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The effectiveness of electrified fencing using copper electrodes for slug (*Airon* spp.) control with direct electric current and voltage

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Abstract

Terrestrial slugs of the genus *Arion* are native to Europe, where they represent an important agricultural pest. This study determined the effectiveness of electrified fencing on barrier crossing by slugs. The fences were placed in glass insectariums. DC (direct current) voltages (2, 4, 6, 8 and 10 V) applied across the fence were tested together with limiting electric current values (0.1, 0.01 and 0.001 mA). Four categories of behavior were identified for slugs in the presence of an electrified fence: the animals (1) were stationary, (2) were moving but avoided the electrodes, (3) touched the electrodes and/or attempted unsuccessfully to cross the electrified fence and (4) succeeded in crossing the electrified fence. The effect of the applied voltages and the limiting current values on slug movement was highly significant. Forty-one percent of slugs crossed the fence at the lowest applied voltage, whereas only 1% of slugs succeeded in crossing at the highest voltage. The lowest limiting current values resulted in the most frequent fence crossings. For larger voltages and limiting currents, the frequency of slug crossings was effectively zero at fence regions positioned on the glass walls of the insectariums. In conclusion, this method of slug prevention may be highly effective, environmentally friendly and may result in deterrence, not death, of terrestrial slugs, a ubiquitous pest responsible for significant economic damage in agriculture.

Additional key words: behavioral events; crossing; pests; repellent; terrestrial mollusks.

Resumen

Efectividad de las vallas electrificadas con electrodos de cobre en el control de las babosas (*Arion* spp.) bajo corriente continua y voltaje eléctrico

Las babosas terrestres del género *Arion* son nativas de Europa, donde representan una importante plaga agrícola. En este trabajo se determinó la eficacia de usar barreras electrificadas para impedir el paso de las babosas. Se colocaron vallas electrificadas en insectarios de vidrio y se aplicaron voltajes de CC (2, 4, 6, 8 y 10 V), limitados por diferentes valores de corriente eléctrica (0,1, 0,01 y 0,001 mA). Se identificaron cuatro diferentes respuestas de comportamiento de las babosas: (1) se quedaron quietas, (2) se movieron evitando los electrodos, (3) tocaron los electrodos e/o intentaron, sin éxito, cruzar la valla y (4) lograron cruzar la valla electrificada. El efecto de los voltajes aplicados y de los valores de corriente limitantes en el movimiento de las babosas fue muy significativo. El 41% de las babosas cruzó la valla con el menor voltaje aplicado, mientras que sólo el 1% de las babosas logró cruzar con el voltaje más alto. Los valores más bajos de corriente dieron lugar a los cruces más intensos de la valla. Para tensiones y corrientes más altas la frecuencia de los cruces de las babosas fue prácticamente cero en las zonas de la valla colocada en las paredes de vidrio de la insectarios. En conclusión, este método de control de las babosas puede ser muy eficaz, respetuoso con el medio ambiente y producir disuasión, no la muerte, de las babosas terrestres, una plaga responsable de importantes pérdidas económicas en la agricultura.

Palabras clave adicionales: cruce; eventos de comportamiento; moluscos terrestres; plagas; repelente.

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Abbreviations used: ANOVA (analysis of variance); DC (direct current); IPM (integrated pest management).

Introduction

Herbivorous terrestrial slugs and snails are destructive agricultural pests. They cause economic damage to a wide variety of plants, including vegetables, forage crops, tree fruits, shrubs, flowers, ground green cover, and newly sown lawngrasses (Port and Port, 1986; South, 1992; Faberi *et al*., 2006). Moreover, these mollusks play an important role in transmitting and spreading diseases to cultivated plants and in decreasing plant host resistance (Ohlendorf, 1999). Slugs of the genus *Arion* are an especially significant agricultural pest in Europe (Frank, 1998), North America (Hammond *et al.,* 1999) and Asia (Ahmadi, 2004). Slug-mediated damage is typically contained through the use of molluscicides because these chemicals are generally considered to represent the most effective measure for terrestrial mollusk control (Godin, 1983).

However, the widespread use of biocidal chemicals is rarely innocuous. Growers and farmers often experience difficulty controlling these pests with conventional bait pellets containing methiocarb and metaldehyde (Salvio *et al*., 2008). The efficacy of these pellets can be markedly degraded in wet conditions (Hata *et al*., 1997), resulting in unsatisfactory levels of pest control. Importantly, poison baits can be toxic to other non-target soil invertebrates, (such as the beneficial carabid beetles), to birds and to mammals such as shrews and field mice (Hagin and Bobnick, 1991; Purvis, 1996). There is no antidote for metaldehyde; long-term skin exposure of levels > 50 mg kg^{-1} leads to dermatitis, whereas eye exposure can cause conjunctivitis (Purvis, 1996). Acetylcholinesterase inhibitor-based pellets are highly toxic and have caused the deaths of pets and humans. Carbamates are believed to be the most potent class of molluscicides (Miller *et al*., 1988; Radwan *et al*., 1992), but they can be toxic to warm-blooded organisms (Maddy *et al*., 1977). Clearly, there is a substantial impetus to develop selective and toxic mollusk-deterrent compounds that have minimal effects on other species.

The development of effective alternatives to conventional molluscicides, particularly those that could be used in an integrated control strategy, would reduce plant losses, improve plant quality, and offer a sustainable strategy for controlling slug and snail pests with reduced molluscicide input. The development of alternative snail and slug control methods compatible with integrated pest management (IPM) strategies used to control other pests would help satisfy increasing market demands for ornamental plants and edible crops grown under environmentally responsible production methods (Schüder *et al*., 2003).

An alternative approach to poisoning snails/slugs chemically or biologically (*i.e*., the use of the slug-parasitic nematode *Phasmarhabditis hermaphrodita* [Schneider]; Grimm, 2002) would prevent their access to target plants. Copper barriers are believed to create an electrical current when they react to snail or slug secretions (Schüder *et al*., 2003).

The fundamental biophysical parameters that determine the efficacy of electrical fencing as a deterrent to slug movement was investigated in present research. The aim of this work was to assess the interactions of terrestrial slugs (in particular *Arion* slugs) using electric current and voltage and to determine electrical parameters that are sufficient to block the passage of slugs past an electrical fence. The results of this work established recommended values that limit the amplitude of the electric current, thereby minimizing power consumption (electrical fences would mostly be battery powered) and potential harm to the operator while at the same time providing a highly effective slug deterrent.

Material and methods

Experiments were performed at the Laboratory of Entomology, Dept. of Agronomy, Biotechnical Faculty, University of Ljubljana. Four hundred five slugs, mainly representatives of *Arion lusitanicus* J. Mabille and *Arion subfuscus* (Draparnaud), were collected beneath the hedges, near the compost heap and near the brook at the laboratory field of the Biotechnical Faculty in Ljubljana (46° 04' N, 14° 31' E, 299 m a.s.l.). The slugs collected had an average body weight of 4.2 ± 2.3 g (n = 50) and were of various ages and lengths because we wanted to analyze a comprehensive sample of outdoor slug behaviors (Laznik *et al*., 2010).

An Agilent 3631A power source was used as a DC voltage or current source. The instrument as a voltage source and tested DC voltages of 2, 4, 6, 8 or 10 V was used. For each applied voltage, three limiting current values were tested: 0.1, 0.01 and 0.001 mA. Notably, it was not necessary for a limiting value of the set current to be reached when the slug touched or crossed the electrodes of the fence. This issue is explored in more detail in the Discussion section.

The slugs were placed in a glass insectarium (width-length-depth 500-350-400 mm). At the bottom of the

Table 1. Definitions of behavioral events occurring during the experiments

Index	Event
1	The slug is placed inside the fence but does not move.
2	The slug moves in the area inside the fence and does not reach or touch the inner electrode.
3	The slug touches the electrodes with tentacles, elevates the body in search of a "safe passage" to try to cross the electrode but does not succeed in crossing the fence.
4	The slug crosses the fence.

insectarium, three regions (area 200 mm × 140 mm) were delimited with an electrical fence. In the insectarium 3 slugs were placed, one slug in each region. The fence was constructed from electrodes made of copper adhesive tape (thickness 0.1 mm, width 10 mm) separated by 10 mm. The DC voltage source was applied to the electrodes. The behavioral response of the slugs was visually observed for approximately 10 minutes at each set of applied voltages and selected maximal currents. Each experiment was repeated three times in one day. In a subset of experimental paradigms, experiments were repeated the following day. In total, each experiment was repeated nine times.

The typical behavioral responses of the slugs during the experiment were classified in terms of four events, as described in Table 1. The numbers used to index the events were used to quantify the analysis. For example, the index value for event 2 is 2. To perform the data analysis, these index values were used as the values of the response variable "event." For ease of presentation, the term "the events" will also be used at times to refer to this response variable. For example, to calculate the average value of the events for a given combination of voltage and current, the index values were averaged for all of the slugs observed at that combination of voltage and current.

A two-way analysis of variance (ANOVA) was carried out to evaluate the differences in the response of *Arion* slugs to 15 different combinations of applied voltage and limiting electric current. The same (ANOVA) method was used to evaluate the time taken to cross the fence. Before analysis, each variable was tested for homogeneity of variance and the values transformed by arcsine square root if necessary. Duncan's multiple range test ($p \leq 0.05$) was used to analyze the differences between individual treatment means (Hoshmand, 2006). All statistical analyses were performed using Statgraphics Plus for Windows 4.0 (Statistical Graphics Corp., Manugistics, Inc., Rockville, Maryland, USA). The data are presented as untransformed means (Trdan *et al.,* 2006).

Results

General analysis: the response to voltage and current

The analysis indicated that voltage significantly affected the average index values for the events ($F = 5.50$; $df = 4, 386$; $p = 0.0003$). A statistical significance was obtained for electric current ($F = 11.41$; $df = 2, 386$; $p < 0.0001$). However, no significant influence of interaction between the voltage and current was observed ($F = 0.93$; $df = 8, 386$; $p = 0.4880$). Neither voltage ($F = 0.79$; $df = 4, 386$; $p = 0.5359$) nor current values ($F = 0.84$; $df = 2, 386$; $p = 0.4369$) had a significant effect on the time taken to cross the fence.

Individual analysis: tests of the differences between individual means

Results showed that higher current values produced less influence of voltage on the events (see Table 2). At the largest limiting current values (0.1 mA), the influence of voltage on the events was minimal. The statistical differences in the events at a current of 0.1 mA ranged from 2.63 ± 0.23 at the 2 V level to 2.56 ± 0.16 at the 8 V level. However, when the current was limited to 0.001 mA the set source voltages played a much more significant role. The most significant value of the events (3.37 ± 0.19) was observed at the lowest source voltage (2 V), whereas the lowest value of the events, 2.56 ± 0.17, was seen at the highest source voltage (10 V). Statistically significant differences between the events were also obtained for a limiting current value of 0.01 mA, where the average values ranged from 2.96 ± 0.12 at 6 V to 2.37 ± 0.16 at 8 V.

The effect of limiting current on the average crossing times was not statistically significant. A difference observed at voltages of 8 V and 10 V can be attributed to a single event (Table 2).

The analysis of the average values of the events and the average crossing times at different applied source voltages (Table 3) revealed statistically significant

Table 2. Average values of the events and average time (min) taken by slugs (*Arion* spp.) to cross copper adhesive tapes during exposure to different combinations of limiting current and source voltage. Capital and lower-case letters correspond to the grouping of means by Duncan's multiple range test ($p<0.05$) for DC electric current-limiting value and voltage, respectively. Between rows, data with different letters differ statistically

Voltage (V)	DC electric current-limiting value (mA)		
	0.001	**0.01**	**0.1**
Average values of the events (± SE)			
2	3.37 ± 0.19^{cB} (n = 27)	2.93 ± 0.22^{bA} (n = 27)	2.63 ± 0.23^{aA} (n = 27)
4	3.26 ± 0.21^{cB} (n = 27)	2.81 ± 0.13^{abA} (n = 27)	2.63 ± 0.14^{aA} (n = 27)
6	3.22 ± 0.13^{bcB} (n = 27)	2.96 ± 0.12^{bB} (n = 27)	2.56 ± 0.14^{aA} (n = 27)
8	2.78 ± 0.12^{abB} (n = 27)	2.37 ± 0.16^{aA} (n = 27)	2.33 ± 0.21^{aA} (n = 27)
10	2.56 ± 0.17^{aA} (n = 27)	2.56 ± 0.16^{abA} (n = 27)	2.56 ± 0.16^{aA} (n = 27)
p-value	0.0012	0.0495	0.7354
Average crossing time of the slugs (± SE)			
2	6.13 ± 0.64^{bA} (n = 16)	4.91 ± 0.80^{aA} (n = 11)	5.38 ± 0.65^{aA} (n = 8)
4	6.06 ± 0.57^{bA} (n = 16)	5.67 ± 2.40^{aA} (n = 3)	5.50 ± 1.50^{aA} (n = 2)
6	6.33 ± 0.91^{bA} (n = 9)	6.00 ± 1.73^{aA} (n = 3)	—
8	4.00 ± 0.00^{aA} (n = 1)	7.00 ± 0.00^{aB} (n = 1)	4.00 ± 2.00^{aA} (n = 3)
10	9.00 ± 0.00^{cA} (n = 1)	—	—
p-value	0.0462	0.7578	0.9410

—: no slugs had crossed the copper adhesive tapes.

Table 3. Average values of the events (± SE) and average crossing time of the slugs (*Arion* spp.) during exposure to different values of source voltages regardless of the values of limiting current and during exposure to different values of limiting current regardless of the value of the source voltage. Mean values followed by the same letter are not significantly different according to Duncan's multiple range test ($p<0.05$)

	Average values of the events (± SE)	**Average crossing time in minutes (± SE)**
Voltage (V)		
2	2.97 ± 0.13^{b} (n = 81)	5.57 ± 0.41^{ab} (n = 35)
4	2.90 ± 0.10^{b} (n = 81)	5.95 ± 0.53^{ab} (n = 21)
6	2.91 ± 0.08^{b} (n = 81)	6.25 ± 0.77^{ab} (n = 12)
8	2.49 ± 0.10^{a} (n = 81)	4.60 ± 1.25^{a} (n = 5)
10	2.56 ± 0.09^{a} (n = 81)	9.00 ± 0.00^{b} (n = 1)
p-value	0.0003	0.0488
DC current (mA)		
0.1	2.54 ± 0.08^{a} (n = 135)	5.08 ± 0.60^{a} (n = 13)
0.01	2.73 ± 0.07^{a} (n = 135)	5.33 ± 0.65^{a} (n = 18)
0.001	3.04 ± 0.08^{b} (n = 135)	6.16 ± 0.37^{a} (n = 43)
p-value	0.0000	0.4369

differences for average crossing times ($p=0.0488$). The values ranged from 4.60 ± 1.25 at 8 V to 6.25 ± 0.77 at 6 V of applied voltage. The values at 10 V were disregarded owing to a single confounding event. Significant differences between the event means were also obtained. The means at the higher applied voltages (2.49 ± 0.10 at 8 V and 2.56 ± 0.09 at 10 V) differed significantly from the means at the lower applied voltages (2.97 ± 0.13 at 2 V, 2.90 ± 0.10 at 4 V, and 2.91 ± 0.08 at 6 V). At the higher applied voltages, the slugs often tended to move inside the fence without touching it (index value 2). At the lower applied voltages, the slugs almost always tended to touch the electrodes but did not cross them (index value 3).

Analysis of the average value of the events and the average crossing time at different values of limiting electrical current (Table 3) revealed no significant differences in average crossing times ($p=0.4369$), whereas significant differences were found for the average values of the events ($p<0.0000$). At the two highest values of limiting current, the slugs often tended to move around the enclosure but avoided the electrodes (average event values of 2.54 ± 0.08 at 0.1 mA and 2.73 ± 0.07 at 0.01 mA), whereas at the lowest value of limiting current the slugs almost always touched the electrodes but failed to cross the fence (3.04 ± 0.08).

Discussion

Prior investigations have shown that copper barriers present an effective mechanical and physiochemical barrier for slugs because an electrochemical reaction between the copper and the snails' or slugs' secretions results in small electric currents (Sullivan and Cheng, 1976; Schüder *et al.,* 2003). Our results show that both the source voltage and the amount of electric current that flows through the slug during the touching and/or crossing of the electrical fence affect the efficacy of the barrier. At the lowest limiting current (0.001 mA), 31% of the slugs crossed the fence, whereas only 10% of the slugs crossed the fence at the highest limiting current. The present results show that the amplitude of the source voltage plays a critical function in slug behavioral control. Only 1% crossing was detected at the highest voltage (10 V), whereas 43% of slugs crossed the fence at the lowest applied voltage (2 V). It should be noted that if the limiting current was set at a certain value, it did not necessarily have to be reached during the time that the slugs were crossing or touching the electrodes.

As shown in previous studies, mollusks take up copper through ingestion (Berger and Dallinger, 1989), and directly through the foot, at least in the form of copper compounds (Ryder and Bowen, 1977). We hypothesized that by taking up copper sulfate and/or other copper compounds through the foot on contact with the patina of the fence, the slug experienced the toxic sublethal effects of copper (Cu^{2+}) or its salts. The current- and voltage-dependence of slug behavior observed in our study suggests that electrolytically produced heavy metal cations (Cu^{2+}) and local changes in pH represent aversive stimuli that act as a behavioral deterrent in parallel with the effects of the electric field (the voltage drop across the animal) itself. Consistent with this hypothesis, exposure to Cu^{2+} was shown to represent a sublethal stressor in pleurocercid snails (Paulson *et al.,* 1983) and was toxic for bivalves and polychaetes as well as gastropods (Kidwai and Ahmed, 1999; Cheung *et al*., 2002). Smith *et al.* (2009) showed that metal chelation disrupts the crosslinking of macromolecule polymer gels in gastropod mollusks. These adhesive gels carry relatively high percentages of negatively charged amino acids (Pawlicki *et al.,* 2004) that exhibit high-affinity EDTA-sensitive binding of divalent cations such as Ca^{2+} and Mg^{2+} (Smith *et al.,* 2009) and should therefore be strongly affected by electrolytically produced protons and Cu^{2+}. Accordingly, heavy metals such as Cu^{2+} impact gastropod chemoreception, resulting in decreased feeding behavior, foot paralysis and death (Cuthbert *et al.,* 1976).

As shown by Davies and Hawkins (1998), molluscan mucus contains mostly water. Water is therefore an important resource for the slug and has a strong influence on its behavior. In addition to the toxic effect of the copper patina itself, it may also be possible that copper chlorides (Rickett and Payer, 1995), urates (Bernardi *et al.,* 2009) and other compounds present in the patina produce a dehydration of the mucus. Such dehydration would stress the animal and compel it to minimize contact with the dehydrating substrate.

Another study was conducted to determine whether polytetrafluoroethylene could be used to confine slugs *Deroceras reticulatum* (O.F. Müller) to an experimental plot. Polytetrafluoroethylene proved to be 100% effective in containing slugs within a restricted area over a 17-h period and was more convenient to apply and more effective than copper foil as a means of retaining slugs in plots (Symondson, 1993).

Coto and Saunders (1987) evaluated four methods for keeping slugs inside experimental units. The methods consisted of four barriers [car grease, grease plus salt, glue (Resistol 5000) plus salt and an electric wire fence] placed around the units, which were planted with beans. Resistol 5000 plus salt gave good results in the laboratory but not in the field. The study concluded that none of the barriers could be recommended to retain slugs inside specific units and that if any physical barrier is to be used, overpopulation inside the units should be avoided. However, small units could be used if the experiment was performed in the field and with natural populations.

Chemoreception represents one of the most sensitive behavioral modalities of gastropods exposed to pollutants (Brown, 1976; Cuthbert *et al.,* 1976). It remains to be seen whether exposure to an electric field and/or current affects the chemoreceptive sensors located in the tentacles and the foot, the orientation responses and the feeding behavior of gastropod slugs and snails. Moreover, the effects of the heavy metal that forms the fence, relative to the effect of the exposure to electricity, remain to be determined. Finally, we note that the efficacy of copper barriers might be reduced in the field due to moisture, rain and corrosion (Godin, 1983).

The level of corrosion depends on chloride concentration, oxygen availability and acidity of the soil and possibly also on other factors (Afonso *et al*., 2009). The impact of copper corrosion on the current flow, voltage drop across the barrier electrodes and effectiveness of the barrier as a slug repellent in the field remains to be determined in future studies.

Our investigation has clearly demonstrated the effectiveness of electrical fence barriers with DC voltages of 8-10 V and with electric currents between 0.01 and 0.1 mA on the behavior of slugs (*Arion* spp.), an important agricultural pest. The method can be regarded as an important alternative to limacides, substances that can be harmful to people (especially children) and the environment. From this point of view, we believe that electrical deterrence of slugs is ecologically advanced and that it is also ethical because it does not kill the slugs but only prevents them from damaging the crops. Because of the current high price of the copper tapes, this method is most likely to be used by gardeners and by some growers of high-value crops.

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