Crop Protection 149 (2021) 105751

Contents lists available at ScienceDirect

Crop Protection

journal homepage: www.elsevier.com/locate/cropro

Effects of conventional versus no-tillage systems on the population dynamics of elaterid pests and the associated damage at establishment of maize crops

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ARTICLE INFO

Keywords:
Wireworms
Agriotes
Agriotes sordidus
Agriotes brevis
Agriotes ustulatus
Agriotes litigiosus
Conservation agriculture

ABSTRACT

No-till agriculture, combined with the practices of continuous soil cover by retaining crop residues and of crop rotation, including cover crops, represents a relatively widely adopted management system that aims to increase soil organic matter content as well as long-term sustainability. However, its impacts on wireworm populations in the soil and risk of damage to crops are uncertain, and current recommendations may unjustifiably limit grower options. Consequently, this study examined the effects of no-tillage soil management on the population dynamics of *Agriotes* wireworm pests (Coleoptera: Elateridae) by bait sampling, maize plant damage assessments, and pheromone trapping (adults) within three farms in northeastern Italy, from 2011 through 2016, as compared to conventional tillage. The four-year cropping rotation consisted of winter wheat (*Triticum aestivum*), oilseed rape (*Brassica napus*), maize (*Zea mays*), and soybean (*Glycine max*) under both tillage treatments. The nature and intensity of damage caused by wireworms to maize early stages was assessed each year. Wireworms and beetles comprised of four different species (*A. brevis*, *A. sordidus*, *A. ustulatus*, and *A. litigiosus*) were captured, with the numerically dominant species (*A. sordidus*) accounting for over 90% of all captures. All species responded similarly to tillage practices. No effects of tillage operations were associated with beetle captures ($P > 0.28$) and larval densities ($P > 0.45$). No differences were observed between tillage treatments in wireworm feeding maize damage scores ($P > 0.17$; means for no-till and conventional tillage maize were 3.82 and 4.14 percent damage, respectively). These results suggest that switching from a conventional tillage system to a no-till maize production may not cause an increase of wireworm damage to maize, even though no-till conditions have been historically associated with increased wireworm damage risk. Possible causes of these results are discussed.

1. Introduction

Conservation tillage practices of reduced to no soil disturbance, combined with the practices of continuous soil cover by retaining crop residues and of crop rotation, including cover crops, represent the cornerstone of a conservation agriculture that is spreading globally (FAO, 2019). Reduction of tillage intensity decreases input costs (Derpsch et al., 2014; Toliver et al., 2012); leaving surface residue cover controls soil erosion (Palm et al., 2014), improves organic matter content in turn improves soil quality (Schwilch et al., 2018), and in some instances, increases crop yields and net farm income (Pittelkow et al., 2015a,b). While there are many advantages of reduced and no-till (NT) crop production systems over conventional tillage (CONV) ones (e.g., ploughing followed by harrowing and hoeing, without residue retention), one potential disadvantage is the greater risk of wireworm injury to crops from soil (Salt and Hollick, 1949; Saussure et al., 2015; Poggi et al., 2018).

Wireworms are the subterraneous larvae of elaterid beetles that damage maize and other field crops by feeding belowground on seeds, roots, and stems (Furlan and Kreutzweiser, 2015; Milosavljević et al., 2019; Furlan et al., 2020a); they cause significant damage to maize and corn crops globally yet with different risk levels (Veres et al., 2020). When wireworm densities are high enough, damage can reach extreme levels, including the loss of entire fields (Furlan, 2014; Saussure et al., 2015). Crops susceptible to injury by wireworms in the northern regions of Italy (regions of the Po Plain and Venetian Friulan Plain) have an

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https://doi.org/10.1016/j.cropro.2021.105751
Received 11 February 2021; Received in revised form 28 June 2021; Accepted 29 June 2021

estimated annual value to the regional economy exceeding €3.5 billion, including €1.3 billion of maize (FAOSTAT, 2018). As wireworms persist multiple years in the soil (Furlan, 2005), they span several crops in a rotation, threatening the susceptible ones depending on the presence of risk factors (Furlan et al., 2017a,b; Poggi et al., 2018). This makes wireworm populations difficult to eradicate from infested fields.

The most destructive wireworm pests of maize in northern Italy and many parts of southern Europe belong to the *Agriotes* genus, and *A. brevis* Candeze, *A. sordidus* Illiger, and *A. ustulatus* Schaller are the most common species in maize fields (Furlan, 2014; Furlan et al., 2017a,b). They spend from two to three years in the soil passing through both larval and pupal stages before reaching adulthood (Furlan, 1998, 2004). These species are divided into two groups, based on their lifestyles: i) *Agriotes* species overwintering as adults (e.g. *A. sordidus* and *A. brevis* [Furlan, 2004]), and ii) *Agriotes* species not overwintering as adults (e.g. *A. ustulatus* [Furlan, 1998],). The alate adults of these species are active outside of the soil and can live for about several months in species overwintering as adults (i.e., *A. sordidus* and *A. brevis*), and only for a few days in species not-overwintering as adults (i.e., *A. ustulatus*) (Furlan, 1998, 2004).

Currently, maize production is damaging to soil and heavily dependent on pesticides applications and extensive tillage to avoid economic loss from wireworms (Veres et al., 2020). Conventional treatments for wireworms in maize consist of seed treatments with neonicotinoid insecticides at sowing to protect seeds and seedlings (Furlan and Kreutzweiser, 2015). They are easily applied and provide immediate yet temporary seed and seedling protection from wireworms (Milosavljević et al., 2019). The addition of alternative management strategies would reduce the frequency of neonicotinoid applications necessary to attain adequate control.

CONV tillage has historically been considered a mortality factor for wireworms (Barsics et al., 2013); however, it is only effective when larvae are active in the upper layers of the soil surface, within the depth of tillage (Jansson and Lecrone, 1991; Seal et al., 1992). Mortality is caused by direct mechanical injury, or exposure to soil surface and predation (Furlan, 1996, 1998, 2004). Consequently, it can be assumed that wireworms will become more abundant when plowing is reduced or eliminated. Nevertheless, this has not been the general trend for reasons that are not well understood. Increased wireworm infestations have been associated with the presence of surface residues and/or cover crops that serve as host plants (Jansson and Lecrone, 1991). Several wireworm species are favored with the higher moisture, cooler temperatures, and generally higher content of organic matter in the soils under reduced and no till systems compared to CONV (Seal et al., 1992).

Reduced and no tillage practices, along with diversified crop rotations, and cover crops, can however change the dynamics of wireworm populations in the soil by modifying their habitats (Esser et al., 2015) or by changing the number of available food options to wireworms (Le Cointe et al., 2020). This can result in wireworm pest status changing or staying the same over time, resulting in more damage to crops (Saussure et al., 2015), less damage (Esser et al., 2015), or no effects on damage to crops (Milosavljević et al., 2016, 2017; Furlan et al., 2017a; Cherry and Sandhu, 2020). The direction and magnitude of change can, however, vary depending on the crops and wireworm species, geographical locations, and management practices (Barsics et al., 2013). Therefore, each wireworm-crop situation is different and should be considered separately.

The effects of no till farming practices on wireworm pests in maize fields are inconclusive, and current recommendations may unjustifiably limit grower options. Consequently, this study assessed the effects of NT practices combined with summer-fall cover crops on the dynamics of populations of *Agriotes* wireworms (*A. brevis*, *A. sordidus*, *A. ustulatus*, and *A. litigiosus* Rossi) attacking maize during early growth stages in northeastern Italy (Furlan, 1996, 2004, 2014; Furlan et al., 2017a,b; Furlan et al., 2020a,b) and the extent of damage caused by feeding wireworms to seeds and seedlings of maize as an important susceptible crop in the rotations, as compared to CONV practices without cover crops. Attaining uniform maize stands is more important because it does not compensate as well as many other crops when there are gaps in the row (Lamichhane et al., 2018, 2020a). The four-year cropping rotation consisted of winter wheat (*Triticum aestivum* L.), oilseed rape (*Brassica napus* L.), maize (*Zea mays* L.), and soybean (*Glycine max* [L.] Merr.) under both tillage regimes.

2. Materials and methods

2.1. Field sites and growing practices

The study was conducted from 2011 to 2016 at three Veneto Agricoltura's research farms in the Veneto Region of Italy: 1) Vallevecchia (12.95 Y°, 45.628 X°, 45° 37′ 39.807″ N, 12° 57′ 0.36″ E), 2) Diana (12.315 Y°, 45.576 X°, 45° 34′ 33.486″ N, 12° 18′ 54.787″ E), and 3) Sasse Rami (11.87 Y°, 45.055 X°, 45° 3′ 17.925″ N, 11° 52′ 11.551″ E). Each farm received both the NT and CONV practice types of soil management on two adjacent or closely located fields (1–1.5 ha in size), and with similar soil conditions (VV.AA, 2019). The Vallevecchia farm site had silty soil (34% sand, 43% silt, 23% clay) with 1.7 percent of soil organic matter (SOM) at the start of the trial; the Diana farm site had silt loam soil (8% sand, 66% silt, 26% clay) with 1.5 percent of SOM at the beginning of the trial; and the Sasse Rami farm site had silt loam soil (18% sand, 58% silt, 24% clay) with 1.4 percent of SOM at the start of the trial. The NT treatments consisted of a combination of crops seeded into standing stubble with low disturbance discs and in some instances decompaction techniques, combined with summer-fall cover crops. The CONV treatments consisted of ploughing followed by harrowing and hoeing, and without residue retention and cover crops. Each field was subjected to the same crop rotation scheme: wheat (*T. aestivum*) - oilseed rape (*B. napus*) - maize (*Z. mays*) - soybean (*G. max*), with non-coinciding starting dates. This system enabled us to have all four crops at the same time on each farm, each year. This system further enabled us to collect both pest abundance and plant injury measurements (see data collection sections below for more details) from three NT maize fields (i.e., Diana, Sasse Rami, and Vallevecchia: replicates) and three CONV maize fields (Diana, Sasse Rami, and Vallevecchia: replicates) in each year of the study. After the first few years, the four-year rotations were changed to three-year rotations without the oilseed rape, because of the difficulties with sod seeding, in achieving sufficient emergence density, with inevitable poor yield performance. In order to achieve good germination and the subsequent adequate plant density, the small size of rape seeds requires careful seed bed preparation to guarantee a uniform and superficial depth of seeding, difficult to obtain with no-tillage, which in most cases has an irregular surface.

In the NT plots, permanent soil cover was maintained by the fall cover crops (barley [*Hordeum vulgare* L.] + vetch [*Vicia sativa* L.]/ barley/wheat) and the summer cover crops (sorghum, *Sorghum vulgare* Pers. var. *sudanense*) planted after and before the main crops. In all locations, the soil was cultivated according to the same cultivation protocol, which involved the use of the same fertilizers and the same varieties for each crop grown in a rotation, with a higher seeding density in NT plots compared to CONV plots (for maize: 8.5 (9.0 in 2016) seeds/m^2 [NT] vs. 7.5 seeds/m^2 [CONV]; for soybean: 48 seeds/m^2 [NT]vs. 44 seeds/m^2 [CONV]; and for wheat: 500 seeds/m^2 [NT] vs. 450 seeds/m^2 [CONV]). Fungicide treatments were applied to all maize seeds based on typical farming practices in this region (VV.AA, 2019), and included 1 l/t seed Celest® XL (Metalaxil-m + Fludioxonil) (Lamichhane et al., 2020b). The commercial maize hybrid Korimbos was used at all locations. Other agronomic information and practices implemented at monitored fields over the eight years of observation are described in VV. AA (2019).

2.2. Assessment of wireworm population

Wireworm populations were monitored in all plots once per year, in periods from late February until mid-April, using soil bait traps described by Chabert and Blot (1992) and following the methods described by Furlan (2014). There was one trapping grid per site, each having twelve bait traps placed approximately 20 m × 10 m apart. Each trap was comprised of a plastic pot 10 cm in diameter with holes in the bottom. The pots were filled with vermiculite, 30 ml of wheat seeds and 30 ml of maize seeds; they were then moistened before being placed into the soil 4–5 cm below the soil surface, after which they were covered with an 18-cm diameter plastic lid placed 1–2 cm above the pot rim. All traps were retrieved after 10 days and transported to the laboratory where they were assessed for wireworms by hand while the remaining contents were put into Berlese funnels fitted with a 0.5-cm mesh screen at the bottom (Furlan, 2014). The trap contents were allowed to dry out for at least 20 days in a sheltered place without lamps, and the larvae that fell into the collecting vials were counted and identified. Collected larvae were identified to species based on morphological characteristics (Furlan et al., 2021a), and the number of larvae per trap was recorded for each elaterid species.

2.3. Beetle monitoring

Beetle populations were monitored in all plots with the YATLORf (Yf) sex pheromone traps produced by Italy's ROSA Micro. Commercially available sex pheromone lures (CSALOMON®; Plant Protection Institute Centre for Agricultural Research, Budapest, Hungary) were used in all traps. The lures were produced by the Plant Protection Institute Centre for Agricultural Research, Budapest, Hungary. Compositions of single lures comprised *A. brevis* geranyl butanoate + (*E,E*)-farnesyl butanoate 1:1 (15 + 15 mg; Tóth et al., 2002b); *A. sordidus* Illiger geranyl hexanoate 30 mg (Tóth et al., 2002a); *A. litigiosus* geranyl isovalerate 50 mg; and *A. ustulatus* (*E,E*)-farnesyl acetate 50 mg (Tóth et al., 2003). The traps were positioned at least 200 m from each other to prevent them interfering with one another (Furlan et al., 2020a). During monthly trap servicing, pheromone lures were replaced in all traps. The baits were serviced seasonally according to the life cycle and behaviour of each target species, as described below. On 10 March, the traps were baited with the sexual pheromone for *A. brevis* in the lower position and placed with their top side facing down. On 10 April, the captured insects were collected, and the trap was baited with the pheromone for *A. sordidus* in the middle position and placed with its top side facing down. On every inspection, all traps were cleaned-up, and the excess soil and other residuals were removed. Around 10 May, the captured insects were removed and the pheromone bait for *A. sordidus* (at approx. 30 days) was swapped for a new one, again in the middle position, and the trap placed with its top side facing down. Around 10 June, the captured insects were collected and the bait for *A. brevis* in the bottom position was removed; *A. ustulatus* lure was placed in the top position. Around 10 July, the captured insects were removed and the bait for *A. ustulatus* was swapped for a new one in the same position. On 10 August, all captured beetles and other insects were collected, and the trap was removed.

On every inspection date, all traps were retrieved from the soil, emptied into respective plastic bags, and re-deployed in the field immediately. Bags were labelled, put on ice in portable coolers, and transported to the laboratory where they were assessed for beetles by hand. Prior to the assessment, samples were kept stored in the walk-in refrigerator at 5–8 °C. Collected beetles were identified to species based on morphological characteristics (Platia, 1994) and the number of captured beetles per trap was recorded for each elaterid species.

2.4. Estimating wireworm damage to maize crop

The extent of and patterns in crop damage by wireworms was assessed on emerged plants in all experimental plots. At the 2nd and 3rd and 6th through 8th leaf stages of the maize, 2 sub-plots of 20 m × 4 rows of maize plants per portion of untreated field (0.1–0.2 ha) were randomly inspected visually for signs of wireworm damage. Assessment took place by counting the number of healthy and attacked plants. The number of plants with typical symptoms of wireworm damage (i.e., wilting of central leaves, broken central leaf due to holes in the collar, wilting of whole small plants [Furlan, 2014; Saussure et al., 2015; Furlan et al., 2017a]) was recorded. Additionally, soil within 10 cm diameter around affected or missing plants (at least 50 per field at random) was excavated up to a depth of 5–10 cm in search of larvae in or near these plants and to assess other causes of missing seed/plant. Larval specimens were collected with a forceps and preserved in 70% ethanol. Collected larvae were identified to species, based on morphological characteristics (Furlan et al., 2021a). The total wireworm damage was calculated as the sum of damaged emerged plants and damaged seeds/seedlings; the percentage of total sown seeds missing due to wireworm attacks from seeding to eight leaves was calculated.

Therefore, as in Lamichhane (2021), the rate of seedling emergence was determined by using the following formula:

$$Healthy\ plant\ density\ (\%) = 100X\frac{TES}{SD}$$

Where TES is the total number of emerged healthy seedlings and SD is the sowing density.

The damage rate due the different biotic and abiotic factors was calculated using the following formula:

$$Damage(\%) = 100X\frac{TDS}{TES}$$

Where TDS is the number of damaged seeds/seedlings and SD the sowing density.

The results from 2013 were excluded from analysis because the extreme climatic conditions (unusual, prolonged heavy rain) made impossible a reliable comparison between the tillage systems.

2.5. Statistical methods

All statistical analyses were performed using IBM SPSS Statistics, version 22.0.0 (IBM Corp., Armonk, New York). Count data of adults (expressed as integers) and larvae/trap were analyzed using a generalized linear model with a negative binomial and Poisson distribution, respectively. The linear model included the fixed effects of tillage systems (NT and CONV), locations (Diana, Sasse Rami, and Vallevecchia), and years. Least square means and standard error were estimated. Post-hoc pairwise comparisons among levels were performed using Bonferroni correction. The same statistical approach was used to assess whether the densities of total and *A. sordidus* larvae differed between NT and CONV systems in periods of 2011–2013 and 2014–2016. ANOVA was performed on plant density and wireworm damage for years 2011–2016.

3. Results

3.1. Assessment of wireworm populations

The captures of total wireworms (with totals of 0.325 larvae/bait for NT and 0.438 larvae/bait for CONV; Table 1) and each individual species (Table 1) in bait traps did not differ between the NT and CONV managements. Wireworm captures did not differ between years and study farms either (Table 1).

Even though the observed wireworm densities did not differ between single years of monitoring (Table 1), a general diminishing trend was found by comparing the mean values of total larval captures in two subsequent 3-yr periods (Table 2). Within both 3-yr periods, there was no significant difference detected between NT and CONV treatments for

Table 1

Lest square means and standard error (SE) of number of total *Agriotes* larvae/bait in the spring season and of the single *Agriotes* species (*A. sordidus*, *A. brevis*, *A. ustulatus*, *A. litigiosus*) in three farms, during six years of monitoring (2011–2016). W: Wald-chi-square.

Factors	Levels	Total larvae		*A. sordidus* larvae		*A. brevis* larvae		*A. ustulatus* larvae	
		mean	SE	mean	SE	mean	SE	Mean	SE
Conduction	NT	0.325	0.105	0.301	0.102	0.0002	0.0003	5.6E-10	1.2E-04
	CONV	0.438	0.125	0.360	0.113	0.0003	0.0005	1.5E-09	3.3E-04
	W	0.57		0.17		0.16		0.2	
	P	0.449		0.677		0.685		0.654	
Farm	DIANA	0.559	0.171	0.442	0.152	0.0019	0.0017	6.0E-06	8.2E-01
	SASSERAMI	0.303	0.112	0.270	0.106	0.0001	0.0002	3.3E-17	1.8E-11
	VALLEVECCHIA	0.318	0.136	0.299	0.133	0.0001	0.0003	4.0E-06	5.4E-01
	W	2.14		1.05		3.93		0.96	
	P	0.343		0.592		0.14		0.62	
Year	2011	0.497	0.189	0.423	0.175	0.030	0.050	1.6E-06	2.8E-01
	2012	0.586	0.247	0.569	0.244	0.008	0.022	4.5E-17	3.7E-11
	2013	0.566	0.235	0.428	0.206	0.011	0.024	1.5E-05	2.6E+00
	2014	0.475	0.276	0.419	0.262	0.022	0.046	3.4E-06	5.9E-01
	2015	0.219	0.143	0.167	0.127	0.008	0.019	4.3E-06	7.3E-01
	2016	0.170	0.126	0.177	0.131	0.000	0.000	3.9E-17	6.7E-12
	W	4.61		3.81		1.85		1.34	
	P	0.465		0.577		0.87		0.931	
	N	60		60		60		60	

Table 2

Least squares means and standard error (SE) of number of total *Agriotes* larvae and of *A. sordidus* per bait, in the spring season, comparing NT vs. CONV within two subsequent three-year periods (2011–2013 and 2014–2016), in three farms.

Period	Levels	No. Total larvae/bait		No. *A. sordidus* larvae/bait	
		mean	SE	mean	SE
2011–2013	NT	0.468	0.196	0.438	0.162
	CONV	0.632	0.167	0.496	0.173
	W	0.42		0.06	
	P	0.515		0.807	
	N	34		34	
2014–2016	NT	0.199	0.128	0.17	0.117
	CONV	0.266	0.153	0.233	0.143
	W	0.15		0.16	
	P	0.698		0.693	
	N	26		26	

the number of total larvae and individual wireworm species, of whom *A. sordidus* was the most abundant (Table 2, Fig. 1).

3.2. Beetle monitoring

Similar to wireworms, beetle captures in pheromone traps did not differ between the NT and CONV managements (Table 3). Trap captures of *A. sordidus* adults differed between years, with a significant decrease being observed in trap counts of this species from 2015 to 2016; among farms, Diana significantly differed from the other two locations, for three out of four species, with a prevalence of *A. brevis* and *A. ustulatus*, while *A. litigiosus* being scarce.

3.3. Wireworm plant damage

The observed plant damage caused by wireworms to maize did not differ significantly between the NT and CONV treatments (Table 4) over a six-year study period (2011–2016). Notably, all the larvae (n = 44) morphologically identified from damaged plants during crop assessments were *A. sordidus*. The seed/plant damage caused by other animals (mainly birds) was negligible.

Failing of seed germination and abiotic factors caused most of the missing plants in both the NT and CONV treatments (Table 4). The main abiotic cause of missing plants observed in NT system was the opening of the sowing furrow due to soil drying up after sowing that caused seeds/seedlings to desiccate before emergence. In CONV system (and present also in the NT treatments) the formation of crust, mainly in farms with silt-clay soils, prevented the emergence of maize seedlings.

4. Discussion

Multiple studies have shown how conservation tillage affects wireworms in the soil without consensus on the subject (Esser et al., 2015; Saussure et al., 2015; Crotty et al., 2016; Milosavljević et al., 2016, 2017; Furlan et al., 2017a, 2020a; Poggi et al., 2018; Cherry and Sandhu, 2020; Le Cointe et al., 2020). Our results support the hypothesis that NT can be used in maize crops without causing increased wireworm damage. In general, larval populations estimated using bait traps were low under both systems in this study, and well below the damage thresholds for the key *Agriotes* species in the considered region (i.e., one, two, and five larvae per bait trap for *A. brevis*, *A. sordidus*, and *A. ustulatus*, respectively [Furlan, 2014]). Adult beetle captures in pheromone traps were also not particularly high and did not exceed damage risk levels of 210, 1100 and 1000 beetles/trap per season for *A. brevis* (year −1), *A. sordidus* (year 1), and *A. ustulatus* (year 2) respectively (Furlan et al., 2020a). Consequently, wireworm injury ratings were found to be low and did not impact negatively on maize investment both in the plots under NT and in those under CONV systems. This indicates that any supposed increase in wireworm injury to maize grown under NT, and CA systems in general (Saussure et al., 2015; Le Cointe et al., 2020), did not occur in this study.

All species, including the dominant (i.e., *A. sordidus* which comprised over 80% of all wireworms collected), responded similarly to tillage regimes (thus minimizing the confounding influence of *A. sordidus* on the overall patterns). In turn, damage levels from *A. sordidus* resulted as being low and maize crops have not suffered from any reductions due to these factors. These observations confirm previous findings from northeastern Italy (e.g., Furlan, 2014; Furlan et al., 2017a) although others have reported increases in wireworm densities in reduced tillage systems in France (Saussure et al., 2015; Le Cointe et al., 2020). However, the distribution and diversity of *Agriotes* species varies considerably across locations with different environmental conditions (Staudacher et al., 2011, 2013; Burgio et al., 2012; Sufyan et al., 2014; Furlan et al., 2017a,b) and not all *Agriotes* species are equally damaging (Furlan, 1996, 1998, 2004, 2014).

The risk of damage to maize from wireworms turned out to be low both in the plots under NT (i.e., <4%) and in those under CONV (i.e., <5%) systems. In line with these findings, twenty-nine years of observations conducted in northeastern Italy on thousands of hectares of land

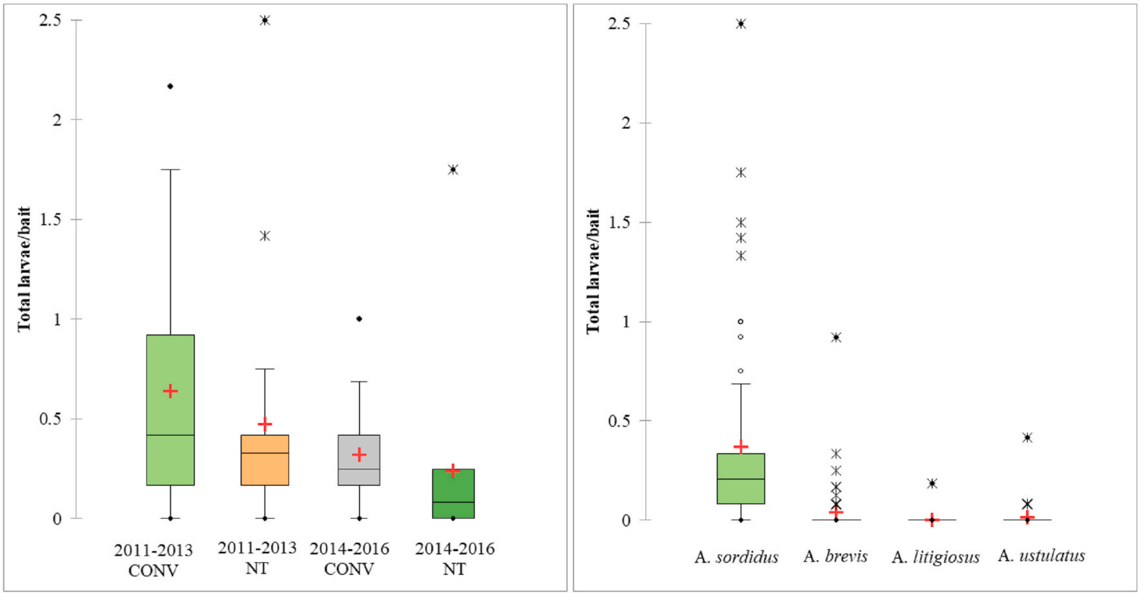

Fig. 1. Larvae per bait trap in NT and CONV tillage treatments (pooled across experimental sites) during two subsequent three-year periods (2011–2013 and 2014–2016). The box represents the 50% of the data, comprehended between the first quartile (the bottom of the box) and the third quartile (the top of the box). The horizontal line in the middle of the box displays the median, whereas the red cross is the mean of the data. The "whiskers", extending outside of the box, are used to indicate variability outside the upper and lower quartiles and their calculation is based on the interquartile range. Points out of the whiskers are outliers. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Least squares means and standard error (SE) of number of *Agriotes* adults/trap, comparing: NT vs. CONV, three years (2014–2016), and three farms. Different letters correspond to different values according to Bonferroni correction, with P ≤ 0.05.

	A. sordidus			*A. ustulatus*			*A. brevis*			*A. litigiosus*	
Treatment	**Mean**	**SE**		**Mean**	**SE**		**Mean**	**SE**		**Mean**	**SE**
CONV	417	57		2.29	0.84		29	4		12	3
NT	372	62		2.07	0.88		30	5		8	2
W	0.27			0.03			0.01			1.16	
P	0.603			0.862			0.958			0.281	
Year	**Mean**	**SE**		**Mean**	**SE**		**Mean**	**SE**		**Mean**	**SE**
2014	366	68	ab	1.11	0.58		25	5		12	3
2015	622	127	a	3.13	1.61		28	6		6	2
2016	45	46	b	3	1.94		36	6		13	4
W	9.97			2.61			2.13			3.12	
P	0.007			0.27			0.345			0.21	
Farm	**Mean**	**SE**		**Mean**	**SE**		**Mean**	**SE**		**Mean**	**SE**
Diana	479	84		21	10	a	118	21	a	0.3	0.11
Sasse Rami	458	97		0.4	0.26	b	33	7	b	77	25
Vallevecchia	279	49		1.24	0.78	b	6	1	c	46	10
W	5.03			23.17			71.94			82.72	
P	0.081			<0.001			<0.001			<0.001	
N	92			92			92			92	

cultivated with maize showed that the risk of economic damage from *A. sordidus, A. brevis, A. ustulatus,* and *A. litigiosus* was negligible (i.e., <5%) and did not differ between the minimum and conventional tillage groups (Furlan et al., 2017a). These findings collectively suggest that, in most cases (i.e., >95%), there is no need for pesticide interventions at planting for wireworm control. This pattern of results further suggests that switching from CONV to NT may not cause an increase of wireworm damage to maize. In such cases, continuous monitoring of wireworms and risk assessment programs can reliably identify areas with yield-threatening wireworm infestations (Furlan, 2014; Furlan et al., 2020a). In this way, control tactics can be applied only in those situations where economic thresholds for maize are exceeded.

The difference in soil cover between the two tillage systems was conspicuous during *A. brevis* early flights, i.e., soil was covered with winter cover crop in NT while the soil was bare in CONV fields. Consequently, this could not be the reason why NT conditions did not increase wireworm damage compared to the CONV tillage system. In fact, abiotic factors caused most of the missing plants in both the NT and CONV treatments. Primary causes of missing plants observed in NT system were the opening of the sowing furrow due to soil drying up after sowing that caused seeds/seedlings to desiccate before emergence, soil compaction after heavy rain, and unsuitable depth of seed deposition by seeder machine due to soil irregularity. The main cause of missing plants observed in the CONV treatments (and present also in the NT treatments) was the formation of crust due to disaggregation of soil structure at the surface, mainly in farms with silt-clay soils, that prevented the emergence of maize seedlings. Nevertheless, maize hybrids differ in their ability to compensate, and yields are somewhat determined by

Table 4
Comparison of healthy plant density (mean, SE) and percentage of missing plants due to biotic (mainly wireworms and birds) and abiotic (mainly soil crust, seedlings desiccation) causes (mean, SE) between NT vs CONV treatments, at three experimental farms during six years of monitoring (2011–2016).

			2011			2012			2014			2015			2016		
			Mean		SE	Mean		SE	Mean		SE	Mean		SE	Mean		SE
Healthy plant density (pl/m^2, %)	NT	pl/m^2	4.22	*a*	0.75	6.15	*a*	0.16	4.94	*a*	0.37	5.72	*a*	0.48	7.15	*a*	0.6
		%	49.6	-	8.83	72.4	-	1.94	58.1	-	4.31	67.3	-	5.61	82.3	-	5.43
	CONV	**pl/m^2**	6.02	*a*	0.59	6.32	*a*	0.21	5.73	*a*	0.32	6.31	*a*	0.04	6.6	*a*	0.3
		%	80.2	-	7.84	84.2	-	2.82	76.4	-	4.2	84.2	-	0.6	88	-	4.06
	ANOVA	**Sign.**	ns			ns			ns			ns			ns		
		P	0.135			0.579			0.183			0.29			0.468		
		F	3.504			0.364			2.592			1.484			0.643		
		df	5			5			5			5			5		
Not germinated seeds (%)	**NT**		12.4	*a*	3.31	7.03	***b***	0.48	15.2	***a***	1.93	17.5	*a*	5.83	9.27	*a*	3.52
	CONV		11	*a*	6.25	13.8	***a***	2.08	8.15	***b***	1.18	11.4	*a*	0.48	4	*a*	0.72
	ANOVA	**Sign.**	ns			*			*			ns			ns		
		P	0.702			0.0243			0.0338			0.349			0.27		
		F	0.17			12.45			10.07			1.124			1.633		
		df	5			5			5			5			5		
Wireworm damaged seeds/plants (%)	**NT**		3.59	*a*	1.69	1.29	*a*	0.84	3.82	*a*	1.81	2.67	*a*	0.89	3.74	*a*	0.86
	CONV		4.63	*a*	1.98	0	*a*	0	3.2	*a*	0.78	2.21	*a*	0.8	4.14	*a*	1.12
	ANOVA	**Sign.**	ns			ns			ns			ns			ns		
		P	0.697			0.168			0.846			0.715			0.819		
		F	0.175			2.826			0.043			0.154			0.06		
		df	5			5			5			5			5		
Missing plants by abiotic factors (%)	**NT**		33.2	***a***	11	16.7	***a***	2.6	20.8	*a*	4.06	9.81	***a***	1.52	4.38	*a*	3.28
	CONV		3.85	***b***	2.71	1.36	***b***	0.42	11.2	*a*	2.86	2.25	***b***	0.43	3.65	*a*	3.53
	ANOVA	**Sign.**	*			**			ns			**			ns		
		P	0.04			0.00127			0.109			0.00431			0.821		
		F	8.99			65.43			4.233			34.02			0.058		
		df	5			5			5			5			5		
Missing plants by birds (%)	**NT**		1.2	*a*	1.2	2.62	*a*	0.61	2.09	*a*	0.53	2.65	***a***	0.45	0.3	*a*	0.24
	CONV		0.29	*a*	0.24	0.64	*a*	0.43	1.1	*a*	0.18	0	***b***	0	0.21	*a*	0.15
	ANOVA	**Sign.**	ns			ns			ns			**			ns		
		P	0.576			0.0575			0.14			0.00101			0.811		
		F	0.37			6.98			3.371			73.75			0.065		
		df	5			5			5			5			5		

maize hybrid characteristics (Lamichhane et al., 2018). Further testing under different environmental conditions may yet clarify different hybrids' ability to compensate for early season losses.

Similarly, crop rotation sequences were the same in CONV and NT fields in this study (with the only exception of cover crops); thus, it is unlikely that they influenced wireworm response patterns to tillage practices. Nonetheless, rotation practices may have suppressed wireworm populations over time, as reflected by the decreasing temporal trends of the total and individual species densities shown in Fig. 1. In turn, lower wireworm densities were observed among the two tillage systems at the end of the study. This agrees with previous studies suggesting that wireworm management in NT systems may benefit from diversifications of rotational crops (Esser et al., 2015; Le Cointe et al., 2020). Other studies have shown that diversifying crop rotations can reduce yield losses in NT systems relative to CONV systems (Pittelkow et al., 2015a,b). Collectively, these results suggest synergies between crop rotations and NT systems in maintaining maize yields and suppressing wireworm infestations. Future studies should examine how, and to what extent, different elaterid pests, including other *Agriotes* species, are affected by NT systems within diverse crop rotations. More specifically, investigations should be directed towards the identification of the factors (likely depending on biodiversity modifications) impacting on wireworm populations in NT systems.

Contrary to previous studies (Saussure et al., 2015; Furlan et al., 2017a,b), NT conditions, including low soil disturbance and continuous food supply for soil pests, did not increase the impact of wireworms on maize crops when compared to CONV systems. One explanation could be that the SOM provided by cover crops and the absence of tillage operations in NT systems boost vigorous seedling growth that can compensate for wireworm damage relative to CONV systems, but in this study, SOM has been keeping low for all the experimental period although it has been slowly increasing. Alternatively, the SOM inputs from cover crop roots might deflect wireworms away from maize crops completely enough to prevent unacceptable injury or damage (Staudacher et al., 2013; Furlan et al., 2020b; Le Cointe et al., 2020). Interestingly, however, slight differences were observed in the SOM/soil organic carbon [SOC] levels, with a slightly significant increase only in the upper soil layer of NT fields (VV.AA, 2019). Nevertheless, the rate at which SOM accumulates, intrinsically linked to the lifespan of soil structural units (Camarotto et al., 2020; VV.AA, 2019).

At the same time, combined with NT, cover crops may have reduced the disturbance of entomopathogens that parasitize wireworms (such as *Metarhizium* spp. and *Beauveria* spp. [Milosavljević et al., 2020]) by preserving their soil habitats (Garbeva et al., 2004; Randhawa, 2017). Other studies have shown clear positive effects of cover crops on improving entomopathogen diversity in the NT systems (Hummel et al., 2002; Marquez, 2017; Randhawa, 2017). This may, at least partially, explain why *Agriotes* larvae populations did not increase in NT system despite risk factor presence increased. Further quantitative investigations are, therefore, needed to define whether the SOM inputs from cover crops and reduced SOM mineralization in NT and CA practices might provide carry-over effects and increased economic returns for maize in the following years.

In summary, opposed to previous studies, NT did not increase the impact of wireworms on maize seeds and seedling establishments early in the growing season, as compared to CONV systems, while at the same time contributing to the increase in soil biodiversity (VV.AA, 2019). These results support previous findings showing decreased and increased pest activity in the soil for diversified NT systems with cover crops or crop residues and less diversified CONV systems without cover crops, respectively (Abdel-Monaim and Abo-Elyousr, 2012; Hwang et al., 2008). Indirectly, our data also suggest that the risk of post emergence seedling damage for maize due to vertebrate pests, especially birds, may be low in NT systems. This is presumably due to the bird feeding habits as corvids are omnivores and do not show any preference for a single food source (Furlan et al., 2021b; Lamichhane, 2021). Consequently, damage caused to germinating maize seeds and emerging seedlings by birds could be avoided if maize is sown without tillage and in the presence of cover crops or crop residues. If corvids are attracted to these other food resource during maize establishment, damage to maize may be irrelevant. However, if no alternatives are available during this period, they may turn their attention to maize.

Funding

Research reported in this publication was supported, in part, by the European Union's LIFE + HELPSOIL project, grant LIFE12 ENV/IT/000578.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank Francesco Fagotto, Francesco Salmaso, and Paolo Giacobbi for their field assistance. Serenella Spolon, Renzo Converso, Francesco Fracasso, and Erica Sartori helped with data collection and processing.

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