Agricultural landscape simplification and insecticide use in the Midwestern United States

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Agronomic intensification has transformed many agricultural landscapes into expansive monocultures with little natural habitat. A pervasive concern is that such landscape simplification results in an increase in insect pest pressure, and thus an increased need for insecticides. We tested this hypothesis across a range of cropping systems in the Midwestern United States, using remotely sensed land cover data, data from a national census of farm management practices, and data from a regional crop pest monitoring network. We found that, independent of several other factors, the proportion of harvested cropland treated with insecticides increased with the proportion and patch size of cropland and decreased with the proportion of seminatural habitat in a county. We also found a positive relationship between the proportion of harvested cropland treated with insecticides and crop pest abundance, and a positive relationship between crop pest abundance and the proportion cropland in a county. These results provide broad correlative support for the hypothesized link between landscape simplification, pest pressure, and insecticide use. Using regression coefficients from our analysis, we estimate that, across the seven-state region in 2007, landscape simplification was associated with insecticide application to 1.4 million hectares and an increase in direct costs totaling between $34 and $103 million. Both the direct and indirect environmental costs of landscape simplification should be considered in design of land use policy that balances multiple ecosystem goods and services.

agriculture | biocontrol | crop pests | land cover change | pesticides

The last century has brought enormous increases in the extent and intensity of agricultural activities (1, 2). During this period, agricultural landscapes across the planet have lost considerable amounts of natural habitat to crop production, plant diversity at the patch and landscape scale has declined, and crop patches have increased in size and connectivity (3, 4). This trend, often termed "landscape simplification" (5, 6), is widely expected to increase insect pest pressure on crops, leading to increased use of insecticides (7, 8).

The link between landscape simplification, pest pressure, and insecticide use is expected on the basis of two lines of logic. First, conversion of diverse natural plant assemblages to monocultures, at both patch and landscape scales, is known to reduce the abundance and diversity of natural enemies of crop pests (9–11), which has been associated with reductions in natural pest-control services (9). Second, increases in the size, density, and connectivity of host crop patches are expected to facilitate movement and establishment of crop pests (10, 12), leading to higher pest pressure regardless of natural enemy activity.

Literature reviews have consistently concluded that the relationship between landscape simplification and pest pressure, although logical, is not well supported by empirical evidence (9, 13, 14). The available studies have been conducted at relatively small spatial scales, have focused on a narrow assortment of crops and pests, and have yielded mixed results (9, 13). Further, it is not well established that increased pest pressure due to landscape simplification is enough to decrease crop yields to the point where increased insecticide use is necessary (9, 13, 14). Understanding relationships between landscape simplification, pest pressure, and insecticide use over a broad range of environmental conditions and crop types is essential if we want science-based policy to guide future landscape change (15, 16). Here, we explore these relationships, along with their agronomic and economic consequences, across 562 counties in seven states of the Midwestern United States.

Results

In this study, landscape simplification was represented by the proportion of land in a county in field crops, vegetable crops, and fruit crops (hereafter "proportion cropland"). We chose this measurement because it is easily estimated and interpreted and because it is tightly correlated with several other indicators of landscape simplification, including average crop patch size, crop patch connectivity, and the proportion of seminatural habitat in a county (*Materials and Methods* and Fig. S1). We evaluated the link between landscape simplification and pest pressure using an index of insecticide application (hereafter "insecticide use"), calculated as the proportion of harvested cropland in a county treated with insecticides. A relationship between pest pressure and insecticide use is expected, given the standard economic assumption that minimizing cost and maximizing income are key objectives of producers, and that these objectives are met using insecticides when pest pressure is observed or expected to cause economic damage (17, 18). The index is positively related to total mass of insecticide applied per year, indicating that it is not confounded by variation in the number of applications (*Materials and Methods* and Fig. S2).

We used spatial regression (19) to relate insecticide use (Fig. 1*A*) to proportion cropland (Fig. 1*B*) after accounting for several other factors that could drive insecticide use and confound our evaluation of the impact of landscape simplification. We included a covariate describing net farm income per hectare of harvested cropland (Fig. 1*C*) to account for the possibility that producers in simplified landscapes have larger incomes, increasing the likelihood that they will use preventative insecticide treatments to manage risk and ensure strong economic returns (20). We also included the proportion of cropland in corn (Fig. 1*D*), soybeans and small grains (Fig. 1*E*), and fruits and vegetables (Fig. 1*F*) as covariates, because these crops vary considerably in the degree to which they receive insecticides, due to differences in pest complexes and the sensitivities of crop yield and crop prices to pest damage (17, 21). These crop-specific variables also accounted for the possibility that simplified land-

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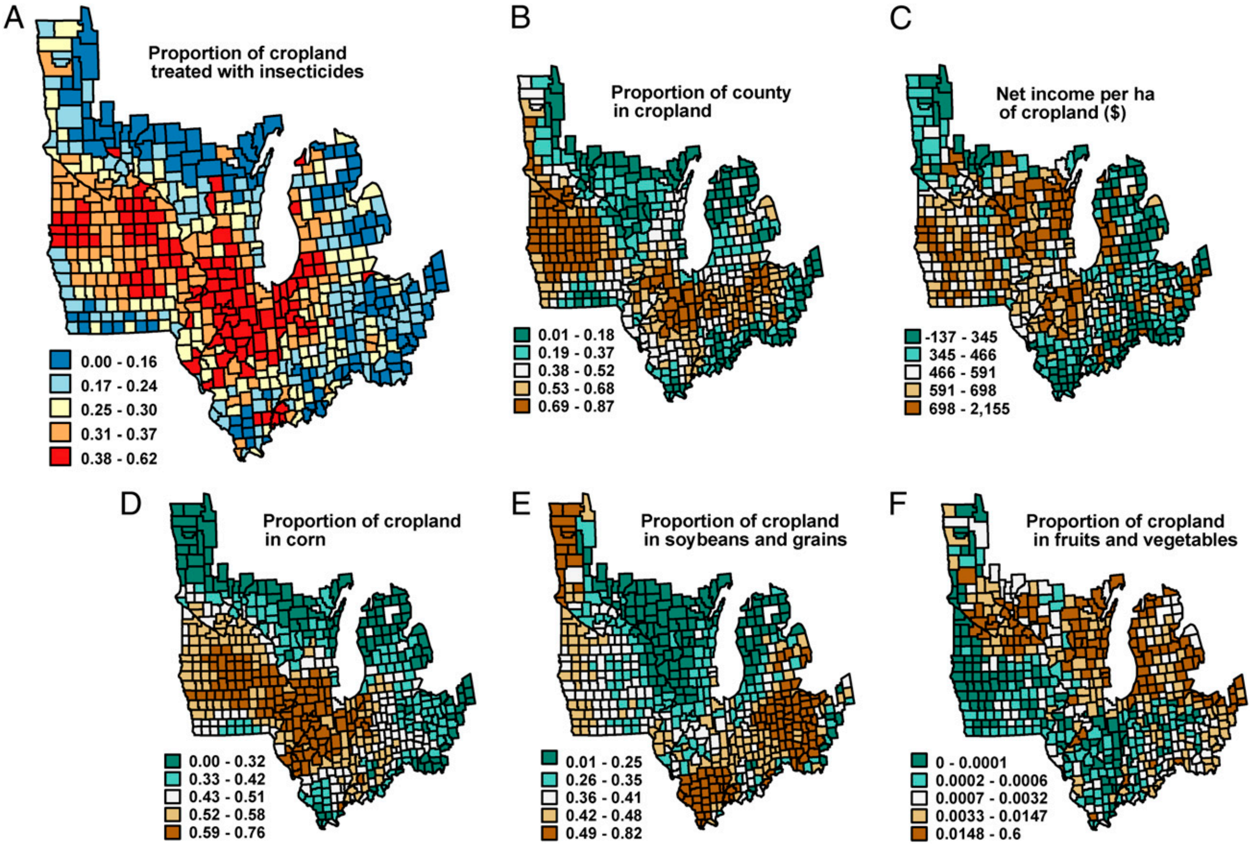

Fig. 1. Spatial distribution of model variables. Proportion of harvested cropland in a county that is treated with insecticide (*A*) compared with the proportion of a county in cropland (*B*), the net income per hectare of harvested cropland (*C*), and the proportions of cropland planted in corn (*D*), soybeans and small grains (*E*), and fruit and vegetable crops (*F*). For all maps, each color shade denotes 20% of the observations. Spatial regression of *A* versus *B*–*F* is presented in Table 1.

scapes are composed of crops with pests that are intensively managed with insecticides. Finally, we chose spatial regression over standard multiple regression to account for spatial structure in model residuals, possibly due to geographic variation in pest dynamics or farmer behavior.

Of the crop-specific covariates, insecticide use was most strongly related to the proportions of cropland in corn ($P < 0.001$) and fruits and vegetables ($P < 0.001$, Table 1). There was a marginally significant relationship between insecticide use and the proportion of cropland in soybeans and small grains ($P = 0.08$). The slope coefficients for crop-type terms indicated that, for a county composed of 43% cropland and netting $537 per harvested hectare (2007 averages for the study region), having all of the cropland planted in corn, soybeans and small grains, or fruits and vegetables would lead to 47, 11, or 95% of the cropland, respectively, being treated with insecticides. These figures are close to those documented by the US Department of Agriculture (USDA), who reported that 25 (10–55), 18 (8–42), and 90% (80–99%) of the corn, soybeans and small grains, and fruits and vegetables, respectively, were treated with insecticides between 2003 and 2005 in the states in this study (21). As expected, insecticide use was also positively related to net income per harvested hectare ($P = 0.008$). The intercept of the spatial regression model was not significantly different from zero ($P = 0.83$), matching the expectation that counties with no cropland would receive no insecticides. After accounting for several covariates, there was a positive relationship between insecticide use and landscape simplification ($P < 0.001$, Table 1, Fig. 2, and Table S1). Given the strong economic motive to minimize insecticide costs, we interpret this positive relationship as correlative support for the hypothesis that landscape simplification increases pest pressure and ultimately leads to increased insecticide use.

Table 1. Results from spatial regression of insecticide use index from 562 counties in seven states of the Midwestern United States

Model term*	Coefficient (SE)	*P*
Intercept	−0.004 (0.02)	0.83
Proportion county in cropland	0.08 (0.02)	<0.001
Net income per harvested ha	0.00003 (0.00001)	0.008
Proportion of cropland in corn	0.42 (0.04)	<0.001
Proportion of cropland in soybeans and small grains	0.06 (0.03)	0.08
Proportion of cropland in fruits and vegetables	0.90 (0.06)	<0.001

*Nagelkerke R^2 for the full spatial regression model was 0.73.

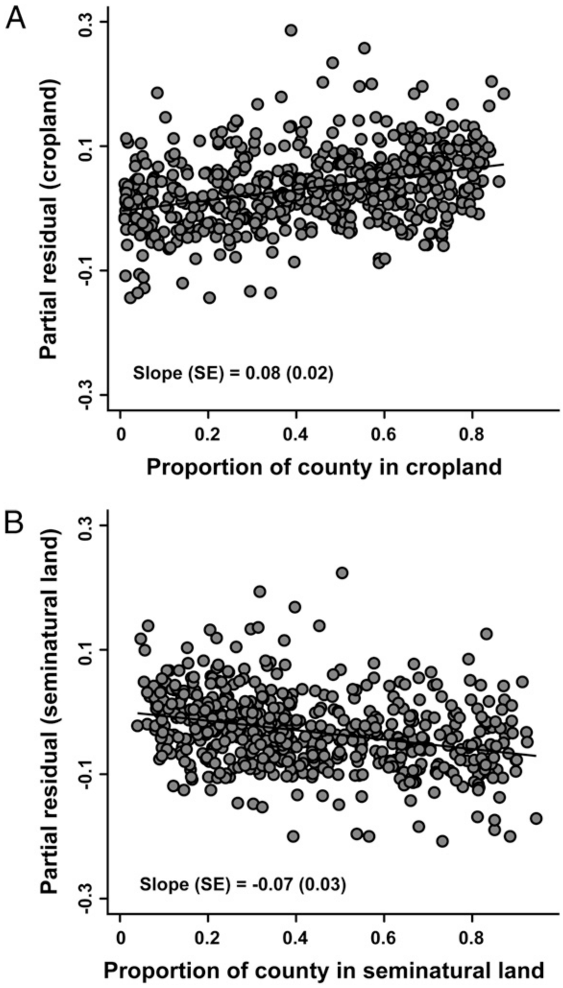

Fig. 2. The partial effects of proportion cropland and proportion seminatural land on insecticide use. In these partial residual plots, *y* values are calculated by adding the residual from the full model to the product of proportion cropland and the slope estimate for proportion cropland (*A*, Table 1) or the product of proportion seminatural land and the slope estimate for proportion seminatural land (*B*, Table S1).

The positive correlation between landscape simplification and insecticide use supports hypothesized relationships between landscape simplification, pest pressure, and insecticide use, but does not necessarily indicate causation. Thus, we examined a second dataset, from the North Central Soybean Aphid Suction Trap Network (22), for additional links between these variables. Suction trap catches during the summer months have been shown to reflect aphid densities in crop fields (23–27) up to 80 km (28) from sampling stations. We obtained data from this network on corn leaf aphid (*Rhopalosiphum maidis*), soybean aphid (*Aphis glycines*), and bird cherry-oat aphid (*Rhopalosiphum padi*) abundance in 2007 for 36 sampling stations across the study region. These aphid species are economically relevant pests of three dominant crops in the region (corn, soybeans, and wheat), and each have specific scouting procedures and economic thresholds for insecticide treatment (29). We summed weekly counts from June 1 through August 30 to obtain a total count per taxon, and then summed counts across taxa to produce an index of pest aphid abundance per sampling station for the summer months of 2007 (hereafter, "aphid abundance"). We regressed the natural log of aphid abundance against the area-weighted average of both insecticide use and proportion cropland within 48 km of suction trap sites. We found a positive relationship between aphid abundance and insecticide use ($P < 0.001$, Fig. 3 *A* and *B*). We also found a positive relationship between aphid abundance and proportion cropland ($P = 0.046$, Fig. 3*C*). These results represent additional correlative support for the hypothesis that simplification of agricultural landscapes leads to higher pest pressure and increased insecticide use.

Assuming causal relationships between landscape composition, pest pressure, and insecticide use (*Discussion*), we used our results to assess the agronomic and economic implications of landscape simplification. For example, a typical county in the region is ∼43% cropland and has ∼74,000 harvested hectares (2007 averages for the study region). When these figures are multiplied by the slope coefficient of 0.08 from Table 1, we estimate that an average county has ∼2,500 ha treated with insecticides due solely to increased pest pressure from landscape simplification. When scaled to the Midwestern United States, we find that ∼1.4 million ha are treated with insecticides due to increased pest pressure from landscape simplification. Given the 95% confidence interval for the coefficient, that total could range from 700,000 to 2.1 million ha.

What does this mean in monetary terms? Increased pest pressure costs producers in two ways. First, there are direct costs associated with the purchase and application of insecticide. Second, there is often a lag between when insect pests begin reducing yields and when it is profitable for producers to invest in insecticide application (30). When we considered both insecticide and yield-related costs, we estimated that increased pest pressure due to landscape simplification costs approximately $48 per affected hectare. When we multiply this estimate by the area treated with insecticide due to landscape simplification, we find that landscape simplification increases the cost of farming by about $122,000 in the average county. Extending this to the region, we estimate that pest pressure due to landscape simplification cost Midwestern farmers approximately $69 million in 2007. Given the 95% confidence interval for the proportion cropland coefficient, that total could range from $34 million to $103 million.

Discussion

A relationship between landscape simplification, pest pressure, and insecticide use has long been assumed. Indirect support for this relationship has come from work on the effects of vegetational diversity and landscape structure on natural enemy abundance and pest colonization (9–12, 31). However, direct evidence for this relationship and an evaluation of its agronomic and economic consequences have been lacking (9, 13, 14). Results from this study provide unique correlative support for this relationship over an unprecedented range of cropping systems and environmental conditions, spanning a globally important farming region.

The strength of the observational approach used in this study is that it allowed us to evaluate the generality of the hypothesized relationship between landscape simplification, pest pressure, and insecticide use across a large area under a broad range of conditions. At these scales, manipulative experiments are simply not possible. The drawback of the approach is that it necessarily relies on correlative evidence. Thus, there could be other factors, besides the ones examined in our study, that are driving landscape-related patterns of insecticide use by influencing farmer decision making. We explored some possible confounding factors, such as the availability of insecticide application equipment and the prevalence of genetically modified crops, and have determined that these variables are not affecting our conclusions (*SI Text*). Other potential confounding factors are more difficult to evaluate. For example, it is possible that producers in simplified landscapes are not strictly basing their insecticide use decisions on the abundance of pests and optimal economics, but

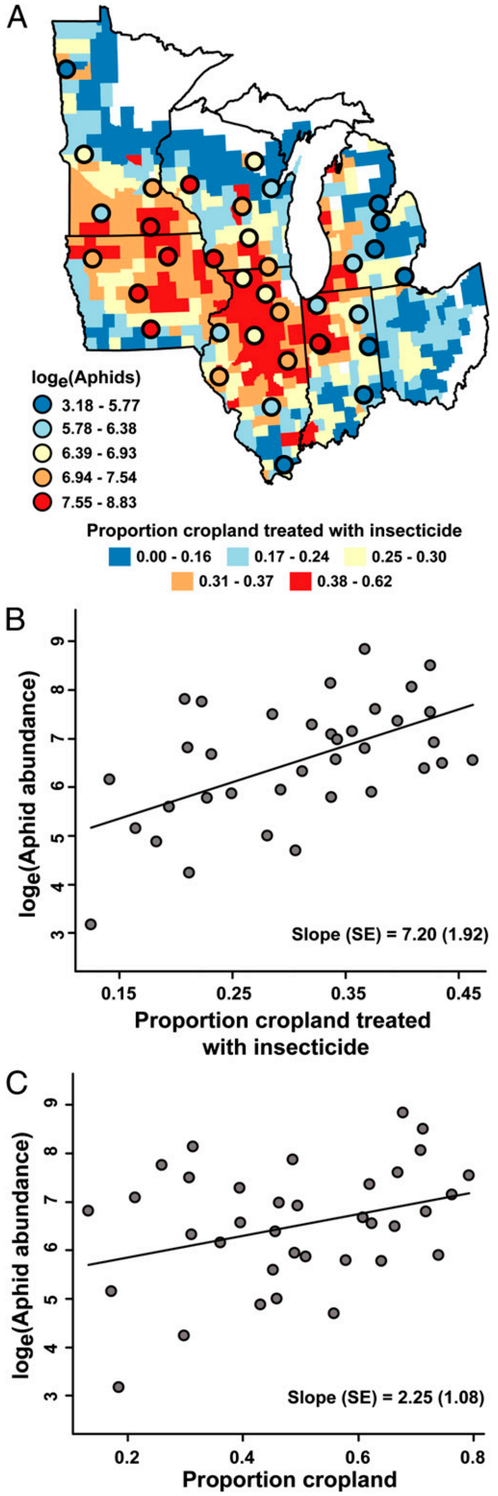

Fig. 3. Spatial correspondence (*A*) and bivariate relationship (*B*) between the proportion of cropland treated with insecticide in a 48-km radius buffer and the natural log of crop pest abundance, as represented by the number of corn leaf aphids (*Rhopalosiphum maidis*), soybean aphids (*Aphis glycines*), and bird cherry-oat aphids (*Rhopalosiphum padi*, a small grains pest) captured in suction traps throughout the Midwestern United States. (*C*) Relationship between the proportion cropland in a 48-km radius buffer and the natural log of crop pest abundance. Suction trap data are from the North Central Soybean Aphid Suction Trap Network (*Results*).

are instead inclined to use more insecticides for unknown cultural reasons. We have done our best to account for latent cultural factors in our analysis through the use of spatial regression techniques. However, cultural factors that are not spatially structured cannot be captured using these methods and thus cannot be ruled out as causative mechanisms.

If we assume that our results do indeed represent causal relationships, then we can use relationships derived from this study to evaluate agronomic and economic implications of landscape simplification. Under this assumption, we estimated that landscape simplification accounts for insecticide application on 1.4 million ha of harvested cropland in the Midwestern United States. For reference, this area is five times larger than the state of Rhode Island. Using an average cost of insecticide application, we estimated that this additional insecticide treatment cost Midwestern farmers approximately $69 million per year. It is useful to view this cost in the context of other costs and benefits considered by farmers. From this perspective, the loss of farm revenue attributable to landscape-mediated changes in pest pressure is relatively small. For example, the net farm income across the region was approximately $26 billion in 2007, which is more than two orders of magnitude higher than the cost associated with increased pest pressure. Commodity prices were exceptionally high in 2007 (32), but even halving these prices still results in a very large difference between costs and gains. Given that the effects of landscape simplification on pest pressure come with relatively small direct costs to producers, it is clear why extensive landscape simplification has occurred in the region.

Thus, the direct costs of pest pressure due to landscape simplification may be considerable, but small compared with net gains that come from farming more land. However, landscape simplification incurs additional costs that are borne by society as a whole. These include indirect costs of increased insecticide use that arise from (*i*) health problems due to direct human exposure or air and water pollution, (*ii*) development of insecticide resistance by crop pests, and (*iii*) mortality of beneficial organisms that perform services across agricultural landscapes (33). Pimentel et al. (33) estimated that these indirect costs can be twice as large as direct costs. Other costs associated with conversion of seminatural land to cropland include (*i*) increases in nutrient leaching and runoff, (*ii*) reductions in flood control, (*iii*) reductions in wildlife and hunting habitat, and (*iv*) reductions in carbon sequestration (1, 34). Quantifying these costs remains a major challenge for environmental scientists and a prerequisite for policy that ameliorates conflicts between individual producer interests and those of society in general (15, 16).

Finally, the need to feed a growing human population is expected to drive further landscape simplification across the globe (35). In addition, agricultural landscapes could face further pressure as demand for bioenergy feedstocks increases (36, 37). Expansion of intensively managed, annual bioenergy crops will likely bring direct and indirect costs similar to those discussed above for food crops (38). In contrast, moderately diverse, minimally managed perennial bioenergy crops could resemble seminatural habitats, and their adoption could help mitigate the negative effects associated with current landscape structure (39–41). In the present economic environment, where production is highly valued and environmental costs are not, first generation bioenergy feedstocks are more profitable for producers (42). Policies that close the profitability gap and encourage production of perennial bioenergy crops could serve multiple purposes if they promote provisioning of multiple ecosystem services, while also providing feedstocks for low-carbon energy (43).

Materials and Methods

2007 Cropland Data Layer. Data on the spatial distribution of cropland and seminatural habitats were derived from the 2007 Cropland Data Layer, a 56-m resolution, remotely sensed land cover map available from the USDA National

Agricultural Statistics Service (44). For our analysis, cropland included all land in field crops (except nonalfalfa hay), vegetable crops, and fruit and nut crops. Seminatural habitats included forests (deciduous forest, conifer forest, and mixed forest), open perennial habitat (grassland, nonalfalfa hay fields, pasture, and fallow cropland), and wetlands (wooded and herbaceous). Proportions of cropland and seminatural land were calculated as the area of each land-cover type divided by the total area of a county. Fifty-six counties with proportions of cropland <0.01 and 6 counties with proportions of urban land (medium- and high-intensity development) >0.75 were excluded from the dataset due to our focus on agricultural landscapes, leaving 562 counties in the analysis. Cropland patch size was the average per county in hectares. Cropland patch connectivity was the inverse of the mean nearest neighbor distance between cropland patches per county in meters. Cropland patch statistics were computed irrespective of crop type, i.e., a contiguous patch could include one or several types of crops. All landscape metrics were computed using the Patch Analyst (45) extension, which implements FRAGSTATS (46) within ArcGIS (47).

2007 Census of Agriculture. Data on the aerial extent of insecticide application, total harvested cropland, corn, soybeans, small grains (wheat, oats, and barley), vegetables, and fruit and nut orchards came from the 2007 Census of Agriculture, available online from the USDA National Agricultural Statistics Service (48). The insecticide use index used in our analysis was calculated as the total area of land treated with insecticides divided by the total area of harvest cropland per county. The proportion of cropland in corn, soybeans and small grains, and fruits and vegetables was calculated by dividing the area of each crop group by the total area of harvested cropland.

Statistical Analyses. We evaluated the relationship between insecticide use and the proportion cropland after accounting for proportions of cropland in corn, soybeans and small grains, and fruits and vegetables, and the net income per hectare of harvested cropland per county. We conducted our analysis using spatial regression with a simultaneous autoregressive error term (i.e., SAR model) (19). A spatial regression model was chosen to account for spatial autocorrelation in model residuals, which might be caused by other geographically structured variables not included in our analysis (e.g., geographic patterns in unmeasured environmental characteristics or social factors). A spatial error model was chosen over a spatial lag model based on Lagrange multiplier tests (19). A SAR model was chosen over a conditional autoregressive (CAR) model because SAR models had lower Akaike information criterion (AIC) values (49) and less remaining spatial autocorrelation in the residuals than equivalent CAR models. To implement spatial models, we computed spatial weights using first-order neighbors, where neighbors were counties that were adjacent to a focal county at one or more points (queen contiguity). Spatial weights were computed using row standardization. We used AIC to evaluate the full, five-variable SAR model along with all possible subsets. AIC values for each of the candidate models were used to rank models. This process gave the full model (Table 1) as the AIC-best model. A Moran's test indicated that there was little remaining spatial autocorrelation (Moran's $I = -0.03$, $P = 0.31$) in the residuals of the full model. Multicollinearity was not a critical issue in the analysis, with variance inflation factors ranging from 1.20 to 2.47 across all independent variables. Modeling was conducted using OpenGeoDa (50), and the spdep (51) and MuMIn (52) packages for R statistical computing software (53).

Cost of Landscape-Mediated Pest Pressure. We estimated an average insecticide treatment cost (chemicals plus application) for the region using data collated by the Crop Protection Research Institute (54). This average was calculated from crop budgets produced by cooperative extension services across the region and was weighted by crop area reported by the USDA National Agricultural Statistics Service for 2008. Specifically, we summed the product of insecticide cost and crop area across all crops and all states and then divided that figure by the summed area across all crops and states. This analysis gave an average value of $32 per treated hectare across the crops and states in this analysis. This value does not include the additional cost to producers of yield loss that could occur between the points where plant damage by pests begins and where insecticide application becomes economically preferable (30). If we assume that chemicals are applied when yield-loss cost equals half of the insecticide application cost (i.e., a 50% action threshold) (55), we can raise our estimate of the cost of pest pressure to $48 per treated hectare, so that it accounts for costs accrued both from insecticide application and from yield loss associated with increased pest activity. Note that a 50% action threshold is not uncommon (55) and more conservative than a 75% action threshold (giving $56 per treated hectare) or a theoretically optimal threshold that approaches 100% (giving $64 per treated hectare).

Insecticide Use Index. The measure of insecticide use in this study was the proportion of harvested cropland treated with insecticide. We assume that this index scales with the total amount of insecticide applied. However, this relationship could be confounded by systematic variation in the number of applications per treated hectare. To evaluate this possibility, we analyzed state-level data from the Agricultural Chemical Use Database (ACUD), available from the USDA National Agricultural Statistics Service (21). State-level data were used because county-level insecticide data are not available.

For this analysis, we compared the area of corn, soybeans, wheat, and potatoes treated with insecticides with the mass of active ingredients applied to those crops for each state participating in the ACUD. To calculate the area of these crops treated per state, we (*i*) multiplied the percentage of each crop treated (averaged over 2003–2005, from the ACUD) by the total area of each crop (from the 2002 Census of Agriculture) and (*ii*) summed the treated areas across the crops. Chemical data from 2003–2005 was used because data from 2007 was not available. Crop area data from the 2002 Census of Agriculture was used because it was closer in time to the available chemical use data than the 2007 Census of Agriculture. To estimate the mass of insecticides applied to these crops per state, we summed the average mass of active ingredient applied to each crop (megagrams, averaged over 2003–2005, from the ACUD). We found a clear positive correlation between the total area of a crop treated with insecticides and the total mass of insecticides applied (Fig. S2). We assume that this state-level relationship holds at the county level as well.

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