



AperTO - Archivio Istituzionale Open Access dell'Università di Torino

Control of western corn rootworm damage by application of soil insecticides at different maize planting times

This is the author's manuscript	
Original Citation:	
Availability:	
This version is available http://hdl.handle.net/2318/1630985	since 2017-03-29T10:57:25Z
Published version:	
DOI:10.1016/j.cropro.2016.11.006	
Terms of use:	
Open Access	
Anyone can freely access the full text of works made available as "Open Access". Works made available under a Creative Commons license can be used according to the terms and conditions of said license. Use of all other works requires consent of the right holder (author or publisher) if not exempted from copyright protection by the applicable law.	

(Article begins on next page)





This is the author's final version of the contribution published as:

Massimo Blandino, Chiara Ferracini, Ivo Rigamonti, Giulio Testa, Matteo A. Saladini, Costanza Jucker, Mauro Agosti, Alberto Alma, Amedeo Reyneri

Control of western corn rootworm damage by application of soil insecticides at different maize planting times

Crop Protection 93 (2017): 19-27 DOI 10.1016/j.cropro.2016.11.006

The publisher's version is available at:

http://www.sciencedirect.com/science/article/pii/S0261219416303192]

This full text was downloaded from iris-Aperto: <u>https://iris.unito.it/</u>

iris-AperTO

University of Turin's Institutional Research Information System and Open Access Institutional Repository

1 Abstract

The western corn rootworm, *Diabrotica virgifera virgifera* LeConte (Coleoptera: Chrysomelidae) (WCR), is one of the most damaging maize crop pests. Damage to maize is primarily caused by the larvae feeding on roots, which results in a reduction of water and nutrient uptake and may cause lodging as well as a substantial reduction in grain yield.

The effects of soil insecticides, applied at different planting times, on controlling WCR
damage were investigated in 76 naturally infested fields in northern Italy over a 4-year
period.

10 Without furrow insecticides, plant density was reduced at all of the considered planting 11 times (+5.3%). Insecticide application let to a significant reduction in the WCR larval 12 density (-36%). As a consequence, the root injury measured by nodal injury scale, was 13 reduced (-75%) as was the incidence of plants with "gooseneck" symptoms (-71%). 14 Furthermore, the soil-applied insecticide plots showed a significant increase in plant 15 biomass yield at the dough stage (+4.9%) and in grain yield at physiological maturity 16 (+8.3). The application of soil insecticides showed a positive yield increase in 95% of the compared production situations. The yield increase was higher than 5% in 70% of 17 18 considered cases. The effect of the soil-applied insecticides on root and plant damage 19 symptoms, and the consequent biomass and grain advantage were steady over the 20 different intervals between planting time and WCR egg hatching.

The results of this study have underlined that the application of a soil insecticide to the furrows at planting leads to a clear control of injuries from insects and a consequent maize yield advantage.

24

26 Key words

27 maize, grain yield, Western Corn Rootworm, insecticide, planting time

28

- 29 Abbreviations: DM, dry matter; GDD, growing degree days; GS, growth stage; IPM,
- 30 Integrated Pest Management; NIS, node injury scale; PS, production situation; RR,

31 relative ratio; WCR, Western Corn Rootworm.

32

34 **1. Introduction**

The Western Corn Rootworm (WCR), Diabrotica virgifera virgifera LeConte 35 36 (Coleoptera: Chrysomelidae) is a dangerous maize (Zea mays L.) pest in several 37 countries. It is native to Central America, and it has been recognized as one of the 38 most destructive pests in the Midwestern United States since the middle of the last century (Park and Tollefson, 2006). In Europe, WCR is considered an invasive species, 39 40 which was accidentally introduced through multiple events from early 1980s till 2000s 41 (Lemic et al., 2015). WCR was reported for the first time in 1992 in Serbia. After 42 introduction and establishment period, WCR rapidly spread to other European maize 43 growing areas and it has currently reached high population levels in Central-Southern Europe, included northern Italy (Kiss et al., 2005). Economic damage is more common 44 in areas in which maize is grown as a continuous crop and where the environmental 45 46 conditions are favourable to the building of high WCR populations.

According to Boriani et al. (2006) an action threshold of about 5 adults/trap/day is used to evaluate captures with 6–8 Pherocon[®] AM traps/field (depending on field size), over a six/eight-week period. Economic damage has been reported in several growing seasons and areas of northern Italy, when the adults captures exceed this threshold, without insecticide application (Blandino et al., 2014).

Since WCR larvae only feed on maize roots and can only survive in small numbers on a limited number of non-maize grasses (Oyediran et al., 2004), crop rotation has proved to be an effective pest management strategy when the action threshold is exceeded. However, the intense use of a simple crop rotation, such as the maizesoybean rotation adopted in the Midwest in the USA, has selected for an insect strain that can lay down eggs in soybean fields. The larvae hatching from these eggs emerge into maize fields the following spring (Gray et al., 2009).

59 Crop rotation is also the main effective integrated pest management (IPM) control 60 option adopted in Europe. However, in the more profitable maize growing areas where continuous maize is preferred, if the pest is widespread and reaches high population 61 62 levels, soil and/or foliar insecticides are frequently applied. Insecticide sprays used to control the adults can be applied at the beginning of female egg laying to reduce 63 oviposition or, in case of extremely high infestation, before silking to reduce silk feeding 64 by WCR adults. In this case, the timing of the insecticide application is critical, and 65 66 needs precise knowledge on the phenology of the WCR population in the field.

The most common strategies used to protect maize roots from WCR are the application 67 68 of a soil insecticide at planting, and the use of an insecticide seed dressing (Sutter et 69 al., 1990; van Rozen and Ester, 2010) when available. Numerous conventional 70 insecticides, in granular and liquid formulations (pyrethroid, organophosphate, 71 neonicotinoid, and phenyl pyrazole classes), are registered for WCR larval control in 72 Europe. These active ingredients have also proved to control other soil insects that 73 could attack maize seedlings, and thus reduce plant density, such as Agriotes spp. 74 wireworms (Ritter and Richter, 2013).

In recent years, the use of maize seeds treated with insecticides belonging to the neonicotinoid class has been restricted in several European countries because of their adverse effects on honeybees (Girolami et al., 2012). This restriction has determined a notable increase in soil insecticide applications for maize crops, thus raising concerns about their undesired side effects on the agroecosystem and non-target organisms, and about their effective benefit to the crop (Furlan and Kreutzweiser, 2015).

The effectiveness of soil-applied insecticides and seed dressings is variable and still debated (Cox et al., 2007), and there are different opinions concerning the effect of

84 planting time applications. Some authors claim that they are ineffective in WCR control and eradication programs (Furlan et al., 2006), but their efficacy in containing root 85 damage has been confirmed. The effects on yield of soil insecticides, such as tefluthrin, 86 thiamethoxam, tebupirimphos and cyfluthrin, are reported guite inconstant, varying 87 88 from none to more than 60% (Cox et al., 2007, 2008; Ma et al., 2009; Dun et al., 2009; 89 Petzold-Maxwell et al., 2013). Many factors can affect the efficacy of soil treatments: 90 the interactions between planting time and soil texture, application depth, organic 91 matter, pH and weather conditions (rainfall), with consequent variable effects on its 92 persistence. In addition to leaching, insecticide persistence could be affected by 93 volatilization and chemical degradation with higher temperatures and lower soil 94 moisture levels (van Rozen and Ester, 2010; Furlan and Kreutzweiser, 2015).

95 In order to correctly address the control strategies for this pest in Europe, there is an 96 urgent need to assess the impact of soil-applied insecticides to control WCR and 97 develop integrated strategies to minimize yield loss in different environments. While 98 the effect of selected insecticides on the control of WCR has often been mentioned 99 under experimental conditions at a single field scale, or in semi-field conditions with 100 artificial rootworm infestations or in small-plot studies (Sutter et al., 1990; Magalhaes 101 et al., 2007), its evaluation under natural infestation conditions at a regional scale has 102 been investigated less (Kuhar et al., 1997; Fuller et al., 1997), especially in Europe 103 where this invasive species is still spreading.

The aim of this study was to verify the effect of soil insecticides on the control of WCR damage and quantify the related yield advantage in naturally infested fields. The effect of the insecticides applied at planting has been investigated in different production situations for full-season maize hybrids in northern Italy, but considering different

intervals between the application times (planting) and the occurrence of the WCRlarvae in the field, or different agronomic conditions for soil tillage and irrigation.

111 **2. Materials and Methods**

112 <u>2.1. Experimental set up</u>

113 The effect of soil insecticide application in seed furrows at planting on the control of 114 WCR larval damage and the consequent maize yield was investigated in 76 production 115 situations (PS) over a 4-year period (2010-2013) in northern Italy. In each location the 116 soil insecticide application at planting time was compared to an untreated control using 117 a completely randomized block design with 3 replicates per treatment. The plots were 118 all 20 m long and 8 rows wide and they were staked out side by side in a fully planted 119 field. Row distance was 0.75 m, while plant distance per row was 0.17-0.20 according 120 to maize hybrid maturity group. All the measurements were conducted in the two 121 middle rows.

122 A list of the compared PS and their main geographic and agronomic information is 123 reported in Table 1.

The choice of the experimental sites was made considering fields with a high WCR infestation recorded in the previous year (above the threshold of 5 adults/trap/day with Pherocon[®] AM traps), according to the information obtained from the adults territorial monitoring and for which a high presence of the pest might be expected during the survey. Moreover, the previous crop was always continuous maize cultivated without any former foliar insecticide application to control WCR populations or other maize pest.

The effect of soil insecticide application was evaluated considering different intervals between planting time and expected egg hatching. The compared PS were subdivided into 3 groups on the basis of the interval of cumulated growing degree days (GDD) from the maize planting date to the end of egg hatching, expressed as the 90% of 1st instar WCR larvae cumulative occurrence (WCR90%). The logistic equation developed by Davis et al. (1996) with a minimum and maximum developmental threshold for the WCR larvae of respectively 11°C and 18°C was used to calculate the cumulated GDD from January 1st to WCR90% and to the maize planting date of each PS. The quantification of the cumulated GDD interval between maize planting date and the end of egg hatching (MP-WCR90%) was performed using the maximum and minimum air temperatures recorded by weather stations located next to each experimental site.

In order to obtain an equal distribution of recorded cases, the considered PS were subdivided into the following MP-WCR90% classes: GDD < 150 °C d⁻¹(23 cases), 150-230 °C d⁻¹ (28 cases), and > 230 °C d⁻¹(25 cases).

The soil insecticide was distributed using a calibrated granular dispenser or sprayer applied to the planter. The insecticide was distributed in seed furrows at a depth of 5-10 cm from the soil surface at the recommended rate for each product according to the equipment setting and the desired seeding depth. No insecticide was applied as a seed dressing in any of the tested PS. The applied soil insecticides belong to the pyrethroid, neonicotinoid or organophosphate classes, and they are listed in Table 1. The formulation and the application rate are reported in the table footnotes.

152 The considered PS included the use of full season maize for both grain and whole 153 plants as silage. The maturity class (FAO 500-700) of the tested hybrids was selected 154 according to the characteristics of the growing area and the adopted planting time. 155 Different irrigation systems were adopted, according to the typical farm management 156 practices used in the area; 11 of the considered trials were performed under non-157 irrigated conditions. In most of the cases, the maize was planted after conventional soil 158 tillage practices, which included a 0.25-0.40 m depth ploughing, followed by disk 159 harrowing; in 9 cases out of 76 trials, minimum tillage techniques were applied instead 160 of ploughing. Other agronomical practices, such as fertilization and weed control, were

161 conducted according to the typical management system of each farm and to the162 ordinary agronomic techniques of the area.

163 In order to evaluate the interaction of soil insecticide with planting times and in 164 agreement with the common full season maize planting time in northern Italy, the 165 planting dates were comprised between mid-March and late May over the four-year 166 period. Very late planting times, after most of the WCR larvae had hatched, were 167 excluded because of the possibility of the negative impact of the lack of maize roots 168 on larval survival.

169

170 2.2. Entomological analyses

171 The WCR larval infestation was recorded in 19 PS, which were representative of the 172 surveyed growing seasons and areas. A 25 cm cube of soil core containing the root 173 system and the surrounding soil was collected and individually washed inside a plastic 174 container (40x53x25 cm) at the time of the maximum larval occurrence, according to 175 the Davis et al. (1996) model. The soil was repeatedly moved to allow all the larvae 176 floating on the water surface to be collected with a thin brush and counted. After being 177 washed, the roots were immediately transferred to the laboratory and individually 178 placed inside a modified Berlese funnel kept at room temperature (23±1°C T, 65±2% 179 RH). All the larvae that emerged from the drying roots were collected in a plastic cup 180 filled with tap water which had been placed at the bottom of each funnel. The funnels 181 were checked daily for at least three weeks.

In all the PS, the WCR damage to the root system was quantified at the beginning of
 adult emergence, using the nodal injury score (NIS) developed by Oleson et al. (2005).

Larval infestation and NIS were recorded on 60 plants (20 plants per plot, randomly selected in the two rows adjacent to the two middle ones) for each soil insecticide treatment and the untreated control in each surveyed PS.

187

188 2.3. Crop measurements

After plant emergence, the homogeneity of crop density in the insecticide-treated and untreated plots of each PS was verified at 2-4 leaf stage (growth stage - GS 12-14, according to BBCH scale).

In all the PS, the crop density and the percentage of plants with "gooseneck" symptoms
were quantified at the dough stage by counting the number of plants in the two middle
rows of each plot along the whole plot length (20 m).

Whole plants were collected manually at the dough stage (GS 85) in a representative PS sub-sample (48 cases over 4 growing seasons) from a 3 m² area (two rows 2 m long) randomly selected in the middle of each plot. Plant samples were weighed in order to establish the biomass yield and then passed through a field chopper. About 3 kg of chopped subsample was weighed before and after being dried at 105°C for 48 hours in order to establish the dry matter (DM) content.

Ears were collected manually at physiological maturity (moisture content between 202 22 - 30%), in all the PS, with the exception of fields fully harvested at the dough stage 203 for silage (16 cases), from a 4.5 m² area (two rows 3 m long) randomly selected in the 204 middle of in each plot and were then passed through an electric sheller. The grain yield 205 was corrected to a commercial moisture level of 14%.

206

207 2.4. Statistical analysis

208 The relative ratio (RR= soil-applied insecticide/untreated control) between the soil-209 applied insecticide in the seed furrows at maize planting and the untreated control was 210 calculated for each measured parameter for all the PS for each MP-WCR90% class 211 and for PS that differ for soil tillage and irrigation. The cases with no root injury and 212 plants with no "gooseneck" symptoms in both the untreated control and insecticide-213 treated plots were excluded for the calculation of the RR, in order to not consider 214 undefined RR values for these parameters. The average RR and the confidence 215 interval were calculated at significance levels of 99.9% (P<0.001), 99% (P<0.01) and 216 95% (P<0.05) for crop density, WCR larval density, root injury, plants with "gooseneck" 217 symptoms, plant biomass at the dough stage and grain yield.

218 The analysis of variance (ANOVA) was used for each recorded parameter to compare 219 the RR obtained in the different MP-WCR90% intervals or for the different soil tillage 220 or irrigation. The residual normal distribution was verified using the Kolmogorov-221 Smirnov test, while the homogeneity of variances was verified using the Levene test. 222 Multiple comparison tests were performed, according to the Tukey test, on the 223 treatment means. Within the same PS, all the environmental and agronomic conditions 224 were the same for the soil insecticide treated and the untreated control, allowing a 225 direct comparison of soil-insecticides application in different conditions.

SPSS for Windows statistical package, Version 21.0 (SPSS Inc., Chicago) was used
for the statistical analysis.

3. Results

The results of the application of soil-insecticides to the maize seed furrows are summarized in Table 2 for the different planting times and compared to the untreated control.

233 Without furrow insecticides, plant density was reduced at all of the considered planting times (P<0.001). On average, the untreated control resulted in a 5.3% lower plant 234 235 density compared to the soil-applied insecticide treatment. Moreover, the advantage of insecticide application was significantly affected by the planting time: in the early 236 237 sowings, which were conducted between mid-March and mid-April (MP-WCR90% > 238 230 GDD), the RR of the soil-applied insecticide/untreated control was significantly 239 higher than that of the later planting times (P=0.007), and the difference in plant density between the insecticide treatments and the control was 7.3%. Conversely, the plant 240 241 density at the 150-230 planting time and <150 °C d⁻¹ increased to 4.8% and 3.7%, 242 respectively. Although no specific measurements were conducted to quantify the 243 possible damage to seedlings caused by other soil insects, the field observations 244 highlighted the presence of Agriotes spp. wireworms in several production situations, 245 particularly in the early sowings.

246 On average in the considered PS, the application of insecticides significantly reduced 247 (P<0.001) the WCR larval density, that is by 36%, compared to the untreated control. 248 A significant effect of soil-applied insecticide on controlling WCR larvae was observed 249 at all the planting times. Although no significant differences (P=0.145) were reported 250 between the RR for the different MP-WCR90% intervals, the effectiveness of soil-251 applied insecticides on reducing the larval population slightly decreased as the 252 intervals between the maize planting and the occurrence of larvae in the soil increased. 253 The average larval reduction obtained by means of the soil-insecticide treatments,

compared to the untreated control, was 45%, 40% and 22%, with MP-WCR90% intervals of < 150, 150-230 and > 230 $^{\circ}$ C d⁻¹, respectively.

Root injuries attributable to WCR larvae were detected in 63 PS (83% of the cases); among these, root damage resulted in visible symptoms in the aerial part of the crop in 36 cases, with the occurrence of "gooseneck" plants. This data confirm that the relationship between adult infestation levels and the impact of WCR on maize damage is highly variable, as a consequence of the interaction with the environmental and agronomic conditions.

The soil-insecticides applied to the maize seed furrow resulted in a significant reduction (P<0.001) of root injury (-75%) and in the occurrence of plants with "gooseneck" symptoms (-71%), compared to the untreated control (Table 2). Moreover, the reduction was similar in all the considered intervals between maize planting and larval occurrence.

267 On average, the soil-applied insecticide significantly increased the plant biomass at 268 the dough stage (+4.9%) and the grain yield at the end of maturity (+8.3%), compared 269 to the untreated control (P<0.001) (Table 2). The insecticide application at planting 270 significantly affected the grain yield at all of the considered intervals between maize 271 planting and larval occurrence, while a not significant increase in plant biomass was 272 only reported for MP- WCR90% intervals < 150 and > 230 of °C d⁻¹ (P<0.05). The RR 273 of the soil-applied insecticide/untreated control for the grain yield increased slightly 274 from late to early planting time, although no significant differences were observed 275 between the different MP-WCR90% intervals.

No evident adult feeding activity on silk has been observed in any of the compared
PSs. The results of the application of soil-insecticides to the maize seed furrows
compared to the untreated control in different agronomic conditions (soil tillage or

irrigation) are summarized in Table 3. The application of soil insecticide confirms a significant effect on the recorded parameters also in these considered conditions. The RR of the soil-applied insecticide/untreated control for all the parameters was not significantly different between the compared tillage practices. Otherwise, a significant increase of RR for grain yield was observed in non-irrigated fields compared to irrigated ones.

Figure 1 represents the percentage of grain yield variations obtained applying the soil insecticides, sorted from the lowest to the highest, in all of the 60 PS considered for this parameter. In 95% of the cases, a positive yield increase was shown, with 70% of the cases resulting in a 5% higher yield increase than the untreated control.

4. Discussion

This study has proved that conventional soil-applied insecticides into seed furrows in growing areas with high *D. v. virgifera* infestations, where maize is grown as a continuous crop, lead to a reduction in the WCR larval presence and in root injury, which in turn contributes to an overall significant grain and biomass yield advantage.

The data collected as part of an extensive comparison of different PS, in intensive maize farming systems and under natural WCR infestation, have confirmed the positive role of soil-applied insecticides on maize yield, as already reported in other specific field experiments (Ma et al., 2009) and in surveys conducted in the USA (Fuller et al., 1997; Kuhar et al., 1997).

Under artificial and controlled infestation, Sutter et al. (1990) reported that yield protection by means of insecticides was effective and significantly higher at greater WCR infestation levels, and the compared insecticides (carbofuran, terbufos, isofenphos active ingredients) did not differ in their crop protection ability. Furthermore, the application of soil insecticide treatments significantly reduced lodging, although with differences according to the active ingredients.

306 Dillen et al. (2010) developed a bio-economic simulation model to assess the absolute 307 and relative competitiveness of alternative WCR larval damage abatement strategies 308 (no control, crop rotation, Bt maize, seed treatment, soil insecticide). The authors 309 reported that, in a Hungarian grain maize monoculture, in growing areas where Bt 310 maize was not deregulated, the application of soil insecticides led to an average 311 economic advantage of 113 € ha⁻¹, and it creates benefits in 54% of the cases. By 312 considering a maize grain price of 170 € t⁻¹ and an average cost of soil insecticide of 313 80 € ha⁻¹, an economically profitability of soil insecticide application was observed in 314 85% of the production situations analyzed in the present study. On average, the

economic advantage of using soil insecticide was 125 € ha⁻¹. Conversely, in other
environmental, agronomic and insect pressure conditions, some authors have reported
insecticide treatments against soil maize pests as not being justified, both in the
presence (Kuhar et al., 1997; Furlan et al., 2006; Cox et al., 2007; Petzold-Maxwell et
al., 2013) and absence of *Diabrotica* populations (Piqué et al., 1998).

320 In the present study, although a general higher effect has been observed concerning 321 the control of the WCR larvae when a short interval elapses between planting time and 322 egg hatching (later planting), the effect of soil-applied insecticide on root damage and 323 gooseneck plant incidence and the consequent biomass and grain advantage were 324 steady for the different planting times. It is important to highlight that the study did not 325 consider very late planting times, after most of the WCR larvae had hatched. 326 Conversely, in experiments that also took into account plantings after the maximum 327 larval occurrence (Hoffmann et al., 2000; Obopile et al., 2013), both root damage and 328 plant lodging were shown to be more reduced by applying soil insecticides at early 329 planting time. The authors attributed the reduction in gain in the late plantings to lower 330 infestations, due to the mortality by starvation of the WCR larvae.

331 The present study, which was conducted in a large number of different production 332 situations, suggests that the effectiveness of conventionally applied soil insecticides is 333 hardly influenced by the maize planting date. However, in specific production 334 situations, a variable response could be expected. The efficacy of this control strategy 335 depends on a number of environmental and application-related factors, such as the 336 level of pest population, the applied active ingredient and its rate, the mechanical and 337 operational aspects, the interaction with pedo-climatic conditions and the insecticide 338 leaching or degradation (van Rozen and Ester, 2010).

339 Although several in-furrow soil insecticide products have been considered, the present 340 study was not designed to compare the efficacy of different active ingredients. Since 341 these direct control products could differ according to formulation, level of solubility and 342 method of placement as well, an *ad hoc* investigation on the impact of the different 343 available solutions is needed. In particular, it is necessary to determine whether a different efficacy on WCR is obtained through the application of systemic or non-344 345 systemic soil insecticides, considering both applications to seed furrows or as seed 346 dressings, where available.

The application of insecticides to seed furrows also plays an important role in controlling other soil insects, such as *Agriotes* spp. wireworms (Ritter and Richter, 2013). Although these larvae are polyphagous, they can feed on maize roots in the same way as *D. v. virgifera* larvae, and can cause comparable economic damage. Moreover, wireworm feeding may prevent germination and increase seedling mortality, which implies a reduction in plant density (Barsics et al., 2013).

353 The data recorded in the present work confirm the higher positive effect of soil-applied 354 insecticides in preserving plant density, especially in early planted maize compared to 355 later planted maize, thus highlighting that the wireworm activity on seedlings had been 356 reduced. These insects, in fact, overwinter in the soil at the larval stage and they are 357 already active at the beginning of spring, and the risk of economic damage is therefore 358 higher for early plantings, which are characterized by a poor early vigor and slow 359 seedling development (Richards, 2000). Conversely, later sowings are characterized 360 by a more rapid development, thus reducing the critical phase in which the crop is 361 grown, and are thus less susceptible to wireworm larval attack. These greater effects 362 of controlling the damage by other insect species and of preserving plant density could

explain the increasing trend in grain yield observed from the late planting time to theearlier one.

The collected data underline that planting-time soil insecticides can be used as an 365 366 effective tool to control the damage caused by soil pests. Nevertheless, their 367 application needs to be evaluated for each production situation and they need to be 368 included in an IPM strategy that is adapted to the local conditions (Vasileiadis et al., 369 2011). The insecticide control activity needs to be combined with the application of 370 other good agronomic practices, in order to guarantee potential compensatory 371 mechanisms that could permit a rapid re-growth of damaged root systems, such as the 372 hybrid choice, irrigation, N fertilization and tillage (Riedell et al., 1992; 1996; Urías-373 López and Meinke, 2001). The data collected clearly underline the different productive 374 benefits of the soil-insecticide application in irrigated and non-irrigated fields.

375 Moreover, considering the greater attention paid to IPM in the EU, through a higher 376 sustainable use of pesticides (Directive 2009/128/EC), the insecticide application 377 needs to be based on an effective pest monitoring programme, in order to identify 378 population thresholds (Lemic et al., 2016). A proper WCR adult monitoring through 379 traps could help growers to avoid the unnecessary use of soil insecticide and to make 380 decisions regarding appropriate management strategies (i.e. crop rotation or 381 application of foliar insecticides). Thresholds (5-6 WCR adults trap-1 day-1, with 6-8 382 traps per field depending on the field size) have been established and introduced in 383 several growing areas to trigger the control of this insect before economic injury levels 384 are reached (Boriani et al., 2006; Kos et al., 2014). Monitoring tools for Agriotes 385 wireworms are at a good stage of development and they need to be considered when 386 deciding on the use of soil insecticides within rational IPM strategies (Furlan, 2014).

387 In conclusion, taking into account the comparison of different PS in continuous maize 388 growing areas with a high occurrence of WCR, the soil insecticide conventionally 389 applied to seed furrows has been shown to lead to a good control of insect injuries and 390 to a clear maize yield advantage. However, maize growers, before deciding whether 391 to adopt soil insecticide measures, should consider the crop and pest history, the insect 392 pressure in relation to economic thresholds and the cost-to-benefit ratio, the damage 393 risk related to other pests and the whole IPM strategy applied to the cropping system. 394 Further studies are still necessary to compare all the available direct control strategies 395 (e.g. different active ingredients, timing and application methods), targeted to control 396 soil pests, and specifically WCR.

398 5. **References**

- Barsics, F., Haubruge, E., Verheggen, F.J., 2013. Wireworms' management: an
 overview of the existing methods, with particular regards to *Agriotes* spp.
 (Coleoptera: Elateridae). Insects 4, 117-152. doi:10.3390/insects4010117.
- Blandino, M., Berrino, G., Reyneri, A., Ferracini, C., Saladini, M.A., Alma, A.,
 Rigamonti, I.E., Jucker, C., Agosti, M., Amato, F., Stassi, P., 2014. Monitoraggio
 diabrotica, quali soglie di intervento. L'Informatore Agrario 9, 15-18.
- Boriani, M., Agosti, M., Kiss, J., Edwards, C.R., 2006. Sustainable management of the
 western corn rootworm, *Diabrotica virgifera virgifera* LeConte (Coleoptera:
 Chrysomelidae), in infested areas: experiences in Italy, Hungary and the USA.
 EPPO Bull 36, 531-537. doi: 10.1111/j.1365-2338.2006.01055.x.
- 409 Cox, W.J., Shields E., Cherney, D.J.R., Cherney, J.H., 2007. Seed-applied insecticides
 410 inconsistently affect corn forage in continuous corn. Agron. J. 99, 1640-1644. doi:
 411 10.2134/agronj2007.0104.
- 412 Cox, W.J., Shields, E., Cherney, D.J.R., 2008. Western corn rootworm damage subtly
- 413 affects corn growth under moderate environmental stress. Crop Science 48, 1164414 1169. doi: 10.2135/cropsci2007.10.0572.
- 415 Davis, P.M., Brenes, N., Allee, L.L., 1996. Temperature dependent models to predict
 416 regional differences in corn rootworm (Coleoptera: Chrysomelidae) phenology.
 417 Environ. Entomol. 25, 767-775. doi: 10.1093/ee/25.4.767.
- Dillen, K., Mitchell, P.D., Tollens, E., 2010. On the competitiveness of *Diabrotica virgifera virgifera* damage abatement strategies in Hungary: a bio-economic
 approach. J. Appl. Entomol. 134, 395-408. doi: 10.1111/j.14390418.2009.01454.x.

- Dun, Z., Mitchell, P.D., Agosti, M., 2009. Estimating *Diabrotica virgifera virgifera virgifera*damage functions with field trial data: applying an unbalanced nested error
 component model. J. Appl. Entomol. 134, 409-419. doi: 10.1111/j.14390418.2009.01487.x.
- 426 Fuller, B.W., Boetel, M.A., Walgenbach, D.D., Grundler, J.A., Hein, G.L., Jarvi, K.J.,
- 427 Keaster, A.J., Landis, D.A., Meinke, L.J., Oleson, J.D., Ostlie, K.R., Tollefson, J.J.,
- 428 Wedberg, J.L., Wilde, G.E., Evenson, P.D., 1997. Optimization of soil insecticide
- 429 rates for managing corn rootworm (Coleoptera: Chrysomelidae) larvae in the North
- 430 Central United States. J. Econ. Entomol. 90 (5), 1332-1340. doi:
 431 10.1093/jee/90.5.1332.
- Furlan, L., 2014. IPM thresholds for *Agriotes* wireworm species in maize in Southern
 Europe. J. Pest Sci. 87, 609-617. doi: 10.1007/s10340-014-0583-5.
- Furlan, L., Canzi, S., Di Bernardo, A., Edwards, C.R., 2006. The ineffectiveness of
 insecticide seed coatings and planting-time soil insecticides as *Diabrotica virgifera*
- 436 *virgifera* LeConte population suppressors. J. Appl. Entomol. 130 (9-10), 485-490.
- 437 doi: 10.1111/j.1439-0418.2006.01103.x.
- Furlan, L., Kreutzweiser, D., 2015. Alternatives to neonicotinoid insecticides for pest
 control: case studies in agriculture and forestry. Environ. Sci. Pollut. Res. 22, 135–
 147. doi: 10.1007/s11356-014-3628-7.
- Girolami, V., Marzaro, M., Vivan, L., Mazzon, L., Greatti, M., Giorio, C., Marton, D.,
 Tapparo, A., 2012. Fatal powdering of bees in flight with particulates of
 neonicotinoids seed coating and humidity implication. J. Appl. Entomol. 136, 17doi: 10.1111/j.1439-0418.2011.01648.x.
- Gray, M.E., Sappington, T.W., Miller, N.J., Moeser, J., Bohn, M.O., 2009. Adaptation
 and Invasiveness of Western Corn Rootworm: Intensifying Research on a

447 Worsening Pest. Annu. Rev. Entomol. 54, 303–321. doi:
448 10.1146/annurev.ento.54.110807.090434.

Hoffmann, M.P., Kirkwyland, J.J., Gardner, J., 2000. Impact of Western Corn
Rootworm (Coleoptera: Chrysomelidae) on sweet corn and evaluation of
insecticidal and cultural control options. J. Econ. Entomol. 93 (3), 805-812. doi:
10.1603/0022-0493-93.3.805.

Kiss, J., Edwards, C.R., Berger, H.K., Cate, P., Cean, M., Cheek, S., Derron, J., Festic,
H., Furlan, L., Igrc-Barcic, J., Ivanova, I., Lammers, W., Omelyuta, V., Princzinger,
G., Reynaud, P., Sivčev, I., Sivicek, P., Urek, G., Vahala, O., 2005. Monitoring of
western corn rootworm (*Diabrotica virgifera virgifera* LeConte) in Europe 19922003. In: «Western Corn Rootworm: Ecology and Management (Vidal S.,
Kuhlmann U., Edwards C.R. eds.), CABI, Wallingford UK, pp. 29-39. doi:
10.1079/9780851998176.0029.

Kos, T., Bažok, R., Gunjača, J., Barčić, J.I., 2014. Western corn rootworm adult
captures as a tool for the larval damage prediction in continuous maize. J. Appl.
Entomol. 138(39), 173-182. doi: 10.1111/jen.12010.

Kuhar, T.P., Youngman, R.R., Laub, C.A., 1997. Risk of western corn rootworm
(Coleoptera: Chrysomelidae) damage to continuous corn in Virginia. J. Entomol.
Sci. 32, 281-289.

Lemic, D., Mikac, K.M., Ivkosic, S.A., Bažok, R. 2015. The Temporal and Spatial
Invasion Genetics of the Western Corn Rootworm (Coleoptera: Chrysomelidae) in
Southern Europe. PLoS ONE 10 (9),e0138796. doi:10.1371/journal.pone.0138796
Lemic, D., Mikac, K.M., Kozina, A., Benitez, H.A., McLean, C.M., Bažok, R., 2016.
Monitoring techniques of the western corn rootworm are the precursor to effective

471 IPM strategies. Pest Manag Sci. 72 (2), 405-17. doi: 10.1002/ps.4072.

Ma, B.L., Meloche, F., Wei, L., 2009. Agronomic assessment of Bt trait and seed or
soil-applied insecticides on the control of corn rootworm and yield. Field Crops
Res. 111, 189-196. doi: 10.1016/j.fcr.2008.12.006.

Magalhaes, L.C., French, B.W., Hunt, T.E., Siegfried, B.D., 2007. Baseline
susceptibility of western corn rootworm (Coleoptera: Chrysomelidae) to
clothianidin. J. Appl. Entomol. 131 (4), 251–255. doi: 10.1111/j.14390418.2007.01153.x.

- 479 Obopile, M., Hammond, R.B., Thomison, P.R., 2013. Interaction among planting dates,
 480 transgenic maize, seed treatment, corn rootworm damage and grain yield. J. Appl.
 481 Entomol. 137, 45-55. doi: 10.1111/j.1439-0418.2012.01716.x.
- Oleson, J.D., Park, Y.L., Nowatzki, T.M., Tollefson, J.J., 2005. Node-injury scale to
 evaluate root injury by corn rootworms (Coleoptera: Chrysomelidae). J Econ
 Entomol. 98 (1), 1-8. doi: 10.1093/jee/98.1.1.
- Oyediran, I.O., Hibbard, B.E., Clark, T.L., 2004. Prairie grasses as hosts of the western
 corn rootworm (Coleoptera: Chrysomelidae). Environ.Entomol. 33, 740–747. doi:
 10.1603/0046-225X-33.3.740.
- Park, Y.L., Tollefson, J.J., 2006. Development and economic evaluation of spatial
 sampling plans for corn rootworm *Diabrotica* spp. (col. Chrysomelidae) adults. J.
 Appl. Entomol. 130, 337-342. doi: 10.1111/j.1439-0418.2006.01076.x.
- 491 Petzold-Maxwell, J.L., Meinke, L.J., Gray, M.E., Estes, R.E., Gassmann, A.J., 2013.
 492 Effect of Bt maize and soil insecticides on yield, injury, and rootworm survival:
 493 implications for resistance management. J. Econ. Entomol.106 (5), 1941-51. doi:
 494 10.1603/EC13216.

- 495 Piqué, J., Eizaguirre, M., Pons, X., 1998. Soil insecticide treatment against maize soil
 496 pests and corn borers in Catalonia under traditional crop conditions. Crop Prot. 17
 497 (7), 557-561. doi: 10.1016/S0261-2194(98)00044-1.
- Richards, R.A., 2000. Selectable traits to increase crop photosynthesis and yield of
 grain crops. Exp. Bot. 51, 447-458. doi: 10.1093/jexbot/51.suppl 1.447.
- Riedell, W.E., Gustin, R.D., Beck, D.L., 1992. Effect of irrigation on root growth and
 yield of plants damaged by western corn rootworm larvae. Maydica 37, 143-148.
- 502 Riedell, W.E., Schumacher, T.E., Evenson, P.D., 1996. Nitrogen fertilizer management
- to improve crop tolerance to corn rootworm larval feeding damage. Agron. J. 88,
 27-32. doi: 10.2134/agronj1996.00021962008800010006x.
- Ritter, C., Richter, E., 2013. Control methods and monitoring of *Agriotes* wireworms
 (Coleoptera: Elateridae). J. Plant Disease Prot. 120 (1), 4-15.
 www.jstor.org/stable/43229259.
- Sutter, G.R., Fisher, J.R., Elliott, N.C., Branson, T.F., 1990. Effect of insecticide
 treatments on root lodging and yields of maize in controlled infestations of western
 corn rootworm (Coleoptera: Chrysomelidae). J. Econ. Entomol. 83, 2414-2420.
 doi: 10.1093/jee/83.6.2414.
- 512 Urías-López, M.A., Meinke, L.J., 2001. Influence of Western Corn Rootworm
 513 (Coleoptera: Chrysomelidae) larval injury on yield of different types of maize. J.
 514 Econ. Entomol. 94 (1), 106-111. doi: 10.1603/0022-0493-94.1.106.
- van Rozen, K., Ester, A., 2010. Chemical control of *Diabrotica virgifera virgifera virgifera*LeConte. J. Appl. Entomol. 134, 376-384. doi: 10.1111/j.1439-0418.2009.01504.x.
 Vasileiadis, V.P., Sattin, M., Otto, S., Veres, A., Pàlinkàs, Z., Ban, R., Pons, X., Kudsk,
- 518 P., van der Weide, R., Czembor, E., Moonen, A.C., Kiss, J., 2011. Crop protection
- 519 in European maize-based cropping systems: current practices and

- 520 recommendations for innovative Integrated Pest Management. Agric. Syst. 104,
- 521 533-540. doi: 10.1016/j.agsy.2011.04.002.