Pesticides and Prairie potholes: Understanding the impacts of neonicotinoid insecticides on Prairie wetland ecosystems

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Prairie Pothole Region (PPR)

Agro-wetland landscape occupying an area ~390,000 km$^2$

Saskatchewan home to 1.8 million wetlands <1 ha
(Wrubleski and Ross, 2011)

“Potholes” filled by annual snowmelt during spring
(van der Kamp & Hayashi, 2009)

Photo courtesy of J. Devries
Over 50% of Canada’s Prairie wetlands have been drained

(Bartzen et al. 2010)
Exponential growth in chemical inputs designed to improve yields
(Meehan et al. 2011)

Agricultural insecticides threaten surface waters at the global scale
(Stehle and Schulz, 2015)
Pesticide Use: Canadian Prairies

- Confidential; sales data used to determine exposure (Brimble et al. 2005)
- 78 to 89% of land receives pesticide application (Leeson & Beckie, 2014)
- Runoff from cropland to wetlands ~1 to 10% (Fawcett et al. 1994)
- 24% of SK wetlands may surpass regulatory requirements (Donald, 1999)
Saskatchewan is the largest user of pesticides in Canada, 36% (Brimble et al., 2005)
Seed-treatments

Majority of use across Canadian Prairies

• 80% of global market share of seed treatments (Jeschke et al., 2011)
• Major Prairie crops (e.g., canola, cereals, pulses)
• THX and CLO most widely used in this region
• 5 active ingredients registered for use in Canada
In 2015, almost 20 million acres were seeded to canola across Canada, making it the 2nd largest crop produced nationally (Stats Canada, 2015).
Potential for environmental persistence

Persist in agricultural soils and can accumulate (Goulson, 2013; Jones et al., 2014)

Highly soluble in water (e.g., CLO = 327 mg/L)

Readily transported through runoff (Hladik & Kolpin, 2015; Main et al., 2016)

Detectable residues in streams, rivers, and wetlands of NA (Starner and Goh, 2012; Anderson et al., 2012; Hladik et al., 2014)
Neonicotinoids bind to and activate post-synaptic nicotinic acetylcholine receptors (nAChR).

Hold the channel open causing continuous nervous system stimulation; **potentially irreversible in invertebrates**

(Sanchez-Bayo, 2012; Morrissey et al., 2015)
Majority of the neonic. debate: Bees!

37 MILLION DEAD BEES

“Once the corn started to get planted our bees died by the millions…”
Europe got the message. When will we?

2013 E.U. 2-year moratorium on neonicotinoid use: IMI, CTH, THX
Neonicotinoid toxicity toward aquatic invertebrates

Chironomus dilutus

Daphnia magna

Morrissey et al. 2015 Environ International
Impacts on aquatic invertebrate consumers

- 15 bird species included in study (Netherlands)
- Population decrease by 3.5% annually in areas with more than 20 ng/L imidacloprid

Hallmann et al. (2014) Nature
Knowledge gaps

Lack of insecticide biomonitoring data: CDN Prairie aquatic systems.

Factors that drive neonicotinoid fate and distribution (across seasons) in actual agroecosystems remain unknown.

Exploration of biological factors are absent (e.g., neonicotinoid mitigation and/or uptake by wetland plants).
Overall research objective

Determine the distribution of neonicotinoid insecticides across the Canadian Prairies and identify how these insecticides get into wetland water.
Are neonicotinoids in wetland water?
Patterns of Use: PPR

- GIS modelling: AAFC crop maps, application rates (Ag. SK), confidential sales data (PMRA)

Field Validation

- Collected 1L subsurface grab samples; 3 ponds per field (65 ha)
- Recorded standard water parameters, wetland depth, surrounding crop, coordinates
- Sediment cores (3) from wetland - 6 cm depth = 1 kg composite
- Insecticide analysis completed at Environment Canada: LC-MS/MS
- Statistical Analysis: General Linear Mixed Model (GLMM)
Spatial scale: widespread pattern of use (2012)
Est. 44% of cropland treated; >215,000 kg mass applied (Main et al., 2014)
Similar pattern across the USA

USGS National Water-Quality Assessment Program
Pesticide National Synthesis Project
Study area: multi-year project

>400 wetlands sampled
Frequent detections in wetlands (all seasons)

LOQ range: 0.5 ng/L to 1.8 ng/L
Effect of surrounding crop

Main et al., 2014 PLOS ONE
Wetland sediment

Rarely contained neonicotinoids: 6% of 134 samples

Maximum Concentration:

THX (20 µg/kg)
IMI (17.5 µg/kg)
CLO (4.4 µg/kg)

LOQ range: 0.9 to 3.0 µg/kg
# Water quality guidelines

<table>
<thead>
<tr>
<th>Source</th>
<th>Reference value (μg/L)</th>
<th>Compound</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>US EPA (2018)</strong></td>
<td>Acute 0.385</td>
<td>Imidacloprid</td>
</tr>
<tr>
<td></td>
<td>Chronic 0.010</td>
<td></td>
</tr>
<tr>
<td><strong>PMRA (proposed)</strong></td>
<td>Chronic 0.041</td>
<td></td>
</tr>
<tr>
<td>EFSA (2008) (Europe)</td>
<td>0.2 (maximum)</td>
<td>Imidacloprid</td>
</tr>
<tr>
<td>RIVM (2008) (Netherlands)</td>
<td>0.067 (average)</td>
<td>Imidacloprid</td>
</tr>
<tr>
<td>RIVM (2014) (Netherlands)</td>
<td>0.0083 (average)</td>
<td>Imidacloprid</td>
</tr>
<tr>
<td>Mineau and Palmer (2013)</td>
<td>0.0086 or 0.029 (average)</td>
<td>Imidacloprid</td>
</tr>
<tr>
<td><strong>Morrissey et al. 2015</strong></td>
<td>0.035 (average)</td>
<td>All neonicotinoids</td>
</tr>
<tr>
<td></td>
<td>0.2 (maximum)</td>
<td></td>
</tr>
</tbody>
</table>
Concentrations in wetland water

Variation in annual mean and maximum levels

Maximum Concentration:
- 2012: (3,110 ng/L);
- 2013: (595 ng/L);
- 2014: (2,092 ng/L)

Chronic: 35 ng/L

Morrissy et al., 2015
Summary 1: Wetland water

Neonicotinoid use is increasing across the Prairies: 2009-12 (+30%)

At least one neonicotinoid detected in wetland water in all seasons: 16% (fall 2012) to 91% (spring 2013)

Highest concentrations in wetlands surrounded by oat, canola, and barley, but no single crop most influenced detections

Only 6% \((n = 134)\) of sediment samples contained an AI

High frequency of detections in spring, before cropping had begun
Why are neonicotinoids detected in wetland water in spring?

Detections between 36% (2012) to 91% (2013)
Comparison of treated and untreated fields

- 16 fields: 8 prev. untreated (oat); 8 CLO-treated (canola)
- 5 weeks of pre-seeding wetland water samples (16 ponds)
- Meltwater, top-/bottom-layer snow, particulate sampled

Main et al., 2016 (AE&E)
Study Timeline

- Top-layer snow
- Bottom-layer snow
- Meltwater
- Wetland water

**SAMPLES COLLECTED**
- MW
- BL
- TL
- PM

**PERIODS**
- ICE OFF
- WW
- MW
- WW
- WW
- WW
- WW
- WW

**MAY 2014**
- SD

**NOTES**
- WW: wetland water
- MW: meltwater
- BL: bottom-layer snow
- TL: top-layer snow
- PM: particulate matter

**STUDY TIMELINE**
Regardless of crop…

- Neonicotinoids detected in 100% of MW, BL snow, and >75% PM
- TL snow <LOQ in all samples collected
- Only clothianidin detected in particulate matter (LOQ: 2 µg/kg)
Regardless of crop type – model explained 76% of the variance in neonicotinoid concentration ($R^2 = 0.76$)  

Significant differences in neonicotinoid concentration: all snow-related sources

Main et al., 2016 (AE&E)
Meltwater showed strongest relationship with initial wetland neonicotinoid concentration

\[(\beta \pm \text{S.E.}: 0.53 \pm 0.22, P = 0.04) - \text{first sampling period}\]

Main et al., 2016 (AE&E)
Concentrations **increase** in shallow wetlands

Main *et al.*, 2016 (AE&E)

Interaction: wetland class and time ($\beta \pm S.E.: -0.03 \pm 0.01, P = 0.001$)
Pre-seeding concentration affects summer concentration \((\beta \pm \text{S.E.}: 0.15 \pm 0.06, P = 0.01)\)

Main et al., 2014 (PLOS ONE)
Summary 2: Transport in Spring

Meltwater major source of neonicotinoids to wetlands in Spring

Concentrations increase in shallower wetlands over time

Neonicotinoids appear to be persisting at these northern latitudes

Potential for chronic exposure? 51% exceeded 35 ng/L (Morrissey et al., 2015)
Can wetland and landscape features predict neonicotinoid concentrations?
High variation across wetlands
But aren’t all wetlands the same?

95x higher – why?

Study wetlands in canola fields (Colonsay, SK)
What factors drive neonicotinoid fate in wetlands?
Rapid Wetland Assessment

Integrated quantitative and qualitative method for examining numerous wetland and ecological variables (Fennessy, 2007; Mack, 2006; Spencer, 1998; Millar, 1976; Stewart and Kantrud, 1971).
Neonicotinoid detections in water

Ecological and landscape drivers

Top 4:
- Shallow marsh spp. identity (34.8)
- Current crop (13.9)
- Veg. disturbance % (13.0)
- Wet meadow spp. (5.0)

21 variables explained 62% of deviance

Main et al., 2015 (ES&T)
Shallow marsh spp. a key indicator of neonicotinoid detection

Main et al., 2015 (ES&T)
Current crop influences detections

Main et al., 2015 (ES&T)
High disturbance equates to high detections

Marginal effect on neonicotinoid detection probability

Percent vegetation disturbance (13.0%)

Main et al., 2015 (ES&T)
Neonicotinoid concentrations in water
Ecological and landscape drivers

Top 4:
- Shallow marsh spp. identity (14.9)
- Central depth (cm; 14.2)
- Wet meadow spp. (12.1)
- Area (ha; 11.6)

23 variables explained 75% of deviance

Main et al., 2015 (ES&T)
Wetland depth: shallow = higher concentrations

Main et al., 2015 (ES&T)
Wet meadow spp. associated with high/low concentrations

Main et al., 2015 (ES&T)
Wetland area: smaller wetlands are more impacted

Main et al., 2015 (ES&T)
All wetlands are not equal...
Summary 3: Wetland and landscape features

Vegetation (i.e., dominant species) and vegetation-related variables (e.g., disturbance %, crop) explained the most model deviance.

Wetland area and depth indicate temporary/seasonal are more susceptible to neonicotinoid contamination.

Wetlands with diverse native species are less contaminated.

Further studies of mitigation or uptake by wetland plants are needed.
Do wetland plants accumulate or attenuate neonicotinoids from fields?
1 to 86 µg/kg detected in non-target wildflowers and field margin vegetation (Botias et al., 2015; David et al., 2016)
Study area (central Saskatchewan)

20 agricultural wetlands (10 vegetated; 10 unvegetated)

1. **Vegetated**: concentric rings of vegetation (Guntenspergen et al., 2002)
2. **Unvegetated**: devoid of vegetation or highly disturbed

All wetlands situated in clothianidin-treated canola fields (Prosper® Bayer CropScience)

Semi-permanent wetlands; >50 cm depth; mean size of 0.6 ha
Collection of wetland water/plants

8 week field study: pre-seeding to early/mid canola growing period
Macrophytes sampled on week 4, 6, 8

- **Aphis triviale**
  - Northern water plantain
  - **n = 20**

- **Typha latifolia**
  - Broadleaf cattail
  - **n = 31**

- **Equisetum arvense**
  - Field horsetail
  - **n = 23**
Types of plants collected during study

- Typha latifolia (Broadleaf Cattail)
- Alisma triviale (North. water plantain)
- Equisetum arvense (Field horsetail)
- Sparganium eurycarpum (Giant bur-reed)
- Mentha arvensis (Field mint)
- Phalaris arundinacea (Reed canary grass)
- Hordeum jubatum (Foxtail barley)
- Beckmannia syzigachne (Slough grass)
- Potamogeton pusillus (Small pondweed)
- Potamogeton richardsonii (Richardson’s pondweed)
- Algae spp.
- Canola sp.
Frequent detection of neonicotinoids

Wetland Water:

Clothianidin detected in 63% of wetland water samples

Additionally, thiamethoxam in 17% and imidacloprid in 7% of samples

Concentrations were not statistically different in center vs. edge of wetland ($\beta \pm $ S.E.: 0.26 $\pm$ 0.28, $P = 0.35$)
Concentrations in water significantly **higher** in unvegetated wetlands

![Graph showing log concentration of clothianidin in unvegetated and vegetated wetlands]

e.g., Clothianidin: ($\beta \pm \text{S.E.}: -0.77 \pm 0.26, P = 0.003$)
Mean water concentrations remained relatively low during this study.

THX max. concentration of 0.425 µg/L during week 6, unvegetated.
6 out of 11 species collected >LOD

Trace positive detections (<LOQ>LOD) in 40% of total plants

Detected CLO, THX, and IMI in different plant species

1st neonic. in plant tissues was detected 1 wk after seeding
Positive detections in non-target wetland plants ranged from 20% to 78% over the study.

LOQ plants (μg/kg, range): CLO, 0.4 to 2; THX, 0.3 to 1.6; IMI, 0.6 to 1.65
Quantifiable concentrations detected in **8%** of plants

<table>
<thead>
<tr>
<th>Plant</th>
<th>Clothianidin</th>
<th>Thiamethoxam</th>
<th>Imidacloprid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canola</td>
<td>2.37 - 22.9 µg/kg</td>
<td>&lt;0.50 - Trace</td>
<td>&lt;1.41</td>
</tr>
<tr>
<td>Typha</td>
<td>&lt;0.50 - Trace</td>
<td>&lt;1.50 - 8.44 µg/kg</td>
<td>&lt;0.60 - 2.61 µg/kg</td>
</tr>
<tr>
<td>Alisma</td>
<td>&lt;1.50 - Trace</td>
<td>&lt;1.30 - Trace</td>
<td>&lt;1.20 - 2.51 µg/kg</td>
</tr>
<tr>
<td>Equisetum</td>
<td>&lt;0.67 - 2.01 µg/kg</td>
<td>&lt;1.35 - Trace</td>
<td>&lt;0.87 - Trace</td>
</tr>
</tbody>
</table>
Canola was significantly higher in CLO and THX than collected wetland plants

Main et al., 2017 (STOTEN)
Summary 4: Macrophyte accumulation

Vegetated wetlands had significantly lower concentrations
Evidence of quantifiable concentrations in 3 field wetland species
No. of positive detections (plants) and higher water concentrations in unvegetated wetlands suggests potential reduction by macrophytes.
Neonicotinoid use is increasing across the PPR (conservative est.)

Frequent detections of neonicotinoids in all seasons sampled

Meltwater major source of transport to wetlands in spring

Vegetation explained the most variation in detection/conc.; Concentrations decreased over time in vegetated wetlands

Evidence of common wetland plants to accumulate neonicotinoids

Temporary and seasonal wetlands most at risk of contamination
Current Postdoctoral Research

Effects of neonicotinoid seed-treatment use on non-target native pollinator communities in Missouri field margins

Objectives:

• Survey levels of neonicotinoids in field margin soils and vegetation
• Validate potential routes of exposure for non-target insects
• Evaluate the effects of annual seed-treatment use on native pollinators
Native pollinators are in decline

Bombus affinis
Rusty patched bumblebee

Cameron et al., 2011.
Koh et al., 2015.
Use of neonicotinoid seed treatments (NSTs)

Estimated Agricultural Use for Thiamethoxam, 2014 (Preliminary)

EPest-Low

Estimated use on agricultural land, in pounds per square mile:
- < 0.02
- 0.02 - 0.11
- 0.12 - 0.52
- > 0.52
- No estimated use

2014

≥ 79%

~44%

Douglas and Tooker, 2015; ES&T

USGS National Water-Quality Assessment Program Pesticide National Synthesis Project
Neonicotinoid impacts on pollinators

Knowledge limited to only a few species; differing sensitivities
(Scott-Dupree et al., 2009; Lundin et al., 2015; Wood & Goulson, 2017)

Wild pollinators negatively affected by neonicotinoids? Sublethal?
(Rundlöf et al., 2015; Stanley et al., 2016; Wood & Goulson, 2017; Woodcock et al., 2017)

Studies evaluating effects on population level = limited (Lundin et al., 2015)

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![Graph showing wild bee density comparison between control and seed coating conditions.](image)

<table>
<thead>
<tr>
<th>Species</th>
<th># studies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apis mellifera</td>
<td>162</td>
</tr>
<tr>
<td>Bombus terrestris</td>
<td>24</td>
</tr>
<tr>
<td>Bombus impatiens</td>
<td>10</td>
</tr>
<tr>
<td>Apis cerana</td>
<td>6</td>
</tr>
<tr>
<td>Bombus spp.</td>
<td>4</td>
</tr>
</tbody>
</table>

Rundlöf et al., 2015
Honeybees are poor bio-indicators for effects on other pollinators including wild bees (Kevan, 1999; Goulson, 2016)
70% of native bees are solitary, ground-nesting.
Overall, regardless of treatment...

Neonicotinoids detected in **72%** of field soils; field margin soils = **54%**

Agricultural field range: 0 to 56.8 ug/kg

Field margin range: 0 to 41.7 ug/kg

<10 ppb

(van der Sluijs *et al.*, 2013)

MDL = 0.100 ppb
Neonicotinoids mainly detected in crop tissues

Crops from treated fields: range: 0 to 435 ug/kg

Detections: 87.5% (post-seed); 19% (mid-growing)

Margin plants: range: 0 to 9.8 ug/kg

Detections: 25% (post-seed); 6.25% (mid-growing)

LOD = 1 to 6 ppb
Wild bees

Collected 2,442 individuals representing 72 species
Ag. fields: Mean bee abundance significantly higher in untreated fields; lower in treated fields

$(\beta \pm SE: 0.56 \pm 0.21, P = <0.001; 95\% CI); \ R^2 = 0.46$
Margin soil concentration had a significant negative effect on bee abundance over time.

Margin conc. x sample period ($\beta \pm SE: -0.27 \pm 0.05, P = <0.001$)
Neonicotinoid concentrations in field margins had a negative effect on bee abundance of Tribe Eucerini

Margin conc. x sample period ($\beta \pm \text{SE}: -0.14 \pm 0.07, P = 0.04$)

$R^2 = 0.14$

credit: beautifulbees.org
Bee tissues indicate presence of pesticides

Bumblebee Queens indicate presence of neonicotinoids/other pesticides

- Imidacloprid soil degradates (IMI desnitro) range: 0 to 72.1 ng/g

Melissodes *spp.* and Halictus *spp.* mainly contained fungicides/herbicides
Acknowledgements


Field / Analytical Support: Wade Boys | Michael Cavallaro | Derek Corcoran | Leanne Ejack | Leanne Flahr | Giorgia Graells | Matthew Hauck | Kyle Kuechle | Kasia Majewski | Chantel Michelson | Jessica Murray | Rachel Owen | Jordan Piercefield | Brandon White | Aidan Wilcox | Alex Zahara

Chemical Analyses: Environment and Climate Change Canada | University of Nebraska-Lincoln | USGS (Sacramento, CA) | USDA (Gastonia, NC)

Project Funding / Collaborators:
Questions?