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# Effects of imidacloprid seed treatments on crop yields and economic returns of cereal crops

Ivan Milosavljević[a,b], Aaron D. Esser[c], Kevin M. Murphy[d], David W. Crowder[a,*]

[a] *Department of Entomology, Washington State University, 166 FSHN Bldg, Pullman, WA, 99164, USA*
[b] *Department of Entomology, University of California, 900 University Ave., Riverside, CA, 92521, USA*
[c] *Washington State University Extension, 210 W Broadway, Ritzville, WA, 99169, USA*
[d] *Department of Crop and Soil Sciences, Washington State University, 273 Johnson Hall, Pullman, WA, 99164, USA*

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ABSTRACT

In the Pacific Northwest United States, cereal crops (barley, oats, wheat) are the foundation of most dryland crop rotations. Nearly 100% of cereal producers use neonicotinoid seed treatments to manage wireworms, regardless of crop and pest density. However, wireworms cause variable damage to different crops, and whether neonicotinoids boost yield and economic returns across crops remains largely unknown. In a field experiment conducted on one commercial farm over two years, we examined effects of imidacloprid seed treatments on wireworm density, yield, and economic returns for barley, oat, and wheat crops. Wheat plots with imidacloprid seed treatments produced greater yields and economic returns over costs than untreated plots, even though wireworm densities were largely unaffected by treatments. However, no differences in yield and economic returns were observed between treatments in barley or oats. Wireworm densities were markedly lower in oats compared to barley and wheat, indicating not all crops provided a permissive environment for wireworms. Our results support the hypothesis that growers may benefit from moving away from applying seed treatments in all cereal crops, but rather targeting management to specific crops, although research at more commercial farm sites remains needed to test the generality of this conclusion. Our results also support the hypothesis that incorporating more tolerant cereal crops (barley and oats) into rotations to replace spring wheat may be a promising option for growers in areas with high wireworm pressure.

## 1. Introduction

Cereals (barley, oats, wheat) are foundational crops in the Pacific Northwest United States (“PNW”; Idaho, Oregon, Washington), contributing over $1.65 billion annually to the economy (USDA NASS, 2017). Cereal crops anchor most rotations in the PNW by having greater profit potential than legumes and other rotational crops (USDA NASS,2017). Cereal crop production is threatened, however, by the re-emergence of wireworms as key pests (Higginbotham et al., 2014; Esser et al., 2015). For decades, organochlorine, organophosphate, and carbamate insecticides were used to control wireworms in cereals (Vernon et al., 2008). After the removal of these broad-spectrum chemicals from the market, however, wireworm problems in the PNW have increased considerably (Etzler et al., 2014; Milosavljević et al., 2016a,b; 2017).

The primary control tactic for wireworms in cereals is seed treatments with neonicotinoids (Alford and Krupke, 2017). Neonicotinoids are persistent pesticides, offering long-term crop seed and seedling protection (Cherry et al., 2017). Common neonicotinoids include imidacloprid (Gaucho, Bayer CropScience), thiamethoxam (Cruiser, Syngenta), and clothianidin (Nipsit Inside, Valent USA). Prophylactic use of these neonicotinoids is largely unsustainable, however, because treatments are needed each year, which increases adverse environmental effects and heightens the potential for resistance. Moreover, neonicotinoids decay over the growing season (Nault et al., 2004), such that treatments are less effective against pests that feed throughout the growing season (Milosavljević et al., 2017). Neonicotinoids are also under scrutiny because of their non-target effects on pollinators and natural enemies, their ability to leach into ground water, and due to pest resistance (Furlan and Kreutzweiser, 2015; Bonmatin et al., 2015).

Use of neonicotinoid seed treatments has other drawbacks. Neonicotinoids do not deliver a lethal dose to wireworms (Van Herk et al., 2007; Vernon et al., 2008), and populations can reach levels that destroy

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* Corresponding author.
*E-mail address:* dcrowder@wsu.edu (D.W. Crowder).

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the crop regardless of treatment (Vernon et al., 2013; Esser et al., 2015). Nevertheless, growers often purchase treated-seed regardless of the cereal crop and wireworm species present, even though all crops are not equally susceptible to wireworms, and not all wireworm species are equally damaging (Johnson et al., 2008, Esser et al., 2015; Milosavljević et al., 2016a,b, 2017). In turn, neonicotinoid treatments provide inconsistent effects on yield in wheat fields (Vernon et al., 2009; Morales-Rodriguez and Wanner, 2014; Esser et al., 2015) and other crops like corn (Maienfisch et al., 2001; Wilde et al., 2004, 2007; Cox et al., 2007a, b; Cherry et al., 2017), cotton (Allen et al., 2018), potatoes (Vernon et al., 2013), soybean (Cox et al., 2008), and sugarcane (Cherry et al., 2013) across different regions. Reliance on neonicotinoids for wireworm control also hampers development of alternative management tactics (Cox et al., 2007a). In turn, producers would benefit from a better understanding of which specific cereal crops (i.e., wheat, barley, oats) benefit from neonicotinoid seed treatments.

Here, we conducted a two-year field study on a commercial farm to assess the effects of seed-applied neonicotinoid imidacloprid in barley (*Hordeum vulgare* L.), oat (*Avena sativa* L.), and wheat (*Triticum aestivum* L.) crops. Our study considered the impacts of imidacloprid seed treatments in affecting densities of sugarbeet wireworm, *Limonius californicus* (Mannerheim), which is widely considered to be the most damaging wireworm species attacking cereal crops in the PNW (Esser et al., 2015; Milosavljević et al., 2016a,b, 2017; Ensafi et al., 2018). Our study also examined whether applications of imidacloprid at planting affected yield and economic returns over costs for each of three crops. Overall, these data will benefit growers as they develop comprehensive integrated pest management (IPM) strategies for *L. californicus* and other wireworms in the PNW that are more targeted for specific cereal crops.

## 2. Materials and methods

### 2.1. Study site and field experiment

Our field experiment examined effects of seed-applied treatments with the neonicotinoid imidacloprid in barley, oat, and wheat crops. Two blocks were conducted in 2014 and 2015 on a commercial farm near Dusty, WA, in a 400 mm annual precipitation zone. The two blocks were 900m apart. The farm site had silt loam soil (13% sand, 15% silt, 72% clay) with a mean pH of 8.10 (SE = 0.08). No-till production (direct double-disk seed placement with row spacing of 30.5 cm) was used with no irrigation. Winter wheat was grown in 2013, the year prior to the initiation of the experiment. The average soil temperature and soil moisture throughout the two growing seasons was 11.45 °C (SE = 0.09) and 14.37% (SE = 0.92), respectively. Weather conditions and soil factors did not differ markedly between growing seasons (AgWeatherNet, 2018).

In each year we planted 24, 1.25 × 5m plots, with a crop treatment: (a) spring barley var. 'Lenetah', (b) spring oats var. 'Monida', or (c) spring wheat var. 'Louise' and an imidacloprid treatment: (a) control or (b) 78g ai/100 kg seed (the highest recommended rate for PNW cereals). Barley, oats, and wheat were directly seeded into stubble with a hoe drill at 72 kg/ha, 62 kg/ha, and 67 kg/ha, respectively. Seed was treated in a cement mixer in 23 kg drums, and fungicide treatments were applied to all seeds based on typical practices (Esser et al., 2015), and included 3.0g ai/100 kg mefenoxam and 12g ai/100 kg difenoconazole mixed in water. Each treatment (3 crops × 2 treatments) was replicated 4 times in a fully factorial design each year (48 total plots across the two years), and plots were randomized each year. Farmer cooperators sowed, maintained, and harvested the plots using commercial field equipment. Planting dates were 08 April 2014 and 26 April 2015, and plots were harvested on 16 August 2014 and 25 August 2015.

### 2.2. Wireworm species present at the field site

Wireworms, the larvae of click beetles (Coleoptera: Elateridae), are voracious generalists that feed belowground on plant structures such as roots, seeds, stems, and tubers (Schallhart et al., 2012; Wallinger et al., 2014; Traugott et al., 2015; Saguez et al., 2017). To determine the species of wireworm(s) present in the plots and their initial density, a total of 10 bait traps were deployed in a zig-zag pattern from the field edge moving toward the center (with 10m spacing), 10d prior to the experiments. Each trap consisted of a nylon stocking filled with 120 $cm^3$ of corn and wheat seeds in a 50:50 mix (Esser, 2012). Traps were immersed in water for 24h prior to field placement to facilitate seed germination; germinating seeds emit $CO_2$, a wireworm attractant (Doane et al., 1975; Chaton et al., 2003; Johnson and Nielsen, 2012). Each trap was deployed in a 20 cm deep hole and covered with the excavated soil from the hole. After 8d, traps and larvae were retrieved and larvae were identified to species based on morphological keys (Lanchester, 1946; Milosavljević et al., 2016a). *Limonius californicus* was the only species collected each year. Extremely high *L. californicus* densities were recorded each year (2014: Mean = 22.3 larvae per trap; SE = 4.83; 2015: Mean = 21.8 larvae per trap; SE = 2.19. These densities were well above the suggested action threshold of 1–2 larvae per trap, and the threshold of 4.0 larvae per trap which indicates potential for "extreme damage" to wheat (Esser, 2012).

### 2.3. Data collection

Wireworm density was measured throughout the duration of the experiments in May, June, July, and August of each year; each month two bait traps were placed diagonally in the opposite corners of each plot, 20 cm from the edge. Traps were placed in similar locations each month amidst crop rows. Traps were removed after being in the ground for 8d. Each bait was inspected for wireworms by hand, identified to species, and the total abundance per plot was recorded.

At the end of each growing season all plots were harvested at 20 cm tall with a commercial combine and weighed in the field with a specialized onboard weighing system (NORAC "U" series universal weigh bars [NORAC, Inc., USA], and an OHAUS model CW-11 indicator; [OHAUS Corp., USA]) to determine yield. To determine economic returns over costs, the costs of treatment (imidacloprid) were subtracted from gross returns (price × yield) each year. Market prices for cereal crops were obtained from Ritzville, WA, Warehouse Free on Board (FOB) on September 15 each year given the specific class of crop (barley, oats, or wheat) (USDA NASS, 2017). Imidacloprid costs each year were determined by surveying three Pacific Northwest seed suppliers and averaging their yearly costs. In initial analyses we considered variation in costs and prices that reflected variability in the USDA data (USDA NASS, 2017), but variability in cereal prices and insecticide costs was low and did not affect conclusions; results presented were thus based on average costs and prices for each year. Costs of fungicides, machinery, and labor were constant over treatments in each year and thus were not included in the economic analysis.

### 2.4. Data analyses

We used ANOVA to assess the effects of insecticide treatment (control or imidacloprid), year (2014 or 2015), and the treatment × year interaction on yields and economic returns over costs for barley, oat, and wheat crops. Separate models were conducted for each crop because yields and economic returns were not comparable across crops. We used Tukey HSD tests to separate means for factors that were significant in the main two-way ANOVA. We examined correlations among yield and economic returns using Pearson's correlation test. We used linear mixed models to assess the effects of crop, imidacloprid treatment, and the crop × imidacloprid interaction on wireworm densities over time; year was included as a blocking variable. The model also included month as a repeated measure, as each plot had four measurements of wireworm density taken in May, June, July, and August that were not statistically independent. All models were fit with normal distributions based on the variance of the response variables. The analyses were conducted in R (R Core Team, 2014).

## 3. Results

### 3.1. Effects of neonicotinoid treatment on yield

Imidacloprid did not affect barley yields ($F_{1,12} = 1.27$, $P = 0.28$) in either year (year effect: $F_{1,12} = 2.52$, $P = 0.14$; treatment × year effect: $F_{1,12} = 0.18$, $P = 0.68$) (Fig. 1). Oat yields were greater in 2014 than 2015 ($F_{1,12} = 11.88$, $P = 0.0048$), and there was a significant treatment × year interaction ($F_{1,12} = 6.47$, $P = 0.026$) (Fig. 1). While imidacloprid and control oat plots had similar yield in 2014, oat yields were lower with the imidacloprid treatment in 2015 ($P = 0.005$) (Fig. 1). Wheat plots treated with imidacloprid had significantly higher yields as compared to fungicide-only seed treatments ($F_{1,12} = 9.38$, $P = 0.0098$) in both years (year effect: $F_{1,12} = 0.83$, $P = 0.38$; treatment × year effect: $F_{1,12} = 1.20$, $P = 0.30$) (Fig. 1).

### 3.2. Effects of neonicotinoid treatment on economic returns over costs

Imidacloprid did not affect economic returns of barley ($F_{1,12} = 1.27$, $P = 0.28$) in either year (year effect: $F_{1,12} = 2.18$, $P = 0.17$; treatment × year effect: $F_{1,12} = 0.16$, $P = 0.69$) (Fig. 2). The economic returns of oat were greater in 2014 than 2015 ($F_{1,12} = 11.34$, $P = 0.0056$), and there was a significant treatment × year interaction ($F_{1,12} = 6.62$, $P = 0.024$) (Fig. 2). Imidacloprid treatments did not affect the economic returns of oats in 2014, but economic returns were lower with the imidacloprid treatment compared to the control in 2015. Similar to yields, imidacloprid seed treatments produced greater economic returns over costs of wheat than did controls ($F_{1,12} = 9.38$, $P = 0.0098$) in both years (year effect: $F_{1,12} = 0.93$, $P = 0.36$; treatment × year effect: $F_{1,12} = 1.17$, $P = 0.30$) (Fig. 2). Strong correlations (Pearson's correlation test, $r > 0.95$) were observed between economic returns over costs and crop yields of wheat, barley, and oats in both years.

### 3.3. Effects of crop type and neonicotinoid treatment on wireworms

Higher wheat yields in the imidacloprid-treated plots did not appear to result from reduced wireworm abundance (Fig. 3), as imidacloprid did not affect wireworm abundance in any crop (treatment: $F_{1,158} = 0.13$, $P = 0.72$; treatment × crop: $F_{2,158} = 0.0082$, $P = 0.99$) (Fig. 3). Effects of imidacloprid on wireworm abundance were consistent over each growing season for each crop (treatment × month: $F_{3,158} = 2.53$, $P = 0.06$; treatment × month × crop: $F_{6,158} = 0.82$, $P = 0.55$) (Fig. 3). However, while the effects of imidacloprid were similar across the two years (treatment × year: $F_{1,158} = 0.17$, $P = 0.68$), for each crop wireworm abundance was lower in 2015 than in 2014 (year: $F_{1,158} = 6.76$, $P = 0.010$; crop × year: $F_{2,150} = 20.3$, $P < 0.0001$) (Fig. 3). Wireworm abundance was also lower in oats than wheat or barley (crop: $F_{2,150} = 9.14$, $P = 0.0018$) (Fig. 3).

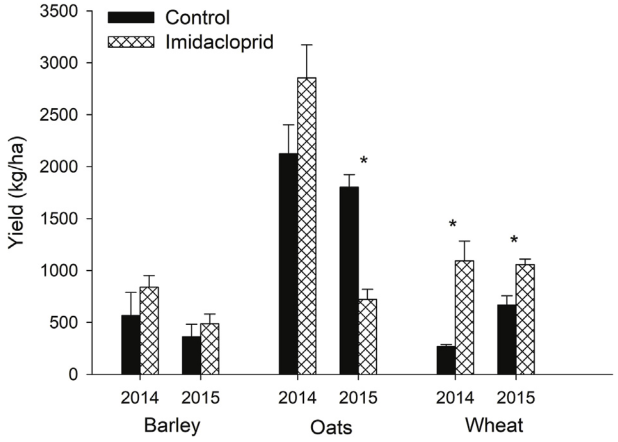

**Fig. 1.** Effects of control and imidacloprid treatments on barley, oat, and wheat yields (kg/ha) in 2014 and 2015. * - indicates significant effect at α = 0.05.

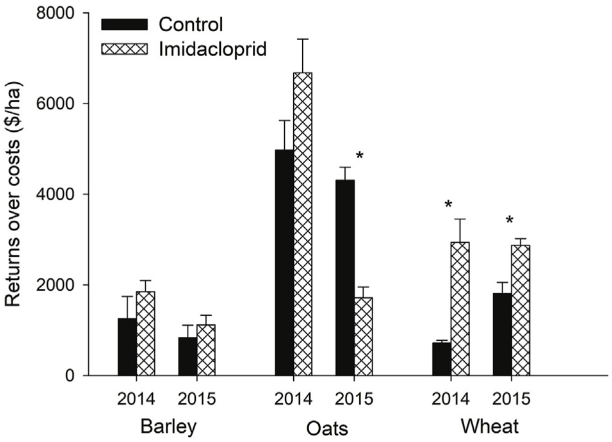

**Fig. 2.** Effects of control and imidacloprid treatments on economic returns over costs ($/ha) of barley, oat, and wheat crops in 2014 and 2015. * - indicates significant effect at α = 0.05.

## 4. Discussion

Our study supports the hypothesis that the benefits of seed-applied imidacloprid targeting *L. californicus* differ across cereal crops. This is in line with studies showing high variability in the effectiveness of neonicotinoid seed treatments against wireworms across different cropping systems (Wilde et al., 2004, 2007; Cox et al., 2007a,b, 2008; Vernon et al., 2009, 2013; Morales-Rodriguez and Wanner, 2014; Esser et al., 2015; Cherry et al., 2013, 2017; Allen et al., 2018). Moving from an unsustainable "one-size-fits-all" strategy of prophylactic use of neonicotinoids at planting to a more targeted IPM approach may thus potentially provide economic benefits for growers that are realized through potential savings from not using seed treatments in certain years, although the generality of this conclusion would benefit from studies at more field sites. Reduced neonicotinoid use could also potentially reduce adverse effects of these chemicals on managed and wild pollinator species and other beneficial insects (Bonmatin et al., 2015). In particular, our results support the hypothesis that growers may benefit from targeting insecticidal treatments only to wheat, where imidacloprid provided benefits across both years. Moreover, the yield of untreated wheat was lower in 2014 compared to 2015, which may have been due to the higher wireworm abundance in 2014 compared to 2015 (Figs. 1 and 3). In contrast, in 2015 imidacloprid actually harmed yield and economic returns over costs of oat crops; while it is unclear what drove this result it is possible that imidacloprid treatments directly harmed yield, especially in 2015 when wireworm populations were extremely low in oat crops. Barley was unaffected by imidacloprid treatments in all years despite extremely high wireworm densities.

Multiple studies show that the neonicotinoids clothianidin, imidacloprid, and thiamethoxam protect yields of corn (Wilde et al., 2004, 2007; Cox et al., 2007a,b; Cherry et al., 2017), cotton (Allen et al., 2018), potatoes (Vernon et al., 2013), soybean (Cox et al., 2008), sugarcane (Cherry et al., 2013), and wheat (Vernon et al., 2009; Morales-Rodriguez and Wanner, 2014; Esser et al., 2015) from feeding damage from wireworms, even when wireworm abundance is unaffected. However, these results are context-dependent, and vary across wireworm species present, crops, types of practice, and environments. From 2008 to 2012, for example, we conducted on-farm trials in Washington to examine varied rates of thiamethoxam seed-applied insecticide in spring wheat (Esser et al., 2015). At a location near Davenport, WA, seed yield and economic returns over cost increased 30% and 24%, respectively, with increasing

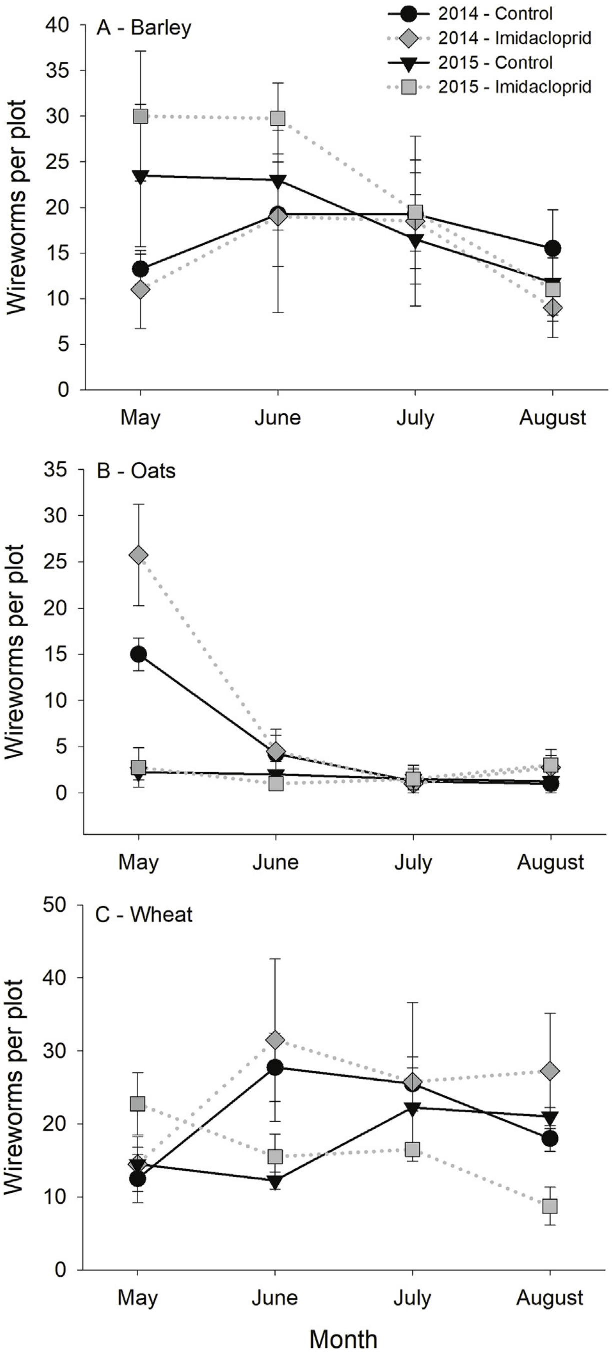

**Fig. 3.** The abundance of *L. californicus* larvae in (a) barley, (b) oat, and (c) wheat plots over the 2014 and 2015 seasons. Shown are the mean (±SE) *L. californicus* abundance per two bait traps in all control (black circles [2014] or triangles [2015]) vs. imidacloprid-treated (gray diamonds [2014] or squares [2015]) plots across different monthly sampling intervals.

thiamethoxam rates. Treatments did not, however, reduce wireworm abundance. In contrast, at a site near Wilbur, WA, seed yield and economic return over costs increased only 4% with higher rates, but wireworm abundance was reduced by 80% with high rates. Interestingly, at Davenport the only wireworm species found was *L. californicus*; at Wilbur the only species was *L. infuscatus* (Motschulsky). This supports the hypothesis that insecticide applications should be targeted only to cereal crops and regions with damaging wireworm populations to increase economic returns.

The abundance of wireworms was not reduced in wheat stands following exposure to imidacloprid in our study. Nevertheless, treating seed still generated higher returns and yields of wheat. This supports the hypothesis that imidacloprid can protect crops from damage at the cost of low toxic efficiency. After feeding on protected roots, immature *L. californicus* become moribund and disoriented for months (Van Herk et al., 2007; Vernon et al., 2008, 2009; Morales-Rodriguez and Wanner, 2014), but they recover later in the same season after the seed treatments have faded out (due to degradation and translocation through plants over time). As a result, field populations of *L. californicus* continue to increase and attack crops throughout the course of an entire growing season, from seeding to harvest (Milosavljević et al., 2015, 2016a; b, 2017). This could explain why we did not observe a decline in *L. californicus* abundance across years here.

In contrast, barley and oats had similar yield and economic returns with or without insecticidal seed treatments, which supports the hypothesis that these two crops may be more tolerant to *L. californicus* damage in the PNW. Similar studies focused on the impacts of various types of neonicotinoids against *L. californicus* in cereal crops are needed to evaluate the generalizability of the present findings. While our results indicate that *L. californicus* likely requires more aggressive management in spring wheat crops than in spring barley or oats, our experiments were conducted at a single level of wireworm pressure. Variation in pest abundance, in conjunction with the wireworm species or species present at a site, would ultimately dictate the implementation of successful IPM tactics (Vernon et al., 2013; Furlan, 2014).

Crop-specific seasonal patterns of root growth, structure, and development may have also contributed to the lower density of *L. californicus* in oats compared to barley and wheat (Furlan, 1996; Landl and Glauninger, 2011; Hiltpold and Turlings, 2012; Milosavljević et al., 2017; Adhikari and Reddy, 2017). Vigorous root growth and production of anti-herbivore compounds like saponins makes oat crops more resistant to pests compared to other cereals (Papadopoulou et al., 1999; Carter et al., 1999; Osbourn, 2003; Field et al., 2006; De Geyter et al., 2007; Turner et al., 2013; Moses et al., 2014). This may explain why fewer *L. californicus* larvae were observed in oats compared to barley and wheat (Johnson and Gregory, 2006; Gfeller et al., 2013; Barsics et al., 2014, 2016) (Fig. 2). This is important because crop rotation is a promising strategy to manage wireworms (Barsics et al., 2013; Traugott et al., 2015; Esser et al., 2015). For example, switching from continuous corn to a soybean and corn rotation reduced wireworm populations and the need for conventional neonicotinoids (Wilde et al., 2004; Cox et al., 2007a,b). In our previous work we found that incorporating a summer fallow period can reduce *Limonius sp.* populations by 50%, likely because wireworms have reduced food availability and egg-laying sites (Esser et al., 2015). Our findings should be considered hypotheses that need further testing to better determine if crop rotations with oats, or barley, could also potentially create a gap in food availability for *L. californicus*, which may benefit subsequent crops grown in a rotation.

Previous studies have also shown differences in the tolerance of various crop varieties (Cox et al., 2007a; Johnson et al., 2008; Higginbotham et al., 2014) and hybrids (Wilde et al., 2004) to wireworm damage. An evaluation of 163 wheat genotypes in Washington, for example, revealed that under high wireworm pressure (*Limonius sp.*), 'Louise' had only 40% plant stand on average, which was less than other varieties (e.g., Hollis [80%], Sonalika [60%], Safed Lerma [60%]), indicating it is relatively susceptible. For growers with *L. californicus* populations that prove difficult to manage, switching from 'Louise' to a more tolerant wheat variety might be beneficial. In addition, growers with *L. californicus* in their fields might benefit from incorporating barley 'Lenetah' or oats 'Monida' into rotations rather than wheat. Other studies have also shown that spring barley var. 'Idagold' was less preferred by *L. californicus*, and suffered less damage, compared to spring wheat var. 'Klasic' (Rashed et al., 2017). Rotations alone will not eradicate wireworms from a field, however, as wireworms can survive on other organic matter in the soil (Furlan, 2004), and treatments may be needed in rotational crops. For example, the proper use of insecticides rates in rotational crops (Vernon et al., 2013; Morales-Rodriguez and Wanner, 2014), may provide benefits to subsequent cereal crops that have limited management options. However, further studies are needed to define whether these pesticides might provide carry-over effects and increased economic returns for cereals the following year.

Our field trials were conducted on a farm dominated by silt loam soil rich in organic matter. As abiotic soil factors impact absorption and leaching potential of imidacloprid pesticide (Bonmatin et al., 2015), they may impact the effectiveness of seed treatments against wireworms across different regions. Examples of these abiotic variables are soil porosity, moisture, pH, temperature, and organic matter content (Nault et al., 2006; Alford and Krupke, 2017), which are also known to influence damage caused by wireworms (Traugott et al., 2015, Milosavljević et al., 2016b). In relation to this, relatively greater wireworm damage and higher leaching potential of imidacloprid have been associated with sandy soil types (Hermann et al., 2013; Rashed et al., 2017; Ensafi et al., 2018). Once leached below the upper portions of the root zone of cereal crops, imidacloprid pesticides are no longer effective against target wireworm pests that feed on crop roots, and become potential groundwater contaminants (Bonmatin et al., 2015). Although this study provided encouraging preliminary results, additional studies are needed to evaluate if the results of this study are consistent across different environments and weather patterns.

The indiscriminate use of neonicotinoid insecticides for wireworm control in cereal crops is likely unsustainable (Barsics et al., 2013; Traugott et al., 2015). On the other hand, blanket use of neonicotinoid seed treatments can be both effective and efficient if the over-riding concern of the grower is insurance against ubiquitous pests that are difficult to scout and for which there are no rescue treatment after planting (Milosavljević et al., 2018). However, reducing the environmental impact of these chemicals is a difficult challenge (Furlan and Kreutzweiser, 2015; Bonmatin et al., 2015). We suggest that the effective control of wireworms in cereal crops should be based on the fundamental principles of IPM, rather than on prophylactic neonicotinoid treatments alone. It is clear that not all crops are affected the same by wireworms (Milosavljević et al., 2016b) and insecticide treatments (Esser et al., 2015). Our results promote a longer-term view towards IPM that incorporates less preferred rotational or trap crops. Moreover, our results support the hypothesis that cereal management would be most effective when a targeted approach that considers pest biology, crop type, and crop variety is implemented in the field.

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