Understanding the extent and consequences of chemical trespass for Illinois ecosystems

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Principal Investigator: T.J. Benson

Co-principal investigator: David Zaya

Illinois Natural History Survey

Prairie Research Institute

University of Illinois Urbana-Champaign

1816 S. Oak St., Champaign, IL 61820

tjbenson@illinois.edu

dzaya1@illinois.edu

Executive Summary

The landscape of Illinois has been devoted to primarily agricultural uses for more than 100 years, and current agricultural approaches increasingly depend on synthetic pesticides for the efficient production of row crops. However, there is increasing concern that these pesticides may enter areas beyond where they were intended to be applied and may negatively impact non-target organisms. We set out to characterize the occurrence and concentration of chemical pesticides and symptoms associated with herbicide exposure in naturally vegetated areas across Illinois. We sampled 185 sites, including 102 randomly selected Illinois Nature Preserves Commission sites and other randomly selected sites previously sampled by the Critical Trends Assessment Program. We visited these sites during two periods in the early and late growing season of 2023, recorded signs of injury to vegetation, and collected tissues and soil samples for analysis of 486 different chemicals.

We detected 41 chemicals in our 523 leaf-tissue and soil-core samples. We found at least one pesticide in 74% of leaf samples and at 97% of sites. Chemicals detected from early visits were largely herbicides, with atrazine, desethyl atrazine, and 2,4-D being by far the most common chemicals encountered. Chemicals detected during late visits included a large number of fungicides (propiconazole was the most common), one prominent insecticide (bifenthrin), and a smaller proportion of sites with the common herbicides from the first visit. Leaves with visible signs of damage did not have greater herbicide concentrations than randomly selected leaves. Cover of row crops in the surrounding landscape predicted concentrations of pesticides in leaf-tissue samples.

We collected condition data from >78,000 individual plants of 400 species, and we found visual evidence consistent with herbicide damage during at least 97% of site visits and at 99% of study sites. We found moderate damage in at least 79% of site visits and at 92% of sites, and severe damage during at least 37% of site visits and at 54% of sites. Oaks (*Quercus* spp.) were among the species showing the most severe symptoms of damage, and redbud (*Cercis canadensis*) and boxelder (*Acer negundo*) were also among the ten species with the most severe symptoms. Cover of row crops in the surrounding landscape predicted symptom severity, as did first-visit concentrations of the four most common herbicides (atrazine, desethyl atrazine, 2,4-D, and metolachlor). The strongest predictor of symptom severity was cover of soybeans in the surrounding landscape. The greatest symptom severity was observed in grassland habitats and the least in forested habitats.

Overall, we found extensive damage and detectable concentrations of multiple pesticides at nearly all sites, both of which were predicted by row-crop cover in the surrounding landscape, and chemicals were statistically associated with damage. These results suggest that not only are pesticides regularly crossing boundaries into non-target areas, but they are also negatively impacting plants in natural habitats. The long-term implications of the damage, however, are currently unknown as are the potential impacts on other non-target organisms.

Introduction

The landscape of Illinois has been devoted to primarily agricultural uses for more than 100 years, and the primary changes to Illinois agriculture over the past 75 years have been related to agricultural intensification (Walk et al. 2010). In addition to a shift to primarily corn and soybean production, a major shift in the second half of the 20th century was the development and increased use of synthetic pesticides (Osteen 1993). The development of herbicides, insecticides, fungicides, and other types of compounds has allowed agricultural producers to limit damage to crops and competition with weeds, and the use of these chemicals has increased substantially (Fernandez-Cornejo et al. 2014). In Illinois, for example, the most recent estimates include >20 million kg of herbicides applied to Illinois crops per year (Wieben 2021).

Pesticides, however, do not stay confined to the areas where they were intended to be applied and these chemicals have long been known to have negative impacts on non-target organisms (e.g., Pimentel 1971). There are multiple ways that pesticides can move from intended to unintended areas, including drift at the time of spraying, volatilization, and movement in water. Although non-target effects have always been a concern, this topic has received increased attention in recent years with the development and widespread adoption of dicamba-resistant soybeans. Dicamba has long been recognized as a volatile herbicide (Behrens and Lueschen 1979) and one that can negatively affect non-target crops (Weidenhamer et al. 1989), but was first registered for use on these new genetically modified crops (both soybeans and cotton) in 2016. Many states saw increases in damage complaints associated with this change,

and reports of crop damage have increasingly been accompanied by reports of damage in residential areas as well as areas with natural vegetation.

Recent efforts to document the presence and concentrations of pesticides in natural areas embedded in agricultural landscapes have found a range of herbicides, fungicides, and insecticides (Hladik et al. 2022, Ward et al. 2022). Although previous studies have been limited in spatial extent, the results are particularly concerning for heavily agricultural states such as Illinois where natural areas and agricultural fields are often found in close proximity. Of particular concern in Illinois are Illinois Nature Preserves and Land and Water Reserves, sites administered by the Illinois Nature Preserves Commission (INPC) which have legal protections associated with their recognition as examples of relatively intact and high-quality natural areas. Past sampling at INPC sites has found signs of damage to plants that are consistent with non-target herbicide exposure, and limited chemical analyses of plant tissues has confirmed the presence of herbicides (Erndt-Pitcher and Kemper 2022).

We set out to characterize the occurrence and concentration of chemical pesticides and symptoms associated with herbicide exposure in naturally vegetated areas across Illinois. Our objectives were to a) characterize what pesticides were observed on vegetation, b) quantify the severity of symptoms at sites across the state, c) quantify the severity of symptoms in individual species, d) test for associations between the surrounding landscape and chemical observations, e) test for associations between the surrounding landscape and severity of symptoms, f) test for associations between the chemical observations and severity of symptoms, g) compare legally

protected sites (INPC) to randomly selected study sites with respect to chemicals encountered and severity of symptoms.

Methods

Site selection

Two types of sites were included in this study. The first were properties under the purview of the Illinois Nature Preserves Commission, as Nature Preserves or Land and Water Reserves. Together we refer to these as "INPC sites". Nearly half (48%) of INPC sites included in this study are owned or managed by the Illinois Department of Natural Resources (IDNR). The rest of the INPC sites are owned by a mixture of entities (20% other government, 15% stewardship organizations, 17% privately owned). The second type of sites were woodland, grassland, and wetland sites across Illinois that have been studied by the Critical Trends Assessment Program ("CTAP sites"). CTAP sites are primarily privately owned (75% of sites included in this study), but some are publicly owned (7% by IDNR, 1% federal, 17% other government). Additionally, two CTAP sites included here are protected as INPC lands (details below). We randomized site selection for both sets of study sites with different methods.

For INPC sites, we based randomization on a spatial dataset provided by the Illinois Department of Natural Resources. The spatial data were provided as ESRI shapefiles and included 606 Nature Preserves and Land and Water Reserves. Each INPC property was assigned to a single county based on the centroid of the polygon that represented that property. We then used a stratified random sampling approach, with stratification at the county level that generally attempted to select one site per

county. A rank was randomly assigned to each property in a county. The first-ranked site was the primary site selected for the county, and the following ranks were considered backups in case a first-ranked site could not be sampled. We made an effort to increase representation of sites south of 39.5°N by randomly selecting second-ranked sites in some counties. This was done to improve latitudinal distribution of sites, and increased coverage in parts of the state with more reports of potential herbicide damage. Our efforts yielded 95 sites, because some counties did not have mapped INPC properties in our spatial data set. We selected additional sites, using the next-ranked property in randomly selected counties. We came up with a list of 115 sites. We aimed to sample 100 of these sites, with the others serving as backups in cases where we could not access the preferred site.

CTAP sites were previously established using a random selection process that was stratified at the township level, using Public Land Survey System townships as guidance. CTAP sampling began in 1997, and study sites had been revisited every five years for botanical, ornithological, and entomological studies. Initially, 30 townships (out of 1745 townships in Illinois) were randomly selected. Within those 30 townships, we randomly selected points that were covered by forest habitat in remotely sensed landcover datasets. Those randomly selected points were randomly ranked, starting from the number one. CTAP staff verified forest cover at those randomly selected points using aerial photography and in-person visits. Staff attempted to receive permission for vegetation, avian, and entomological studies at the highest ranked site, and if unsuccessful they proceeded to the next ranked site within the township. This process was repeated for 30 different townships that were randomly selected for wetlands

(restricting to palustrine emergent wetlands), and another 30 townships for grasslands. In 2023, we concentrated on CTAP sites that were sampled in 2018, each with a history of sampling that went back 5 to 25 years. We pursued permission to sample 90 sites, though we learned that some sites were no longer intact habitat. More details on CTAP site selection methodology can be found in Molano-Flores (2002).

Site visits

In total we sampled 185 sites—102 INPC sites (Appendix 1) and 83 CTAP sites (Figure 1). Two CTAP sites from 2018 were also Nature Preserves (Deer Grove NP in Cook Co, Goose Lake Prairie NP in Grundy Co) that were not in our group of randomly selected INPC sites. An 84th CTAP site sampled in 2018 was randomly selected as an INPC site (Angela's Prairie LWR in Monroe Co) and excluded from the CTAP category for the purposes of this report. Overall, there are approximately 80 INPC sites with some history of CTAP sampling, 30 of which were selected randomly. Only a fraction were included in this year's study of randomly selected sites.

An effort was made to visit each site two times, one corresponding to the early growing season and one to the later growing season. First visits were conducted from May 17 to July 6. Second visits were conducted from July 17 to September 9. Six CTAP sites could not be visited a second time due to landowner permission, flooding, or repeated mowing of grasslands that prevented accurate assessment. During each week of site visits, an effort was made to collect data at sites across the state to avoid confounding spatial and temporal patterns.

During the first visit we conducted the following activities: recorded signs of injury to vegetation during meanders, marked and assessed the condition of individuals for future monitoring, collected up to two tissues samples and one soil sample for chemical analysis. During the second visit we conducted the following activities: recorded signs of injury to vegetation during meanders, collected up to two tissues samples for chemical analysis. During both visits, descriptions of the overall condition of the site and the surrounding environment were taken.

The areas studied for the first and second visits were typically similar in location, but in some cases there was small separation within the study site. Detailed spatial data were collected for both visits. In all cases, we attempted to begin from an 'edge' and proceeded toward the center of the site. The type of edge varied between sites depending on the conditions we encountered. For INPC sites, we always worked from an INPC boundary that was loaded into handheld GPS/GNSS devices. That boundary line was often associated with an edge that abutted an area dominated by anthropogenic activities (e.g. a road), but not always. For CTAP sites, the edge we worked from was a habitat edge, such as the edge of a wooded area or open wetland. This edge often coincided with an anthropogenic edge, but not always. We generally attempted to stay within the same habitat site at CTAP sites, and always avoided crossing property boundaries unless landowner permission was obtained from all parties. For example, if there was a wetland opening in a forested area at a CTAP site, we would work within the wetland or the forested area, but not both, with preference for the habitat that contained previous CTAP sampling.

Meanders

We recorded data on vegetation condition during both visits to a site using timed meanders. In rare cases (<5%) during first visits, meanders were not conducted due to logistical obstacles. The goal of meanders was to record indicators (or absence) of injury at the individual plant or patch level, with observations separated by species. During each meander we walked from the edge of a site or habitat toward the center. Each meander lasted 10 minutes, with up to 3 meanders per visit for larger sites.

Records of injury included symptoms present, the severity of the symptom(s), and the strata where injury were observed (ground cover, understory, canopy). The severity of the symptoms was rated on a six point scale, ranging from "none" (zero) to "high" (five). Intermediate values were "low" (one), "low/medium" (two), "medium" (three), and "medium/high" (four). The guidance provided to observers regarding how to rate the level of injury was to consider how much photosynthetic and homeostatic capability of plant was hindered due to the apparent symptoms. An effort was made to standardize ratings among observers by coordinating data collection at the same time early in the growing season and comparing ratings. Calibration of ratings was repeated halfway through the growing season, in between the periods for first and second site visits.

The symptoms list (see Table 1) included symptoms that are often associated with growth regulator inhibitor herbicides (e.g., cupping of leaves), and other symptoms that are more general signs of stress (e.g., chlorosis, or yellowed leaf tissue). We set a minimum of five species to be included during meander surveys, and typically capped the number of species to include at approximately 15. We could not include all species

due to the high species richness at most sites. When making decisions about which species to include, priority was given to dominant trees, other dominant species, and species that typically display signs that are believed to be associated with herbicides (e.g., most oak species, redbud, boxelder).

When individual plants were within 20 meters of an anthropogenic edge (e.g., road, agricultural field, lawn), their status as being near an edge was recorded. Binoculars (typically 8x or 10x) were used to search for the condition of leaves and stems in the canopy. Photographs were taken of representative individuals of species showing injury, although we learned that our cameras typically were not sufficient to record symptoms in the canopy.

The start and end point of each meander were recorded with a handheld GPS/GNSS device, as well as the path traveled (see Figure 2 for an example). When there were multiple meanders for a site visit, usually the end of the preceding meander and start of the next meander were the same point, but that was not always the case. In most cases, a Garmin 65s (or similar) were used for spatial data collection.

Tissue and soil collection

We collected leaf tissue samples for chemical analysis during both visits to a site and collected a soil sample for chemical analysis during the first visit. Two types of leaf collection were made, and one soil collection.

Once choosing a location to enter a site, we searched for a nearby individual within 20-30 meters from the edge of the study site from which we could collect 50-100 mg of leaf tissue. The location of these plants generally coincided with the start of our

first meander. As the individual we selected for this first tissue sample would be drawn from the species randomly available within this location, we termed this collection the “random” collection, though certain groups were prioritized. We prioritized collection of leaves from trees (especially oaks, redbuds, and hickories, which were believed to be sensitive to chemical herbicides). When a tree was not available, or leaves could not be reached from a nearby tree, we then prioritized other woody plants, or patches of herbaceous plants (of a single species) when woody plants were not available. The individual selected did not need to show signs of injury associated with herbicide damage. However, we did record if any symptoms were present, their severity, the strata in which they were found, as well as the individual's species and estimated distance to the edge. The spatial location of the leaf collection was recorded with a handheld GPS/GNSS device. Photographs were captured of individuals or patches of plants from which leaf tissue was taken. Once all information was recorded, we wore nitrile gloves to gather leaf tissue which was then placed into a labeled zip-top bag. When needed, we used cutting tools that were cleaned with alcohol wipes immediately before and after tissue collection. Tissue collections were placed in a cooler with ice until they could be placed in a freezer. Samples were placed in a freezer typically within 48 hours, though in some cases the period on ice could extend to 72 hours.

When a site visit revealed leaf tissue that showed symptoms typical of herbicide damage, we attempted to collect an "affected" leaf tissue sample. The same methodology of leaf collection was used as for the "random" tissue collection, except the selection of the individual was different. When choosing an affected individual, the same species and life forms were prioritized for collection, but when possible we

targeted a different plant species than the "random" tissue collection. Affected leaf tissue collections had to occur at least 20 meters from the edge of the study site. In many cases, affected leaf tissue was taken from deep within the interior of the study site. If there were multiple affected individuals of a targeted species, we attempted to collect from the individual that was nearest to the center of the study site.

We also marked both affected and nearby unaffected plants for future examination of potential effects and recovery. For marked individuals we recorded diameter at breast height (if it was a tree), the presence and severity of symptoms associated with herbicide damage, geographical location, and for most individuals we also took a photograph. A subset of these individuals will be revisited in 2024.

Soil samples were collected from the same location as the random leaf tissue sample. The first type of soil collection was a soil core, 2 cm in diameter and 15 cm deep. We wore nitrile gloves and cleaned the soil probe with alcohol wipes. The probe was inserted into the soil vertically, and the removed soil was placed in a labeled zip-top bag. When needed, a stainless-steel spoon (already cleaned with alcohol wipes) was used to dislodge soil stuck to the soil probe. If the probe could not be inserted 15 cm into the soil, a series of cores (typically two cores) were collected until their cumulative depth reached 15 cm. The soil probe and metal spoon were cleaned with alcohol wipes after use, and the soil collection was placed on ice in a cooler as soon as possible. The soil was kept on ice until it could be placed in a freezer, in the same manner as the leaf tissue.

Tissue and soil testing

Tissue collections and soil core collections were analyzed by an outside group, Columbia Laboratories (Portland, Oregon; www.columbialaboratories.com). We shipped samples overnight on dry ice to the laboratory. A total of 486 total chemicals were tested in our samples. The larger assay (Columbia Labs' P2220 assay) included 483 chemicals (see Appendix 2). These chemicals included a variety of categories, including several classes of herbicides, fungicides, and insecticides. A second assay tested for three additional herbicides: glufosinate, glyphosate, and aminomethylphosphonic acid (AMPA). AMPA is a degradation product of glyphosate.

We submitted all of our random tissue collections with at least 50 mg of tissue for chemical analysis (total of 338 samples, from both visits). We submitted the majority of our affected tissue samples from the first site visits for chemical analysis (94 samples). After seeing insignificant differences in the chemicals detected for random and affected tissue samples from the first visits, we submitted a smaller subset of affected tissue samples from the second site visits (37 samples). All of these samples were analyzed with the P2220 assay (483 chemicals). A smaller number were analyzed for the three additional herbicides: 44 random tissue samples (39 from the first visit), and 40 affected tissue samples (28 from the first visit). We submitted 52 soil cores from the first visit for analysis, all of them being analyzed for 483 chemicals with the P2220 assay. We stopped soil core analysis after almost all samples contained no detectable chemicals. No soil cores were tested for the three additional herbicides, and we have no reason to suspect them to be more common in the soil as the half-lives for these chemicals are not extreme relative to many in our normal assay.

Quality control for chemical tests

We created control soil and tissue samples to test the ability of the chemical analyses to detect chemical application as well as relative concentrations. For control tissue samples, we included store-purchased dandelion greens that were either washed in water or left unwashed. For chemical applications, we applied two commercial products. The first had 2,4-D as the active ingredient, and we applied standardized amounts mixed to 0.1, 0.5, or 1.2% 2,4-D. We also included a commercial product that contained 2,4-D, mecoprop, and dicamba, mixed to 0.1, 0.02, and 0.01%, respectively. For soil samples, we used the same approach with purchased garden soil and included mixtures of 1.2% for the two commercial products (2,4-D alone, and the mixture of 2,4-D, mecoprop, and dicamba) and a water control. We found that the amount of each pesticide detected was strongly and positively associated with the amount applied, and that negative control samples with no chemical application did not have detectable amounts of pesticides. We did find DEET on some soil samples, including the negative control with no chemical application.

A concern with chemical testing is degradation of pesticide residues with time. Given that cold temperatures slow the breakdown of chemicals, we took multiple steps to reduce degradation by ensuring tissue and soil samples were kept cold before analysis. All samples were placed in ice-filled coolers after field collection, and then frozen upon return to our laboratory. Samples were shipped to the testing laboratory overnight and placed in box-enclosed polystyrene foam coolers packed with dry ice.

The laboratory provided confirmation of receipt for each sample, noting evidence of cooling, temperature of samples, and confirming that samples arrived in good condition.

To examine the potential for chemical degradation in our frozen samples, we statistically examined the influence of the number of days between the dates of collection and chemical analysis on chemical concentrations. We tested the relationship between concentration and time-to-analysis for the most common pesticides we observed with linear models. Concentrations of the most common herbicides and their metabolites, which were primarily found during first site visits (see Results), were not associated with time to analysis (all $p > 0.3$). Concentrations of the most common fungicides and insecticide, which were primarily found during the second site visits (see Results), were also not associated with time to analysis (all $p > 0.2$).

Additionally, Columbia Laboratories is ISO 17025:2017 accredited. The laboratory also holds accreditations with The NELAC Institute, the Oregon Environmental Laboratory Accreditation Program, and the Colorado Department of Public Health and Environment. The laboratory confirmed that all samples were received in good condition, and no results were flagged for potential quality issues.

Statistical analyses

All statistical tests and summaries were conducted using R version 4.3.2 (R Core Team 2023). Hypothesis testing relied heavily on linear mixed-effects models or generalized linear mixed-effects models, implemented using the *lme4* package (Bates et al. 2015). Details of the specific statistical approach for each hypothesis test or summary varied (details below), though they all included random intercepts for study

site identity. In all cases we used model selection with AIC_C to determine the statistical model, fixed effects, and model parameters that best fit the data. For linear mixed-effects models, model selection was conducted on models that were fit with maximum likelihood, and when parameters are reported they come from final models that were later fitted with restricted maximum likelihood. When describing the strength of the model fit for mixed-effects models, we relied on the marginal and conditional R^2 (Nakagawa and Schielzeth 2013, Johnson 2014, Nakagawa et al. 2017), calculated using the *MuMIn* package (Bartoń 2023).

The association between pesticide concentration and landscape context used a linear mixed-effects model for each of the most common chemicals encountered in separate, univariate analyses. In each case the response variable was the concentration of the chemical, or group of chemicals, measured from the "random" leaf tissue samples. We concentrated on the most encountered chemicals: 2,4-D (herbicide), the sum of atrazine (herbicide) and a metabolite (desethyl atrazine), propiconazole (fungicide), bifenthrin (insecticide). The fixed effects (explanatory variables) we tested were the visit number and the prevalence of a particular land use category around the collection point, as calculated by pixels in a circular buffer with a pre-determined radius. We also included an interaction term for visit-by-land use category. The spatial dataset we used for land use in Illinois was the 2023 Cropland Data Layer from the United States Department of Agriculture's National Agricultural Statistics Service (USDA 2024), in the Albers Equal Area Conic projection. Calculation of the proportion of the landscape was conducted using the *rgeos* package in R (Bivand and Rundel 2020). The land use variables included the proportion of corn, soybeans,

forested land, a combination of all areas with natural vegetation (a summed value for all forest, wetland, and grassland types), and development (in four categories).

For each land use variable, preliminary testing of the most appropriate buffer radius as a predictor of chemical concentrations (and later plant injury) was required. We tested the explanatory power of the proportion of land use pixels found in five sizes of circular buffers: 100 meters, 300 meters, 1 km, 3 km, 10 km. We do not report the results of the buffer comparisons, but all results we display are based off of the buffer size that best predicted patterns in pesticide concentrations. In general, herbicides were most associated with the 1 km and 3 km buffers, while fungicides and insecticides were most associated with 100 meter and 300 meter buffers. When visualizing the results of the mixed-effects models, we showed predicted values from the corresponding linear models without the random effect in order to better represent uncertainty around the mean estimate (also because the random intercept contributed practically nothing to the model fit, data not shown).

We used generalized linear mixed-effects models with binary response to compare the prevalence of our most common herbicides on the different types of leaf tissue we collected, random and affected samples. In this case, the response variable was the binary presence or absence of a particular herbicide, where we ran separate univariate analyses for total atrazine and 2,4-D. We converted concentrations of these herbicides to binary presence or absence because we could not meet model assumptions for distributions of residuals using raw values, even after multiple attempts at variable transformation. The conversion made it necessary to use a generalized linear mixed-effects model. Global models were constructed with the binary herbicide

presence as the response variable, with fixed effects of tissue collection type (random or affected) and visit number, plus the interaction of tissue type and visit number. Analyses we present here are restricted to site visits that included an affected tissue collection that was chemically analyzed, but conclusions are the same as if the full data set is included.

We also tested the association of the binary presence or absence of particular observed symptom with concentrations of our most common herbicides (and derivatives). We used a generalized linear model with binomial response (whether the symptom was present or not), and the concentration of the most common herbicides (and derivatives) as explanatory variables. The analysis was restricted to random tissue samples from first site visits for our most encountered genus, oaks (*Quercus*). We restricted the analysis to oaks to control for potential differences in response to chemical exposure among different plant families or groups. We restricted the analysis to first visits because that is when herbicides were most likely to be prevalent in the environment. We restricted our analysis to random tissue samples to avoid possible biases associated with selection of samples showing symptoms consistent with herbicide damage.

We created a large linear mixed-effects model to estimate multiple parameters relating to signs of injury. We used data from the timed meanders to calculate a mean level of symptom severity for each species encountered at a site (the mean across all individuals observed during a single site visit, with "none" rated as zero and "high" rated as 5). In the model, the response variable was the injury level for each species treated as a continuous numerical variable. We tested plant species, observer identity and visit

number as fixed effects (explanatory variables). The random effect was an intercept for site. We included all fixed effects in a global model (with no interactions) and compared the fit of all simpler models with AIC_C. Once arriving at the optimal model, we extracted two sets of variables we were most interested in. First, the fixed-effect coefficients associated with each species, which represented the mean relative injury for each species after controlling for observer and site. Second, the random-effect intercepts associated with each study site, which represented relative injury scores associated with each site, when controlling for observer and species present.

After extracting the coefficients for species and study sites, we conducted analyses using these relative values. For injury coefficients assigned to each plant species, we report the species associated with the greatest level of injury. We emphasize species with at least ten observations (combined between site visits) because distributions of values suggest these observations are more stable (see Results section).

For site-level symptom severity coefficients, we used the values as the response variable in linear models that predicted injury score as a function of the surrounding land use. In this case we did not use linear mixed-effects models because there was only a single value for each study site. Additionally, we used linear models to associate site-level injury coefficients with herbicide concentrations from first visits, while focusing on the most common herbicides and derivatives encountered (atrazine, desethyl atrazine, 2,4-D, metolachlor). We concentrated on first visits because that is when herbicide concentrations were greatest, and because site-level symptom severities were not found to be statistically different between visits (see Results section). Models were

created with one of the four most common herbicides and derivatives as a fixed effect predicting site-level symptom severity coefficients. These models were compared among one another, and with a null model that included no fixed effect.

When comparing study sites on INPC lands to randomly selected CTAP sites, we compared pesticide concentrations, land use variables, and site-level injury coefficients between the two groups using Welch two sample t-tests. For pesticide concentrations, we used data from the visit in which the particular chemical was most prominent (typically first visit for herbicides and second visit for other classes).

Results

Chemical findings

In total, 41 chemicals were detected in 523 leaf tissue and soil core samples. We excluded two chemicals that were regularly used by some observers to repel insects and likely came from applications to observers' clothing (DEET and permethrin), and thus there were 37 chemicals from leaf tissues and two chemicals from soil samples. We cannot rule out the possibility that DEET and permethrin came from other visitors to our study sites, however, we believe the most likely explanation is that the our observation team was the source in most cases. Among the soil samples, rotenone was found at a single site (Wirth Prairie NP) and imazapic at a single site (Forever Fields LWR). No statistical analyses were conducted on soil samples because of the low number of analyses that found any pesticides.

We found at least one pesticide on 74% of leaf samples, and at 97% of sites. The most common chemicals we found varied greatly between the first and second site

visits (Table 2). Chemical results from first site visits were dominated by herbicides, with atrazine, desethyl atrazine, and 2,4-D being by far the most common chemicals encountered. Second site visits had a large number of fungicides (propiconazole was the most common), one prominent insecticide (bifenthrin), and much smaller proportion of sites with the common herbicides from the first visit.

Pesticide and landscape associations

Atrazine and land use

When investigating the best landscape predictors for atrazine concentration in leaf tissues, we used a sum of atrazine and desethyl atrazine (a primary metabolite of atrazine) in our statistical tests. For brevity we refer to the sum of the two analytes as total atrazine. Corn at the 1 km scale strongly predicted total atrazine concentrations, with large differences in the relationship depending on the visit number (Figure 3). During first visits, increasing corn was strongly associated with increased total atrazine. During second visits, there was not as clear a positive association. Statistical support for the visit-by-corn interaction was strong (ΔAIC_C = 16.8, Akaike weight > 0.999). The explanatory power of the fixed effects was relatively strong (marginal R^2 = 0.24, conditional R^2 = 0.24), though much of that power was likely associated with the visit number.

Total atrazine concentrations were correlated with soybeans at the 10km scale, with a positive relationship during the first visits (Figure 4; marginal and conditional R^2 = 0.17). Interestingly, there was strong statistical support for a relationship with soybeans in a 10km buffer (ΔAIC_C = 13.0, Akaike weight > 0.998) and 3 km buffer (ΔAIC_C = 9.8,

Akaike weight > 0.995), but there was no relationship for smaller buffers (null model had the best support, $\Delta AIC_C > 1.2$). This may be because at radii of 3 km and 10 km, the amount of soybean area is very strongly associated with the amount of corn in the area ($R^2 > 0.56$, with slopes approaching 1), but the strength of the relationship drops steeply in smaller buffers (R^2 between 0.02 and 0.20).

A similar relationship was found for total atrazine and forest cover within 10 km, though the relationship was negative (Figure 5). Again, the relationship was stronger for larger buffers, with forest cover having no or weak support at smaller scales. The relationship between total atrazine concentrations and forest cover may be related to the negative relationship of corn and forest cover, especially at larger scales (strongest negative relationship is at the 10 km buffer, $R^2 = 0.52$).

The relationship between the surrounding area with natural vegetation and total atrazine was negative during first visits (Figure 6). Statistical testing revealed a strong relationship at all buffer sizes ($\Delta AIC_C > 7$), but the most supported buffer size was 300 meters (10 km was the next best supported buffer size).

There was a weaker negative relationship between developed areas within 10 km and total atrazine, and the relationship had relatively weak support ($\Delta AIC_C = 2.0$, Akaike weight = 0.83). The relationship has some support at the 3 km buffer size but was not statistically supported at buffer sizes of 1 km or smaller.

2,4-D and land use

The concentration of 2,4-D was predicted by the amount of corn in the surrounding 3 km (Figure 7). The relationship was negative, though it had only weak

statistical support ($\Delta AIC_C = 0.86$, Akaike weight = 0.60, marginal $R^2 = 0.04$, conditional $R^2 = 0.11$).

Statistical tests did not support a relationship between concentration of 2,4-D and soybeans in the surrounding landscape (the null hypothesis had equal of better support for all buffer sizes). We also did not find a significant association with forest cover, developed area, or area with natural vegetation.

Propiconazole and land use

The concentration of propiconazole was most strongly associated with corn within 100 meters (Figure 8). There was strong statistical support for relationship with corn in the surrounding landscape ($\Delta AIC_C = 0.86$, Akaike weight = 0.60), though the pseudo-correlation value was low (marginal $R^2 = 0.08$, conditional $R^2 = 0.14$). There was one extreme outlier case, where a leaf tissue sample from a privately owned CTAP site in Bureau county had a propiconazole concentration that was ten times greater than any other site (there were several other fungicides and insecticides detected on this sample). If removing this outlier, the best pseudo-correlation value increases greatly for the corn-100-m buffer (both $R^2 = 0.17$), and the 10 km buffer becomes the best performing predictor variable associated with corn (both $R^2 = 0.21$) with strong statistical support (Akaike weight = 0.994).

We found a weaker positive association between propiconazole concentration and soybeans in the surrounding 3km, though removing the extreme outlier in Bureau County shifted the optimal buffer size to the soybeans in the surrounding 10 km (Figure 9). There was strong statistical support for soybeans at larger scales predicting

propiconazole concentrations, especially after removing the outlier (ΔAIC_C = 5.3, Akaike weight = 0.93, marginal and conditional R^2 = 0.18; for the model with the outlier and 3 km buffer, ΔAIC_C = 2.7, marginal R^2 = 0.04, conditional R^2 = 0.09).

Propiconazole was negatively associated with forest cover within 300 meters (Figure 10), and negatively associated with areas with natural vegetation within 300 meters (Figure 11). There was statistical support for both relationships with or without the outlier (ΔAIC_C > 4). There was no association with developed areas at any buffer size.

Bifenthrin and land use

Corn in the surrounding 1 km was very strongly positively associated with bifenthrin concentration in our tissue samples, with the strongest relationship during the second visit (Figure 12). There was strong statistical support for the relationship, especially when an interaction with visit number was included (ΔAIC_C = 16.3, Akaike weight > 0.999). The strength of the correlation was somewhat weakened by the presence of moderate outliers (marginal and conditional R^2 = 0.12).

Soybeans in the surrounding 1 km were positively associated with bifenthrin concentration during the second visit (Figure 13). There was strong statistical support for the models that included surrounded soybeans, with the most support for the model that included an interaction with visit number (ΔAIC_C = 2.9, Akaike weight = 0.77). However, there was a substantial amount of noise in the relationship (marginal and conditional R^2 = 0.07).

Bifenthrin concentration during the second visit was negatively associated with forest cover in the surrounding 1 km, and areas with natural vegetation within 1 km. Both of these relationships had a bit more statistical support than the negative relationship with soybeans (Akaike weight > 0.9, marginal and conditional R^2 > 0.075). Bifenthrin concentration was not associated with surrounding developed area, with any buffer size.

Pesticides on random versus affected leaf tissue

There was no statistical difference in the different leaf sample types (affected versus random) with respect to the proportion that had detectable amounts of 2,4-D or atrazine (Table 3). For both, the only supported explanatory variable was the visit number, and the statistical support was similar (for total atrazine, $\Delta AIC_C = 2.0$ compared to the model with tissue category, Akaike weight = 0.63; for 2,4-D, $\Delta AIC_C = 1.6$, Akaike weight = 0.57). During the first visit, about half of sample types had detectable 2,4-D and more than two-thirds of samples had atrazine. The proportion of samples with either herbicide were much lower during the second visit (Table 3), as expected because they are both used primarily early in the growing season and degrade over time.

Symptom severity at the species level

We collected meander data from over 78,000 individual plants or patches, from 400 species. We assigned relative symptom-severity ratings to each plant species encountered during timed meander surveys while controlling for effects of observer, visit number, and study site. The result was a single numerical rating assigned to each

species, with increasing values indicating greater propensity for severe symptoms associated with herbicide damage. The ratings were meant to estimate species' sensitivities (not the degree of exposure) to herbicides that potentially cause symptoms. The relative values among plant species are most informative, as they indicate how many steps on our symptom rating scale species are likely to differ by, when assessed by the same observer at the same time and in the same place. Our symptom severity ratings ranged from zero to five (or "none" to "high").

Species with few observations had extreme values for their estimated symptom severity, and in many cases the values did not seem reliable. Thus, we limit our assessments of individual species to those with at least 10 observations. That may be a conservative cut-off, as a threshold of five observations may also perform well (Figure 14).

We found that numerous oaks were among the species showing the most severe symptoms of damage (Table 4). Additionally, *Cercis canadensis* (redbud) and *Acer negundo* (boxelder) are among the top ten species with the most severe symptoms. There is a general over-representation of trees in this list because they are more conspicuous, some effort was made to target dominant trees at our study sites, and trees are less diverse, thus each species is more likely to meet the minimum number of observations. Smaller species that showed relatively high levels of injury, but which did not meet the threshold of 10 observations, included *Menispermum canadense* (moonseed), *Ptelea trifoliata* (wafer ash), *Ceanothus americanus* (New Jersey tea), *Galium circaezens* (wild licorice), and *Hackelia virginiana* (stickseed). *Hackelia* would

have been rated the species with the highest symptom severity if the threshold is set to a minimum of five observations.

Overall, we found some visual evidence consistent with vegetation injury associated with herbicide damage during 97% of site visits, and at 99% of study sites, when excluding plants within 20 meters of the edge (if plants near the edge are included, the rates are 99% and 100%, respectively). If only considering plants with at least "medium" levels of symptom severity (level "3" on our zero to five scale), we found this level of injury during 79% of site visits and at 92% of sites (excluding plants within 20 meters of the edge). The highest level of injury was recorded during 37% of site visits and at 54% of study sites (excluding plants within 20 meters of the edge).

Other predictors of symptom severity

Our statistical tests showed that there were significant differences among observers in how they rated symptom severity (after controlling for species and study site). However, the differences between observers were generally small. Modeling estimated that the difference in the two most extreme observers was equivalent to nearly one step on our zero-to-five symptom severity scale, with all other observers near the mean. Because we had substantial overlap in species rated during meander surveys and study sites surveyed (due to multiple visits per site being shared among observers), we are able to quantify and control for the observer effect.

We did not find that symptom severity differed between visits. Statistically, the overall symptom severity observed earlier in the growing season (July 7 or earlier) and later in the growing season (July 17 or later) was similar. Anecdotally, we found that to

be the case for trees and larger woody species, but it did appear as though some herbaceous species showed less severe signs of damage later in the growing season.

Symptom severity and landscape context

Site-level symptom severity was most associated with soybeans in the surrounding 1 km (Figure 15). Sites with the greatest injury had at least 18% soybeans within 1 km. The relationship was relative strong (R^2 = 0.23) and well-supported (ΔAIC_C = 7.8 compared to the next best herbicide model, and ΔAIC_C = 45.5 compared to the null model, Akaike weight > 0.97).

After soybeans, the strongest association was with areas with natural vegetation in the surrounding 1 km. This relationship was well-supported (ΔAIC_C = 37.7 compared to null model), the correlation was nearly as strong as the association with soybeans (R^2 = 0.19), but negative—meaning that more area with natural vegetation was associated with lower site-level symptom severity (Figure 16). Site-level symptom severity was also positively associated with corn (ΔAIC_C = 33.6 compared to null model, R^2 = 0.18) and negatively associated with forest cover (ΔAICC = 28.2 compared to null model, R^2 = 0.11). There was statistical support for a negative association with developed area in the surrounding 10 km (ΔAICC = 7.8 compared to null model), but the relationship was weak (R^2 = 0.04).

Symptom severity and chemicals

The relative symptom severity coefficient assigned to each study site was positively associated with first-visit concentrations of each of the four herbicides and

derivatives we tested: atrazine, desethyl atrazine, 2,4-D, and metolachlor. When we only considered the random tissue samples, the strongest association was with atrazine ($\Delta AIC_C = 9.5$ compared to the next best herbicide model, and $\Delta AIC_C = 11.1$ compared to the null model, Akaike weight > 0.97). The relationship was very statistically supported, but it was not an especially tight correlation (Figure 17, $R^2 = 0.07$). For the other three herbicides and derivatives, statistical support was similar (ΔAIC_C was between 1.4 and 1.6 compared to the null, $R^2 = 0.02$ for each model).

When testing the correlation between symptom presence in oaks and chemical concentrations, the only case where the concentration of a chemical was positively associated with the likelihood of encountering an herbicide was cupping/curling and the concentration of 2,4-D. In every case we found concentrations of 2,4-D that were greater than 0.013 mg / kg of leaf tissue (16 of 27 cases), we observed curled or cupped leaves in oaks. For concentrations less than or equal to 0.013 mg / kg, we found curling or cupping in 55% of investigated trees (6 of the remaining 11 cases).

Comparing INPC and random (CTAP) sites

There were no statistical differences in the mean (t-test, $p > 0.05$) or median (Kendall's rank correlation, $p > 0.05$) values for any of the most common chemicals observed when comparing INPC study sites to random CTAP sites. That includes tests of atrazine, desethyl atrazine, 2,4-D, propiconazole, bifenthrin, and azoxystrobin (another common fungicide that our tests detected).

There was not a significant difference in the mean of the site-level symptom severity when comparing INPC and random CTAP sites (t-test, $p = 0.061$), though there

was a trend of slightly higher injury scores at INPC sites. There was clearly a greater range of site-level values at INPC sites (variance was 51% greater for INPC sites). In other words, the sites with the most and the least severe symptoms of herbicide damage were INPC sites (Figure 18).

Comparing habitat types

Study sites were classified into three broad habitat types: forests (n = 83), grasslands (n = 59), and wetlands (n = 41). When comparing chemical concentrations among the habitat types with linear models, there was no significant difference in atrazine or 2,4-D during first visits ($p > 0.5$), and there was no difference in the propiconazole, bifenthrin, or azoxystrobin during the second visits ($p > 0.18$).

There was a significant difference in desethyl atrazine—the metabolite of atrazine—in both means ($F_{2,168} = 4.3$, $p = 0.015$) and medians (Kruskal-Wallis rank sum test, $\chi 2 = 10.5$, $df = 2$, $p = 0.005$). Random tissue collections from forests had the greatest concentrations of desethyl atrazine (mean of 0.031 mg / kg of leaf tissue), and double the value from wetlands (0.015 mg / kg of leaf tissue) which had the lowest concentrations. Post-hoc tests revealed a significant difference between forests and wetlands (adjusted $p = 0.018$), though grasslands were intermediate (0.021 mg / kg of leaf tissue) and not significantly different than either of the other two habitat types ($p = 0.59$ when compared to wetlands, $p = 0.13$ when compared to forests).

When comparing the site-level symptom severity among the habitat types, grasslands had the highest level of symptom severity, and forests had the lowest. Wetlands were intermediate (Figure 19). Statistical tests showed that habitat type was

significantly associated with site-level symptom severity ($F_{2,180} = 12.1$, $p < 0.0001$). Post-hoc tests supported grasslands having significantly higher values than the other two habitat types (adjusted $p < 0.05$), though wetlands and forests were not found to be significantly different (adjusted $p = 0.16$).

When looking at the sites with the greatest injury (Table 5) certain patterns emerge. INPC sites were over-represented, as were open habitats (underrepresentation of forests), those that were narrow or small in area, and sites associated with cemeteries. Study sites associated with cemeteries tended to be open grassland habitat small in area, and surrounded by agricultural fields.

Symptoms encountered

We have captured thousands of photos documenting vegetation with signs of damage that are consistent with herbicide damage. All of the symptoms listed in Table 1 besides death were encountered. The most common symptom encountered were curling or cupping at the leaf margin (Table 6, e.g., Figure 19), which was encountered in 65% of individuals from which leaf collection was made (89% of "affected" leaf tissue samples). Among plants used for the affected tissue samples, the appearance of curling and cupping was significantly associated with the other symptoms encountered in at least 10% of cases ($\chi 2$ tests all with p-value < 0.01). We have included example photographs of symptoms we encountered and recorded while completing this field study. See Figures 20-33.

Discussion

We found extensive damage in INPC and CTAP sites, and detectable concentrations of multiple pesticides at nearly all sites. Both damage and chemical concentrations were predicted by row-crop cover in the surrounding landscape, and chemicals were statistically associated with damage. These results suggest that not only are pesticides regularly crossing boundaries into non-target areas, but they're also negatively impacting plants in natural habitats. The long-term implications of the damage, however, are currently unknown as are the potential impacts on other non-target organisms.

Interestingly, dicamba occurred relatively infrequently in our samples. Although dicamba does have a relatively short half-life, it is not unlike other chemicals we found in high proportions (2,4-D and glyphosate). We also rarely found neonicotinoids (out of eight tested) despite their wide use in seed coatings for both corn and soybeans. Neonicotinoid insecticides are known to be very water soluble, so the mechanism of transport would most likely be surface water runoff, although plants could readily take up these chemicals if they were present. We did not, however, find evidence of neonicotinoids commonly occurring in either soil or plant tissues at our study sites.

The temporal patterns of chemical concentration included greater concentrations of herbicides early in the growing season with a gradual decline, and a pulse of increased fungicides and insecticides later in the growing season. These patterns are not surprising given the timing of application of the chemicals, with herbicide concentrations declining because of decreased application and degradation, and most fungicide and insecticide applications occurring later. Correspondingly, the degree of

plant damage we observed at sites was detectable regardless of sample date, likely because the damage was primarily caused by those earlier-season applications. The implications of the fungicide and insecticide spike later in the season are harder to determine given that we did not have visible indicators associated with these chemicals that were like the expected negative effects of herbicides on plants.

The landscape patterns we observed were consistent with the known uses of the observed chemicals, with atrazine, fungicides, and bifenthrin being more associated with corn than soybeans. There was not a strong pattern between soybeans and 2,4-D in our analysis despite the greater use of this chemical on soybeans relative to corn. That said, we restricted the analyses presented in this report to only our random leaf-tissue samples, and analyses that we have run that include both those random samples as well as samples from plants that were showing symptoms of herbicide exposure did show statistical relationships between landscape-level soybean cover and 2,4-D concentration. Moreover, as mentioned above, 2,4-D does have a relatively short half-life and it is also notable that plant damage was strongly associated with soybean cover.

One particularly troubling aspect of our results was that oak species (*Quercus* spp.) seem to be disproportionately impacted by herbicides entering habitat areas. Oaks perform important roles in structuring natural communities as dominant canopy trees of Illinois forests. Oaks provide mast for priority wildlife species and are hosts to a disproportionate number of moth caterpillars, which act as pollinators and as important food resources for migratory birds (Tallamy 2021). Oak regeneration is already a significant management challenge in midwestern landscapes (e.g., Alexander et al.

2021) and these results suggest that pesticides may be yet another challenge for natural resource professionals to consider.

Pesticides are regularly entering Illinois naturally vegetated areas and are leading to visual symptoms on a range of plant species. The full implications of this observed damage, however, are unknown. We currently do not know the impact of a single exposure event on a plant and its fitness, much less the implications of repeated exposures within and across years. Given the relationships we observed with chemicals and specific row crops, our results do suggest that crop rotation has the potential to result in slightly different chemical exposures from one year to the next. However, we do not know if plants continue to show signs of damage after a single exposure or if there is a cumulative effect of these potential repeat exposures. We are planning to revisit trees marked during the 2023 field season to help answer some of these questions, and we are leveraging 25 years of long-term monitoring recorded in the CTAP dataset to help understand the longer-term implications of these exposures on plant communities.

Beyond the direct effects on plants, herbicides can also influence other trophic levels either via direct effects of exposure (Rohr and McCoy 2009), increasing arthropod susceptibility to insecticides (Belden and Lydy 2000, Anderson and Lydy 2002), or changing the leaf tissue that herbivores are consuming. Beyond the herbicides, little is known about non-target effects of the fungicides and insecticides we detected. Potential negative direct effects of the insecticides on arthropods seem likely, and fungicides could inhibit decomposition (and thus nutrient cycling), decrease fungal biomass, and negatively impact plants by disrupting symbiotic associations with root fungi for

example. Fungicides have also been shown to negatively affect native bumble bees through exposure in pollen (Runnion et al. 2024).

Acknowledgments

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Tables and Figures

Table 1. List of symptoms of vegetation injury recorded during field surveys. Bold symptoms indicate those that are associated with herbicide damage. Symptoms not in bold are general indicators of stress.

Leaves: curled or cupped
sideways, upside down, or drooped
irregular margins
strapped
tattered
twisted, deformed, and/or stunted
veins bleached and/or parallel
Shoots: elongated, coiled, and/or bent
growth suppressed and deformed
Leaves: chlorotic (yellowed)
necrotic (brown/black areas)
2nd growth
Trees: epicormic branching
dieback
death

Table 2. The most common chemicals encountered, separated by visit. Almost all of the positive chemical detections were from leaf tissue, not soil cores.
* Glyphosate was tested for samples from a limited number of sites (67 sites for the first visit, 17 for the second visit). The prevalence of glyphosate given in this table is the percent among those tested, not the percent among all sites.

Visit 1 (May 17 to July 7)		
Chemical	**Class**	**% of Sites**
Atrazine	Herbicide	77%
Desethyl atrazine	Herbicide	64%
2,4-D	Herbicide	52%
* Glyphosate	Herbicide	25%
Metolachlor	Herbicide	10%
Metribuzin	Herbicide	3%
Pydiflumetofen	Fungicide	2%
Acetochlor	Herbicide	1%
Dicamba	Herbicide	1%
Diphenylamine	Fungicide	1%

Visit 2 (July 18 to September 9)		
Chemical	**Class**	**% of Sites**
Propiconazole	Fungicide	41%
Azoxystrobin	Fungicide	34%
Pydiflumetofen	Fungicide	31%
Bifenthrin	Insecticide	25%
Mefentrilfluconazole	Fungicide	22%
Pyraclostrobin	Fungicide	19%
Atrazine	Herbicide	16%
2,4-D	Herbicide	14%
Desethyl atrazine	Herbicide	12%
Cyhalothrin, lambda	Insecticide	9%

Table 3. The prevalence of the two most common herbicides in different types of leaf tissue samples. Counts for atrazine and its metabolite (desethyl atrazine) are summed in this table.

		Atrazine & metabolite				2,4-D		
		Present	**Absent**	**% Present**		**Present**	**Absent**	**% Present**
Visit 1	**Affected**	87	35	71.3	**Affected**	63	59	51.6
	Random	95	40	70.4	**Random**	61	74	45.2
		Present	**Absent**	**% Present**		**Present**	**Absent**	**% Present**
Visit 2	**Affected**	6	43	12.2	**Affected**	6	43	12.2
	Random	10	41	19.6	**Random**	9	42	17.6

Table 4. The species with the greatest severity of symptoms, ranked in descending order. This list is restricted to those species with a minimum of 10 observations during timed meanders.

Rank	Common name	Scientific name	Observations
1	Shingle oak	*Quercus imbricaria*	64
2	Blackjack oak	*Quercus marilandica*	16
3	Redbud	*Cercis canadensis*	46
4	Post oak	*Quercus stellata*	34
5	Black oak	*Quercus velutina*	92
6	Unknown oak	*Quercus* sp.	57
7	Boxelder	*Acer negundo*	77
8	Pin oak	*Quercus palustris*	35
9	Bur oak	*Quercus macrocarpa*	46
10	Swamp white oak	*Quercus bicolor*	19
11	Hackberry/Sugarberry	*Celtis* sp.	17
12	White oak	*Quercus alba*	122
13	Persimmon	*Diospyros virginiana*	44
14	Unknown hawthorn	*Crataegus* sp.	14
15	Red oak	*Quercus rubra*	66
16	Shagbark hickory	*Carya ovata*	83

Table 5. Sites with the greatest symptom severity, after controlling for observer and species present. The Symptom Severity is a relative measure that has a mean of zero, and indicates the relative damage score for a site when controlling for species encountered and observer. For example, if the same observer rated the same plant species at Emma Vance Woods NP and an average study site, we would expect the species to be more damaged by more than one step on our six-point damage scale.

Rank	**Study site**	**Symptom severity**
1	Emma Vance Woods NP	1.24
2	Roberts Cemetery Savanna NP	1.14
3	(random wetland, Edwards Co)	1.03
4	Edna Edwards Burnett LWR	0.97
5	Brownlee Cemetery Prairie NP	0.93
6	Gillespie Prairie LWR	0.90
7	Chauncey Marsh NP	0.87
8	(random grassland, Livingston Co)	0.86
9	Munson Township Cemetery Prairie NP	0.82
10	Beadles Barrens NP	0.80
11	(random grassland, Mason Co)	0.77
12	Karcher's Post Oak Woods NP	0.77
13	Wirth Prairie NP	0.76
14	(random grassland, Shelby Co)	0.71
15	Sunbury Railroad Prairie NP	0.68

Table 6. Prevalence of symptoms of vegetation damage in tissue samples. Asterisks indicate general signs of stress that are not especially associated with herbicide damage. Separate summaries were calculated for tissue collections from randomly selected plants, and tissue samples from notably affected individuals.

	Prevalence (%)	
Symptom	**Affected tissue**	**Random tissue**
* chlorotic leaves	40.4	20.2
curled or cupped leaves	88.9	53.7
death	0.0	0.0
dieback	20.5	12.0
shoots elongated, coiled, and/or bent	9.4	6.0
epicormic branching	12.9	5.8
new growth suppressed and deformed	28.7	13.9
irregular margins on leaves	31.6	16.0
* necrotic leaves	37.4	22.0
* second growth (leaves)	6.4	5.8
epinasty (leaf petioles sideways, upside down, drooped)	39.8	25.4
strapped leaves	9.4	3.1
tattered leaves	25.7	16.5
twisted, deformed, and/or stunted leaves	65.5	44.2
veins bleached and/or parallel	2.9	0.5

Figure 1. Map of study sites. The Random Sites are those that were originally included as part of the Critical Trends Assessment Program.

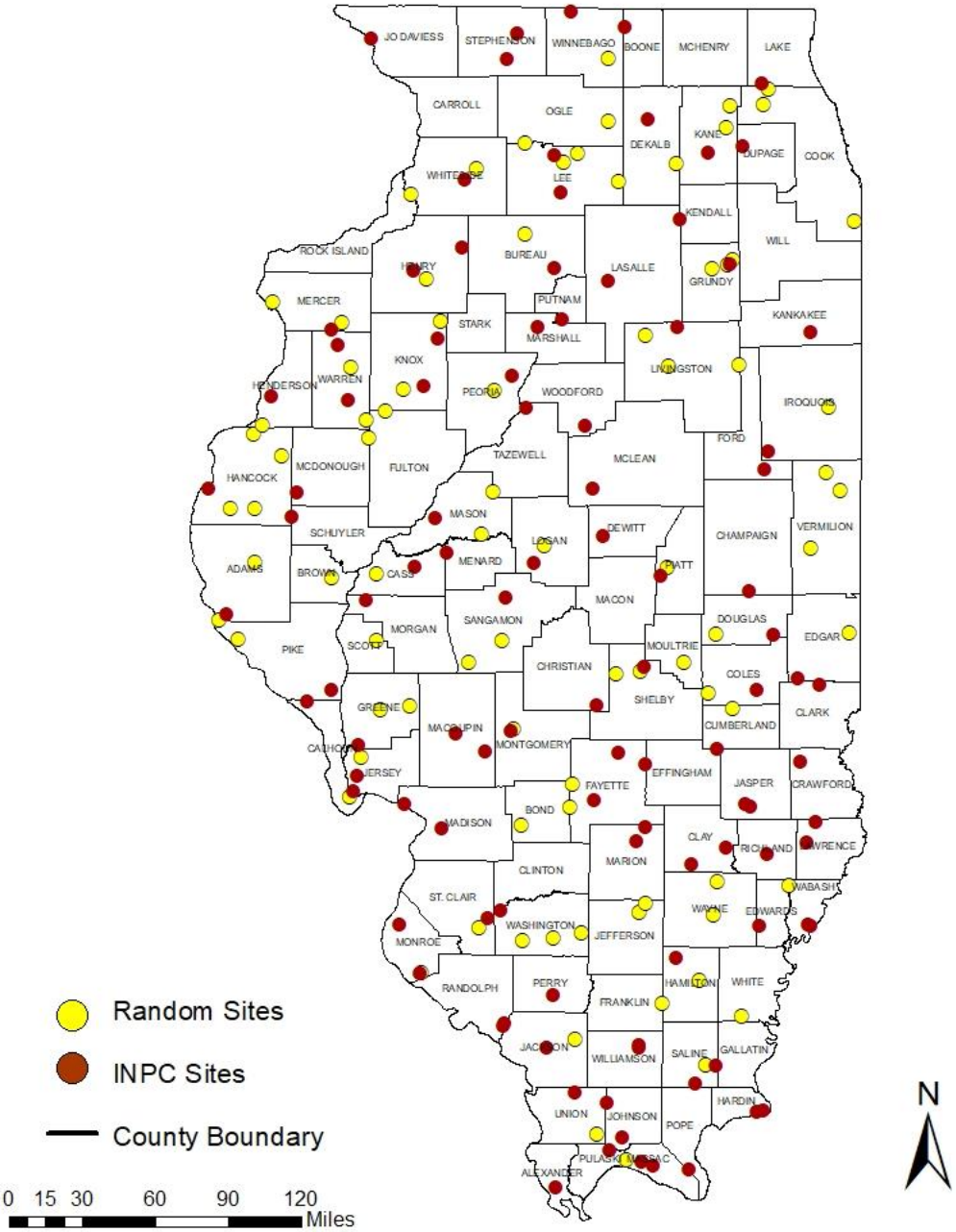

Figure 2. Example of timed meander recording symptom severity. This meander occurred at McMaster Woods Nature Preserve in Greene County. The blue curve indicates the path of the meander. The red circle with white star indicates the location of the random tissue sampling and soil sampling. Red pins indicate individuals that were noted for future study.

Figure 3. Total atrazine concentration and proportion of the surrounding 1 km that is in corn. Pesticide concentrations are from random leaf tissues collected at each site visit. Landscape estimates come from remotely sensed data (USDA NASS Cropland Data Layer). Error bars around the mean estimates represent +/- two standard errors.

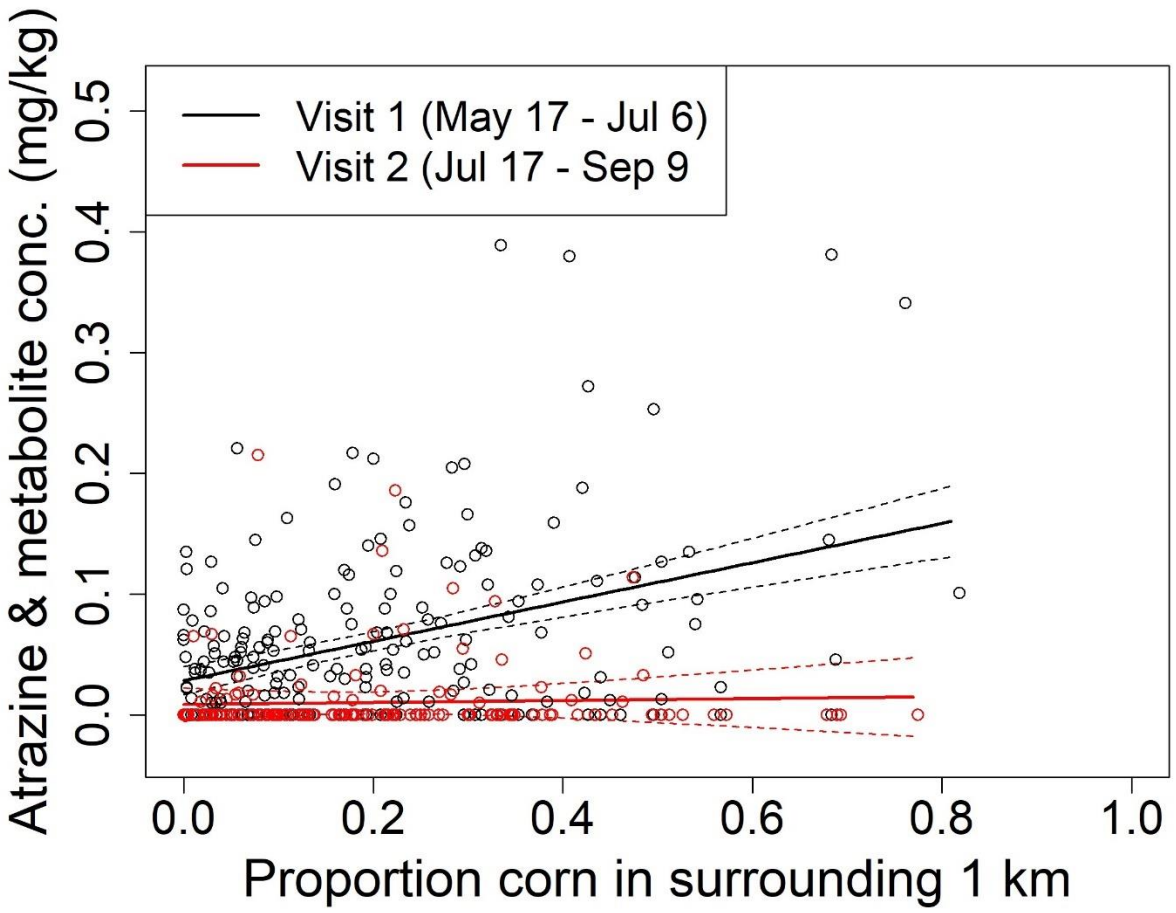

Figure 4. Total atrazine concentration and proportion of the surrounding 10 km that is in soybeans. Pesticide concentrations are from random leaf tissues collected at each site visit. Landscape estimates come from remotely sensed data (USDA NASS Cropland Data Layer). Error bars around the mean estimates represent +/- two standard errors.

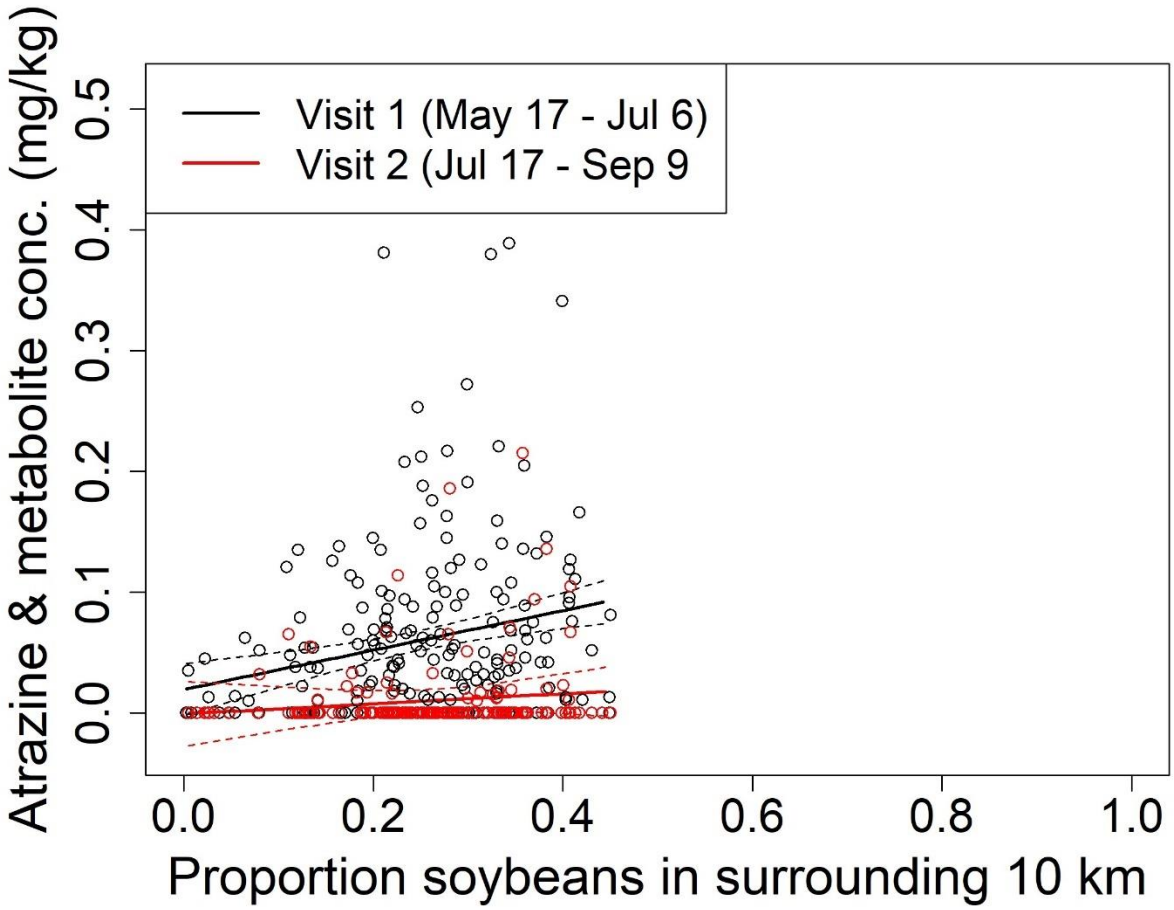

Figure 5. Total atrazine concentration and proportion of the surrounding 10 km that is forested. Pesticide concentrations are from random leaf tissues collected at each site visit. Landscape estimates come from remotely sensed data (USDA NASS Cropland Data Layer). Error bars around the mean estimates represent +/- two standard errors.

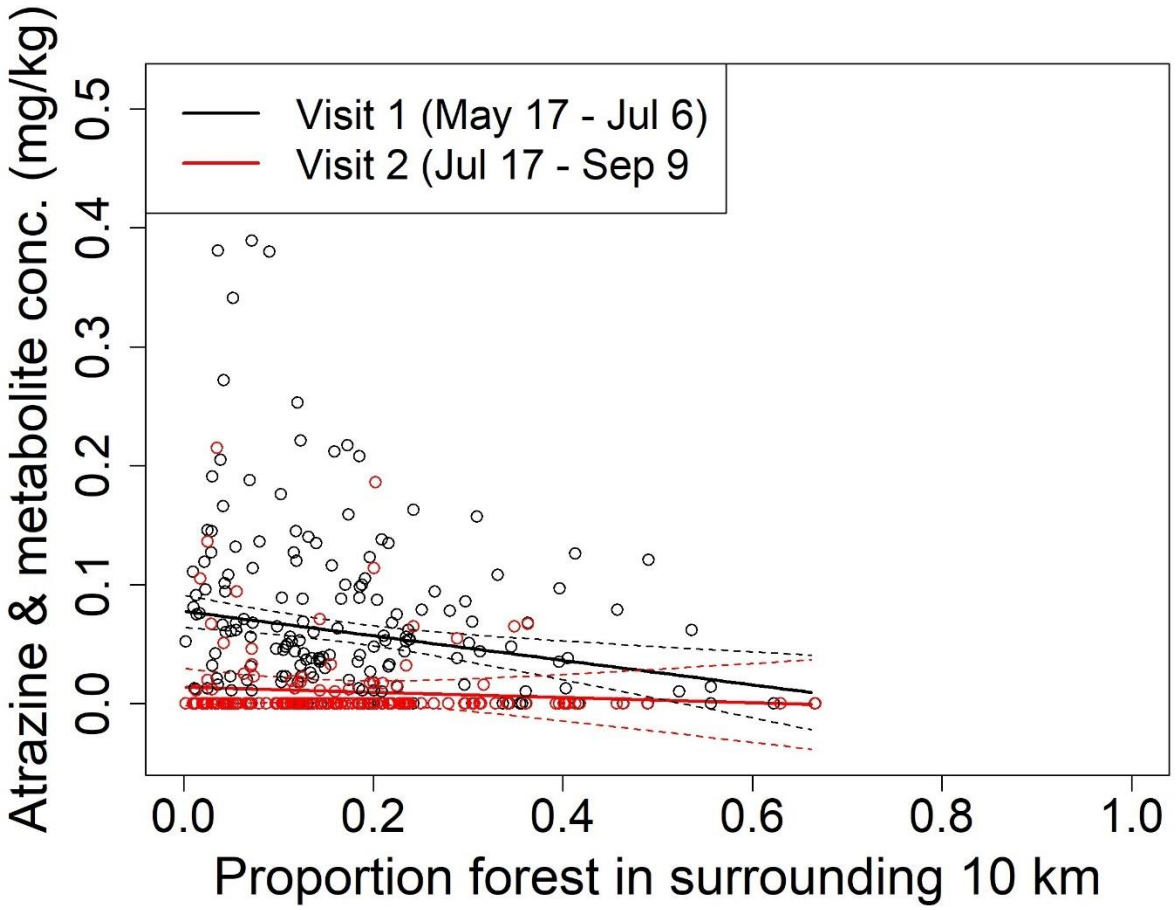

Figure 6. Total atrazine concentration and proportion of the surrounding 300 meters that is areas with natural vegetation. Pesticide concentrations are from random leaf tissues collected at each site visit. Landscape estimates come from remotely sensed data (USDA NASS Cropland Data Layer). Error bars around the mean estimates represent +/- two standard errors.

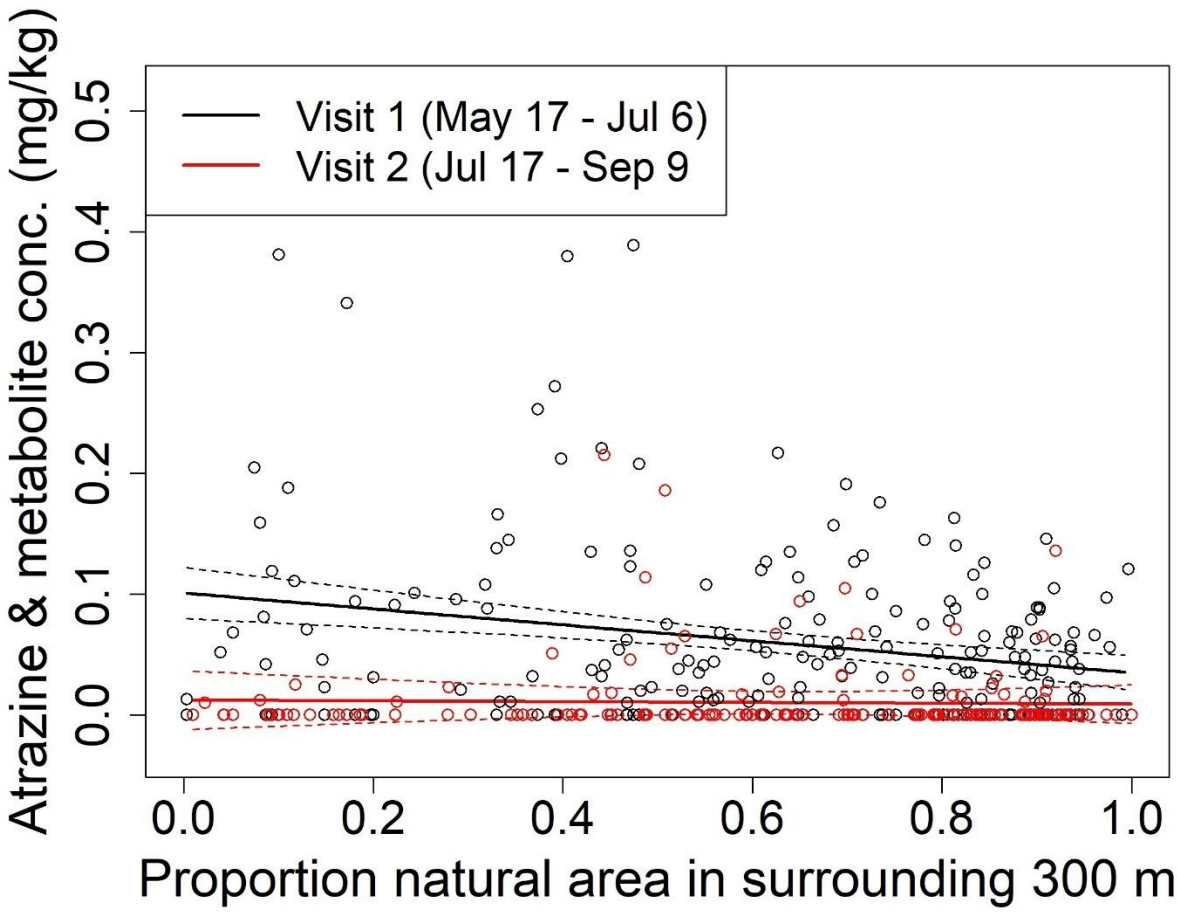

Figure 7. Concentration of 2,4-D and proportion of the surrounding 3 km that is in corn. Pesticide concentrations are from random leaf tissues collected at each site visit. Landscape estimates come from remotely sensed data (USDA NASS Cropland Data Layer). Error bars around the mean estimates represent +/- two standard errors.

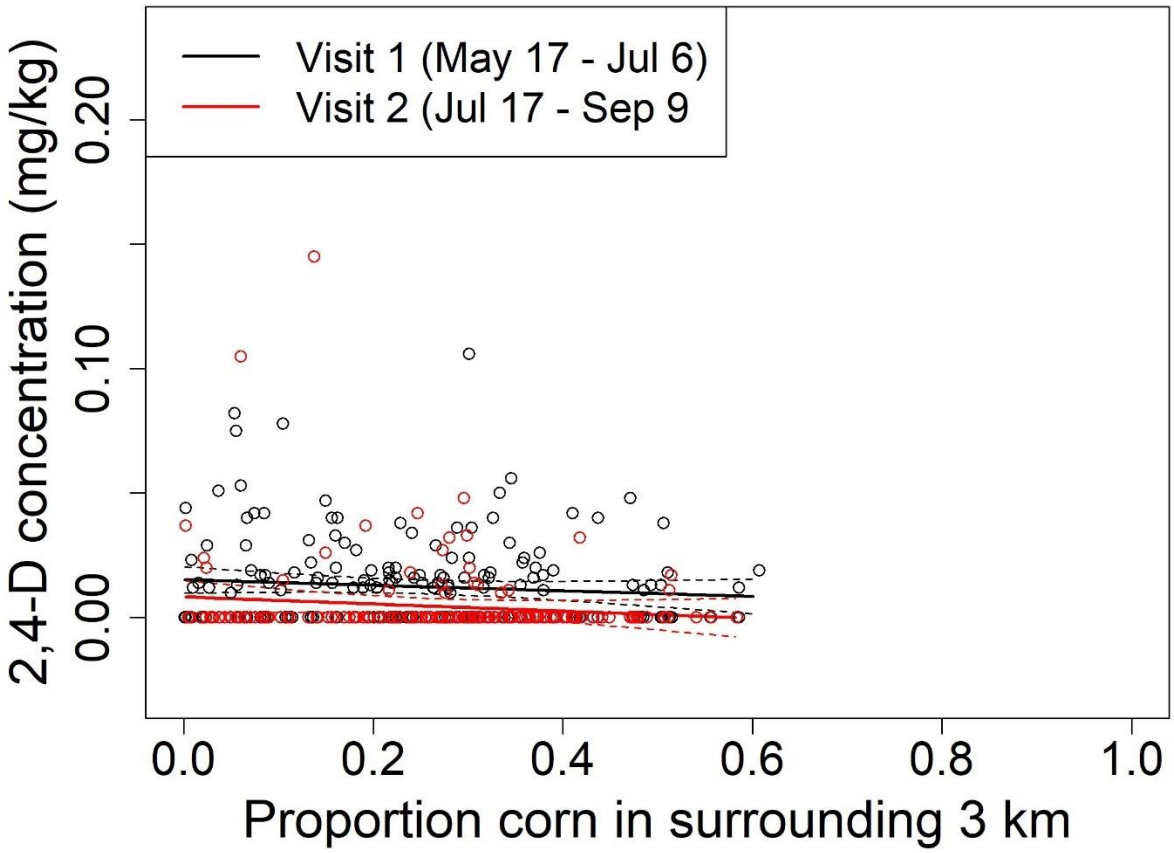

Figure 8. Propiconazole concentration and proportion of the surrounding 100 meters that is in corn. Pesticide concentrations are from random leaf tissues collected at each site visit. Landscape estimates come from remotely sensed data (USDA NASS Cropland Data Layer). Error bars around the mean estimates represent +/- two standard errors. One extreme outlier during visit 2 is not included in the plot to improve clarity.

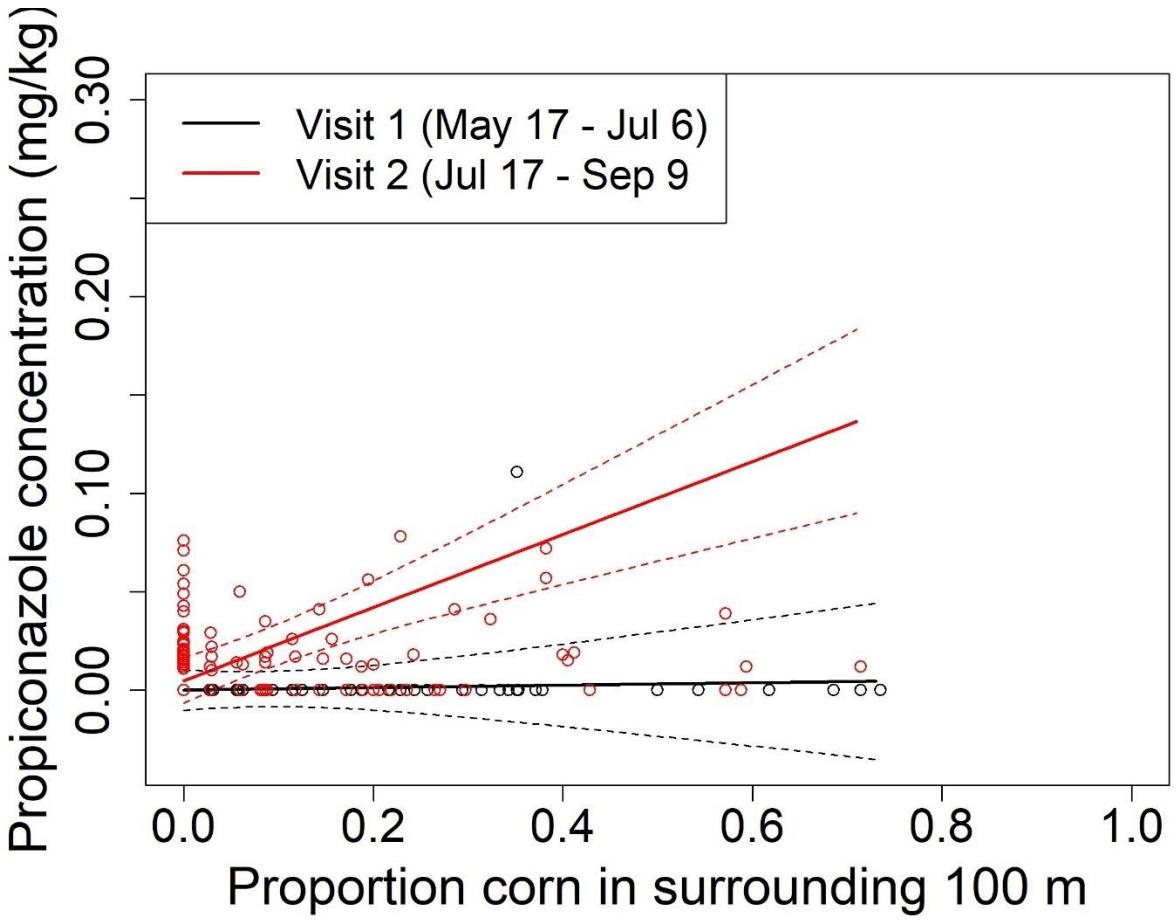

Figure 9. Propiconazole concentration and proportion of the surrounding 10 km that is in soybeans. Pesticide concentrations are from random leaf tissues collected at each site visit. Landscape estimates come from remotely sensed data (USDA NASS Cropland Data Layer). Error bars around the mean estimates represent +/- two standard errors. One extreme outlier during visit 2 is not included in the plot to improve clarity.

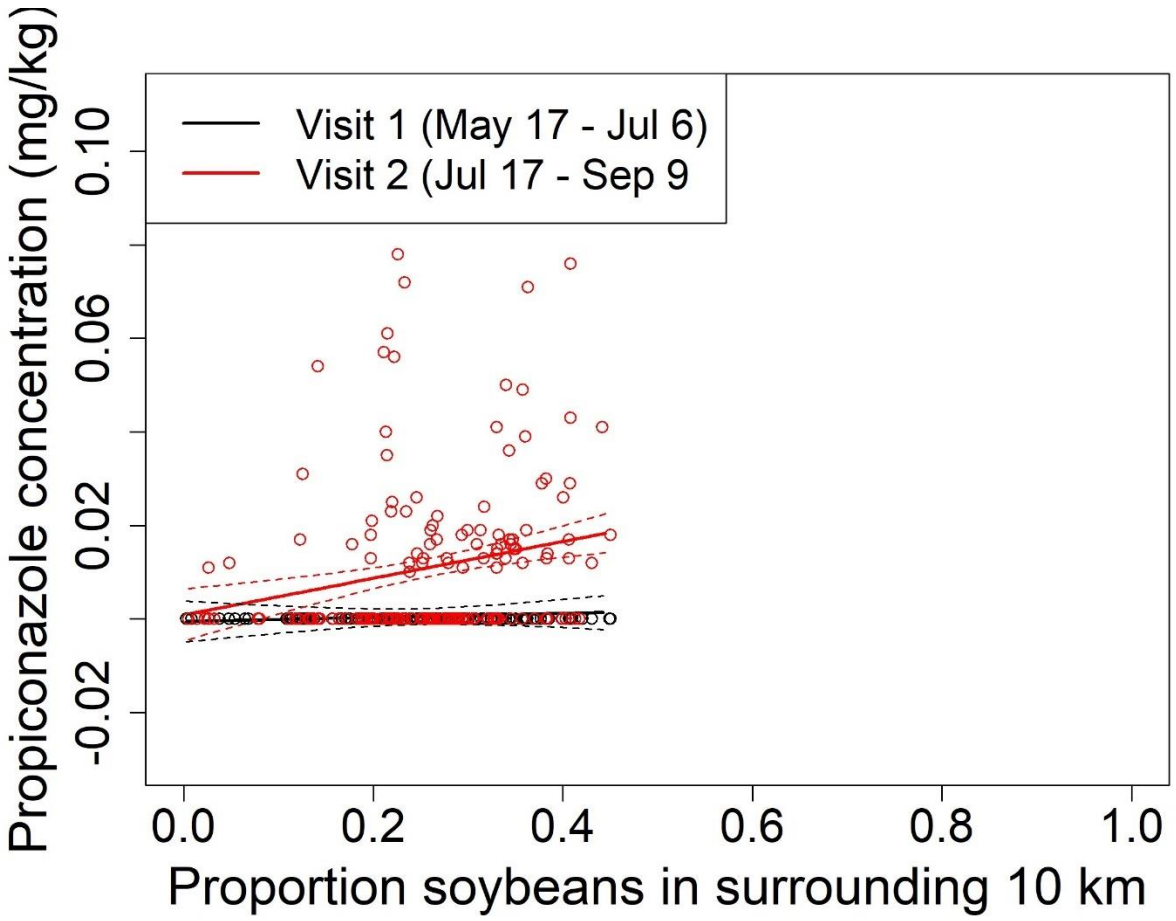

Figure 10. Propiconazole concentration and proportion of the surrounding 300 meters that is forested. Pesticide concentrations are from random leaf tissues collected at each site visit. Landscape estimates come from remotely sensed data (USDA NASS Cropland Data Layer). Error bars around the mean estimates represent +/- two standard errors. One extreme outlier during visit 2 is not included in the plot to improve clarity.

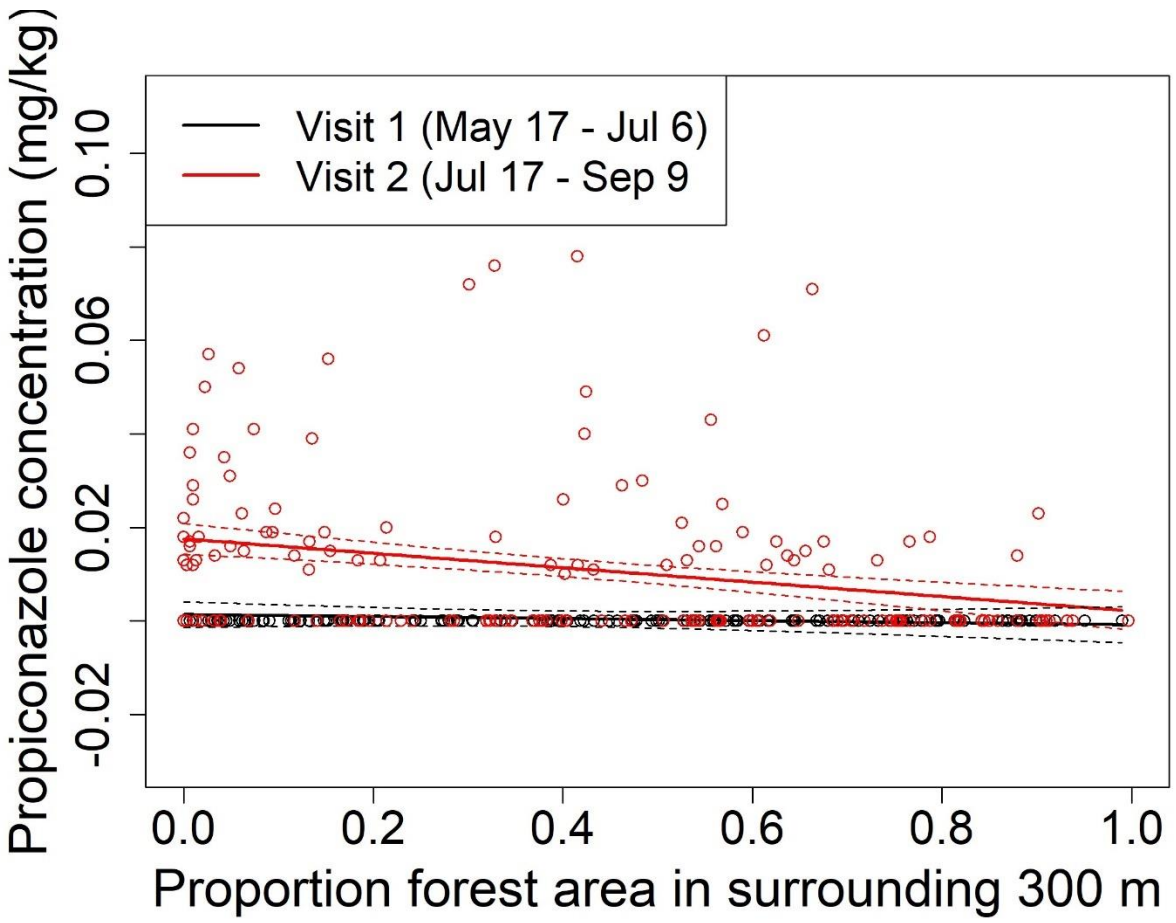

Figure 11. Propiconazole concentration and proportion of the surrounding 300 meters that is in areas with natural vegetation. Pesticide concentrations are from random leaf tissues collected at each site visit. Landscape estimates come from remotely sensed data (USDA NASS Cropland Data Layer). Error bars around the mean estimates represent +/- two standard errors. One extreme outlier during visit 2 is not included in the plot to improve clarity.

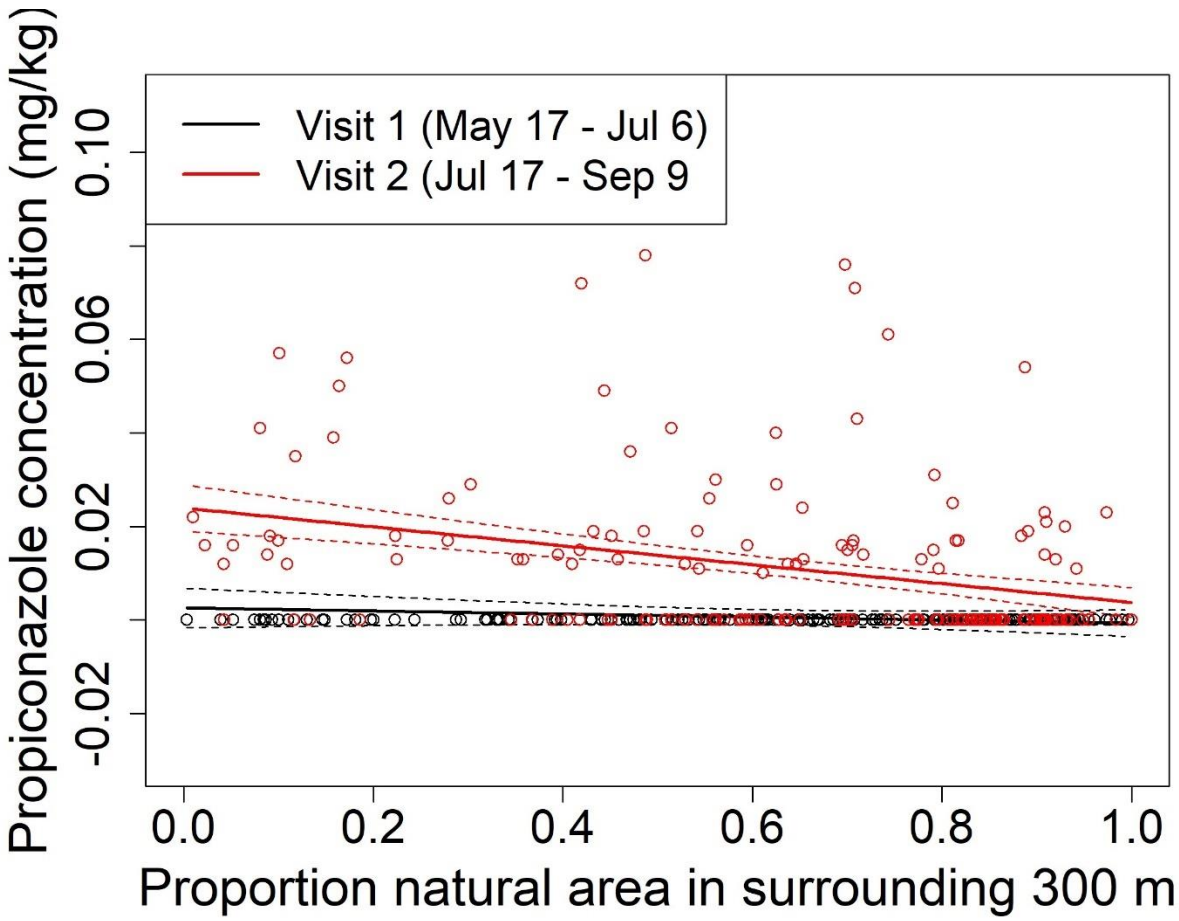

Figure 12. Bifenthrin concentration and proportion of the surrounding 1 km that is in corn. Pesticide concentrations are from random leaf tissues collected at each site visit. Landscape estimates come from remotely sensed data (USDA NASS Cropland Data Layer). Error bars around the mean estimates represent +/- two standard errors.

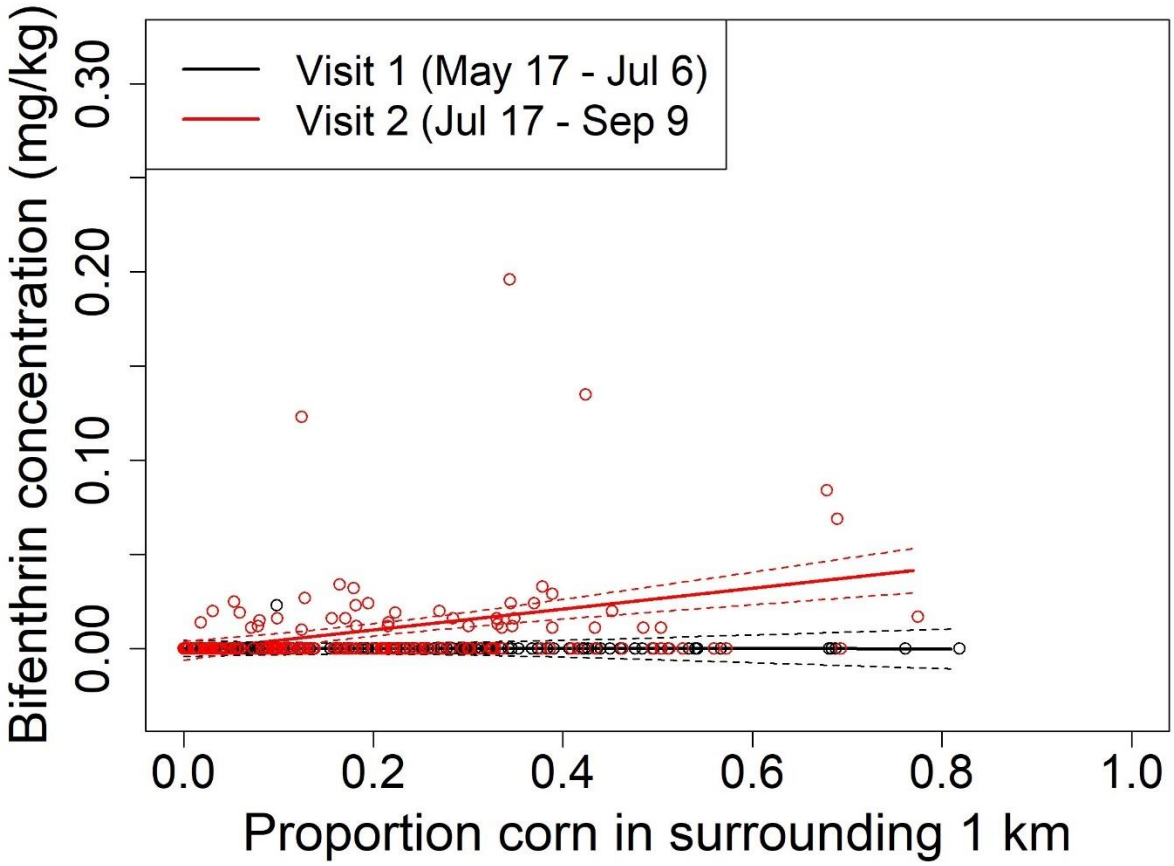

Figure 13. Bifenthrin concentration and proportion of the surrounding 1 km that is in soybeans. Pesticide concentrations are from random leaf tissues collected at each site visit. Landscape estimates come from remotely sensed data (USDA NASS Cropland Data Layer). Error bars around the mean estimates represent +/- two standard errors.

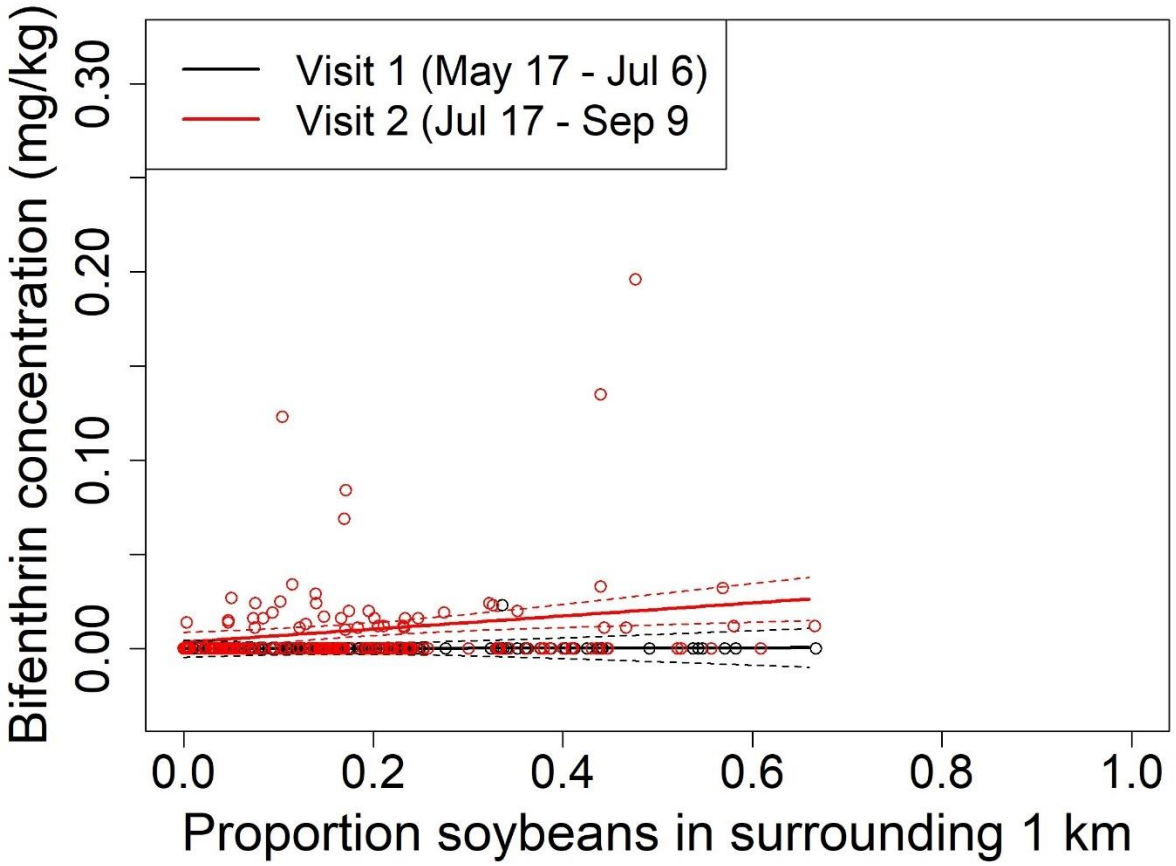

Figure 14. Species-level symptom severity ratings plotted against the number of observations. Each point represents a species encountered during meander surveys. The black dashed line indicates 10 observations, and the red dashed line indicates 5 observations. In this report, we concentrate on reporting relative values for species with at least 10 observations.

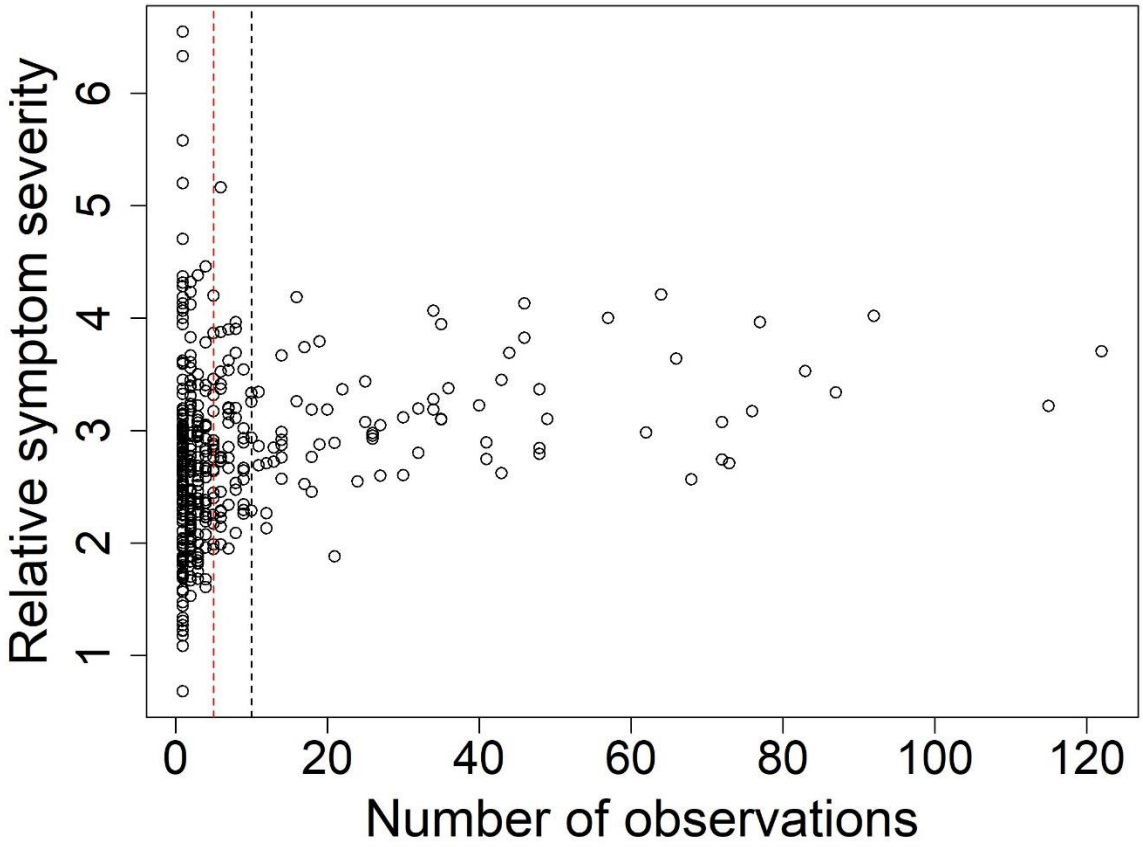

Figure 15. Relative site-level symptom severity and the relationship with the proportion of the surrounding 1 km in soybeans. Increasing values for site-level symptom severity indicate more signs of herbicide damage. The site-level symptom severity was determined by statistical models that controlled for observer effects and the species encountered at the site. Landscape estimates come from remotely sensed data (USDA NASS Cropland Data Layer).

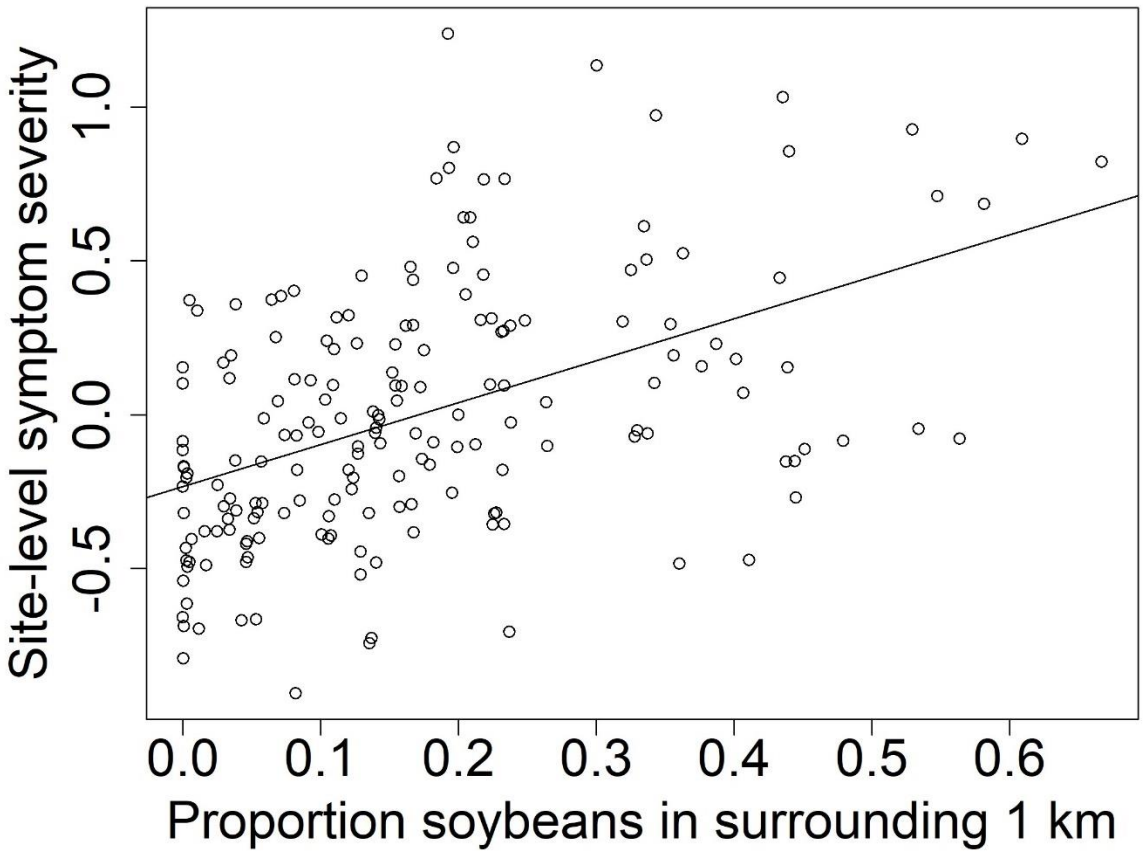

Figure 16. Relative site-level symptom severity and the relationship with the proportion of the surrounding 1 km in areas with natural vegetation. Increasing values for site-level symptom severity indicate more signs of herbicide damage. The site-level symptom severity was determined by statistical models that controlled for observer effects and the species encountered at the site. Landscape estimates come from remotely sensed data (USDA NASS Cropland Data Layer).

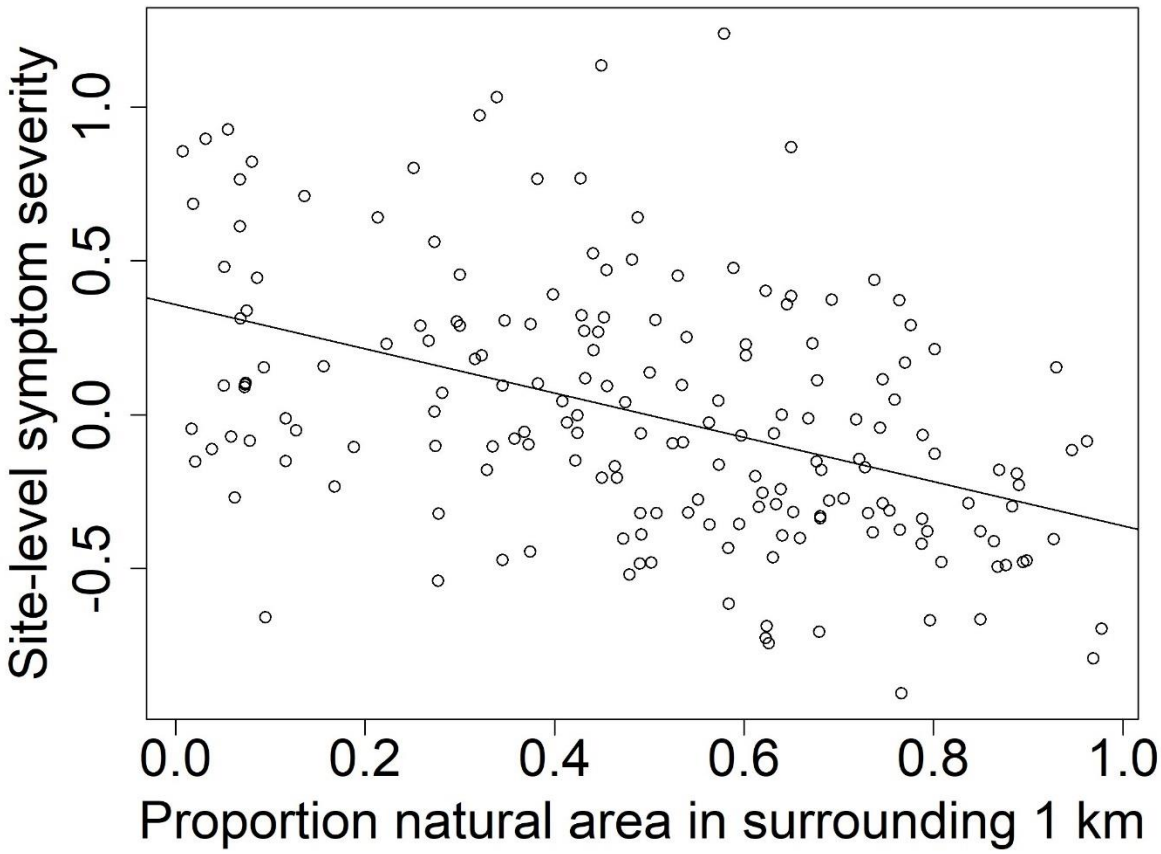

Figure 17. Relative site-level symptom severity and the relationship with the concentration of atrazine in leaf tissues. Increasing values for site-level symptom severity indicate more signs of herbicide damage. The site-level symptom severity was determined by statistical models that controlled for observer effects and the species encountered at the site. Atrazine concentration was determined from random leaf tissue samples.

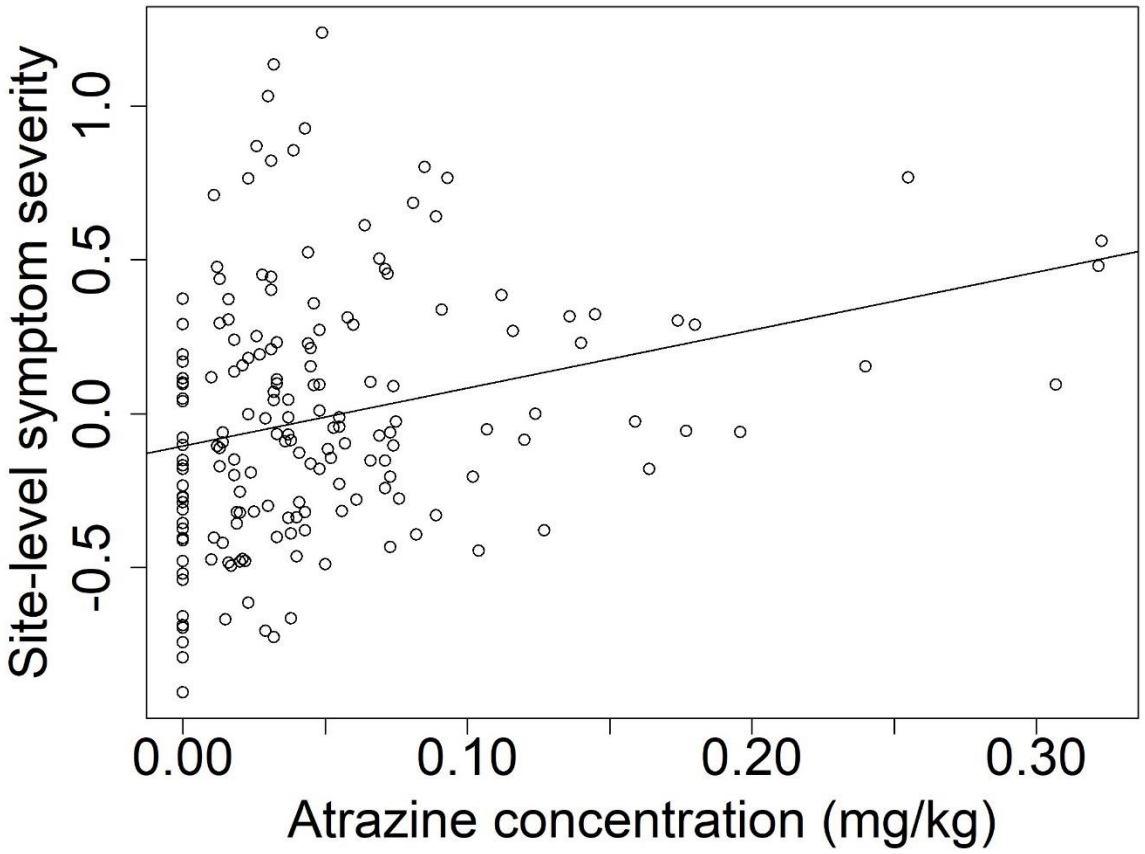

Figure 18. Comparison of relative site-level symptom severity between INPC study sites and randomly selected sites that were originally included in the Critical Trends Assessment Program. Increasing values for site-level symptom severity indicate more signs of herbicide damage. The site-level symptom severity was determined by statistical models that controlled for observer effects and the species encountered at the site.

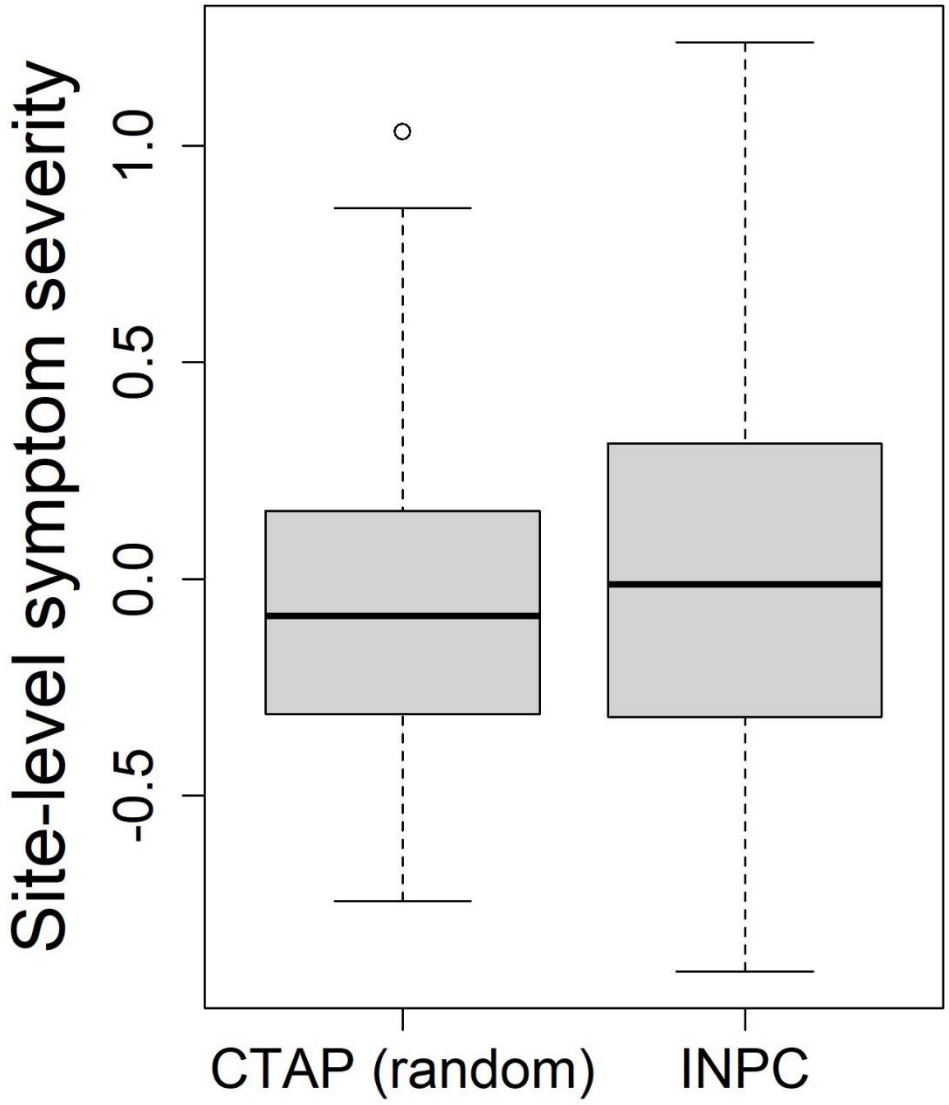

Figure 19. Comparison of relative site-level symptom severity among habitat types. Increasing values for site-level symptom severity indicate more signs of herbicide damage. The site-level symptom severity was determined by statistical models that controlled for observer effects and the species encountered at the site.

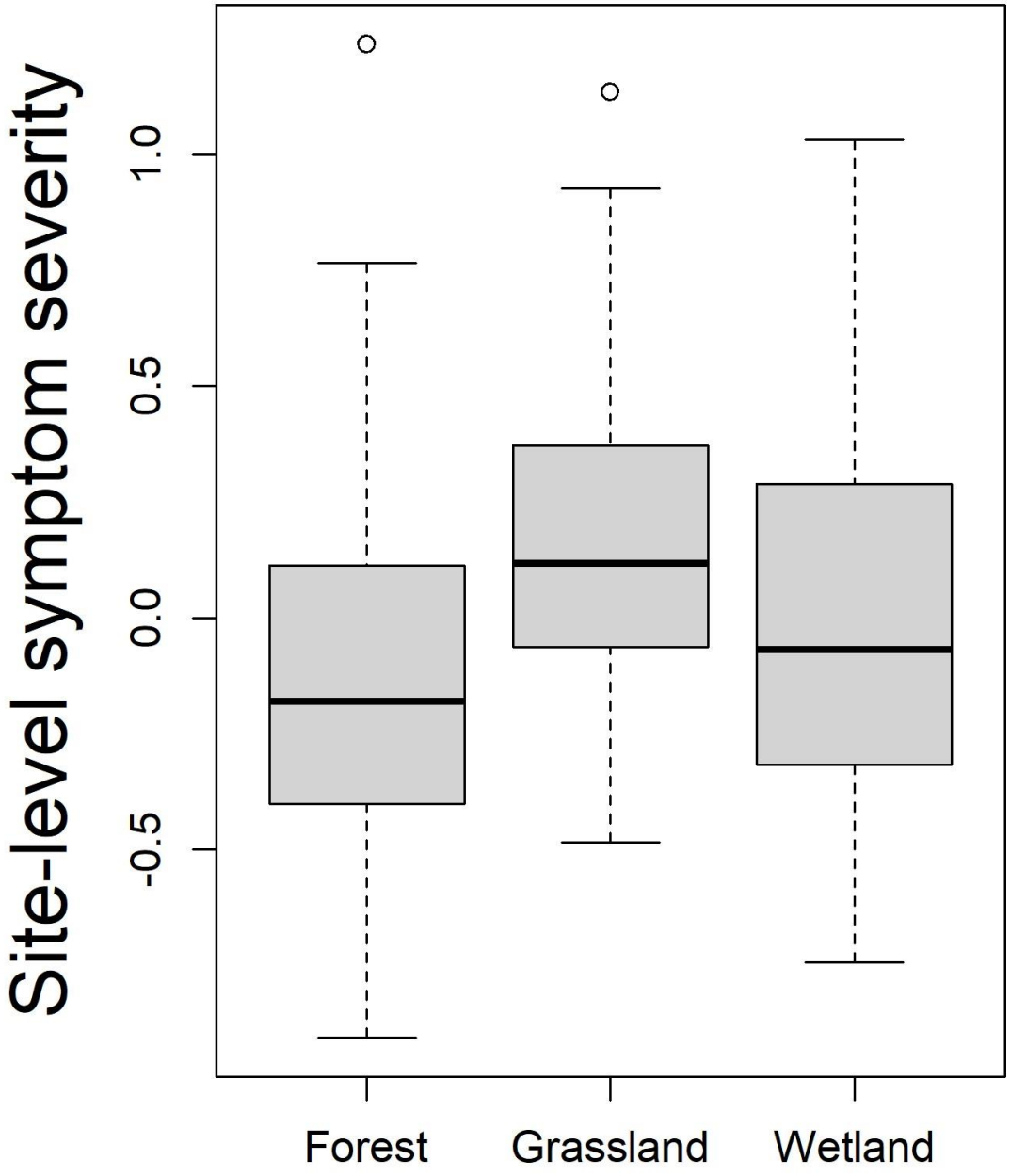

Figure 20. *Quercus imbricaria* leaves showing signs of cupping and twisting. Statistical models suggested this species had the greatest degree of injury.

Figure 21. *Carya glabra* showing signs of cupping, deformed growth, and chlorosis. This photograph was taken at Denby Prairie NP in Macoupin County on 15 June 2023.

Figure 22. *Cercis canadensis* showing signs of cupping, deformed and stunted leaves, suppressed new growth, irregular margins, bleached (and perhaps parallel) veins. Statistical models suggested that this species was among the most susceptible to injury, especially when excluding oaks. This photograph was taken on private property on 7 August 2023.

Figure 23. *Carya ovata* showing signs of mild cupping, deformed and twisted leaves, and some epinasty. This photograph was taken at Mettler Woods in DeWitt County on 9 August 2023.

Figure 24. *Acer negundo* with deformed growth, twisted and cupped leaves, and chlorosis. Statistical models suggested that this species was among the most susceptible to injury, especially when excluding oaks. This photograph was taken at Amboy Marsh NP in Lee County on 12 June 2023.

Figure 25. An oak (most likely *Quercus rubra* or *Q. velutina*) with several symptoms consistent with herbicide injury (cupping, leaf deformation, suppression of new growth, epinasty, irregular margins) and signs of general stress (chlorosis, necrosis, dieback). This photograph was taken on 7 August 2023.

Figure 26. *Quercus bicolor* with suppressed new growth, deformed leaves, tattered leaves, cupping, and chlorosis. This photograph was taken at Edna Edwards Burnett LWR in Champaign County on 18 May 2023.

Figure 27. A hawthorn (possibly *Crataegus mollis*) with leaves that are cupped, deformed, and twisted, and new growth which is suppressed or deformed. This photograph was taken at Sunbury Railroad Prairie NP in Livingston County.

Figure 28. *Quercus macrocarpa* with leaves that are twisted, probably some tattered leaves, and suppressed new growth. This photograph was taken at Sawyer-Coffel LWR in Perry County on 21 June 2023.

Figure 29. Quercus velutina with deformed and suppressed new growth, twisted leaves, light cupping of leaves, and necrosis. This photograph was taken at Prospect Cemetery Prairie NP in Ford County on 22 July 2023.

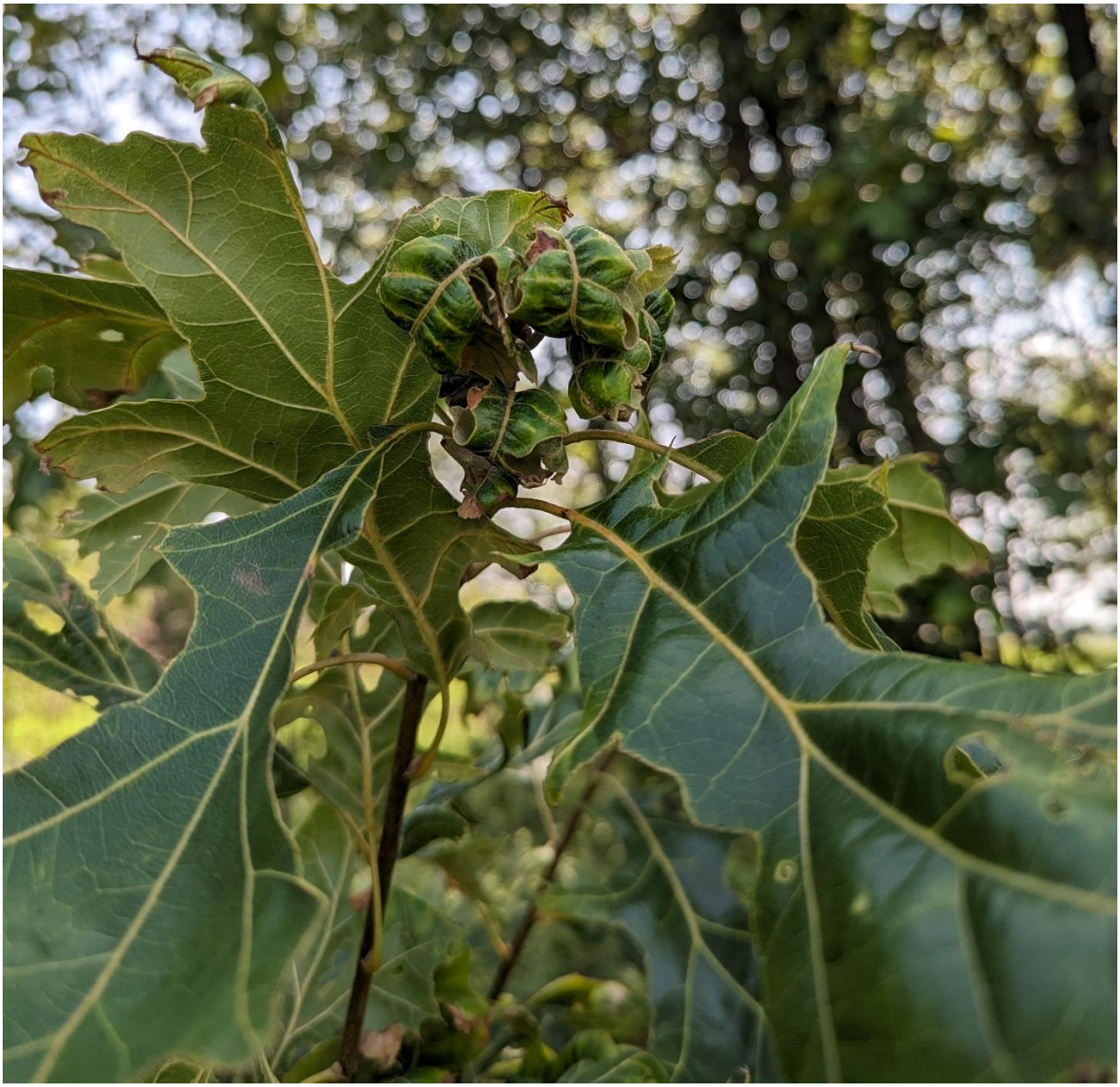

Figure 30. *Quercus marilandica* with cupped leaves, epinasty, growth suppression, and chlorosis. This photograph was taken at Ellison Creek Sand Prairie NP in Henderson County on 10 August 2023.

Figure 31. *Carya ovata* with cupped leaves. This photograph was taken on 24 May 2023 on private property (not designated as an INPC property).

Figure 32. *Amorpha canescens* with epinasty, twisted leaves, and perhaps some cupping of leaflets. This photograph was taken at Wirth Prairie in Stephenson County on 7 August 2023.

Figure 33. Hickory (*Carya* sp.) with severe epinasty, cupped leaflets, twisted leaves, chlorosis, necrosis, and suppression of new growth. This photograph was taken on 7 August 2023 on private property (not designated as an INPC property).

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APPENDICES

Appendix 1. List of dedicated Nature Preserves and Land and Water Reserves included in this study.

INPC Study Site	County	Primary Habitat Type
Beall Woods LWR	Wabash	Forest
Cedar/Draper's Bluff LWR	Johnson	Forest
Forever Fields LWR	Knox	Wetland
Franklin Creek NP	Lee	Forest
Freeport Prairie NP	Stephenson	Grassland
Gillespie Prairie LWR	Macoupin	Wetland
Massasauga Prairie NP	Warren	Grassland
Mermet Swamp NP	Massac	Wetland
Mineral Marsh NP	Henry	Wetland
Red Hills Seep Springs LWR	Lawrence	Forest
Amboy Marsh NP	Lee	Forest
Anderson Prairie LWR	Christian	Grassland
Angela's Prairie LWR	Monroe	Forest
Baber Woods NP	Edgar	Forest
Beadles Barrens NP	Edwards	Grassland
Beall Woods NP	Wabash	Forest
Big Creek Woods Memorial NP	Richland	Forest
Bohm Woods NP	Madison	Forest
Brownlee Cemetery Prairie NP	Mercer	Grassland
Buck Hill Bottom LWR	Washington	Forest
Burnside Forest NP	Fayette	Forest
Carpenter Park NP	Sangamon	Forest
Casper Bluff LWR	Jo Daviess	Grassland
Cedar Glen NP	Hancock	Forest
Chauncey Marsh NP	Lawrence	Wetland
Colored Sands Bluff NP	Winnebago	Forest
Cretaceous Hills NP	Pope	Forest
Cuba Marsh LWR	Lake	Wetland
Dean Hills NP	Fayette	Forest
Denby Prairie NP	Macoupin	Grassland
Eagle Cliff Prairie NP	Monroe	Grassland
Edna Edwards Burnett LWR	Champaign	Grassland
Ellison Creek Sand Prairie NP	Henderson	Grassland
Emma Vance Woods NP	Crawford	Forest

Fall Creek Gorge LWR	Adams	Forest
Flag Pond LWR	Clay	Forest
Funks Grove NP	McLean	Forest
George S. Park Memorial Woods NP	Putnam	Forest
Gooseberry Island NP	Kankakee	Forest
Grigsby Marsh LWR	McDonough	Wetland
Grisley Woods LWR	Williamson	Forest
Guthrie Cave LWR	Union	Forest
Haw Creek Sedge Meadow LWR	Knox	Forest
Heron Pond-Little Black Slough NP	Johnson	Forest
Horseshoe Geological Area LWR	Saline	Forest
Horseshoe Lake NP	Alexander	Forest
Jasmine Hollow LWR	Piatt	Forest
Jennings Family Hill Prairie NP	Calhoun	Forest
John Clyde Spitler Woods NP	Cumberland	Forest
Johnson's Mound NP	Kane	Forest
Karcher's Post Oak Woods NP	Hamilton	Forest
Karl Bartel Wildlife Sanctuary LWR	Marion	Wetland
Katelyn's Woods LWR	Jersey	Forest
Kinnikinnick Creek NP	Boone	Forest
Lafarge Barker Bluff LWR	Hardin	Forest
Lafarge Limestone Glade NP	Hardin	Forest
Lake Murphysboro Hill Prairies LWR	Jackson	Forest
Letcher Basin LWR	Woodford	Grassland
Loda Cemetery Prairie NP	Iroquois	Grassland
Long Branch Sand Prairie NP	Mason	Grassland
Loy Prairie LWR	Marion	Grassland
Lyndon Prairie NP	Whiteside	Grassland
Margaret Guzy Pothole Wetlands LWR	Shelby	Grassland
Martin T. Snyder Memorial NP	Clay	Forest
Matthiessen Dells NP	LaSalle	Forest
McAdams Peak LWR	Jersey	Forest
McMaster Woods NP	Greene	Forest
Meredosia Hill Prairie NP	Morgan	Grassland
Mettler Woods NP	DeWitt	Forest
Missionary Oblates' Woods NP	Madison	Forest
Munson Township Cemetery Prairie NP	Henry	Grassland
Myer Woods NP	Bureau	Forest
North Elkhart Hill Grove LWR	Logan	Forest

Oak Bluff Savanna NP	Marshall	Grassland
Otey-Grisley Forest NP	Williamson	Forest
P & E Refuge LWR	Saline	Forest
Panther Creek Hill Prairie LWR	Cass	Forest
Piney Creek Ravine NP	Randolph	Forest
Prairie Ridge LWR	Jasper	Grassland
Prospect Cemetery Prairie NP	Ford	Grassland
Robert Ridgway Grasslands NP	Jasper	Grassland
Roberts Cemetery Savanna NP	Montgomery	Grassland
Rock Cave LWR	Effingham	Forest
Rocky Branch NP	Clark	Forest
Sawyer - Coffel LWR	Perry	Wetland
Section 8 Woods NP	Pulaski	Forest
Sielbeck Forest LWR	Massac	Forest
Singing Woods NP	Peoria	Forest
Spring Creek LWR	Tazewell	Forest
Spring Grove Cemetery Prairie NP	Warren	Grassland
Sunbury Railroad Prairie NP	Livingston	Grassland
Swayne Hollow NP	Randolph	Forest
Truitt-Hoff NP	DuPage	Wetland
Tucker-Millington Fen NP	Kendall	Wetland
Twin Culvert Cave NP	Pike	Forest
Upper Embarras Woods NP	Douglas	Forest
Wagon Lake LWR	St Clair	Wetland
Warbler Woods LWR	Coles	Forest
Wilkinson-Renwick Marsh NP	DeKalb	Wetland
Williams Creek Bluff LWR	Schuyler	Forest
Wirth Prairie NP	Stephenson	Grassland
Witter's Bobtown Hill Prairie NP	Menard	Grassland

Appendix 2. Analytes tested in tissue and soil samples. The limit of quantitation measures the mass (mg) of the analyte per kg of leaf tissue. Some chemicals can be categorized into multiple categories (e.g., herbicide and fungicide), although in some of these cases we only list one of the uses.

Analyte	**Limit of quantitation (mg / kg of leaf tissue)**	**Category**
1, NAA	0.01	Herbicide
2,4,5-T	0.01	Herbicide
2,4,5-TP	0.01	Herbicide
2,4-D	0.01	Herbicide
2,4-DB	0.01	Herbicide
2,4-DP (Dichlorprop)	0.01	Herbicide
Abamectin (Avermectin)	0.01	Insecticide
Acephate	0.02	Insecticide
Acequinocyl	0.01	Insecticide
Acetamiprid	0.01	Insecticide
Acetochlor	0.02	Herbicide
Acifluorfen	0.01	Herbicide
Acrinathrin	0.01	Insecticide
Alachlor	0.02	Herbicide
Aldicarb	0.01	Insecticide
Aldicarb sulfone (Aldoxycarb)	0.01	Insecticide
Aldicarb-sulfoxide	0.01	Insecticide
Aldrin	0.01	Insecticide
Ametoctradin	0.01	Fungicide
Ametryn	0.01	Herbicide
Aminocyclopyrachlor	0.01	Herbicide
Anilazine	0.03	Fungicide
Aspon	0.01	Insecticide
Asulam	0.01	Herbicide
Atrazine	0.01	Herbicide
Atrazine-desethyl	0.01	Herbicide
Azinphos-ethyl	0.01	Insecticide
Azinphos-methyl	0.01	Insecticide
Azoxystrobin	0.01	Fungicide
Benalaxyl	0.01	Fungicide
Bendiocarb	0.01	Insecticide
Benfluralin	0.01	Herbicide

Benoxacor	0.01	Herbicide
Bensulide	0.01	Herbicide
Bentazon	0.01	Herbicide
Benzovindiflupyr	0.01	Fungicide
BHC alpha isomer	0.01	Insecticide
BHC beta isomer	0.01	Insecticide
BHC delta isomer	0.01	Insecticide
Bifenazate	0.01	Insecticide
Bifenox	0.01	Herbicide
Bifenthrin	0.01	Insecticide
Binapacryl	0.04	Insecticide; Fungicide
Bioresmethrin	0.01	Insecticide
Bitertanol	0.02	Fungicide
Boscalid	0.01	Fungicide
Broflanilide	0.01	Insecticide
Bromacil	0.02	Herbicide
Bromophos-ethyl	0.02	Insecticide
Bromophos-methyl	0.01	Insecticide
Bromopropylate	0.01	Insecticide
Bromoxynil	0.01	Herbicide
Bromuconazole	0.01	Fungicide
Bupirimate	0.01	Fungicide
Buprofezin	0.01	Insecticide
Butachlor	0.01	Herbicide
Butoxycarb	0.01	Insecticide
Butralin	0.02	Herbicide
Butylate	0.01	Herbicide
Cadusafos	0.01	Insecticide
Captafol	0.1	Fungicide
Captan	0.02	Fungicide
Carbaryl	0.01	Insecticide
Carbendazim	0.01	Fungicide
Carbofuran	0.01	Insecticide
Carbofuran, 3-hydroxy	0.01	Insecticide
Carbophenothion	0.01	Insecticide
Carbophenothion methyl	0.01	Insecticide
Carboxin	0.01	Fungicide
Carfentrazone-ethyl	0.01	Herbicide
Chlorantraniliprole	0.01	Insecticide
Chlordane, cis-	0.01	Insecticide
Chlordane, trans-	0.01	Insecticide
Chlordimeform	0.01	Insecticide

Chlorfenapyr	0.02	Insecticide
Chlorfenson (Ovex)	0.01	Insecticide; Fungicide
Chlorfenvinphos	0.01	Insecticide
Chlorimuron-ethyl	0.01	Herbicide
Chlornitrofen (CNP)	0.02	Herbicide
Chlorobenzilate	0.01	Insecticide
Chloroneb	0.01	Fungicide
Chlorothalonil	0.04	Fungicide; Insecticide
Chlorpropham (CIPC)	0.01	Herbicide
Chlorpyrifos (ethyl)	0.01	Insecticides
Chlorpyrifos-methyl	0.01	Insecticides
Chlorsulfuron	0.01	Herbicide
Chlorthal-dimethyl (Dacthal)	0.01	Herbicide
Chlorthion	0.02	Insecticide
Chlorthiophos	0.01	Insecticide
Clethodim	0.01	Herbicide
Clethodim sulfone	0.01	Herbicide
Clethodim sulfoxide	0.01	Herbicide
Clofentezine	0.01	Insecticide
Clomazone	0.01	Herbicide
Clopyralid	0.01	Herbicide
Clothianidin	0.01	Insecticide
Coumaphos	0.01	Insecticide
Crotoxyphos	0.01	Insecticide
Cyanazine	0.01	Herbicide
Cyanofenphos	0.01	Insecticide
Cyanophos	0.04	Insecticide
Cyantraniliprole	0.01	Insecticide
Cyazofamid	0.01	Fungicide
Cycloate	0.01	Herbicide
Cycloxydim	0.01	Herbicide
Cyfluthrin	0.03	Insecticides
Cyhalothrin, lambda	0.01	Insecticides
Cymoxanil	0.01	Fungicide
Cypermethrin	0.01	Insecticide
Cyprodinil	0.01	Fungicide
Cyromazine	0.01	Insecticide
DCPMU	0.01	Herbicide
DDD, o,p'-	0.01	Insecticide
DDD, p,p'-	0.01	Insecticide

DDE, o,p'-	0.01	Insecticide
DDE, p,p'-	0.01	Insecticide
DDT, o,p'-	0.01	Insecticide
DDT, p,p'-	0.01	Insecticide
DEF (Tribufos)	0.01	Insecticide; Herbicide; Synergist
Deltamethrin	0.01	Insecticide
Demeton-S	0.02	Insecticide
Demeton-S methyl-sulfone	0.02	Insecticide
Demeton-s-methyl	0.02	Insecticide
Desmedipham	0.01	Herbicide
Diallate	0.01	Herbicide
Diazinon	0.01	Insecticide
Diazoxon	0.01	Insecticide
Dicamba (Banvel)	0.01	Herbicide
Dichlobenil	0.01	Herbicide
Dichlofenthion	0.01	Insecticide
Dichlofluanid	0.01	Fungicide
Dichlorobenzamide	0.01	Herbicide
Dichlorvos	0.01	Insecticide
Diclobutrazol	0.01	Fungicide
Diclofop (acid)	0.01	Herbicide
Diclofop-methyl	0.01	Herbicide
Dicloran	0.04	Fungicide
Dicofol, p,p'-/o,p'-	0.02	Insecticide
Dicrotophos	0.01	Insecticide
Dieldrin	0.01	Insecticide
Diethofencarb	0.01	Insecticide
Diethyltoluamide (DEET)	0.01	Insecticide
Difenoconazole	0.01	Fungicide
Diflubenzuron	0.01	Insecticide
Diflufenzopyr	0.01	Herbicide
Dimethenamid	0.01	Herbicide
Dimethoate	0.01	Insecticide
Dimethomorph	0.01	Fungicide
Diniconazole	0.01	Fungicide; Herbicide
Dinocap	0.01	Fungicide; Insecticide
Dinoseb (Dinitro)	0.01	Fungicide; Herbicide, Insecticide

Dinotefuran	0.01	Insecticide
Dioxathion	0.01	Insecticide
Diphenamid	0.01	Herbicide
Diphenylamine (DPA)	0.01	Fungicide
Disulfoton	0.02	Insecticide
Disulfoton sulfone	0.01	Insecticide
Disulfoton sulfoxide	0.01	Insecticide
Dithianon	0.01	Fungicide
Dithiopyr	0.01	Herbicide
Diuron	0.01	Herbicide
DNOC	0.01	Fungicide; Herbicide; Insecticide
Edifenphos	0.01	Fungicide
Endosulfan (α isomer)	0.02	Insecticide
Endosulfan (β isomer)	0.02	Insecticide
Endosulfan sulfate	0.01	Insecticide
Endrin	0.02	Insecticide
Endrin aldehyde	0.02	Insecticide
EPN	0.01	Insecticide
EPTC	0.01	Herbicide
Esfenvalerate/Fenvalerate	0.02	Insecticide
Etaconazole	0.01	Fungicide
Ethaboxam	0.01	Fungicide
Ethalfluralin	0.01	Herbicide
Ethiofencarb	0.01	Insecticide
Ethion	0.01	Insecticide
Ethirimol	0.01	Fungicide
Ethofumesate	0.01	Fungicide
Ethoprophos	0.01	Insecticide
Ethoxyquin	0.01	Fungicide; Herbicide
Etofenprox	0.01	Insecticide
Etoxazole	0.01	Insecticide
Etridiazole	0.01	Fungicide
Etrimfos	0.01	Insecticide
Famoxadone	0.02	Fungicide
Famphur	0.01	Insecticide
Fenamidone	0.01	Fungicide
Fenamiphos	0.01	Insecticide
Fenamiphos Sulfone	0.01	Insecticide
Fenamiphos Sulfoxide	0.01	Insecticide
Fenarimol	0.01	Fungicide

Fenazaquin	0.01	Insecticide
Fenbuconazole	0.01	Fungicide
Fenbutatin oxide	0.01	Insecticide
Fenchlorphos	0.01	Insecticide
Fenhexamid	0.01	Fungicide
Fenitrothion	0.01	Insecticide
Fenobucarb (Baycarb)	0.01	Insecticide; Herbicide
Fenoxaprop-P-Ethyl	0.01	Herbicide
Fenoxycarb	0.01	Insecticide
Fenpropathrin	0.01	Insecticide
Fenpyroximate	0.01	Insecticide
Fenson	0.02	Insecticide
Fensulfothion	0.01	Insecticide
Fenthion	0.01	Insecticide
Fenuron	0.01	Herbicide
Fipronil	0.01	Insecticide
Flonicamid	0.01	Insecticide
Fluazifop	0.01	Herbicide
Fluazinam	0.01	Fungicide
Fluchloralin	0.01	Herbicide
Flucythrinate	0.03	Insecticide
Fludioxonil	0.01	Fungicide
Flufenacet	0.01	Herbicide
Flumioxazin	0.01	Herbicide
Fluometuron	0.01	Herbicide
Fluopicolide	0.01	Fungicide
Fluopyram	0.01	Fungicide; Insecticide
Fluoxastrobin	0.01	Fungicide
Fluprimidol	0.01	Herbicide; Fungicide
Flupyradifurone	0.01	Insecticide
Fluridone	0.01	Herbicide
Fluroxypyr (free acid)	0.01	Herbicide
Flusilazol	0.01	Fungicide
Fluthiacet Methyl	0.01	Herbicide
Flutolanil	0.01	Fungicide
Flutriafol	0.01	Fungicide
Fluvalinate -tau	0.01	Insecticide
Fluxapyroxad	0.01	Fungicide
Folpet	0.02	Fungicide
Fomesafen	0.01	Herbicide

Fonofos	0.01	Insecticides
Foramsulfuron	0.01	Herbicide
Forchlorfenuron	0.01	Herbicide
Formetanate	0.01	Insecticide
Furathiocarb	0.01	Insecticide
Halosulfuron-methyl	0.01	Herbicide
Haloxyfop (free acid)	0.01	Herbicide
Heptachlor	0.01	Insecticide; Fungicide
Heptachlor epoxide	0.01	Insecticide; Fungicide
Hexachlorobenzene (HCB)	0.01	Fungicide
Hexaconazole	0.01	Fungicide
Hexazinone (Velpar)	0.01	Herbicide
Hexythiazox	0.01	Insecticide
Hydroprene	0.01	Insecticide
Imazalil	0.01	Fungicide
Imazamox	0.01	Herbicide
Imazapic	0.01	Herbicide
Imazapyr	0.01	Herbicide
Imazaquin	0.01	Herbicide
Imazethapyr	0.01	Herbicide
Imidacloprid	0.01	Insecticide
Imidoxone (Phosmet-Oxon)	0.01	Insecticide
Indaziflam	0.01	Herbicide
Indoxacarb	0.01	Insecticide
Iprobenfos	0.01	Fungicide
Iprodione	0.02	Fungicide
Isazophos	0.01	Insecticide
Isobenzan	0.01	Insecticide
Isocarbophos	0.01	Insecticide
Isodrin	0.01	Insecticide
Isofenphos	0.01	Insecticide
Isofenphos-methyl	0.01	Insecticide
Isofenphos-OA	0.01	Insecticide
Isoprocarb	0.01	Insecticide
Isopropalin	0.01	Herbicide
Isoprothiolane	0.01	Insecticide; Fungicide
Isoproturon	0.01	Herbicide
Isoxaben	0.01	Herbicide
Isoxaflutole	0.01	Herbicide

Kresoxim-methyl	0.01	Fungicide
Lactofen	0.02	Herbicide; Fungicide
Lenacil	0.01	Herbicide
Lindane	0.01	Insecticide
Linuron	0.01	Herbicide
Malaoxon (Malathion-o-analog)	0.01	Insecticide
Malathion	0.01	Insecticide
Mandipropamid	0.01	Fungicide
MCPA	0.01	Herbicide
MCPB	0.01	Herbicide
MCPP (Mecoprop)	0.01	Herbicide
Mecarbam	0.01	Insecticide
Mefentrilfluconazole	0.01	Fungicide
Mepanipyrim	0.01	Fungicide
Mesosulfuron Methyl	0.01	Herbicide
Mesotrione	0.01	Herbicide
Metalaxyl/Mefenoxam	0.01	Fungicide
Metconazole	0.01	Fungicide
Methacrifos	0.01	Insecticide
Methamidophos	0.01	Insecticide
Methidathion	0.01	Insecticide
Methiocarb	0.01	Insecticide
Methiocarb sulfone	0.01	Insecticide
Methiocarb sulfoxide	0.01	Insecticide
Methomyl	0.01	Insecticide
Methoxychlor	0.01	Insecticide
Methoxyfenozide	0.01	Insecticide
Metobromuron	0.01	Herbicide
Metolachlor	0.01	Herbicide
Metolcarb	0.01	Insecticide
Metrafenone	0.01	Fungicide
Metribuzin	0.01	Herbicide
Metsulfuron-methyl	0.01	Herbicide
Mevinphos	0.01	Insecticide
Mexacarbate	0.01	Insecticide
MGK-264	0.01	Synergist
Mirex	0.01	Insecticide
Molinate	0.01	Herbicide
Monocrotophos	0.01	Insecticide
Monolinuron	0.01	Herbicide
Myclobutanil	0.01	Fungicide

Naled	0.01	Insecticide; Fungicide
Napropamide	0.01	Herbicide
Neburon	0.01	Herbicide
Nicosulfuron	0.01	Herbicide
Nitrapyrin	0.02	Bactericide; Nitrification inhibitor
Nitrofen	0.02	Herbicide
Norflurazon	0.01	Herbicide
Novaluron	0.01	Insecticide
Nuarimol	0.02	Fungicide
Omethoate	0.01	Insecticide
O-Phenylphenol	0.01	Fungicide
Oryzalin	0.01	Herbicide
Oxadiazon	0.01	Herbicide
Oxadixyl	0.01	Fungicide
Oxamyl	0.01	Insecticide
Oxamyl-oxime	0.01	Insecticide
Oxathiapiprolin	0.01	Fungicide
Oxychlordane	0.01	Insecticide
Oxydemeton-Methyl	0.01	Insecticide
Oxyfluorfen	0.01	Herbicide
Oxythioquinox	0.02	Fungicide; Insecticide
Paclobutrazol	0.01	Herbicide; Fungicide
Paraoxon-ethyl	0.01	Insecticide
Paraoxon-methyl	0.01	Insecticide
Parathion-ethyl	0.01	Insecticide
Parathion-methyl	0.03	Insecticide
PCP (Pentachlorophenol)	0.01	Herbicide; Fungicide; Insecticide
Penconazole	0.01	Fungicide
Pendimethalin	0.01	Herbicide
Penflufen	0.01	Fungicide
Pentachloroaniline (PCA)	0.01	Fungicide
Pentachloroanisole	0.01	Herbicide; Fungicide; Insecticide
Pentachlorobenzene (PCB)	0.01	Fungicide

Pentachlorothioanisole (PCTA)	0.03	Fungicide
Penthiopyrad	0.01	Fungicide
Permethrin	0.01	Insecticide
Perthane	0.01	Insecticide
Phenmedipham	0.01	Herbicide
Phenothrin	0.01	Insecticide
Phenthoate	0.01	Insecticide
Phorate	0.01	Insecticide
Phorate OA	0.01	Insecticide
Phorate Sulfone	0.01	Insecticide
Phorate Sulfoxide	0.01	Insecticide
Phosalone	0.01	Insecticide
Phosmet	0.01	Insecticide
Phosphamidon	0.01	Insecticide
Phoxim	0.01	Insecticide
Phthalimide	0.02	Fungicide
Picloram	0.01	Herbicide
Pinoxaden	0.01	Herbicide
Piperonyl Butoxide	0.01	Synergist
Pirimicarb	0.01	Insecticide
Pirimiphos-Ethyl	0.01	Insecticide
Pirimiphos-Methyl	0.01	Insecticide
Pirimisulfuron-Methyl	0.01	Herbicide
Prallethrin	0.01	Insecticide
Prochloraz	0.01	Fungicide
Procymidone	0.01	Herbicide; Fungicide
Prodiamine	0.01	Herbicide
Profenofos	0.01	Insecticide
Profluralin	0.01	Herbicide
Promecarb	0.01	Insecticide
Prometon	0.01	Herbicide
Prometryne	0.01	Herbicide
Pronamide (Propyzamide)	0.01	Herbicide
Propachlor	0.01	Herbicide
Propamocarb	0.01	Fungicide
Propanil	0.01	Herbicide
Propargite	0.01	Insecticide
Propazine	0.01	Herbicide
Propetamphos	0.01	Insecticide
Propham	0.01	Herbicide
Propiconazole	0.01	Fungicide

Propoxur	0.01	Insecticide
Propoxycarbazone sodium	0.01	Herbicide
Prosulfuron	0.01	Herbicide
Prothioconazole	0.01	Fungicide
Prothiofos	0.01	Insecticide
Pydiflumetofen	0.01	Fungicide
Pymetrozine	0.01	Insecticide
Pyraclostrobin	0.01	Fungicide
Pyraflufen-ethyl	0.01	Herbicide
Pyrazophos	0.01	Fungicide; Insecticide
Pyrethrins	0.01	Insecticide
Pyridaben	0.01	Insecticide
Pyridate	0.01	Herbicide
Pyrifluquinazon	0.01	Insecticide
Pyrimethanil	0.01	Fungicide
Pyriproxifen	0.01	Insecticide
Pyroxasulfone	0.01	Herbicide
Pyroxsulam	0.01	Herbicide
Quinalphos	0.01	Insecticide
Quinclorac	0.01	Herbicide
Quinoxyfen	0.01	Fungicide
Quintozene(PCNB)	0.01	Fungicide
Quizalofop (free acid)	0.01	Herbicide
Resmethrin	0.01	Insecticide
Rimsulfuron	0.01	Herbicide
Rotenone	0.01	Herbicide; Insecticide
S-421	0.01	Synergist
Saflufenacil	0.01	Herbicide
Sebuthylazine	0.01	Herbicide
Sedaxane	0.01	Fungicide
Sethoxydim	0.01	Herbicide
Simazine	0.01	Herbicide
Simetryn	0.01	Herbicide
Spinetoram	0.01	Insecticide
Spinosad (α, β isomers)	0.01	Insecticide
Spirodiclofen	0.01	Insecticide
Spiromesifen	0.01	Insecticide
Spirotetramat	0.01	Insecticide
Spirotetramat-enol	0.01	Insecticide
Spiroxamine	0.01	Fungicide

Sulfallate	0.01	Herbicide
Sulfentrazone	0.03	Herbicide
Sulfometuron-methyl	0.01	Herbicide
Sulfosulfuron	0.01	Herbicide
Sulfotep	0.01	Insecticide
Sulfoxaflor	0.01	Insecticide
Sulprofos	0.01	Insecticide
Tebuconazole	0.01	Fungicide
Tebufenozide	0.01	Insecticide
Tebuthiuron	0.01	Herbicide
Tecnazene	0.01	Fungicide; Herbicide
Tefluthrin	0.01	Insecticide
Tembotrione	0.01	Herbicide
Terbacil	0.04	Herbicide
Terbufos	0.01	Insecticide
Terbufos sulfone	0.01	Insecticide
Terbufos sulfoxide	0.01	Insecticide
Terbuthylazine	0.01	Herbicide
Terbutryn	0.01	Herbicide
Tertrachlorvinphos	0.01	Insecticide
Tetraconazole	0.01	Fungicide
Tetradifon	0.01	Insecticide
Tetramethrin	0.01	Insecticide
Tetrasul	0.01	Insecticide
Thiabendazole	0.01	Fungicide; Insecticide
Thiabendazole, 5-hydroxy	0.01	Fungicide; Insecticide
Thiacloprid	0.01	Insecticide
Thiamethoxam	0.01	Insecticide
Thifensulfuron-methyl	0.01	Herbicide
Thiobencarb (benthiocarb)	0.01	Insecticide
Thiodicarb	0.01	Insecticide
Thiometon	0.02	Insecticide
Thionazin	0.01	Insecticide; Fungicide
Thiophanate-methyl	0.01	Fungicide
Tolclofos-methyl	0.01	Fungicide
Tolfenpyrad	0.01	Insecticide; Fungicide
Tolylfluanid	0.01	Fungicide
Topramezone	0.01	Herbicide

Tralkoxydim	0.01	Herbicide
Triadimefon	0.01	Fungicide
Triadimenol	0.01	Fungicide
Tri-allate	0.01	Herbicide
Triasulfuron	0.01	Herbicide
Triazophos	0.01	Insecticide
Tribenuron-methyl	0.01	Herbicide
Trichlorfon	0.01	Insecticide
Triclopyr	0.02	Herbicide
Trifloxystrobin	0.01	Fungicide
Trifloxysulfuron -sodium	0.01	Herbicide
Triflumizole	0.01	Fungicide
Trifluralin	0.01	Herbicide
Triflusulfuron-methyl	0.01	Herbicide
Triforin	0.01	Fungicide
Trinexapac (acid)	0.01	Herbicide
Trinexapac Ethyl	0.01	Herbicide
Triticonazole	0.01	Fungicide
Vinclozolin	0.01	Fungicide
Zoxamide	0.01	Fungicide
None		
Glyphosate	0.05	Herbicide
AMPA	0.05	Herbicide
Glufosinate	0.05	Herbicide