Arthropod-Plant Interactions (2023) 17:517–528
https://doi.org/10.1007/s11829-023-09973-w

ORIGINAL PAPER

# Predicting crop damage caused by wireworms and the effect of tillage on trap efficiency

**Todd Kabaluk**[1] · **Alicia Chaigneau**[1] · **Lorenzo Furlan**[2]

Received: 4 January 2023 / Accepted: 19 April 2023 / Published online: 10 May 2023

## Abstract

A novel wireworm 'probe' trap is described, characterized, and used in field trials to (i) determine effects of different spring tillage treatments on its efficiency capturing *Agriotes obscurus* L. Coleoptera: Elateridae wireworms; and (ii) assess its ability to predict crop damage. In pot trials, its attractiveness to other wireworm species was determined. In a forage/grass field, spring tillage treatments included: ploughing, rototilling, glyphosate-sprayed then ploughing, glyphosate-sprayed then rototilling, glyphosate-sprayed untilled, and untilled. The number of wireworms captured in tilled treatments increased until 20 October. The number of wireworms captured in untilled treatments remained low. Subterranean $CO_2$ levels in tilled treatments decreased after tillage and over the trapping period, suggesting the increase in captured wireworms occurred because trap $CO_2$ levels were not overwhelmed by soil levels. The decrease in subterranean $CO_2$ was less pronounced in untilled-glyphosate and relatively unchanged in untilled-no glyphosate, corresponding to the lower number of wireworms captured. In a separate trial determining the trap's ability to predict crop damage, a 2 m-wide section was rototilled in grass/forage fields in the spring of Year 1. Probe traps assessed wireworm levels in August and October of Year 1 to predict crop damage for potato and corn planted in Year 2. The *y*-intercept of linear equations suggested that wireworms captured in October better-predicted potato damage and corn emergence although equations were significant only for August. October-captured wireworms $\leq 21$ mm in length correlated better with crop damage than larger wireworms. Pot studies revealed the probe trap to also attract *A. litigiousus*, *A. sordidus*, *A. brevis*, and *A. ustulatus*.

**Keywords** Elaterid · *Agriotes* · Risk assessment · Integrated pest management · Pest monitoring · Carbon dioxide

## Introduction

Polyphagous soil-dwelling wireworms, the larvae of click beetles (Coleoptera: Elateridae), are major insect pests that can cause significant economic losses in a wide range of agricultural crops. If integrated pest management (IPM) principles, particularly pest monitoring, are insufficiently implemented in conventional agriculture, farmers will prophylactically apply insecticides to protect crops from wireworm feeding (Veres et al. 2020). In organic agriculture, particularly in North America, there is no such product protection and farmers either attempt to mitigate some damage using a variety of non-chemical methods (Andrews et al. 2008; Kabaluk 2016; Poggi et al. 2021) or avoid production in areas with a high population density once they are discovered. Given the variability of wireworm population densities among and within geographic regions (Parker and Howard 2001; Furlan 2014; Roche et al. 2023), both conventional and organic farmers can be faced with uncertainty regarding the risk of wireworm damage, especially when entering new areas for cultivation. The consequences of this uncertainty can include unnecessary insecticide application if the density is low (Furlan et al. 2017), or in the case of organic agriculture, unexpected crop loss if the density is high and environmental conditions favor feeding damage (Furlan et al. 2017; Poggi et al. 2018; Roche et al. 2023). Knowing the risk of wireworm damage in areas targeted for cropping can help farmers and pest managers make control decisions, or whether to plant the crop at all.

Much has been written on methods to predict the risk that insect pests pose to crop production (e.g. Binns et al. 2000).

---

Handling Editor: Giselher Grabenweger.

✉ Todd Kabaluk
Todd.Kabaluk@agr.gc.ca

[1] Agriculture and Agri-Food Canada, Agassiz, BC, Canada

[2] Veneto Agricoltura, Viale dell'Università, Legnaro, PD, Italy

In most cases, the determination of pest density is conducted over time within the cropping year as density increases (or fluctuates with environmental conditions or predator density), with a control measure (e.g. insecticide) applied after a pre-determined threshold density is detected (Binns et al. 2000; Barzman et al. 2015). Because of their subterranean habitat, cryptic nature, and multi-year existence in the damaging larval stage, wireworms are not amenable to most of the risk assessment methods designed for other pests so different procedures are needed. Such approaches have included methods for detecting their levels or presence as larvae and/or adults (beetles), together with climatic and agro-environmental factors in the years, and even days, preceding cropping (Furlan et al. 2017, 2020; Poggi et al. 2018; Roche et al. 2023).

Larval and/or beetle monitoring are key activities whose outcomes indicate conspicuous risk of damage, and are essential in use with other risk factors. Beetle monitoring using pheromone-baited traps can be less time consuming than monitoring larvae, and the association between beetle levels and crop damage (maize) have been demonstrated for three European *Agriotes* species (Furlan et al. 2020). The most direct approach for determining larval density would be to extract soil samples, count the larvae, i.e. absolute sampling (Vernon and van Herk 2022), and estimate the population density based on larvae per soil volume, or larvae per area for the sample depth. This approach has been avoided because of the intensity of effort. Alternatively, traps can be used, i.e. those that produce a carbon dioxide attractant (Doane et al. 1975), generated by germinating seeds (Apablaza et al. 1977) or aerobic fermentation of a carbohydrate substrate (Kabaluk et al. 2012). Such traps are removed and the trapped wireworms counted, resulting in relative density. Each method is confounded by the vertical and tenuously predictable wireworm movement in the soil profile according to season and in combination with edaphic factors (Jung et al. 2014). With each method, (absolute and relative) there can be uncertainty, mostly due to edaphic factors, as to whether sampled densities appropriately represent an absolute or relative population level, or whether they represent a snapshot of wireworm presence in the sampled portion of the soil profile. However, a certain amount of the uncertainty has been reduced by accounting for soil temperature and moisture (Furlan 2014; Furlan et al. 2017).

Given the importance of larval monitoring to assess the risk of wireworm damage in arable land, we developed an easy-to-use trap (‘probe trap’; Kabaluk 2012) and in a replicated field trial, sought to understand the effect of different tillage methods applied to a rotational crop on its efficiency in capturing wireworms, relating it to the flux of trap and soil carbon dioxide. Having identified a tillage method from this trial that resulted in high wireworm capture, we used it to develop a protocol to predict wireworm damage to potato and corn one year in advance of planting. Our field trials conveniently comprised, essentially, a single wireworm species—*Agriotes obscurus* L. and a small percentage (estimated to be less than 10%) of *A. lineatus* L. (van Herk, personal communcication). With essentially a single species present, we could elucidate treatment effects in the absence of the confounding effect of multiple species. Knowing that most agricultural regions will comprise numerous pestilent species, particularly in Europe, we tested the trap’s ability to attract other species in pot experiments.

## Materials and methods

### Characteristics of wireworm trap

A prototype $CO_2$-emitting wireworm trap (‘probe trap’; Kabaluk 2012) was constructed using a 50 ml plastic centrifuge tube (VWR Canada, Mississauga, Ontario) as the wireworm collection tube with an inner 15 ml plastic centrifuge tube (VWR Canada), or ‘bait barrel’, whose bottom portion was cut so that its height fit into the collection tube (Fig. 1). The lid of the bait barrel, into which the bait barrel was threaded, was glued underneath the lid of the collection tube. The bait barrel contained 4.25 g rolled oats, and once saturated with water, numerous pre-drilled 1.5 mm holes in the upper region of the bait barrel enabled their aerobic fermentation and passage of $CO_2$ from the bait barrel into the collection tube, exiting through 12–6.5 mm holes in its midsection. The $CO_2$ attracted wireworms (Doane et al. 1975) which entered the trap through the holes, accumulating them in the collection tube. The trap was designed for ease of handling (it can be roughly handled without dislodging any components), rapid deployment, easy retrieval of trapped larvae, and minimal wireworm escape. During the trap’s development, its $CO_2$ production in the lab was compared to grain bait traps—450 ml plastic pots containing vermiculite, and corn and wheat seed (Vernon et al. 2009, modeled on those reported in Chabert and Blot 1992) whose $CO_2$ production results from respiration during seed germination. Carbon dioxide production was measured in passively ventilated Plexiglass boxes at 21 °C using the technique described in Kabaluk et al. (2012). One trap of each type was placed in each of four replicate and randomized boxes, and $CO_2$ ppm measured every 6 min for 15 days. For each trap, the average ppm $CO_2$ was calculated for each time point. The averages were mathematically processed according to Kabaluk et al. (2012) to create a dataset of time versus cumulative- (mol) and rate (μmol/min) of $CO_2$ production. These data were fit with transition functions generated in TableCurve 2D (Systat Software, USA) and the functions’ data graphed in Excel.

**Fig. 1** Wireworm probe trap (prototype) comprising outer collection tube (50 ml centrifuge tube) and an inner bait barrel (15 ml centrifuge tube), the latter containing 4.5 g rolled oats to generate carbon dioxide by aerobic fermentation

## The effect of tillage on wireworm trapping efficiency and $CO_2$ production

The ability of probe traps to capture wireworms under differentially tilled conditions was assessed in 2009. The field site located at 49.242°, − 121.756° consisted of silt loam soil growing seeded and well-established orchard grass (*Dactylis glomerata* L. (Poaceae)) and tall fescue (*Festuca arundinacea* Schreb. (Poaceae)) with volunteer white clover (*Trifolium repens* L. (Fabaceae)) and annual bluegrass (*Poa annua* L. (Poaceae)) for at least five years and unmaintained except for mowing. Six treatments, with each plot measuring 10 m × 10 m, were arranged in a randomized complete block design with four replications.

Blocks were separated by 10 m of the untilled forage. Within blocks, adjacent plots were separated by 2 m untilled forage. The six treatments were: ploughing (Pl), rototilling (Ro), glyphosate-sprayed (to kill the vegetation) followed by ploughing (Pl-Gl), glyphosate-sprayed followed by rototilling (Ro-Gl) (all four of these treatments, when generalized, referred to as ‘tilled’ herein), glyphosate-sprayed but untilled (Un-Gl), and untilled (Un) (these two treatments, when generalized, referred to as ‘untilled’ herein). Plots receiving glyphosate were sprayed with RoundUp™ on 7 May according to the label rate. Using a tractor, Pl and Pl-Gl plots were ploughed to 25 cm on 21 May with a 4-row rollover plough followed by discing and cultipacking to create an even soil surface. Ro and Ro-Gl plots were rototilled to a 20 cm depth the same day with a rototiller driven by the power take-off (PTO) of the tractor, then cultipacked (discing omitted as it was unnecessary for rototilled soil). Within each plot, horticultural pot labels were placed 1 m apart in a 9 m × 9 m grid, with end rows 1 m inward from the plot edge. Labels were inscribed sequentially from 1 to 81, with each label representing a position where a probe trap could be placed. All plots were maintained weed free with a periodic glyphosate spray until 7 July when one probe trap was installed at each of nine randomly selected labeled positions within each plot. Inserting the probe traps into the soil was accomplished using a 2.5 cm (outside diameter) soil probe to extract soil to a depth of 15 cm and then pushing the trap down to the bottom of the cavity. Soil was smoothed over the top of the trap, firmed with a footstep, and re-marked with the pot label (general method can be viewed at https://www.youtube.com/watch?v=yH8gr3irvSQ). Probe traps were extracted by lifting them out of the soil with a narrow shovel (https://www.youtube.com/watch?v=c_6ln_K2ppw) on 21 July and taken to the lab where each wireworm was counted and length measured with a caliper. Subsequent extraction dates were 12 August, 1 September, 29 September, and 20 October with each date’s probe traps having remained in the soil for two weeks. Fresh traps were placed at new, randomly chosen marked positions within each plot. The mean number of wireworms/trap*day was plotted across extraction dates for each treatment using Excel and fit with exponential and linear functions using TableCurve 2D. These same data were subjected to ANOVA (by sampling date) with ‘tillage’ (Pl, Ro, Un) and ‘glyphosate’ (Gl, noGl) as factors and a T x G interaction, using $\alpha = 0.05$. The number and frequency of wireworm sizes were plotted using Excel, with frequency values modeled using peak functions in TableCurve 2D.

Over part of the period of wireworm trapping and beyond, soil $CO_2$ was measured at a depth of 20 cm in the center of each plot. This was accomplished as follows: after tillage (as described above), a 60 cm long, 4.0 cm (inside diameter) polyvinyl chloride tube was inserted 40 cm deep into a cavity created with a soil probe. The bottom of the tube was sealed, but the lower 35 cm had been drilled to create 8 − 1.25 cm holes that were covered with 1 mm nylon mesh to allow gas exchange between the inside of the tube and outside soil, and prevent soil from falling into the tube. Between $CO_2$ sampling dates, the top of the tube was sealed with a cap. On each sampling date, the cap was removed and the $CO_2$ sensor of a Vaisala GMT220 (Vaisala Oyj, Finland) gently (to not disturb the gas) lowered into the tube to sample $CO_2$ at depth of 20 cm below the soil surface. $CO_2$ values, appearing on the attached transmitter, were recorded on 12, 18 August; 1, 15, 29 September; 6, 20, 27 October; and 24 November. The mean $\%CO_2$ was plotted across measurement dates for each treatment using Excel. These same data were subjected to ANOVA (by sampling date) with 'tillage' (Pl, Ro, Un) and 'glyphosate' (Gl, noGl) as main effects and a T × G interaction, using $\alpha = 0.05$.

To relate $CO_2$ levels to the number of wireworms/trap*day, the $CO_2$ level in each plot on the trap extraction date and previously measured $CO_2$ level were averaged to create an $x$,$y$ dataset comprising mean $\%CO_2$ ($x$) and wireworm catch for the 1, 29 September and 20 October extraction dates. These data were sorted in ascending order by $\%CO_2$ and the mean $\%CO_2$ and mean number of wireworms/trap*day calculated by groups in $0.05\%CO_2$ increments. The data were plotted and fit with a linear function in Excel, with linear regression analysis conducted using R (R Core Team 2021).

## Predicting wireworm feeding damage one year before cropping potato and corn

Within a 4 km radius of the rural town of Agassiz, British Columbia, Canada (within proximity of the field site previously described) five farm fields that had grown, and were currently growing long term forage for a minimum of two previous years were selected for the study. In early May of Year 1 (2010), a 4 m wide section of grass was mowed to approximately 20 cm in height, followed by rototilling a 2 m wide section through the center of its length to a depth of 20 cm (the 'trapped' section). Rototillage was chosen because it resulted in acceptable trapping efficiency in the tillage trial described in the previous section. The length of each trapped section varied with farm field: Field 1–126 m, Field 2–122 m, Field 3–102 m, Field 4–44 m, and Field 5–150 m. The trapped section was maintained free of weeds throughout the summer by light tillage using a harrow or spraying with glyphosate at the label rate of Roundup™. On 20 July, probe traps were installed (method previously described) every 2 m through middle and down the length of the trapped section starting 1 m inward from the end. After two weeks, the traps were removed on 3 August ('August' traps) and taken to the lab where the wireworms from each trap were counted and length measured with a caliper. The trapping process was repeated by installing traps on 22 September and extracting them on 7 October ('October' traps). The placement of the October traps was offset by 1 m which avoided trapping in the same place as the August traps. In April of the following year (Year 2; 2011), a 4 m wide strip (the 'cropped' sections) either side of and parallel to the trapped section was ploughed, disced and cultipacked to create planting beds for field corn (CV. unknown) and potato (CV. 'Red Chieftain'). Planting occurred in May. Using a stand-up corn planter, eight corn rows were seeded down the length of one cropped section at 15 cm intra-row and 0.5 m inter-row spacing such that the edge rows were 0.5 m from the trapped section and 0.5 m from the outside, untilled grass. The opposite 4 m cropped section was planted with seed potatoes using a small scale planter pulled with a tractor. Seed tubers were spaced 30 cm intra-row and 1 m inter-row such that the edge rows were also 0.5 m from the tilled/trapped section and 0.5 m from the outside, untilled grass. Weeds were managed by hand, and potatoes were hilled mid-season. The cropped and trapped sections were partitioned into 10 m long perpendicular subsections for sampling corn and potato or compiling the counts of trapped wireworms (one subsection comprised 5 traps/extraction date in Year 1). Two weeks after planting, emerged corn plants were counted in each subsection by centering a 4 m long quadrat containing the middle four rows. The quadrat contained 120 seed sites and percent emergence was calculated and used in analyses. For potato, up to 100 new tubers (that number was not always achievable) were randomly sampled in mid-September from each subsection by centering the 4 m long quadrat containing two potato rows. Each tuber was weighed, and the wireworm feeding holes counted.

The number and frequency of trapped wireworm sizes were plotted using Excel, with frequency values modeled using peak functions in TableCurve2D. For further presentation and analysis, means were compiled first by subsection*field, with these values used to calculated means per field. Wireworm feeding holes and percent corn emergence were plotted against wireworm levels and fit with linear models using Excel. Linear regression analysis was performed using R. Wireworm size classes (greater than and less than or equal to 21 mm) were correlated to crop damage using Pearson's correlation coefficient ($r$) in R.

## Attractiveness of the probe trap to other *Agriotes*

The entirety of the presented research took place from 2009 to 2011 during which the field trial locations comprised mostly *A. obscurus* with a small proportion ($< 0.1$) of *A. lineatus*. To develop and extend a wireworm risk assessment protocol to other species using our findings, it was important to determine the attractiveness of the probe trap to these species. To accomplish this, groups of 5 of each of *A. obscurus*, *A. brevis*, *A. litigiosus*, *A. sordidus*, and *A. ustulatus* were placed into a small hole in the sandy loam soil of each of ten 2.2L (17.5 cm rim diameter) plastic pots. Water had been previously added to field capacity. For each species, one probe trap and one grain bait trap ('classic') as described by Chabert and Blot (1992) (except we used a 9 cm diameter pot), was randomly assigned to each of five replicate pots after 24 h by creating a cavity in the soil and centering the trap in the pot (one trap/pot). Excavated soil was replaced over the trap. Pots were kept at room temperature and 2–3 mm (30–46 ml) of water/pot provided daily. Traps were inspected for wireworms on the eighth day after trap placement. The trial was repeated using *A. sordidus* and *A. ustulatus*. Proportion of wireworms recaptured were arcsine transformed and analyzed using PROC GLM in SAS (SAS Institute, USA). The model comprised wireworm species and trap type as main effects, and S x T interaction. Means were separated using Duncan's Multiple Range Test, $\alpha = 0.05$.

## Results

### Characteristics of wireworm trap

After 15 days, the cumulative production of $CO_2$ attained by a single probe trap was 0.058 mol, roughly half of that produced by a grain bait trap (Fig. 2a). The onset of $CO_2$ production of a probe trap occurred earlier, peaking on the third day (Fig. 2b), which in subsequent studies was found to be typical of aerobically fermenting rolled oats (T.K., unpublished data). The output of $CO_2$ by the probe traps declined to near zero by the fifteenth day, suggesting that it would no longer attract wireworms. The rate of $CO_2$ production of the grain bait traps on day 15, while attaining its peak, was still high resulting in the continued cumulative $CO_2$ increase.

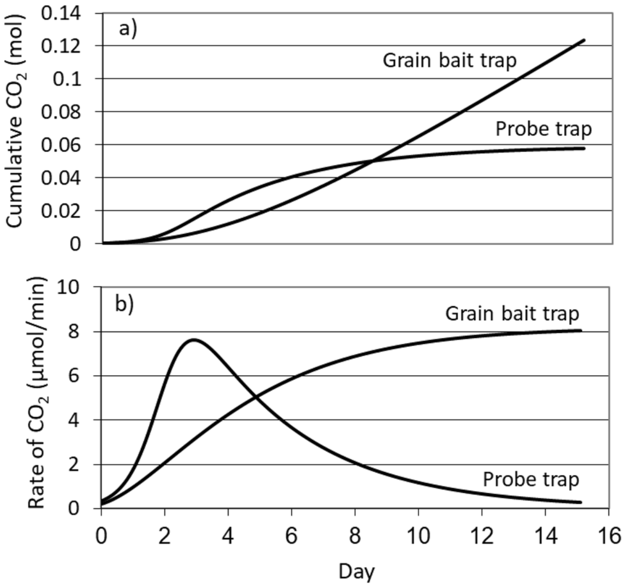

**Fig. 2** Carbon dioxide production of probe trap and conventional grain bait trap. Cumulative $CO_2$ production (**a**); Rate of $CO_2$ production (**b**)

### The effect of tillage on wireworm trapping efficiency and $CO_2$ production

The number of wireworms captured in the four tillage treatments (the remaining two were untilled) increased continually from the commencement of trapping until 20 October, the date of the last trap recovery. A significantly greater number of wireworms were captured in tillage treatments on every sampling date except 21 July (Fig. 3). The levels of wireworms in the untilled treatments remained unchanged and low, except on 1 September when capture was more variable for three treatments (Ro-Gl, Ro, and Un-Gl). The size distribution of wireworms captured within each treatment is shown in Fig. 4. The proportional distribution of wireworm sizes captured in the four tilled treatments closely fit peak functions while there was considerably more variation in untilled treatments and a less discernable peak. All modeled distributions were normal, with the peak frequencies centering on wireworm lengths ranging from 15.2 to 17 mm ($\bar{x}$ = 15.8 mm ± 0.8). Figure 4 also makes clear that the total of wireworms captured was greater in tilled treatments (horizontal bars; note that Pl values are obscured due to co-incidence of left and right *y*-axes ranges). Over time (Fig. 5), the distribution of wireworm sizes shifted slightly toward a larger proportion of larger wireworm sizes, or at least, the lowest proportion of the smallest sizes occurred at the end of trapping on 10 October. The size of wireworms in greatest proportion shifted from $\bar{x}$= 13.8 mm ± 0.1 for 21 July – 1 September to $\bar{x}$= 16.7 mm for each of 29 September and 10 October, suggesting the growth of wireworms during the season. The greatest number of wireworms captured in

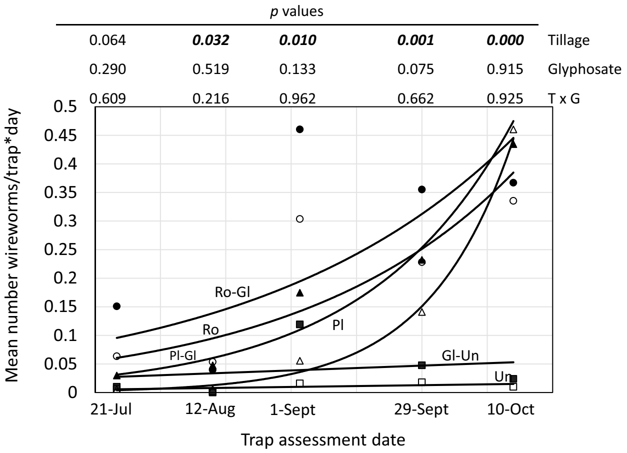

**Fig. 3** The effect of prior tillage and glyphosate application on wireworm trapping efficiency using probe trap. Ploughed (Pl), rototilled (Ro), glyphosate followed by ploughing (Pl-Gl), glyphosate followed by rototilling (Ro-Gl), glyphosate without tillage (Un-Gl), untilled (no glyphosate) (Un). *p* values are for data within trap assessment date, arising from ANOVA of treatments

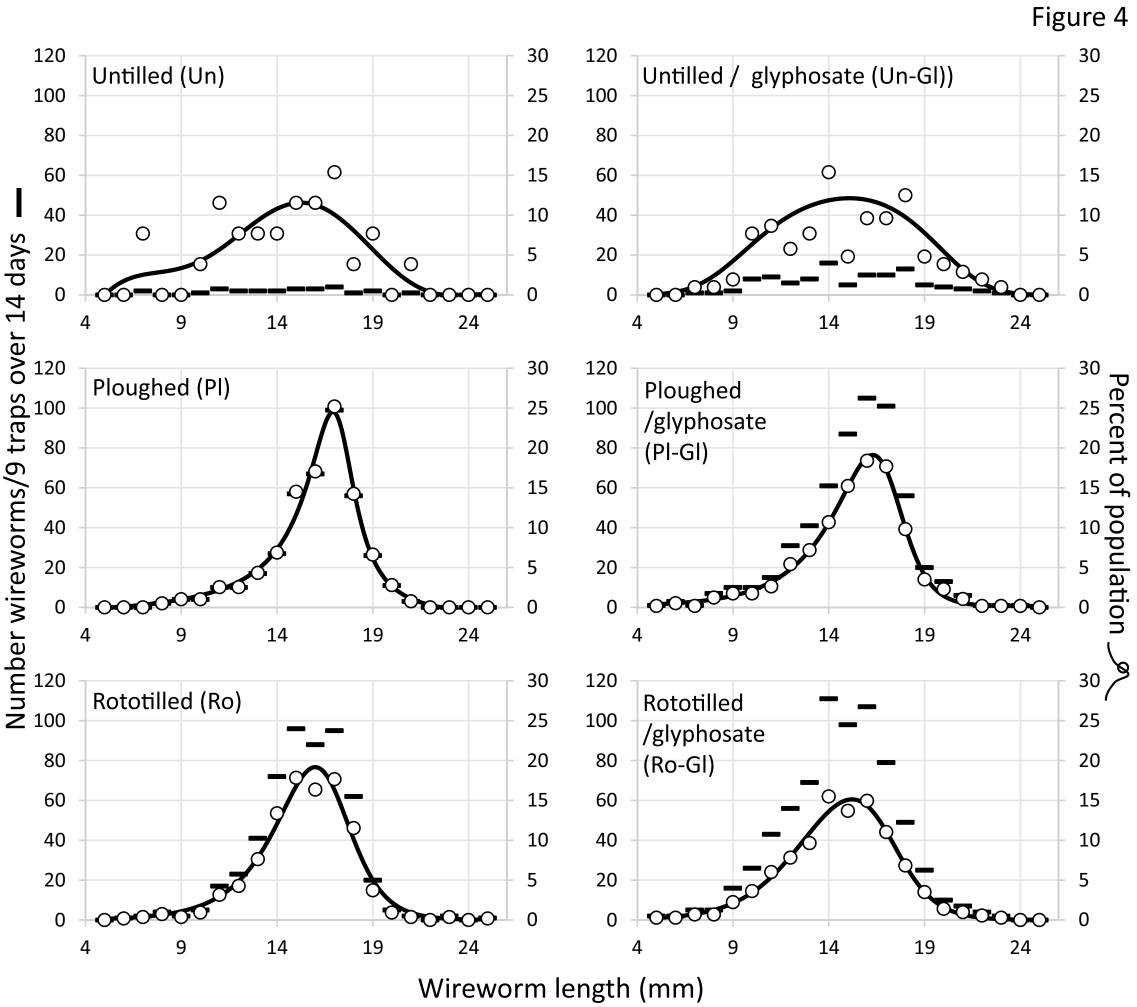

**Fig. 4** Size distribution of wireworms by tillage treatments. Data from all sampling dates are combined. Left *y*-axis is number of wireworms/9 traps over 14 days (horizontal black bars); right *y*-axis is percent of population represented by each size (peak function fitting data (white circles))

a single trap over 14 days was 53 in the Pl treatment on 20 October.

Between 12 August and 29 September, soil $CO_2$ decreased noticeably in all treatments except in untilled (no glyphosate) forage which remained relatively unchanged, with the exception of one anomalous sampling date (1 September; Fig. 6). For all but the untilled (no glyphosate) treatment, $CO_2$ levels began to increase from 6 October until the last $CO_2$ sampling date on 24 November. Glyphosate applied to untilled grass had lower soil $CO_2$ levels than untilled grass (no glyphosate) between 1 September and 27 October. Tukey's mean separation of interaction values on 1 September revealed that $CO_2$ levels in ploughed (no glyphosate) and untilled (no glyphosate; anomalous value) were significantly lower than untilled (with glyphosate), while on 6 October (where $p = 0.051$ for glyphosate main effect) untilled (no glyphosate) was significantly greater than all other treatments. In pooling data from all treatments (for selected dates as described in Materials and Methods), soil $CO_2$ levels were found to be inversely related to wireworm capture (Fig. 7).

## Predicting wireworm feeding damage one year before cropping potato and corn

There was a positive linear relationship between the mean number of wireworms/trap*field in Year 1 and wireworm damage to harvested potatoes (feeding holes/tuber) in Year 2 and a inverse linear relationship with corn emergence in Year 2 (Fig. 8). For wireworms captured in August, the coefficients of determination for potato and corn were significantly greater than for wireworms captured in October. While our trapping method was not intended to estimate actual wireworm densities in the field, it was interesting that

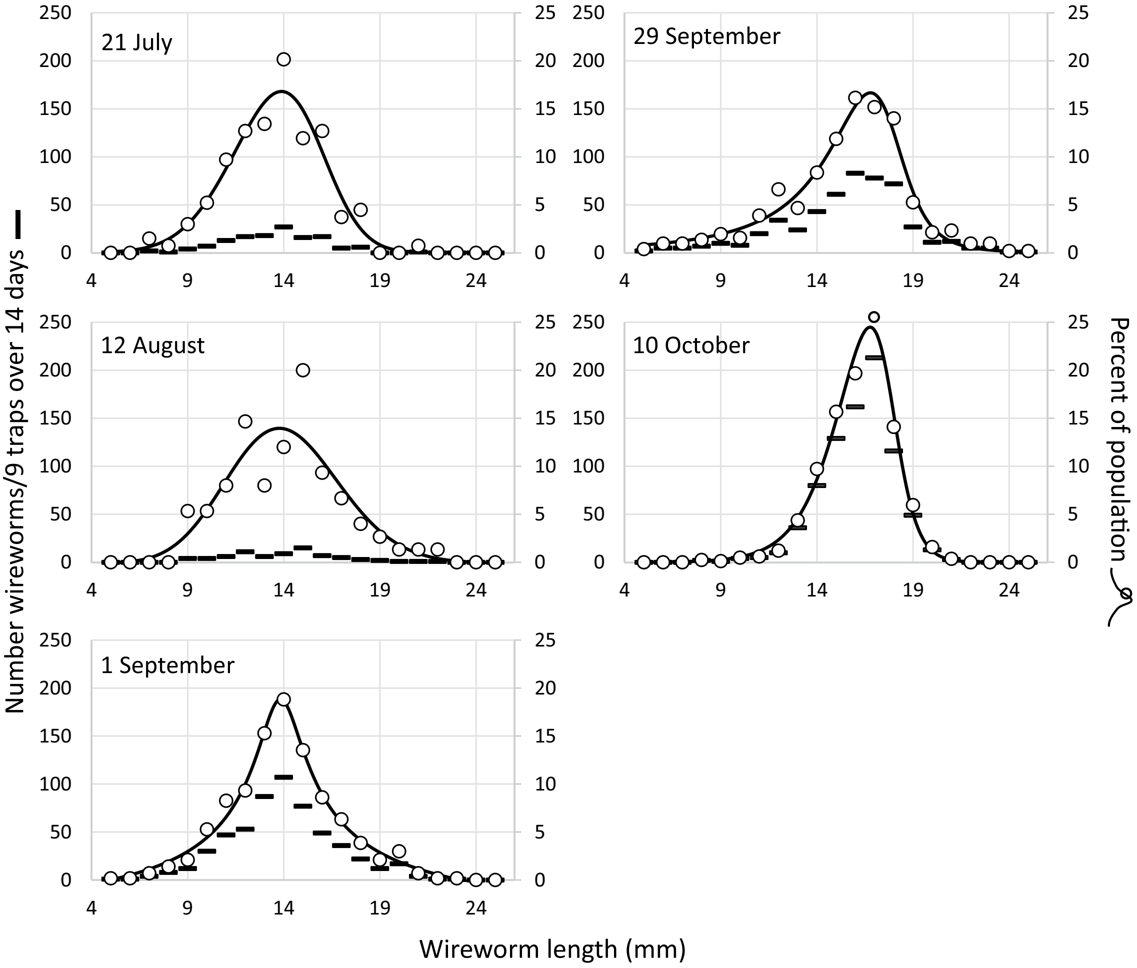

**Fig. 5** Size distribution of wireworms by date. Data from all tillage treatments are combined. Left *y*-axis is number of wireworms/9 traps over 14 days (horizontal black bars); right *y*-axis is percent of population represented by each size (peak function fitting data (white circles))

the *y* intercepts of regressions for wireworms captured in October would be the expected values if there were no wireworms in the field, i.e. $x = 0$: $y = 0.017$ (almost no damage) for potato, and $y = 1.00$ (100 percent emergence) for corn. The linear relationship in potato, with $p = 0.057$, was close to being significant ($\alpha = 0.05$), but not significant for corn.

Similar to the tillage/glyphosate trial, wireworm size increased with a later sampling period (Fig. 9). For August samples, the peak frequency centered on wireworms 14 mm in length, while October samples centered on 18 mm, with a second smaller peak centering on 26 mm. Wireworms 21 mm in length and smaller were closely and significantly correlated to potato damage and corn emergence (Table 1). Wireworms greater than 21 mm were clearly uncorrelated to both potato damage and corn emergence. Using all sizes, *r* values indicated close correlations, but significant only for August wireworms ($\alpha = 0.05$). As would be expected, Pearson's *r* for August (all sizes) and October (all sizes) wireworms were congruent with coefficients of determination ($R^2$) reported in Fig. 8.

## Attractiveness of the probe trap to other *Agriotes*

Both the probe- and classic traps recaptured a proportion of each wireworm species released (Table 2). There was no significant difference in the proportion of wireworms recaptured between trap types (Trial 1: $p = 0.1763$; Trial 2: $p = 0.5480$). There was a significant difference among species for proportion recaptured (Trial 1: $p = 0.0013$; Trial 2: $p = 0.0413$). There was no significant trap type x species interaction (Trial 1: $p = 0.4663$; Trial 2: $p = 0.1078$) so the data were combined to assess differential attraction of wireworm species to the traps (Table 3). Interestingly, the species present in the field trials, *A. obscurus*, was recaptured with the lowest frequency, followed by *A. sordidus*, the latter of which was used in both runs of the pot trial.

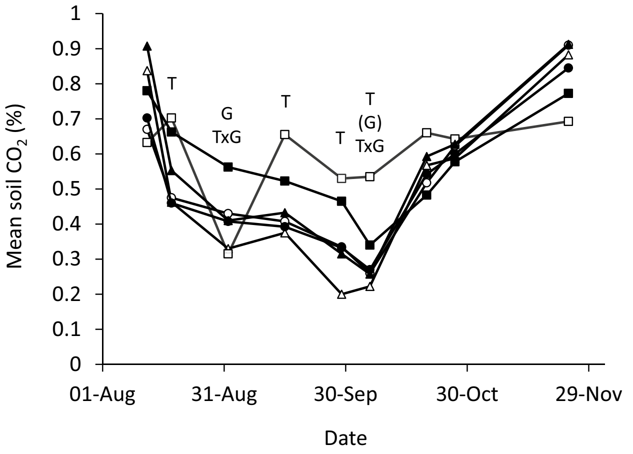

**Fig. 6** Carbon dioxide levels in soil within tillage treatments over time. Ploughed (triangle); rototilled (circle); untilled (square). White fill is without glyphosate; black fill is with glyphosate. Letters above points (T = tillage, G = glyphosate) indicate those treatments had a significant effect ($\alpha = 0.05$) using ANOVA within each date. (G) was $p = 0.051$

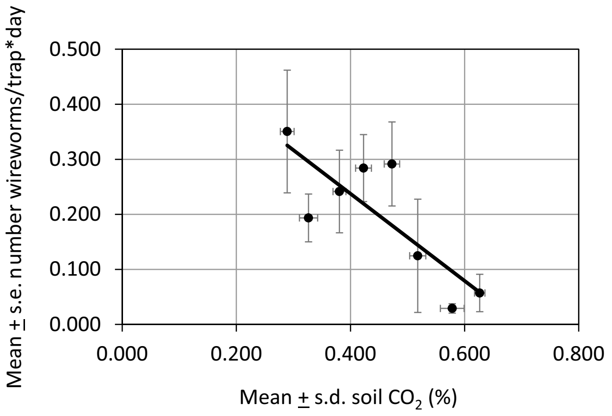

**Fig. 7** Relationship between soil CO$_2$ and wireworm trap catch. $y = -0.792x + 0.554$; $R^2 = 0.656$, $p = 0.015$

*A. brevis* was recaptured with the greatest frequency, at 0.44 of those released.

## Discussion

Tillage of the established vegetation was necessary for capturing wireworms in the probe traps. It seems likely that tillage increased soil CO$_2$ efflux, initially through ‘degassing’ (Calderón and Jackson 2002) and over time by the decomposition of plant biomass and associated CO$_2$ efflux (Pumpanen et al. 2003). Under this scenario, the traps would create a more pronounced CO$_2$ gradient to which wireworms could respond (Doane et al. 1975) and reduce the competition of CO$_2$-emitting plant roots. Furthermore, the increased porosity of tilled soil would have better-enabled CO$_2$ diffusion from the traps. This

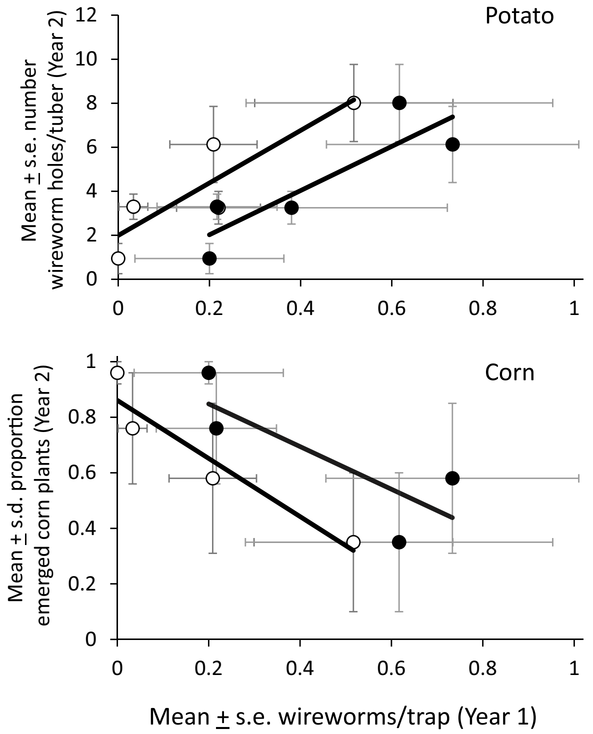

**Fig. 8** Relationships between levels of captured wireworms in Year 1 and wireworm damage to potato and corn in Year 2. White circles are August traps; black circles October traps. Potato (August): $y = 11.934x + 1.990$; $R^2 = 0.787$, $p = 0.045$; Potato (October): $y = 10.038x + 0.017$; $R^2 = 0.752$, $p = 0.057$; Corn (August): $y = -1.046x + 0.861$; $R^2 = 0.906$, $p = 0.045$; Corn (October): $y = -0.770x + 1.002$; $R^2 = 0.655$, $p = 0.191$

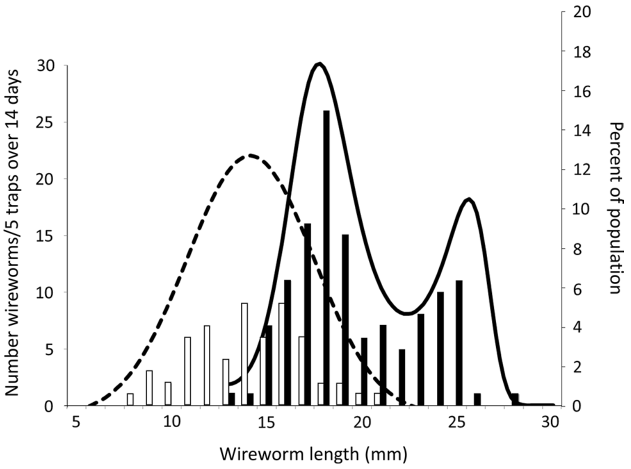

**Fig. 9** Size distribution of wireworms captured in August (white bars, dashed curve) and October (black bars, solid curve) across all experimental fields

**Table 1** Correlations between mean wireworm (*Agriotes obscurus*) catch per field and feeding damage in harvested potatoes and emergence of corn, according to wireworm size

| Trapping period and wireworm size | Wireworm holes/potato tuber |  | Percent corn emergence |  |
|---|---|---|---|---|
|  | Pearson's $r$ ($p$ value) | n fields | Pearson's $r$ ($p$ value) | n fields |
| August (all sizes) | 0.89 (0.045) | 5 | – 0.95 (0.050) | 4 |
| October (all sizes) | 0.87 (0.055) | 5 | – 0.81 (0.185) | 4 |
| October ($\leq$21 mm) | 0.96 (0.010) | 5 | – 0.99 (0.007) | 4 |
| October ($>$21 mm) | 0.21 (0.732) | 5 | – 0.04 (0.955) | 4 |

**Table 2** Recapture of *Agriotes* wireworm species in probe- and classic traps in pot trials

| Trial 1 |  |  |  |  | Trial 2 |  |
|---|---|---|---|---|---|---|
| Trap | Species | Proportion wireworms trapped ($\bar{x}$ (s.d.)) | *N* pots |  | Mean proportion wireworms trapped ($\bar{x}$ (s.d.)) | *N* pots |
| Probe | *A. brevis* | 0.40 (0.18) | 5 |  | – |  |
|  | *A. litigiosis* | 0.32 (0.20) | 5 |  | – |  |
|  | *A. obscurus* | 0.15 (0.09) | 4 |  | – |  |
|  | *A. sordidus* | 0.08 (0.10) | 5 |  | 0.100 (0.10) | 4 |
|  | *A. ustulatus* | 0.20 (0.18) | 5 |  | 0.450 (0.09) | 4 |
|  | Mean | 0.23 (0.15) |  | Mean | 0.28 (0.10) |  |
| Classic | *A. brevis* | 0.48 (0.10) | 5 |  | – |  |
|  | *A. litigiosis* | 0.36 (0.16) | 5 |  | – |  |
|  | *A. obscurus* | 0.05 (0.09) | 4 |  | – |  |
|  | *A. sordidus* | 0.28 (0.16) | 5 |  | 0.20 (0.14) | 4 |
|  | *A. ustulatus* | 0.32 (0.10) | 5 |  | 0.25 (0.02) | 4 |
|  | Mean | 0.30 (0.12) |  | Mean | 0.23 (0.08) |  |

**Table 3** Differential attraction of *Agriotes* wireworm species to bait traps in pot trials

| Trial 1 |  |  | Trial 2 |  |
|---|---|---|---|---|
| Species | Mean proportion wireworms trapped ($\bar{x}$ (s.d.)) | *N* pots | Mean proportion wireworms trapped ($\bar{x}$ (s.d.)) | *N* pots |
| *A. brevis* | 0.44 (0.15)$^{a}$ | 10 | – |  |
| *A. litigiosis* | 0.34 (0.18)$^{ab}$ | 10 | – |  |
| *A. ustulatus* | 0.26 (0.15)$^{bc}$ | 10 | 0.35 (0.16) a | 8 |
| *A. sordidus* | 0.18 (0.18)$^{bc}$ | 10 | 0.15 (0.13) b | 8 |
| *A. obscurus* | 0.01 (0.11)$^{c}$ | 8 | – |  |

would have attracted wireworms from a greater distance, although the reach of $CO_2$ diffusion has yet to be characterized. Another factor to consider is that wireworms are not in a constant state of feeding or responding to a food source. Sufyan et al. (2014) found that feeding of *A. obscurus* larvae ceased during ecdysis: 7–10 days prior to moulting and 2–3 after. It is unknown whether tillage had a direct effect on feeding behavior.

Numerically, but not significantly, slightly more wireworms were captured in untilled plots sprayed with glyphosate (Un-Gl) compared to untilled, growing grass (Un) (Fig. 3). The increased catch corresponded to slightly lower $CO_2$ levels in Un-Gl than Un. While the relative retention of soil $CO_2$ in Un can be understood in terms of root respiration, it was surprising to see that despite killing all the vegetation with glyphosate in untilled plots (Un-Gl), $CO_2$ levels were not lower than what we observed. We suspect that when untilled, the soil porosity was lower than in tilled plots and reduced $CO_2$ diffusion. Furthermore, the roots of glyphosate-killed vegetation would be expected to be colonized by soil microorganisms, maintaining (relative to tilled treatments) soil $CO_2$ levels (Johal and Rahe 1984). Compared to tilled treatments, the higher $CO_2$ levels in Un-Gl may have been one reason for lower wireworm capture; another reason may have been because wireworms were feeding on dead root tissue and fungal mycelia (Zacharuk 1962), with little incentive to respond to $CO_2$ from the traps, i.e. a simulated food source. At its maximum, the trap itself produced $CO_2$ at a rate of 7.6 µmol/min at room temperature (Fig. 2). Assuming this rate to be representative of traps in the field, it was attractive in an environment where soil $CO_2$ levels were in the range of 0.4% (4000 ppm) and below when considering wireworm trap catches in tilled treatments from 1 September onward. The lower catch prior to this date may have been because there was no gradient between trap and soil $CO_2$ levels for wireworms to follow. The combined levels of trap and soil $CO_2$ may also have been repellent, as Doane et al. (1975) found that *Ctenicera destructor* (taxonomically revised to *Selatosomas destructor*), another pestilent wireworm, was repelled by 1–1.5% $CO_2$. The highest levels early during the trapping period of our study ranged from 0.63 to 0.91%. $CO_2$ levels immediately surrounding the trap would have been greater. Overall it was clear that the $CO_2$ level in the soil is an important factor to consider as we found it to be significant relatedly to wireworm catch (Fig. 7).

The frequencies of different wireworm sizes captured in tilled treatments fit closely to a normal distribution while the fit of those in untilled treatments was more diffuse and apparently unassociated, closely, to any probability distribution (Fig. 4). If traps can be considered to sample wireworms from the surrounding soil, then increased soil porosity and horizontal extent of trap $CO_2$, and perhaps increased mobility of wireworms to the trap would result in a larger and more representative sample of their size. For the untilled treatments, a random selection of wireworms could have been more tightly associated with the subterranean food sources (living roots in Un; dead roots and fungal mycelia (Zacharuk 1962; Johal and Rahe 1984)) in Un-Gl with little incentive to orient to $CO_2$ from the traps, resulting in the diffuse association with an ordered distribution. With decreased availability of food sources in the tilled treatments, wireworms in feeding phase would be responsive to the traps and result in a tighter association to the normal distribution.

The modal wireworm length shifted from 13.8 mm ± 0.1 for wireworms captured from 21 July to 1 September to 16.7 mm for each of 29 September and 10 October, reflecting wireworm growth with time. These two sizes would correspond to approximately L6-7 and L8 out of 11 instars according to Sufyan et al. (2014) (note that Table 2 in Sufyan et al. 2014, the 'wireworm average length' and 'head width' columns are reversed) and reflected wireworm growth over time.

The increase in the number of wireworms captured was proportional to the increase in feeding damage on harvested potato tubers and to the decrease in corn emergence the following year (Fig. 8). It was unlikely that wireworms trapped in October were predictive of corn emergence ($p = 0.191$), and all other linear relationships were significant ($\alpha = 0.05$), or nearly so ($p = 0.057$ for October wireworms in relation to potato damage). Furlan (2014) reported similar success in predicting damage to corn by sampling wireworms during February–April, in advance of seeding, and having the added challenge of identifying species—specific thresholds for each of *A. ustulatus*, *A. brevis*, and *A. sordidus*. He stated that to attain accurate predictions, there must be no alternative food sources during wireworm monitoring, soil temperatures must be > 8C for 10 days (not necessarily consecutive), and soil moisture must be at= or near field capacity. While not measured, soil temperature during our sampling periods certainly exceeded 8 °C, and food availability was minimal since the sections in the grass fields were tilled in the spring and kept weed free through the monitoring periods. Soil moisture approaching field capacity seems high, and it is doubtful that the soil moisture at our field sites was in that range. Still, not achieving maximal wireworm capture does not mean that a close correlation to crop damage cannot be made, but rather, that the parameters for the equation modeling the crop damage vs. wireworm capture relationship (in our case, linear relationships) may differ.

Interestingly, October samples, when extrapolated to zero wireworms, predicted almost no potato damage (0.017 holes/tuber) and complete corn emergence (a proportion emergence of 1.00), although this was considered a chance occurrence. Furthermore, it is not uncommon to find wireworm-damaged potatoes when wireworms are undetected using baits (Horton 2006) and by direct sampling (French and White 1965). The size distribution of wireworms shifted to larger specimens between August and October samples, presumably, due to wireworm growth (Fig. 9). A second peak size approaching and reaching 25 mm may have reflected a combination of growth of during fall feeding—a known behavior of wireworms (Vernon and van Herk 2022). Regardless, the number of smaller wireworms captured were more closely correlated with crop damage the following year (Table 1). Both August wireworms, with an overall smaller size compared to those in October, and the smaller class of October wireworms (≤ 21 mm) provided the closest correlations to crop damage. October wireworms ≥ 21 mm were entirely uncorrelated to crop damage and appeared to obscure any correlation with crop damage when they were combined with those ≤ 21 mm (see Table 1 'October (all sizes)'). Sufyan et al. (2014) showed that under a constant temperature, *A. obscurus* larvae remained for a longer period of time as older instars than younger instars, similarly determined for *A. ustulatus* (Furlan 1998). If it is assumed that older instars also spend a longer time moulting and therefore not feeding, then our finding of the lack of correlation of October wireworms with crop damage can be supported. Furthermore, larger wireworms transitioning to adult beetles would be entirely uncorrelated with crop damage the following year.

An important variable that wasn't evaluated in our study was wireworm feeding damage in potato during different harvest periods. In reviewing field trials from 2004 to 2010, Vernon and van Herk (2022) showed that potatoes harvested earlier had less damage than those harvested later, reflecting continued or increased feeding by wireworms. This would cause either a proportional shift of regression lines in Fig. 8 upward for potatoes harvested later and downward for those harvested earlier, or change the slope of the response if the change in potato damage was different between lower and higher wireworm densities.

Our field site comprised almost entirely *A. obscurus*. Our pot studies demonstrated that the probe trap can attract other species, and with the exception of *A. sordidus*, in greater numbers than *A. obscurus*. Given that the probe trap attracted proportionally, but not differentially, fewer wireworms of each species than grain bait traps in our pot study, any thresholds using the probe trap for risk assessment would need to be adjusted accordingly. This would be the case for any trap design as each's catch efficiency would vary according to any number of factors. For example, in grain bait traps, Landl et al. (2010) found that increasing the number of holes into which wireworms entered the trap, increased catch. Our data confirmed what seems obvious—that an increase of $CO_2$ production by a trap (Fig. 2) increases its attractiveness (Table 2). The $CO_2$ production of our trap was limited by the quantity of rolled oats in the bait barrel. In an unpublished study, we found that the amount of $CO_2$ produced is directly proportional to the quantity of the substrate producing it, so levels can be easily predicted. The rate of escape or wireworm emigration would also vary according to trap type—a factor also needing consideration when determining threshold wireworm levels.

We identified the importance of tillage in trapping efficiency, and applied a selected tillage practice (rototilling) in testing the predictive monitoring protocol. We modeled our protocol on the commercial potato production cycle in that after 2 years of a rotational crop, the field would be tilled (rototilled or ploughed then disced) in the spring of the third year. Our rototilled 2 m section, applied in the spring, simulated this tillage. Then, under commercial production, potatoes would be planted and subject to fall feeding of wireworms. The placement of the probe traps late in the season simulated tubers at this time of year. We placed the traps during two periods—August and October—to account for the unpredictability of the specific feeding period. While our results reasonably predicted damage to both potato and corn, our method was unrealistic in that trap density was greater than what would be practical in a commercial setting, and that potato and corn crops were directly adjacent to the trapped section. In addressing the former, we compiled datasets to make correlations between crop damage and different numbers of traps, and binomial sampling using a range of tally numbers for both trap catch and crop (potato) damage. These analyses are available upon request from the corresponding author. Despite the shortcomings of wireworm risk assessment, including ours, we have posted a suggested, conservative, protocol for farmers which can be viewed at https://peipotatoagronomy.com/wp-content/uploads/2022/10/Wireworm-Monitoring-Fact-Sheet-Kabaluk.pdf and https://www.youtube.com/watch?v=Uc53odATyZg (each accessed 8 March, 2023).

Overall, the ability to predict crop damage based on wireworm sampling alone—across years, geography, and agro-environmental conditions, will remain elusive without considering the numerous variable abiotic and biotic factors affecting trapping efficiency. Even within year, Horton (2006) found that the same number of wireworms/trap sampled at different times at the same site (different plots) in the spring resulted in different levels of harvested potato damage, likely reflecting variation in the vertical movement of wireworms. Several authors, notably Benefer et al. (2012); Furlan et al. (2017); Parker and Seeny (1997); Roche et al. (2023), Poggi et al. (2018, 2021) have commented on, reviewed, or studied such a range of biotic and abiotic factors that affect the risk that wireworms pose to crops, rightly concluding that these factors are essential in predictive models and serve to improve them. While we've shown soil $CO_2$ to also be a factor, its measurement and inclusion in models might contribute to this improvement. A less obvious, and likely subtle factor to consider is whether there is an innate seasonal drive of wireworms, i.e. in a uniform and controlled environment, do wireworms sense season that would result in a varying levels of feeding intensity or attraction to $CO_2$?

While we found that our probe trap performed well in the current study, its comparative (to the classic grain bait trap) trapping efficiency in the pot studies was inferior. With other conditions being equal, trapping efficiency is a function of trap design, and can be expected to vary among designs. It follows, that design-specific wireworm thresholds should be used. Perhaps these thresholds would be best scaled, at present, according to the Chabert and Blot (1992) trap which has been used to make reasonable crop damage predictions (Furlan 2014). In other studies, our probe trap gave inconsistent results, likely due to variations in edaphic conditions. The specific problems included a proliferation of saprophytic fungus sometimes growing from the oats in the bait barrel that filled the collection tube. At other times a lack of oxygen caused anaerobic fermentation of the oats, resulting in minimal $CO_2$ production. We have since redesigned the bait barrel so that these occurrences might be minimized.

**Acknowledgements** We thank Beth McCannel for lab coordination and technical assistance, Anita Poon for proof-reading, and two anonymous authors whose comments heightened the quality of this manuscript.

**Funding** Open Access provided by Agriculture & Agri-Food Canada.

**Data availability** Data are available upon request to the corresponding author.

## Declarations

**Conflict of interest** The authors have no conflicts of interest to declare that are relevant to the content of this article.

## References

Andrews N, Ambrosino M, Fisher G, Rondon SI (2008) Wireworm : Biology and nonchemical management in potatoes in the Pacific Northwest. Pacific Northwest Extension Publication PNW607. https://catalog.extension.oregonstate.edu/sites/catalog/files/project/pdf/pnw607.pdf. Accessed 12 Dec 2022

Apablaza JU, Keaster AJ, Ward RH (1977) Orientation of corn-infesting species of wireworms towards baits in the laboratory. Environ Entomol 6(5):715–718

Barzman M, Bàrberi P, Birch AN, Boonekamp P, Dachbrodt-Saaydeh S, Graf B, Hommel B, Jensen JE, Kiss J, Kudsk P, Lamichhane JR, Messean A, Moonen A-C, Ratnadass A, Ricci P, Sarah J-L, Sattin M (2015) Eight principles of integrated pest management. Agron Sustain Dev 35:1199–1215

Benefer CM, Knight ME, Ellis JS, Hicks H, Blackshaw RP (2012) Understanding the relationship between adult and larval *Agriotes* distributions: the effect of sampling method, species identification and abiotic variables. Appl Soil Ecol 53:39–48

Binns MR, Nyrop JP, van der Werf W (2000) Sampling and monitoring in crop protection: the theoretical basis for developing practical decision guides. CABI Publishing, Wallingford

Calderón FJ, Jackson LE (2002) Rototillage, discking, and subsequent irrigation: Effects on soil nitrogen dynamics, microbial biomass, and carbon dioxide efflux. J Environ Qual 31:752–758

Chabert A, Blot Y (1992) Estimation des populations larvaires de taupins par un piège attractif. Phytoma 436:26–30

Doane JF, Lee YW, Klinger J, Westcott ND (1975) The orientation response of *Ctenicera destructor* and other wireworms (Coleoptera: Elateridae) to germinating grain and to carbon dioxide. Can Entomol 107(12):1233–1252

French N, White JH (1965) Observations on wireworm populations causing damage to ware potatoes. Plant Pathol 14:41–43

Furlan L (1998) The biology of *Agriotes ustulatus* Schäller (Col., Elateridae). II. Larval development, pupation, whole cycle description and practical implications. J Appl Entomol 122:71–78

Furlan L (2014) IPM thresholds for *Agriotes* wireworm species in maize in Southern Europe. J Pest Sci 87(4):609–617

Furlan L, Contiero B, Chiarini F, Colauzzi M, Sartori E, Benvegnù I, Giandon P (2017) Risk assessment of maize damage by wireworms (Coleoptera: Elateridae) as the first step in implementing IPM and in reducing the environmental impact of soil insecticides. Environ Sci Pollut Res 24:236–251

Furlan L, Contiero B, Chiarini F, Benvegnù I, Tóth M (2020) The use of click beetle pheromone traps to optimize the risk assessment of wireworm (Coleoptera: Elateridae) maize damage. Sci Rep 10:8780

Horton DR (2006) Quantitative relationship between potato tuber damage and counts of Pacific coast wireworm (Coleoptera Elateridae) in baits: seasonal effects. J Entomol Soc Brit Columbia 103:37–48

Johal GS, Rahe JE (1984) Effect of soilborne plant-pathogenic fungi on the herbicidal action of glyphosate on bean seedlings. Phytopathol 74:950–955

Jung J, Racca P, Schmitt J, Kleinhenz B (2014) SIMAGRIO-W: Development of a prediction model for wireworms in relation to soil moisture, temperature and type. J Appl Entomol 138:183–194

Kabaluk T (2016) Wireworms: know your pest to make the best control decisions. BC Org Grower 19(3):19–21

Kabaluk JT, Young BMS, Doreau AM, Mackovic CR (2012) A simple computation-based approach for measuring the carbon dioxide production of respiring biological samples in passively ventilated chambers. Entomol Exp Appl 145(2):175–180

Kabaluk, T (2012) The probe trap: an easy-to-use trap for capturing larvae of Elateridae. Agriculture and Agri-Food Canada INV 08934.

Landl M, Furlan L, Glauninger J (2010) Seasonal fluctuations in *Agriotes* spp. (Coleoptera: Elateridae) at two sites in Austria and the efficiency of bait trap designs for monitoring wireworm populations in the soil. J Plant Dis Prot 117:268–272

Parker WE, Howard JJ (2001) The biology and management of wireworms (*Agriotes* spp.) on potato with particular reference to the UK. Agric Entomol 3:85–98

Parker WE, Seeney FM (1997) An investigation into the use of multiple site characteristics to predict the presence and infestation level of wireworms (*Agriotes* sup., Coleoptera: Elateridae) in individual grass fields. Ann Appl Biol 130(3):409–425

Poggi S, Le Cointe R, Riou JB, Larroude P, Thibord JB, Plantegenest M (2018) Relative influence of climate and agro-environmental factors on wireworm damage risk in maize crops. J Pest Sci 91:585–599

Poggi S, Le Cointe R, Lehmhus J, Plantegenest M, Furlan L (2021) Alternative strategies for controlling wireworms in field crops: A review. Agriculture 11:436

Pumpanen J, Ilvesniemi H, Hari P (2003) A process-based model for predicting soil carbon dioxide efflux and concentration. Soil Sci Soc Am J 67:402–413

R Core Team (2021) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna

Roche J, Plantegenest M, Larroudé P, Thibord JB, Le Cointe R, Poggi S (2023) A decision support system based on Bayesian modelling for pest management: application to wireworm risk assessment in maize fields. Smart Agric Technol 4:100162

Sufyan M, Neuhoff D, Furlan L (2014) Larval development of *Agriotes obscurus* under laboratory and semi-natural conditions. Bull Insectol 67(2):227–235

Veres A, Wyckhuys KAG, Kiss J, Tóth F, Burgio G, Pons X, Avilla C, Vidal S, Razinger J, Bazok R, Matyjaszczyk E, Milosavljević I, Vi LX, Zhou W, Zhu Z, Tarno H, Hadi B, Lundgren J, Bonmatin JM, van Lexmond MB, Aebi A, Rauf A, Furlan L (2020) An update of the Worldwide Integrated Assessment (WIA) on systemic pesticides. Part 4: alternatives in major cropping systems. Environ Sci Pollut Res 27:29867–29899

Vernon RS, van Herk WG (2022) Wireworms as pests of potato. In: Giordanengo P, Vincent C, Alyokhin A (eds) Insect pests of potato: global perspectives on biology and management, 2nd edn. Academic Press, Amsterdam, pp 103–164

Vernon RS, van Herk WG, Cloduis M, Harding C (2009) Wireworm management I: stand protection versus wireworm mortality with wheat seed treatments. J Econ Entomol 102(6):2126–2136

Zacharuk RY (1962) Distribution, habits, and development of *Ctenicera destructor* (Brown) in western Canada, with notes on the related species *C. aeripennis* (KBY.) (Coleoptera: Elateridae). Can J Zool 40:539–552