Bulletin of Insectology **66** *(1): 135-142, 2013*
ISSN 1721-8861

Effect of male mass trapping of *Agriotes* species on wireworm abundance and potato tuber damage

Muhammad SUFYAN[1], Daniel NEUHOFF[1], Lorenzo FURLAN[2]
[1]*Institute of Organic Agriculture, University of Bonn, Germany*
[2]*Veneto Agricoltura, Legnaro (PD), Italy*

Abstract

The use of sex pheromones as an option to control wireworms via mass trapping and the biology of *Agriotes lineatus* (L.) were investigated in a long-term field experiment at an organic research farm in North Rhine-Westphalia, Germany. Plots supplied with sex pheromone traps were compared with untreated control plots. Over 5 years, a total of 12,378 male adults of *A. lineatus*, *Agriotes obscurus* (L.) and *Agriotes sputator* (L.) were captured in six traps located at 40 m distance in a grass-clover ley. The swarming period of the males lasted from late April to late August with one major and a small peak in the successive years for all three species. During 2006 and 2008 *A. lineatus* was the dominant species trapped with 4,005 male adults followed by *A. obscurus* (3,045) and *A. sputator* (1,213). The total number of wireworms captured over all sampling dates only slightly differed between the two pheromone treated plots (201 individuals) and the two control plots (230 individuals) suggesting no effect of mass trapping on wireworm abundance. The peak oviposition period of *A. lineatus* lasted from May to early June. Over a 30 month period the larvae passed through 8 instar stages (life cycle not completed) and attaining L4 instar stage before the first and L8 before the second overwintering. Non-chemical wireworm control will have to focus on cultural approaches including soil tillage and rotation design taking data on biology into account.

Key words: pheromone traps, click beetles, Coleoptera Elateridae, male capture, tuber holes, *Agriotes lineatus* biology.

Introduction

Wireworms (*Agriotes* spp.) the larvae of click beetles (Coleoptera Elateridae), are known as important soil insect pests of agricultural crops. Potatoes are particularly susceptible to this pest and even populations at or below the limit of detection of standard soil sampling techniques are capable of causing economic damage to potatoes (Miles, 1942). Due to their long life cycle and soil dwelling habitat they are difficult to control. Adult click beetles emerge from overwintering cells in early spring and females lay eggs singly or in clusters just below the soil surface preferentially in locations such as leys (Fox, 1973). The newly hatched larvae known as wireworms, feed on a variety of crop roots until they pupate and emerge after 2-5 years depending on species, region and environmental conditions (Jansson and Seal, 1994; Parker and Seeny, 1997).

According to recent surveys *Agriotes lineatus* (L.), *Agriotes obscurus* (L.), *Agriotes sputator* (L.), *Agriotes ustulatus* (Schaller) and *Agriotes sordidus* (Illiger) are the predominant species occurring in West Germany (Burghause and Schmitt, 2011), and they live in both agro- and natural ecosystems (Platia, 1994). To monitor the flight behaviour of these species, specific synthetic sex pheromones for male trapping have been developed (Toth *et al*., 2003) and the recent development of YATLOR traps proved to be highly efficient in capturing male click beetle (*Agriotes*) species (Furlan *et al*., 2001). However, Hicks and Blackshaw (2008) noted a considerable variability in the performance of sex pheromone trapping systems and optimal trap spacing for several *Agriotes* species. Recent studies on the range of attraction of pheromone traps to some *Agriotes* species suggested that an estimated distance of 20 m between individual traps would be needed to permit substantial mass trapping (Sufyan *et al*., 2011). A prediction of potential wireworm damage based on male trapping with pheromones is not yet possible (Blackshaw and Vernon, 2008). In general sex pheromone traps have been proven to be effective for monitoring and may have a potential to suppress or eradicate low density populations, but the full potential for pest management is still unclear (El-Sayed *et al*., 2006). There are more than 200 studies from 1970 to 2005 targeted on managing pest populations by mass trapping, mainly for Lepidoptera, Coleoptera, Diptera and Homoptera (El-Sayed, 2012). Mass trapping of different pests such as *Leucinodes orbonalis* Guenee (Cork *et al*., 2001; 2003; 2005), *Ips duplicatus* (Sahlberg) (Schlyter *et al*., 2001) and *Ephestia kuehniella* Zeller (Trematerra and Gentile, 2010) resulted in a reduction of insecticide consumption and in a significant yield increase of different agricultural crops. Pheromone mediated mating disruption is also an alternate strategy in biological control programs and has been successful for agricultural pests such as *Pectinophora gossypiella* (Saunders) (Doane *et al*., 1983) and *Palpita unionalis* (Hubner) (Hegazi *et al*., 2007). Although the majority of successful mass trapping systems has been carried out with lepidopterous pests, the method has also been suggested for click beetles (El-Sayed *et al*., 2006).

The objective of our study was to investigate whether regular male mass trapping via sex pheromones over a five year period will result in a decrease of soil wireworm abundance and subsequently in reduced damage of potato tubers. Simultaneously we studied the biology of *A. lineatus* in order to identify cultural approaches for non-chemical wireworm control.

Materials and methods

Location

The study was conducted at the organic research farm 'Wiesengut' of the University of Bonn in Hennef from 2004 to 2010 in a grass-clover ley (sown in 2003 and ploughed in 2009) known to be a favourable breeding habitat for adult click beetles (Parker and Seeny, 1997). The mixed farm with suckler cows is characterized by slightly acid alluvial soils with a loamy texture. The regional climate in the Rhineland area is mild with an annual average temperature of 10.3 °C providing on average some 850 mm of rain per year. For our study mean monthly temperature (figure 1) and precipitation (table 1) during April, May, June, July and August were recorded on the farm. In addition we calculated the sum of temperature above 0 °C from the beginning of year to the first flight peak of three *Agriotes* species for the experimental years 2006-2008 (table 2).

Experimental design and trap installation

Four equal-sized plots each one measuring 20 × 30 m = 600 m² were selected in the grass-clover ley following a pair-wise arrangement (figure 2). On the Northern side two plots were supplied with YATLOR pheromone traps at a distance of 40 m. On the Southern part of the ley two control plots without pheromone traps were established at a distance of 65 m to the pheromone traps. Single pheromone traps for the three target species (*A. lineatus*, *A. obscurus* and *A. sputator*) were placed randomly in the centre of the plot at a distance of one meter. The YATLOR traps in use were made of plastic in an Italian laboratory and proved to be suitable for catching both flying and crawling species all along the season (Oleschenko *et al*., 1987; Kudryavtsev *et al*., 1993). Pheromones were delivered by Csalomon (Plant Protection Institute, HAS, Budapest, Hungary) and comprised a mixture of geranyl octanoate and geranyl butanoate in a 9:1 ratio for *A. lineatus*, geranyl hexanoate, geranyl octanoate in a 1:1 ratio for *A. obscurus* and only geranyl butanoate for *A. sputator* (Toth *et al*., 2003). The traps were deployed in early April and sampling continued at approximately one-week intervals until August of each experimental year. Pheromone lures were replaced in intervals of 4-6 weeks. The trapped beetles were removed weekly and stored at −20 °C for killing. Dead male beetles were counted and after 2006 identified on the basis of pronotum and elytral characteristics. Weekly countings were related to captures per day.

Soil sampling and wireworm extraction procedure

Soil cores were taken in all plots once in 2004, three times in 2006 and twice from 2007 to 2009, either in spring (May) or in autumn (September or late October). Sampling dates were selected to coincide with the presumed feeding periods of the larvae, which tend to move to deeper soil layers with increasing soil drought or extreme temperatures (Staley *et al*., 2007). Up to forty cores per plot and assessment date (minimum 20) were sampled using a 13 cm diameter soil corer (26 cm depth) in a W-pattern excluding the outer 3 meter of each plot side. All samples were initially hand-sorted for the presence of wireworms and collected individuals were counted and identified. Once hand-sorted, samples were placed in tullgren funnels (26 cm in diameter) provided with a 0.5 cm mesh and collecting vials at the bottom. The soil cores were dried for 4 to 8 weeks in a sheltered place to extract the remaining specimens.

Damage assessment in potatoes

In early spring 2009, i.e. five years after regular removal of all male click beetles, the grass-clover ley was inverted by ploughing. Hence potatoes cv. *Belana* was planted (4 tubers per m^2) on 15 April 2009 and managed according to the farm standards. Prior to the final harvest (potato harvester) from every plot two rows each one measuring a length of 5 m were harvested by hand. From each row, samples of 100 graded tubers (marketable size) were randomly taken, washed and assessed for wireworm damage using a rating from 0 to 3 corresponding to 0, 1-2, 3-5 and >5 holes per tuber.

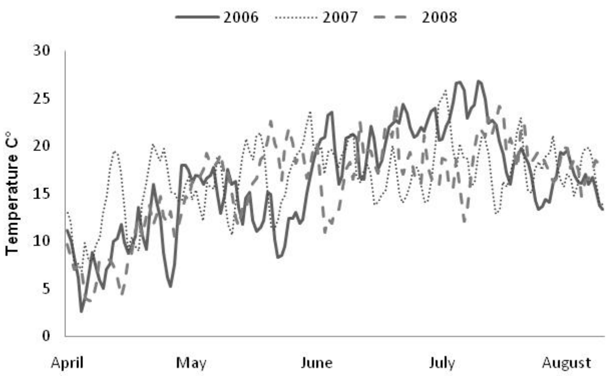

Figure 1. Mean temperature pattern from April to August during the swarming period of *Agriotes* species (*A. lineatus*, *A. obscurus* and *A. sputator*) in experimental years 2006-2008.

Table 1. Sum of monthly rain (mm) during the main activity period of *Agriotes* species from April to August during 2004-2008.

	2004	2005	2006	2007	2008
April	56	95	60	0	71
May	87	81	123	125	20
June	80	25	55	110	115
July	113	201	35	98	96
August	179	100	120	139	53
Total	515	502	393	472	355

Table 2. Sum of temperature (°C) from the beginning of year to the first flight peak of three *Agriotes* species (*A. lineatus*, *A. obscurus* and *A. sputator*) during 2006-2008.

Species	2006	2007	2008
A. lineatus	691	1024	905
A. obscurus	691	952	905
A. sputator	1861	1665	838

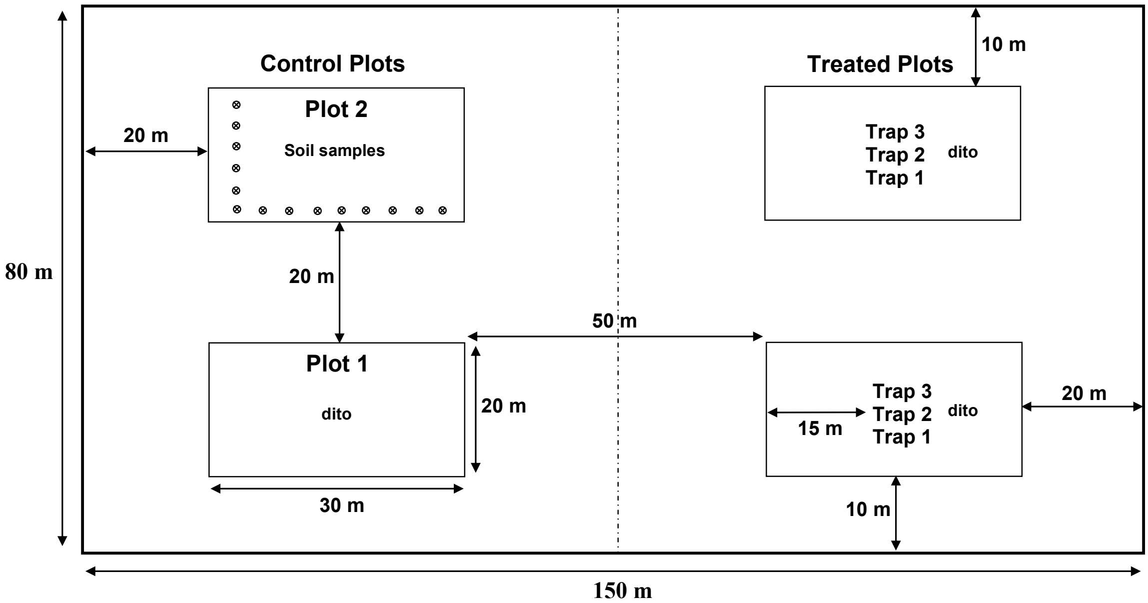

Figure 2. Experimental design of the trial (2004-2009) on grass-clover ley, Wiesengut experimental station, field 1, Trap 1 = *A. lineatus*, Trap 2 = *A. obscurus* and Trap 3 = *A. sputator*.

Biological study of *A. lineatus* in semi-natural conditions

A wooden rearing cage (size: 1 m^2; depth 1 m) was established at the border of an open field for the life-cycle study of *A. lineatus* from 2008 to 2010. The rearing cage was closed with netted walls (1-2 mm mesh) and a top (1 m^2) that allowed ventilation and rain to infiltrate. The cage was filled with a soil/sand mixture (1:1) excluding larvae of *A. lineatus.* Crops were grown according to the local cropping system with maize, grass-clover, and wheat. During periods of low rainfall, the rearing cage was irrigated (10 mm) at least once per week to maintain a suitable soil moisture level in the upper part of the soil.

Adult collection and introduction into the rearing cage

A. lineatus adults (males and females) were collected by placing out forage traps (2×2 m plastic nets) on bare soil known to be infested with *A. lineatus*. The plastic sheets were covered with fresh forage of *Lolium* and/or other grasses and red-clover (*Trifolium pratense* L.) and were inspected at least twice per week along with forage replacement. Adult beetles gathered below the forage on the sheets were regularly collected and sexed. From early April to mid-May groups (50-100) of collected adult males and females of *A. lineatus* (1:1 ratio) were repeatedly released into the cage (in total 350-400 adults).

Larval development

Soil sampling in the cage started from June 2008 onwards. Two soil cores (6 cm diameter × 25 cm deep) were taken twice per month and hand-sorted within 1-2 hours after collection. Hand-sorting of soil samples, although very time consuming, is still regarded to be the most accurate larval extraction method (Gange *et al*., 1991; Penev, 1992). The head-width of all collected larvae was measured and recorded at each assessment date. The whole soil core material including larvae were returned to the cage after each assessment. To avoid crop disturbance and killing of the young larvae during collection soil samples were replaced by bait traps (Chabert and Blot, 1992) from July 2008. Bait traps comprised of a plastic pot (10 cm in diameter) with holes drilled at the bottom filled with vermiculite, 30 ml of wheat seeds and 30 ml of corn seeds. Generally corn/wheat bait traps have been considered equally or more effective than soil cores for estimating wireworm populations (Parker, 1996; Simmons *et al*., 1998). Traps inspections were done every 15 days with concurrent replacement of trap material. Traps were checked by hand-sorting and detected wireworms were counted, identified and measured using DISKUS software microscopic system (www.hilgers.com) and finally returned to the cage. The larvae were assigned to the corresponding instars based on the head measurements (Klausnitzer, 1994).

Statistical analysis

Data were evaluated through analysis of variance by using SAS (version 9.1, SAS Institute, Cary, NC, USA). Comparisons of means were calculated with Tukey's test ($\alpha \leq 0.05$). Data on beetle flight behaviour were calculated on the basis of beetle captures per day.

Results

Pheromone trap catches

From 2004 to 2008 in an area of 1,200 m^2 a total of 12,378 male adults of *A. lineatus*, *A. obscurus* and *A. sputator* were captured by using YATLOR sex pheromone traps. The highest catches were made in 2007 (3,075 beetles) followed by 2008 (2,986 beetles). In 2005 trap catches of male adults were lowest with 1,743

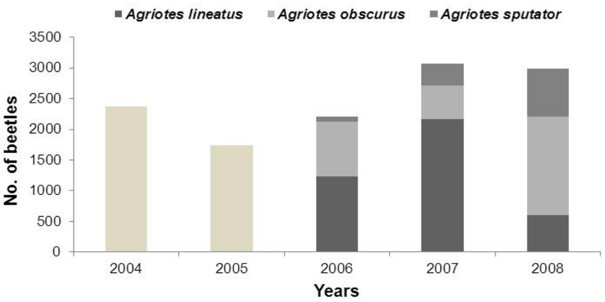

Figure 3. Catches of male adults of *A. lineatus*, *A. obscurus* and *A. sputator* species in six pheromone traps (2 per species) over the period 2004-2008, species identification since 2006.

individuals captured (figure 3). Species identification started in 2006 and the dominant species captured on average of three years were *A. lineatus* (48%) and *A. obscurus* (37%), while trap captures of *A. sputator* from 2006 to 2008 were considerably lower with a share of 15%. In 2006 *A. lineatus* was dominant with 1,236 specimens (56%) followed by *A. obscurus* (892) (41%) and *A. sputator* (74) (3%). In 2007 again the leading trapped species was *A. lineatus* with 2,161 (70%) outcompeting *A. obscurus* (549) (18%) and *A. sputator* with 365 specimens (12%). Contrarily, in 2008 *A. obscurus* was the most captured species (1,604) (54%) outcompeting *A. lineatus* (608) (20%) and *A. sputator* (774) (26%) respectively.

Flight pattern

Pheromone traps proved to be highly selective to distinguish between the species, with some sporadic catches of cross attractions due to the presence of common pheromone components in some species. Untargeted species (spiders, earwigs and Carabidae) captures were less than 1%.

The flight peaks of *A. lineatus* differed between the years. In 2006 the active period of male swarming lasted from the beginning of May to the middle of August with one main peak (153 specimens/day) in mid May and one weaker peak (36 specimens/day) in the middle of June respectively (figure 4). In 2007 the first flight peak was earlier (end of April) when 154 males were captured per day and a second weaker peak following in the beginning of June (48 males captured per day). In contrast to the preceding years *A. lineatus* captures in 2008 were relatively more uniform throughout the swarming period.

A. obscurus showed a comparable flight pattern to *A. lineatus* during the swarming period. The flight peaks noted in 2006 were in the second and third week of May with 68 and 38 adults trapped per day respectively (figure 5). In 2007 the first peak was about two weeks earlier compared with 2006. A second peak followed in the middle of June, with a steady decrease of the daily captures until the end of August. A similar flight pattern of one major (54 beetles per day) and one smaller peak (34 per day) was noted in 2008 during the middle of May and end of June.

The flight pattern of *A. sputator* showed a greater variation between the years. The first catches in 2006 were recorded in early July with a peak capture of only 8 beetles per day. In 2007 the swarming period lasted from early April to late August with one main peak (30 beetles per day) and a weaker peak (11 per day) in early and mid June respectively. Flight peaks in 2008 were detected in the beginning of May. Again the weekly captures decreased to the middle of August (figure 6).

Wireworm captures and tuber damage

In total 431 wireworms of all instar stages, exclusively *Agriotes* species were captured in the four experimental plots over all sampling dates. The total number of wireworms captured over all sampling dates only slightly differed between pheromone treated (201 individuals) and control plots (230 individuals). At the beginning of the experiment (2004) the total number of wireworms captured was 0.58 per soil core in the treated and 0.31 in the untreated plots respectively (not significant). At two

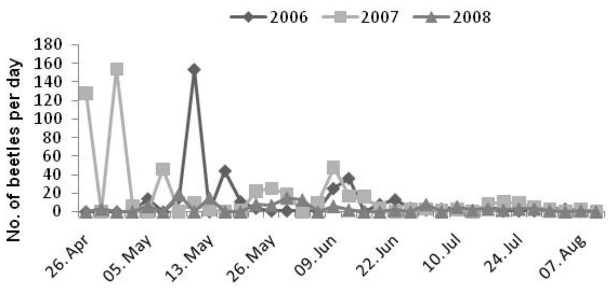

Figure 4. Flight peaks of *A. lineatus* captured in two pheromone traps over the period 2006-2008.

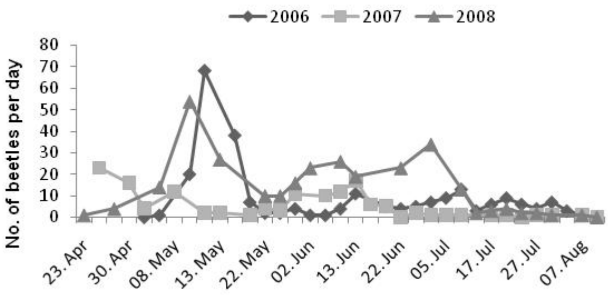

Figure 5. Flight peaks of *A. obscurus* captured in two pheromone traps over the period 2006-2008. Drawn from Sufyan *et al.*, submitted to Journal of Applied Entomology.

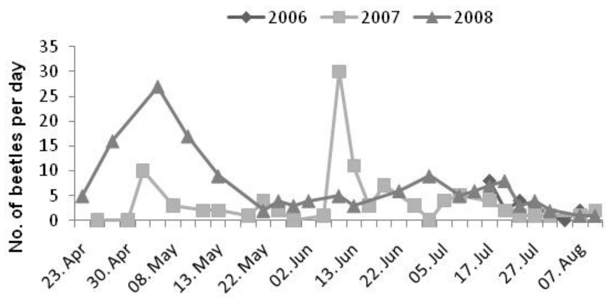

Figure 6. Flight peaks of *A. sputator* captured in two pheromone traps over the period 2006-2008.

out of nine sampling dates (May 2006 and Oct 2006), the number of wireworms per soil core was significantly lower in pheromone treated compared with control plots, the highest difference occurring in October 2006 with 0.26 compared with 0.88 wireworms per soil core (figure 7). At all other sampling dates no differences in soil wireworm abundance were noted between the treatments. The development of soil wireworm abundance over time did not follow any consistent pattern. The larval population showed a pernicious ubiquitous distribution in the treated and untreated plots with overlapping generations of all three captured species during the study.

A final assessment of wireworm holes in potatoes grown in 2009 after a five years removal of male click beetles via pheromone traps did not show any difference to the control. The extent of potato crop damage (1-2 holes per tuber) varied from 36 to 32% in treated and untreated plots respectively (figure 8). The percentage of tubers with no holes tended to be higher in control (48%) compared with 28% in the treated plots. Similarly the percentage of tuber damage with 3-5 and more holes per tuber was not affected by the treatments.

Life cycle of *A. lineatus* in rearing cage

Eggs

The first eggs of *A. lineatus* in the rearing cage were observed in late April 2008. Females started egg laying 15-20 days after the introduction of adults into the rearing cage. Peak oviposition occurred between May and early June. The eggs were creamy white to grey brown, and were laid singly or in clusters. Most of the eggs were oviposited in the upper 3-4 cm of the soil and some eggs were laid immediately on the soil surface provided that soil was covered with sward.

Larval population density

In total 287 larvae were collected and assessed by soil sampling and bait traps from 2008 to 2010. The majority of the population (256 larvae) was recorded in the second year (2009). There were very low numbers of larvae trapped by soil sampling and bait traps during the first year (15 wireworms) and third year (16 wireworms) of development (table 3). The maximum number of larvae was captured in October 2009 with 91 individuals of L5 to L8 followed by 43 wireworms of the same instar stages in November 2009.

Larval development

In total 8 larval instars for *A. lineatus* were recorded during the 30 months assessment period (cycle not completed) under semi-natural conditions (figure 9). The larvae reached the L4 instar stage with an average length of 8 mm before their first overwintering. Larval development continued in May of the following year. The variability of the larval length of the same instars and the high diversity of occurring instars was noticeable at every single assessment date. Larval stages overlapped at most of the assessment dates with a maximum range of overlap up to 4 instars, while monthly overlap was up to 5 instar stages (figure 9). The highest instar stage ever noted (L8) was recorded in autumn 2009 during the second year of development. Larvae from the L5 to L8 instar stage entered into a second overwintering and exceeded 18 mm length. Larval stages assessed during the third year were similar to those in the second.

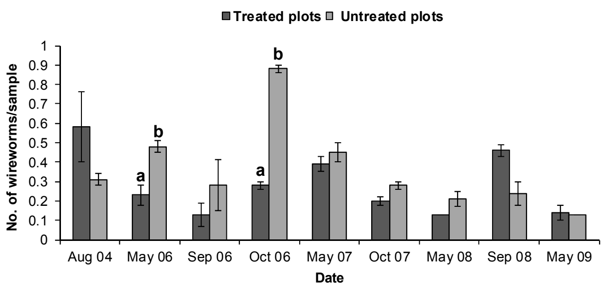

Figure 7. Number of wireworms (*A. lineatus*, *A. obscurus* and *A. sputator*) detected per soil core from 2004-2009 in pheromone treated versus untreated plots, Tukey's test (α = 0.05).

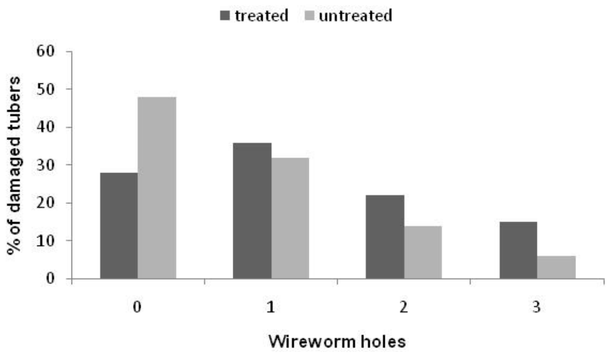

Figure 8. Mean percentage of damaged tubers in pheromone treated and untreated plots with different wireworm holes in 2009, the means of the treatments are not significantly different (α = 0.05).

Discussion

The main objective of the present long-term study was to assess, whether regular male mass trapping of three key *Agriotes* species over five years results in a decrease of soil wireworm abundance and a subsequent reduction of damages in potatoes. This approach has been proposed by El-Sayed *et al*. (2006), but has never been tested for click beetles under field conditions. While male mass trapping turned out to be successful, no effect on the subsequent soil wireworm population could be observed. Possible explanations of our observations require a closer analysis of click beetle biology and the environmental conditions of the experiment.

Male trapping

We captured click beetle males of three *Agriotes* species for five consecutive years and trapped in total over twelve thousand specimens in an area of 1200 m^2. Recent findings on the range of attraction of pheromone traps for *A. lineatus* and *A. obscurus* have shown that up to a distance of 15 m from the traps at least 50% of the

Table 3. *A. lineatus* larval development in a rearing cage from 2008-2010. Data are sum of two bait traps in one cage.

	Total	Percentage of total larvae per instar								Heat sum > 9 °C	
	larvae	1	2	3	4	5	6	7	8	Soil	Total
June 2008	0									*	
July	4	75	25							*	
August	0									*	
September	5		20	80						*	
October	6			50	50					*	
May 2009	14			57	36		7			186	186
June	28			21	18	43	18			237	423
July	14			7	29	14	36	14		321	744
August	31					13	45	42		337	1081
September	35				3	14	23	51	9	224	1305
October	91					2	24	54	20	98	1403
November	43					2	30	58	10	25	1428
May 2010	0									95	1523
June	6					33	17	50		204	1727
July	0									308	2035
August	6					17	17	66		261	2296
September	4						25	75		183	2479
October	0									73	2552

* Soil temperature data not available.

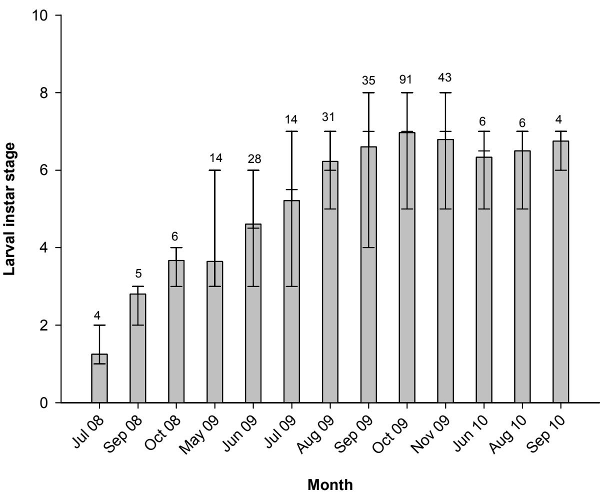

Figure 9. Development of larval instars from *A. lineatus* over a 30 months period under semi-natural conditions in rearing cage in the field. Bars represent the mean larval stage at the end of each month, while error bars represents minimum and maximum instar stage with median values.

males have been trapped within one month, most of them already during the first days (Sufyan *et al*., 2011). Given the experimental design with maximum distances within a plot of 15 m to the traps and the high number of total captures it is assumed that a considerable proportion of the males have been trapped. Also, maximum sampling ranges, i.e. the distance from which a pheromone trap is able to attract males, for *A. lineatus* 43 m after 15 days (Hicks and Blackshaw, 2008) and 54 m after 12 days (Sufyan *et al*., 2011) suggest that the control plots were properly arranged (65 m) in our experiment.

The annual variation of male captures suggests a gradual increase in the number of trapped beetles (*A. lineatus*, *A. obscurus* and *A. sputator*) from 2005 onward until the last assessment year (2008). A similar increase of pheromone male captures of *A. ustulatus* and *Agriotes rufipalpis* Brulle was noted in long-term experiments in Hungary, where 533 beetles were trapped in the first year and 5,349 beetles two years later (Toth *et al*., 2001). Likewise Karabatsas *et al*. (2001) observed a gradual increase of the *A. rufipalpis* population from 285 to 6,722 beetles during a four year monitoring in Greece. Similarly Milonas *et al*. (2010) using a different trap and experimental design, reported trap captures of more than 13,000 in two years for *A. rufipalpis* in Greece. Male trapping efficacy can be affected by the type and quantity of dispensers used in the experiments (Vernon and Toth, 2007; Milonas *et al*., 2010). The increased tendency of male trapping over time in the present study may either be due to the immigration of gravid females into the pheromone-treated areas or to the migration of males. Recent experiments of Schallhart *et al*. (2009) have shown that the natural dispersal of males of *A. obscurus* may exceed 80 m, suggesting a possible hazardous migration of the males towards the pheromone traps. Also, it remains unclear, whether the trap captures accurately reflect the true population of the area (Trematerra and Gentile, 2010).

Similar to our approach, Stelinski and Gut (2009) and Vickers (1997) studied mating disruption of moth pests of important fruits including *Argyrotaenia velutinana* (Walker), *Pandemis pyrusana* Kearfott and *Cydia pomonella* (L.). In these two studies the reproductive potential of codling moth was adversely affected with reductions in both fecundity and fertility by delays in mating.

Flight behaviour

Monitoring *Agriotes* species (*A. lineatus*, *A. obscurus* and *A. sputator*) with species-specific pheromones gave a good indication of presence and peaks of these populations in the present study and by Ester *et al*. (2001). In our study the maximum flight peak reached 154 beetles per day in two traps for *A. lineatus* and 86 beetles per day in two traps for *A. obscurus*. These values are comparable with those reported by Gomboc *et al*. (2001) with flight peaks of 150 adults of *A. lineatus* and 45 of *A. obscurus* in Slovenia. Karabatsas *et al*. (2001) in contrast captured a much higher number (>1000 males) of *A. rufipalpis* already in early April in Greece.

The development of insects is strongly affected by weather conditions (Zaslavski, 1988) and it is suggested that climate change has the potential to affect future population dynamics and intensity in agricultural systems (Strand, 2000; Bommarco, 2001). Interestingly in our study no clear relationship between the sum of temperature and the first flight peak could be observed. The available data include only a period of 3 years, which may be a too short period to evaluate to what extent the temperature affect flight behaviour. However, during this short period study there were some fluctuations noted in trap catches as well as temperature. There were no indications that weather conditions (temperature and rain) have a decisive effect on the size of trap catches. In 2006 the first flight peak of *A. lineatus* and *A. obscurus* was observed after a sum of 691 °C temperature (above 0 °C from the beginning of year), while the values for *A. sputator* (1861 °C temperature) were much higher (table 2). In 2007 the corresponding values for the temperature sum tended to be higher for *A. lineatus* and *A. obscurus* but were slightly lower for *A. sputator*. In 2008 all three species attained their first flight peak at a temperature sum of around 900 °C.

Wireworm abundance

Given the high number of captured males it can be assumed that a majority of the males in the sampling area has been trapped. However, male mass trapping over five years did not result in a decrease of the wireworm population in the soil. The missing effect of male mass trapping on wireworm abundance may either be due to the click beetles mating and moving behaviour or the immigration of gravid females. It is likely that the males already mated before being captured. The overall wireworm injuries of potatoes in our study were high, since less than 50% of the tubers were not affected by wireworm holes. Consequently the development of efficient control strategies against wireworms in organic potato production is urgently needed.

Biology of *A. lineatus*

In our study we monitored the development of *A. lineatus* in a rearing cage over a period of three years. A maximum of 8 larval instar stages were recorded after three years based on the number of moults and frequency distribution of larval body parameters indicated earlier by Klausnitzer (1994). After completing first year development the larvae reached L4 stage in current study compared to 5-9 instar stages in *A. ustulatus* and *A. sordidus* in Italy (Furlan, 1998; 2004). Similar differences were noted in instar stages in the following year of development in both studies. The number of larval instars among *Agriotes* species might be influenced by intrinsic and extrinsic factors. According to Furlan (2004) more instars tend to be found when larvae had not been allowed to stay at low temperature during winter period. Based on our data it can be expected that the life cycle of *A. lineatus* will last in Germany between four to five years.

Conclusions

Our study gives a first empirical hint that male mass trapping is not a suitable approach to reduce wireworm populations in the soil. To clarify this issue larger scale experiments would be required. Currently, pheromone traps are sensitive enough to detect low-density populations and trapping systems may indicate to growers the presence/absence of wireworm infestation (Furlan and Toth, 1999). A clear relationship between pheromone trap catches of adult click beetles and wireworm populations in the soil still needs to be established. Non-chemical wireworm control, currently have to focus on cultural approaches including soil tillage and rotation design that take data on biology into account.

Acknowledgements

We are thankful for the excellent technical assistance from Frank Täufer, Henning Riebeling and Johannes Siebigteroth in the field.

References

BLACKSHAW R. P., VERNON R. S., 2008.- Spatial relationships between two *Agriotes* click-beetle species and wireworms in agricultural fields.- *Agricultural and Forest Entomology*, 10: 1-11.

BOMMARCO R., 2001.- Using matrix models to explore the influence of temperature on population growth of arthropod pests.- *Agricultural and Forest Entomology*, 3: 275-283.

BURGHAUSE F., SCHMITT M., 2011.- Monitoringergebnisse der Schnellkäfergattung *Agriotes* (Coleoptera: Elateridae) in den Jahren 2008 bis 2010 in Rheinland-Pfalz.- *Gesunde Pflanzen*, 63 (1): 27-32.

CHABERT A., BLOT Y., 1992.- Estimation des populations larvaires de taupins par un piege attractif.- *Phytoma*, 436: 26-30.

CORK A., ALAM S. N., DAS A., DAS C. S., GHOSH G. C., PHYTHIAN S., FARMAN D. I., HALL D. R., MASLEN N. R., VEDHAM K., ROUF F. M. A., SRINIVASAN K., 2001.- Female sex pheromone of brinjal fruit and shoot borer, *Leucinodes orbonalis* (Lepidoptera: Pyralidae): blend optimization.- *Journal of Chemical Ecology*, 27: 1867-1877.

CORK A., ALAM S. N., ROUF F. M. A., TALEKAR N. S., 2003.- Female sex pheromone of brinjal fruit and shoot borer, *Leucinodes orbonalis*: trap optimization and application in IPM trials.- *Bulletin of Entomological Research*, 93: 107-113.

CORK A., ALAM S. N., ROUF F. M. A., TALEKAR N. S., 2005.- Development of mass trapping technique for control of brinjal shoot and fruit borer, *Leucinodes orbonalis* (Lepidoptera: Pyralidae).- *Bulletin of Entomological Research*, 95: 589-596.

DOANE C. C., HAWORTH J. K., DOUGHERTY D. G., 1983.- Nomate PBW, a synthetic pheromone formulation for wide area control of the pink bollworm. In: *Proceedings 10th International Congress Plant Protection*, Brighton, England.

EL-SAYED A. M., 2012.- *The Pherobase: database of pheromones and semiochemicals*.- [online] URL: www.pherobase.com

El-Sayed A. M., Suckling D. M., Wearing C. H., 2006.- Potential of mass trapping for long term pest management and eradication of invasive species.- *Journal of Economic Entomology*, 99: 1550-1564.

Ester A., Rozen V. K., Griepink F. C., 2001.- Previous research of monitoring of *Agriotes* spp. with sex pheromones, pp. 305-310. In: *Proceedings of XXI IWGO Conference*, Legnaro-Padua-Venice, Italy, October 27 - November 3, 2001.

Fox C. J. S., 1973.- Influence of vegetation on the distribution of wireworms in grassland: observations on *Agriotes obscurus* (Coleoptera: Elateridae).- *Phytoprotection*, 54: 69-71.

Furlan L., 1998.- The biology of *Agriotes ustulatus* Schäller (Coleoptera: Elateridae). II. Larval development, pupation, whole cycle description and practical implications.- *Journal of Applied Entomology*, 122: 71-78.

Furlan L., 2004.- The biology of *Agriotes sordidus* Illiger (Coleoptera: Elateridae).- *Journal of Applied Entomology*, 128: 696-706.

Furlan L., Toth M., 1999.- Evaluation of the effectiveness of the new *Agriotes* sex pheromone traps in different European countries, pp. 171-175. In: *Proceedings of the XX Conference of the International Working Group on Ostrinia and other maize pests*.

Furlan L., Toth M., Yatsinin V., Ujvary I., 2001.- The project to implement IPM strategies against *Agriotes* species in Europe: what has been done and what is still to be done, pp. 253-262. In: *Proceedings of XXI IWGO Conference*, Legnaro-Padua-Venice, Italy, October 27 - November 3, 2001.

Gange A. C., Brown V. K., Barlow G. S., Whitehouse D. M., Moreton R. J., 1991.- Spatial distribution of garden chafer larvae in a golf tee.- *Journal of Sports Turf Research Institute*, 67: 8-13.

Gomboc S., Milevoj L., Bitenc P., Bobnar A., Celar F., Furlan L., Toth M., 2001.- Two-years of monitoring click beetles and wireworms in Slovenia, pp. 283-292. In: *Proceedings of XXI IWGO Conference*, Legnaro-Padua-Venice, Italy, October 27 - November 3, 2001.

Hegazi E. M., Konstantopoulou M. A., Milonas P., Herz A., Mazomenos B. E., Khafagi W. E., Zaitun A., Abdel-Rahman S. M., Helal I., El-Kemny S., 2007.- Mating disruption of the jasmine moth *Palpita unionalis* (Lepidoptera: Pyralidae) using a two pheromone component blend: A case study over three consecutive olive growing seasons in Egypt.- *Crop Protection*, 26: 837-844.

Hicks H., Blackshaw R. P., 2008.- Differential responses of three *Agriotes* click beetle species to pheromone traps.- *Agricultural and Forest Entomology*, 10: 443-448.

Jansson R. K., Seal D. R., 1994.- Biology and management of wireworm on potato, pp. 31-53. In: *Proceedings of the International Conference on Advances in Potato Pest Biology and Management.* October 1991, Jackson Hole, Wyoming, USA.

Karabatsas K., Taakiris V., Zarpas K., Tsitsipis J. A., Toth M., Furlan L., 2001.- Seasonal fluctuation of adult and larvae of *Agriotes* spp. (Col. Elateridae) in central Greece, pp. 269-275. In: *Proceedings of XXI IWGO Conference*, Legnaro-Padua-Venice, Italy, October 27 - November 3, 2001.

Klausnitzer B., 1994.- Familie Elateridae, pp. 118-189. In: *Die Larven der Käfer Mitteleuropas, Myxophaga/Polyphaga* Band 2 (Klausnitzer B., Ed.).- Gustav Fisher Verlag, Jena, Germany.

Kudryavtsev I., Siirde K., Laats K., Ismailov V., Pristavko V., 1993.- Determination of distribution of harmful click beetle species (Coleoptera: Elateridae) by synthetic sex pheromones.- *Journal of Chemical Ecology*, 19: 1607-1611.

Miles H. W., 1942.- Wireworms and agriculture.- *Journal of the Royal Agricultural Society of England*, 102: 1-13.

Milonas P. G., Kontodimas D. C., Michaelakis A., Raptopoulos D. G., Konstantopoulou M. A., 2010.- Optimization of pheromone trapping method for click beetles, (*Agriotes* spp.) in Greece.- *Phytoparasitica*, 38: 429-434.

Oleschenko I. N., Ismailov V. Y., Soone J. H., Laats K. V., Kudryavtsev I. B., 1987.- A trap for pests. USSR Author's Cer. No. 1233312.- *Byll. Izobretenii*, 11: 299.

Parker W. E., 1996.- The development of baiting techniques to detect wireworms (*Agriotes* spp., Coleoptera: Elateridae) in the field, and the relationship between bait-trap catches and wireworm damage to potato.- *Crop Prot*, 15: 521-527.

Parker W. E., Seeney F. M., 1997.- An investigation into the use of multiple site characteristics to predict the presence and infestation levels of wireworms (*Agriotes* spp., Coleoptera: Elateridae) in individual grass fields.- *Annals of Applied Biology*, 130: 409-425.

Penev L. D., 1992.- Qualitative and quantitative spatial variation in soil wireworm assemblages in relation to climatic and habitat factors.- *Oikos*, 63: 180-192.

Platia G., 1994.- *Coleoptera, Elateridae*. Fauna d'Italia Vol. 33.- Calderini, Bologna, Italy.

Schallhart N., Wallinger C., Juen, A., Traugott, M., 2009.- Dispersal abilities of adult click beetles in arable land revealed by analysis of carbon stable isotopes.- *Agricultural and Forest Entomology*, 11: 333-339.

Schlyter F., Zhang Q.-H., Liu G.-T., Ji L.-Z., 2001.- A successful case of pheromone mass trapping of the bark beetle *Ips duplicatus* in a forest island, analysed by 20-year time-series data.- *Integrated Pest Management Reviews*, 6: 185-196.

Simmons C. L., Pedigo, L. P., Rice M. E., 1998.- Evaluation of seven sampling techniques for wireworms (Coleoptera: Elateridae).- *Environmental Entomology*, 27 (5): 1062-1068.

Staley J., Mortimer S. R., Morecroft M. D., Brown V., Masters G. J., 2007.- Summer drought alters plant-mediated competition between foliar- and root-feeding insects.- *Global Change Biology*, 13: 866-877.

Strand J. F., 2000.- Some agrometeorological aspects of pest and disease management for the 21st century.- *Agricultural and Forest Meteorology*, 103: 73-82.

Stelinski L. L., Gut L. J., 2009.- Delayed mating in tortricid leafroller species: simultaneously aging both sexes prior to mating is more detrimental to female reproductive potential than aging either sex alone.- *Bulletin of Entomological Research*, 99: 245-251.

Sufyan M., Neuhoff D., Furlan L., 2011.- Assessment of the range of attraction of pheromone traps to *Agriotes lineatus* and *Agriotes obscurus*.- *Agricultural and Forest Entomology*, 3 (13): 313-319.

Toth M., Imeri Z., Szarukan I., Körösi R., Furlan L., 2001.- First results of click beetle trapping with pheromone traps in Hungary 1998-2000, pp. 263-267. In: *Proceedings of XXI IWGO Conference*, Legnaro-Padua-Venice, Italy, October 27 - November 3, 2001.

Toth M., Furlan L., Yatsynin V. G., 2003.- Identification of pheromones and optimisation of bait composition for click beetle pests (Coleoptera: Elateridae) in Central and Western Europe.- *Pest Management Science*, 59: 417-425.

Trematerra P., Gentile P., 2010.- Five years of mass trapping of *Ephestia kuehniella* Z. a component of IPM in a flour mill.- *Journal of Applied Entomology*, 134: 149-156.

Vernon R. S., Tóth M., 2007.- Evaluation of pheromones and a new trap for monitoring *Agriotes lineatus* and *Agriotes obscures* in the Fraser Valley of British Columbia.- *Journal of Chemical Ecology*, 33: 345-351.

Vickers R. A., 1997.- Effect of delayed mating on oviposition pattern, fecundity and fertility in codling moth, *Cydia pomonella* L. (Lepidoptera: Tortricidae).- *Australian Journal of Entomology*, 36: 179-82.

Zaslavski V. A., 1988.- *Insect development: photoperiodic and temperature control*.- Springer, Berlin, Germany.

Authors' addresses: Daniel Neuhoff (corresponding author: d.neuhoff@uni-bonn.de), Muhammad Sufyan, Institute of Organic Agriculture, University of Bonn, Katzenburgweg 3, D-53115 Bonn, Germany; Lorenzo Furlan, Veneto Agricoltura, viale dell'Università 14, 35020 Legnaro PD, Italy.

Received August 10, 2012. Accepted March 25, 2013.