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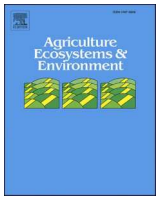

Neonicotinoid retention and transport in a maize cropping system with contour prairie strips

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ABSTRACT

Conservation areas established in agricultural fields can provide habitat for native organisms, but they also have the potential to accumulate and expose organisms to insecticides. Prairie strips are zones of cropland that have been converted to native prairie vegetation. Prairie strips increase biodiversity and reduce nutrient runoff, but they may also accumulate insecticides that endanger visiting organisms or facilitate the movement of insecticides across the landscape. In a study of paired catchments with ongoing neonicotinoid inputs, we measured the impact of prairie strips (10 % of cropland) on the accumulation and movement of the neonicotinoid insecticide clothianidin (CLO) into surface soil, deep soil, plant tissue, and groundwater across multiple slope positions during three phases of a maize growing season. While CLO accumulates in maize leaf tissue midseason following neonicotinoid application, we did not find evidence that prairie plant species in prairie strips accumulate CLO at concentrations lethal to pollinator insects. We also found that downslope soils contained the highest CLO concentrations in both catchments, showing that prairie strips did not eliminate downslope insecticide runoff. Our study adds to the existing literature examining prairie strip effects on downslope agrochemical transport, showing that when prairie strips are planted in cropland with ongoing neonicotinoid inputs, they can provide safe, low-insecticide habitat for visiting organisms amidst their other services, but may not reduce offsite insecticide runoff.

1. Introduction

Conservation areas in agricultural fields may provide valuable habitat for native wildlife, but they run the risk of exposing native wildlife to harmful insecticides associated with adjacent cropland (Bass et al., 2015, Gibbons et al., 2015, Morrissey et al., 2015, Mogren and Lundgren, 2016, Forister et al., 2016, Wood and Goulson 2017, Wagner et al., 2021). Neonicotinoid insecticides are broad-spectrum insecticides applied as an aerial spray or as an ingredient on coated seeds. They impair the growth, reproduction, foraging, and navigation of both pest insects and non-target native insects (Lundin et al., 2015, Wood and Goulson 2017, Crall et al., 2018, Goulson 2013). The majority of applied neonicotinoid compounds are not taken up by crop plants (Sur and Stork, 2003), but are mobilized into non-target "compartments" of the landscape, including air (Nuyttens et al., 2013), water (Smalling et al., 2018, Schaafsma et al., 2015), crop leaf tissue and nectar (Hall et al., 2022, Mogren and Lundgren, 2016), deep soil horizons (Radolinski et al., 2019), groundwater (Hladik et al., 2014, Thompson et al., 2021), and adjacent habitat areas (Hladik et al., 2018, Gibbons et al., 2015, Morrissey et al., 2015). The high mobility of neonicotinoids makes them particularly likely to accumulate in or be transported through farmland conservation features (Gibbons et al., 2015; Morrissey et al., 2015; Mogren and Lundgren, 2016; Wood and Goulson, 2017).

Prairie strips are perennial conservation areas that are established on farms to reduce soil movement and nutrient runoff from farmland, and to provide habitat for a suite of native insects and pollinators without

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disproportionately reducing crop yields (Schulte et al., 2017, Hernandez-Santana et al., 2013, Pérez-Suárez et al., 2014, Gutierrez-Lopez et al., 2014, Kemmerling et al., 2022, Kemmerling et al., 2023, Dolezal et al., 2019). The conservation benefits of prairie strips may be undermined if they accumulate insecticides in plant tissue and soils or facilitate the transport of neonicotinoids within the landscape. Prairie strips, which comprise 10 % of a row crop catchment in strips ≥30 feet wide, have been shown to reduce downslope runoff of sediment, nitrogen, and phosphorus (Zhou et al., 2014), and may inhibit neonicotinoid transport through similar mechanisms. For example, prairie strips may increase neonicotinoids in deep soil and groundwater layers via infiltration and leaching, as their dense perennial root systems change soil structure and can create channels for preferential flow (Smalling et al., 2018, Radolinski et al., 2019, Henning et al., 2024). Prairie strips may also increase plant neonicotinoid uptake due to the density of perennial roots (Hall et al., 2022, Mogren and Lundgren, 2016). At a site formerly planted with neonicotinoid-treated seeds, Hladik et al. (2017) report that converting 10 % of a row crop catchment to prairie strips reduced neonicotinoid runoff to downslope soils, but prairie strip effects have not yet been measured in cropping systems with ongoing neonicotinoid inputs where insecticide runoff is likely to be greatest. Soil biochemical changes that accompany conversion to perennial vegetation may promote or inhibit accumulation of neonicotinoids (Pietrzak et al., 2020). Compared to cropland soils, prairie strip soils have higher soil organic carbon (SOC) that can protect neonicotinoids from degradation (Smith et al., 2014, Zhang et al., 2018, Satowski et al., 2018, Morrison et al., 2022), but at the same time, higher dissolved organic carbon, higher soil moisture, and lower oxygen availability may also enhance neonicotinoid degradation (via denitrification and dehalogenation pathways; Iqbal et al., 2015, Smith et al., 2014, Mitchell et al., 2015, Parte and Kharat, 2019).

Here we seek to determine how prairie strips affect the transport of the most widely used neonicotinoid insecticide in U.S. maize cropping systems, clothianidin (CLO, Simon-Delso et al., 2015). We measured CLO residues in surface soil, deep soil, plant tissue, and groundwater at multiple times of year and at multiple slope positions during a single maize growing season in two agricultural catchments: one with prairie strips and one without. We hypothesized that prairie strips planted in cropping systems with ongoing neonicotinoid inputs promote neonicotinoid transport into deep soil, plant tissue, and groundwater compartments via leaching and plant uptake (Hall et al., 2022, Radolinski et al., 2019). Thus, we predict overall greater CLO levels in plant leaf tissue, deep soil, and groundwater in prairie strips, and that greater plant accumulation and leaching in prairie strips will result in reduced soil CLO runoff downslope in the prairie strip catchment (Hladik et al., 2017).

2. Methods

2.1. Site description

We collected surface soil, deep soil, plant tissue, and groundwater samples from a farm in Story County, Iowa that is part of the Iowa State University Science-based Trials of Rowcrops Integrated with Prairie Strips project (STRIPS; https://www.nrem.iastate.edu/research/STRIPS/). The 12-hectare field area is managed with a maize-soybean (MSMMSM) rotation, grass waterways, and 15–30 % crop residue retention, a management regime typical of the region (USDA 2023; Table S1). The site is divided into two catchments: one catchment with 10 % prairie strip cover (78 % *Zea maize* + 10 % prairie strips + 12 % grass waterway) and one catchment with no prairie strips (88 % maize + 12 % grass waterway, Figure S1, Table S1). Five prairie strips were planted perpendicular to the prairie strip catchment slope in 2015, sown with a mix of 33 forbs and 8 grasses (Hall et al., 2022; English, 2020; Table S2). Prior to 2015, prairie strip areas were managed identically to the surrounding cropland, including the consistent use of neonicotinoid-treated maize and soybean seed for at least 5 years. We sampled in 2021, a maize year in which catchments were planted with Hoegemeyer 8009AM hybrid maize seed treated with a LumiGEN portfolio, including approximately 0.25 mg clothianidin (CLO) neonicotinoid per kernel (DeVries and Wright, 2021).

2.1.1. Surface soil and deep soil collection

Surface soil (0–10 cm) and deep soil (90–100 cm) samples were collected on three days during the 2021 growing season to quantify soil CLO residues one week pre-planting (April 21), five weeks post-planting (June 1), and eleven weeks post-planting (July 16). Soils were collected from six sampling locations within each catchment, arranged from summit to footslope, and were collected from both crop and prairie areas within the prairie strip catchment (Figure S1). We selected sampling locations that represented the path of maximum soil movement within the catchments following rain events (Stephenson et al., 2024). Deep soils were collected to 100 cm depth using a hydraulic sampling probe (Giddings #25-TS Model HDGSRTS). To avoid damaging crop and prairie vegetation, deep soil samples were collected at the edge of the grass waterway, slightly offset from surface soil sampling locations (Figure S1). Soils were stored in Whirlpak bags at 4°C immediately following collection, and within 48 hours, sieved to 2 mm to homogenize soil and remove gravel and litter fragments, and then stored at −20°C.

2.1.2. Plant tissue collection

Leaf tissue was collected from maize in rowcrop areas of both catchments and from black-eyed susan (*Rudbeckia hirta*) and common milkweed (*Ascleipas syriaca*) in prairie strips on June 1 and July 16. Black-eyed susan and milkweed were selected to represent short-term and long-term bloom durations, respectively, as neonicotinoid uptake rate varies with plant phenology (Mogren and Lundgren, 2016). Milkweed was also selected because monarch butterflies (*Danaus plexippus*), a pollinator species of conservation concern, feed directly on milkweed leaf tissue during their larval stage. We sampled one individual of each plant species nearest to its corresponding surface soil sample (Figure S1). At each rowcrop sampling location, one maize leaf was collected from the plant at the midpoint of the plant's stem. At each prairie strip sampling location, we collected one leaf from one black-eyed susan basal rosette and one leaf from the midpoint of one milkweed stem. All leaf tissue samples were stored in Whirlpak bags at 4°C immediately following collection, then at −20°C within 48 hours of sample collection.

2.1.3. Groundwater collection

Groundwater samples were collected on two sampling dates, April 21 and June 2, 2021. Wells were installed at the foot slope of each catchment, constructed using 50 mm i.d. polyvinyl chloride tubes with 0.6-m well screens and a depth of 4.5 m. Groundwater wells were purged prior to sample collection. On each sampling date, one groundwater sample was collected from each catchment by connecting 6.35 mm diameter new nylon tubing to a new 2 L amber HDPE filter flask and inserting the tube into the well. Using a hand pump, suction was applied to the flask, and the sample was transferred to the HDPE bottle and stored at 4°C immediately following collection. There was not sufficient surface water runoff for sample collection during the 2021 growing season. Rainfall during the study period averaged 2.48 mm per day, significantly lower than the 30-year average rainfall of 3.99 mm per day during the same period (Iowa Environmental Mesonet, ISU 2024).

2.1.4. Soil physiochemical analysis

Surface soil samples collected in April 2021 were submitted to the Michigan State University Soil and Plant Nutrient Lab (East Lansing, MI, USA, http://www.spnl.msu.edu/) for analysis of physical and chemical properties known to influence neonicotinoid transport and degradation: pH, cation exchange capacity (CEC), and % clay (Ousely, 2017; Zhang

et al., 2018).

2.2. Neonicotinoid analysis

CLO concentrations were quantified in all field-collected surface soil, deep soil, plant tissue, and groundwater samples using previously published extraction and LC-MS/MS analysis methods (Hall et al., 2020, Hall et al., 2022) performed by the Iowa State University Veterinary Diagnostic Lab (Ames, IA, USA, https://vetmed.iastate.edu/vdl). CLO was quantified using a method detection limit ranging from 1 ng/g to 20 ng/g for soil, 0.5 ng/g to 20 ng/g for plant tissue, and 0.5 ng/g to 50 ng/g for groundwater. Calibration curves and quality control replicates were prepared using neonicotinoid-free soil, milkweed leaf tissue, and water. No compounds were detected in matrix blanks. For calibration standards, the measured limit of quantification (LOQ) was $\leq$ 20 % RSD of the nominal concentration, and the measured concentration of the remainder of the calibrants was $\leq$ 15 % of the nominal concentration.

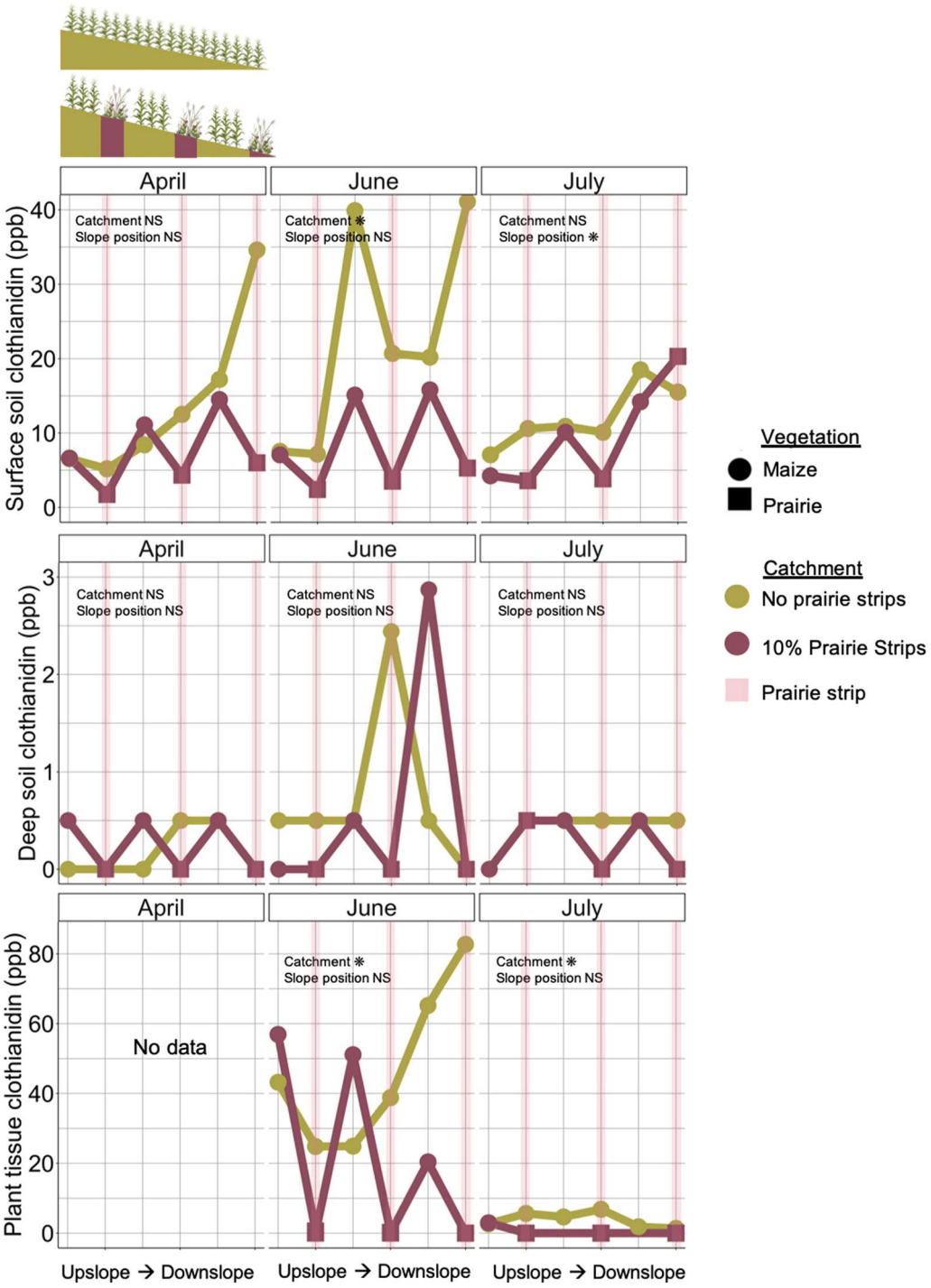

Fig. 1. Clothianidin (CLO) concentrations in surface soils (0–10 cm), deep soils (90–100 cm) and plant leaf tissue (prairie forbs and maize) at each slope position. Line color represents catchment, and vertical pink lines represent prairie strip locations within the prairie strip catchment only. ANOVA results represent significant ($p < 0.05$, *) and not significant ($p > 0.05$, NS) differences between treatment groups. CLO was last applied to cropland on April 25, 2021.

2.3. Data analysis

All data were then analyzed with linear models using CLO (ppb) as a response variable. Linear models were checked for normal residuals and homogeneous variance using the Shapiro–Wilks normality test (Zuur et al., 2009). We tested the effects of catchment (maize cropping system with and without 10 % prairie strips), slope position (six positions from summit to footslope), sampling date (April 21, June 1, and July 16), and their interactions on CLO in each landscape compartment using a two-factor analysis of variance (ANOVA) in R (version 4.2.3; R Core Team, 2022). We performed a separate ANOVA within each sampling date (April, June, July) to determine the effects of prairie strips and slope position on CLO within each phase of the growing season. We also performed a separate two-way ANOVA on samples from the prairie strip catchment to determine the effect of vegetation (maize vs. prairie), slope position, sampling date, and their interactions on CLO in each landscape compartment. Finally, to determine the effects of soil physiochemical properties (pH, CEC, % clay) on surface soil CLO, we performed a two-way ANOVA performed an additional two-factor ANOVA to evaluate the effects of prairie strips and slope position on significant soil physiochemical predictors of CLO.

3. Results and discussion

We hypothesized that in cropping systems with ongoing neonicotinoid inputs, prairie strips accumulate CLO from adjacent cropland via increased preferential flow into deep soils (Jørgensen et al., 2002, Alaoui, 2015, Radolinski et al., 2018) and increased CLO uptake into plant tissue (Ferchaud and Mary, 2016); however, we found no evidence for either of these accumulation mechanisms (Fig. 1). CLO was detected in all maize leaf tissue samples across both catchments, but only in two prairie forb leaf tissue samples (two black-eyed susan plants), and average CLO concentrations were 10-fold greater in maize tissue (average 24.33 ppb) than in prairie forbs (average 0.22 ppb, Fig. 1, Table S5). As is typical for neonicotinoid-treated seedlings, plant tissue CLO decreased from June to July as translocated CLO was diluted into growing plant biomass (Balfour et al., 2016, Fig. 1). CLO concentrations in prairie strip forbs were well below acute lethal doses for pollinator species studied to date (Wood and Goulson 2017, Krishnan et al., 2021), consistent with findings from a recent plant tissue neonicotinoids survey across prairie strip sites by Hall et al. (2022). While these findings suggest that prairie strips do not accumulate and expose pollinators to acutely toxic levels of neonicotinoids, neonicotinoid exposure has only been studied for a limited number of species (EFSA 2012). Repeated exposure of insects to low-level neonicotinoids in prairie strips may produce more subtle, long-term effects on individual and population health (Feltham et al., 2014, Sandrock et al., 2014, Spurgeon et al., 2016).

Within the prairie strip catchment, prairie strip areas contained lower soil and plant CLO compared to adjacent maize areas (surface soil $p = 0.011$, deep soil $p = 0.072$, plant tissue $p < 0.001$, Table S3). Low CLO in prairie strip surface soils may be due simply to lower CLO inputs, as neonicotinoid insecticides are not applied in prairie strip areas. However, because prairie strip soils do receive CLO inputs from upslope cropland areas (Table 1; Fig. 1), lower CLO in prairie strips could be explained by physiochemical soil properties like higher soil pH (average 5.73 prairie strip soil pH, average 5.48 cropland soil pH, $p = 0.051$, Table S4), which controls neonicotinoid sorption and degradation (Ousley et al., 2017, Zhang et al., 2018, Parte and Kharat, 2019), but future work that experimentally manipulates chemistry of field-collected soils would better elucidate controls on neonicotinoid residence time under different land management regimes. Low CLO concentrations in prairie strip soils, plants, and groundwater may also be a function of low precipitation at the site (Figure S2) and/or the presence of grass waterways in the center of each catchment (Figure S1). April 2021 was the 3rd most severe April drought recorded in Story County, Iowa since 1895 (NOAA 2024), and drought conditions remained in the county through August. In a wetter year with more frequent rain events, we might expect that prairie strips would receive more neonicotinoid transport from upslope crop soils and show higher CLO concentrations in all compartments (Radolinski et al., 2019). Grass waterways at our study site may have also directed what little rainfall did occur into surface flow downslope rather than vertical flow into deep soil horizons, and because our deep soil sampling locations were positioned nearer to each grass waterway to mitigate crop damage, we may have captured deep soils with relatively more surface flow and less infiltration.

We also expected that increased neonicotinoid leaching and plant uptake in prairie strips would result in reduced neonicotinoid runoff in the prairie strip catchment; however, at this site, prairie strips did not reduce neonicotinoid runoff through these mechanisms. Footslope surface soils contained the highest CLO levels in both catchments (41.10 ppb in no prairie strip catchment in June, 20.3 ppb in prairie strip catchment in July, Fig. 1, Table 1). These findings contrast those of Hladik et al., (2017), who reported nondetectable neonicotinoids in footslope soils of 10 % prairie strip catchments where neonicotinoid application had ceased 2–3 years prior. This suggests that when 10 % prairie strips are integrated into catchments with active neonicotinoid use, they do not remove all CLO via intermittent filtration along the catchment slope. Again, however, the downslope runoff we observed may be due to the downslope mobilization of neonicotinoids in grass waterways.

Our study finds that when neonicotinoid inputs are ongoing, and when prairie strips are planted in tandem with grass waterways, prairie strips may not be a sufficient management strategy to reduce insecticide runoff. Yet, even under continual neonicotinoid inputs in surrounding cropland, prairie strips accumulate little to no neonicotinoids in their plant tissue, indicating that prairie strips *can* provide habitat without exposing visiting native organisms to acute harm. To conclusively determine which conditions may make prairie strip plantings either safe havens, neutral vegetation, ecological sinks, or even ecological traps, we recommend continued measurements of neonicotinoids in cropland-

Table 1
Results from ANOVA evaluating predictors of clothianidin (CLO) in surface soil (0–10 cm), deep soil (90–100 cm), all plant leaf tissue (both maize and prairie forbs), and maize leaf tissue only (excluding prairie strip forbs). Groundwater data are omitted as CLO was below detection limit in all groundwater samples. Bold values indicate significance at $p < 0.05$. Underlined values indicate significance at $p < 0.1$. R^2 values represent percent variation in CLO explained by each model.

	Surface soil (0–10 cm) $R^2 = 0.503$			**Deep soil (90–100 cm)** $R^2 = 0.086$			**Plant leaf tissue (maize & prairie)** $R^2 = 0.534$			**Maize leaf tissue** $R^2 = 0.698$		
Factor	**Sums of Sq.**	**F Value**	**P Value**	**Sums of Sq.**	**F Value**	**P Value**	**Sums of Sq.**	**F Value**	**P Value**	**Sums of Sq.**	**F Value**	**P Value**
Catchment	575.60	14.0987	**0.0012**	0.0685	0.2331	0.6344	2239.9	10.0168	**0.006**	28.0	0.1005	0.7605
Slope position	1165.54	5.7098	**0.0019**	2.7152	1.8491	0.1489	1263.4	1.1300	0.3843	864.2	0.6201	0.6904
Month	180.06	2.2052	0.1363	1.2490	2.1264	0.1454	4788.5	21.4137	**0.0003**	7943.9	28.5004	**0.001**
Catchment* Slope position	332.44	1.6285	0.1983	2.9649	2.0192	0.1195	2272.4	2.0324	0.1284	5.3	0.0191	0.8939
Catchment* Month	217.83	2.6678	0.0939	0.1311	0.2232	0.8019	1534.2	6.8609	**0.0186**	648.6	1.1635	0.3662

adjacent prairie plantings, and exposure studies with field-representative neonicotinoid levels. Future studies might also measure neonicotinoids in soil, plant, and water immediately following a rain event to determine if prairie strips and grass waterways facilitate downslope neonicotinoid transport at a finer temporal scale than we captured in our study.

CRediT authorship contribution statement

Corinn E. Rutkoski: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Sarah E. Evans:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Lisa A. Schulte:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of Competing Interest

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Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2024.109111.

References

Alaoui, A., 2015. Modelling susceptibility of grassland soil to macropore flow. J. Hydrol. 525, 536–546.
Balfour, N.J., Carreck, N.L., Blanchard, H.E., Ratnieks, F.L.W., 2016. Size matters: Significant negative relationship between mature plant mass and residual neonicotinoid levels in seed-treated oilseed rape and maize crops. Agric., Ecosyst. Environ. 215, 85–88.
Bass, C., Denholm, I., Williamson, M.S., Nauen, R., 2015. The global status of insect resistance to neonicotinoid insecticides. Pestic. Biochem. Physiol. 121, 78–87.
R. Core Team, 2022. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.
Crall, J.D., Switzer, C.M., Oppenheimer, R.L., Ford Versypt, A.N., Dey, B., Brown, A., Mackay, E., Guérin, C., Pierce, N.E., Combes, S.S., de Bivort, B.L., 2018. Neonicotinoid exposure disrupts bumblebee nest behavior, social networks, and thermoregulation. Science 362, 683–686.
DeVries, T.A., Wright, R.J., 2021. Evaluation of traited corn rootworm and refuge corn hybrids in combination with aztec HC at planting for larval corn rootworm control. Arthropod Manag. Tests.
Dolezal, A.G., St. Clair, A.L., Zhang, G., Toth, A.L., O'Neal, M.E., 2019. Native habitat mitigates feast–famine conditions faced by honey bees in an agricultural landscape. PNAS 116 (50), 25147–25155.
English, L., 2020. Understanding the variation in vegetation composition of prairie restorations within crop fields [Master's thesis, Iowa State University]. Iowa State University Digital Repository. https://dr.lib.iastate.edu/handle/20.500.12876/94275.
Feltham, H., Park, K., Goulson, D., 2014. Field realistic doses of pesticide imidacloprid reduce bumblebee pollen foraging efficiency. Ecotoxicology 23 (3), 317–323.
Ferchaud, F., Mary, B., 2016. Drainage and nitrate leaching assessed during 7 years under perennial and annual bioenergy crops. Bioenergy Res. 9, 656–670.
Gibbons, D., Morrissey, C., Mineau, P., 2015. A review of the direct and indirect effects of neonicotinoids and fipronil on vertebrate wildlife. Environ. Sci. Pollut. Res. 22, 103–118.
Goulson, D., 2013. An overview of the environmental risks posed by neonicotinoid insecticides. J. Appl. Ecol. 50, 977–987.
Gutierrez-Lopez, J., Asbjornsen, H., Helmers, M.J., Isenhart, T.M., 2014. Regulation of soil moisture dynamics in agricultural fields using strips of native prairie vegetation. Geoderma 226 238–249.
Hall, M.J., Dang, V., Bradbury, S.P., Coats, J.R., 2020. Optimization of QuEChERS method for simultaneous determination of neonicotinoid residues in pollinator forage. Molecules 25 (12), 2732.
Hall, M.J., Zhang, G., O'Neal, M.E., Bradbury, S.P., Coats, J.R., 2022. Quantifying neonicotinoid insecticide residues in milkweed and other forbs sampled from prairie strips established in maize and soybean fields. Agric., Ecosyst. Environ. 325, 107723.
Henning, E.J., Kolka, R.K., Helmers, M., 2024. Infiltration within native prairie vegetative strips embedded in row crop fields across Iowa. J. Soil Water Conserv.
Hernandez-Santana, V., Xiaobo, Zhou, Zhou, X., Helmers, M.J., Asbjornsen, H., Kolka, R., Tomer, M.D., 2013. Native prairie filter strips reduce runoff from hillslopes under annual row-crop systems in Iowa, USA. J. Hydrol. 477, 94–103.
Hladik, M.L., Bradbury, S., Schulte, L.A., Helmers, M., Witte, C., Kolpin, D.W., Garrett, J. D., Harris, M., 2017. Neonicotinoid insecticide removal by prairie strips in row-cropped watersheds with historical seed coating use. Agric., Ecosyst. Environ. 241, 160–167.
Hladik, M.L., Kolpin, D.W., Kuivila, K.M., 2014. Widespread occurrence of neonicotinoid insecticides in streams in a high corn and soybean producing region, USA. Environ. Pollut. 193, 189–196.
Hladik, M.L., Main, A.R., Goulson, D., 2018. Environmental risks and challenges associated with neonicotinoid insecticides. Environ. Sci. Technol. 52 (6), 3329–3335.
Iqbal, J., Parkin, Timothy B., Parkin, T.B., Helmers, M.J., Zhou, Xiaobo, Zhou, Xiaobo, Zhou, X., Castellano, M.J., 2015. Denitrification and nitrous oxide emissions in annual croplands, perennial grass buffers, and restored perennial grasslands. Soil Sci. Soc. Am. J. 79, 239–250.
ISU [Iowa State University], 2024. Iowa Environmental Mesonet. https://mesonet.agron.iastate.edu/(accessed 15 February 2024).
Jørgensen, P.R., Hoffmann, M., Kistrup, J.P., Bryde, C., Bossi, R., Villholth, K.G., 2002. Preferential flow and pesticide transport in a clay-rich till: field, laboratory, and modeling analysis. Water Resour. Res. 38 (11), 1246.
Kemmerling, L.R., McCarthy, A.C., Brown, C.S., Haddad, N.M., 2023. Butterfly biodiversity increases with prairie strips and conservation management in row crop agriculture. Insect Conserv. Divers. 16 (6), 828–837.
Kemmerling, L.R., Rutkoski, C.R., Evans, S.E., Helms, J.A., Cordova-Ortiz, E.S., Smith, J. A., Vázquez Custodio, J.A., Vizza, C., Haddad, N.M. Prairie Strips and Lower Land Use Intensity Increase Biodiversity and Ecosystem Services. Frontiers in Ecology and Evolution 10.
Lundin, O., Rundlöf, M., Smith, H.G., Fries, I., Bommarco, R., 2015. Neonicotinoid insecticides and their impacts on bees: a systematic review of research approaches and identification of knowledge gaps. PLoS ONE 10 (8).
Mitchell, D.C., Zhou, Xiaobo, Zhou, X., Parkin, T.B., Helmers, M.J., Castellano, M.J., 2015. Comparing nitrate sink strength in perennial filter strips at toeslopes of cropland watersheds. J. Environ. Qual. 44, 191–199.
Mogren, C., Lundgren, J., 2016. Neonicotinoid-contaminated pollinator strips adjacent to cropland reduce honey bee nutritional status. Sci. Rep. 6, 29608.
Morrison, B.A., Xia, K., Stewart, R.D., 2022. Soil organic matter can delay—but not eliminate—leaching of neonicotinoid insecticides. J. Environ. Qual. 51, 1270–1281.
Morrissey, C.A., Mineau, P., Devries, J.H., Sanchez-Bayo, F., Liess, M., Cavallaro, M.C., Liber, K., 2015. Neonicotinoid contamination of global surface waters and associated risk to aquatic invertebrates: a review. Environ. Int. 74, 291–303.
NOAA National Centers for Environmental information, Climate at a Glance: County Rankings, published February 2024, retrieved on February 15, 2024 from ⟨https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/county/rankings⟩.
Nuyttens, D., Devarrewaere, W., Verboven, P., Foqué, D., 2013. Pesticide-laden dust emission and drift from treated seeds during seed drilling: a review. Pest Manag. Sci. 69 (5), 564–575.

Ously, M.N., 2017. Abiotic fate mechanism: Hydrolysis study on selected neonicotinoids [Master's thesis, California State University]. California State University Digital Repository. ⟨https://scholarworks.calstate.edu/concern/theses/4j03d099c?locale=en⟩.
Parte, S.G., Kharat, A.S., 2019. Aerobic degradation of clothianidin to 2-chloro-methyl thiazole and methyl 3-(thiazole-yl) methyl guanidine produced by pseudomonas stutzeri smk. J. Environ. Public Health.
Pérez-Suárez, M., Castellano, M.J., Kolka, R.K., Asbjornsen, H., Helmers, M.J., 2014. Nitrogen and carbon dynamics in prairie vegetation strips across topographical gradients in mixed Central Iowa agroecosystems. Agric., Ecosyst. Environ. 188, 1–11.
Pietrzak, D., Kania, J., Kmiecik, E., Malina, G., Wątor, K., 2020. Fate of selected neonicotinoid insecticides in soil–water systems: current state of the art and knowledge gaps. Chemosphere 255.
Radolinski, J., Wu, J., Xia, K., Stewart, R., 2018. Transport of a neonicotinoid pesticide, thiamethoxam, from artificial seed coatings. Sci. Total Environ. 618, 561–568.
Radolinski, J., Wu, J., Xia, K., Hession, W.C., Stewart, R.D., 2019. Plants mediate precipitation-driven transport of a neonicotinoid pesticide. Chemosphere 222, 445–452.
Sandrock, C., Tanadini, L.G., Pettis, J.S., Biesmeijer, J.C., Potts, S.G., Neumann, P., 2014. Sublethal neonicotinoid insecticide exposure reduces solitary bee reproductive success. Agric. For. Entomol. 16 (2), 119–128.
Schaafsma, A.W., Limay-Rios, V., Baute, T.S., Smith, J.L., Xue, Y., 2015. Neonicotinoid insecticide residues in surface water and soil associated with commercial maize (corn) fields in southwestern Ontario. PLoS One 10.
Schulte, L.A., Niemi, J., Helmers, M.J., Liebman, M., Arbuckle, J.G., James, D.E., Kolka, R.K., O'Neal, M.E., Tomer, M.D., Tyndall, J.C., Asbjornsen, H., Drobney, P., Neal, J., Van Ryswyk, G., Witte, C., 2017. Prairie strips improve biodiversity and the delivery of multiple ecosystem services from corn-soybean croplands. PNAS 114 (42), 11247–11252.
Simon-Delso, N.V., Amaral-Rogers, L.P., Belzunces, J.M., Bonmatin, M., Chagnon, C., Downs, L., Furlan, D., W., Gibbons, C., Giorio, V., Girolami, D., Goulson, D.P., Kreutzweiser, C., Krupke, H., Liess, M., Long, E., McField, M., Mineau, P., Mitchell, E.A.D., Morrissey, C.A., Noome, D.A., Pisa, L., Settele, J., Stark, J.D., Tapparo, A., Van Dyck, H., Van Praagh, J., Van der Sluijs, J.P., Whitehorn, P.R., Wiemers, M., 2015. Systemic insecticides (neonicotinoids and fipronil): trends, uses, mode of action and metabolites. Environ. Sci. Pollut. Res. 22 (1), 5–34.
Smalling, K.L., Hladik, M.L., Sanders, C., Kuivila, K.M., 2018. Leaching and sorption of neonicotinoid insecticides and fungicides from seed coatings. J. Environ. Sci. Health Part B-Pestic. Food Contam. Agric. Wastes 53, 176–183.
Smith, T.E., Kolka, R.K., Zhou, X., Helmers, M.J., Cruse, R.M., Tomer, M.D., 2014. Effects of native perennial vegetation buffer strips on dissolved organic carbon in surface runoff from an agricultural landscape. Biogeochemistry 120, 121–132.
Spurgeon, D., Hesketh, H., Lahive, E., Svendsen, C., Baas, J., Robinson, A., Horton, A., Heard, M., 2016. Chronic oral lethal and sub-lethal toxicities of different binary mixtures of pesticides and contaminants in bees (Apis mellifera, Osmia bicornis and Bombus terrestris). EFSA Support. Publ. 13 (9).
Stephenson, J.A., Liebman, M., Niemi, J., Cruse, R., Tyndall, J., Witte, C., James, D., Helmers, M., 2024. The influence of prairie strips sown in midwestern corn and soybean fields on sediment discharge throughout the year. J. Soil Water Conserv.
Sur, R., Stork, A., 2003. Uptake, translocation and metabolism of imidacloprid in plants. Bull. Insect 56, 35–40.
Thompson, D.A., Kolpin, D.W., Hladik, M.L., Barnes, K.K., Vargo, J.D., Field, R.W., 2021. Prevalence of neonicotinoids and sulfoxaflor in alluvial aquifers in a high corn and soybean producing region of the Midwestern United States. Sci. Total Environ. 782, 146762.
Wagner, D.L., Grames, E.M., Forister, M.L., Berenbaum, M.R., Stopak, D., 2021. Insect decline in the Anthropocene: death by a thousand cuts. Proc. Natl. Acad. Sci. 118 (2), e2023989118.
Wood, T.J., Goulson, D., 2017 Jul. The environmental risks of neonicotinoid pesticides: a review of the evidence post 2013. Environ Sci Pollut Res Int 24 (21), 17285–17325. https://doi.org/10.1007/s11356-017-9240-x. Epub 2017 Jun 7. PMID: 28593544; PMCID: PMC5533829.
Zhang, P., Ren, C., Sun, H., Min, L., 2018. Sorption, desorption and degradation of neonicotinoids in four agricultural soils and their effects on soil microorganisms. Sci. Total Environ. 615, 59–69.
Zhou, X., Helmers, M.K., Asbjornsen, H., Kolka, R., Tomer, M.D., Cruse, R.M., 2014. Nutrient removal by prairie filter strips in agricultural landscapes. J. Soil Water Conserv. 69 (1), 54–64.
Zuur, A.F., Ieno, E.N., Walker, N.J., Saveliev, A.A., Smith, G.M., 2009. Mixed effects models and extensions in ecology with R 574. Springer.