusty Blackbird
77	Passeriformes	Icteridae	<i>Euphagus cyanocephalus</i>	Brewer's Blackbird
78	Passeriformes	Icteridae	<i>Quiscalus mexicanus</i>	Great-tailed Grackle
79	Passeriformes	Icteridae	<i>Xanthocephalus xanthocephalus</i>	Yellow-headed Blackbird
80	Passeriformes	Mimidae	<i>Oreoscoptes montanus</i>	Sage Thrasher
81	Passeriformes	Mimidae	<i>Toxostoma crissale</i>	Crissal Thrasher
82	Passeriformes	Mimidae	<i>Toxostoma lecontei</i>	LeConte's thrasher
83	Passeriformes	Motacillidae	<i>Anthus cervinus</i>	Red-throated Pipit
84	Passeriformes	Motacillidae	<i>Anthus rubescens</i>	American Pipit
85	Passeriformes	Motacillidae	<i>Anthus spragueii</i>	Sprague's Pipit
86	Passeriformes	Motacillidae	<i>Motacilla alba</i>	White Wagtail
87	Passeriformes	Paridae	<i>Baeolophus wollweberi</i>	Bridled Titmouse
88	Passeriformes	Paridae	<i>Parus sclateri</i>	Mexican Chickadee
89	Passeriformes	Parulidae	<i>Cardellina rubrifrons</i>	Red-faced Warbler
90	Passeriformes	Parulidae	<i>Dendroica cerulea</i>	Cerulean Warbler
91	Passeriformes	Parulidae	<i>Dendroica chrysoparia</i>	Golden-cheeked Warbler
92	Passeriformes	Parulidae	<i>Dendroica discolor</i>	Prairie Warbler
93	Passeriformes	Parulidae	<i>Dendroica dominica</i>	Yellow-throated Warbler
94	Passeriformes	Parulidae	<i>Dendroica fusca</i>	Blackburnian Warbler
95	Passeriformes	Parulidae	<i>Dendroica graciae</i>	Grace's Warbler
96	Passeriformes	Parulidae	<i>Dendroica magnolia</i>	Magnolia Warbler
97	Passeriformes	Parulidae	<i>Dendroica occidentalis</i>	Hermit Warbler
98	Passeriformes	Parulidae	<i>Dendroica pensylvanica</i>	Chestnut-sided Warbler
99	Passeriformes	Parulidae	<i>Dendroica petechia</i>	Yellow Warbler
100	Passeriformes	Parulidae	<i>Dendroica townsendi</i>	Townsend's Warbler
101	Passeriformes	Parulidae	<i>Geothlypis trichas</i>	Common Yellowthroat
102	Passeriformes	Parulidae	<i>Helmitheros vermivorum</i>	Worm-eating Warbler
103	Passeriformes	Parulidae	<i>Icteria virens</i>	Yellow-breasted Chat
104	Passeriformes	Parulidae	<i>Limnothlypis swainsonii</i>	Swainson's Warbler
105	Passeriformes	Parulidae	<i>Mniotilta varia</i>	Black-and-white Warbler
106	Passeriformes	Parulidae	<i>Myioborus pictus</i>	Painted Redstart
107	Passeriformes	Parulidae	<i>Oporornis agilis</i>	Connecticut Warbler
108	Passeriformes	Parulidae	<i>Oporornis formosus</i>	Kentucky Warbler
109	Passeriformes	Parulidae	<i>Oporornis philadelphia</i>	Mourning Warbler
110	Passeriformes	Parulidae	<i>Oporornis tolmiei</i>	MacGillivray's Warbler
111	Passeriformes	Parulidae	<i>Seiurus motacilla</i>	Louisiana Waterthrush
112	Passeriformes	Parulidae	<i>Seiurus noveboracensis</i>	Northern Waterthrush
113	Passeriformes	Parulidae	<i>Setophaga nigrescens</i>	Black-throated gray warbler
114	Passeriformes	Parulidae	<i>Setophaga ruticilla</i>	American Redstart
115	Passeriformes	Parulidae	<i>Vermivora chrysoptera</i>	Golden-winged Warbler
116	Passeriformes	Parulidae	<i>Vermivora luciae</i>	Lucy's Warbler
117	Passeriformes	Parulidae	<i>Vermivora pinus</i>	Blue-winged Warbler
118	Passeriformes	Parulidae	<i>Vermivora ruficapilla</i>	Nashville Warbler
119	Passeriformes	Parulidae	<i>Vermivora virginiae</i>	Virginia's Warbler
120	Passeriformes	Parulidae	<i>Wilsonia canadensis</i>	Canada Warbler

	Order	Family	Species	English
121	Passeriformes	Parulidae	<i>Wilsonia citrina</i>	Hooded Warbler
122	Passeriformes	Parulidae	<i>Wilsonia pusilla</i>	Wilson's Warbler
123	Passeriformes	Peucedramidae	<i>Peucedramus taeniatus</i>	Olive Warbler
124	Passeriformes	Poliophtidae	<i>Poliophtila caerulea</i>	Blue-gray gnatcatcher
125	Passeriformes	Poliophtidae	<i>Poliophtila californica</i>	California Gnatcatcher
126	Passeriformes	Poliophtidae	<i>Poliophtila melanura</i>	Black-tailed Gnatcatcher
127	Passeriformes	Reguliidae	<i>Regulus calendula</i>	Ruby-crowned Kinglet
128	Passeriformes	Reguliidae	<i>Regulus satrapa</i>	Golden-crowned Kinglet
129	Passeriformes	Sylviidae	<i>Phylloscopus borealis</i>	Arctic Warbler
130	Passeriformes	Thraupidae	<i>Piranga hepatica</i>	Hepatic Tanager
131	Passeriformes	Troglodytidae	<i>Catherpes mexicanus</i>	Canyon Wren
132	Passeriformes	Troglodytidae	<i>Cistothorus palustris</i>	Marsh Wren
133	Passeriformes	Troglodytidae	<i>Cistothorus platensis</i>	Sedge Wren
134	Passeriformes	Troglodytidae	<i>Salpinctes obsoletus</i>	Rock Wren
135	Passeriformes	Troglodytidae	<i>Thryomanes bewickii</i>	Bewick's Wren
136	Passeriformes	Troglodytidae	<i>Thryothorus sinaloa</i>	Sinaloa Wren
137	Passeriformes	Troglodytidae	<i>Troglodytes aedon</i>	House Wren
138	Passeriformes	Turdidae	<i>Catharus bicknelli</i>	Bicknell's Thrush
139	Passeriformes	Turdidae	<i>Catharus guttatus</i>	Hermit Thrush
140	Passeriformes	Turdidae	<i>Catharus minimus</i>	Grey-cheeked thrush
141	Passeriformes	Tyrannidae	<i>Contopus cooperi</i>	Olive-sided Flycatcher
142	Passeriformes	Tyrannidae	<i>Contopus pertinax</i>	Greater Pewee
143	Passeriformes	Tyrannidae	<i>Contopus sordidulus</i>	Western wood pewee
144	Passeriformes	Tyrannidae	<i>Contopus virens</i>	Eastern wood pewee
145	Passeriformes	Tyrannidae	<i>Empidonax alnorum</i>	Alder Flycatcher
146	Passeriformes	Tyrannidae	<i>Empidonax difficilis</i>	Pacific-slope Flycatcher
147	Passeriformes	Tyrannidae	<i>Empidonax flaviventris</i>	Yellow-bellied Flycatcher
148	Passeriformes	Tyrannidae	<i>Empidonax fulvifrons</i>	Buff-breasted Flycatcher
149	Passeriformes	Tyrannidae	<i>Empidonax hammondi</i>	Hammond's Flycatcher
150	Passeriformes	Tyrannidae	<i>Empidonax minimus</i>	Least Flycatcher
151	Passeriformes	Tyrannidae	<i>Empidonax occidentalis</i>	Cordilleran Flycatcher
152	Passeriformes	Tyrannidae	<i>Empidonax traillii</i>	Willow Flycatcher
153	Passeriformes	Tyrannidae	<i>Empidonax virescens</i>	Acadian Flycatcher
154	Passeriformes	Tyrannidae	<i>Empidonax wrightii</i>	Gray flycatcher
155	Passeriformes	Tyrannidae	<i>Myiarchus tuberculifer</i>	Dusky-capped Flycatcher
156	Passeriformes	Tyrannidae	<i>Pyrocephalus rubinus</i>	Vermilion Flycatcher
157	Passeriformes	Tyrannidae	<i>Sayornis nigricans</i>	Black Phoebe
158	Passeriformes	Tyrannidae	<i>Sayornis phoebe</i>	Eastern Phoebe
159	Passeriformes	Tyrannidae	<i>Sayornis saya</i>	Say's Phoebe
160	Passeriformes	Tyrannidae	<i>Tyrannus couchii</i>	Couch's Kingbird
161	Passeriformes	Tyrannidae	<i>Tyrannus crassirostris</i>	Thick-billed Kingbird
162	Passeriformes	Tyrannidae	<i>Tyrannus melancholicus</i>	Tropical Kingbird
163	Passeriformes	Tyrannidae	<i>Tyrannus verticalis</i>	Western Kingbird
164	Passeriformes	Tyrannidae	<i>Tyrannus vociferans</i>	Cassin's Kingbird
165	Passeriformes	Vireonidae	<i>Vireo atricapilla</i>	Black-capped Vireo
166	Passeriformes	Vireonidae	<i>Vireo bellii</i>	Bell's Vireo
167	Passeriformes	Vireonidae	<i>Vireo gilvus</i>	Warbling Vireo
168	Pelecaniformes	Threskiornithidae	<i>Plegadis chihi</i>	White-faced Ibis
169	Pelecaniformes	Threskiornithidae	<i>Plegadis falcinellus</i>	Glossy Ibis
170	Piciformes	Picidae	<i>Picoides arizonae</i>	Arizona Woodpecker
171	Piciformes	Picidae	<i>Picoides dorsalis</i>	American Three-toed Woodpecker
172	Piciformes	Picidae	<i>Picoides pubescens</i>	Downy Woodpecker
173	Piciformes	Picidae	<i>Picoides scalaris</i>	Ladder-backed Woodpecker
174	Podicipediformes	Podicipedidae	<i>Podiceps nigricollis</i>	Eared grebe
175	Strigiformes	Strigidae	<i>Megascops trichopsis</i>	Whiskered screech owl
176	Strigiformes	Strigidae	<i>Micrathene whitneyi</i>	Elf Owl
177	Strigiformes	Strigidae	<i>Otus flammeolus</i>	Flammulated Owl

Table C3: Herbivorous birds in the BBS data (diet consisting of $\geq 80\%$ plants and grains, according to EltonTraits database).

	Order	Family	Species	English
1	Anseriformes	Anatidae	Aix sponsa	Wood Duck
2	Anseriformes	Anatidae	Alopochen aegyptiaca	Egyptian Goose
3	Anseriformes	Anatidae	Anas americana	American Wigeon
4	Anseriformes	Anatidae	Anas cyanoptera	Cinnamon Teal
5	Anseriformes	Anatidae	Anas discors	Blue-winged Teal
6	Anseriformes	Anatidae	Anas penelope	Eurasian Wigeon
7	Anseriformes	Anatidae	Anas strepera	Gadwall
8	Anseriformes	Anatidae	Anser albifrons	Greater White-fronted Goose
9	Anseriformes	Anatidae	Aythya affinis	Lesser Scaup
10	Anseriformes	Anatidae	Aythya americana	Redhead
11	Anseriformes	Anatidae	Aythya collaris	Ring-necked Duck
12	Anseriformes	Anatidae	Aythya valisineria	Canvasback
13	Anseriformes	Anatidae	Branta canadensis	Canada Goose
14	Anseriformes	Anatidae	Branta hutchinsii	Cackling Goose
15	Anseriformes	Anatidae	Chen caerulescens	Snow Goose
16	Anseriformes	Anatidae	Chen rossii	Ross's Goose
17	Anseriformes	Anatidae	Cygnus buccinator	Trumpeter Swan
18	Anseriformes	Anatidae	Cygnus columbianus	Tundra Swan
19	Anseriformes	Anatidae	Cygnus olor	Mute Swan
20	Anseriformes	Anatidae	Dendrocygna autumnalis	Black-bellied whistling duck
21	Anseriformes	Anatidae	Dendrocygna bicolor	Fulvous whistling duck
22	Columbiformes	Columbidae	Columba livia	Rock Pigeon
23	Columbiformes	Columbidae	Columba inca	Inca Dove
24	Columbiformes	Columbidae	Columba talpacoti	Ruddy ground dove
25	Columbiformes	Columbidae	Patagioenas fasciata	Band-tailed Pigeon
26	Columbiformes	Columbidae	Stigmatopelia chinensis	Spotted Dove
27	Columbiformes	Columbidae	Streptopelia roseogrisea	African collared dove
28	Columbiformes	Columbidae	Zenaida macroura	Mourning Dove
29	Galliformes	Odontophoridae	Callipepla californica	California Quail
30	Galliformes	Odontophoridae	Callipepla gambelii	Gambel's Quail
31	Galliformes	Odontophoridae	Colinus virginianus	Northern Bobwhite
32	Galliformes	Odontophoridae	Oreortyx pictus	Mountain Quail
33	Galliformes	Phasianidae	Alectoris chukar	Chukar
34	Galliformes	Phasianidae	Centrocercus minimus	Gunnison sage-grouse
35	Galliformes	Phasianidae	Centrocercus urophasianus	Greater sage-grouse
36	Galliformes	Phasianidae	Dendragapus canadensis	Spruce Grouse
37	Galliformes	Phasianidae	Dendragapus fuliginosus	Sooty Grouse
38	Galliformes	Phasianidae	Dendragapus obscurus	Dusky Grouse
39	Galliformes	Phasianidae	Lagopus lagopus	Willow Ptarmigan
40	Galliformes	Phasianidae	Lagopus leucura	White-tailed Ptarmigan
41	Galliformes	Phasianidae	Lagopus muta	Rock Ptarmigan
42	Galliformes	Phasianidae	Tympanuchus phasianellus	Sharp-tailed Grouse
43	Gruiformes	Rallidae	Fulica americana	American Coot
44	Passeriformes	Cardinalidae	Spiza americana	Dickcissel
45	Passeriformes	Emberizidae	Aimophila carpalis	Rufous-winged Sparrow
46	Passeriformes	Emberizidae	Calcarius mccownii	McCown's Longspur
47	Passeriformes	Emberizidae	Passerina ciris	Painted Bunting
48	Passeriformes	Emberizidae	Passerina cyanea	Indigo Bunting
49	Passeriformes	Emberizidae	Pipilo fuscus	Canyon Towhee
50	Passeriformes	Emberizidae	Zonotrichia atricapilla	Golden-crowned Sparrow
51	Passeriformes	Emberizidae	Zonotrichia leucophrys	White-crowned Sparrow
52	Passeriformes	Emberizidae	Zonotrichia querula	Harris's Sparrow
53	Passeriformes	Fringillidae	Carduelis hornemanni	Hoary Redpoll
54	Passeriformes	Fringillidae	Carduelis lawrencei	Lawrence's Goldfinch
55	Passeriformes	Fringillidae	Carduelis pinus	Pine Siskin
56	Passeriformes	Fringillidae	Carduelis tristis	American Goldfinch
57	Passeriformes	Fringillidae	Carpodacus cassinii	Cassin's Finch
58	Passeriformes	Fringillidae	Leucosticte australis	Brown-capped rosy finch
59	Passeriformes	Fringillidae	Leucosticte tephrocotis	Gray-crowned rosy finch
60	Passeriformes	Fringillidae	Loxia curvirostra	Red Crossbill
61	Passeriformes	Passerellidae	Ammospiza leconteii	LeConte's sparrow
62	Passeriformes	Passerellidae	Spizella pallida	Clay-colored sparrow
63	Passeriformes	Passeridae	Passer domesticus	House Sparrow
64	Passeriformes	Viduidae	Vidua macroura	Pin-tailed Whydah
65	Psittaciformes	Psittacidae	Melospittacus undulatus	Budgerigar

D Summary statistics

Table D1: Summary Statistics before matching

Share corn, soy and cotton	<25%			$\geq 25\%$		
Variable	N	Mean	SD	N	Mean	SD
Share soy, corn and cotton	7198	0.068	0.071	39854	0.721	0.197
Cropland share (1km buffer)	7198	0.623	0.219	39854	0.742	0.231
Cropland share (10km buffer)	7198	0.541	0.205	39854	0.682	0.225
Corn share	7198	0.042	0.052	39854	0.394	0.17
Soy share	7198	0.017	0.038	39854	0.291	0.164
Cotton share	7198	0.009	0.031	39854	0.036	0.118
Richness	7198	22.924	7.679	39854	29.335	8.444
Abundance	7198	187.852	106.027	39854	219.69	114.336
Shannon diversity	7198	2.446	0.431	39854	2.653	0.411
Richness insectivores	7198	4.438	2.508	39854	5.615	2.719
Abundance insectivores	7198	23.124	36.409	39854	21.809	29.912
Shannon div. insectivores	7198	1.058	0.528	39854	1.344	0.511
Richness herbivores	7198	3.422	1.397	39854	4.636	1.273
Abundance herbivores	7198	42.321	41.33	39854	55.613	42.919
Shannon div. herbivores	7198	0.884	0.406	39854	1.086	0.345

Table D2: Summary Statistics after matching

Share corn, soy and cotton Variable	<25%			≥ 25%		
	N	Mean	SD	N	Mean	SD
Share soy, corn and cotton	7104	0.044	0.052	8399	0.501	0.287
Cropland share (1km buffer)	7104	0.625	0.219	8399	0.726	0.239
Cropland share (10km buffer)	7104	0.542	0.206	8399	0.659	0.237
Corn share	7104	0.029	0.04	8399	0.26	0.189
Soy share	7104	0.011	0.025	8399	0.183	0.161
Cotton share	7104	0.005	0.016	8399	0.059	0.145
Richness	7104	22.883	7.697	8399	25.344	7.757
Abundance	7104	187.725	105.778	8399	171.172	90.115
Shannon diversity	7104	2.444	0.432	8399	2.604	0.407
Richness insectivores	7104	4.437	2.515	8399	4.614	2.353
Abundance insectivores	7104	23.028	34.467	8399	19.131	30.216
Shannon div. insectivores	7104	1.057	0.529	8399	1.156	0.516
Richness herbivores	7104	3.413	1.4	8399	4.149	1.353
Abundance herbivores	7104	42.069	41.342	8399	44.469	36.373
Shannon div. herbivores	7104	0.881	0.407	8399	1.047	0.356

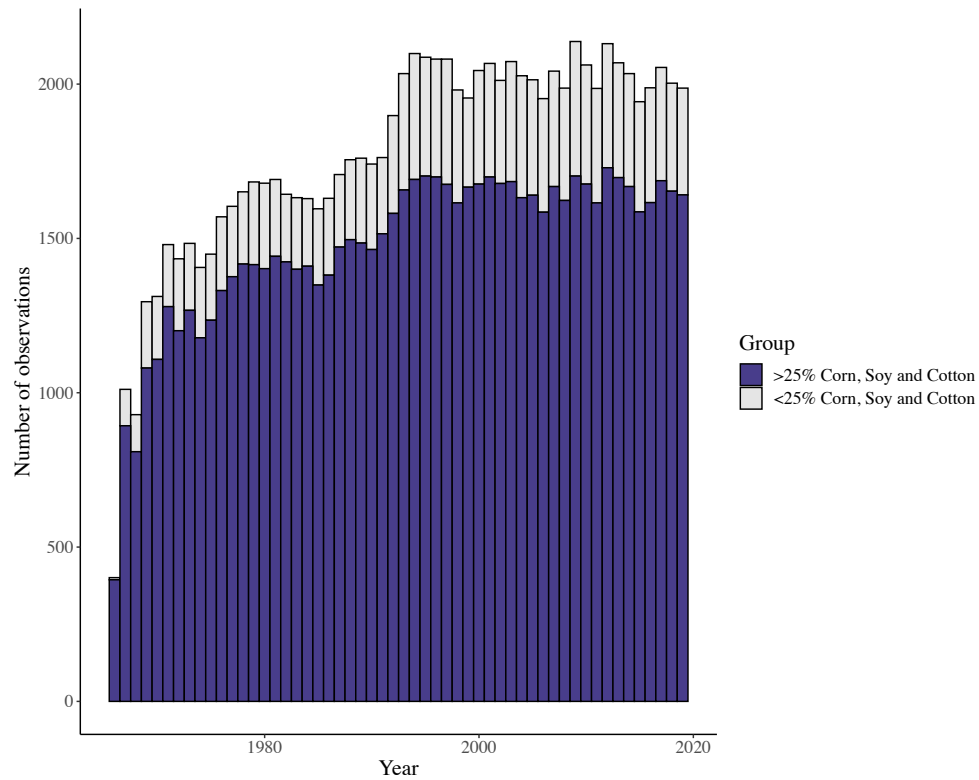


Figure D1: Number of routes in the unmatched sample per year, divided into groups surrounded by >25% and <25% corn, soy and cotton in a 1 km-buffer.

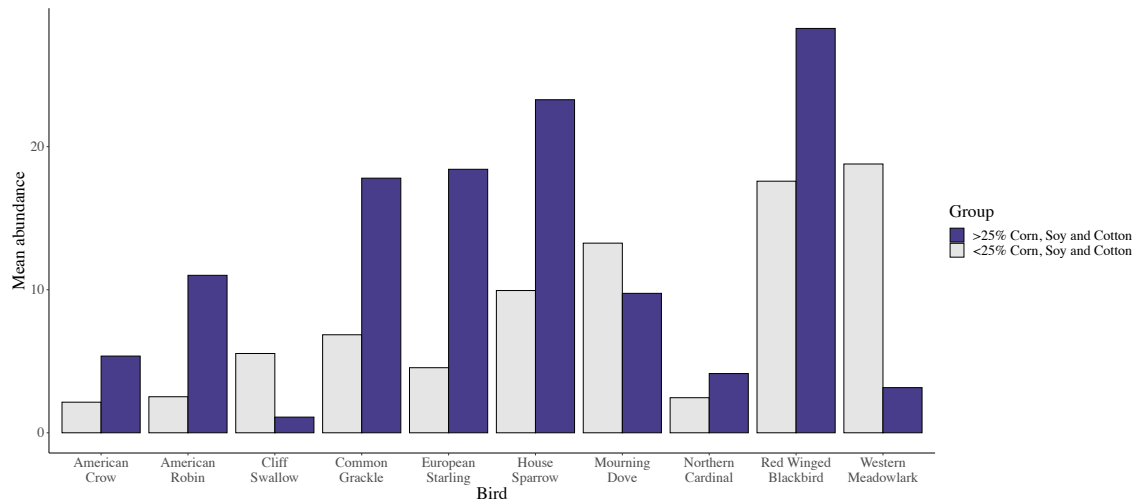


Figure D2: Comparison of mean abundance of the 10 most common birds in the unmatched sample between routes surrounded by >25% and <25% corn, soy and cotton in a 1 km-buffer.

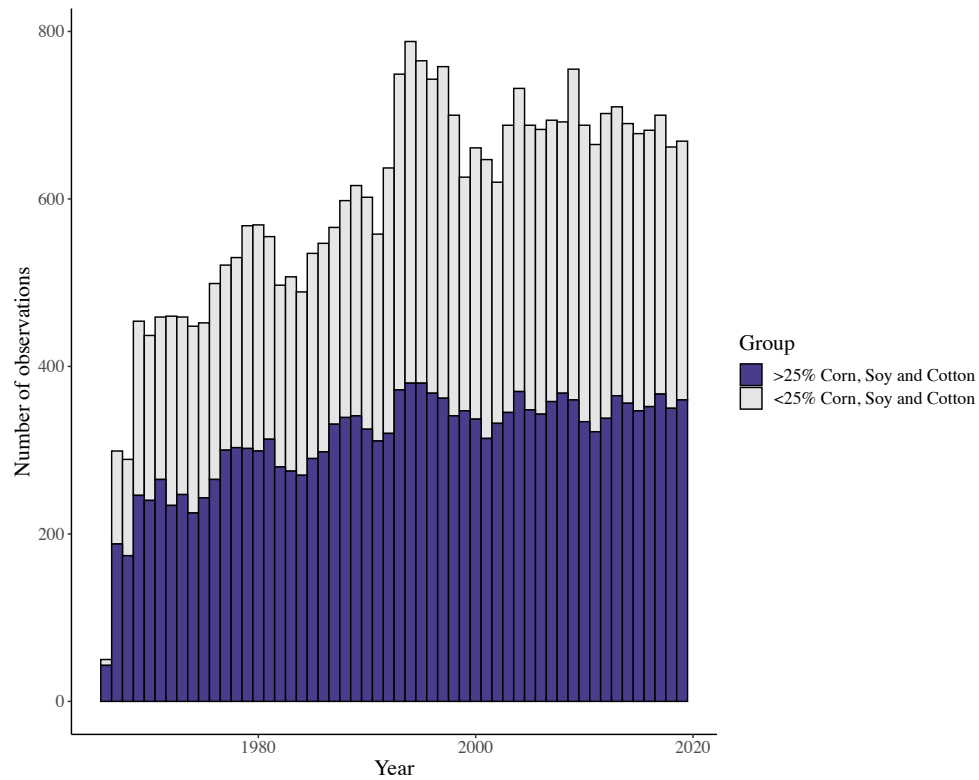


Figure D3: Number of routes in the matched sample per year, divided into groups surrounded by >25% and <25% corn, soy and cotton in a 1 km-buffer.

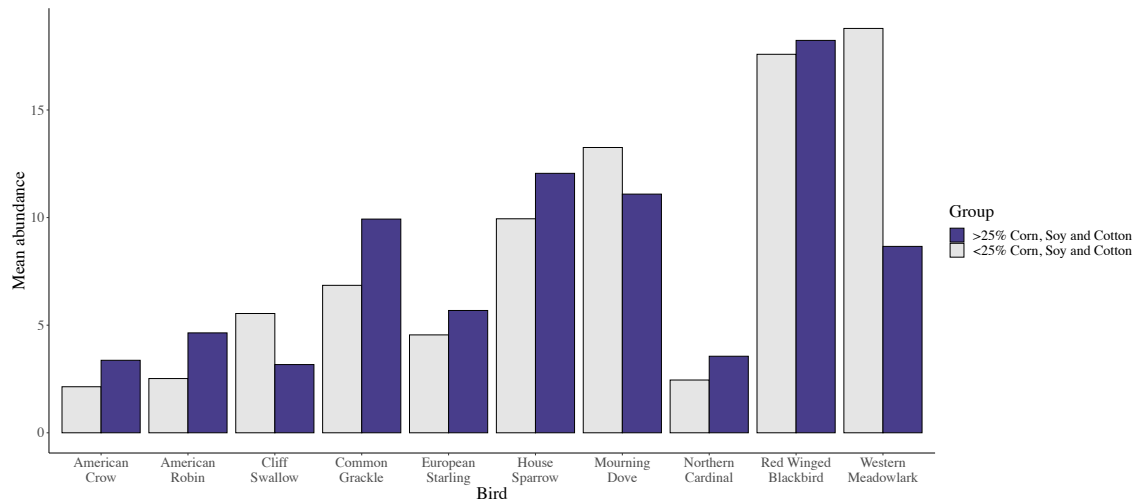


Figure D4: Comparison of mean abundance of the 10 most common birds in the matched sample between routes surrounded by >25% and <25% corn, soy and cotton in a 1 km-buffer.

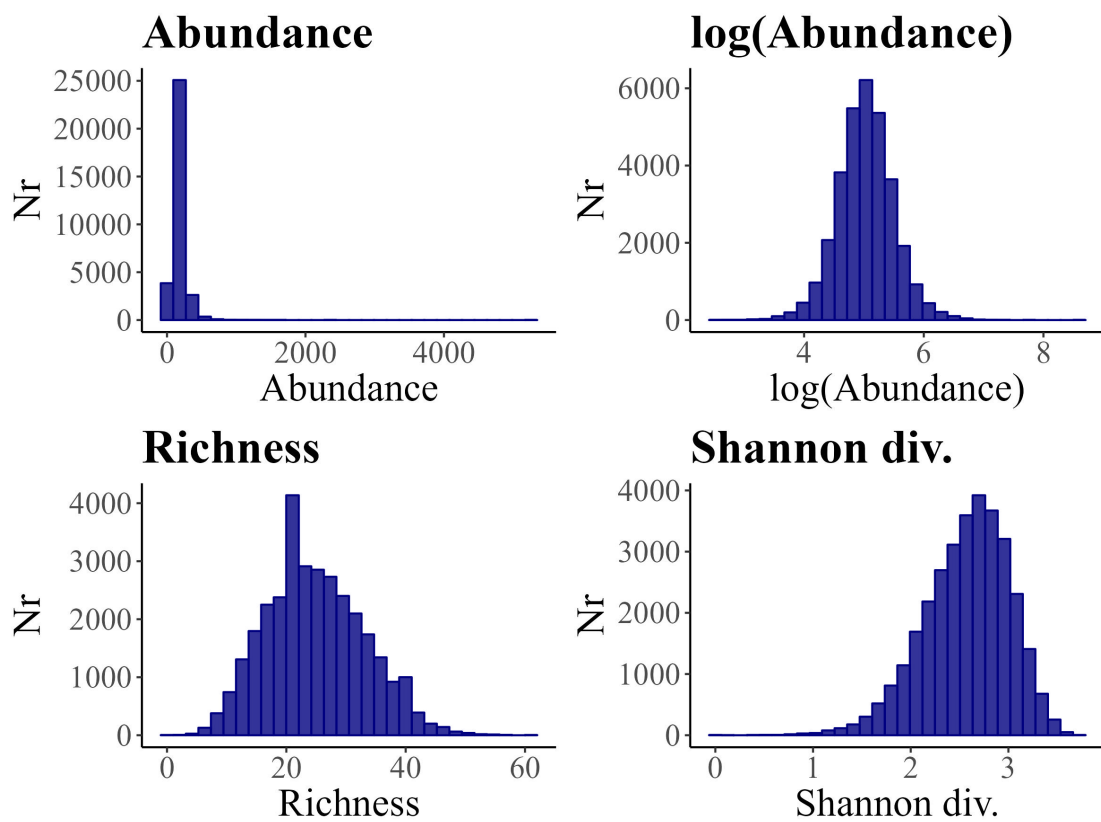


Figure D5: Histograms of abundance, log(abundance), richness and Shannon diversity in matched sample.

Table D3: Mean abundances of 50 most common bird species in the **unmatched** sample before 1996, sorted by abundance in areas with $\geq 25\%$ corn, soy and cotton (CSC).

	Bird	$\geq 25\%$ CSC	$< 25\%$ CSC	Difference (in %)
1	Red-winged Blackbird	31.48	17.03	45.89
2	House Sparrow	29.07	12.46	57.13
3	Common Grackle	20.26	6.60	67.44
4	European Starling	18.31	4.35	76.22
5	Mourning Dove	9.45	14.89	-57.62
6	American Robin	8.92	2.08	76.66
7	American Crow	4.97	1.89	61.99
8	Barn Swallow	4.92	3.92	20.44
9	Eastern Meadowlark	4.43	4.31	2.76
10	Song Sparrow	4.42	0.39	91.15
11	Western Meadowlark	4.02	18.67	-364.36
12	Northern Bobwhite	3.98	5.44	-36.69
13	Dickcissel	3.88	5.58	-43.71
14	Northern Cardinal	3.81	2.68	29.82
15	Horned Lark	3.61	11.24	-211.86
16	Rock Pigeon	3.43	1.29	62.47
17	Brown-headed Cowbird	3.41	4.71	-38.04
18	Indigo Bunting	3.03	0.16	94.89
19	Ring-necked Pheasant	2.86	4.08	-42.64
20	Common Yellowthroat	2.52	0.62	75.31
21	Northern Mockingbird	2.17	4.49	-106.85
22	Killdeer	2.02	1.77	12.46
23	Blue Jay	2.02	0.93	54.00
24	Chimney Swift	1.98	0.63	68.29
25	American Goldfinch	1.79	0.41	77.13
26	House Wren	1.67	0.89	46.88
27	Savannah Sparrow	1.63	1.22	25.06
28	Great-tailed Grackle	1.49	1.43	4.11
29	Chipping Sparrow	1.46	0.11	92.14
30	Vesper Sparrow	1.44	0.81	43.86
31	Field Sparrow	1.30	0.20	84.62
32	Brown Thrasher	1.08	0.93	13.70
33	Bobolink	1.05	0.67	36.60
34	Eastern Kingbird	1.02	1.65	-62.26
35	Purple Martin	0.98	0.53	46.32
36	Gray Catbird	0.97	0.15	84.62
37	Red-headed Woodpecker	0.82	0.41	49.76
38	Grasshopper Sparrow	0.80	1.96	-145.24
39	Baltimore Oriole	0.78	1.10	-41.68
40	(Yellow-shafted Flicker) Northern Flicker	0.77	0.45	41.58
41	Mallard	0.77	0.68	11.80
42	Tufted Titmouse	0.76	0.10	86.75
43	Cliff Swallow	0.74	4.46	-500.36
44	Red-bellied Woodpecker	0.73	0.30	58.95
45	Cattle Egret	0.69	1.77	-155.81
46	Yellow-billed Cuckoo	0.65	0.73	-12.05
47	Wood Thrush	0.56	0.01	99.04
48	Carolina Wren	0.53	0.25	52.72
49	Eastern Towhee	0.52	0.33	35.67
50	House Finch	0.52	0.11	79.66
	Mean	4.09	3.04	2.97

Table D4: Mean abundances of 50 most common bird species in the **matched** sample before 1996, sorted by abundance in areas with $\geq 25\%$ corn, soy and cotton (CSC).

	Bird	$\geq 25\%$ CSC	$< 25\%$ CSC	Difference (in %)
1	Red-winged Blackbird	20.49	17.17	16.20
2	House Sparrow	17.56	12.35	29.68
3	Common Grackle	12.41	6.56	47.18
4	Mourning Dove	11.64	14.92	-28.12
5	Western Meadowlark	9.14	18.71	-104.75
6	European Starling	6.48	4.35	32.92
7	Dickcissel	6.01	5.44	9.47
8	Horned Lark	4.68	11.39	-143.17
9	Barn Swallow	4.27	3.91	8.44
10	American Robin	4.19	2.09	50.17
11	Brown-headed Cowbird	4.14	4.64	-12.15
12	Northern Bobwhite	4.06	5.39	-32.93
13	Eastern Meadowlark	4.03	4.33	-7.29
14	Ring-necked Pheasant	3.94	4.08	-3.56
15	American Crow	3.50	1.89	45.94
16	Northern Cardinal	3.38	2.66	21.41
17	Northern Mockingbird	3.11	4.49	-44.46
18	Cliff Swallow	2.26	4.33	-91.90
19	Blue Jay	1.94	0.93	52.16
20	Common Yellowthroat	1.92	0.63	67.13
21	Indigo Bunting	1.81	0.15	91.49
22	Killdeer	1.75	1.78	-1.75
23	Rock Pigeon	1.63	1.30	20.05
24	Lark Bunting	1.50	6.82	-356.17
25	Song Sparrow	1.49	0.40	73.34
26	Eastern Kingbird	1.41	1.64	-16.38
27	Vesper Sparrow	1.22	0.82	33.02
28	Brown Thrasher	1.18	0.92	21.62
29	House Wren	1.17	0.89	23.91
30	Grasshopper Sparrow	1.16	1.94	-67.66
31	Great-tailed Grackle	1.12	1.45	-29.67
32	Chimney Swift	1.02	0.61	40.51
33	Cattle Egret	1.01	1.80	-78.89
34	Western Kingbird	0.93	2.61	-180.75
35	American Goldfinch	0.92	0.41	55.01
36	Red-headed Woodpecker	0.90	0.41	54.74
37	Bobolink	0.78	0.67	13.87
38	Purple Martin	0.77	0.53	30.65
39	Yellow-billed Cuckoo	0.73	0.73	0.68
40	Field Sparrow	0.73	0.20	72.13
41	Red-bellied Woodpecker	0.72	0.30	58.03
42	Baltimore Oriole	0.68	1.10	-61.35
43	Yellow-headed Blackbird	0.64	0.30	52.91
44	Savannah Sparrow	0.63	1.23	-94.59
45	(Yellow-shafted Flicker) Northern Flicker	0.59	0.45	24.50
46	Eastern Towhee	0.53	0.34	35.52
47	Mallard	0.52	0.68	-31.19
48	Carolina Wren	0.49	0.25	49.23
49	Scissor-tailed Flycatcher	0.47	1.63	-245.56
50	Lark Sparrow	0.47	1.72	-267.34
	Mean	3.16	3.29	-15.36

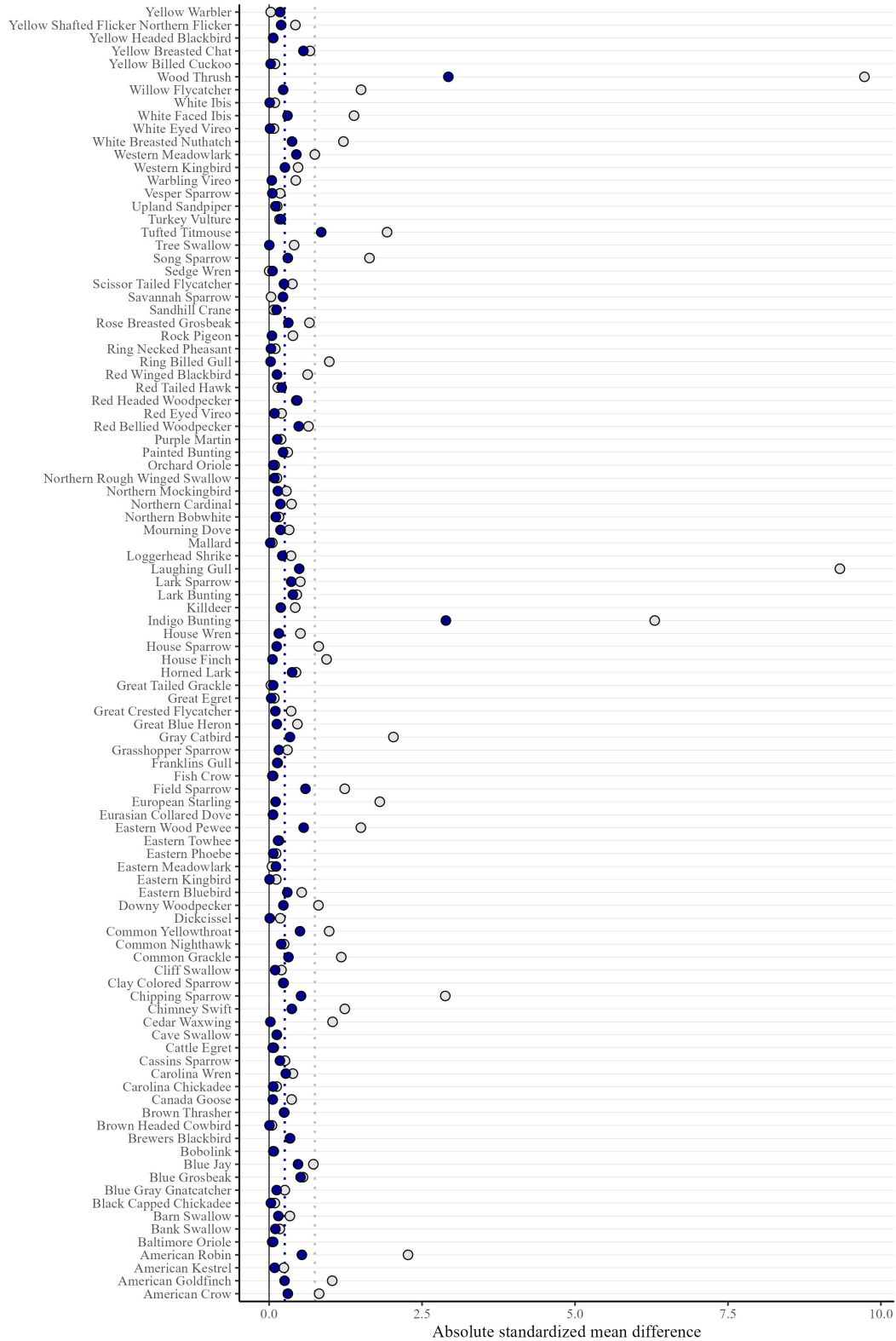


Figure D6: Absolute standardized mean differences between the top 100 bird species in regions with more or less than 25% share of corn, soy and cotton in 1992, before (grey dots) and after matching (blue dots). Grey dotted line indicates average difference before matching, blue dotted line indicates average difference after matching.

E Output tables

Table E1: Overall effect of GM crops on all, insectivorous and herbivorous birds.

	All Birds			Insectivores			Herbivores		
Dependent Variables:	Richness	log(Abundance)	Shannon Div.	Richness	log(Abundance)	Shannon Div.	Richness	log(Abundance)	Shannon Div.
Model:	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
<i>Variables</i>									
GMExposure × CroplandShare	0.2209	0.1434**	-0.0013	0.6324**	0.3828***	0.1302**	-0.3044**	-0.1406	0.0326
	(0.8089)	(0.0553)	(0.0490)	(0.2783)	(0.1279)	(0.0624)	(0.1300)	(0.0984)	(0.0535)
<i>Fixed-effects</i>									
ID	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observer	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Fit statistics</i>									
Observations	31,996	31,993	31,996	31,996	31,565	31,996	31,996	31,860	31,996
R ²	0.82303	0.70698	0.76258	0.69975	0.62176	0.59893	0.63205	0.67242	0.61950
Within R ²	0.02314	0.02774	0.01018	0.00876	0.00698	0.00579	0.00445	0.01774	0.00206
<i>Clustered (state & year) standard-errors in parentheses</i>									
<i>Signif. Codes: ***: 0.01, **: 0.05, *: 0.1</i>									

Table E2: Effect of GM corn, soy and cotton on all, insectivorous and herbivorous birds.

	All Birds			Insectivores			Herbivores		
Dependent Variables:	Richness	log(Abundance)	Shannon Div.	Richness	log(Abundance)	Shannon Div.	Richness	log(Abundance)	Shannon Div.
Model:	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
<i>Variables</i>									
GM _{Soy} Adoption × SoyShare	0.0378	0.1007	-0.0256	0.1702	0.2618	0.0160	-0.7054*	-0.2434	-0.0219
	(1.717)	(0.1311)	(0.1135)	(0.5658)	(0.3091)	(0.1569)	(0.3557)	(0.1552)	(0.1171)
GM _{Corn} Adoption × CornShare	-0.3759	0.1575	-0.0099	0.6938	0.2426*	0.1656	0.0268	-0.0253	0.1086
	(1.705)	(0.1197)	(0.1107)	(0.4698)	(0.1327)	(0.1117)	(0.3311)	(0.1942)	(0.0886)
GM _{Cotton} Adoption × CottonShare	2.761	0.2247*	0.1004	1.815**	1.219***	0.3545***	-0.2055	-0.2170	-0.0575
	(2.330)	(0.1199)	(0.0684)	(0.8135)	(0.1516)	(0.0847)	(0.3011)	(0.2520)	(0.0722)
<i>Fixed-effects</i>									
ID	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observer	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Fit statistics</i>									
Observations	31,996	31,993	31,996	31,996	31,565	31,996	31,996	31,860	31,996
R ²	0.82309	0.70700	0.76261	0.69989	0.62229	0.59905	0.63211	0.67244	0.61957
Within R ²	0.02349	0.02781	0.01032	0.00922	0.00837	0.00608	0.00460	0.01781	0.00223

Clustered (state & year) standard-errors in parentheses

*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

F Aggregated dynamic effects (main results)

Table F1: Average treatment effects calculated from dynamic effect coefficients (from Fig. 4)

	Estimate	Std. Error	t value	p value
All birds				
Richness	-0.03	0.49	-0.07	0.94
log(Abundance)	0.10	0.04	2.78	0.01
Shannon div.	-0.03	0.02	-1.34	0.19
Insectivores				
Richness	0.64	0.15	4.20	0.00
log(Abundance)	0.21	0.09	2.44	0.02
Shannon div.	0.11	0.04	3.07	0.00
Herbivores				
Richness	-0.22	0.05	-4.07	0.00
log(Abundance)	-0.02	0.08	-0.21	0.83
Shannon div.	0.03	0.02	1.42	0.17

G Corn, soy and cotton exposure of BBS routes in sample

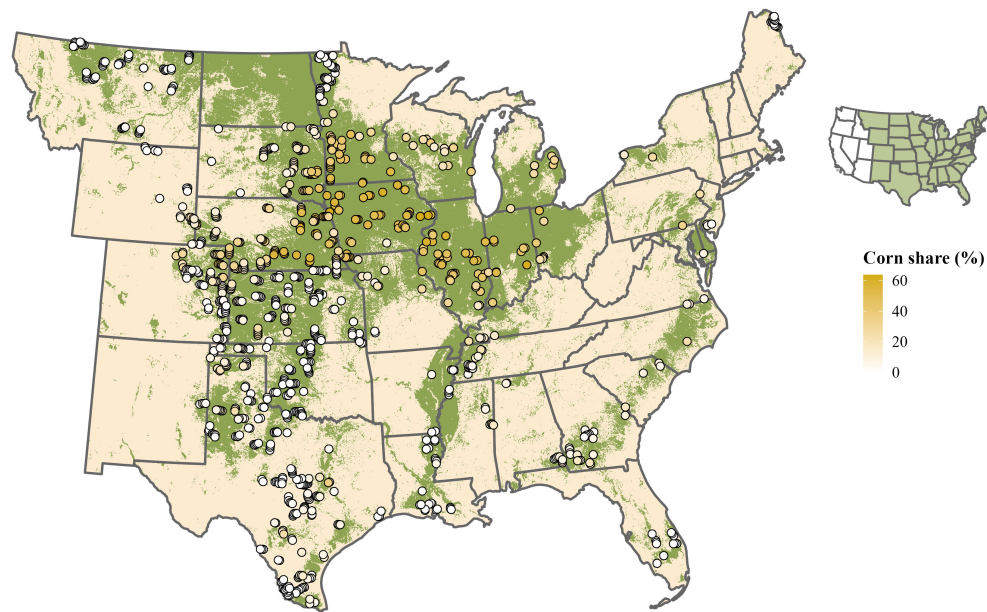


Figure G1: Share of corn of overall crop composition surrounding BBS routes in sample in a 1 km-buffer.

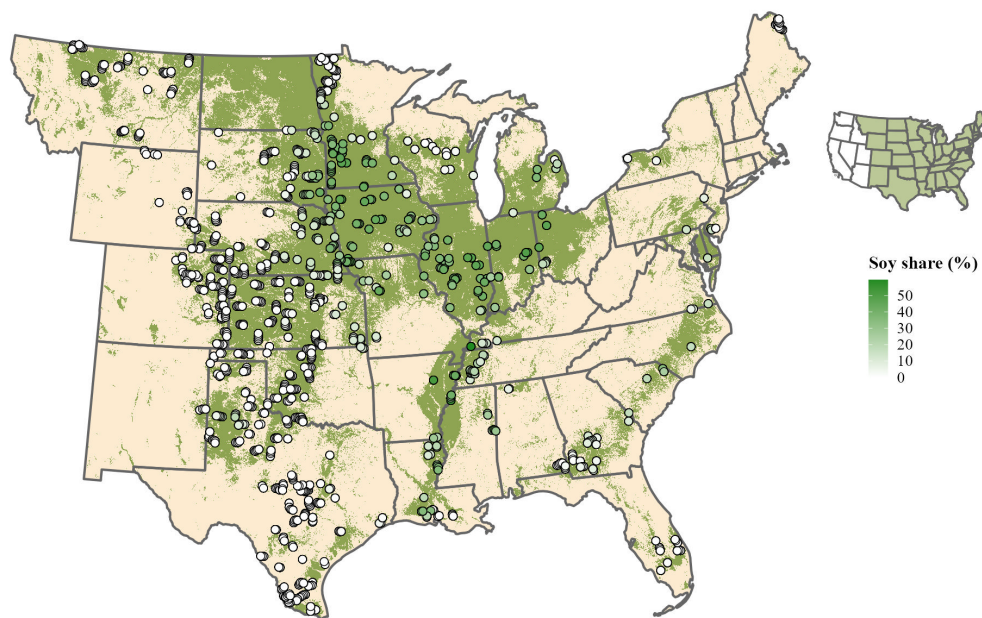


Figure G2: Share of soy of overall crop composition surrounding BBS routes in sample in a 1 km-buffer.



Figure G3: Share of cotton of overall crop composition surrounding BBS routes in sample in a 1 km-buffer.

H Event study plots

Using model (6) in the methods section, we estimate the dynamic effects of GM corn, soy and cotton adoption on bird populations individually. For each year, we estimate the difference between routes with high and low exposure to these crops individually, after controlling for common and time constant variation using fixed effects.

All birds

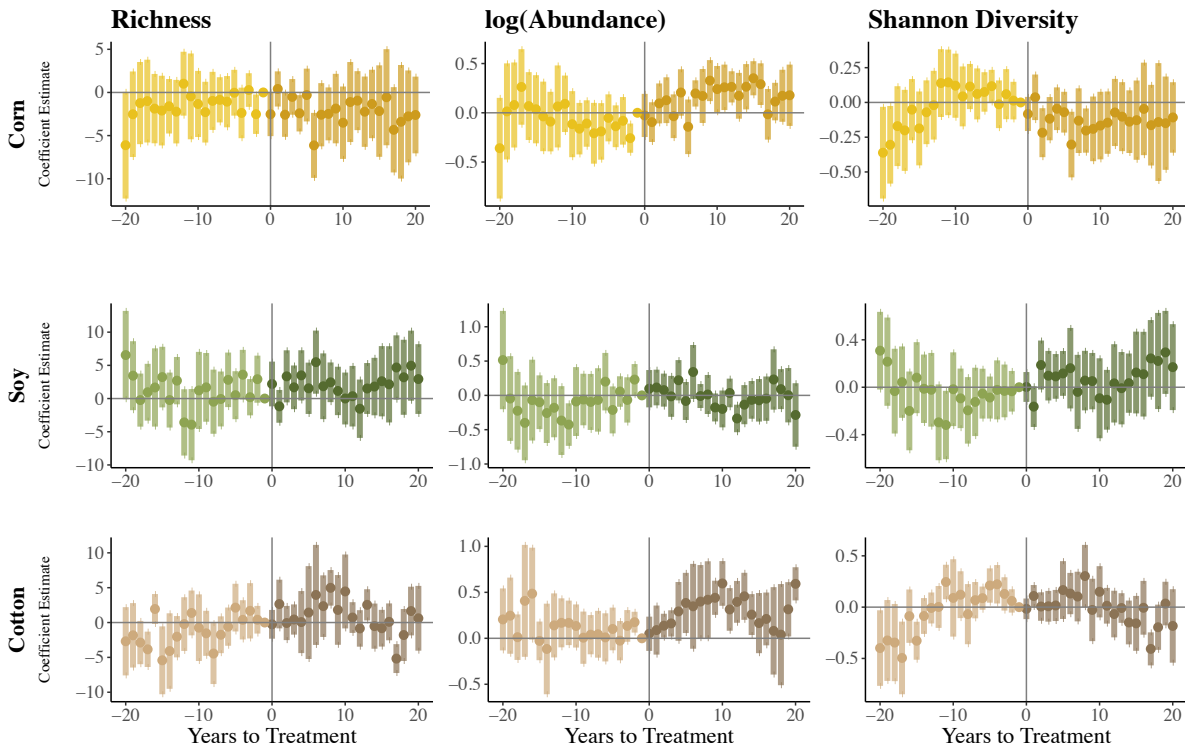


Figure H1: Dynamic crop-specific effects of GM corn (yellow), soy (green) and cotton (brown) varieties on all birds. Bars indicating 95% confidence intervals, event time indicating years to approval of GM corn, soy and cotton varieties in 1996.

Looking at the dynamic effects on overall bird populations, we find a positive effect of corn and cotton on abundance, and an initially positive effect of cotton on richness (Fig. H1). Cotton also has a positive effect on insectivorous bird richness and abundance (Fig. H2). Corn does not have an effect on insectivorous birds in this model. We also observe some parallel trend violations, especially when looking at effects on Shannon diversity, but also in the effects of soybeans on insectivorous bird richness. Finally, there are no clear effects of

any of the three crops on herbivorous birds (Fig. H3).

Insectivores

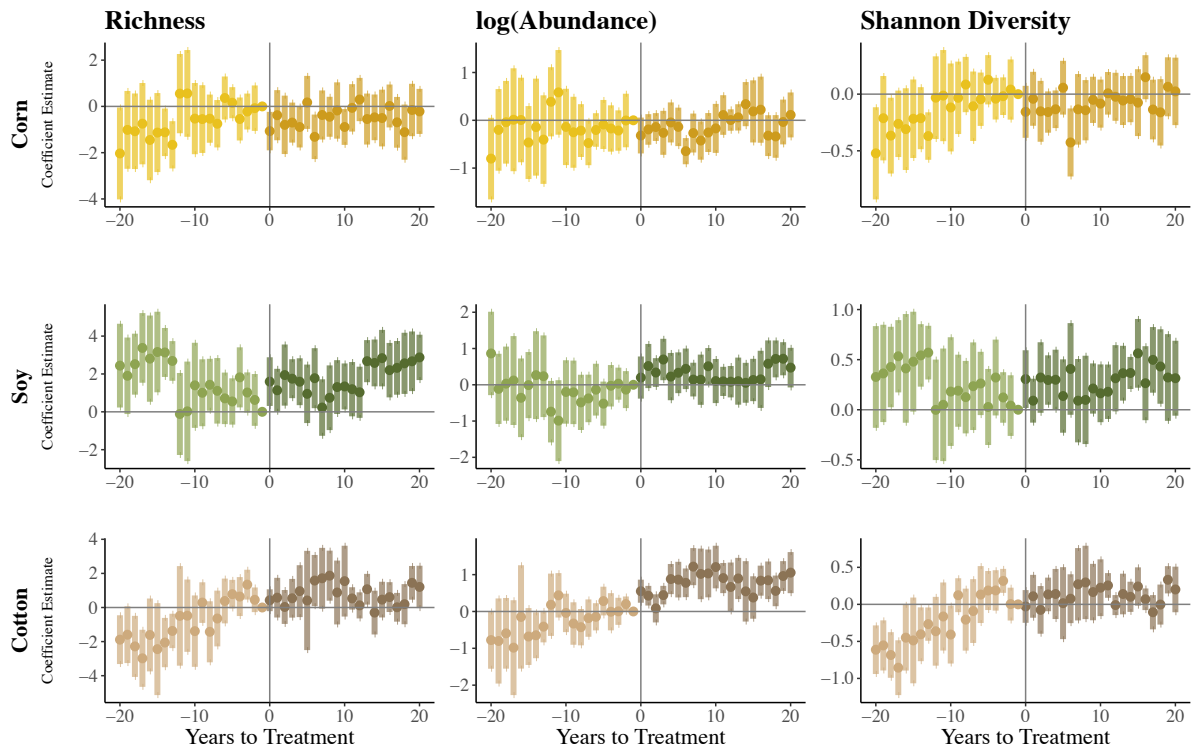


Figure H2: Dynamic crop-specific effects of GM corn (yellow), soy (green) and cotton (brown) varieties on insectivorous birds. Bars indicating 95% confidence intervals, event time indicating years to approval of GM corn, soy and cotton varieties in 1996.

Herbivores

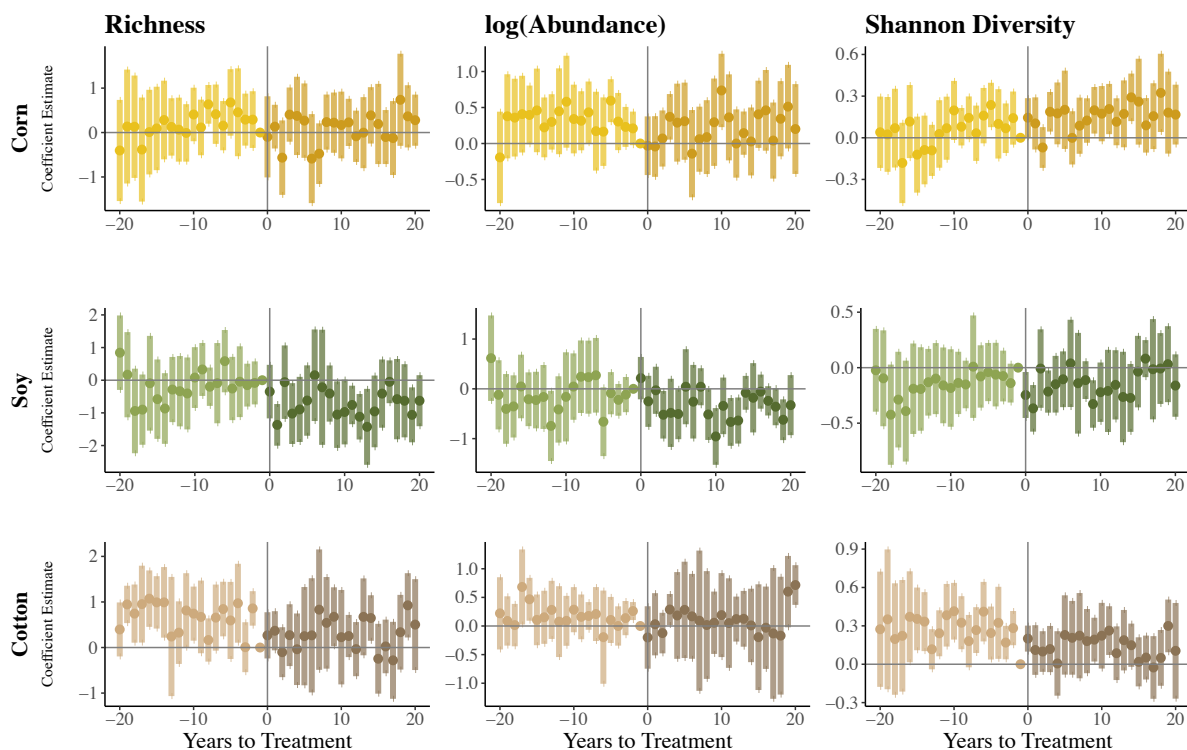


Figure H3: Dynamic crop-specific effects of GM corn (yellow), soy (green) and cotton (brown) varieties on herbivorous birds. Bars indicating 95% confidence intervals, event time indicating years to approval of GM corn, soy and cotton varieties in 1996.

I Individual bird species

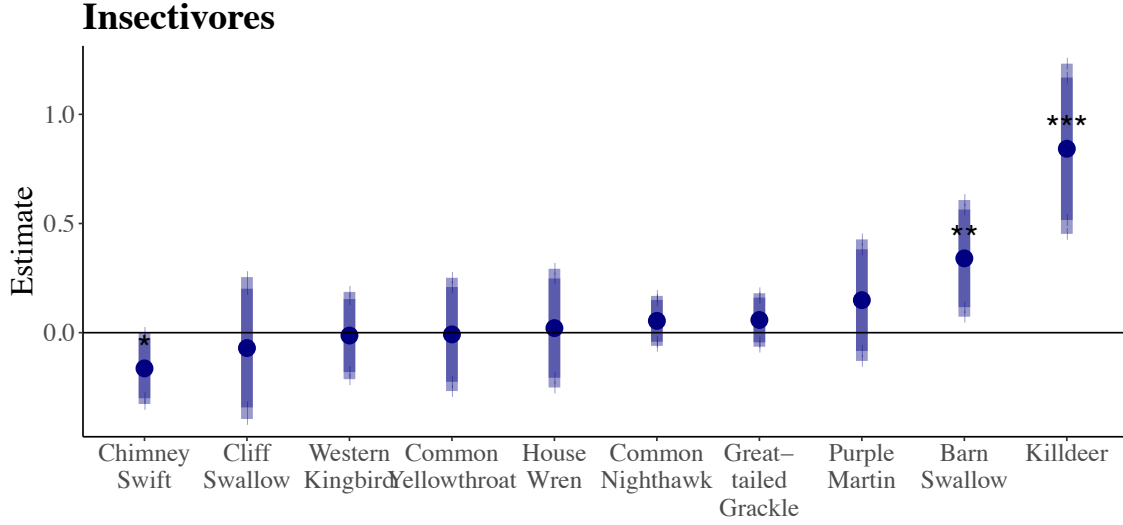


Figure I1: Estimated effect of GM crops on insectivorous birds, after inverse hyperbolic sine transformation. Dark and light bars indicating 90% and 95% confidence intervals respectively, and stars indicating p-values (* : $P < 0.1$, ** : $P < 0.05$, *** : $P < 0.01$).

We estimate the impact of GM corn, soy, and cotton on the abundance of individual bird species. In order to avoid multiple hypothesis testing problems when examining hundreds of bird species, we focus on smaller subsets of species and broader patterns. Of the 100 most common species in our region of interest, we estimate the effect on the 10 most common birds whose diet consists of more than 80% insects and the 10 most common birds with a diet of more than 80% plants and seeds (see Table C2 and C3 in Appendix C for a full list of species). Fig. I1 and I2 present the effects on individual herbivorous and insectivorous species, respectively. The coefficients of the effects on individual bird species further support the results from the previous section: Herbivorous birds are mostly negatively affected by GM introduction while insectivorous birds are largely positively affected by GM crop introduction.

We then again split the treatment by crop and estimate the effect of GM corn, soy and cotton each on individual bird species (Figs. I3 and I4). These results line up with the results from the estimation of crop-specific effects in the previous section. Corn has mostly a positive

effect on herbivorous species, whereas soy has a mostly negative effect. The coefficients of the effect of cotton on the abundance of herbivorous bird species do not show a distinct pattern. Meanwhile, the positive effect on insectivorous birds seems to be driven by cotton and corn, whose effect coefficients are mostly positive.

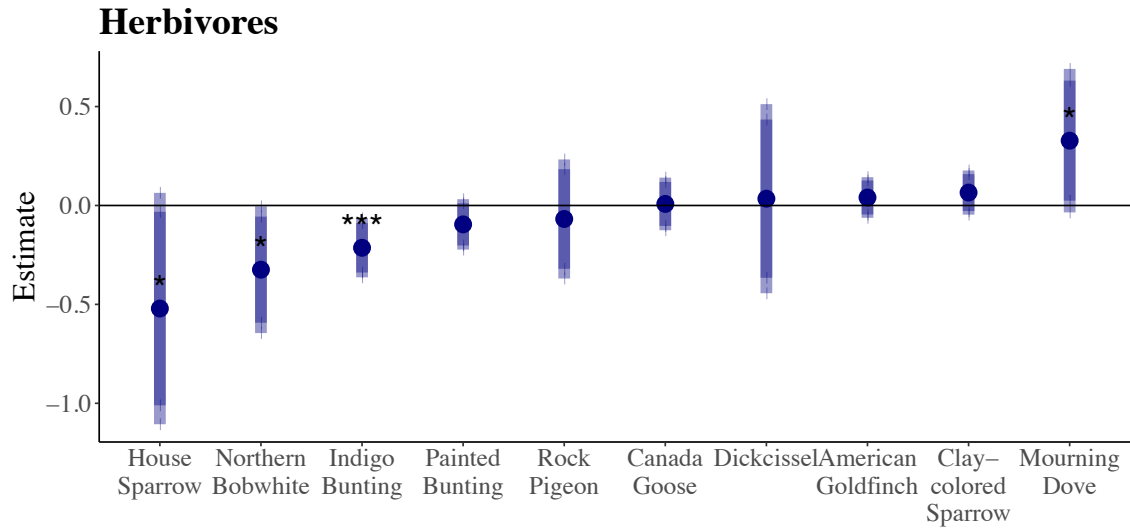


Figure I2: Estimated effect of GM crops on herbivorous birds, after inverse hyperbolic sine transformation. Dark and light bars indicating 90% and 95% confidence intervals respectively, and stars indicating p-values (* : $P < 0.1$, ** : $P < 0.05$, *** : $P < 0.01$).

Insectivores

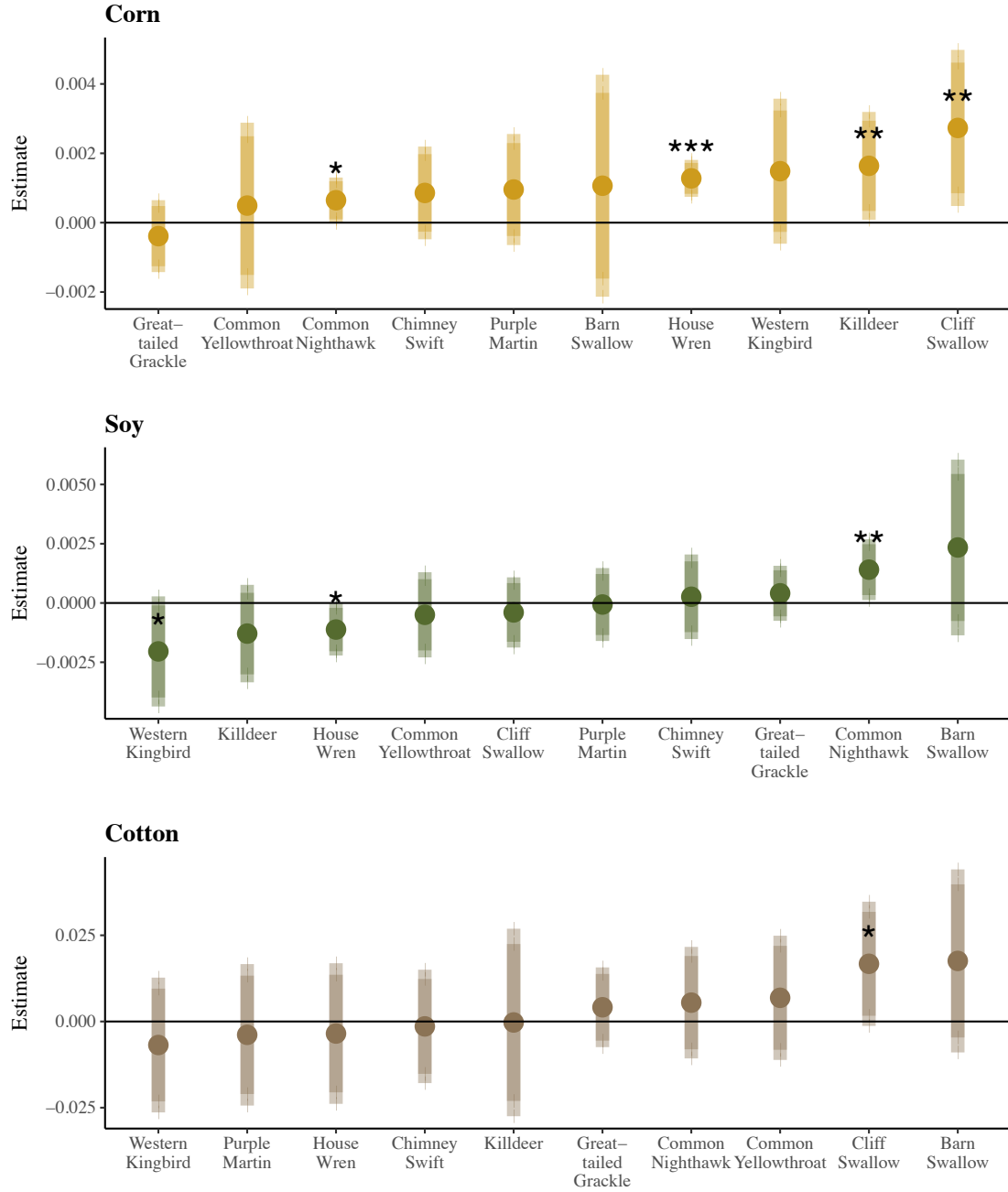


Figure I3: Estimated effect of GM corn, cotton and soy on insectivorous birds, after inverse hyperbolic sine transformation. Dark and light bars indicating 90% and 95% confidence intervals respectively, and stars indicating p-values (* : $P < 0.1$, ** : $P < 0.05$, *** : $P < 0.01$).

Herbivores

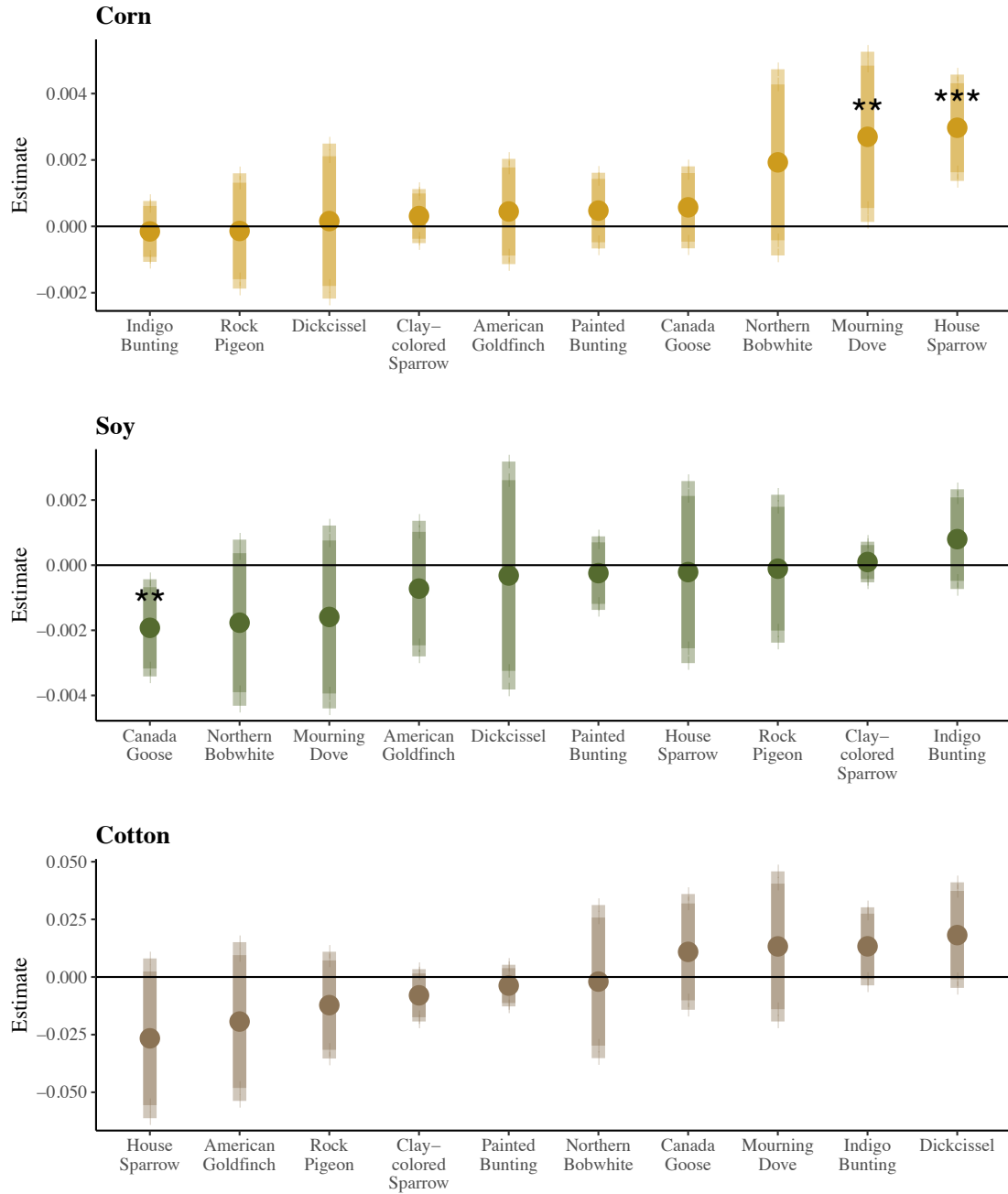


Figure I4: Estimated effect of GM corn, cotton and soy on herbivorous birds, after inverse hyperbolic sine transformation. Dark and light bars indicating 90% and 95% confidence intervals respectively, and stars indicating p-values (* : $P < 0.1$, ** : $P < 0.05$, *** : $P < 0.01$).

J Event study plots: placebo treatment 1981

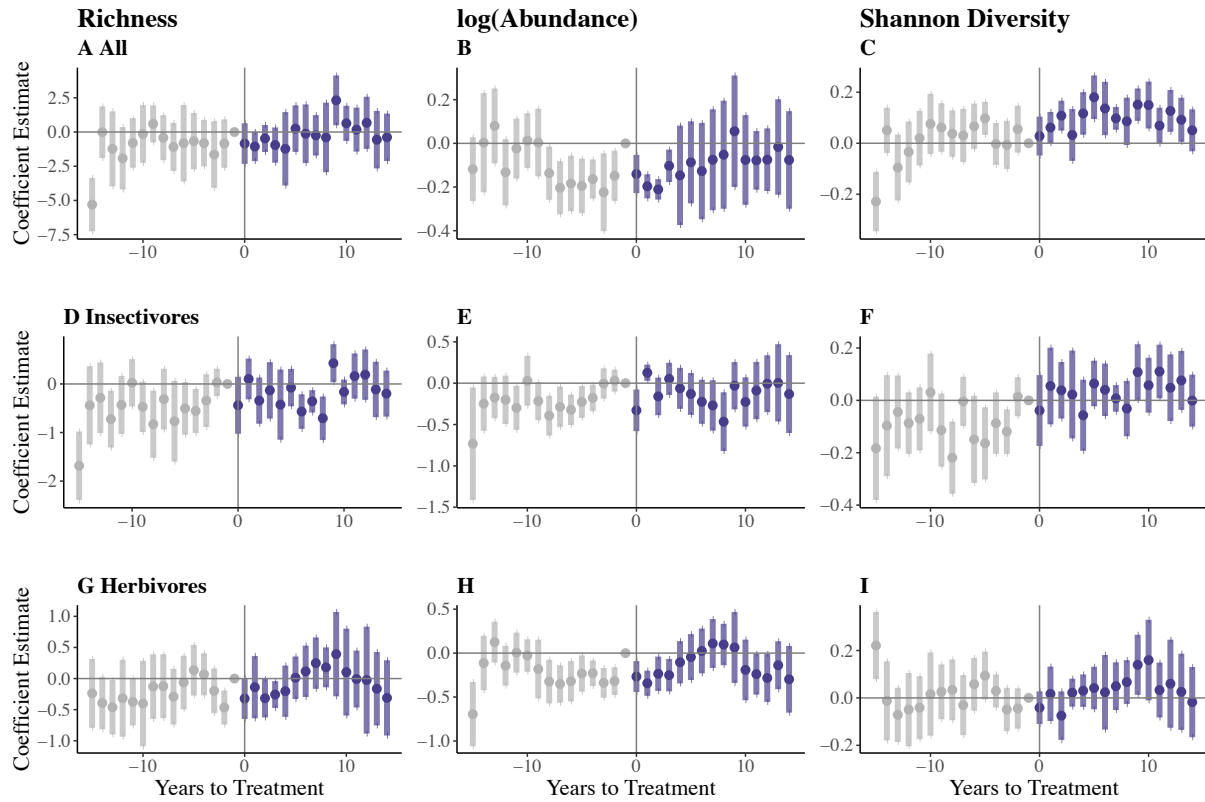


Figure J1: Dynamic overall effect of placebo-GM corn, soy and cotton on all, insectivorous and herbivorous birds. Exposure to corn, soy and cotton calculated as in main estimation, but 1981 defined as start of treatment. Bars indicating 95% confidence intervals, event time indicating years to 1981. Sample restricted to 15 years pre and post treatment, 1981-2010.

All birds

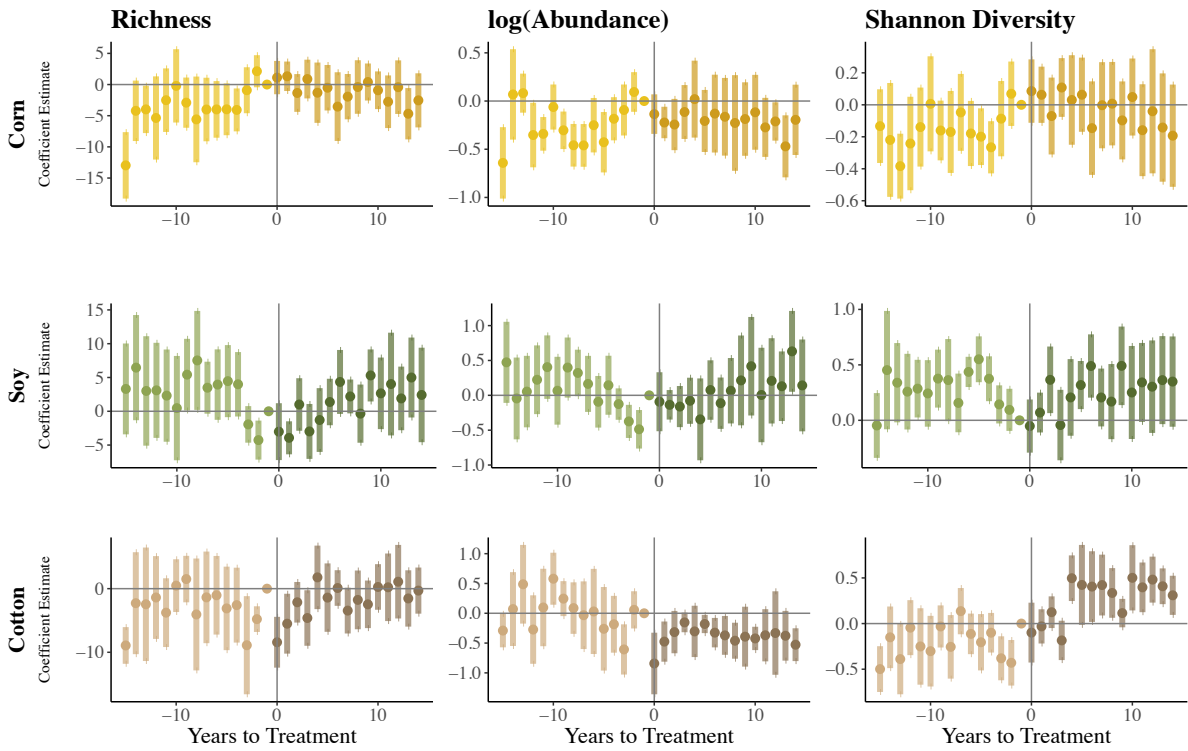


Figure J2: Dynamic crop-specific effects of placebo-GM corn (yellow), soy (green) and cotton (brown) varieties on all birds. Exposure to corn, soy and cotton calculated as in main estimation, but 1981 defined as start of treatment. Bars indicating 95% confidence intervals, event time indicating years to 1981. Sample restricted to 15 years pre and post treatment, 1967-1995.

Insectivores

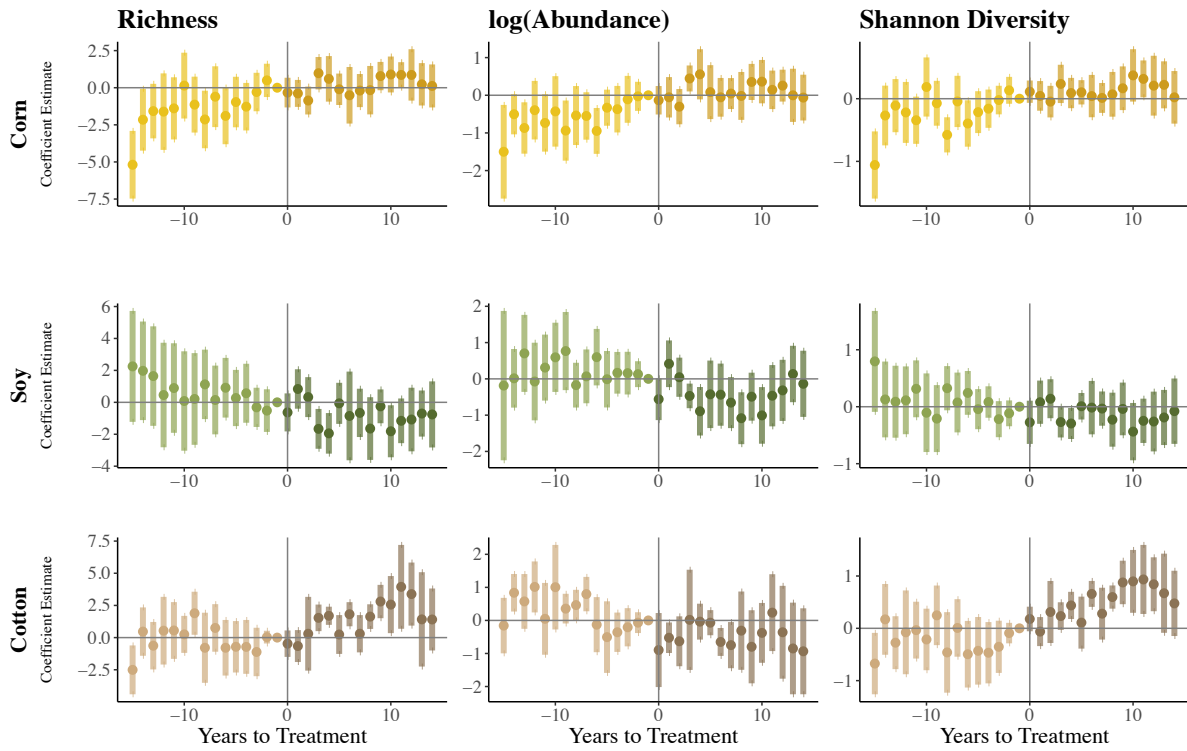


Figure J3: Dynamic crop-specific effects of placebo-GM corn (yellow), soy (green) and cotton (brown) varieties on insectivorous birds. Exposure to corn, soy and cotton calculated as in main estimation, but 1981 defined as start of treatment. Bars indicating 95% confidence intervals, event time indicating years to 1981. Sample restricted to 15 years pre and post treatment, 1967-1995.

Herbivores

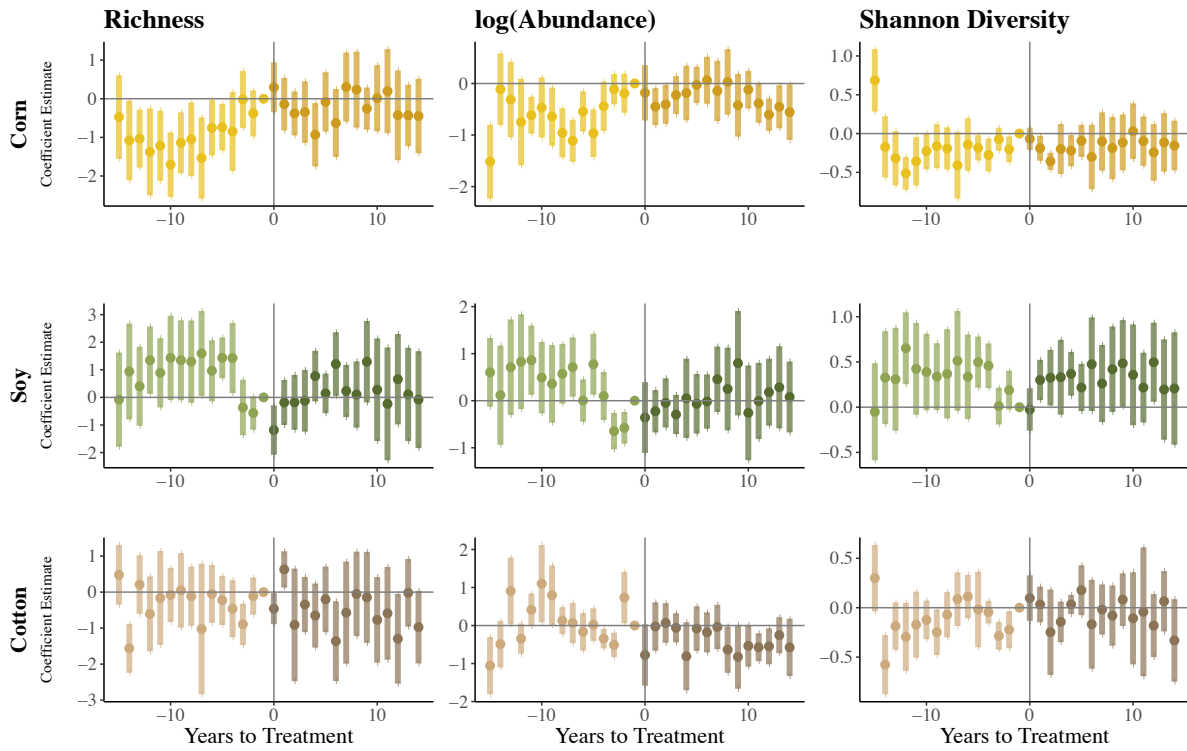


Figure J4: Dynamic crop-specific effects of placebo-GM corn (yellow), soy (green) and cotton (brown) varieties on herbivorous birds. Exposure to corn, soy and cotton calculated as in main estimation, but 1981 defined as start of treatment. Bars indicating 95% confidence intervals, event time indicating years to 1981. Sample restricted to 15 years pre and post treatment, 1967-1995.

K Event study plots: placebo treatment 2006

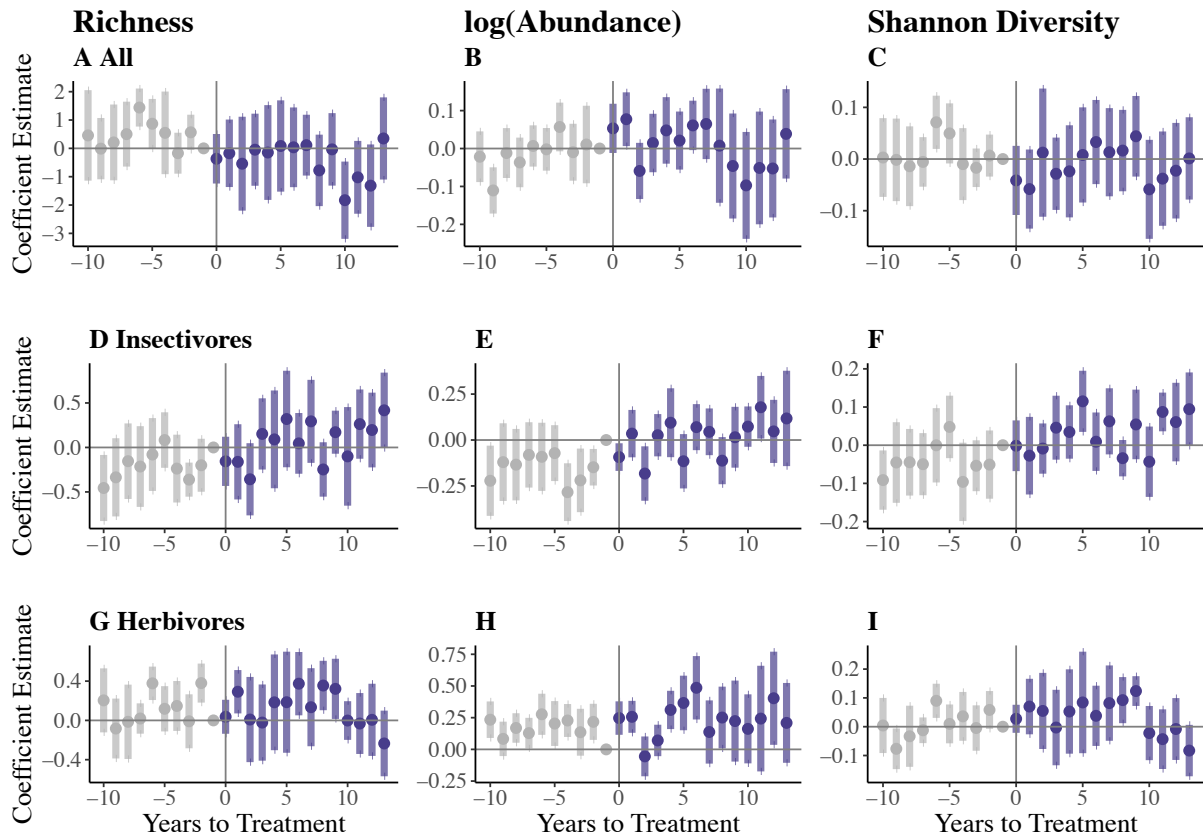


Figure K1: Dynamic overall effect of placebo-GM corn, soy and cotton on all, insectivorous and herbivorous birds. Exposure to corn, soy and cotton calculated as in main estimation, but 2006 defined as start of treatment. Bars indicating 95% confidence intervals, event time indicating years to 2006. Sample restricted to 1996 onwards.

All birds

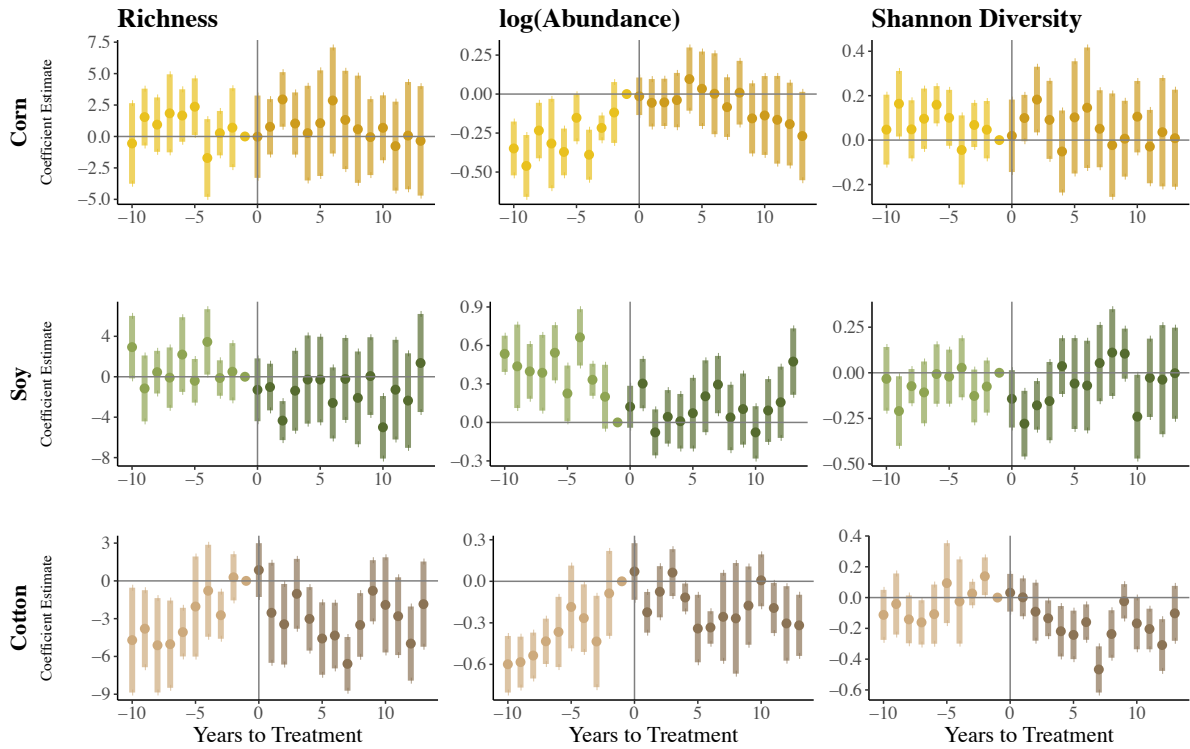


Figure K2: Dynamic crop-specific effects of placebo-GM corn (yellow), soy (green) and cotton (brown) varieties on all birds. Exposure to corn, soy and cotton calculated as in main estimation, but 2006 defined as start of treatment. Bars indicating 95% confidence intervals, event time indicating years to 2006. Sample restricted to 1996 onwards.

Insectivores

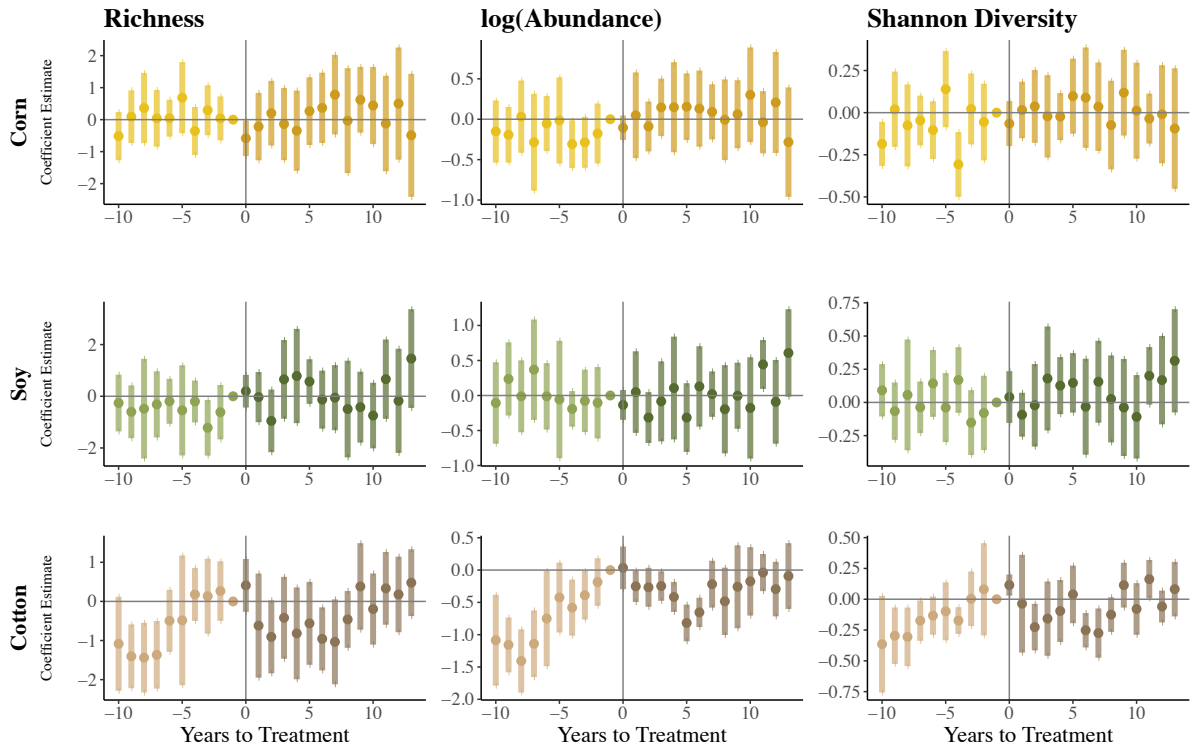


Figure K3: Dynamic crop-specific effects of placebo-GM corn (yellow), soy (green) and cotton (brown) varieties on insectivorous birds. Exposure to corn, soy and cotton calculated as in main estimation, but 2006 defined as start of treatment. Bars indicating 95% confidence intervals, event time indicating years to 2006. Sample restricted to 1996 onwards.

Herbivores

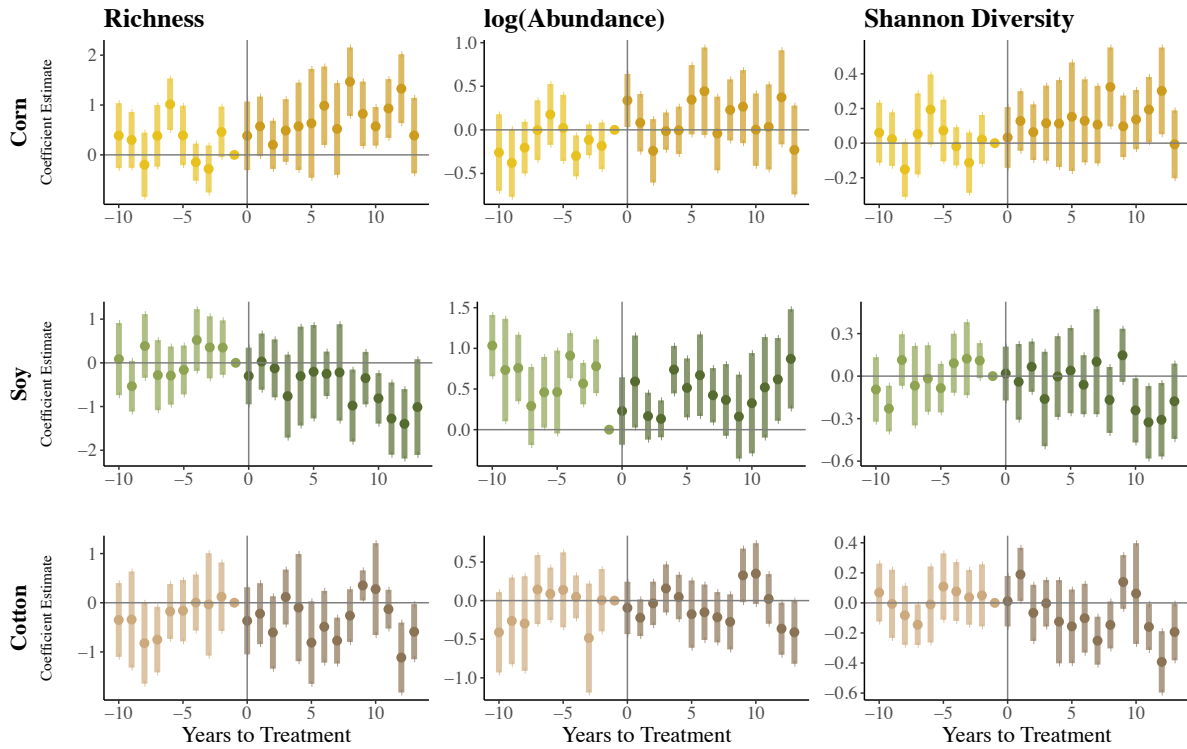


Figure K4: Dynamic crop-specific effects of placebo-GM corn (yellow), soy (green) and cotton (brown) varieties on herbivorous birds. Exposure to corn, soy and cotton calculated as in main estimation, but 2006 defined as start of treatment. Bars indicating 95% confidence intervals, event time indicating years to 2006. Sample restricted to 1996 onwards.

L Event study plots: all available years

Here, we present the results of the event study estimation over the entire time span. In the main results (Figure 4) and in Appendix H, only 20 years pre- and post-1996 are presented (but also estimated using all years).

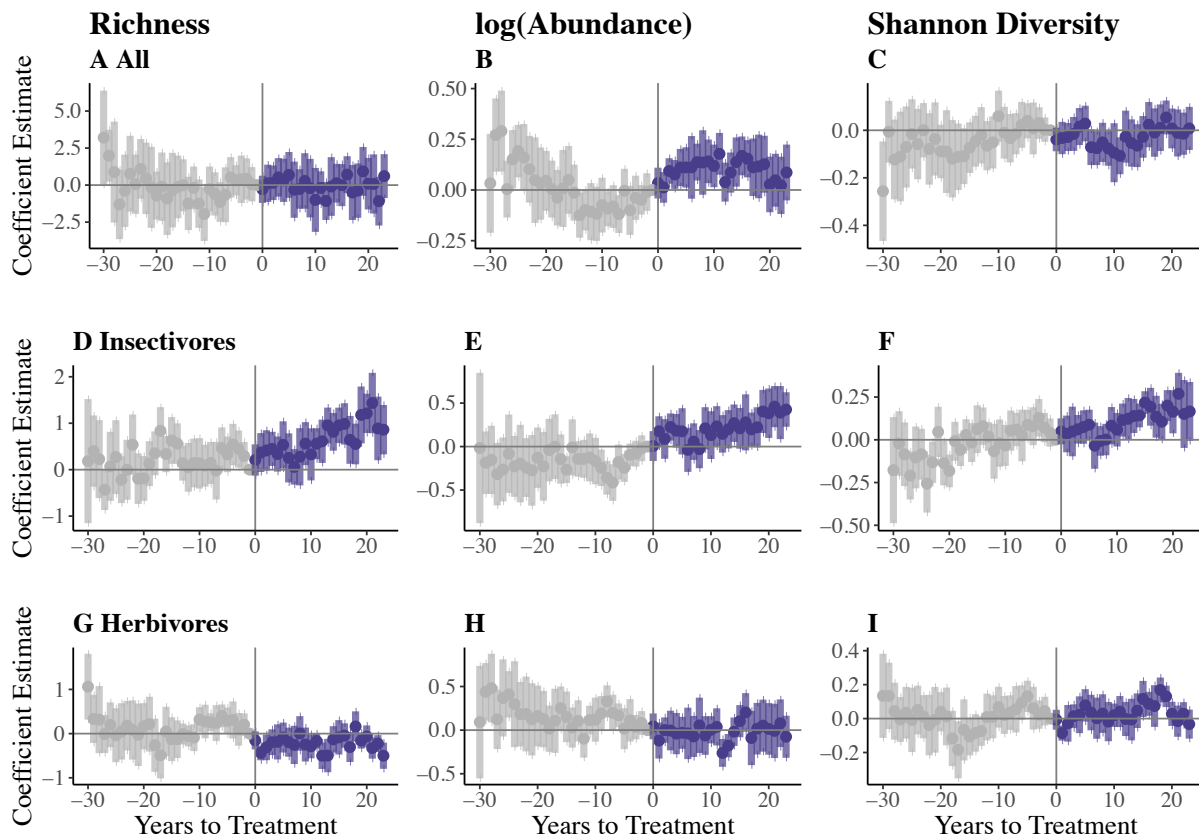


Figure L1: Dynamic crop-specific effects of GM crop varieties on all birds. Bars indicating 95% confidence intervals, event time indicating years to approval of GM corn, soy and cotton varieties in 1996.

All birds

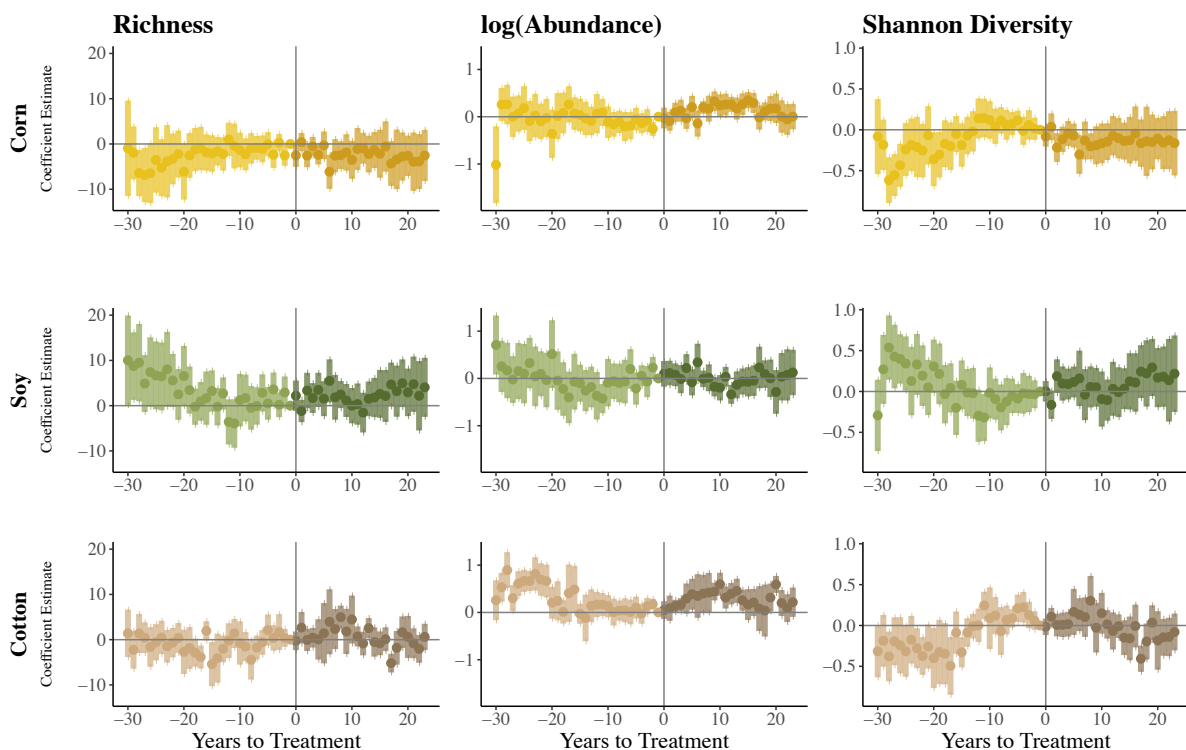


Figure L2: Dynamic crop-specific effects of GM corn (yellow), soy (green) and cotton (brown) varieties on all birds. Bars indicating 95% confidence intervals, event time indicating years to approval of GM corn, soy and cotton varieties in 1996.

Insectivores

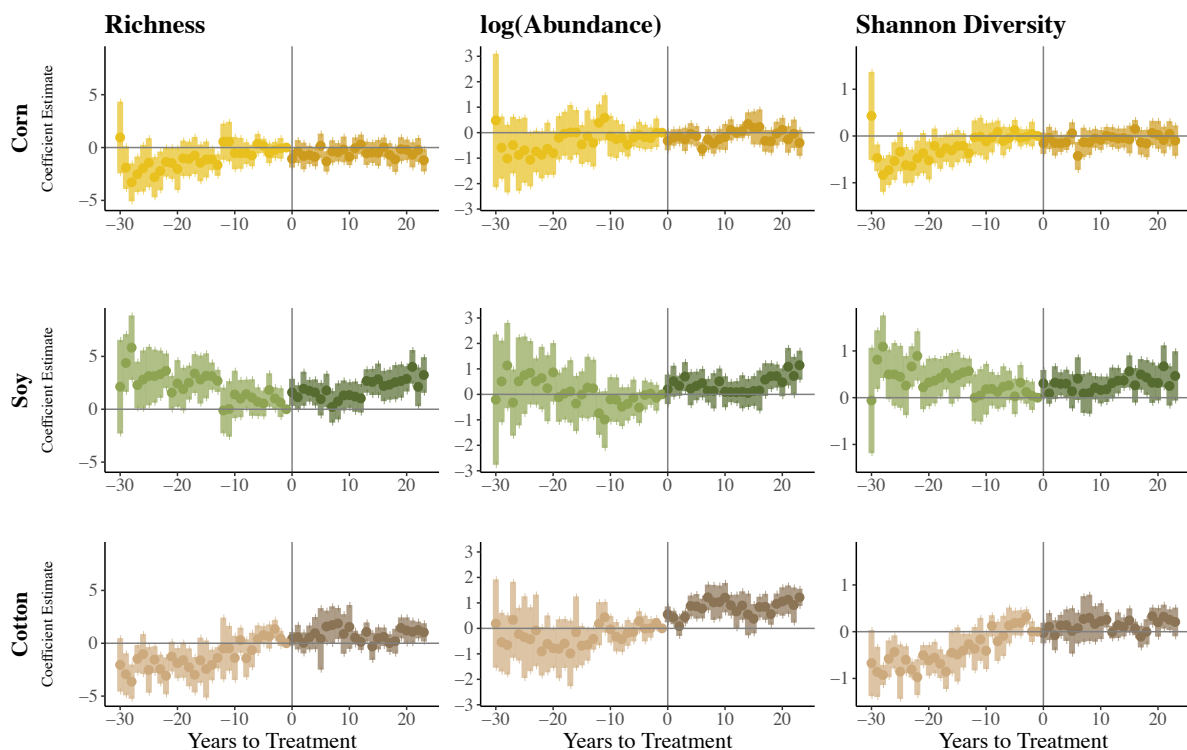


Figure L3: Dynamic crop-specific effects of GM corn (yellow), soy (green) and cotton (brown) varieties on insectivorous birds. Bars indicating 95% confidence intervals, event time indicating years to approval of GM corn, soy and cotton varieties in 1996.

Herbivores

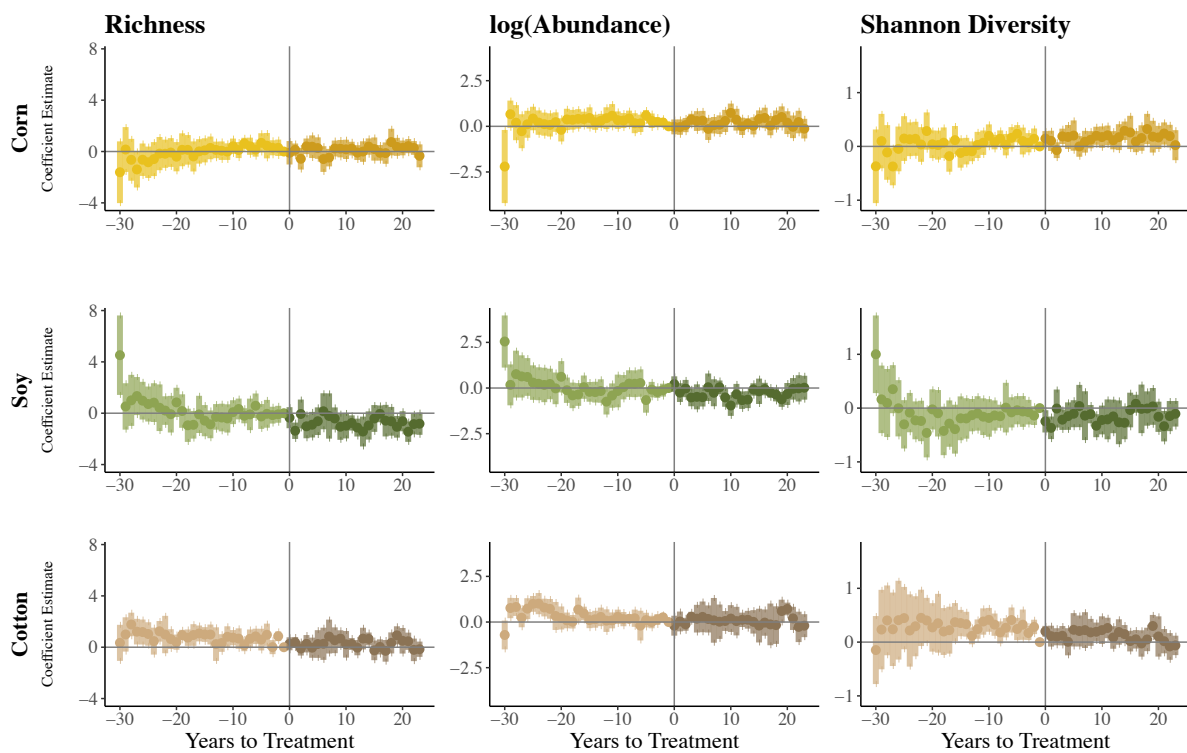


Figure L4: Dynamic crop-specific effects of GM corn (yellow), soy (green) and cotton (brown) varieties on herbivorous birds. Bars indicating 95% confidence intervals, event time indicating years to approval of GM corn, soy and cotton varieties in 1996.

M Estimation with varying cropland shares over time

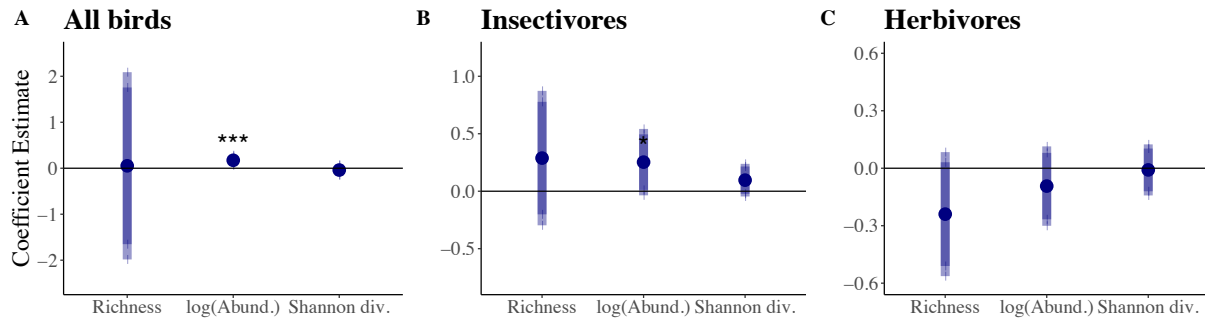


Figure M1: Overall effect of GM crops on all, insectivorous and herbivorous birds after matching with treatment calculated based on varying cropland shares between 1978 and 2012. Dark and light bars indicating 90% and 95% confidence intervals, respectively, and stars indicate p-values (* : $P < 0.1$, ** : $P < 0.05$, *** : $P < 0.01$).

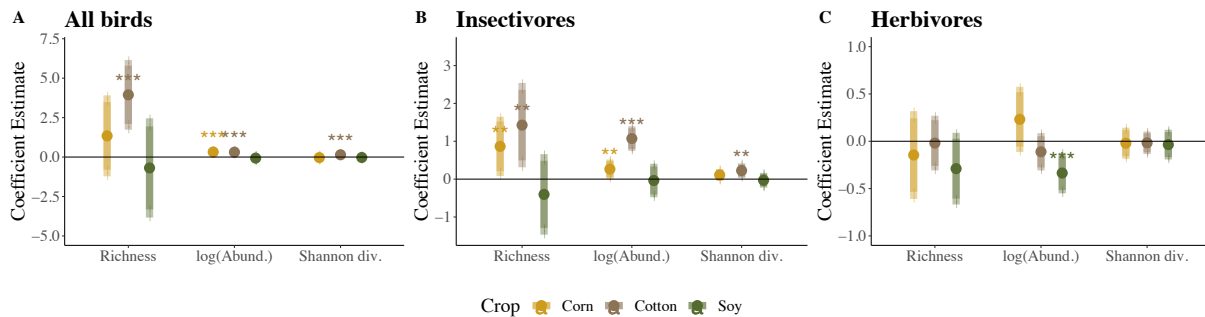


Figure M2: Effect of GM corn, soy and cotton on all, insectivorous and herbivorous birds after matching with treatment calculated based on varying cropland shares between 1978 and 2012. Dark and light bars indicating 90% and 95% confidence intervals respectively, and stars indicating p-values (* : $P < 0.1$, ** : $P < 0.05$, *** : $P < 0.01$).

N Estimation with sample split by body size

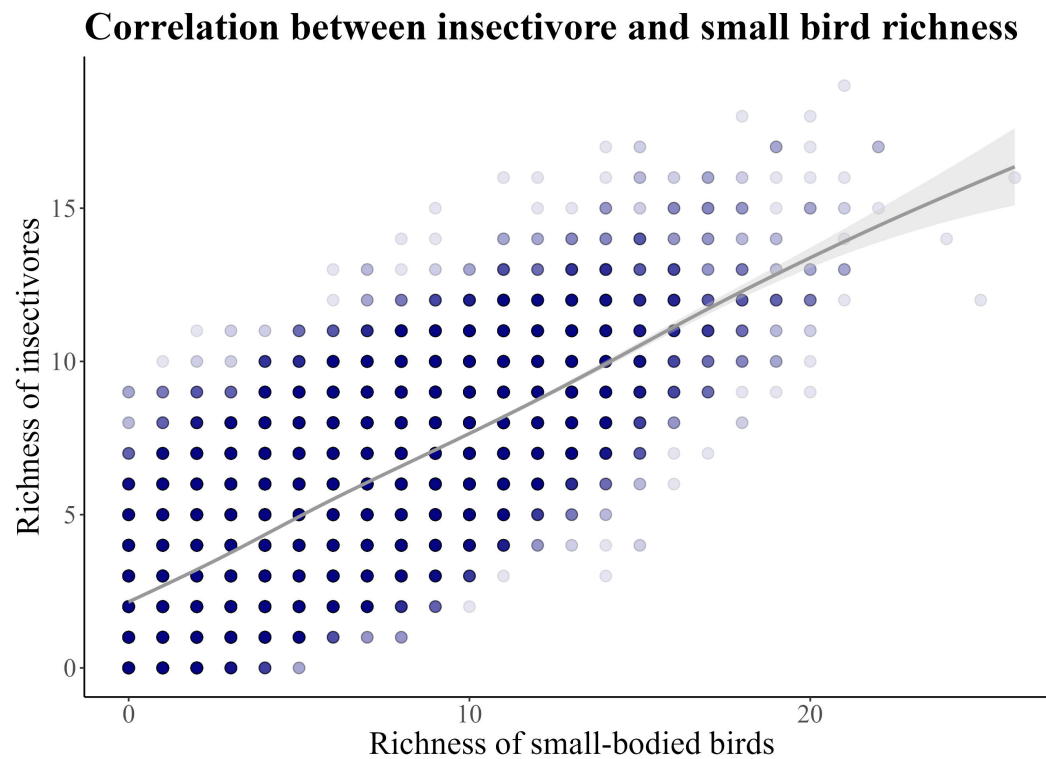


Figure N1: Correlation between richness of insectivorous (birds with a diet consisting of $\geq 80\%$ insects) and richness of small-bodied (birds in bottom quartile of body mass) birds in sample.

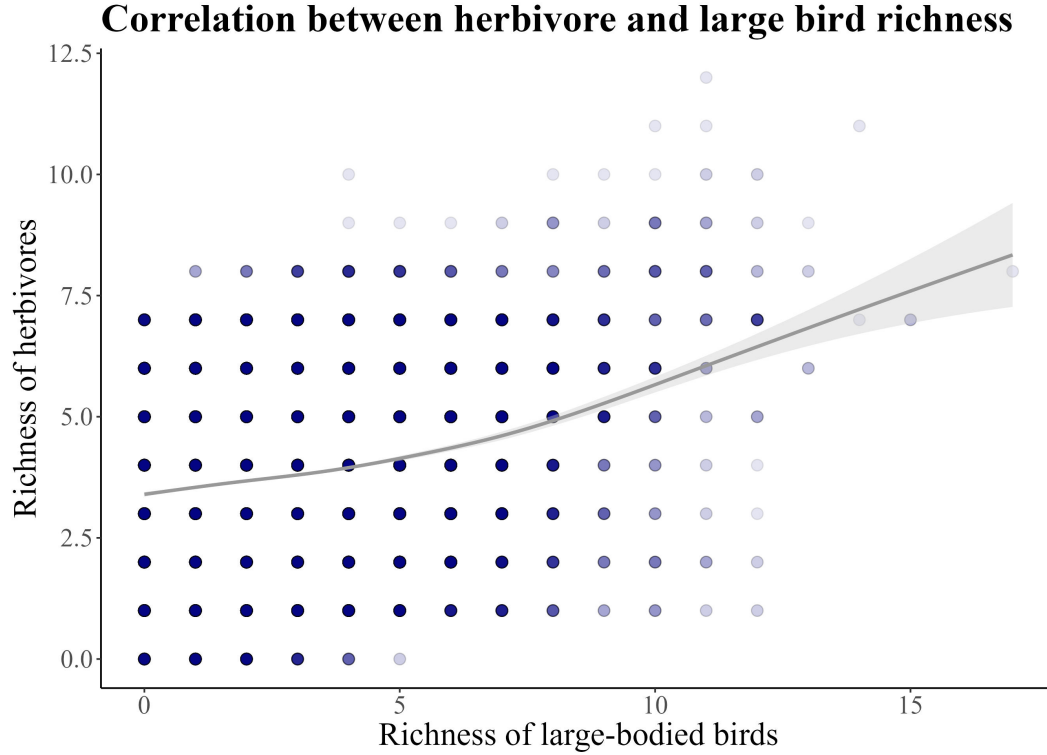


Figure N2: Correlation between richness of herbivores (birds with a diet consisting of $\geq 80\%$ plants and seeds) and richness of large-bodied (birds in top quartile of body mass) birds in sample.

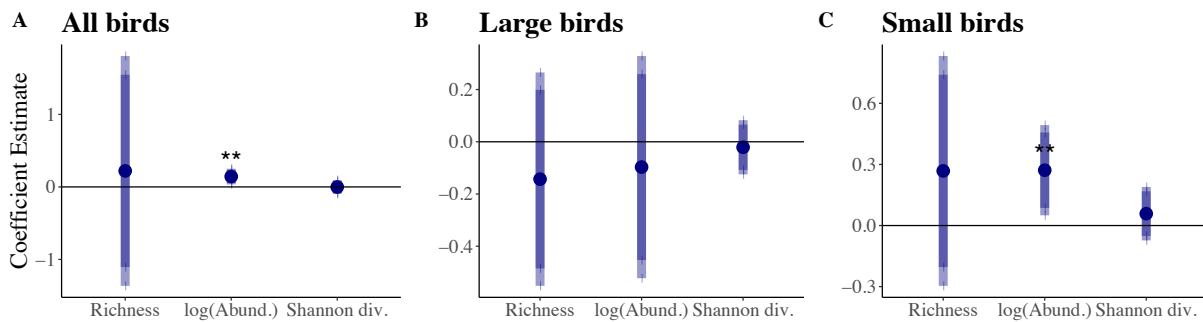


Figure N3: Overall effect of GM crops on all, large-bodied (body mass in top quartile) and small-bodied (body mass in bottom quartile) birds. Dark and light bars indicating 90% and 95% confidence intervals, respectively, and stars indicate p-values (* : $P < 0.1$, ** : $P < 0.05$, *** : $P < 0.01$).

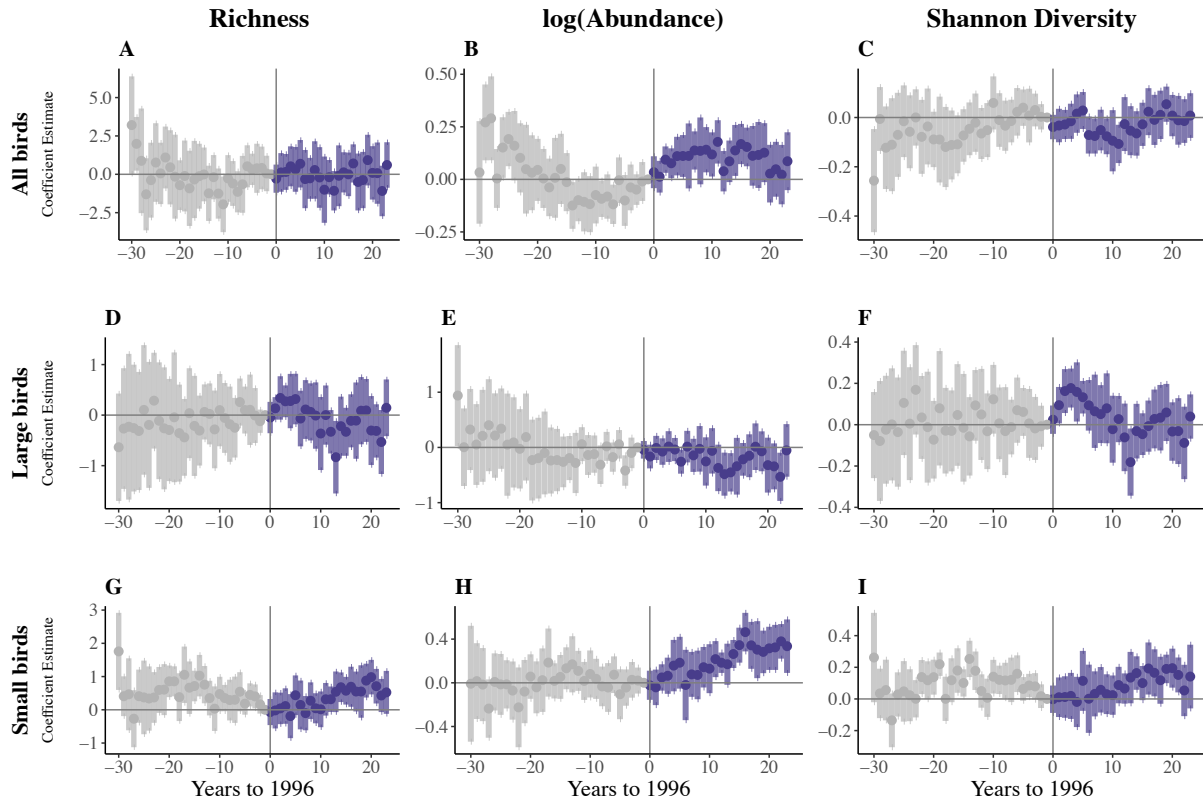


Figure N4: Dynamic overall effect of GM crops on all, large-bodied and small-bodied birds. Bars indicate 95% confidence intervals. Years to 1996 indicates years to and since commercialization of GM corn, soy and cotton varieties in 1996.

O Discussion of mechanisms

As we find positive impacts on insectivorous birds and slightly negative impacts on herbivorous birds, we test whether insecticides and herbicides provide insight into how adopting GM crops impacts bird communities. We use the USGS Pesticide National Synthesis Project data to quantify changes in the total amounts of active pesticide ingredients and then calculate a risk quotient by dividing the total amount of a pesticide active ingredient by its bird LD50 value (lethal dose 50, the amount in mg per kg body mass of an animal that kills 50% of individuals) [19, 10].

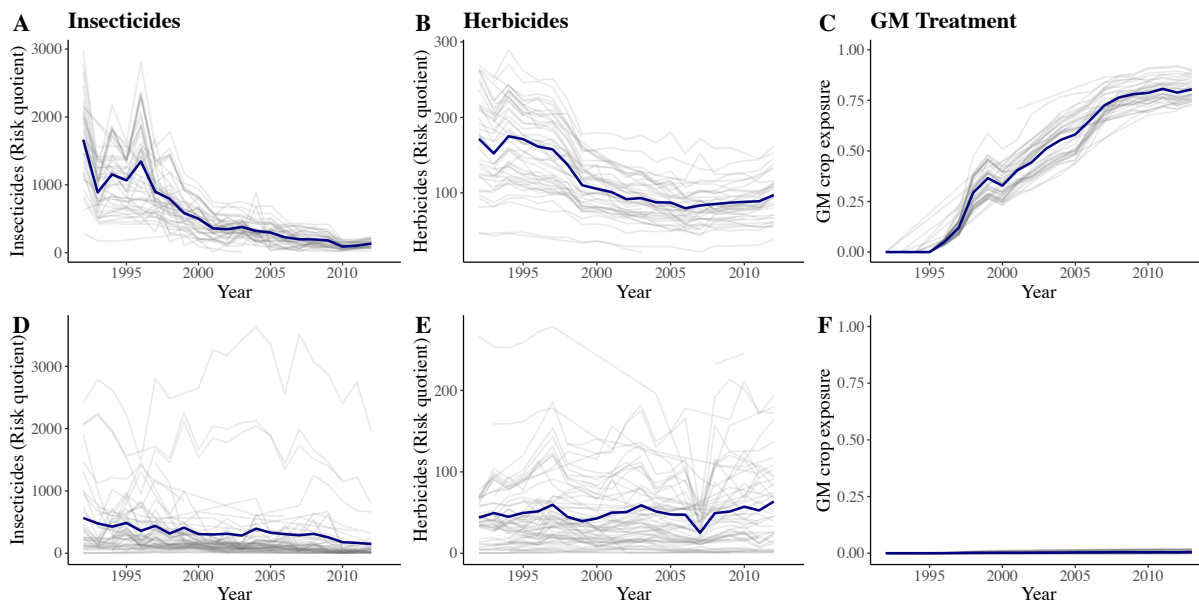


Figure O1: Insecticide and herbicide risk quotients, as well as exposure to GM treatment of observation routes in counties with a share of more than 80% corn, soy and cotton (top row) and ones with less than 2% corn, soy and cotton (bottom row). Average values in blue. Cutoffs chosen to visualize a broadly similar number of observations in each sample. Observations with a maximum value of insecticide, herbicide or glyphosate use in the top 1% were removed to filter out extreme outliers, for visualization purposes. Pesticide data are cut off in 2014, because from 2015 onwards data on neonicotinoid seed treatments are no longer collected.

To visualize the impact of the introduction of GM crops on pesticide toxicity, we compare the change in the pesticide risk quotient over time between BBS routes dominated by corn, soy, and cotton and routes in other areas (Fig. O1). GM crop exposure steeply increases

from 1996 onwards along BBS routes surrounded by high shares of corn, soy, and cotton (panel C), while it remains close to zero surrounding the other routes (panel F). We find that the insecticide risk quotient starts dropping off considerably after 1996 in areas that are highly exposed to GM crops (panel A), while it remains relatively constant with only a slight, continuous decrease in insecticide toxicity in areas with low GM crop exposure (panel D). The decrease in the insecticide risk quotient is substantial in high GM areas: it drops from around 1200 to around 200. Notably, before the introduction of GM crops, the insecticide risk quotient in high GM areas was about double the one in non-GM areas and decreased to about the same level afterward.

Looking at the development of the herbicide risk quotient, the pattern is less clear. There is also a pronounced drop after the introduction of GM crops in high GM areas (panel B), but it sets in only in 1998, decreasing from around 170 to 100. Still, on non-GM areas, the herbicide risk quotient stays largely the same over the same time period (panel E), so that the drop in herbicide risk quotient is a likely result of GM crops despite the delay of two years. These results are in line with previous findings. Bird lethality of pesticides on corn and cotton was reduced following GM crop adoption [22]. More recent research has similarly found a decrease in insecticide toxicity and a smaller initial decrease but a later reversal in herbicide toxicity [19], which is visible in panel A and B of Figure O1.

If we compare these trends to the overall amounts of insecticides and herbicides used (Appendix W, Fig. W2), we find that the reduction in insecticide toxicity closely corresponds to the reduction in pesticide amounts, indicating that the reduction in toxicity is mainly due to overall reduced pesticide applications. On the other hand, the reduction in total amounts of herbicides is considerably smaller in relative terms than the reduction in toxicity, pointing towards a shift in the types of pesticides as an underlying driver. This is in line with a large increase in glyphosate use in high GM areas after 1996, which likely replaced other, potentially more toxic, herbicides.

We also test the impact of GM crop adoption on pesticide toxicity using our main estimation's

Two-Way Fixed Effects model, with insecticide and herbicide toxicity as an outcome and GM crop adoption as a treatment variable. We find that insecticide toxicity is reduced on corn and cotton, but not soy (which we expected, as GM soy is only cultivated as HT varieties), and herbicide toxicity decreases on corn and soy (Appendix X, Fig. X1 and Fig. X2). Although we see from the coefficients in panel E, Fig. X1 that the pesticide toxicity trend was on a different trajectory for cotton compared to other crops prior to the introduction of GM varieties, which makes the interpretation challenging, the reduction in pesticide risk quotient per county following the adoption of GM cotton is of about the same magnitude as the reduction of the corn pesticide risk quotient, despite a smaller area being grown with cotton. Connecting these results to the effects of GM crops on bird populations, two possible pathways of pesticide impacts appear likely. First, GM crop adoption could lead to larger survival rates of non-target insects and increase available resources to birds if the Bt trait allows more targeted protection against pest insects and thus reduces overall toxicity to insects. Second, the reduction in pesticide toxicity to birds could mean that birds are exposed to lower levels of toxicity. As insectivorous birds generally have lower body mass than herbivorous birds and are therefore more susceptible to toxic pesticides, the positive effect on insectivorous birds we observe is in line with both pathways (see Appendix N, Fig. N1 and Fig. N2 for correlations between diet- and body size-specific bird richness). In addition, we also show that splitting the sample into large- and small-bodied birds instead of herbivorous and insectivorous birds yields largely the same results: a positive effect of GM crops on small-bodied birds and a negative but insignificant effect on large-bodied birds (Appendix N, Fig. N3 and Fig. N4).

One way to test pesticide toxicity as measured through LD50 values as a mechanism is to include it as a control variable in estimating GM crop impacts on bird outcomes. The pesticide toxicity variable would absorb the variation in bird populations that are associated with GM crops and cause the coefficients of GM crop exposure (i.e., the treatment variable in the main estimation) to shift toward zero if pesticides are the main mechanism that relates

GM crops to bird diversity. However, we don't observe the convergence of the direct GM crop effect towards zero after including pesticide toxicity, which is either due to compounding measurement error in the pesticide data or due to pesticide toxicity working through pathways that are not well measured using LD50 values (see Appendix X for a thorough discussion).

In a final step, we also examine the impact of GM crops on crop diversity as measured by crop richness and crop Shannon index. We don't find conclusive evidence on the impact of GM crops on either of these indices (Appendix Y, Fig. Y1 and Fig. Y2), which suggests that changes in crop diversity are not the primary driver of the bird impacts we observe.

P Estimation by family

We estimate the impact of GM crops on richness, abundance and Shannon diversity of the 10 most common bird families in the sample. The families are chosen in two steps: first, only families with at least 10 species are considered. Second, those families are sorted by bird abundance, and the ten families with the highest abundances are chosen. Then, richness, abundance and Shannon diversity within those families are calculated, and these indices used as outcomes in the estimations using equations (2) and (5).

Table P1: Families with ≥ 10 species.

	Family	Number of species in family
1	Anatidae	48
2	Parulidae	47
3	Scolopacidae	40
4	Tyrannidae	35
5	Laridae	33
6	Passerellidae	27
7	Accipitridae	24
8	Picidae	24
9	Icteridae	22
10	Corvidae	20
11	Strigidae	18
12	Fringillidae	17
13	Phasianidae	17
14	Cardinalidae	15
15	Ardeidae	14
16	Emberizidae	14
17	Trochilidae	14
18	Columbidae	13
19	Vireonidae	13
20	Alcidae	12
21	Turdidae	12
22	Mimidae	11
23	Paridae	11
24	Rallidae	11
25	Troglodytidae	11
26	Charadriidae	10

Table P2: Mean abundances of the 10 most common families at BBS routes.

Family	Mean abundance
Icteridae	50.87
Columbidae	14.35
Cardinalidae	11.22
Passerellidae	10.56
Tyrannidae	5.23
Mimidae	4.52
Corvidae	4.37
Turdidae	4.28
Troglodytidae	2.21
Parulidae	2.10

Table P3: Bird species in each of the 10 most common families.

Family	Species	English
Cardinalidae	<i>Piranga flava</i>	Hepatic Tanager
Cardinalidae	<i>Piranga hepatica</i>	Hepatic Tanager
Cardinalidae	<i>Piranga rubra</i>	Summer Tanager
Cardinalidae	<i>Piranga olivacea</i>	Scarlet Tanager
Cardinalidae	<i>Piranga ludoviciana</i>	Western Tanager
Cardinalidae	<i>Cardinalis cardinalis</i>	Northern Cardinal
Cardinalidae	<i>Cardinalis sinuatus</i>	Pyrrhuloxia
Cardinalidae	<i>Pheucticus ludovicianus</i>	Rose-breasted Grosbeak
Cardinalidae	<i>Pheucticus melanocephalus</i>	Black-headed Grosbeak
Cardinalidae	<i>Passerina caerulea</i>	Blue Grosbeak
Cardinalidae	<i>Passerina amoena</i>	Lazuli Bunting
Cardinalidae	<i>Passerina cyanea</i>	Indigo Bunting
Cardinalidae	<i>Passerina versicolor</i>	Varied Bunting
Cardinalidae	<i>Passerina ciris</i>	Painted Bunting
Cardinalidae	<i>Spiza americana</i>	Dickcissel
Columbidae	<i>Columba livia</i>	Rock Pigeon
Columbidae	<i>Patagioenas leucocephala</i>	White-crowned Pigeon
Columbidae	<i>Patagioenas flavirostris</i>	Red-billed Pigeon
Columbidae	<i>Patagioenas fasciata</i>	Band-tailed Pigeon
Columbidae	<i>Columbina inca</i>	Inca Dove
Columbidae	<i>Leptotila verreauxi</i>	White-tipped Dove
Columbidae	<i>Zenaida asiatica</i>	White-winged Dove
Columbidae	<i>Zenaida macroura</i>	Mourning Dove
Columbidae	<i>Streptopelia decaocto</i>	
Columbidae	<i>Streptopelia roseogrisea</i>	
Columbidae	<i>Columbina passerina</i>	
Columbidae	<i>Columbina talpacoti</i>	
Columbidae	<i>Stigmatopelia chinensis</i>	Spotted Dove
Corvidae	<i>Cyanocorax luxuosus</i>	Green Jay
Corvidae	<i>Cyanocorax yncas</i>	Green Jay
Corvidae	<i>Gymnorhinus cyanocephalus</i>	Pinyon Jay
Corvidae	<i>Cyanocitta stelleri</i>	Steller's Jay
Corvidae	<i>Cyanocitta cristata</i>	Blue Jay
Corvidae	<i>Aphelocoma ultramarina</i>	Mexican Jay
Corvidae	<i>Nucifraga columbiana</i>	Clark's Nutcracker
Corvidae	<i>Pica pica</i>	Black-billed Magpie
Corvidae	<i>Pica hudsonia</i>	Black-billed Magpie
Corvidae	<i>Pica nuttalli</i>	Yellow-billed Magpie
Corvidae	<i>Corvus brachyrhynchos</i>	American Crow
Corvidae	<i>Corvus ossifragus</i>	Fish Crow
Corvidae	<i>Corvus cryptoleucus</i>	Chihuahuan Raven
Corvidae	<i>Corvus corax</i>	Common Raven
Corvidae	<i>Aphelocoma californica</i>	
Corvidae	<i>Aphelocoma woodhouseii</i>	
Corvidae	<i>Perisoreus canadensis</i>	
Corvidae	<i>Aphelocoma coerulescens</i>	
Corvidae	<i>Aphelocoma insularis</i>	
Corvidae	<i>Corvus caurinus</i>	

Family	Species	English
Icteridae	<i>Xanthocephalus xanthocephalus</i>	Yellow-headed Blackbird
Icteridae	<i>Dolichonyx oryzivorus</i>	Bobolink
Icteridae	<i>Sturnella magna</i>	Eastern Meadowlark
Icteridae	<i>Sturnella neglecta</i>	Western Meadowlark
Icteridae	<i>Icterus spurius</i>	Orchard Oriole
Icteridae	<i>Icterus cucullatus</i>	Hooded Oriole
Icteridae	<i>Icterus bullockii</i>	Bullock's Oriole
Icteridae	<i>Icterus pectoralis</i>	Spot-breasted Oriole
Icteridae	<i>Icterus gularis</i>	Altamira Oriole
Icteridae	<i>Icterus graduacauda</i>	Audubon's Oriole
Icteridae	<i>Icterus galbula</i>	Baltimore Oriole
Icteridae	<i>Icterus parisorum</i>	Scott's Oriole
Icteridae	<i>Agelaius phoeniceus</i>	Red-winged Blackbird
Icteridae	<i>Molothrus bonariensis</i>	Shiny Cowbird
Icteridae	<i>Molothrus aeneus</i>	Bronzed Cowbird
Icteridae	<i>Molothrus ater</i>	Brown-headed Cowbird
Icteridae	<i>Euphagus carolinus</i>	Rusty Blackbird
Icteridae	<i>Euphagus cyanocephalus</i>	Brewer's Blackbird
Icteridae	<i>Quiscalus quiscula</i>	Common Grackle
Icteridae	<i>Quiscalus major</i>	Boat-tailed Grackle
Icteridae	<i>Quiscalus mexicanus</i>	Great-tailed Grackle
Icteridae	<i>Agelaius tricolor</i>	
Mimidae	<i>Toxostoma curvirostre</i>	Curve-billed Thrasher
Mimidae	<i>Toxostoma rufum</i>	Brown Thrasher
Mimidae	<i>Toxostoma longirostre</i>	Long-billed Thrasher
Mimidae	<i>Toxostoma bendirei</i>	Bendire's Thrasher
Mimidae	<i>Toxostoma redivivum</i>	California Thrasher
Mimidae	<i>Toxostoma crissale</i>	Crissal Thrasher
Mimidae	<i>Oreoscoptes montanus</i>	Sage Thrasher
Mimidae	<i>Mimus gundlachii</i>	Bahama Mockingbird
Mimidae	<i>Mimus polyglottos</i>	Northern Mockingbird
Mimidae	<i>Dumetella carolinensis</i>	
Mimidae	<i>Toxostoma lecontei</i>	
Parulidae	<i>Icteria virens</i>	Yellow-breasted Chat
Parulidae	<i>Seiurus aurocapilla</i>	Ovenbird
Parulidae	<i>Helmitheros vermivorum</i>	Worm-eating Warbler
Parulidae	<i>Vermivora chrysoptera</i>	Golden-winged Warbler
Parulidae	<i>Mniotilta varia</i>	Black-and-white Warbler
Parulidae	<i>Protonotaria citrea</i>	Prothonotary Warbler
Parulidae	<i>Limnothlypis swainsonii</i>	Swainson's Warbler
Parulidae	<i>Oporornis agilis</i>	Connecticut Warbler
Parulidae	<i>Geothlypis trichas</i>	Common Yellowthroat
Parulidae	<i>Setophaga ruticilla</i>	American Redstart
Parulidae	<i>Cardellina rubrifrons</i>	Red-faced Warbler
Parulidae	<i>Myioborus pictus</i>	Painted Redstart

Family	Species	English
Parulidae	<i>Seiurus motacilla</i>	Louisiana Waterthrush
Parulidae	<i>Seiurus noveboracensis</i>	Northern Waterthrush
Parulidae	<i>Vermivora pinus</i>	Blue-winged Warbler
Parulidae	<i>Vermivora peregrina</i>	Tennessee Warbler
Parulidae	<i>Vermivora celata</i>	Orange-crowned Warbler
Parulidae	<i>Vermivora luciae</i>	Lucy's Warbler
Parulidae	<i>Vermivora ruficapilla</i>	Nashville Warbler
Parulidae	<i>Vermivora virginiae</i>	Virginia's Warbler
Parulidae	<i>Oporornis tolmiei</i>	MacGillivray's Warbler
Parulidae	<i>Oporornis philadelphia</i>	Mourning Warbler
Parulidae	<i>Oporornis formosus</i>	Kentucky Warbler
Parulidae	<i>Wilsonia citrina</i>	Hooded Warbler
Parulidae	<i>Dendroica kirtlandii</i>	Kirtland's Warbler
Parulidae	<i>Dendroica tigrina</i>	Cape May Warbler
Parulidae	<i>Dendroica cerulea</i>	Cerulean Warbler
Parulidae	<i>Parula americana</i>	Northern Parula
Parulidae	<i>Parula pityayumi</i>	Tropical Parula
Parulidae	<i>Dendroica magnolia</i>	Magnolia Warbler
Parulidae	<i>Dendroica castanea</i>	Bay-breasted Warbler
Parulidae	<i>Dendroica fusca</i>	Blackburnian Warbler
Parulidae	<i>Dendroica petechia</i>	Yellow Warbler
Parulidae	<i>Dendroica pensylvanica</i>	Chestnut-sided Warbler
Parulidae	<i>Dendroica striata</i>	Blackpoll Warbler
Parulidae	<i>Dendroica caerulescens</i>	Black-throated Blue Warbler
Parulidae	<i>Dendroica palmarum</i>	Palm Warbler
Parulidae	<i>Dendroica pinus</i>	Pine Warbler
Parulidae	<i>Dendroica dominica</i>	Yellow-throated Warbler
Parulidae	<i>Dendroica discolor</i>	Prairie Warbler
Parulidae	<i>Dendroica graciae</i>	Grace's Warbler
Parulidae	<i>Dendroica townsendi</i>	Townsend's Warbler
Parulidae	<i>Dendroica occidentalis</i>	Hermit Warbler
Parulidae	<i>Dendroica chrysoparia</i>	Golden-cheeked Warbler
Parulidae	<i>Dendroica virens</i>	Black-throated Green Warbler
Parulidae	<i>Wilsonia canadensis</i>	Canada Warbler
Parulidae	<i>Wilsonia pusilla</i>	Wilson's Warbler
Passerellidae	<i>Ammodramus savannarum</i>	Grasshopper Sparrow
Passerellidae	<i>Arremonops rufivirgatus</i>	Olive Sparrow
Passerellidae	<i>Amphispiza bilineata</i>	Black-throated Sparrow
Passerellidae	<i>Chondestes grammacus</i>	Lark Sparrow
Passerellidae	<i>Calamospiza melanocorys</i>	Lark Bunting
Passerellidae	<i>Spizella passerina</i>	Chipping Sparrow
Passerellidae	<i>Spizella atrogularis</i>	Black-chinned Sparrow
Passerellidae	<i>Spizella pusilla</i>	Field Sparrow
Passerellidae	<i>Spizella breweri</i>	Brewer's Sparrow
Passerellidae	<i>Passerella iliaca</i>	Fox Sparrow
Passerellidae	<i>Junco phaeonotus</i>	Yellow-eyed Junco
Passerellidae	<i>Zonotrichia leucophrys</i>	White-crowned Sparrow
Passerellidae	<i>Zonotrichia atricapilla</i>	Golden-crowned Sparrow
Passerellidae	<i>Zonotrichia querula</i>	Harris's Sparrow
Passerellidae	<i>Zonotrichia albicollis</i>	White-throated Sparrow
Passerellidae	<i>Pooecetes gramineus</i>	Vesper Sparrow
Passerellidae	<i>Passerculus sandwichensis</i>	Savannah Sparrow
Passerellidae	<i>Melospiza melodia</i>	Song Sparrow
Passerellidae	<i>Melospiza lincolni</i>	Lincoln's Sparrow
Passerellidae	<i>Melospiza georgiana</i>	Swamp Sparrow
Passerellidae	<i>Aimophila ruficeps</i>	Rufous-crowned Sparrow
Passerellidae	<i>Pipilo chlorurus</i>	Green-tailed Towhee
Passerellidae	<i>Pipilo maculatus</i>	Spotted Towhee
Passerellidae	<i>Pipilo erythrophthalmus</i>	Eastern Towhee
Passerellidae	<i>Spizella pallida</i>	
Passerellidae	<i>Ammodramus lecontei</i>	

Family	Species	English
Troglodytidae	Salpinctes obsoletus	Rock Wren
Troglodytidae	Catherpes mexicanus	Canyon Wren
Troglodytidae	Troglodytes aedon	House Wren
Troglodytidae	Troglodytes troglodytes	Winter Wren
Troglodytidae	Cistothorus platensis	Sedge Wren
Troglodytidae	Cistothorus palustris	Marsh Wren
Troglodytidae	Thryothorus ludovicianus	Carolina Wren
Troglodytidae	Thryomanes bewickii	Bewick's Wren
Troglodytidae	Campylorhynchus brunneicapillus	Cactus Wren
Troglodytidae	Troglodytes pacificus	
Troglodytidae	Thryothorus sinaloa	Sinaloa Wren
Turdidae	Sialia sialis	Eastern Bluebird
Turdidae	Sialia mexicana	Western Bluebird
Turdidae	Sialia currucoides	Mountain Bluebird
Turdidae	Myadestes townsendi	Townsend's Solitaire
Turdidae	Catharus fuscescens	Veery
Turdidae	Catharus bicknelli	Bicknell's Thrush
Turdidae	Catharus ustulatus	Swainson's Thrush
Turdidae	Catharus guttatus	Hermit Thrush
Turdidae	Hylocichla mustelina	Wood Thrush
Turdidae	Turdus migratorius	American Robin
Turdidae	Catharus minimus	
Turdidae	Zoothera naevia	Varied Thrush
Tyrannidae	Myiarchus tuberculifer	Dusky-capped Flycatcher
Tyrannidae	Myiarchus cinerascens	Ash-throated Flycatcher
Tyrannidae	Myiarchus crinitus	Great Crested Flycatcher
Tyrannidae	Myiarchus tyrannulus	Brown-crested Flycatcher
Tyrannidae	Pitangus sulphuratus	Great Kiskadee
Tyrannidae	Myiodynastes luteiventris	Sulphur-bellied Flycatcher
Tyrannidae	Tyrannus melancholicus	Tropical Kingbird
Tyrannidae	Tyrannus couchii	Couch's Kingbird
Tyrannidae	Tyrannus vociferans	Cassin's Kingbird
Tyrannidae	Tyrannus crassirostris	Thick-billed Kingbird
Tyrannidae	Tyrannus verticalis	Western Kingbird
Tyrannidae	Tyrannus tyrannus	Eastern Kingbird
Tyrannidae	Tyrannus forficatus	Scissor-tailed Flycatcher
Tyrannidae	Tyrannus savana	Fork-tailed Flycatcher
Tyrannidae	Contopus cooperi	Olive-sided Flycatcher
Tyrannidae	Contopus pertinax	Greater Pewee
Tyrannidae	Empidonax flaviventris	Yellow-bellied Flycatcher
Tyrannidae	Empidonax virescens	Acadian Flycatcher
Tyrannidae	Empidonax alnorum	Alder Flycatcher
Tyrannidae	Empidonax traillii	Willow Flycatcher
Tyrannidae	Empidonax minimus	Least Flycatcher
Tyrannidae	Empidonax hammondi	Hammond's Flycatcher
Tyrannidae	Empidonax difficilis	Pacific-slope Flycatcher
Tyrannidae	Empidonax occidentalis	Cordilleran Flycatcher
Tyrannidae	Empidonax fulvifrons	Buff-breasted Flycatcher
Tyrannidae	Sayornis nigricans	Black Phoebe
Tyrannidae	Sayornis phoebe	Eastern Phoebe
Tyrannidae	Sayornis saya	Say's Phoebe
Tyrannidae	Pyrocephalus rubinus	Vermilion Flycatcher
Tyrannidae	Contopus sordidulus	
Tyrannidae	Sayornis phoebe	Eastern Phoebe
Tyrannidae	Camptostoma imberbe	
Tyrannidae	Tyrannus dominicensis	
Tyrannidae	Contopus virens	
Tyrannidae	Empidonax wrightii	

Table P4: Average share of insects in diet across species of each family, average share of plants and seeds in diet across species of each family and average body mass across species of each family.

	Family	Insectivorous diet (%)	Herbivorous diet (%)	Body mass (g)
1	Cardinalidae	48.00	41.33	29.12
2	Columbidae	3.33	74.44	206.31
3	Corvidae	25.00	19.29	247.77
4	Icteridae	63.33	17.62	62.61
5	Mimidae	56.67	8.89	65.08
6	Parulidae	84.26	2.98	10.93
7	Passerellidae	37.50	52.92	23.68
8	Troglodytidae	83.00	5.00	15.16
9	Turdidae	60.91	5.45	40.27
10	Tyrannidae	82.00	3.00	26.85

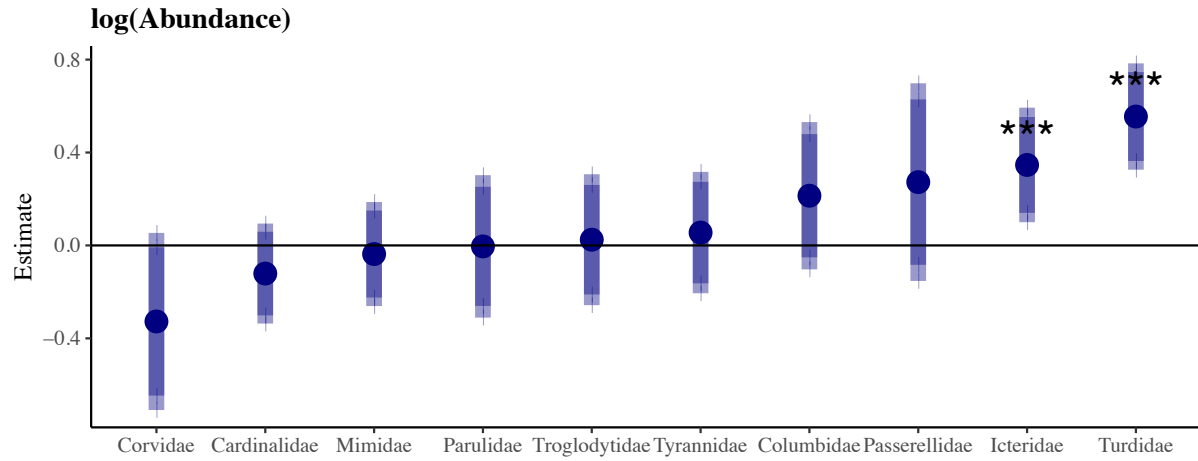


Figure P1: Overall effect of GM crops on birds of the 10 most common families in the sample. Dark and light bars indicating 90% and 95% confidence intervals, respectively, and stars indicate p-values (* : $P < 0.1$, ** : $P < 0.05$, *** : $P < 0.01$).

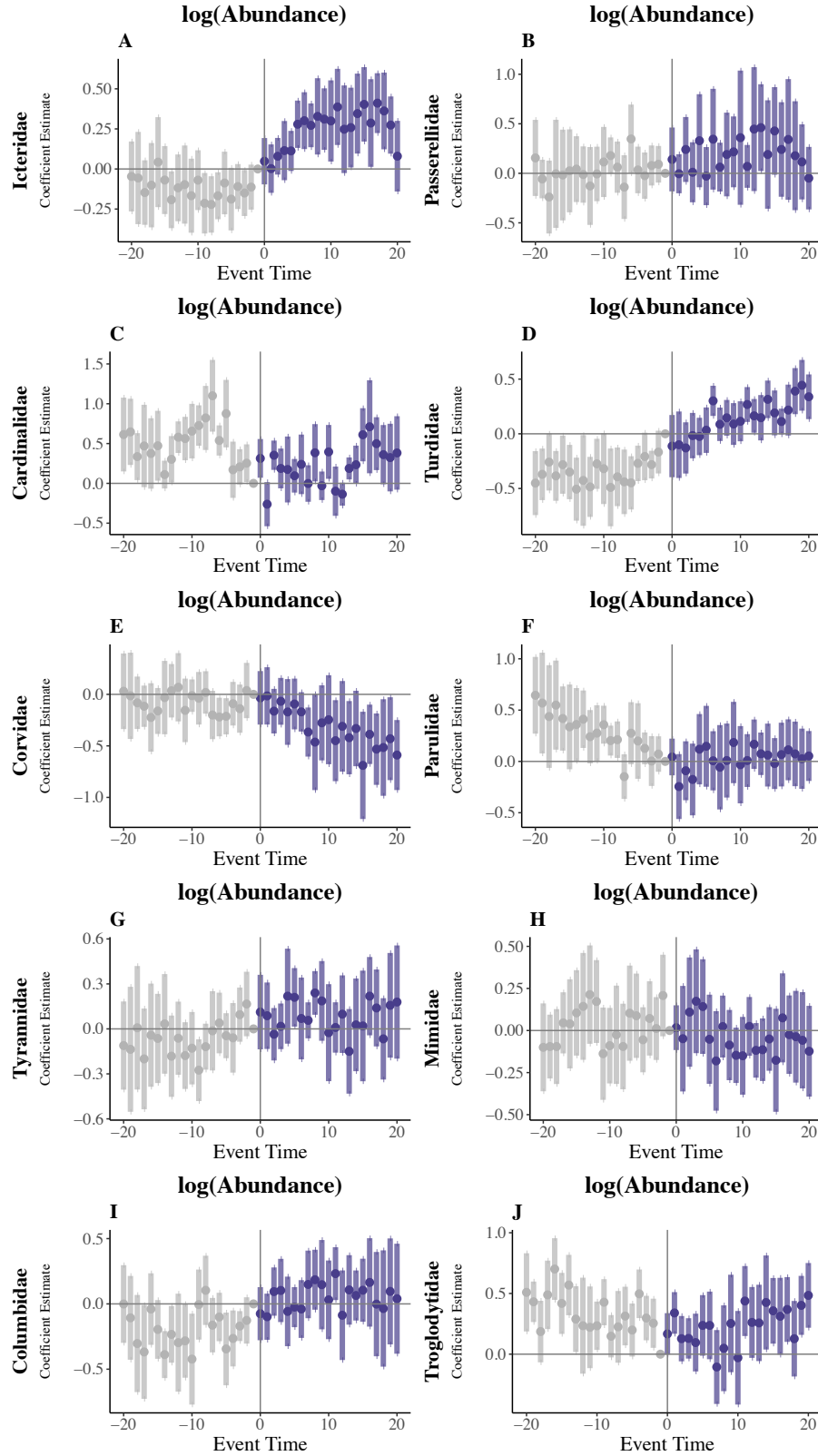


Figure P2: Dynamic overall effect of GM crops on birds of the 10 most common families in the sample. Bars indicate 95% confidence intervals. Years to 1996 indicates years to and since commercialization of GM corn, soy and cotton varieties in 1996.

Q Birds in North Dakota

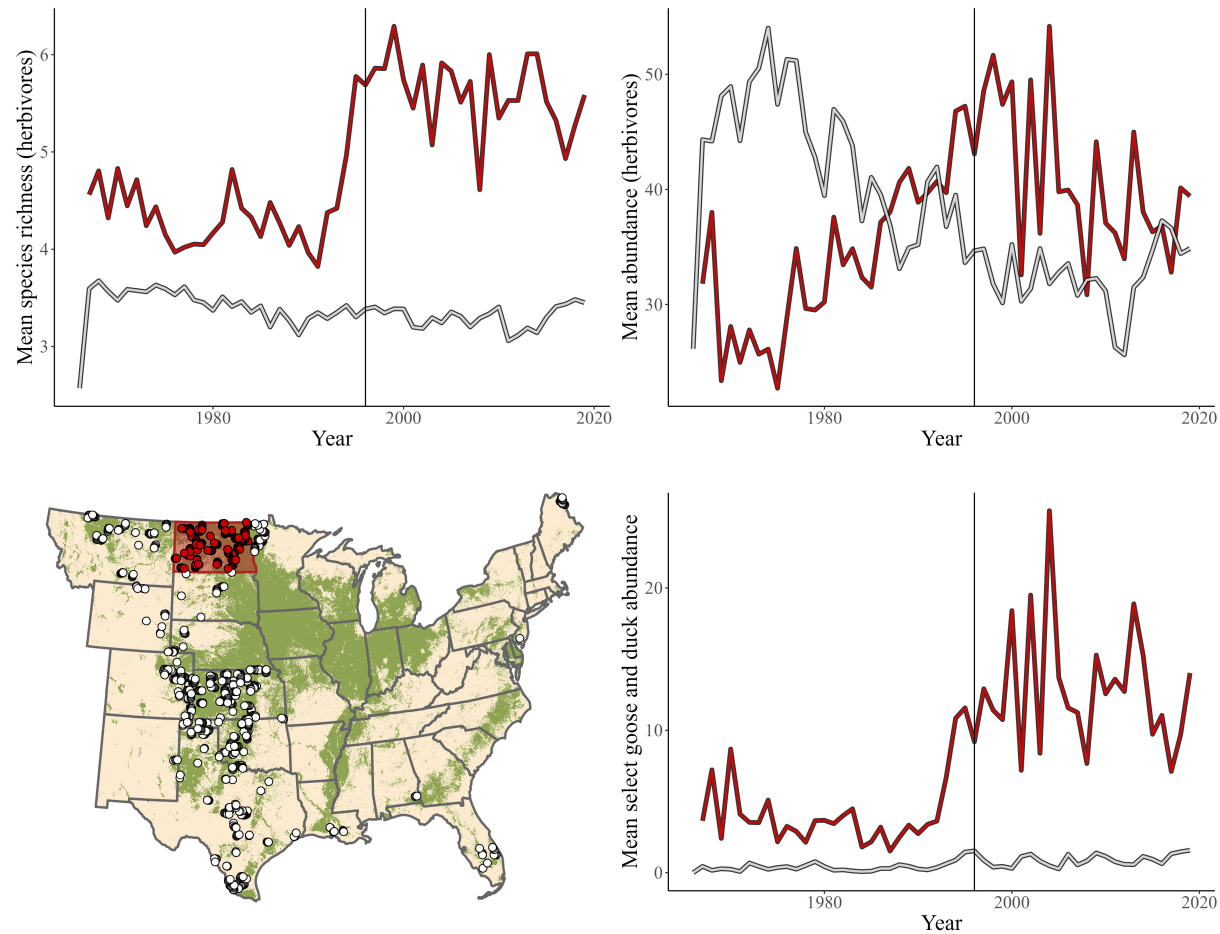


Figure Q1: Average species richness and mean abundance of herbivores, as well as mean abundance of select geese and ducks (Canada goose, blue winged teal and gadwall) over time on routes surrounded by less than 25% corn, soy and cotton in North Dakota (red) and the rest of the sample (white).

R Estimation with alternative matching cutoff (50% corn, soy and cotton)

Table R1: Summary Statistics before matching, using an alternative 50% corn, soy and cotton cutoff.

Share corn, soy and cotton	<50%			$\geq 50\%$		
Variable	N	Mean	SD	N	Mean	SD
Share soy, corn and cotton	13927	0.141	0.128	33125	0.618	0.24
Cropland share (1km buffer)	13927	0.625	0.223	33125	0.765	0.224
Cropland share (10km buffer)	13927	0.539	0.203	33125	0.712	0.218
Corn share	13927	0.092	0.106	33125	0.331	0.173
Soy share	13927	0.028	0.056	33125	0.263	0.14
Cotton share	13927	0.021	0.071	33125	0.024	0.094
Richness	13927	24.887	8.717	33125	29.812	8.188
Abundance	13927	202.723	126.4	33125	219.905	107.485
Shannon diversity	13927	2.509	0.44	33125	2.668	0.403
Richness insectivores	13927	4.9	2.8	33125	5.66	2.655
Abundance insectivores	13927	26.561	49.19	33125	20.097	18.308
Shannon div. insectivores	13927	1.144	0.562	33125	1.366	0.492
Richness herbivores	13927	3.713	1.409	33125	4.76	1.219
Abundance herbivores	13927	45.725	45.955	33125	56.882	41.173
Shannon div. herbivores	13927	0.929	0.389	33125	1.108	0.337

Table R2: Summary Statistics after matching, using an alternative 50% corn, soy and cotton cutoff.

Share of corn, soy and cotton	<50%			$\geq 50\%$		
Variable	N	Mean	SD	N	Mean	SD
Share soy, corn and cotton	13477	0.14	0.129	16579	0.624	0.247
Cropland share (1km buffer)	13477	0.627	0.224	16579	0.766	0.231
Cropland share (10km buffer)	13477	0.54	0.205	16579	0.716	0.225
Corn share	13477	0.092	0.107	16579	0.33	0.183
Soy share	13477	0.027	0.055	16579	0.255	0.144
Cotton share	13477	0.021	0.07	16579	0.039	0.123
Richness	13477	24.976	8.756	16579	28.592	7.776
Abundance	13477	203.059	126.507	16579	188.494	87.771
Shannon diversity	13477	2.511	0.443	16579	2.697	0.384
Richness insectivores	13477	4.933	2.812	16579	5.346	2.54
Abundance insectivores	13477	26.707	48.968	16579	18.894	17.877
Shannon div. insectivores	13477	1.151	0.563	16579	1.317	0.5
Richness herbivores	13477	3.687	1.401	16579	4.616	1.245
Abundance herbivores	13477	45.343	46.092	16579	48.166	36.195
Shannon div. herbivores	13477	0.924	0.39	16579	1.128	0.333

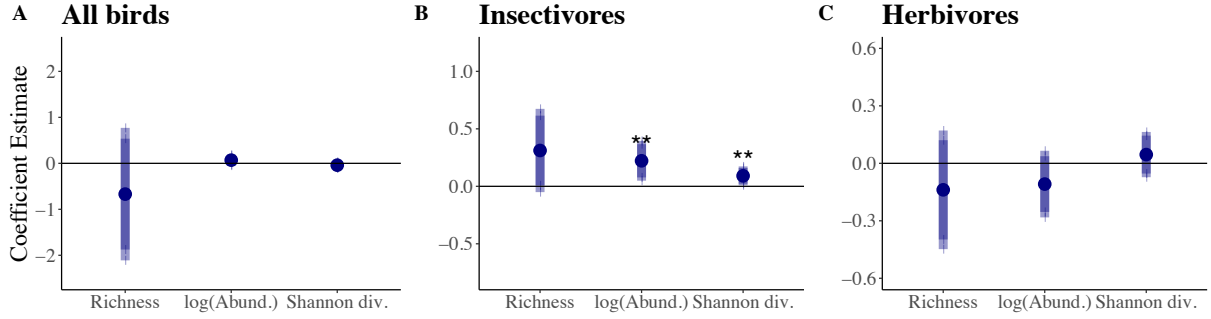


Figure R1: Overall effect of GM crops on all, insectivorous and herbivorous birds after matching using an alternative 50% corn, soy and cotton share cutoff. Dark and light bars indicating 90% and 95% confidence intervals, respectively, and stars indicate p-values (* : $P < 0.1$, ** : $P < 0.05$, *** : $P < 0.01$).

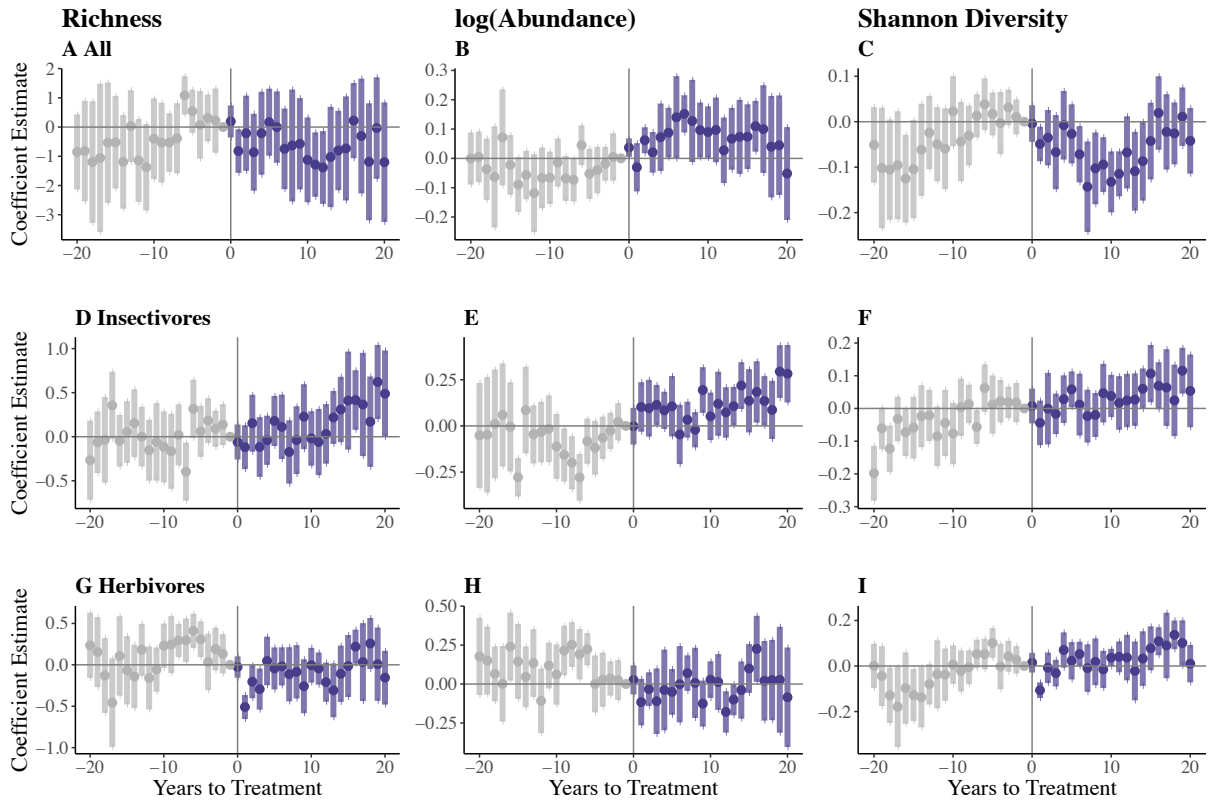


Figure R2: Dynamic overall effect of GM crops on all, insectivorous and herbivorous birds after matching using an alternative 50% corn, soy and cotton share cutoff. Bars indicate 95% confidence intervals, event time (horizontal axis) indicates years since approval of GM corn, soy and cotton varieties in 1996.

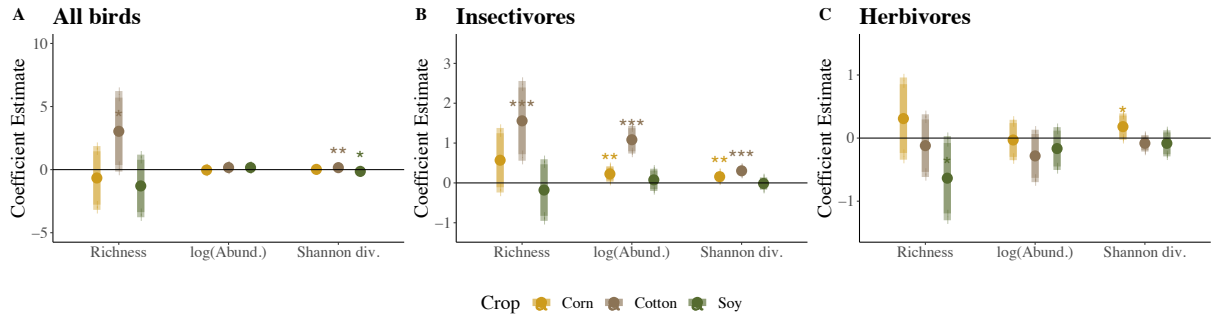


Figure R3: Effect of GM corn, soy and cotton on all, insectivorous and herbivorous birds after matching using an alternative 50% corn, soy and cotton share cutoff. Dark and light bars indicating 90% and 95% confidence intervals respectively, and stars indicating p-values (* : $P < 0.1$, ** : $P < 0.05$, *** : $P < 0.01$).

All birds

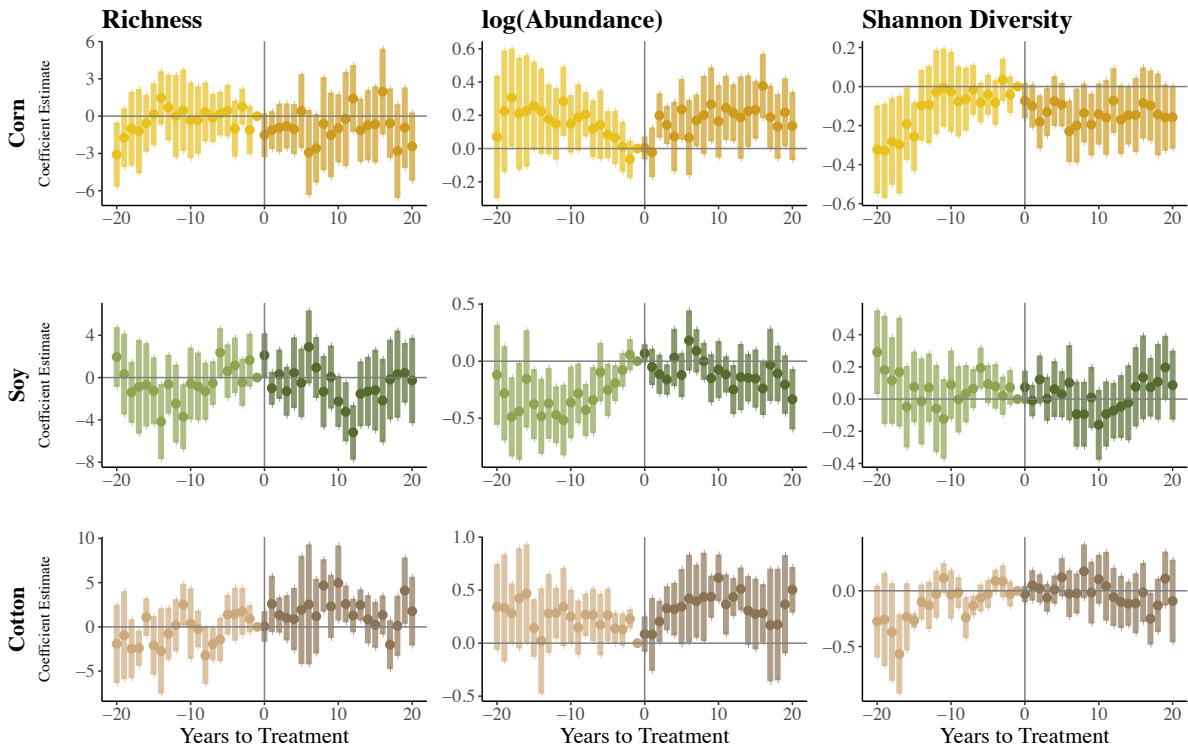


Figure R4: Dynamic crop-specific effects of GM corn (yellow), soy (green) and cotton (brown) varieties on all birds after matching using an alternative 50% corn, soy and cotton share cutoff. Bars indicating 95% confidence intervals, event time indicating years to approval of GM corn, soy and cotton varieties in 1996.

Insectivores

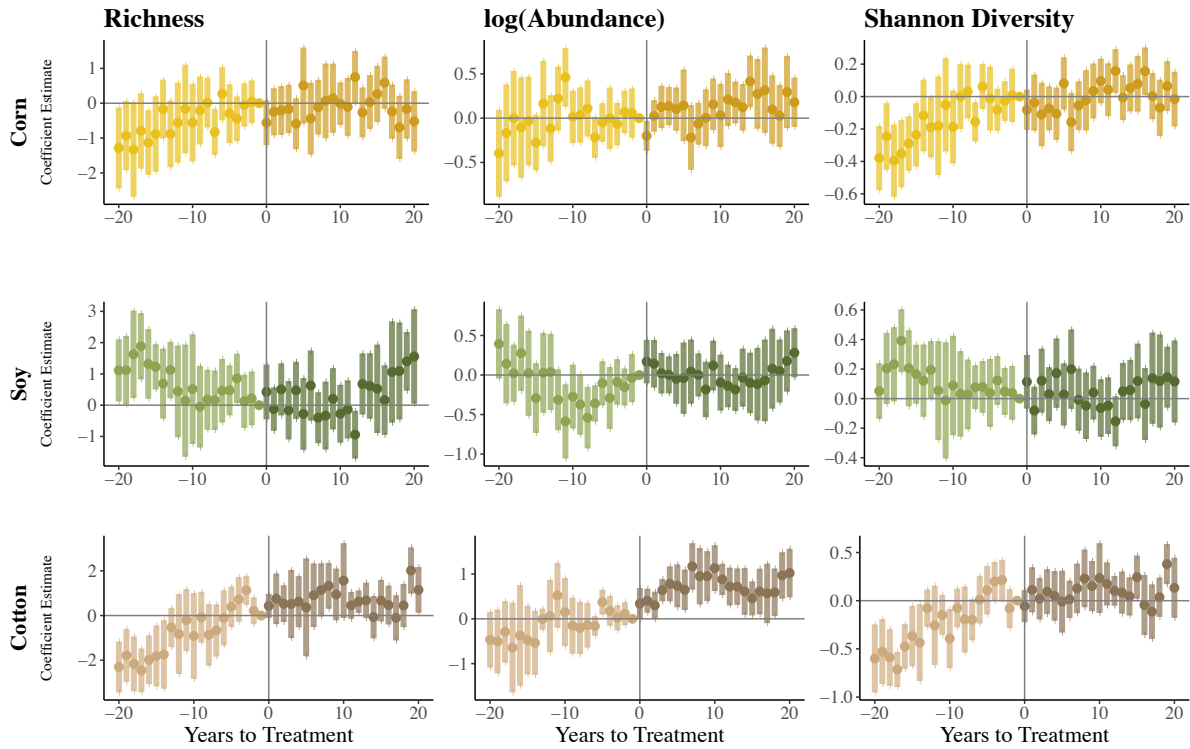


Figure R5: Dynamic crop-specific effects of GM corn (yellow), soy (green) and cotton (brown) varieties on insectivorous birds after matching using an alternative 50% corn, soy and cotton share cutoff. Bars indicating 95% confidence intervals, event time indicating years to approval of GM corn, soy and cotton varieties in 1996.

Herbivores

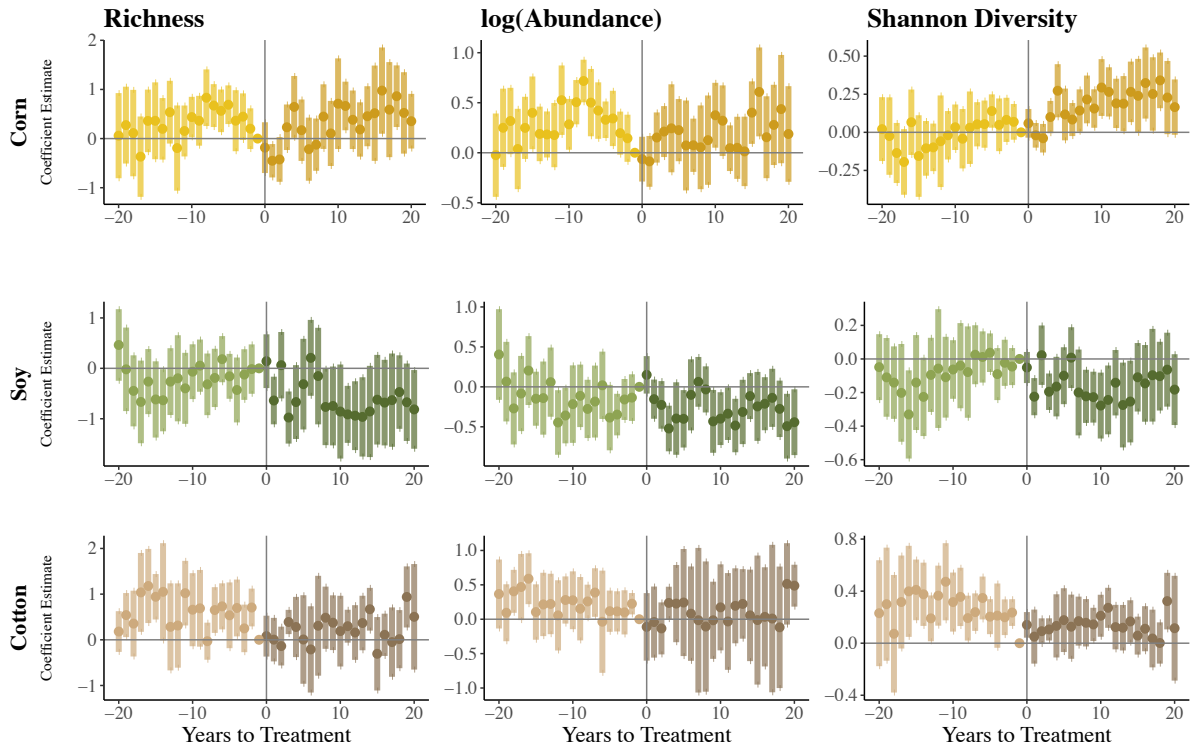


Figure R6: Dynamic crop-specific effects of GM corn (yellow), soy (green) and cotton (brown) varieties on herbivorous birds after matching using an alternative 50% corn, soy and cotton share cutoff. Bars indicating 95% confidence intervals, event time indicating years to approval of GM corn, soy and cotton varieties in 1996.

S Standardized matching

Table S1: Summary Statistics after matching based on standardized bird abundances (note that the indices here are calculated based on real bird abundances after the matching procedure).

Share corn, soy and cotton	<25%			≥ 25%		
Variable	N	Mean	SD	N	Mean	SD
Share soy, corn and cotton	7104	0.044	0.052	8599	0.538	0.3
Cropland share (1km buffer)	7104	0.625	0.219	8599	0.773	0.234
Cropland share (10km buffer)	7104	0.542	0.206	8599	0.7	0.236
Corn share	7104	0.029	0.04	8599	0.285	0.199
Soy share	7104	0.011	0.025	8599	0.206	0.178
Cotton share	7104	0.005	0.016	8599	0.046	0.125
Richness	7104	22.883	7.697	8599	23.609	7.094
Abundance	7104	187.725	105.778	8599	177.278	94.58
Shannon diversity	7104	2.444	0.432	8599	2.487	0.389
Richness insectivores	7104	4.437	2.515	8599	4.237	2.223
Abundance insectivores	7104	23.028	34.467	8599	18.172	28.463
Shannon div. insectivores	7104	1.057	0.529	8599	1.074	0.509
Richness herbivores	7104	3.413	1.4	8599	4.114	1.351
Abundance herbivores	7104	42.069	41.342	8599	47.129	37.964
Shannon div. herbivores	7104	0.881	0.407	8599	0.99	0.367

Table S2: Mean abundances of 50 most common bird species in the **matched** sample before 1996, sorted by abundance in areas with $\geq 25\%$ corn, soy and cotton (CSC).

	Bird	$\geq 25\%$ CSC	$< 25\%$ CSC	Difference (in %)
1	Red-winged Blackbird	25.24	17.17	31.96
2	House Sparrow	22.28	12.35	44.58
3	Common Grackle	14.29	6.56	54.10
4	Mourning Dove	10.63	14.92	-40.36
5	European Starling	9.39	4.35	53.70
6	Western Meadowlark	7.95	18.71	-135.29
7	Dickcissel	5.69	5.44	4.39
8	Horned Lark	5.43	11.39	-109.89
9	American Robin	5.01	2.09	58.40
10	Barn Swallow	4.41	3.91	11.28
11	Eastern Meadowlark	4.26	4.33	-1.46
12	Ring-necked Pheasant	3.80	4.08	-7.56
13	Brown-headed Cowbird	3.70	4.64	-25.23
14	Northern Bobwhite	3.65	5.39	-47.55
15	American Crow	3.25	1.89	41.87
16	Northern Mockingbird	2.74	4.49	-63.92
17	Northern Cardinal	2.53	2.66	-4.91
18	Cliff Swallow	1.95	4.33	-121.76
19	Rock Pigeon	1.86	1.30	30.05
20	Killdeer	1.85	1.78	3.84
21	Song Sparrow	1.83	0.40	78.33
22	Great-tailed Grackle	1.61	1.45	10.14
23	Common Yellowthroat	1.51	0.63	58.23
24	Lark Bunting	1.41	6.82	-383.90
25	Blue Jay	1.30	0.93	28.70
26	Indigo Bunting	1.19	0.15	87.05
27	Eastern Kingbird	1.14	1.64	-43.56
28	Vesper Sparrow	1.10	0.82	25.72
29	Grasshopper Sparrow	0.99	1.94	-96.18
30	Chimney Swift	0.96	0.61	36.89
31	Brown Thrasher	0.96	0.92	4.07
32	Savannah Sparrow	0.94	1.23	-31.77
33	Bobolink	0.92	0.67	26.91
34	American Goldfinch	0.92	0.41	54.85
35	Western Kingbird	0.90	2.61	-190.34
36	House Wren	0.88	0.89	-0.72
37	Cattle Egret	0.87	1.80	-107.53
38	Purple Martin	0.70	0.53	23.53
39	Red-headed Woodpecker	0.66	0.41	38.41
40	Baltimore Oriole	0.60	1.10	-81.99
41	Yellow-billed Cuckoo	0.57	0.73	-26.93
42	Mallard	0.57	0.68	-20.28
43	Scissor-tailed Flycatcher	0.54	1.63	-202.31
44	Field Sparrow	0.50	0.20	59.82
45	Lark Sparrow	0.49	1.72	-253.99
46	Common Nighthawk	0.45	0.96	-110.95
47	(Yellow-shafted Flicker) Northern Flicker	0.45	0.45	0.50
48	Yellow-headed Blackbird	0.42	0.30	27.55
49	Chipping Sparrow	0.40	0.12	71.08
50	Red-bellied Woodpecker	0.38	0.30	20.05
	Mean	3.32	3.30	-22.45
	Mean	3.16	3.29	-15.36

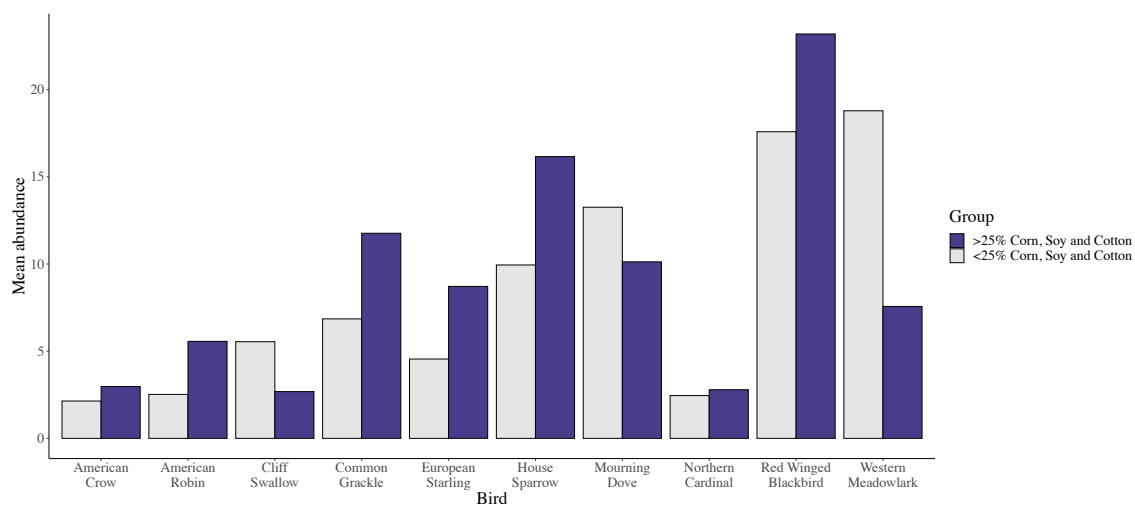


Figure S1: Comparison of mean abundance of the 10 most common birds in the standardized and matched sample between routes surrounded by >25% and <25% corn, soy and cotton in a 1 km-buffer.

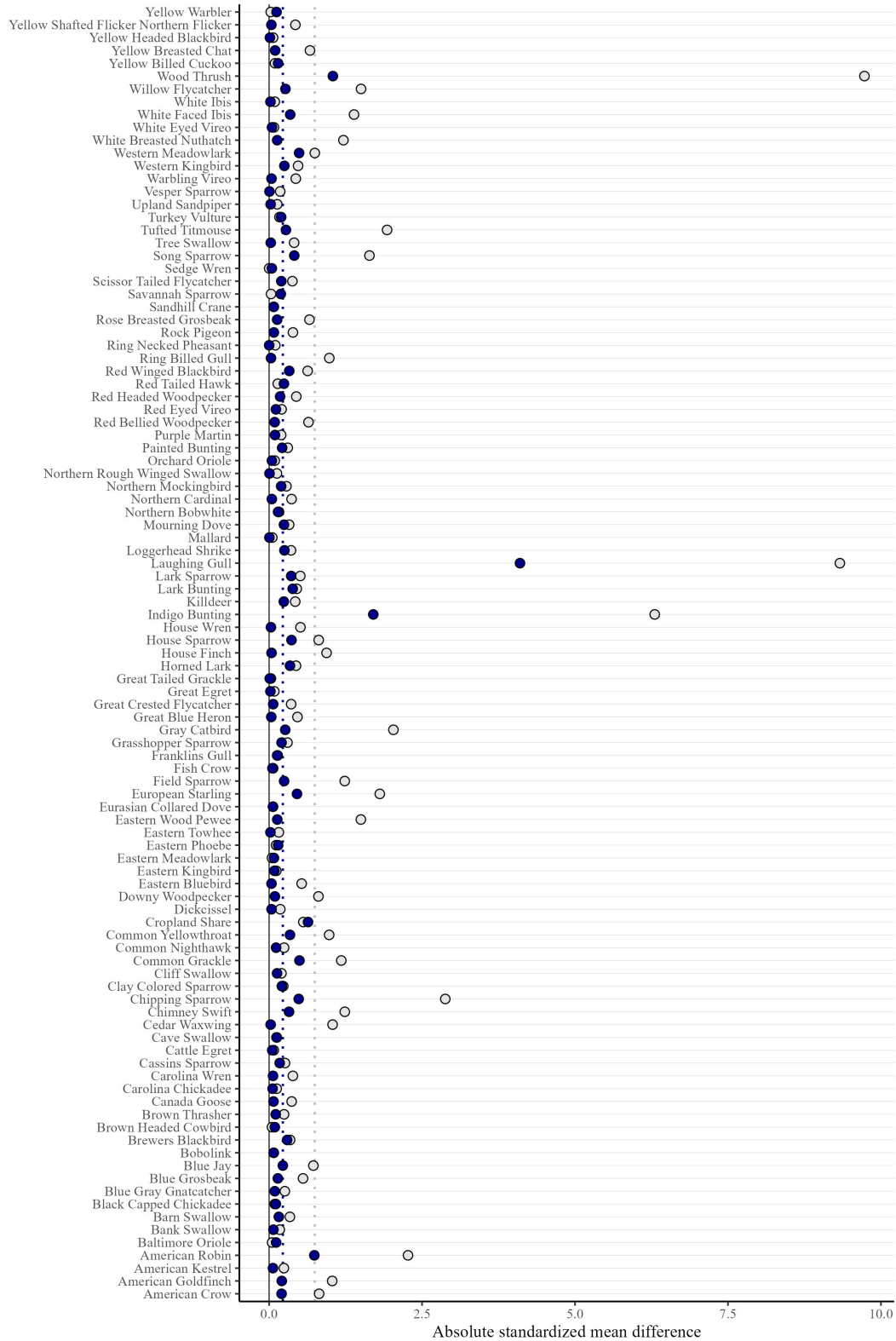


Figure S2: Absolute standardized mean differences between the top 100 bird species in regions with more or less than 25% share of corn, soy and cotton in 1992, before (grey dots) and after standardized matching (blue dots). Grey dotted line indicates average difference before matching, blue dotted line indicates average difference after matching.

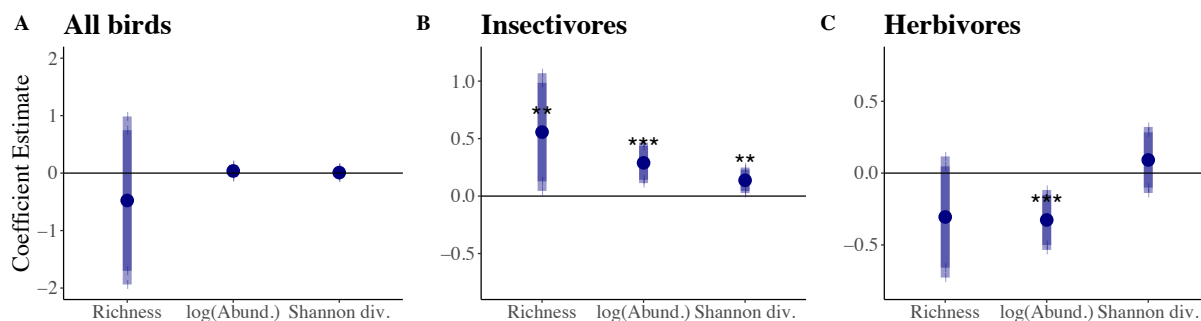


Figure S3: Overall effect of GM crops on all, insectivorous and herbivorous birds after standardized matching. Dark and light bars indicating 90% and 95% confidence intervals, respectively, and stars indicate p-values (* : $P < 0.1$, ** : $P < 0.05$, *** : $P < 0.01$).

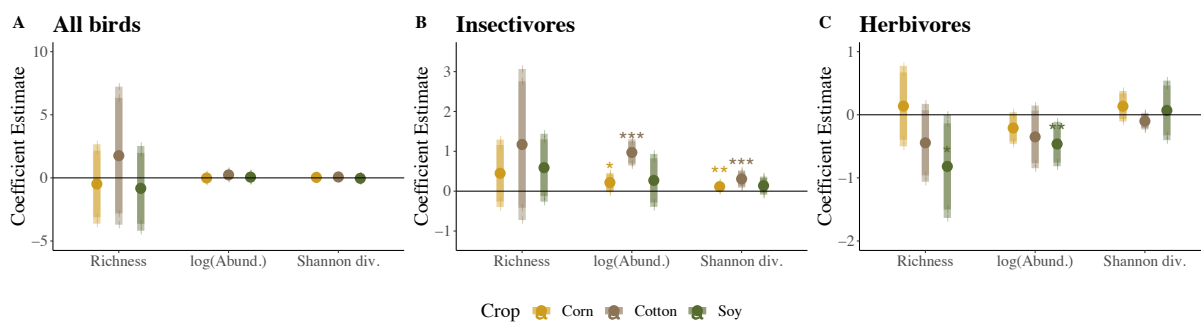


Figure S4: Effect of GM corn, soy and cotton on all, insectivorous and herbivorous birds after standardized matching. Dark and light bars indicating 90% and 95% confidence intervals respectively, and stars indicating p-values (* : $P < 0.1$, ** : $P < 0.05$, *** : $P < 0.01$).

T Residuals plots

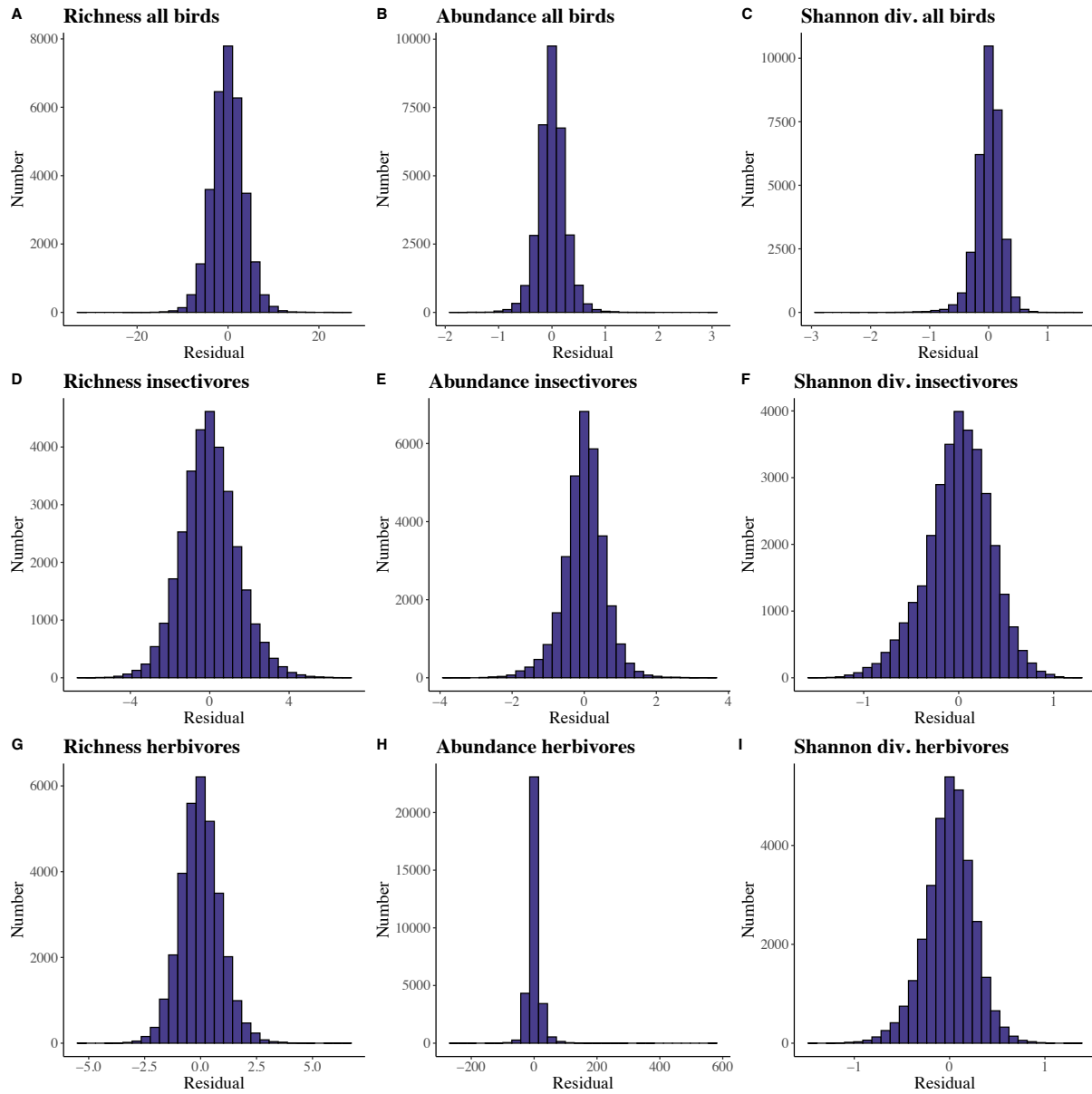


Figure T1: Histograms of residuals from the regressions using the static framework from equation (2) in the Methods section.

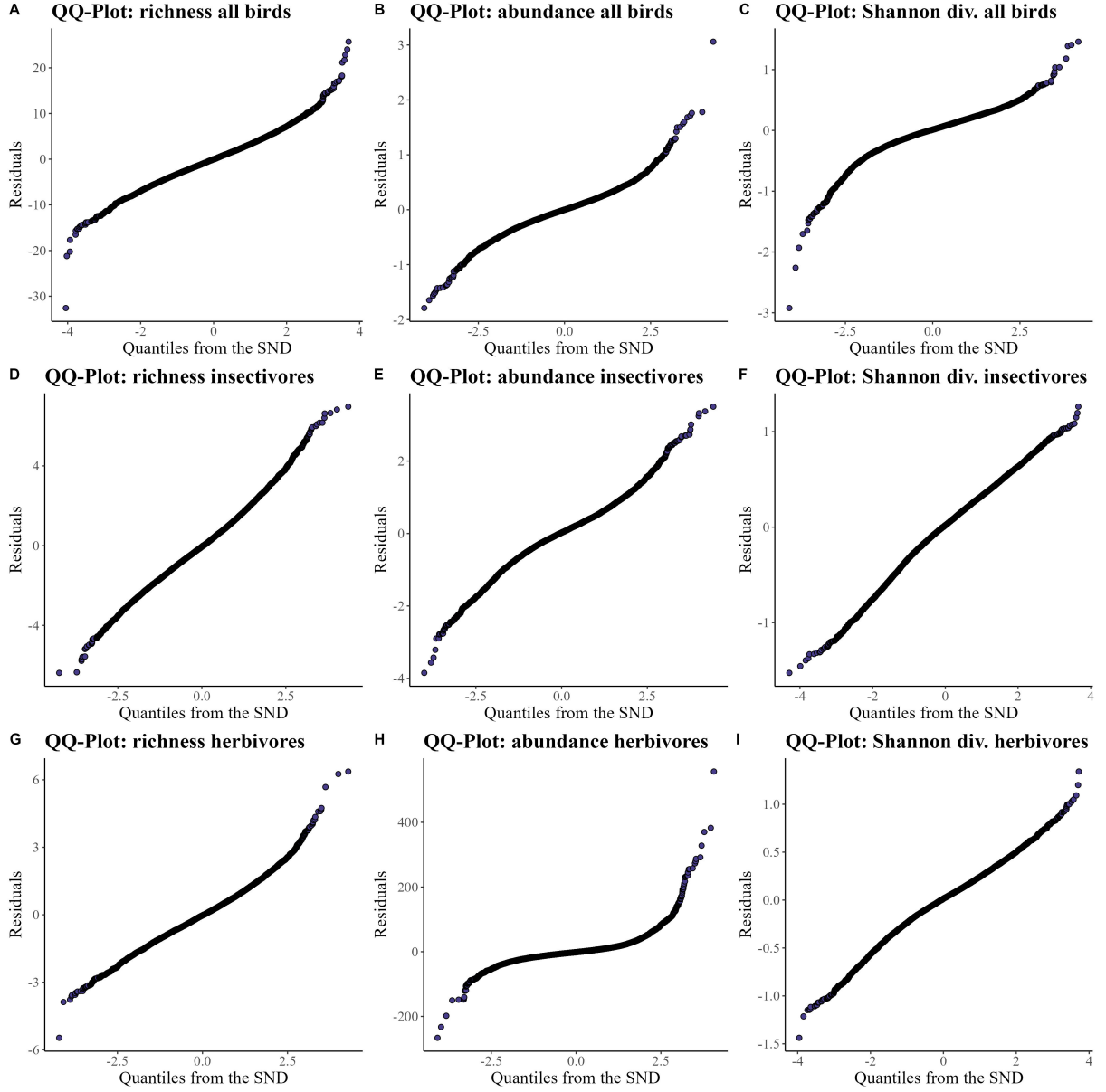


Figure T2: QQ-plots of residuals from the regressions using the static framework from equation (2) versus a theoretical standard normal distribution. If the residuals are normally distributed, the dots in the QQ-plot should form a straight line.

U Estimation with Poisson regression

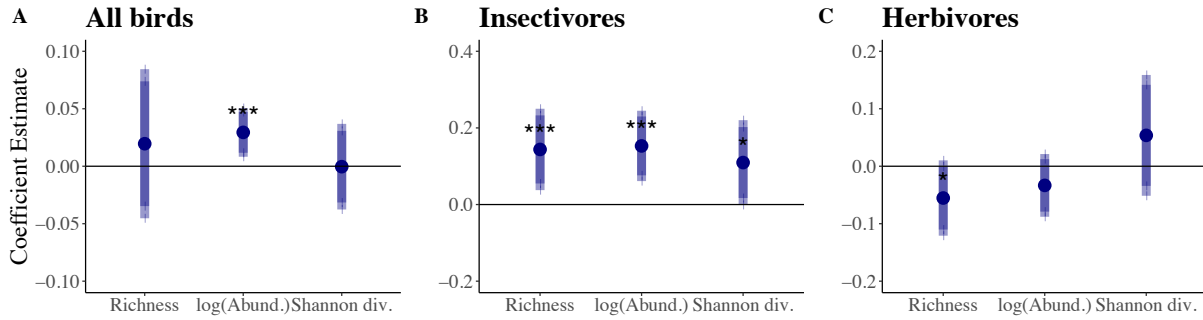


Figure U1: Overall effect of GM crops on all, insectivorous and herbivorous birds using poisson regression. Dark and light bars indicating 90% and 95% confidence intervals, respectively, and stars indicate p-values (* : $P < 0.1$, ** : $P < 0.05$, *** : $P < 0.01$).

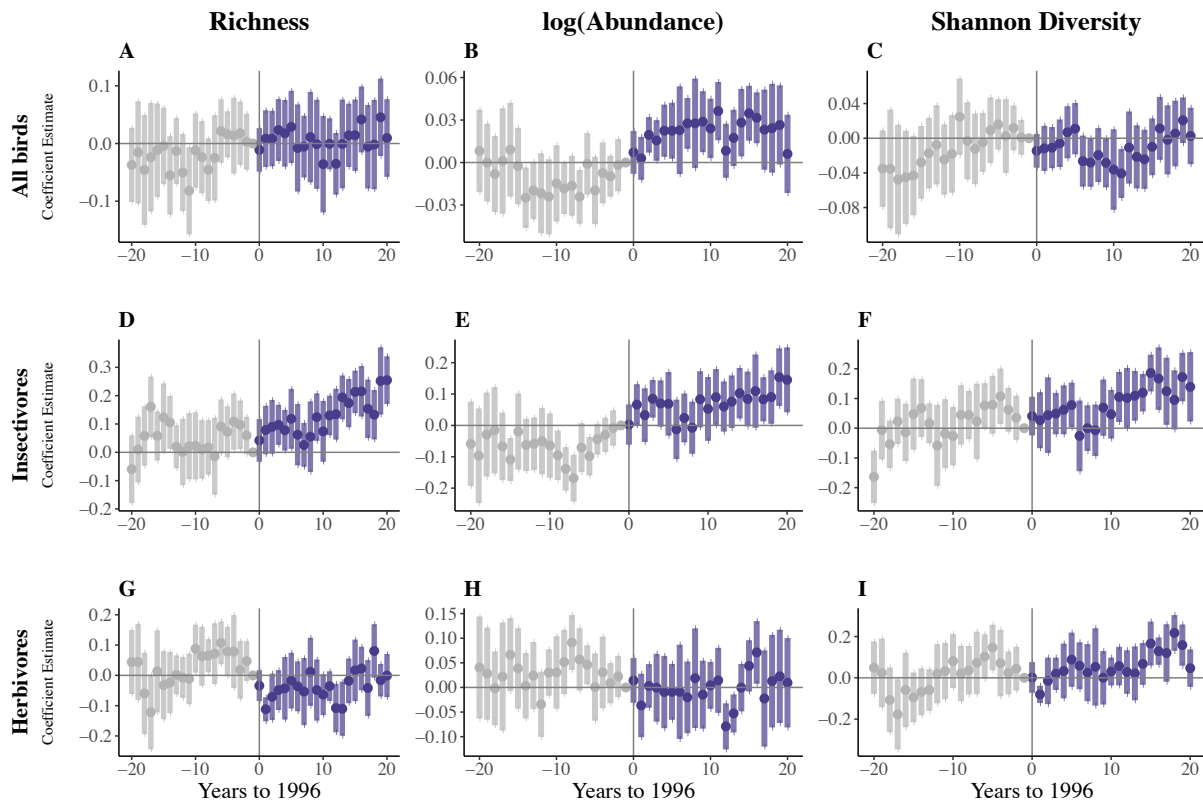


Figure U2: Dynamic overall effect of GM crops on all, insectivorous and herbivorous birds using poisson regression. Bars indicate 95% confidence intervals. Years to 1996 indicates years to and since commercialization of GM corn, soy and cotton varieties in 1996.

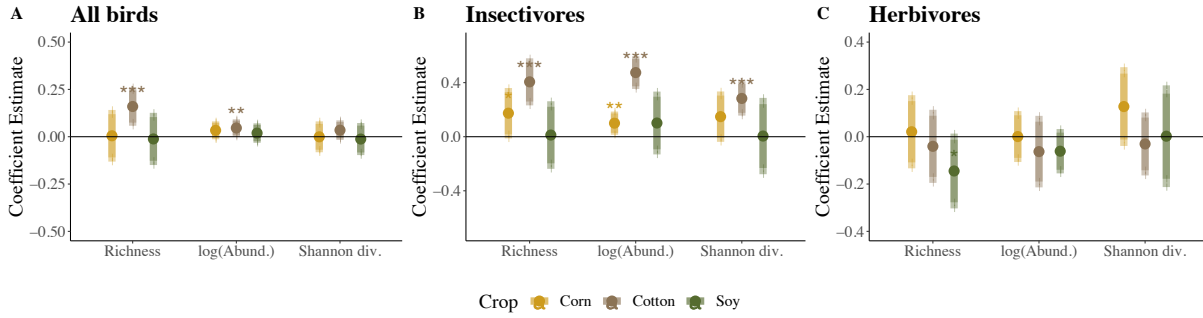


Figure U3: Effect of GM corn, soy and cotton on all, insectivorous and herbivorous birds using poisson regression. Dark and light bars indicating 90% and 95% confidence intervals respectively, and stars indicating p-values (* : $P < 0.1$, ** : $P < 0.05$, *** : $P < 0.01$).

All birds

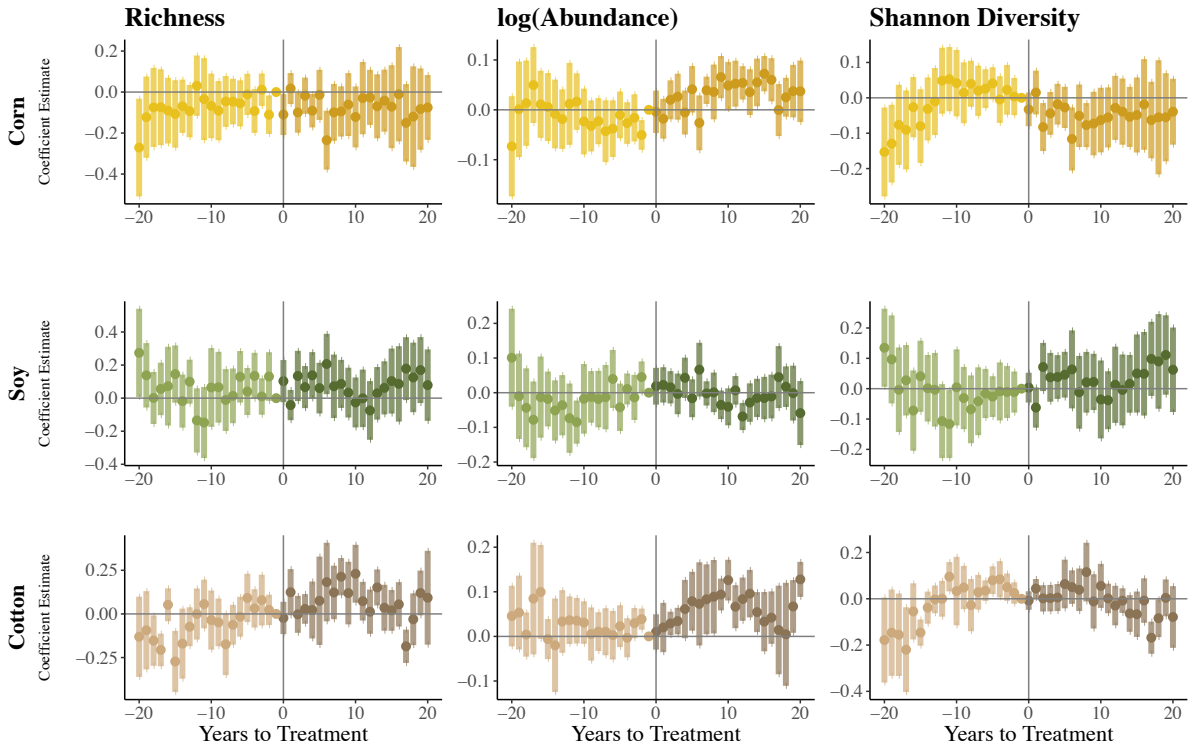


Figure U4: Dynamic crop-specific effects of GM corn (yellow), soy (green) and cotton (brown) varieties on all birds using poisson regression. Bars indicating 95% confidence intervals, event time indicating years to approval of GM corn, soy and cotton varieties in 1996.

Insectivores

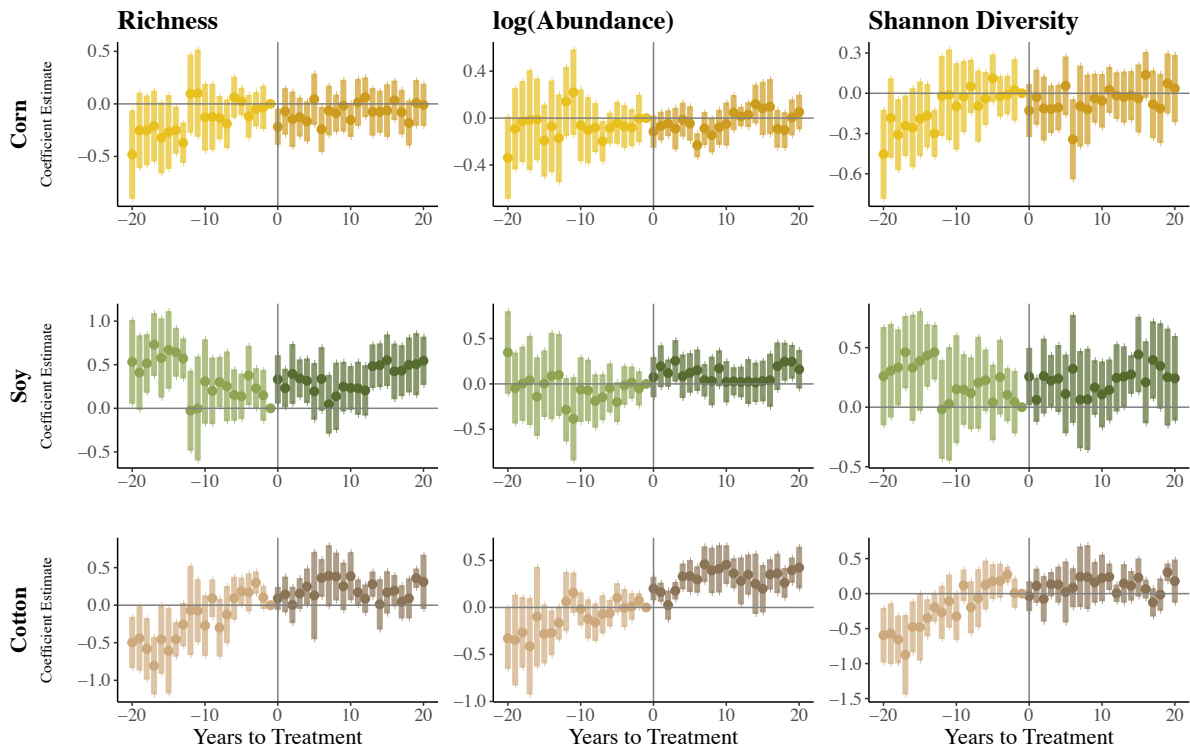


Figure U5: Dynamic crop-specific effects of GM corn (yellow), soy (green) and cotton (brown) varieties on insectivorous birds using Poisson regression. Bars indicating 95% confidence intervals, event time indicating years to approval of GM corn, soy and cotton varieties in 1996.

Herbivores

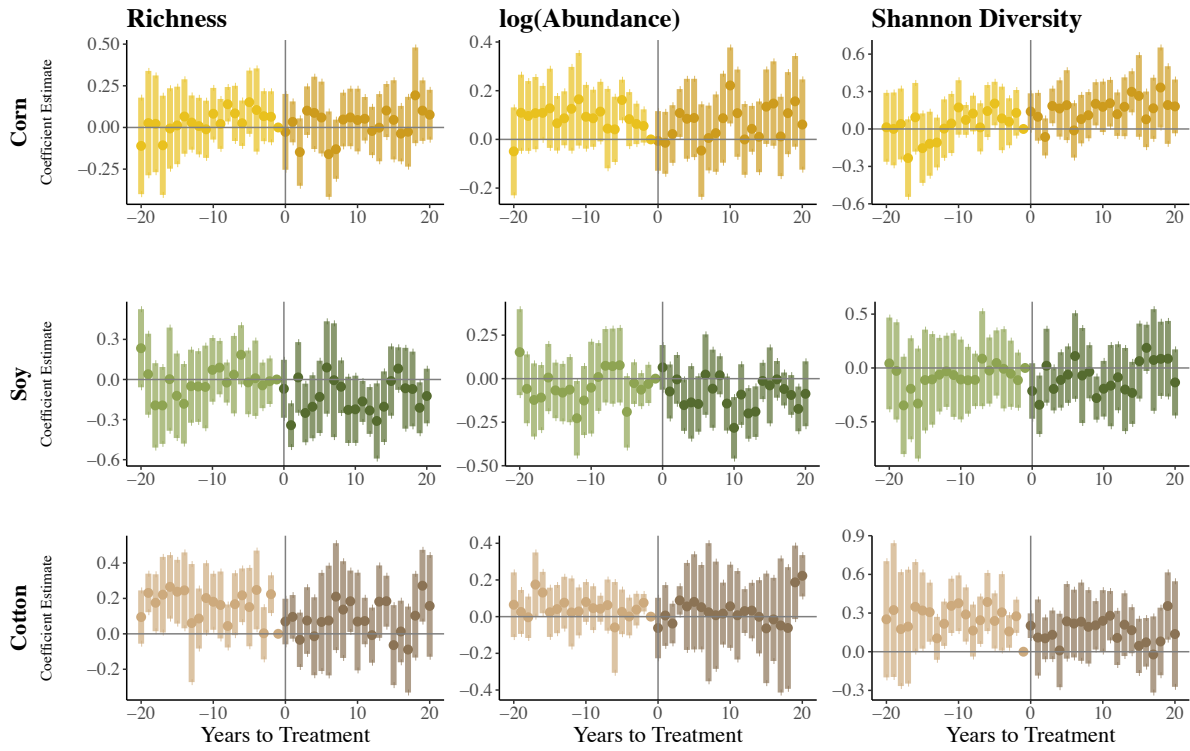


Figure U6: Dynamic crop-specific effects of GM corn (yellow), soy (green) and cotton (brown) varieties on herbivorous birds using poisson regression. Bars indicating 95% confidence intervals, event time indicating years to approval of GM corn, soy and cotton varieties in 1996.

V List of pesticides and toxicity values

Table V1: The pesticide compounds covered in the USGS NAWQA data.

Compound	Compound	Compound	Compound	Compound	Compound
1-METHYL CYCLOPROPENE	CLOMAZONE	FENARIMOL	LINURON	PROHEXADIONE	TRI-ALLATE
2,4-D	CLOPYRALID	FENAZAQUIN	MALATHION	PROHYDROJASMON	TRIADIMEFON
2,4-DB	CLORANSULAM-METHYL	FENBUCONAZOLE	MALEIC HYDRAZIDE	PROMETON	TRIADIMENOL
6-BENZYLADENINE	CLOTHIANIDIN	FENBUTATIN OXIDE	MANCOZEB	PROMETRYN	TRIASULFURON
ABAMECTIN	COLLECTOTRICHUM SPORES	FENHEXAMID	MANDIPROPAMID	PROPACHLOR	TRIAZAMATE
ABSCISIC ACID	CONIOTHYRIUM MINITANS	FENOXAPROP	MANEB	PROPAMOCARB HCL	TRIBENURON METHYL
ACEPHATE	COPPER	FENOXYCARB	MCPA	PROPANIL	TRIBUFOS
ACEQUINOCYL	COPPER HYDROXIDE	FENPROPATHRIN	MCPB	PROPARGITE	TRICHLORFON
ACETAMIPRID	COPPER OCTANOATE	FENPYROXIMATE	MECOPROP	PROPACAZINE	TRICLOPYR
ACETOCHLOR	COPPER OXYCHLORIDE	FENSULFOTHION	MEFENOXAM	PROPICONAZOLE	TRIDIPHANE
ACIBENZOLAR	COPPER OXYCHLORIDE S	FENTIN	MEFLUIDIDE	PROPOXUR	TRIFLOXYSTROBIN
ACIFLUORFEN	COPPER SULFATE	FENVALERATE	MEPIQUAT	PROPOXYCARBAZONE	TRIFLOXYLSULFURON
ALACHLOR	COPPER SULFATE TRIBASIC	FERBAM	MESOSULFURON	PROPYZAMIDE	TRIFLUMIZOLE
ALDICARB	CPPU	FIPRONIL	MESOTRIONE	PROSULFURON	TRIFLURALIN
ALLYL ISOTHIOCYANATE	CRYOLITE	FLAZASULFURON	METALAXYL	PROTHIOCONAZOLE	TRIFLUSULFURON
ALPHA CYPERMETHRIN	CUPROSUS OXIDE	FLONICAMID	METALDEHYDE	PSEUDOMONAS FLUORESCENS	TRIFORINE
ALUMINUM PHOSPHIDE	CYANAMIDE	FLORASULAM	METAM	PYDIFLUMETOFEN	TRIMETHACARB
AMETOCTRADIN	CYANAZINE	FLORPYRAUXIFEN	METAM POTASSIUM	PYDIFLUMETOFEN	TRINEXAPAC
AMETRYN	CYANTHRANILIPROLE	FLUAZIFOP	METCONAZOLE	PYRACLOSTROBIN	TRITICONAZOLE
AMINOPYRALID	CYAZOFAMID	FLUAZINAM	METHAMIDOPHOS	PYRAFLUFEN ETHYL	UNICONAZOLE
AMITRAZ	CYCLANILIDE	FLUBENDIAMIDE	METHAZOLE	PYRASULFOTOLE	VERNOLATE
AMITROLE	CYCLANILIPROLE	FLUCARBAZONE	METHIDATHION	PYRETHRINS	VINCLIZOLIN
AMMONIUM SULFAMATE	CYCLOATE	FLUCHLORALIN	METHIOCARB	PYRIDABEN	ZETA-CYPERMETHRIN
AMPELOMYCES QUISQUALIS	CYDIA POMONELLA	FLUCYTHRINATE	METHOMYL	PYRIDATE	ZINC
ANLAZINE	CYFLUFENAMID	FLUDIOXONIL	METHOXYCHLOR	PYRIMETHANIL	ZINEB
ARSENIC ACID	CYFLUMETOFEN	FLUENSULFONE	METHOXYFENOZIDE	PYRIOFENONE	ZIRAM
ASPERGILLUS FLAVUS	CYFLUTHRIN	FLUFENACET	METHYL BROMIDE	PYRIPROXYFEN	ZOXAMIDE
ASULAM	CYHALOFOP	FLUMETRALIN	METHYL ISOTHIOCYANATE	PYRITHIOBAC-SODIUM	
ATRAZINE	CYHALOTHRIN-GAMMA	FLUMETSULAM	METHYL PARATHION	PYROXASULFONE	
AUREOBASIDIUM PULLULANS	CYHALOTHRIN-LAMBDA	FLUMICLORAC	METHYLIODIDE	PYROXSULAM	
AVIGLYCINE	CYMOXANIL	FLUMIOXAZIN	METIRAM	QUINCLORAC	
AZADIRACTHIN	CYPERMETHRIN	FLUOMETURON	METOLACHLOR	QUINOXYFEN	
AZINPHOS-METHYL	CYPROCONAZOLE	FLUOPICOLIDE	METOLACHLOR-S	QUINTOZENE	
AZOXYSTROBIN	CYPRODINIL	FLUOPYRAM	METOLACHLOR & METOLACHLOR-S	QUIZALOFOP	
BACILLUS AMYLOLIQUEFACIEN	CYROMAZINE	FLUOXASTROBIN	METRAFENONE	RESMETHRIN	
BACILLUS CEREUS	CYTOKININ	FLUPYRADIFURONE	METRIBUZIN	REYNOUTRIA SACHALINENSIS	
BACILLUS FIRMS	DALAPON	FLURIDONE	METSULFURON	RIMSULFURON	
BACILLUS MYCOIDES	DAMINOZIDE	FLUROXYPPYR	MEVINPHOS	ROTEENONE	
BACILLUS PUMILIS	DAZOMET	FLUSILAZOLE	MOLINATE	RYANODINE	
BACILLUS SUBTILIS	DCPA	FLUTHIACET-METHYL	MONOCROTOPHOS	SABADILLA	
BACILLUS THURINGIENSIS	DECAN-1-OL	FLUTOLANIL	MSMA	SAFLUFENACIL	
BACTERIOPHAGE	DELTAMETHRIN	FLUTRIAFOL	MYCLOBUTANIL	SEDAXANE	
BARBAN	DEMETON	FLUVALINATE	MYROTHECIUM VERRUCARIA	SETHOXYDIM	
BARIUM POLYSULFIDE	DESMEDIPHAM	FLUVALINATE TAU	NALED	SILICATES	
BEAUVERIA BASSIANA	DIALLATE	FLUXAPYPROXAD	NAPHTHYLACETAMIDE	SIMAZINE	
BENDIOCARB	DIAMINON	FOLPET	NAPHTHYLACETIC ACID	SODIUM ARSENITE	
BENFLURALIN	DICAMBA	FOMESAFEN	NAPROPAMIDE	SODIUM CHLORATE	
BENOMYL	DICHLORBENIL	FONOFOS	NAPHTALAM	SODIUM METABORATE	
BENSULFURON	DICHLONE	FORAMSULFURON	NAPTHA	SPINETORAM	
BENSULIDE	DICHLOROPROPENE	FORMETANATE	NEEM OIL	SPINOSYN	
BENTAZONE	DICHLOROPROP	FOSAMINE	NICOSULFURON	SPIRODICLOFEN	
BENZOBICYCLOX	DICLOFOP	FOSETYL	NORFLURAZON	SPIROMESIFEN	
BENZOVINDIFLUPYR	DICLORAN	GALLEX	NORURON	SPIROTETRAMAT	
BICYCLOPYRONE	DICLOSULAM	GAMMA AMINOBUTYRIC ACID	NOSEMA LOCUSTAE CANN	STEINERNEMA CARPOCAP	
BIFENAZATE	DICOFOL	GARLIC JUICE	NOVALURON	STEINERNEMA RIOBRAVI	
BIFENOX	DICROTAPHOS	GENTAMICIN SULFATE	ORTHOSULFAMURON	STREPTOMYCES LYDICUS	
BIFENTHRIN	DIEENOCHLOR	GIBBERELIC ACID	ORYZALIN	STREPTOMYCIN	
BISPYRIBAC	DIEHATYTL	GLIOCLADUM VIRENS	OXADIAZON	SUCROSE OCTANOATE	
BLAD PROTEIN	DIFENOCONAZOLE	GLUFOSINATE	OXAMYL	SULFALLATE	
BORDEAUX MIXTURE	DIFENZOQUAT	GLYPHOSATE	OXATHIPIPROLIN	SULFCARBAMIDE	
BOSCALID	DIFLUBENZURON	HALAUXIFEN	OXYDEMOTON-METHYL	SULFENTRAZONE	
BROMACIL	DIFLUFENZOPYR	HALOSULFURON	OXYFLUORFEN	SULFOMETURON	
BROMOXYNIL	DIMETHENAMID	HARPIN PROTEIN	OXYTETRACYCLINE	SULFOSATE	
BUPROFEZIN	DIMETHENAMID-P	HEXAZINONE	PACLOBUTRAZOL	SULFOSULFURON	
BURKHOLDERIA CEPACIA	DIMETHENAMID & DIMETHENAMID-P	HEXYTHIAZOX	PAECILOMYCES LILACINUS	SULFOXAFLOL	
BURKHOLDERIA SPP	DIMETHIPIN	HYDRAMETHYLNON	PARAQUAT	SULFUR	
BUTRALIN	DIMETHOATE	HYDRATED LIME	PARATHION	SULFURIC ACID	
BUTYLATE	DIMETHOMORPH	HYDROGEN PEROXIDE	PASTEURIA NISHIZAWAE	SULPROFOS	
CALCIUM CHLORIDE	DIMETHYL ARSINIC ACID	HYDROXYPROPANOIC ACID	PEBULATE	TCA	
CALCIUM POLYSULFIDE	DIMETHYL DISULFIDE	HYMEXAZOL	PELARGONIC ACID	TCMTB	
CAPTAFOF	DINOCAP	IBA	PENDIMETHALIN	TEBUCONAZOLE	
CAPTAN	DINOSEB	IMAZALIL	PENFLUFEN	TEBUFENOZIDE	
CARBARYL	DINOTEFURAN	IMAZAMETHABENZ	PENXOSULAM	TEBUPIRIMPHOS	
CARBOFURAN	DIPHENAMID	IMAZAMOX	PENTHIOPYRAD	TEBUTHIURON	
CARBOPHENOTHION	DIGUAT	IMAZAPIC	PETHRIN	TEFLUTHRIN	
CARBOXIN	DISULFOTON	IMAZAPYR	PETROLEUM DISTILLATE	TEMBOTRIONE	
CARFENTHAZONE-ETHYL	DITHIOPYR	IMAZAQUIN	PETROLEUM OIL	TEMPEPHOS	
CHENOPODIUM AMBROSIOIDES	DIURON	IMAZETHAPYR	PHENMEDIPHAM	TERRACIL	
CHINOMETHIONAT	DNOC	IMAZOSULFURON	PHORATE	TERBUFOS	
CHLORAMBEN	DODINE	IMIDACLOPRID	PHOSALONE	TERRBUTRYN	
CHLORANTRANILIPROLE	DSMA	INDAZIFLAM	PHOSMET	TETRABOROHYDRATE	
CHLORDIMEFORM	EMAMECTIN	INDOXACARB	PHOSPHAMIDON	TETRACONAZOLE	
CHLORETHOXYFOS	ENDOSULFAN	IODOSULFURON	PHOSPHORIC ACID	TETRAOXOSULFATE	
CHLORFENAPYR	ENDOTHAL	IPCONAZOLE	PHYTOPHTHORA SPORES	TETRATHIOCARBONATE	
CHLORIDAZON	EPN	IPRODIONE	PICLORAM	THIABENDAZOLE	
CHLORIMURON	EPTC	ISARIA FUMOSOROSEA	PICOXYSTROBIN	THIACLOPRID	
CHLORMEQUAT	ESFENVALERATE	ISAZOFOS	PINOLENE	THIAMETHOXAM	
CHLOROBENZILATE	ETHABOXAM	ISOENPHOS	PINOXADEN	THIAZOPYR	
CHLORONEB	ETHALFLURALIN	ISOFTAMID	PIPERONYL BUTOXIDE	THIDIAZURON	
CHLOROPICRIN	ETHAMETSULFURON	ISOPROPALIN	PIRIMICARB	THIENCARBAMIDE-METHYL	
CHLOROTHALONIL	ETHEPHON	ISOXABEN	POLYHEDROSIS VIRUS	THIFENSULFURON	
CHLOROXURON	ETHION	ISOXAFLOTOL	POLYOXORIM	THIOBENCARB	
CHLORPROPHAM	ETHOFUMESATE	KAOLIN CLAY	POTASSIUM BICARBONATE	THIODICARB	
CHLORPYRIFOS	ETHOPROPHOS	KASUGAMYCIN	POTASSIUM CARBONATE	THIOPHANATE-METHYL	
CHLORSULFURON	ETOXAZOLE	KINOPRENE	POTASSIUM OLEATE	THIRAM	
CHROMOBACTERIUM SUBTUGAE	ETRIPIDAZOLE	KRESOXIM-METHYL	POTASSIUM SILICATE	TOLCLOFOS-METHYL	
CINNAMALDEHYDE	FAMOAXADONE	L-GLUTAMIC ACID	PRIMISULFURON	TOLFENPYRAD	
CLETHODIM	FATTY ALCOHOLS	LACTOFEN	PRODIAMINE	TOPRAMEZONE	
CLODINAFOP	FENAMIDONE	LEAD ARSENATE	PROFENOFOS	TRALOXOXYDIM	
CLOFENTEZINE	FENAMIPHOS	LINDANE	PROFLURALIN	TRALOMETHRIN	

Table V2: LD50 values (mg/kg bodymass) of pesticide compounds representing toxicity to rats, honey bees, fish and birds. Data based on [19] and <https://pubchem.ncbi.nlm.nih.gov/> (Accessed 1.11.2023). For rats and birds, acute oral LD50 values were documented, while acute exposure LC50 and acute contact LD50 were collected for fish and honey bees, respectively.

Compound	Rat	Honey Bee	Fish	Bird
1 2,4-D	537.00	11.50	285300.00	536.37
2 2,4-DB	1960.00	14.50	8050.00	5000.00
3 ACETOCHLOR	1455.50	1715.00	1250.00	1133.37
4 ALACHLOR	1235.00	36.20	4200.00	2000.00
5 AMETRYN	150.00	100.00	8500.00	3445.00
6 AMINOPYRALID	1160.00	107.40	100000.00	2250.00
7 ATRAZINE	2836.00	97.00	20500.00	7118.50
8 BENTAZONE	2780.00	200.00	794000.00	2029.00
9 BICYCLOPYRONE	1100.00	200.00	794000.00	1206.00
10 BROMOXYNIL	5000.00	14.50	13800.00	208.50
11 BUTYLATE	2189.50	26.00	6900.00	4640.00
12 CARFENTRAZONE-ETHYL	4659.00	27.90	1800.00	2250.00
13 CHLORIMURON	5000.00	12.50	8400.00	2510.00
14 CHLORSULFURON	4102.00	25.00	40000.00	9235.00
15 CLETHODIM	5545.00	100.00	19000.00	2000.00
16 CLOPYRALID	1630.00	100.00	751000.00	1855.86
17 CYANAZINE	759.00	96.70	17400.00	747.50
18 DICAMBA	3019.50	100.00	135400.00	936.55
19 DIFLUFENZOPYR	182.00	75.00	106000.00	2250.00
20 DIMETHENAMID	1039.00	94.00	4500.00	1908.00
21 DIMETHENAMID-P	2714.50	94.00	8150.00	1068.00
22 DIURON	1293.50	145.03	5100.00	2000.00
23 EPTC	1243.00	11.00	16750.00	550.00
24 FLUAZIFOP	3400.00	200.00	100000.00	3528.00
25 FLUFENACET	1465.00	25.00	5840.00	1608.00
26 FLUMETSULAM	10000.00	100.00	300000.00	2250.00
27 FLUMICLORAC	3310.00	106.00	1100.00	2250.00
28 FLUMIOXAZIN	2721.00	105.00	2300.00	2250.00
29 FLUROXYPYR	589.00	25.00	14300.00	2000.00
30 FLUTHIACET-METHYL	5000.00	100.00	91.50	2250.00
31 FORAMSULFURON	5000.00	163.00	100000.00	2788.00
32 GLUFOSINATE	3500.00	345.00	150000.00	2000.00
33 GLYPHOSATE	4936.50	100.00	15895.00	4245.00
34 HALOSULFURON	5000.00	100.00	72350.00	5620.00
35 IMAZAPYR	1680.00	100.00	100000.00	2150.00
36 IMAZAQUIN	5000.00	100.00	320000.00	2150.00
37 IMAZETHAPYR	1910.00	100.00	344000.00	2150.00
38 IODOSULFURON	5600.00	80.00	100000.00	2000.00
39 ISOXAFLUTOLE	8866.00	100.00	160000.00	2150.00
40 LACTOFEN	5000.00	160.00	2900.00	2510.00
41 LINURON	5000.00	120.86	9200.00	505.00
42 MCPA	2850.00	25.00	198500.00	377.00
43 MESOTRIONE	5000.00	100.00	532000.00	2000.00
44 METOLACHLOR	2439.00	200.00	8500.00	2352.00
45 METOLACHLOR-S	3836.00	200.00	7550.00	2194.00
46 METRIBUZIN	3530.00	60.40	92000.00	311.93
47 METSULFURON	1196.00	25.00	550000.00	2510.00
48 NICOSULFURON	1160.00	20.00	1000000.00	2000.00
49 OXYFLUORFEN	5000.00	100.00	400.00	3100.00
50 PARAQUAT	1988.50	34.00	12475.00	252.66
51 PENDIMETHALIN	2463.50	100.00	960.00	1421.00
52 PRIMISULFURON	1090.00	100.00	210000.00	2150.00
53 PROMETRYN	5000.00	99.00	4500.00	3395.00
54 PROPACHLOR	2855.00	25.00	255.00	518.25
55 PROSULFURON	9000.00	100.00	157500.00	1622.00
56 PYRAFLUFEN ETHYL	5000.00	100.00	100.00	2000.00
57 PYRIDATE	112.00	100.00	1650.00	1269.00
58 PYROXASULFONE	5000.00	100.00	970000.00	2250.00
59 QUINCLORAC	5050.00	181.29	225000.00	1974.68
60 QUIZALOFOP	4550.00	100.00	100000.00	2000.00
61 RIMSULFURON	1800.00	100.00	390000.00	1623.16
62 SAFLUFENACIL	986.00	100.00	10950.00	2000.00
63 SETHOXYDIM	5000.00	10.00	85800.00	3755.00
64 SIMAZINE	2830.50	96.70	70250.00	6250.00
65 SULFENTRAZONE	2427.50	25.10	93800.00	2250.00
66 SULFOSATE	1679.00	62.13	450000.00	1487.50
67 TEMBOTRIONE	1480.00	100.00	100000.00	2250.00
68 THIENCARBAZONE- METHYL	1480.00	210.00	105500.00	2250.00
69 THIFENSULFURON	2000.00	12.50	1000.00	2510.00
70 TOPRAMEZONE	2676.00	100.00	100000.00	2000.00

	Compound	Rat	Honey Bee	Fish	Bird
71	TRALKOXYDIM	5000.00	100.00	7500.00	3725.00
72	TRIBENURON METHYL	2689.00	100.00	100000.00	2250.00
73	TRICLOPYR	748.00	100.00	9650.00	1698.00
74	TRIFLURALIN	2215.00	24.17	120.00	2000.00
75	ACIFLUORFEN	2000.00	12.50	400.00	1573.00
76	CLOMAZONE	3184.50	25.00	13160.00	2510.00
77	ETHALFLURALIN	4750.00	46.00	119.00	1100.00
78	FENOXAPROP	934.00	100.00	580.00	3755.00
79	FOMESAFEN	3125.00	100.00	3355000.00	5000.00
80	IMAZAMOX	712.00	25.00	120500.00	1898.00
81	NORFLURAZON	5000.00	235.00	12200.00	1755.00
82	CLOTRANSULAM-METHYL	5000.00	25.00	86000.00	2250.00
83	MSMA	1766.50	25.00	499000.00	834.00
84	NAPTALAM	1700.00	113.20	76100.00	4640.00
85	TRI-ALLATE	3612.00	31.05	1300.00	2251.00
86	ACEPHATE	803.00	1.80	796000.00	247.50
87	ALPHA-CYPERMETHRIN	239.50	0.04	1.86	2000.00
88	BIFENTHRIN	134.65	0.01	3.20	2550.00
89	CARBARYL	230.00	0.84	3470.00	1156.50
90	CARBOFURAN	5.00	0.16	530.00	1.99
91	CHLORANTRANILIPROLE	5000.00	4.00	2160.00	2250.00
92	CHLORETHOXYFOS	3.30	0.09	45.65	28.00
93	CHLORPYRIFOS	132.00	0.07	108.00	26.65
94	CLOTHIANIDIN	3500.00	0.04	104200.00	1211.50
95	CYFLUTHRIN	767.00	0.02	0.87	2708.33
96	CYHALOTHRIN-GAMMA	2500.00	0.01	1.11	2000.00
97	CYHALOTHRIN-LAMBDA	77.75	0.05	3.42	3950.00
98	CYPERMETHRIN	644.90	0.03	4.70	8500.00
99	DELTAMETHRIN	62.10	0.02	1.86	1000.00
100	DIAZINON	299.25	0.38	2985.00	4.75
101	DIMETHOATE	231.30	0.12	7150.00	27.07
102	DISULFOTON	4.20	3.70	2600.00	9.43
103	ESFENVALERATE	206.50	0.03	0.25	1478.51
104	ETHOPROPHOS	40.50	4.80	2070.00	21.58
105	ETOXAZOLE	5000.00	200.00	2800.00	2000.00
106	FENPYROXIMATE	421.30	11.00	1.00	2000.00
107	FIPRONIL	97.50	0.01	83.00	39.19
108	FLUBENDIAMIDE	2000.00	200.00	73.95	2000.00
109	FONOFOS	13.00	5.99	28.50	17.63
110	HEXYTHIAZOX	5000.00	200.00	530.00	3620.27
111	IMIDACLOPRID	424.90	0.06	229100.00	35.36
112	LINDANE	85.00	0.66	90.00	90.83
113	MALATHION	981.10	0.47	778.70	400.16
114	METHOMYL	22.35	0.49	1220.00	20.52
115	METHYL PARATHION	12.50	2.70	5220.00	9.16
116	PERMETHRIN	758.15	0.06	6.00	12909.00
117	PHORATE	1.52	6.00	19.00	4.96
118	PROPARGITE	2413.20	62.00	155.00	4640.00
119	SPIROMESIFEN	2250.00	200.00	16.00	2000.00
120	TEBUPIRIMPHOS	2.80	0.32	48.35	20.30
121	TEFLUTHRIN	25.25	0.28	3.80	2462.00
122	TERBUFOS	2.95	4.10	9.80	12.24
123	THIAMETHOXAM	1563.00	0.02	107000.00	1552.00
124	ZETA-CYPERMETHRIN	234.00	0.00	1.01	4640.00
125	ALDICARB	0.65			
126	PARATHION	2.00			
127	AZINPHOS-METHYL	7.00			
128	DICROTOPHOS	13.00			
129	ETHION	13.00			
130	ENDOSULFAN	18.00			
131	METHYL IODIDE	76.00			
132	PHOSMET	92.50			
133	TRIBUFOS	150.00			
134	DIMETHYL DISULFIDE	290.00			
135	PROFENOFOS	358.00			
136	PROPANIL	367.00			
137	THIODICARB	398.00			
138	FLUOMETURON	1450.00			
139	PHOSPHORIC ACID	1530.00			
140	SODIUM METABORATE	2330.00			

Compound	Rat	Honey Bee	Fish	Bird
141 ETHEPHON	3400.00			
142 SODIUM CHLORATE	4330.00			
143 DECAN-1-OL	4700.00			
144 CRYOLITE	5000.00			
145 KAOLIN CLAY	5000.00			
146 MALEIC HYDRAZIDE	3800.00			10000.00
147 DSMA	821.00			
148 PROMETON	503.00			
149 PEBULATE	921.00			
150 BROMACIL	641.00			
151 ASULAM	2000.00			2000.00
152 THIOBENCARB	920.00			6157.67
153 MOLINATE	369.00			
154 PICLORAM	8200.00			2000.00
155 BENSULIDE	271.00			1386.00
156 ORYZALIN	10000.00			1000.00
157 DICLOFOP	563.00			10000.00
158 CHLORIDAZON	647.00			
159 CYCLOATE	1678.00			
160 DCPA	3000.00			
161 IMAZAMETHABENZ	5000.00			
162 DIFENZOQUAT	470.00			
163 VERNOLATE	1200.00			
164 BENFLURALIN	10000.00			2000.00
165 NAPROPAMIDE	5000.00			
166 CHLORAMBEN	3500.00			
167 TEBUTHIURON	644.00			500.00
168 DICHLORPROP	344.00			
169 ETHOFUMESATE	1130.00			
170 HEXAZINONE	1690.00			2258.00
171 PROPAZINE	3840.00			
172 TRIDIPHANE	1500.00			2510.00
173 DESMEDIPHAM	9600.00			2480.00
174 CALCIUM CHLORIDE	1000.00			
175 TERBACIL	1700.00			
176 DICHLOBENIL	2710.00			
177 FATTY ALCOHOLS	10080.00			
178 MEPIQUAT	5000.00			
179 PHENMEDIPHAM	4000.00			3000.00
180 MECOPROP	650.00			
181 THIDIAZURON	5350.00			16000.00
182 DIQUAT	231.00			247.50
183 PINOXADEN	5000.00			
184 TRICHLORFON	450.00			61.70
185 FENAMIPHOS	8.00			4.27
186 METHAMIDOPHOS	7.50			30.17
187 TRIMETHACARB	178.00			64.26
188 SULPROFOS	65.00			65.00
189 BACILLUS THURINGIENSIS	5000.00			
190 PHOSPHAMIDON	11.50			2.45
191 METHOXYCHLOR	1855.00			2000.00
192 FORMETANATE	20.00			21.50
193 AMITRAZ	400.00			3894.00
194 PIPERONYL BUTOXIDE	6150.00			
195 FENVALERATE	70.20			4000.00
196 TEBUFENOZIDE	5000.00			
197 METHIOCARB	20.00			43.25
198 NALED	92.00			52.00
199 POTASSIUM OLEATE	5000.00			
200 SPINOSYN	3738.00			
201 INDOXACARB	1732.00			
202 GARLIC JUICE	174.00			
203 HYDROXYPROPANOIC ACID	3543.00			2250.00
204 METHOXYFENOZIDE	5000.00			
205 NOVALURON	5000.00			
206 DIFLUBENZURON	4640.00			
207 HYDRATED LIME	7300.00			
208 SPIRODICLOFEN	2500.00			
209 FENPROPATHRIN	46.00			1089.00
210 FLONICAMID	884.00			
211 BIFENAZATE	5000.00			
212 PYMETROZINE	5820.00			
213 ABAMECTIN	10.00			
214 PYRETHRINS	584.00			
215 CHENOPODIUM AMBROSIOIDES	2000.00			
216 SULFOXAFLOL	1000.00			
217 ALPHA CYPERMETHRIN	79.00			
218 DINOTEFURAN	2450.00			
219 ACETAMIPRID	417.00			
220 SPINETORAM	1322.00			
221 BUPROFEZIN	2198.00			
222 FLUPYRADIFURONE	300.00			

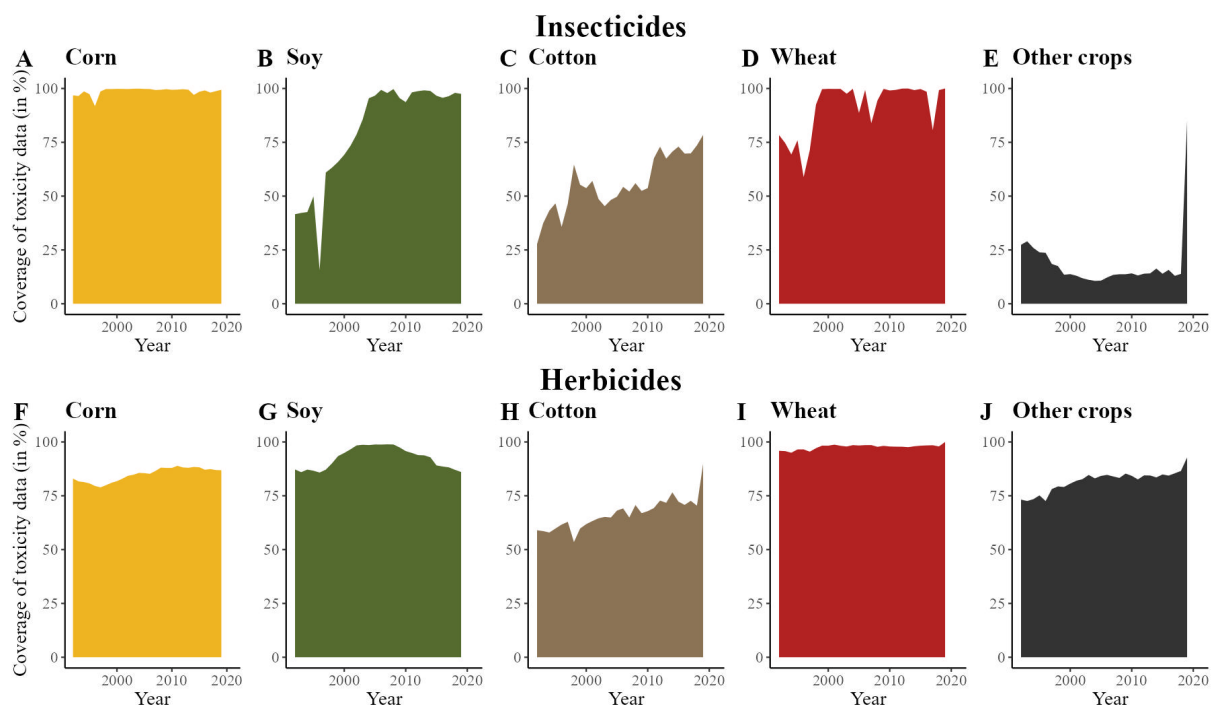


Figure V1: Share of insecticide and herbicide use (total weight) over time that is covered by LD50 values for birds.

W GM crop impact on pesticide amounts

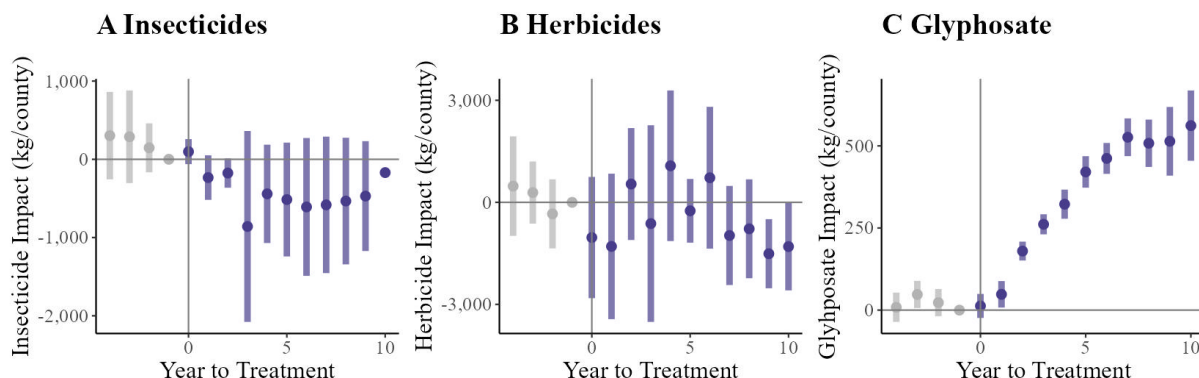


Figure W1: The impact of an additional percentage point of GM crop adoption on insecticide, herbicide and glyphosate use per county.

To demonstrate the impact of GM crops on each pesticide, we use model (5) to estimate the effect of GM crops on insecticide, herbicide and glyphosate use (in kg) in the counties and years where we estimate the impact of GM crops on birds. We find a decrease in insecticide use following GM crop adoption and no change in herbicide use (Fig. W1). At the same time, glyphosate use increased markedly, suggesting that there was a major shift in herbicide use following GM crop adoption. This pattern also persists when we look at average pesticide trends between counties with high and low share of corn, soy and cotton (Fig. W2).

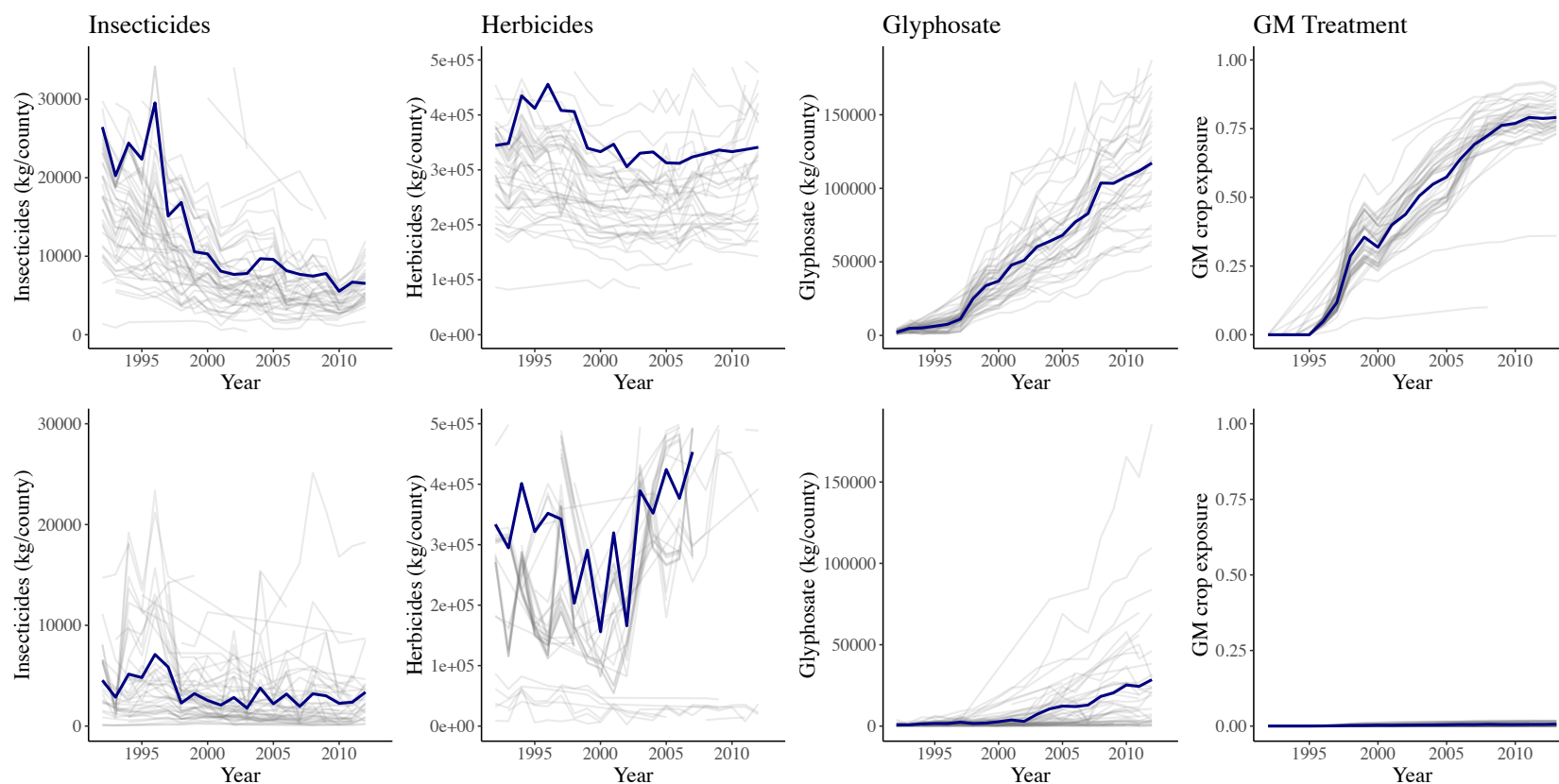


Figure W2: USGS Pesticide National Synthesis Project data on state level. Insecticide, herbicide and glyphosate active ingredient use, as well as exposure to GM treatment in counties with a share of more than 80% corn, soy and cotton (top row) and ones with less than 2% corn, soy and cotton (bottom row). Average values in blue. Cutoffs chosen to visualize a broadly similar number of observation in each sample. Observations with a maximum value of insecticide, herbicide or glyphosate use in the top 1% were removed to filter out extreme outliers, for visualization purposes.

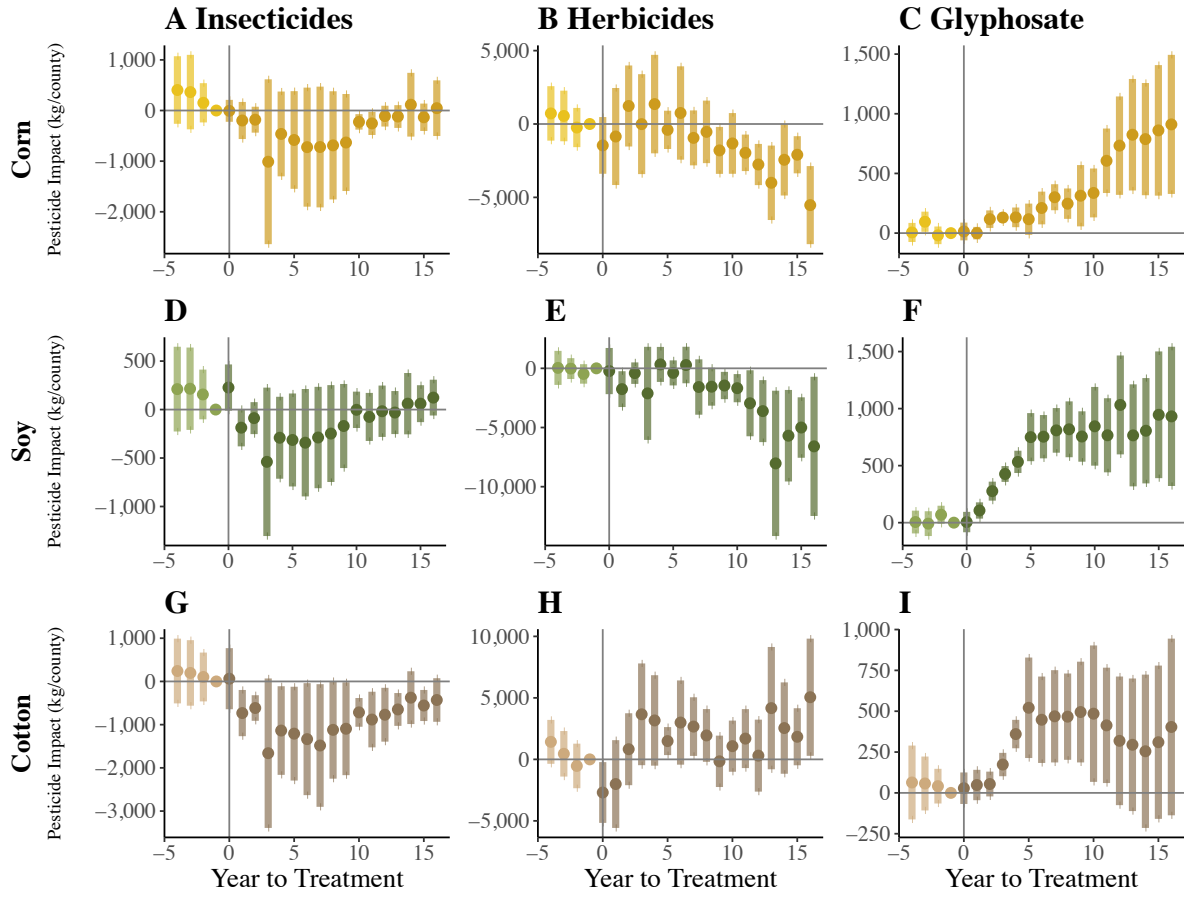


Figure W3: The impact of an additional percentage point of GM corn (yellow), soybeans (green) and cotton (brown) adoption on insecticide, herbicide and glyphosate use per county.

We also estimate the impact of GM corn, soybeans and cotton individually on insecticide, herbicide and glyphosate use using model (6). We find the largest decrease in insecticide use on cotton, followed by corn and soy, although the insecticide use reductions on corn and soy are not statistically significant (Fig. W3, panel G, A and D). The reduction of insecticide use being smallest on soy-growing areas is expected, as GM soy does not incorporate the insect-repellent Bt trait. We find initial increases in total herbicide use on cotton (panel H), and no change on soybeans and corn (panel B and E). Finally, we find a strong increase in glyphosate use on soybeans, and a smaller increase on corn and cotton (panel F, C and I, respectively).

X GM crop impacts on toxicity to birds

As in Appendix W, we estimate the impact of GM crop adoption on pesticide toxicity using models (5) and (6) with insecticide and herbicide risk quotient as an outcome and GM crop adoption as a treatment variable (Fig. X1 and Fig. X2).

To statistically test pesticide toxicity as a mechanism, we include a control for pesticide toxicity in the regression model used to estimate the effect of GM crops on bird populations. If direct pesticide toxicity is the primary mechanism through which GM crops affect birds, the toxicity variable would absorb the variation in bird populations that are associated with GM crops and cause the coefficients of GM crop exposure (i.e. the treatment variable in the main estimation) to shift towards zero. However, the estimated direct effect of GM crop adoption on bird diversity does not change substantially or consistently after including our measure of pesticide toxicity (Fig. X3). There are several possible explanations for this. First, it could be that the observed impact of GM crops is due to other reasons than changes in pesticide use. However, it is unlikely that pesticide use is not at least partially responsible for the effect, as it is the most prominent impact of GM crop adoption and because pesticides have been shown to have large impacts on bird populations. Second, it could be that the pesticide data is not precise enough for this purpose, as it is based on surveys and is rather coarse in the first place. While it might be sufficient to see broad patterns as presented in Fig. O1 (Appendix O), the measurement error might compound to a degree that the data is not accurate enough to explain the observed effects at BBS route-level. To support this argument, we plot the residuals of two regressions against each other: pesticide toxicity on weather controls and fixed effects against GM crop adoption on weather controls and fixed effects (Fig. X4). For pesticide toxicity to absorb variation from GM crop adoption in the regression, there would have to be a correlation between the residuals, which we don't observe here. It is therefore, possible that the fixed effects remove too much observation for this strategy to work. Third, the pesticide toxicity impacts might work through a different pathway than what is measured through LD50, which is toxicity following oral ingestion.

This pathway might be accurate for pesticides that are used as seed coatings or as granular and are indeed orally ingested, but possibly less so for spray applications. One of these pathways would be through trophic levels if the change in pesticide use leads to a change in toxicity to and survival rates of non-target insects, which was our initial assumption when estimating effects on birds of different feeding guilds.

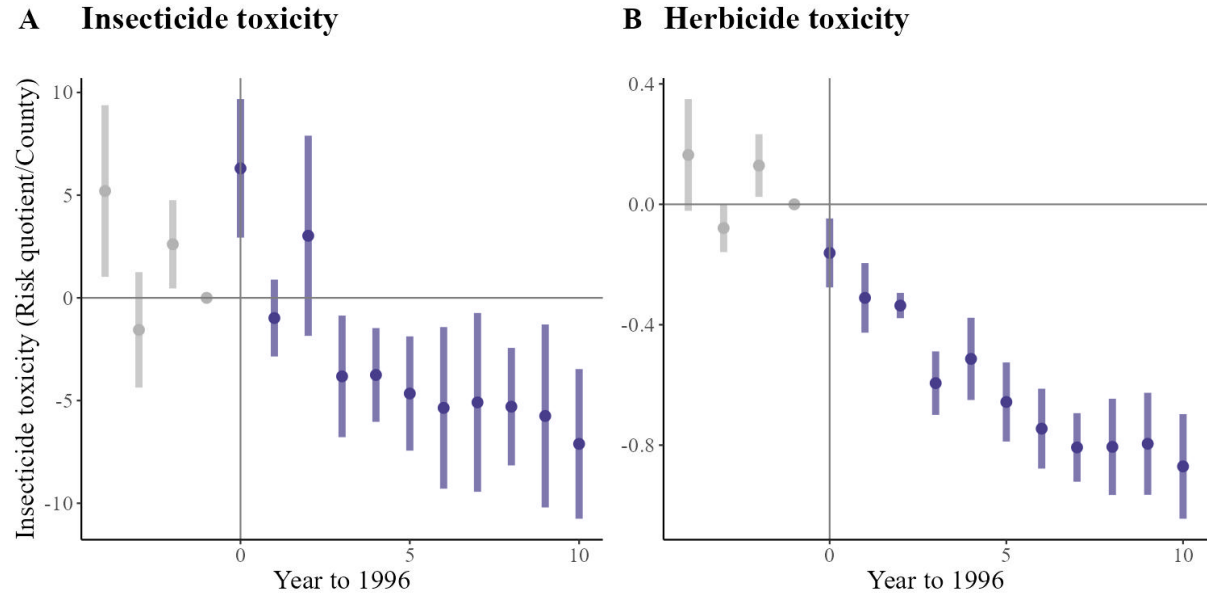


Figure X1: The impact of an additional percentage point of GM crop adoption on insecticide and herbicide bird toxicity in counties that have bird observations used in this study.

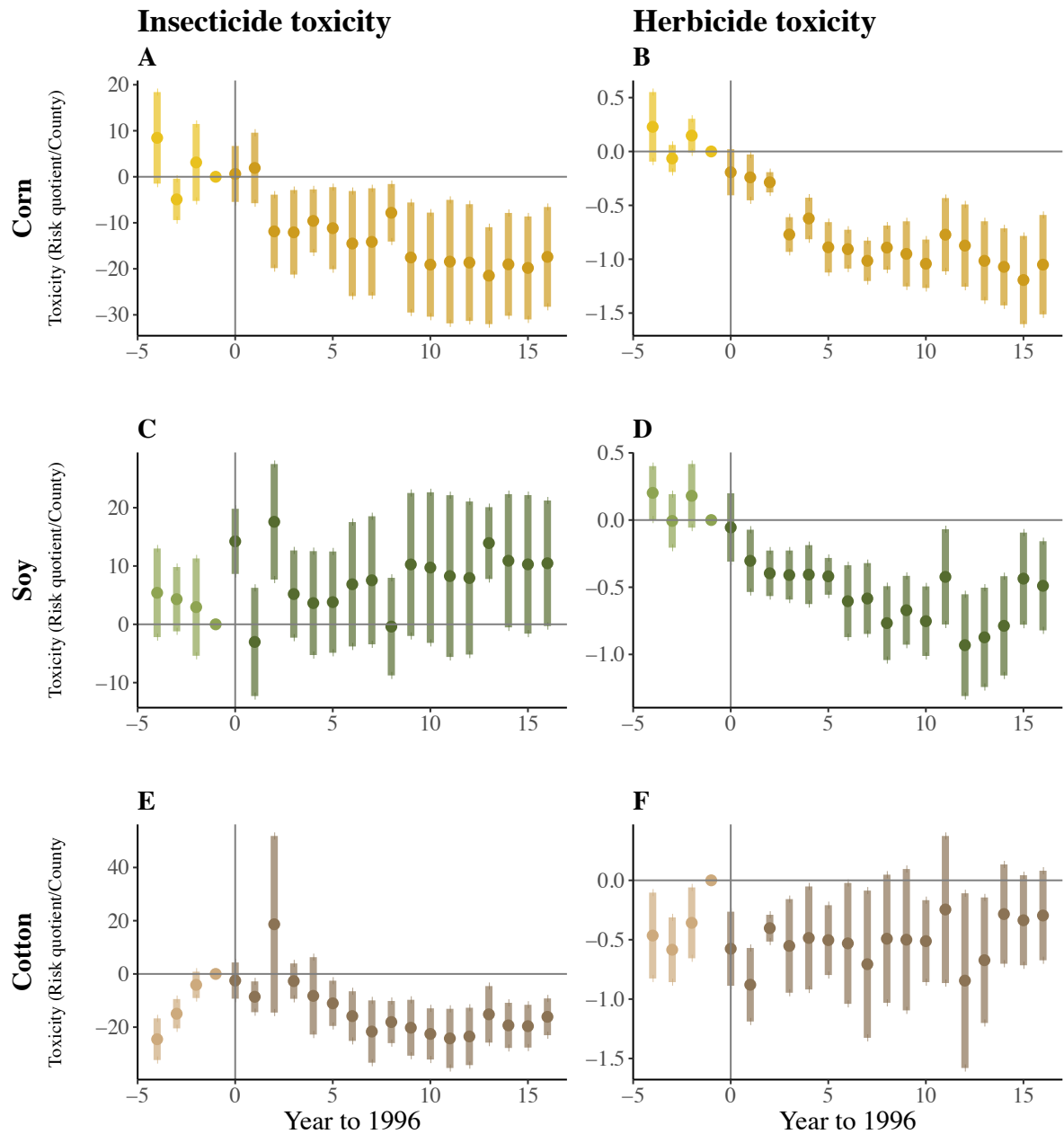


Figure X2: The impact of an additional percentage point of GM corn (yellow), soybeans (green) and cotton (brown) adoption on insecticide and herbicide bird toxicity in counties that have bird observations used in this study.

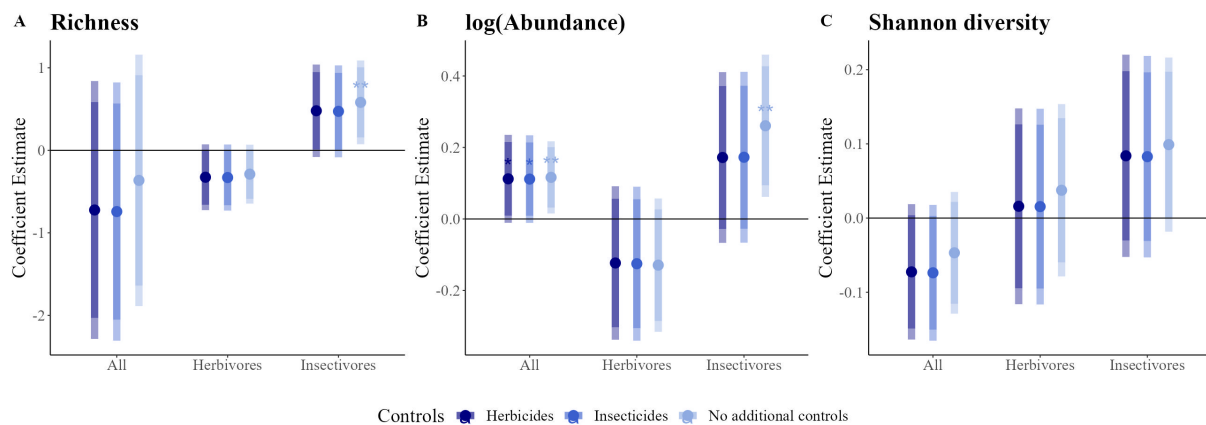


Figure X3: The impact of GM crops on all, insectivorous and herbivorous birds with and without controls for insecticide and herbicide bird toxicity. Dark and light bars indicating 90% and 95% confidence intervals respectively, and stars indicating p-values (* : $P < 0.1$, ** : $P < 0.05$, *** : $P < 0.01$).

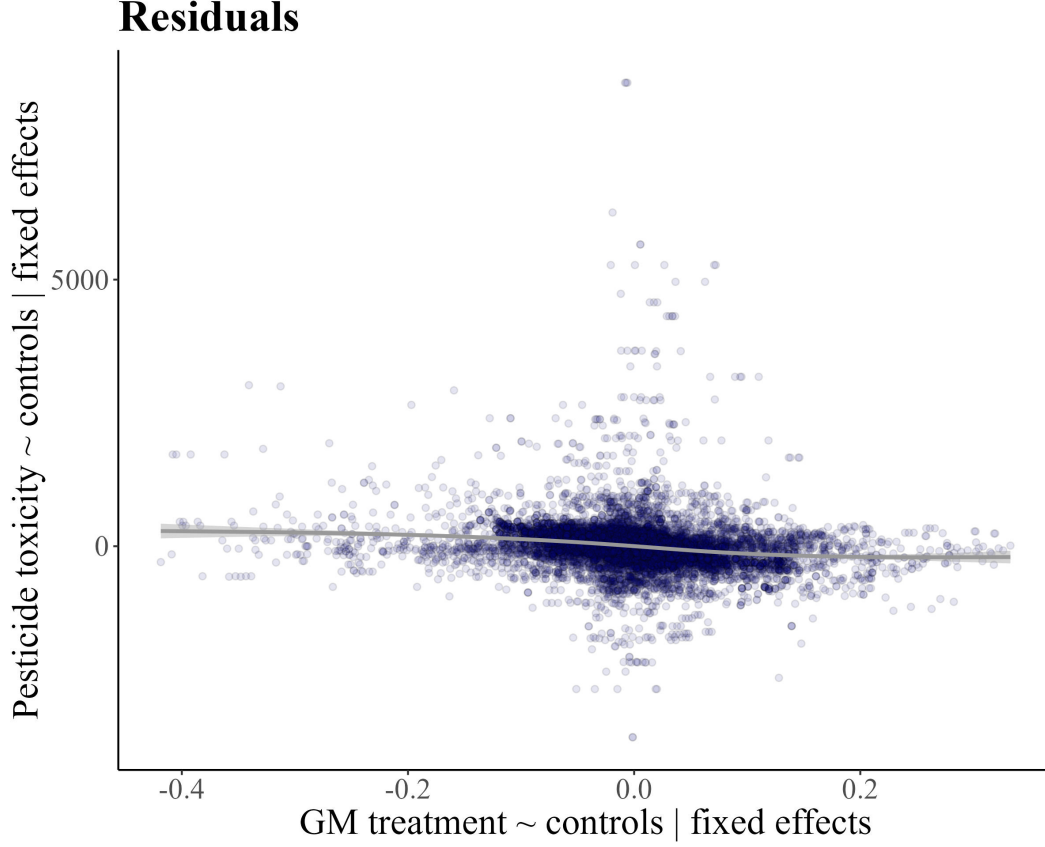


Figure X4: Residuals of the estimation of GM crop adoption on controls and fixed effects plotted against residuals of the estimation of pesticide toxicity on controls and fixed effects.

The residuals plotted on the x-axis are from the regression:

$$\text{GMExposure}_{it} = \gamma X_{it} + \delta_t + \eta_i + \lambda_o + \epsilon_{it} \quad (7)$$

The residuals plotted on the y-axis are from the regression:

$$\text{PesticideToxicity}_{it} = \gamma X_{it} + \delta_t + \eta_i + \lambda_o + \epsilon_{it} \quad (8)$$

where $\text{PesticideToxicity}_{it}$ is the pesticide toxicity risk quotient of pesticide use in county i in year t .

Y GM crop impacts on crop diversity

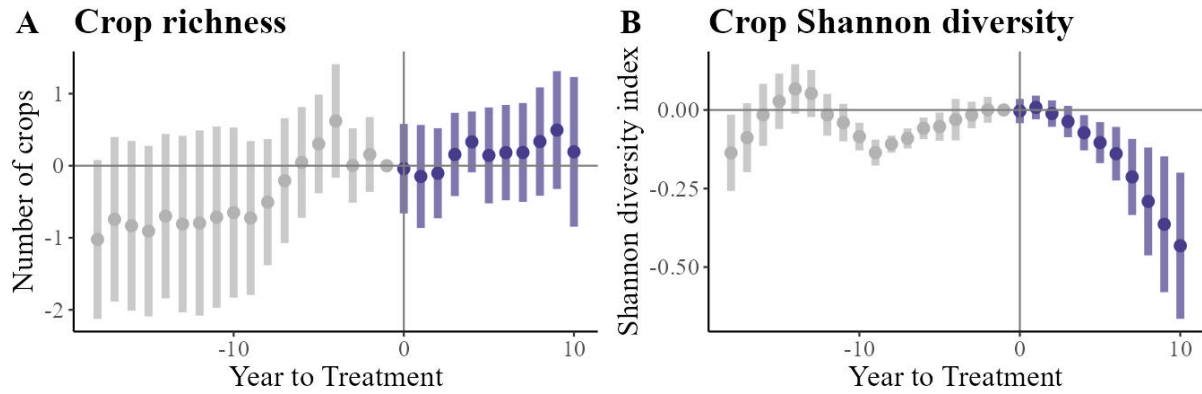


Figure Y1: The impact of an additional percentage point of GM crop adoption on crop richness (number of crops grown) and crop Shannon diversity in counties that have bird observations used in this study.

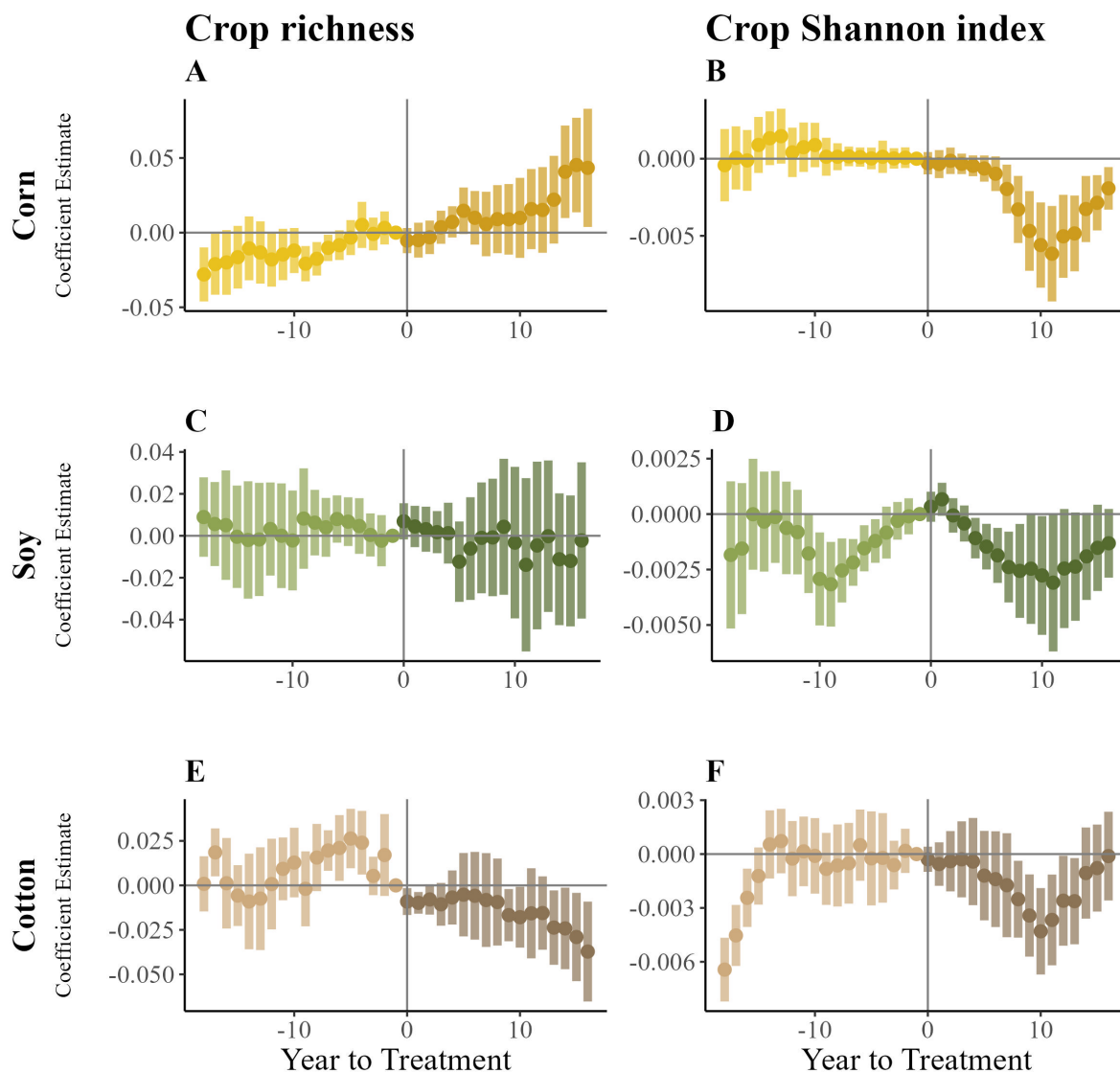


Figure Y2: The impact of an additional percentage point of GM corn (yellow), soybeans (green) and cotton (brown) adoption on crop richness (number of crops grown) and crop Shannon diversity in counties that have bird observations used in this study.