Wireworm management in conservation agriculture

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Abstract

Conservation Agriculture (CA), which combines three principles (1) limitation of soil disturbance, (2) its permanent cover and (3) crop diversification, is growing worldwide as a low-input system. By limiting soil disturbance, this farming system provides favourable conditions for the development of soil-dwelling organisms including insect pests. Despite potentially high wireworm densities in CA systems, economic damage to maize crop is rarely observed. In this study, we investigated the long-term influence of three tillage practices of decreasing intensity (mouldboard ploughing (MP), surface tillage (ST) and no-tillage (NT)) on wireworm density to confirm that reducing tillage intensity does increase wireworm density. In addition, we hypothesised that the presence of crop residues can limit damage caused by wireworms by diverting them from the main crop and altering their feeding behaviour. Accordingly, we examined whether covering the soil with a mulch at sowing date or leaving below-ground residues of a cover crop grown before maize sowing can limit wireworm damage on maize compared to leaving the soil bare. This study, using CA systems as a case study, improves our understanding of how cover crop management can help reducing wireworm damage for the following crop and illustrates the interest of manipulating pest feeding behaviour to design promising strategies of Integrated Pest Management (IPM).

Keywords Integrated pest management, Wireworms, *Agriotes lineatus*, Conservation Agriculture, Tillage, Cover crops

Introduction

Meeting the challenge of sustainable crop production requires in-depth analysis of agro-ecological factors that determine crop damage (Médiène et al. 2011). Conservation Agriculture (CA), which combines reduction of soil disturbance, its permanent cover and crop diversification (FAO 2019), is known to improve soil structure and hydrology and to benefit biodiversity (Kladivko 2001; Holland 2004; Power 2010; Henneron et al. 2015). Most farmers adopting CA opt for its partial implementation (Lahmar 2010; Scopel et al. 2013) and focus, at least in a first step, on tillage reduction (RT), i.e., excluding ploughing. Ploughing has a direct impact on soil organisms by mechanically injuring or killing individuals and indirectly by altering habitat quality and changing food availability and distribution (Holland 2004). In the absence of inversion tillage, soil organic matter remains in the top soil layer (Panettieri et al. 2014; Zhang et al. 2017; Peigné et al. 2018) providing “board and lodging” for soil organisms (Tebrügge and Düring 1999; Kladivko 2001; Daraghmeh et al. 2009). Several studies have evidenced the beneficial effects of reducing tillage on soil biodiversity (Bottinelli et al. 2017; Wang et al. 2017) but also on ground dwelling arthropods such as spiders (Witmer et al. 2003) or aerial natural enemies (Rusch et al. 2011; Tamburini et al. 2016; Chabert and Sarthou 2017). However, reducing soil tillage can also benefit pests, especially soil dwelling pests. For example, Glenn and Symondson (2003) concluded that tillage reduction increases slug populations in a wide range of crops.

Wireworms of the genus *Agriotes* (Coleoptera: Elateridae), the larvae of click beetles, damage a wide range of important crops including maize or potatoes, and have long been among the most notorious soil dwelling pests in Europe (Miles and Petherbridge 1927; Balachowski and Mesnil 1935; Traugott et al. 2008). Wireworms are generalist herbivores, feeding on a wide range of plants. They may also survive by feeding on soil organic matter (Traugott et al. 2008, 2015), but there is no evidence that wireworms can survive or grow on non-live vegetable tissues only (Barsics et al. 2013; Ritter and Richter 2013). In the last 15 years, damage due to wireworms have upsurged. Understanding their ecology and the factors influencing their pest potential have then become a key issue in crop protection (Furlan 2014; Poggi et al. 2018, 2021; Veres et al. 2020). The influence of the tillage regime on wireworms has been evidenced in several previous studies but there still is no consensus. Saussure et al. (2015) identified tillage as one of the most influential factors on wireworm damage to maize crop but with opposite effects between years, possibly due to different weather conditions. The timing of ploughing can also influence wireworm pest potential. Saussure et al. (2015) noticed that winter tillage has a weaker effect than spring tillage and Furlan et al. (2020) observed that wireworm damages to maize crops were reduced when meadows were ploughed just before maize sowing.

Despite potentially high infestation levels in CA systems, economic damage to maize crop is rarely observed (Furlan et al. 2021). Part of the explanation could lie in the continuous supply of fresh organic matter on which the wireworms feed (Sonnemann et al. 2012), diverting them from maize crop. The interest of crop diversification to reduce wireworm damage to maize crops have been previously evidenced. For example, Staudacher et al., 2013, showed that adding wheat or a plant mixture between rows of maize reduced wireworm damage by 38% and 55%, respectively. Previous studies also demonstrated the effect of intercropping wheat to reduce damage to maize

(Thibord et al. 2015; Le Cointe et al. 2020a). However, competition between intercrop and maize can sometimes offset the benefits.

Cover crops, which are grown during the non-crop period, and mulching, which consists in covering topsoil with a layer of material(s) (Acharya et al. 2005), are common practices in CA and are increasingly adopted for the multiple ecosystem services they provide. Indeed, cover cropping and mulching limit erosion, reduce weed development and increase soil organic matter. Moreover, mulching and cover cropping avoid the competition that occurs between intercrops and maize.

In this study, we investigated the influence of tillage on wireworm populations and the influence of mulching and cover crops on wireworm damage to maize plants. Three tillage treatments of decreasing intensity were studied: (i) mouldboard ploughing, (ii) surface tillage and (iii) no-tillage. We also tested whether covering soil with mulch at sowing date or leaving below-ground residues of a cover crop grown before maize sowing can limit wireworm damages on maize compared to leaving soil bare. We finally discuss how conservation agriculture can deal with pests by continuously covering soil with organic matter and diversifying the crop species grown in sequences (i.e. rotation) and/or in associations.

Materials and methods

Experiment 1: long-term influence of tillage on wireworm density

We evaluated the long-term influence of tillage regimes on wireworm density after an experimental period of nineteen years. The experimental site was the experimental platform of Kerguéhennec in western France (N 47°53, W 02°44). The climate is oceanic with a mean annual temperature and annual cumulative precipitation of 10.8°C and 1060 mm, respectively. The tillage system was established in 2000 in a randomized complete block design with three replicates. Each treatment plot size was 25 m × 12 m. The crop rotation was wheat-maize-wheat-rapeseed. Three tillage treatments of decreasing intensity were studied: (i) mouldboard ploughing (T1_MP, with mouldboard ploughing at a depth of 25 cm and rotary harrowing at a depth of 7 cm before sowing), (ii) surface tillage (T2_ST, with chisel ploughing at a depth of 12 cm) and (iii) no-tillage (T3_NT). Wireworm monitoring was conducted in June 2019 when plots were cultivated with maize using soil sampling/sorting. Within each plot, eight soil samples (24 replicates for each tillage treatment) of a standard volume of eight litres (a cube of $20 \times 20 \times 20$ cm^3) were collected from the top 20 cm soil layer. Collected wireworms were counted and identified to species level using molecular barcoding (Folmer et al. 1994) or multiplex PCR (Staudacher et al. 2010; Mahéo et al. 2020).

Experiment 2: mulch and cover crop to limit wireworm damage on maize

The experiment was designed to assess whether covering soil with mulch at sowing date or leaving below-ground residues of a cover crop grown before maize sowing can limit wireworm damage to maize compared to leaving soil bare. We compared the following treatments to bare soil (T1) as a control: a mulch of ramial chipped wood (RCW) (T2), a mulch of ground wheat seedlings (T3), and the below-ground residues of a wheat cover crop (T4) grown before maize sowing. The experiment was conducted in a climate chamber during two months. Environmental conditions were 16h light / 8h dark photoperiod at a temperature of 20°C (day) / 18°C (night). Soil was a 2.25mm sieved potting soil (Traysubstrat, ref: 092, white peat: 75 %, brown peat: 25 %). Soil moisture was maintained at 30% with daily tap water sub-irrigations. The experiment was conducted in polystyrene pots 9 x 9 x 7 cm filled with 250 cm^3 of soil. Pots were placed in trays and the holes in the bottom of the pots were sealed with a mesh to prevent wireworms passing from one pot to another. Wireworms used in this experiment were bred at the INRAE IGEPP (*A. lineatus* beetles collected at INRAE Le Rheu, rearing method after Le Cointe et al., 2020b).

At the beginning of the experiment, one-year-old wireworms, previously starved during 4 weeks at 25°C, were placed in pots (2 per pot) with soil. In cover crop treatment T4, wheat was sown 1 cm deep (20 seeds per pot) and grown during 28 days, while soil was left bare in other treatments. At maize sowing date, the above-ground parts of the wheat seedlings were cut below the collar, removed and the soil surface was gently scraped on the first millimetres. In T1, the soil was left bare, in T2, the soil was covered with RCW mulch, and in T3, the soil was covered with the above-ground parts of wheat seedlings removed from T4 and ground previous to application. RCW mulch included only hardwood species coming from green areas and was dried in an oven for two days at 70°C before experiment to defaunate.

Then, one maize seed (commercial hybrid "MILLESIM") was sown in the centre of each pot, 2 cm deep in each treatment. After 28 days, maize seedlings were removed, carefully rinsed in water, and the presence and the type of symptoms recorded. Two types of symptoms were considered, perforated seeds without seedling emergence and seedling emergence with damage on root and crown.

Each treatment was replicated 16 times and the entire experiment was repeated twice (32 replicates).

Statistical analyses

All statistical analyses were performed using the software R (R Core Team2022). We used generalized linear mixed models (function 'glmer' of the 'lme4' package; Bates et al. 2015) with a distribution appropriate to the response variable analysed: Poisson (link: log) for count data (response variable: wireworm abundance in experiment 1), and binomial (link: logit) for binary data (response variable: number of maize seedlings damaged in experiment 2). In experiment 1, tillage treatment was included as a fixed effect and block as a random factor. In experiment 2, soil cover / cover crop treatments were included as fixed effects and repetition as a random factor. The significance of the fixed effects was tested using type II Wald chi-square tests (function 'Anova', package 'car'; Fox and Weisberg 2019). Finally, pairwise comparisons of the estimated marginal means between tillage treatments for wireworm abundance in experiment 1, and between treatments in experiment 2 were tested using the Tukey method ('emmeans' function from the 'emmeans' package; Lenth 2022).

Results

Experiment 1: long-term influence of tillage regime on wireworm density

We collected 205 larvae in 72 soil samplings (i.e., an average of 2.84 wireworms per soil sampling). All larvae belonged to the genus *Agriotes.* The predominant species was *A. lineatus* (190 larvae, i.e., 92%). We also found 15 larvae of *A. sputator* (8%). Figure 1 shows the distribution of the number of wireworms counted in the soil samples according to the tillage treatment. We found a maximum of 13 wireworms in one soil sampling from a total number of 99 *Agriotes* larvae in the no-tillage treatment (T3_NT). In the surface tillage treatment (T2_ST), we found a maximum of 12 wireworms in one soil sampling from a total number of 80 *Agriotes* larvae. In contrast, in the mouldboard ploughing treatment (T1_MP), only 26 wireworms in total with a maximum of 6 wireworms in one soil sampling was found. The average number of wireworms in the mouldboard ploughing treatment (T1_MP) (lsmeans = 0.94) was significantly lower compared to reduced tillage treatments (χ^2 = 37.25, df = 2, P =0.0001). The average number of wireworms in the no-tillage treatment (T3_NT) (lsmeans = 3.57) was higher compared to the surface tillage treatment (T2_ST) (lsmeans = 2.89) but the difference was not significant (χ^2 = 2.02, df = 1, P =0.15).

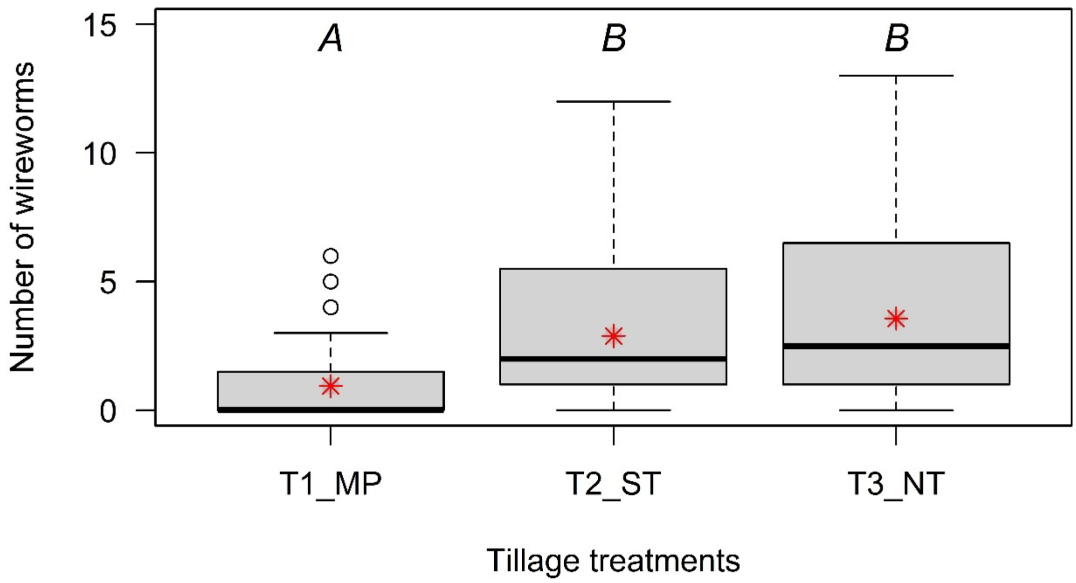

Fig.1. Wireworm density in soil sampling according to tillage intensity: mouldboard ploughing (T1_MP), surface tillage (T2_ST), no-tillage (T3_NT). Treatments with different letters differ significantly (P-value<0.05, LSMeans). Red asterisks indicate the average number of wireworms found in soil samples (8 replicates per tillage treatment).

Experiment 2: mulch and cover crop to limit wireworm damage on maize

Wireworm damage differed significantly between treatments (Figure 2) both in terms of damage incidence (total incidence ANOVA: $\chi^2 = 11.52$, df = 3, P =0.009) and damage severity (perforated seeds incidence ANOVA: $\chi^2 = 10.93$, df = 3, P =0.01). After two months without food source, *Agriotes lineatus* wireworms caused damage at a high rate in the absence of a soil cover. As shown in Figure 2, 68 ± 8% of the maize seedlings were damaged when the soil was left bare at maize sowing (T1). The severity of damage also reached a high level, as in 35 ± 8% of the replicates no plant emerged at all (n=31). When soil was covered with RMC mulch (T2) and wheat mulch (T3), the total incidence decreased to 53 ± 8 % and to 56 ± 8 %, respectively, but differences to bare soil treatments were not significant ($\chi^2 = 1.51$, df = 2, P =0.56). Soil cover at sowing date also limited damage severity, with 21 ± 7 % of the replicates showing perforated seeds without plant emergence in RMC mulch treatment (T2). Nevertheless, the difference to the bare soil treatment was not significant ($\chi^2 = 3.13$, df = 1, P =0.07). In contrast, when soil was covered with a mulch of ground wheat seedlings (T3), damage severity decreased to 6 ± 4 % and differed significantly to the bare soil treatment (χ^2 = 6.60, df = 1, P =0.01). Finally, when wireworms were added to soils with wheat roots from the cover crop as a food source before maize sowing (T4), both total incidence (25 ± 7 %) and perforated seed incidence (6 ± 4 %) decreased significantly compared to the bare soil treatment.

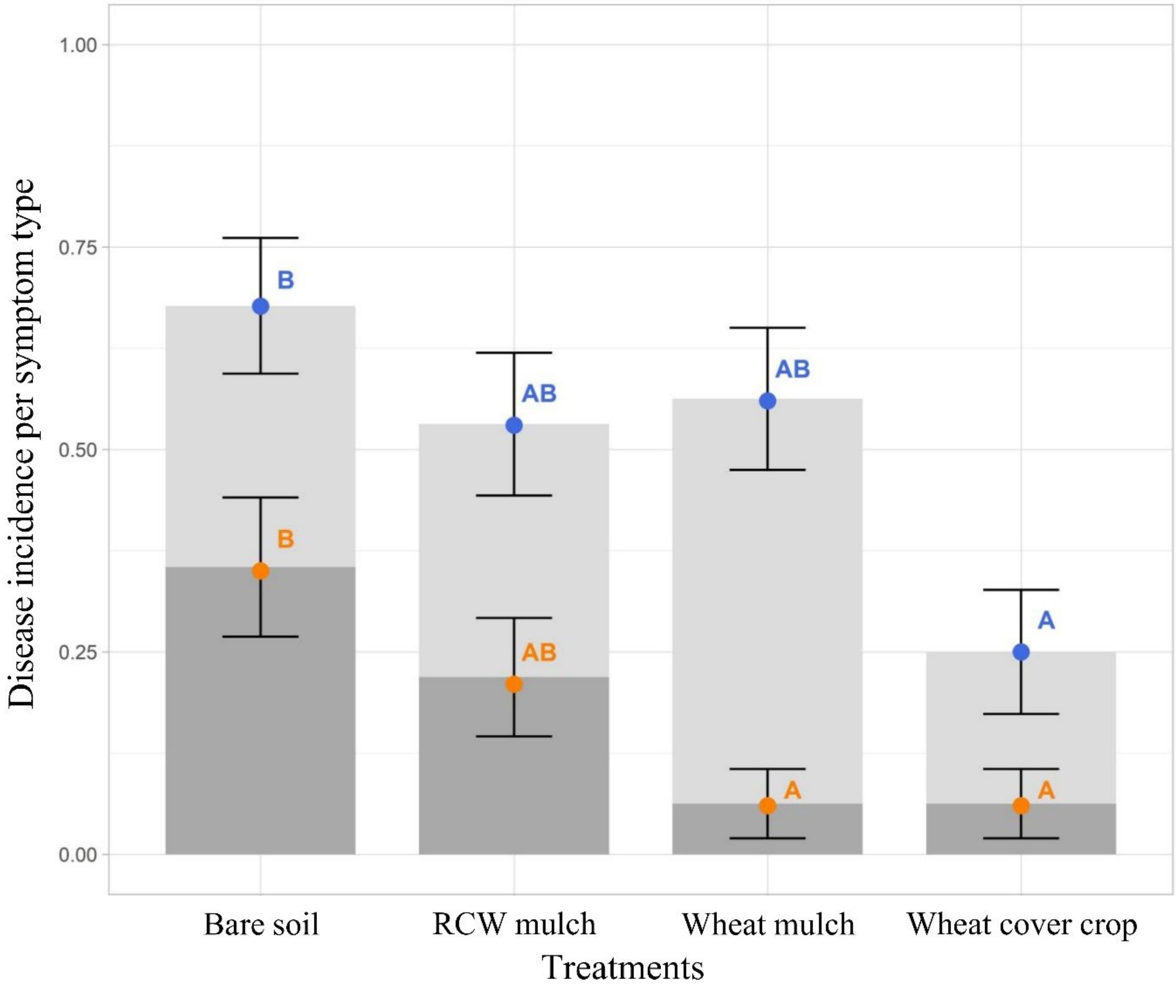

Fig.2. Influence of soil cover and cover crop on wireworm damage to maize plants. Bars show the mean cumulated incidence 4 weeks after sowing of perforated seeds without seedling emergence (dark grey with orange points), and of seedling emergence with damage on root and crown (light grey with blue points). Different letters indicate significant differences between treatment (P-value<0.05, LSMeans).

Discussion

Conservation Agriculture (CA), based on reduced soil disturbance, permanent soil cover and crop diversification is a promising way to improve soil quality (Craheix et al. 2016), like organic farming (Henneron et al. 2015). In this study, we investigated the influence of reducing tillage (i.e., no inversion tillage) on wireworm density, and the influence of soil cover on their damage to maize. In accordance with previous studies (Le Cointe et al. 2020a; Furlan et al. 2021), our results suggest that the implementation of conservation agriculture does not necessarily lead to an increase of wireworm damage to maize crops.

Influence of tillage on wireworm abundance in a long-term experiment.

In line with previous studies, which hypothesize that reducing tillage could improve soil habitat suitability for soil dwelling organisms (Parker and Howard 2001; Traugott et al. 2015; Saussure et al. 2015; Crotty et al. 2016), we confirmed that reducing tillage results in an increase in wireworm populations. For example, Seal et al., (1997), demonstrated that an intensive ploughing in summer reduced wireworm populations (genus: *Conoderus*), while no change was observed in unploughed plots. This decrease in the wireworm population was ascribed to bird predation and desiccation of the larvae.

Contrary to Furlan et al. (2021), who did not find any differences between tillage treatments neither on wireworm populations nor on damage, our results showed that reducing tillage entailed an increase in wireworm abundance. This may be due to the sampling methods. In our study, we used soil samplings / sorting while Furlan et al. (2021) used bait traps which catch only the active part of the wireworm population (i.e., wireworms in a feeding phase). It is possible that the proportion of wireworms in a feeding phase is lower in no-till systems, due to the continuous supply of fresh organic matter. Another explanation refers to the sampling period. Furlan et al. (2021) carried out their sampling between late February and mid-April (i.e., before seed bed preparation) while our sampling took place in June, i.e., after soil layers inversion in ploughed plots, which may have redistributed wireworms into deeper soil layers. Tillage timing has been demonstrated to be an important factor to reduce damage. Furlan et al. (2020) demonstrated that damage in plots ploughed just before maize sowing was much lower than the damage in plots ploughed in autumn-winter. The effect of tillage timing may vary depending on wireworm species present, and notably on their life-cycle (overwintering species versus non-overwintering species). It is probably higher when it corresponds to sensitive stages, i.e., eggs and first larval instars. It should be noticed that the main species was *A. sordidus* in Furlan et al., (2021) while it was *A. lineatus* in our study.

It is currently hypothesised that wireworm oviposition is reduced in the absence of a soil cover (Evans and Gough 1942; Parker and Howard 2001). Our results confirm this hypothesis, as the highest numbers of wireworms were found in the no-tillage plots (where soil is permanently covered) compared to surface tillage, where periods with bare soil are similar to ploughed plots. Finally, our results showed a clear difference between ploughing (i.e. inversion tillage) and both surface tillage and no-tillage (see Fig.1). This result is in accordance with the findings of Hooibeekhoeve (Belgium) in a long-term experiment (Wechselberger et al. 2019). During their monitoring, most wireworms were found in plots with no-inversion tillage while few were found in plots ploughed with mouldboard and a spading machine. Similar to the conclusions from our study, they consider ploughing as the most effective soil cultivation method to reduce wireworm populations.

Influence of soil cover on wireworm damage to maize plants

Reducing tillage is usually the first step on the path to conservation agriculture. Permanent soil covers, notably through the use of mulch or cover crops, have been shown to be of utmost importance on the provision of ecosystem services (Lahmar 2010; Scopel et al. 2013). However, the potential contribution of soil cover with organic mulch to integrated pest management has not yet been evaluated. Our experiment conducted under controlled conditions suggests that covering soil with mulch at sowing date can limit wireworm damage to maize compared to bare soil. In the absence of a soil cover and after two months without food source, *Agriotes lineatus* wireworms caused damage in a high proportion (68% of replicates with damage) and with great severity (35% of seeds with severe attacks preventing plant emergence). There is growing interest in soil amendment with exogenous organic matter and especially with Ramial Chipped Wood (RCW). Previous studies have highlighted the potential benefits of using this type of amendment to promote soil diversity and consequent bioregulation (Leclercq-Dransart et al. 2020) but studies on the effect of RCW on soil dwelling pests are rare. Our results show that covering soil with RCW mulch resulted in a moderate and non-significant reduction in damage, both in terms of total incidence (53 % of replicates with damage) and of severity (21 % of seeds with severe attacks preventing plant emergence). This result is nevertheless encouraging and it would be interesting to test whether covering the soil well before sowing of maize could increase this effect, as wireworms may be more prone to use decomposed RCW as a food source.

Other types of mulching have been shown beneficial to pest control. For instance, Brust (1994) evidenced a reduction of foliage destruction by the Colorado potato beetle in potato plots covered with wheat straw mulch, associated with higher populations of natural enemies, resulting in increased yield. In our study, we also showed that covering the soil with a mulch of ground wheat seedlings weakly and non-significantly reduced the total incidence of damage (56 % of replicates with damage), but resulted in a strong and significant reduction in damage severity (only 6 % of seeds with severe attacks preventing plant emergence).

In conservation agriculture systems, cover crops are widely used and provide multiple agroecosystem services. They are mainly used to increase soil fertility, limit erosion and suppress weed. Our experiment gives evidence that careful management of cover crops can reduce wireworm damage to the following crop. The presence of wheat roots in the cover crop treatment (T4), which were probably used as a food source by wireworms, resulted in a significant reduction in the incidence (25 % of replicates with damage) and severity of damage (only 6 % of seeds with severe attacks preventing plant emergence) caused to maize compared to bare soil. Pellegrino et al. (2021) showed that cover crops did not increase wireworm damage in organic sweet potato (*Ipomoea batatus* L.). Reinbacher et al. (2021) showed that preventive application of an entomopathogens fungus (EPF) in winter cover crops increased the abundance of EPF in the soil for the subsequent cropping season and that the concentrations reached by EPF were high enough to reduce wireworm survival. However, the reduction in wireworm damage was not sufficient to be profitable in potatoes, a crop particularly susceptible to wireworm damages.

Conclusion

The current upsurge in damage caused by wireworms to many crops requires the development of new agro-ecological methods to control these pests (Veres et al. 2020). We showed that feeding fresh organic matter to the wireworms may divert them from maize seedlings for a certain period, which may be long enough for the seedlings to develop tolerance to wireworm attacks (i.e., the 8-leaf stage). Hence, the manipulation of pest feeding behaviour using companion plants and incorporating cover crops to soil just before sowing (Furlan et al. 2020) appears a promising approach within the conceptual framework of Integrated Pest Management (IPM), taking into account the specific nature of each pest species and the damage thresholds of each crop.

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Conflicts of Interest: The authors declare no conflict of interest.

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