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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

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

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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>

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 1st
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 1st 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⁻¹(23 cases), 150-
144 230 °C d⁻¹ (28 cases), and > 230 °C d⁻¹(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 m² 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 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.

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 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⁻¹, 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⁻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.

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⁻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

315 economic advantage of using soil insecticide was 125 € ha⁻¹. 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⁻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 (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

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