Effects of Neonicotinoids and Crop Rotation for Managing Wireworms in Wheat Crops

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ABSTRACT Soil-dwelling insects are severe pests in many agroecosystems. These pests have cryptic life cycles, making sampling difficult and damage hard to anticipate. The management of soil insects is therefore often based on preventative insecticides applied at planting or cultural practices. Wireworms, the subterranean larvae of click beetles (Coleoptera: Elateridae), have re-emerged as problematic pests in cereal crops in the Pacific Northwestern United States. Here, we evaluated two management strategies for wireworms in long-term field experiments: 1) treating spring wheat seed with the neonicotinoid thiamethoxam and 2) replacing continuous spring wheat with a summer fallow and winter wheat rotation. Separate experiments were conducted for two wireworm species—*Limonius californicus* (Mannerheim) and *Limonius infuscatus* (Motschulsky). In the experiment with *L. californicus*, spring wheat yields and economic returns increased by 24–30% with neonicotinoid treatments. In contrast, in the experiment with *L. infuscatus*, spring wheat yields and economic returns did not increase with neonicotinoids despite an 80% reduction in wireworms. Thus, the usefulness of seed-applied neonicotinoids differed based on the wireworm species present. In experiments with both species, we detected significantly fewer wireworms with a no-till summer fallow and winter wheat rotation compared with continuous spring wheat. This suggests that switching from continuous spring wheat to a winter wheat and summer fallow rotation may aid in wireworm management. More generally, our results show that integrated management of soil-dwelling pests such as wireworms may require both preventative insecticide treatments and cultural practices.

KEY WORDS crop rotation, Elateridae, neonicotinoid, soil-dwelling pest, wheat

Soil-dwelling insects are economically damaging pests in many agricultural ecosystems (Jackson et al. 2000). These pests often have cryptic life cycles, making sampling difficult and damage hard to anticipate. Moreover, damage from soil-dwelling insects can be mistakenly attributed to factors such as poor germination, herbicide carryover, or other pests (European and Mediterranean Plant Protection Organization 2005, Gratwick 1989, Parker and Howard 2001, Vernon 2010). These factors have made soil-dwelling insects difficult to manage in many agroecosystems.

Due to the difficulties in estimating prevalence and damage, soil-dwelling pests are often managed with cultural practices or prophylactic insecticides applied at planting (Potter et al. 1996, Albajes et al. 2003, Wilde et al. 2004). For example, crop rotation is often used to manage soil pests such as western corn rootworm, *Diabrotica virgifera virgifera* LeConte (Coleoptera: Chrysomelidae) (Levine and Oloumi-Sadeghi 1991, Gray et al. 2009). Corn and soybean rotations limit rootworm populations because eggs laid in corn hatch the next year in soybean and die (Mabry and Spencer 2003). Other cultural practices used for management of soil-dwelling pests include manipulation of planting and harvest dates, soil drying or flooding, trap cropping, soil amendments, and burning of crop residues (Kumar and Goh 1999, Andrews et al. 2008, Landl and Glauninger 2011).

In addition to cultural practices, neonicotinoid insecticides applied as seed treatments are commonly used for managing soil-dwelling pests (Koch et al. 2005, Nault et al. 2006, Cox et al. 2007, Wilde et al. 2007). Neonicotinoids have enduring residual activity and can often be used at low rates, making them widely used for many crop pests (Elbert et al. 2008). Moreover, neonicotinoids can provide both seed and foliar protection for several weeks or months after planting (Wilde et al. 2001, Nault et al. 2004, Koch et al. 2005, Jeschke et al. 2010), making their use common among farmers in many systems.

Wireworms, the subterranean larvae of click beetles (Coleoptera: Elateridae), are economical agricultural pests in North America and globally (Marske and Ivie 2003; Vernon et al. 2008, 2009). Wireworms persist in the soil as larvae for several years and are often present in crop fields at planting. Wireworms damage crops by feeding or drilling into below-ground plant structures such as germinating grains, roots, stems, tubers, and transplants (Thomas 1940). This injury can cause wilt, stunting, and even death to juvenile plants (Willis et al.

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2010). When wireworm densities are extremely high, the yields of entire fields can be lost (Popov et al. 2001). Key agricultural crops affected include wheat, barley, rye, potatoes, corn, tobacco, most vegetables, and small fruits (Thomas 1940, Zacharuk 1963, Turnock 1968, Vernon 2005). Historically, wireworms were effectively managed with inexpensive and potent broad-spectrum insecticides including organochlorines, organophosphates, and carbamates. However, deregistration of many of these products has contributed to the resurgence of wireworms as pests (Vernon et al. 2009).

Here, we conducted long-term field experiments to evaluate the effectiveness of seed-applied neonicotinoids and crop rotation in controlling wireworms. We conducted separate experiments for two prevalent wireworm species in the Pacific Northwestern United States, the sugar beet wireworm *Limonius californicus* (Mannerheim) and the western field wireworm *Limonius infuscatus* (Motschulsky). Specifically, our trials evaluated whether use of the neonicotinoid thiamethoxam in continuous spring wheat cropping systems affected wireworm abundance, crop yields, and economic benefits. In the same experiments, we also evaluated whether a no-till summer fallow and winter wheat crop rotation affected wireworm abundance compared with continuous spring wheat systems with the varying neonicotinoid rates.

Materials and Methods

Study Sites and Wireworms. The first experiment was initiated in 2008 on a commercial farm near Davenport, WA. The second experiment was initiated in 2009 at a second commercial farm near Wilbur, WA. Prior to the initiation of experiments, we extensively sampled each farm site using soil bait traps (Esser 2012) to determine the wireworm species present. Larvae collected in traps from both locations were transported to the laboratory for identification using the taxonomic keys of Lanchester (1946). Importantly, *L. californicus* was the only wireworm species collected from the Davenport location, while *L. infuscatus* was the only species collected from the Wilbur location. These two species are the predominant species in eastern Washington and northern Idaho based on extensive sampling we have conducted on >150 commercial farms (Milosavljević and Esser, personal observation).

The Davenport site is located in a 350 mm annual precipitation zone; the Wilbur site is in a 300 mm annual precipitation zone. Both sites were continuous direct-seeded cropping systems without fallow for >10 yr prior to the experiments. Historically, both sites had extensive use of the organochlorine Lindane, which was applied at planting in both fields every year until 2006. After 2006, but prior to the experiments, the neonicotinoid thiamethoxam was applied each year at these sites at a rate of 7 g ai/100 kg. In the year prior to establishing the experiments, both sites had extensive wireworm damage, with the grower chemically removing >25% of the crop at the Davenport site and 100% of the crop at the Wilbur site.

Field Experiments. Each of our two field experiments (one targeting *L. californicus* in Davenport, WA, and one targeting *L. infuscatus* in Wilbur, WA) included the same treatments: 1) four continuous spring wheat cropping treatments with variable rates of thiamethoxam seed-applied insecticide (0, 10, 20, or 39 g ai/100 kg seed) and 2) a no-till summer fallow and winter wheat treatment (with no-till summer fallow in years 1 and 3 and winter wheat in years 2 and 4). This experimental design allowed us to determine whether continuous spring wheat had greater yields, economic returns, and yields when thiamethoxam was applied. Moreover, we were also able to determine if a no tillage-based summer fallow system with winter wheat reduced wireworm abundance compared with a continuous spring wheat cropping system. Each experiment was a randomized complete block design with four replicates of each treatment (20 plots total in each experiment). The treatment applied to each plot was maintained throughout the duration of the experiment. Plots were 10 m wide and 304 m long. Each experiment was run for 4 yr, with the *L. californicus* experiment (in Davenport, WA) running from 2008 to 2012 and the *L. infuscatus* experiment (in Wilbur, WA) running from 2009 to 2013. Grower cooperators planted, maintained, and harvested the plots.

Wheat was treated in a cement mixer in 23 kg batches. Seed-applied fungicides were applied to all treatments based on practices typical of this region and included 12 g ai/100 kg difenoconazole, 3.0 g ai/100 kg mefenoxam, and 1,252 ml/100 kg water. Spring wheat varieties varied each year based on cooperator preference and seed availability. At Davenport in 2008 and 2010 'Tara 2002' and 'Jedd' Dark Northern Spring (DNS) wheat was planted, respectively. In 2009 and 2011 'Waikea' hard white spring wheat was planted. At Wilbur 'WB 926' DNS wheat was planted in 2009–2011 and 'Fuzion' DNS wheat in 2012. All spring wheat was seeded at 67 kg/ha with a direct seed hoe drill with Anderson openers on 30.5-cm row spacing. Planting dates at Davenport were 28 April 2008, 28 April 2009, 12 April 2010, and 22 April 2011; planting dates at Wilbur were 28 April 2009, 26 April 2010, 29 April 2011, and 24 April 2012.

Winter wheat was seeded at 90 kg/ha each year in early to mid-September (Davenport: 15 September 2008 and 28 September 2010; Wilbur: 14 September 2009 and 21 September 2011). The same drill that seeded the spring wheat was used to seed the winter wheat. At each site thiamethoxam rates and varieties varied by year based on market standards and availability, respectively. At Davenport, in 2008 'Eltan' soft white winter wheat was treated with 7 g ai/100 kg thiamethoxam, and in 2010 'ORCF 103' soft white winter wheat was treated with 12 g ai/100 kg thiamethoxam. At Wilbur, 'Eddy' hard red winter wheat was used both years and was treated with 7 g ai/100 kg thiamethoxam in 2009, and 12 g ai/100 kg thiamethoxam in 2011.

Spring and winter wheat were harvested at the same time in each year at each site. At Davenport, plots were harvested on 4 September 2008, 29 August 2009, 29 August 2010, and 23 September 2011; at Wilbur, plots were harvested on 27 August 2009, 24 August 2010, 8 September 2011, and 22 August 2012. The plots were harvested at ~20 cm tall, and the stubble was left standing. No-till summer fallow plots (2008 and 2010 in Davenport and 2009 and 2011 at Wilbur) were maintained mostly weed free, and free of volunteer crops, with three to four glyphosate herbicide applications (depending on weed pressure) during the summer.

Data Collection. Wireworm abundance in each plot was measured each year prior to spring seeding when soil temperatures were between 7–10°C (Esser 2012). A final sample was taken the spring after the fourth year of the experiment to capture potential reductions in wireworms from the final year. Abundance was determined using four modified solar bait traps (Esser 2012) placed in the center of each plot spaced at 38, 114, 190, and 266 m along the length of the plot. Traps were placed in similar locations within plots each year. In no-till summer fallow and winter wheat plots, traps were placed between rows of crops or stubble. Traps were put in approximately the same location in each plot each year. At each location, traps from all plots were removed on the same day; traps were left between 8 and 14 d in the ground depending on weather. Traps were kept at ≈10°C for no more than 2 d before being assessed by hand for wireworms present.

The four continuous spring wheat treatments with varying thiamethoxam rates were also evaluated for grain yield, test weight, grain protein percentage, and economic returns. Each plot was harvested with a commercial combine and weighed in the field with a specialized seed box equipped with a NORAC "U" series universal weigh bars and an OHAUS model CW-11 indicator. Grain samples were collected from each plot to measure test weight and grain protein. Grain protein percentage was measured using near infrared transmittance protein analyzer on 12% moisture basis. Gross economic data were calculated using Ritzville, WA, Warehouse Free on Board (FOB) wheat prices on September 15 each year given the specific class of wheat. Grain protein and test weight premiums and discounts were included in the calculation, as they are the factors that impact market price per bushel. Economic returns over costs were calculated by subtracting the thiamethoxam price each year from the gross return. Thiamethoxam costs each year were determined by surveying three seed suppliers and averaging their yearly costs. Fungicide costs, labor costs, machinery costs, etc. remain constant over spring wheat treatments at each location and therefore were not included in the economic analysis. Yields, test weights, grain protein, and economic returns for the no-till summer fallow–winter wheat treatment are not reported because they are not directly comparable with the spring wheat treatments (due to differences in the crop).

Data Analyses. We first analyzed whether wireworm abundance differed by treatment prior to initiation of the experiments. This allowed us to determine if any differences in wireworms over the course of the trials was directly caused by the treatment, rather than variation in populations prior to the trials. This was tested using analysis of variance (ANOVA), with wireworm abundance as the response and treatment (four insecticide rates or crop rotation) as the explanatory variable. The distribution of wireworm abundance across treatments prior to the start of experiments met ANOVA assumptions of normality and homogeneity of variance.

We first analyzed whether thiamethoxam treatments affected wireworms (number of total wireworms), yields, test weights, protein, and returns over costs. For these analyses, only data from the four continuous spring wheat treatments were included. To analyze whether wireworm abundance was affected by insecticide concentration over time, we used general linear models with study year, insecticide concentration, and their interaction as explanatory variables. The model was fit with a negative binomial distribution based on the distribution of the wireworm count data. These models were conducted in SAS (SAS Institute 2012). To analyze yields, test weights, protein, and returns over costs, we used analysis of covariance (ANCOVA) with study year, insecticide concentration, and their interaction as explanatory variables. Each response variable met ANCOVA assumptions of normality and homogeneity of variance. These analyses were conducted in JMP (SAS Institute 2013). In both analyses we treated insecticide concentration as a continuous variable and study year as a categorical variable. We analyzed the data for each experiment separately because they were independent in terms of the wireworm species present.

In each experiment, we also compared wireworm abundance in the continuous spring wheat treatments with that in the no-till summer fallow and winter wheat treatment. Abundance was averaged across the 4-yr trials to account for the variation in the cropping systems. We used ANOVA followed by post hoc Tukey tests to determine if wireworm abundance (ln transformed to normalize the distributions; data met assumptions of normality and homogeneity of variance after transformation) differed across our five treatments (four spring wheat treatments and the no-till summer fallow and winter wheat treatment). Separate analyses were conducted for each wireworm species. These analyses were conducted in JMP (SAS Institute 2013).

Results

Effects of Thiamethoxam on Wireworms. In experiments with *L. californicus* (Davenport; $F_{4,15} = 1.04$, $P = 0.42$) and *L. infuscatus* (Wilbur; $F_{4,15} = 0.045$, $P = 0.99$), there were no differences in wireworm abundance across treatments prior to the start of experiments. At Davenport, increasing thiamethoxam rates did not decrease *L. californicus* abundance ($\chi^2 = 1.79$, $P = 0.18$), and there was no interaction between rates and study year ($\chi^2 = 2.06$, $P = 0.56$; Fig. 1A). In contrast, increasing thiamethoxam rates significantly decreased *L. infuscatus* abundance at the Wilbur site ($\chi^2 = 32.0$, $P < 0.0001$;

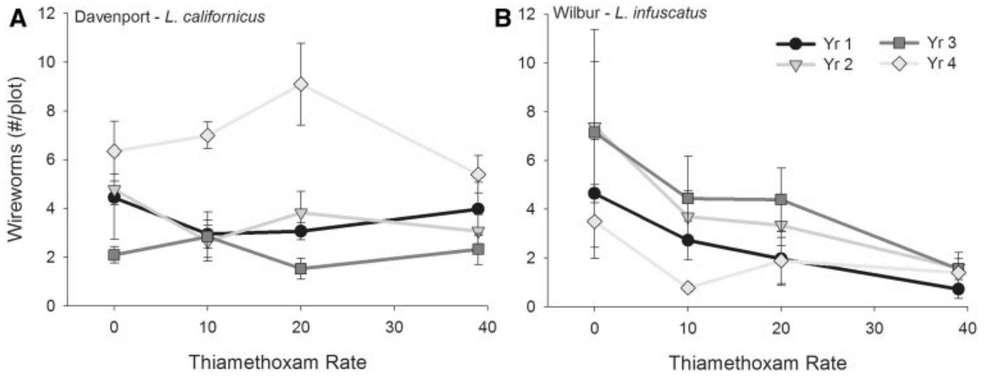

Fig. 1. Effects of thiamethoxam rates on wireworm abundance in experiments at (A) Davenport, WA, and (B) Wilbur, WA, with wireworm species *L. californicus* and *L. infuscatus*, respectively. Shown are the means (± SE) for wireworm abundance (total across four traps per plot) at each location with four rates of thiamethoxam in each year of the study.

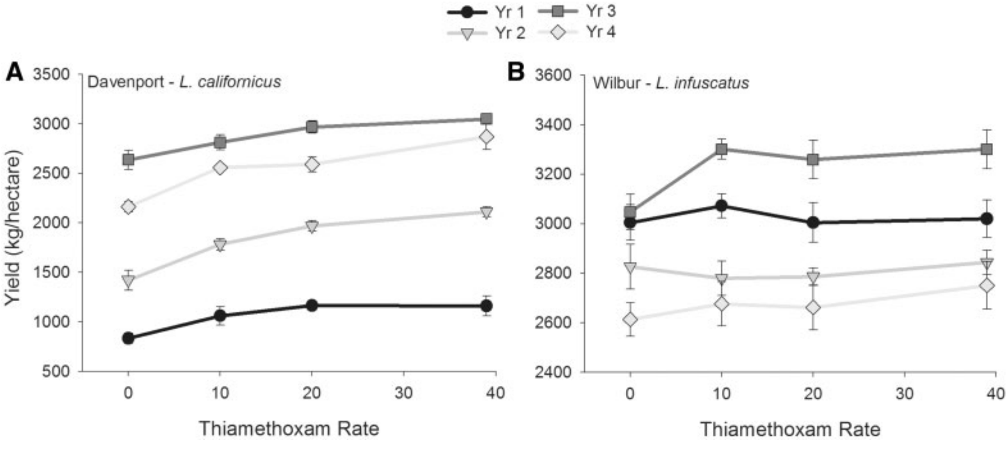

Fig. 2. Effects of thiamethoxam rates on yields (kg per hectare) in experiments at (A) Davenport, WA, and (B) Wilbur, WA, with wireworm species *L. californicus* and *L. infuscatus*, respectively. Shown are the means (± SE) for yield at each location with four rates of thiamethoxam applied at planting in each year of the study.

Fig. 1B). At this location, *L. infuscatus* abundance was lowest in the final year of the study ($\chi^2 = 147.0$, $P < 0.0001$), although increasing concentrations had a more significant effect in early compared with later years ($\chi^2 = 8.92$, $P = 0.030$; Fig. 1B).

Effects of Thiamethoxam on Yields, Crop Quality, and Economic Returns. At the Davenport site with *L. californicus*, increasing thiamethoxam rates significantly increased yields ($F_{1,56} = 87.6$, $P < 0.0001$) and economic returns ($F_{1,56} = 65.3$, $P < 0.0001$; Fig. 2, Table 1); in contrast, at the Wilbur site with *L. infuscatus*, yields ($F_{1,56} = 3.19$, $P = 0.079$) and economic returns ($F_{1,56} = 2.31$, $P = 0.13$) did not increase with greater thiamethoxam rates (Fig. 3, Table 1). Protein content decreased as the thiamethoxam rates increased at Davenport (Table 1). There was a significant effect of study year on these responses (Table 1). Yields and returns increased over time at the Davenport site (Fig. 2) but not at the Wilbur site (Fig. 3). There were no significant effects of the insecticide rate × study year interaction for any of the variables tested (Table 1).

Table 1. Results of ANCOVA models examining the effects of thiamethoxam rates on continuous wheat yield, test weight (TW), protein, and returns over costs (R/C) in on-farm trials at Davenport and Wilbur, WA

Location	Response	Rate		Study year		Interaction	
		$F_{1,56}$	P	$F_{3,56}$	P	$F_{3,56}$	P
Davenport	Yield	87.6	<0.0001	420.7	<0.0001	2.73	0.052
Davenport	TW	0.57	0.45	275.6	<0.0001	1.02	0.39
Davenport	Protein	5.71	0.20	806.1	<0.0001	1.59	0.02
Davenport	R/C	65.3	<0.0001	1185	<0.0001	2.59	0.062
Wilbur	Yield	3.19	0.079	46.1	<0.0001	0.94	0.43
Wilbur	TW	0.21	0.65	284.7	<0.0001	0.75	0.53
Wilbur	Protein	2.89	0.095	201.0	<0.0001	2.42	0.076
Wilbur	R/C	2.31	0.13	122.4	<0.0001	0.47	0.71

The wireworm species present at each location was *L. californicus* and *L. infuscatus*, respectively.

Effects of Crop Rotation on Wireworms. At the Davenport site, the no-till summer fallow and winter wheat rotation had lower *L. californicus* abundance than any of the continuous wheat treatments, regardless of

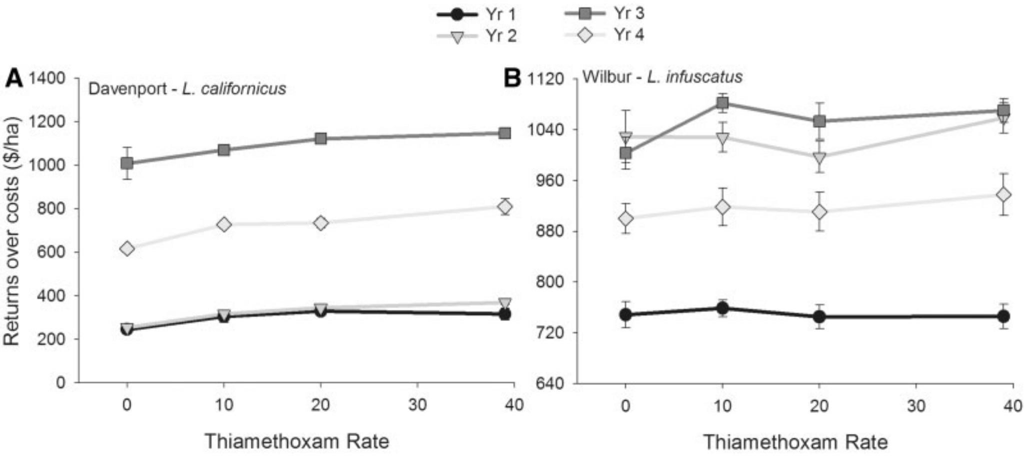

Fig. 3. Effects of thiamethoxam rates on economic returns over costs (US$; per hectare) in experiments at (A) Davenport, WA, and (B) Wilbur, WA, with wireworm species *L. californicus* and *L. infuscatus*, respectively. Shown are the means (± SE) for economic returns over costs at each location with four rates of thiamethoxam in each year of the study.

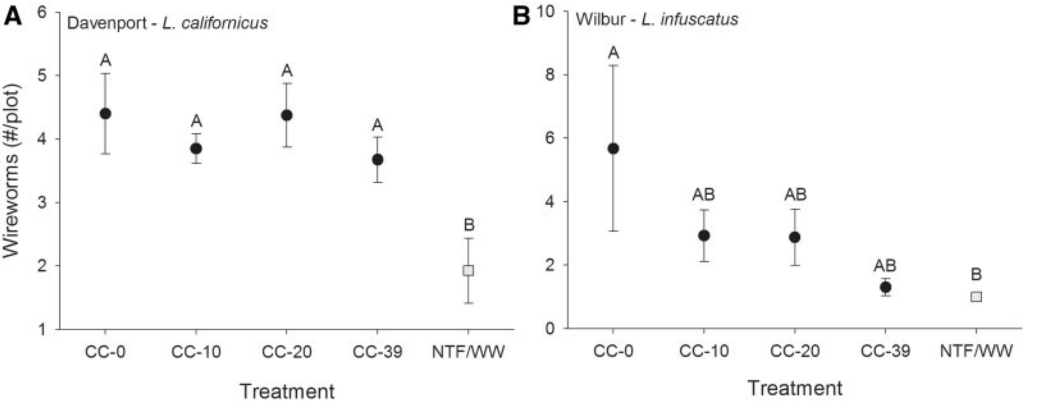

Fig. 4. Effects of crop rotation on wireworm abundance (total across four traps per plot) in experiments conducted at (A) Davenport, WA, and (B) Wilbur, WA, with wireworm species *L. californicus* and *L. infuscatus*, respectively. Shown are the means (± SE) for wireworm abundance at each location with five treatments: four continuous spring wheat cropping treatments with varying rates of thiamethoxam applied at planting (labeled CC with the rate) or the no-till summer fallow and winter wheat rotation (labeled NTF/WW). Different letters indicate significant differences between treatments at each location.

the rate of thiamethoxam ($F_{4,15} = 6.02$, $P = 0.0043$; Fig. 4A). At the Wilbur site, there were significant differences in *L. infuscatus* abundance between treatments ($F_{4,15} = 3.66$, $P = 0.029$), but the no-till summer fallow and winter wheat rotation only lowered total wireworms significantly compared with a continuous spring wheat system without thiamethoxam (Fig. 4B). At this location *L. infuscatus* abundance was not significantly different between the no-till summer fallow and winter wheat rotation and continuous spring wheat with any rate of thiamethoxam at planting (Fig. 4B).

Discussion

Multiple studies have shown that seed treatments with neonicotinoids provide excellent stand and yield protection from certain wireworm species (e.g., Maienfisch et al. 2001; Wilde et al. 2004, 2007; Vernon et al. 2009, 2013a, b). For example, Maienfisch et al. (2001) showed thiamethoxam applied at rates from 40 to 315 g ai/100 kg seed provided excellent long-lasting protection for various crops in different climatic regions against wireworm species in the genera *Agriotes* and *Melanotus*. Vernon et al. (2009) similarly showed that the neonicotinoids imidacloprid and thiamethoxam protected wheat stands from damage from wireworms in the genus *Agriotes*. Our results similarly suggest that thiamethoxam applied at planting can reduce wireworm populations or increase yields and economic returns in areas with *Limonius spp*. However, it is clear that not all *Limonius* species respond similarly to insecticidal treatments.

We established two independent long-term field experiments in different locations in east–central

Washington; each location had only a single wireworm species collected in samples. Where *L. californicus* was present, increasing thiamethoxam rates significantly increased yields and economic returns despite a lack of reductions in wireworm abundance. These results could potentially be due to increased intoxification effects caused by higher rates of thiamethoxam (Vernon et al. 2008, 2009). It is also possible that neonicotinoids increased plant vigor (Ford et al. 2010), with greater rates promoting wheat growth. However, further data are needed to confirm either of these hypotheses. In contrast, where *L. infuscatus* was present, increasing rates of thiamethoxam did not increase yields or economic returns despite significant decreases in wireworm abundance.

We observed differences in the sites in terms of yields over time. At the Davenport site, yields increased over time; in contrast, yields were fairly consistent at the Wilbur site. Although these trends could be due in part to reduced impacts of *L. californicus* at the Davenport site over time, it is likely that environmental variation also played a major role. At the Davenport site conditions were particularly poor for growing wheat, with extremely low precipitation in the first 2 yr of the study, and yields were low across the region (i.e., not just at our study site). In contrast, growing conditions were more favorable throughout the course of the study at the Wilbur location, which may explain variation in yields between the two sites and across years.

Our results suggest that the two species differed in their susceptibility to thiamethoxam, potentially due to a higher LD_{50} for *L. californicus* compared with *L. infuscatus*. Other studies have shown that variation in susceptibility to insecticides can vary widely across wireworm species even within a genus (Vernon et al. 2008). These results might also be affected by variation in the seasonal phenology of the two species. If *L. californicus* remains active later in the season compared with *L. infuscatus*, which is supported by data collected in fields where both species co-occur (Milosavljević, personal observation), then seed treatments at planting might be less effective against *L. californicus* due to degradation and translocation through wheat plants.

Wireworm species also can vary significantly in damage caused to crops (Willis et al. 2010). Ongoing work suggests that *L. infuscatus* is less damaging than *L. californicus* at similar abundance (Milosavljević and Esser, personal observation), such that reductions in abundance of *L. infuscatus* did not translate into higher yields. Our experiments support this hypothesis, as yields were similar in Wilbur, WA, regardless of *L. infuscatus* population levels. Despite this, returns over costs did not decline with increasing thiamethoxam rates, suggesting that treatments provided some protection that at least equaled the cost of the pesticide.

Multiple studies have shown that neonicotinoids reduced feeding damage caused by wireworms (Van Herk et al. 2007, Wilde et al. 2007, Vernon et al. 2008). Long-term laboratory studies revealed that wireworm populations in the genera *Agriotes*, *Ctenicera*, and *Limonius* were not significantly reduced by neonicotinoids. However, the neonicotinoids imidacloprid and clothianidin caused prolonged periods of morbidity (over 150 d) during which the pests where incapable of directional movement and did not feed (Van Herk et al. 2007, Vernon et al. 2008). Moreover, in several field studies Vernon et al. (2009, 2013b) showed that the abundance of wireworms in the genus *Agriotes* was not reduced in wheat stands following exposure to three neonicotinoids. However, wheat stands were protected due to intoxication caused by the neonicotinoids. Similar results have been shown on potatoes where neonicotinoids protected tubers from feeding damage but wireworm populations were not reduced (Vernon et al. 2009b). These results suggest that damaging wireworm species might be effectively managed by neonicotinoids through nonlethal means. This could partially explain why we did not observe a decline in *L. californicus* abundance in the Davenport site yet thiamethoxam treatments increased yields and economic returns. Nevertheless, treating seed still generated higher returns and yields.

Our results suggest that thiamethoxam can be an effective tool for managing wireworms in cereals. However, this insecticide does not eliminate populations from fields, such that annual treatments may be necessary. In turn, IPM strategies for wireworms are likely to be most effective when cultural management practices are combined with insecticides. Cultural management practices such as crop rotation and tillage affect every aspect of crop production (McLaughlin and Mineau 1995). For example, crop rotation provides economic benefits by improving soil moisture, nutrient availability, reducing soil erosion, and controlling soil-dwelling pests (Peters et al. 2003). Multiple studies have been conducted to examine effects of crop rotations in wireworm management (Thomas 1940, Miles 1942, Seal et al. 1992, Willis et al. 2010). However, results have been context-dependent and differ significantly based on the wireworm species present, cropping system, and region.

Willis et al. (2010) conducted replicated 3-yr field studies to evaluate the effect of crop rotations on the abundance of eight wireworm species in the genera *Conoderus*, *Melanotus*, and *Glyphonyx* common for that region. In farming systems with corn, soybean, fallow, cotton, sweet potato, or tobacco plants, they found that wireworms had greater abundance and more species in crops following corn or soybean. However, wireworm populations across these three genera were generally reduced in crops following tobacco, peanut, or sweet potato crops. Similarly, Seal et al. (1992) examined the effects of crop rotations on four common wireworm species in the genus *Conoderus* infesting sweet potato fields in Georgia. They found that the highest total wireworm numbers were recorded in sweet potato fields following corn or peanuts. However, results differed by species, suggesting that the effects of crop rotations depend on the biology of particular wireworm species.

Results of our experiments suggest that switching from continuous spring wheat cropping to a no-till summer fallow and winter wheat rotation might aid in reducing wireworm populations. We did not similarly evaluate a no-till summer fallow and spring wheat rotation because this system is not commonly used in our region. For both wireworm species examined, a no-till summer fallow and winter wheat rotation reduced populations by >50% compared with a continuous spring wheat cropping.

Incorporating fallow may deprive wireworms of food, reducing populations in subsequent years. Fallowing fields might also reduce wireworm populations by drying out soil (Summers and Godfrey 2009), and when fallow fields are cultivated egg and larval populations can be disrupted (Willis et al. 2010). Fallow could also impact wireworm populations if adults avoid laying eggs in wheat stubble compared with plots containing spring wheat. Over the course of the study we noticed a trend that smaller wireworms (< 9 mm), which are indicative of eggs laid the previous year (Vernon et al. 2009), became less common over time in the no-till summer fallow plots. This indicates that avoidance of fallow for oviposition likely played a large part in our results, although more data are needed to support this hypothesis. Moreover, it is possible that some of the reduction in wireworm abundance may have resulted from reduced attractiveness of baits in the presence of winter wheat plants as compared with spring wheat plots that were fallow at the time of sampling. However, wireworm abundance was also reduced in no-till summer fallow plots compared with spring wheat plots, suggesting that decreased attractiveness of baits in the presence of winter wheat was not solely responsible for reductions in abundance. Our results show that understanding the seasonality of cropping systems and the host preferences of different wireworm species is essential for incorporating cultural practices such as crop rotations into IPM programs for wireworm management.

Our results, and those of previous studies, suggest that prophylactic insecticidal treatments and crop rotations can be effective in managing wireworms, especially when they are used in combination. However, it is clear that there is no "one size fits all" strategy for all wireworms. There are >100 different wireworm species of economic importance in the Holarctic region (Vernon and Van Herk 2012), and these species have dramatic variation in feeding preferences and phenology (Jewett 1945, Gibson et al. 1958, Rabb 1963, Doane 1967, Seal et al. 1992, Furlan 2004). Moreover, different species are not equivalent in terms of damage potential, and are differentially susceptible to pesticides. Thus, a critical need for wireworm IPM is to better understand the factors that affect the distributions of various species across cropping systems. This would allow for more targeted management practices to be employed based on particular species present rather than assuming all control tactics are equally viable in all cases.

Soil-dwelling pests such as wireworms are notoriously difficult to manage because of their cryptic life cycles. To develop species-specific IPM strategies, long-term field experiments can be effective to evaluate combinations of tactics such as prophylactic insecticidal treatments and cultural practices such as crop rotations or variation in tillage. Long-term studies such as those reported here increase the likelihood of uncovering effective strategies by reducing effects of seasonal variability and more accurately representing commercial production practices. In many cases, combining chemical and cultural management tactics is likely to generate the highest yields and economic returns for soil-dwelling pests. In turn, researchers should strive to find the best combination of tactics that are applicable for the pests and cropping systems in their regions, realizing that variation in species may play a key role in the effectiveness of chemical and cultural management strategies.

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