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

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## 1 **Abstract**

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

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

10 Without furrow insecticides, plant density was reduced at all of the considered planting  
11 times (+5.3%). Insecticide application led 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  
17 the compared production situations. The yield increase was higher than 5% in 70% of  
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.

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

24

25

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

33

## 34 **1. Introduction**

35 The Western Corn Rootworm (WCR), *Diabrotica virgifera virgifera* LeConte  
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  
39 century (Park and Tollefson, 2006). In Europe, WCR is considered an invasive species,  
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  
44 Europe, included northern Italy (Kiss et al., 2005). Economic damage is more common  
45 in areas in which maize is grown as a continuous crop and where the environmental  
46 conditions are favourable to the building of high WCR populations.

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

52 Since WCR larvae only feed on maize roots and can only survive in small numbers on  
53 a limited number of non-maize grasses (Oyediran et al., 2004), crop rotation has  
54 proved to be an effective pest management strategy when the action threshold is  
55 exceeded. However, the intense use of a simple crop rotation, such as the maize-  
56 soybean rotation adopted in the Midwest in the USA, has selected for an insect strain  
57 that can lay down eggs in soybean fields. The larvae hatching from these eggs emerge  
58 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  
61 continuous maize is preferred, if the pest is widespread and reaches high population  
62 levels, soil and/or foliar insecticides are frequently applied. Insecticide sprays used to  
63 control the adults can be applied at the beginning of female egg laying to reduce  
64 oviposition or, in case of extremely high infestation, before silking to reduce silk feeding  
65 by WCR adults. In this case, the timing of the insecticide application is critical, and  
66 needs precise knowledge on the phenology of the WCR population in the field.

67 The most common strategies used to protect maize roots from WCR are the application  
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).

75 In recent years, the use of maize seeds treated with insecticides belonging to the  
76 neonicotinoid class has been restricted in several European countries because of their  
77 adverse effects on honeybees (Girolami et al., 2012). This restriction has determined  
78 a notable increase in soil insecticide applications for maize crops, thus raising  
79 concerns about their undesired side effects on the agroecosystem and non-target  
80 organisms, and about their effective benefit to the crop (Furlan and Kreuzweiser,  
81 2015).

82 The effectiveness of soil-applied insecticides and seed dressings is variable and still  
83 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  
85 and eradication programs (Furlan et al., 2006), but their efficacy in containing root  
86 damage has been confirmed. The effects on yield of soil insecticides, such as tefluthrin,  
87 thiamethoxam, tebuirimphos and cyfluthrin, are reported quite inconstant, varying  
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 Kreuzweiser, 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.

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

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

110



## 111 **2. Materials and Methods**

### 112 2.1. Experimental set up

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.

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

131 The effect of soil insecticide application was evaluated considering different intervals  
132 between planting time and expected egg hatching. The compared PS were subdivided  
133 into 3 groups on the basis of the interval of cumulated growing degree days (GDD)  
134 from the maize planting date to the end of egg hatching, expressed as the 90% of 1<sup>st</sup>  
135 instar WCR larvae cumulative occurrence (WCR90%). The logistic equation developed

136 by Davis et al. (1996) with a minimum and maximum developmental threshold for the  
137 WCR larvae of respectively 11°C and 18°C was used to calculate the cumulated GDD  
138 from January 1<sup>st</sup> to WCR90% and to the maize planting date of each PS. The  
139 quantification of the cumulated GDD interval between maize planting date and the end  
140 of egg hatching (MP-WCR90%) was performed using the maximum and minimum air  
141 temperatures recorded by weather stations located next to each experimental site.  
142 In order to obtain an equal distribution of recorded cases, the considered PS were  
143 subdivided into the following MP-WCR90% classes: GDD < 150 °C d<sup>-1</sup>(23 cases), 150-  
144 230 °C d<sup>-1</sup> (28 cases), and > 230 °C d<sup>-1</sup>(25 cases).  
145 The soil insecticide was distributed using a calibrated granular dispenser or sprayer  
146 applied to the planter. The insecticide was distributed in seed furrows at a depth of 5-  
147 10 cm from the soil surface at the recommended rate for each product according to the  
148 equipment setting and the desired seeding depth. No insecticide was applied as a seed  
149 dressing in any of the tested PS. The applied soil insecticides belong to the pyrethroid,  
150 neonicotinoid or organophosphate classes, and they are listed in Table 1. The  
151 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 the  
162 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 ( $23\pm 1^{\circ}\text{C}$  T,  $65\pm 2\%$   
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.

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

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

187

### 188 2.3. Crop measurements

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

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

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

201 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 m<sup>2</sup> 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.

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

228

### 229 **3. Results**

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

233 Without furrow insecticides, plant density was reduced at all of the considered planting  
234 times ( $P < 0.001$ ). On average, the untreated control resulted in a 5.3% lower plant  
235 density compared to the soil-applied insecticide treatment. Moreover, the advantage  
236 of insecticide application was significantly affected by the planting time: in the early  
237 sowings, which were conducted between mid-March and mid-April ( $MP-WCR90\% >$   
238  $230 \text{ GDD}$ ), 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  
240 between the insecticide treatments and the control was 7.3%. Conversely, the plant  
241 density at the 150-230 planting time and  $< 150 \text{ }^\circ\text{C d}^{-1}$  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,

254 compared to the untreated control, was 45%, 40% and 22%, with MP-WCR90%  
255 intervals of < 150, 150-230 and > 230 °C d<sup>-1</sup>, respectively.

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

262 The soil-insecticides applied to the maize seed furrow resulted in a significant reduction  
263 (P<0.001) of root injury (-75%) and in the occurrence of plants with “gooseneck”  
264 symptoms (-71%), compared to the untreated control (Table 2). Moreover, the  
265 reduction was similar in all the considered intervals between maize planting and larval  
266 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<sup>-1</sup> (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.

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

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

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

289



## 290 **4. Discussion**

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

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

300 Under artificial and controlled infestation, Sutter et al. (1990) reported that yield  
301 protection by means of insecticides was effective and significantly higher at greater  
302 WCR infestation levels, and the compared insecticides (carbofuran, terbufos,  
303 isofenphos active ingredients) did not differ in their crop protection ability. Furthermore,  
304 the application of soil insecticide treatments significantly reduced lodging, although  
305 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<sup>-1</sup>, and it creates benefits in 54% of the cases. By  
312 considering a maize grain price of 170 € t<sup>-1</sup> and an average cost of soil insecticide of  
313 80 € ha<sup>-1</sup>, an economically profitability of soil insecticide application was observed in  
314 85% of the production situations analyzed in the present study. On average, the

315 economic advantage of using soil insecticide was 125 € ha<sup>-1</sup>. Conversely, in other  
316 environmental, agronomic and insect pressure conditions, some authors have reported  
317 insecticide treatments against soil maize pests as not being justified, both in the  
318 presence (Kuhar et al., 1997; Furlan et al., 2006; Cox et al., 2007; Petzold-Maxwell et  
319 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  
344 different efficacy on WCR is obtained through the application of systemic or non-  
345 systemic soil insecticides, considering both applications to seed furrows or as seed  
346 dressings, where available.

347 The application of insecticides to seed furrows also plays an important role in  
348 controlling other soil insects, such as *Agriotes* spp. wireworms (Ritter and Richter,  
349 2013). Although these larvae are polyphagous, they can feed on maize roots in the  
350 same way as *D. v. virgifera* larvae, and can cause comparable economic damage.  
351 Moreover, wireworm feeding may prevent germination and increase seedling mortality,  
352 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

363 explain the increasing trend in grain yield observed from the late planting time to the  
364 earlier one.

365 The collected data underline that planting-time soil insecticides can be used as an  
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<sup>-1</sup> day<sup>-1</sup>, 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 (Borioni 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.

397

398 **5. References**

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