DEPARTMENT for ENVIRONMENT, FOOD and RURAL AFFAIRS

Research and Development

Final Project Report

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Project title	Integrated control of slug damage in organic vegetable crops
DEFRA project code	**OF0158**
Contractor organisation and location	IACR-Long Ashton Research Station Long Ashton Bristol, BS41 9AF
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Executive summary (maximum 2 sides A4)

Slugs are important pests of a wide range of organic vegetable crops, which are high quality products, desired by consumers. Slug problems are especially acute in comparison to conventional vegetable production because use of chemical control measures is prohibited. The purpose of this project is to provide organic vegetable growers with effective integrated pest management techniques for control of slug damage. The project builds on the results of MAFF Project No. OF0137 (September 1996 to March 1999), which demonstrated that biological control using slug-parasitic nematodes (*Phasmarhabditis hermaphrodita*) can give effective and long-lasting control of slug damage to organic vegetable grown in polytunnels in autumn and early spring.

Project OF0158 has established a number of techniques that are suitable for use by organic growers for integrated control of slug damage. Importantly, ineffective techniques were also identified. The results clearly indicate that no one method of control will give a sufficient reduction in slug damage where problems are severe. Suitable combinations of control measures are necessary. Key points are summarised below:

- Cover crops: where these are grown for short periods only to prevent nutrient leaching, ryegrass should result in less severe slug problems in a following crop, compared to legumes such as red clover or vetch.
- Where a fertility–building leguminous crop is required, lucerne appears to result in slower growth in the slug population than other popular legumes (clovers and vetch) .

- A period without a fertility crop over winter, following an annual vetch crop, reduced slug populations to levels similar to those on plots without cover crop, by the following spring.
- Slug-parasitic nematodes (*Phasmarhabditis hermaphrodita*), electrical barriers and hand-picking of slugs can all be effective methods of control. They provide additive effects for slug control and, as an integrated package, they can make the difference between a valuable crop and almost complete failure due to slug damage.
- Single applications of nematodes were ineffective in some experiments. Work in a related EU project indicates that the commercial strain of the nematode is now less effective than new strains isolated at Long Ashton Research Station.
- The carabid beetle, *Pterostichus melanarius*, was not able to prevent contamination of cabbages by slugs at harvest in September, even though crops were grown in the field throughout the beetles' main period of activity. Numbers of adult *P. melanarius* are thought to be drastically reduced by ploughing and associated cultivations in spring, compared with autumn cultivation. Since soil is normally cultivated in spring before planting most organic vegetable crops that are grown over the summer, this probably prevents beetles from reaching high numbers in most such crops. However, even in a field experiment where large numbers of beetles were introduced to a summer cabbage crop, *P. melanarius* had no significant effect on the contamination of cabbage heads by slugs, which may have used the cabbage heads as refuges from beetle predation.
- Mechanical control of weeds (hand hoeing) did not reduce slug damage, even when done as frequently as twice per week.
- Although coriander has been shown to be an antifeedant for slugs (*D. reticulatum*) under laboratory conditions (Dodds *et al.*, 1999), a 2-m wide strip of this herb grown at the edge of a cabbage crop resulted in increased slug numbers within the coriander strip and in the cabbage crop at 1 m from the strip.
- Anaerobically digested compost showed strong mollusc-repellent and molluscicidal effects in laboratory studies in Switzerland, but the effects were rapidly lost when the material was stored and also after application in the field. For this reason, it is unlikely to be suitable as a practical method of slug control.
- Importantly, work in OF0158 has identified the possibility of devising systems of integrated control of slugs and weeds, both of which are the major crop protection problems facing growers of organic vegetables and soft fruit. Further work is warranted in order to develop practical systems for protecting crops from slugs whilst benefiting from their feeding activities in killing weeds.
- Contacts with organic growers have revealed that a number of the methods that are advocated for slug control in organic systems do not appear to be based on any published scientific results. This, of course, does not mean that such methods are ineffective. However, it does indicate that further work should be done to test their validity and to investigate ways to integrate their use with other methods.

Scientific report (maximum 20 sides A4)

Introduction

Organic vegetables are high quality products, desired by consumers. Slugs are important pests of a wide range of organic vegetable crops, where problems are especially acute in comparison to conventional vegetable production, because use of chemical control measures is prohibited. A survey of crop protection problems in organic vegetable production in the UK in the late 1980s, demonstrated that slugs are the most harmful pests and are second only to weeds as a crop protection problem in such crops (Peacock & Norton, 1990). The purpose of this project is to provide organic vegetable growers with effective integrated pest management techniques for control of slug damage.

This project builds on the results of MAFF Project No. OF0137 (September 1996 to March 1999), which demonstrated that biological control using slug-parasitic nematodes (*Phasmarhabditis hermaphrodita*) can give effective and long-lasting control of slug damage to organic vegetable grown in polytunnels in autumn and early spring (Glen *et al.*, 1999). However, experience with this and other biocontrol agents indicates that it is likely to be most effective when it is used as part of an integrated pest management approach. Individual elements and the ways in which they might be integrated are outlined briefly below.

Biocontrol with the nematode Phasmarhabditis hermaphrodita

The slug-parasitic nematode, *Phasmarhabditis hermaphrodita* (Wilson *et al.*, 1993), is produced in liquid culture with a selected bacterium (Wilson *et al.*, 1995a,c) by MicroBio Ltd in liquid fermenters, infective larvae are harvested and formulated in fine clay. Nematodes formulated in this way remain viable for several months under refrigeration and can be sent safely by mail. Formulated nematodes are mixed with water and applied as an aqueous suspension to the soil surface either as a drench, e.g., on a small scale using a watering can fitted with a rose or, for larger scale use, nematodes are applied through standard spraying equipment (Wilson *et al.*, 1994a,b, 1995 a,d, 1996, 1999, 2000, Glen *et al.*, 1994, 1996, 2000; Ester & Geleen, 1996; Speiser & Andermatt, 1996; Glen & Wilson, 1997; Hass *et al.*, 1999a,b). This nematode is likely to be most effective in organic vegetable crops when applied in relatively cool moist conditions, in autumn and spring (Glen *et al.*, 1999). Complementary methods of control are required, particularly to protect crops in warmer summer weather, and further studies are needed in order to investigate how to integrate the use of nematode biocontrol with other methods.

Role of carabid beetles as predators and techniques to maximise impact on slug populations

Collaborative research by the University of Cardiff and IACR - Long Ashton on predation by carabid beetles and slugs, has shown that slugs are important prey for the carabid beetle *Pterostichus melanarius*, in arable fields (Symondson *et al.*, 1996) where this carabid is capable of exerting a useful degree of control on slug populations, throughout its main period of activity, from early June to September (Bohan *et al.*, 2000, 2001; Symondson *et al.*, 2002). Crops susceptible to slugs that might benefit from this predatory activity include summer and autumn cabbage and cauliflowers, as well as Brussels sprouts.

Cultivation as a method of control

The value of cultivation and seed-bed preparation for controlling slugs has been well demonstrated in arable crops (Gould, 1961; Hunter, 1967; Stephenson, 1975; Glen *et al.*, 1989, 1990, 1992b; Glen, 2000). The aim in OF0158 was to test methods of mechanical cultivation and other techniques that are suitable for organic vegetable crops. Emphasis was to be placed on techniques that have already been developed for weed control since it was thought likely that such techniques would destroy slugs as well as weeds, if used in a suitable way. It would also be cost-effective for organic vegetable growers to use the same equipment and techniques for control of both problems, because, as already noted, weeds and slugs have been identified as the major crop protection problems in organic vegetables (Peacock & Norton, 1990).

Intercropping with attractive or repellent crops

The presence of certain weeds that are palatable to slugs has been shown to reduce the severity of slug damage to wheat seedlings (Cooke *et al.*, 1996, 1997). Although providing slugs with alternative food in the form of weeds was not as effective as the use of molluscicide pellets in reducing slug damage, intercropping with attractive plants in order to divert slug damage from a target crop could be a valuable component of integrated control.

In contrast, many plant species in the family Apiaceae (Umbelliferae) have been shown to be neuroactive and distasteful to slugs (Dodds *et al.*, 1999). Unfortunately, many of these species are inherently poisonous to mammals, but the herb, coriander, is one of the most active antifeedants in the Apiaceae under laboratory conditions (Dodds *et al.*, 1999). It is possible that antifeedant crops could be grown as intimate mixtures with attractive crops, with control measures such as nematodes targeted solely on soil around the attractive crop. However, one other intercropping configuration deserves special attention, because slug problems in many vegetable crops are thought to result from the movement of slugs from field margins. Therefore, it was important to test whether it is possible to reduce the movement of slugs from field margin habitats into organic vegetable crops by growing coriander around the edges of fields. Studies of slug damage to oilseed rape crops adjacent to wildflower strips indicate that slugs move up to about 1 m from field margins into crops (Frank, 1998). Thus, coriander was grown as a 2 m wide strip at the edge of a crop of organic cabbage.

Modification of crop rotations to minimise the risk of slug damage

Given that crop rotations in organic vegetable growing must include crops, such as red clover and green manures, to build fertility just before vegetable crops are planted, it may be possible to select cultivars of clover or other crops that are resistant to slugs which are less likely than others to encourage the build up of slug populations before vegetable crops are planted. Differences in the suitability of white clover cultivars are known (e.g. Glen *et al.*, 1992a) but no information is available on the palatability to slugs of other fertility-building crops.

Use of molluscicidal and slug repellent mulches

A partner in an EC-funded project (FAIR5-PL97-3355), at the Swiss Research Station for Organic Farming (FiBL), has experimented with a special compost for slug control. In laboratory tests, this compost showed strong molluscicidal activity against all pest slug species. In a field trial in 1996, the compost gave similar results to metaldehyde bait pellets. During the course of OF0158, FiBL was evaluating the use of plant extracts as additives to mulch material. Developments in this Swiss research closely monitored with a view to undertaking collaborative studies as part of the project described here.

Population studies

In order to evaluate the potential contributions of individual techniques described above, as well as combinations of techniques, slug populations and damage in organic vegetable crops were assessed using spatially structured sampling grids (Bohan *et al.*, 2000), paying particular attention to the distribution of slug populations in field boundaries and the edge of cropped land, because movement of slugs from field margins is thought to be important in slug damage to vegetable crops.

Integrated pest management

Little is known about the potential to exploit different combinations of control measures for control of slug damage in organic vegetables. A key aspect of this project was to identify which techniques are likely to have greatest potential and to identify combinations of technique that could be of greatest value.

Methods

A series of replicated field experiments was undertaken to meet Objectives 1, 2, 3, 4, 5, 7 and 8. Field experiments for Objectives 1 and 3 were done mainly in polythene tunnels, because such organic crops are very susceptible to slug damage and the high value of these crops would justify the cost of nematodes together with other control measures. In all polythene tunnel experiments, because the plot size was relatively small (e.g. 1.75 x 2 m), individual plots were separated by barriers made from plastic lawn edging coated with Fluon to restrict slug movement (Symondson, 1993a) between plots. All work with nematodes was done in collaboration with MicroBio Ltd, the company which produces this nematode biocontrol agent. Unless it is stated otherwise, nematodes were applied at the recommended rate of 300,000 m^{-2}. In the final year, a collaborative experiment on the use of nematodes for slug control in organic strawberries was done with Haygrove Fruit Ltd, near Kington in Herefordshire. Field experiments for Objectives 2,4, 5 and 7 were done in outdoor plots. Studies for Objective 7 paid particular attention to the distribution of slug populations in field boundaries and the edge of cropped land. For Objective 5, laboratory studies of slug growth rates and survival were undertaken as well as field experiments. Objective 6 was achieved through liaison with Dr Bernhard Speiser of the Swiss Research Station for organic Farming (FiBL). Further details of individual experiments are given in the next section.

Results

Objective 1. Evaluate biocontrol with nematodes in combination with other methods

In an experiment (99.057) established in October 1998 in Chinese cabbage grown in a polythene tunnel, nematodes were applied as bands (covering 50% of the total soil area) along crop rows at the standard rate within the treated bands, with or without mechanical weed control at intervals of 0.5, 1 or 2 weeks (see Objective 3). There were four replicates of each of the eight treatment combinations. Slug damage was severe in all treatments with no significant differences between nematode-treated and untreated plots (67.3 and 70.3% leaf area destroyed, respectively; Least Significant Difference (LSD) = 10.0). Similar results were obtained from a related experiment in 1998-99 in OF0137. The lack of effect of slug-parasitic nematodes in both experiments was puzzling, since conditions were suitable and the same batch of nematodes were effective in an experiment in mini-plots containing steam-sterilised soil (Aalten *et al.*, unpublished). This suggests that nematode antagonists may have been responsible for a rapid kill of slug-parasitic nematodes in the polytunnels.

A replicated experiment was established in polytunnels in autumn 1999, to investigate the effect of previous cover cropping on nematode survival. Soil was left as bare fallow or sown with three different fertility building crops (red clover, vetch or ryegrass), before planting Chinese cabbage in October. Soil was treated with nematodes (or untreated) at the time of planting Chinese cabbage. Nematode treatment reduced damage significantly ($P < 0.05$) with the mean angular % percentage leaf area being 22.1 on nematode-treated plots compared to 26.6 on untreated plots (LSD = 3.2) (back-transformed means 14.1% and 20.0% respectively. The performance of the nematodes, however, was not influenced by the preceding cover crop, suggesting that the cover crop did not influence nematode survival. (See Objective 4 for further details of this experiment).

In an experiment (99.047) in courgettes planted in April 1999, nematodes were applied as a drench to soil at planting time, either over all the plot, or in a 30 cm x 30 cm patch centred on each plant (Table 1). Nematodes had no effects in the first two weeks after planting, but damage to courgette stems was significantly less in plots with nematodes applied overall, in weeks 3 and 4 after planting ($P < 0.05$).

Two experiments (01.055 and 01.056) were established in autumn 2000 to investigate the value of nematodes for control of slug damage to Chinese cabbage, alone or in combination with electrical barriers and hand removal of slugs. Nematodes were applied at weekly intervals for 6 weeks from planting, either to the whole area of each plot (both experiments) or to a band 15 cm wide along the plot row (01.055 only). Weekly treatments were made because of poor results with single nematode treatments in previous years. All nematode treatments significantly reduced slug damage compared to untreated plots. Moreover, they complemented the other treatments in both experiments, as described under Objectives 3 and 8.

Table 1. Effects of nematode treatments on the mean angular percentage damage to courgette stems by slugs in the first 5 weeks after planting in a polythene tunnel (experiment 99.047).

No. weeks after planting and nematode treatment	**Nematode treatment**		
	No nematodes	**Overall**	**Patch**
1	17.1	17.0	19.7
2	41.4	39.0	36.1
3	63.5	46.9	51.4
4	74.0	55.5	60.8
5	75.0	61.5	66.0
Least Significant Diff. (*P*= 0.05)	15.5 for comparing nematode treatments 8.4 for comparing dates within each nematode treatment		

In a field trial of nematode applications in organic strawberries in collaboration with Haygrove Fruit near Kington in 2001, there were 32 plots arranged in four blocks of 8 plots. The strawberries were grown in Spanish tunnels and each plot was 7.5 m (width of tunnel) x 12 m. Each plot consisted of five raised double rows of strawberry plants planted in holes in Mypex, which covered the ground to provide weed control. Plants were watered by trickle irrigation. Nematode treatments were as shown in Table 2.

Table 2. Slug damage in the eight treatments in a field experiment in organic strawberries, 2001 (Timing 1: 10 April. Timing 2: 30 April. Timing 3: 24 May. Timing 4: 20 June).

Treatment	**% Strawberry fruits damaged by slugs**	**Angular % Strawberry fruits damaged by slugs**
A. Nematodes applied at timing 1	1.4	3.45
B. Nematodes applied at timing 2	0.8	2.24
C. Nematodes applied at timing 3	1.4	3.02
D. Nematodes applied at timing 4	2.9	4.97
E. Nematodes applied at timings 1 & 2	1.8	3.57
F. Nematodes applied at timings 3 & 4	0.7	1.84
G. Nematodes applied at timings 1, 2, 3 & 4	1.3	2.26
H. No nematodes (untreated control)	1.2	2.55
Least Significant Difference (LSD) (*P* = 0.05)		2.66

Nematodes were applied in all treatments as a coarse spray at a rate equivalent to 150,000 m^{-2} over the total area of each plot, but nematodes were applied only to a small area of soil at the base of each plant, through the planting holes in the Mypex, on the basis that (i) the vast majority of slugs damaging the fruits would emerge through these holes in order to feed, (ii) this was the only practical method of application. The same total dose of nematodes (1.5×10^5 m^{-2}) was applied in all nematode treatments (1 to 7). This was applied all at once (treatments A to D), or in two half doses (treatments E and F) or in four 1/4 doses (treatment G). Fruit damage was assessed at weekly intervals for 14 weeks from 25 June until 26 September, on the plants in the middle 4-m of the central row of each plot, to minimise the problem of slugs moving from plot to plot and thus masking the treatment effects. Little damage was recorded (Table 2) and, although there were significant differences between weeks in damage severity ($P < 0.001$), there was no evidence that any nematode treatment significantly affected damage ($P = 0.3$). Nor was there evidence of a significant interaction between treatment and damage on different dates.

Objective 2. Quantify the impact of carabid beetle predators on slug populations in organic vegetable crops and devise techniques to manage and manipulate their numbers to maximise their impact on slug populations

Pitfall traps were placed in three outdoor field experiments (two in 1999, one in 2000) in cabbage crops, to assess activity-density of carabid beetles in cabbage crops, from June to September in 1999 and 2000. However, few beetles were recorded in pitfall traps in these experiments and it is thought likely that, as suggested by Purves (1996), the spring cultivations done before these crops were planted may have inflicted heavy mortality on *P. melanarius* and other carabids that pupate in soil in springtime.

One final experiment (01.054) was established in late May 2001, in which beetle numbers were manipulated. There were 50 individual plots, each 6 m x 6 m. Each row of plots was separated by a polythene barrier to restrict beetle movement between plots, inserted to a depth of 20 cm into the soil by tractor-mounted implement on 29 May 2001 and extending to a height of 10 cm above soil level. Within each row, each plot was separated by plastic lawn edging to restrict beetle movement. Cabbage seedlings were planted on 30 May. There were six beetle treatments (Table 3), in a randomised block design. Each block consisted of 10 plots. Five plots per block were randomly assigned to the treatment where no beetles were added. Beetles (25, 50, 100, 150 or 200) were added to each of the remaining five plots per block.

Pterostichus melanarius were collected and added to these plots from late May onwards, with beetles being added on each date in numbers that were in proportion to the total numbers to be added. The target total number of beetles added per plot was achieved in mid July, and pitfall trapping was then started within each plot. Four pitfall traps were inserted in the soil of each plot, placed 1 m apart at the corners of a square in the middle. The traps were normally covered by lids so that no beetles could fall in, but the traps were opened on one day every week and examined the next morning, until early September. When this was done, 10 individuals per plot were removed and immediately frozen. The crops (foreguts) of these beetles were dissected out, weighed and processed for ELISA-testing. Any beetles removed in this way from the plots where beetles had been added, were replaced by fresh beetles.

In order to assess slug numbers and activity, a single 30 cm hardboard square was placed within the central 2 m square of each plot, every second week during the trial. Chicken layers meal was placed under the traps as bait and the traps were examined the following morning. Traps and bait were then removed. At the time of cabbage harvest in September, 16 cabbage plants were removed from the central square in each plot. Slug numbers and species were recorded a) on the soil under each plant; and b) on and within each plant head.

Table 3. Numbers of beetles trapped and number of slugs recorded at harvest (Expt 01.054). The first value for the Least Significant Difference (LSD) between treatments is for comparing plots where no beetles were added with other treatments. The second LSD is for comparing plots with different numbers of added beetles.

Number of beetles Introduced to each plot	**Mean no. beetles in pitfall traps over 8-wk period**		**Mean number of slugs per 16 plants <u>on or in cabbages</u>**		**Mean number of slugs per 16 plants <u>on soil</u> beneath cabbages**	
	Mean Square root	**Back-trans-formed mean**	**Mean Square root**	**Back-trans-formed mean**	**Mean Square root**	**Back-trans-formed mean**
0	3.11	9.6	3.80	14.4	0.89	0.8
25	3.30	10.9	3.28	10.8	0.00	0
50	2.81	7.9	3.69	13.6	1.09	1.2
100	2.83	8.0	3.94	15.5	0.28	0.1
150	3.02	9.1	3.74	14.0	1.08	1.2
200	4.00	16.0	4.65	21.6	0.89	0.8
LSD (*P* = 0.05)	0.80 1.04		0.80 1.04		0.35 0.46	

The mean number of beetles recorded in pitfall traps over an 8-week period was not significantly related to the number of beetles added (Table 3). There was, however, a significant interaction between the numbers of beetles added and date of sampling ($P < 0.05$). This was due to the fact that, in the treatment where 200 beetles were added, trap catches of beetles were initially higher than in plots without added beetles, but this difference disappeared by about the middle of the trapping period. For example on the second sampling date (25 July), the back-transformed mean trap catches in these two treatments were 49 and 24, respectively. By 5 September they were 4.6 and 5.2, respectively. This, and the large numbers of beetles recorded in plots where none were added, suggest that beetles were able to move from plot to plot despite the presence of barriers, so that differences between treatments were obscured.

ANOVA showed no significant effect of the beetle treatment on the numbers of slugs recorded on and under the cabbage plants at harvest (Table 3). However, note that the LSD values suggest that numbers of slugs on cabbages from plots with 200 added beetles were perhaps significantly higher than plots with no or 25 added beetles. These differences must be treated with caution. Correlation and regression analysis of the number of slugs on and under cabbage plants at harvest, in relation to the number of beetles recorded in pitfall traps per plot, revealed no significant relationships.

The results of this experiment, together with previous years' results in this project, indicate that beetle predators of slugs cannot be regarded as useful components of integrated control of slugs in organic cabbage.

Objective 3. Evaluate mechanical and cultural methods of control, especially methods of weed control, for their effects in reducing slug numbers and damage

In a polytunnel experiment in 1998-99 (99.057), no mechanical control was compared with vigorous hand hoeing of weeds at intervals of 2 weeks, one week and twice weekly (8 replicates of each of four treatments). There was no evidence of any effects on slug damage to Chinese cabbage (Table 4). This and a parallel experiment in OF0137 clearly indicate that mechanical hoeing for weed control cannot be considered as providing any worthwhile contribution to slug control.

Table 4. Mean percent leaf area of Chinese cabbage plants damaged by slugs, in the first 6 weeks after planting, in relation to different frequencies of hoeing for weed control. (LSD = Least Significant Difference, *P* = 0.05).

Hoeing treatment	No hoe	Hoe at 2-wk intervals	Hoe at 1-wk intervals	Hoe at ½-wk intervals
% Leaf area damaged by slugs	70.1	70.7	65.2	69.6
LSD	14.2			

An experiment (99.047) was established in April 1999 to investigate the feasibility of using prototype electrical barriers (Snailaway Ltd), alone or in combination with nematode treatments. The upper wall of each electrical barrier consisted of two horizontal conducting bands, each connected to a 9-volt battery terminal. Normally, no current flows but when a slug or snail attempted to cross, the resulting 9-volt charge is sufficient to kill or deter it. The upper conducting band overhangs the lower in such a way that the gap cannot be bridged by slug mucus alone (which would result in current draining from the battery). In addition, each plot received one of three nematode treatments, as described in Objective 1. Nematode treatments gave some protection to plants (see Objective 1), but the most effective protection was provided by the electrical barriers which prevented the severe slug damage that caused almost complete crop failure of unprotected plants (Fig. 1). With few exceptions, only plants protected by barriers survived to produce fruits. Interestingly, slug damage to fruits on plants grown within electrical barriers tended to be less severe after mid June even though after that date the plants had outgrown the protection provided by the electrical barriers. The key period for protection was clearly the early phase when the plants were readily killed by slugs.

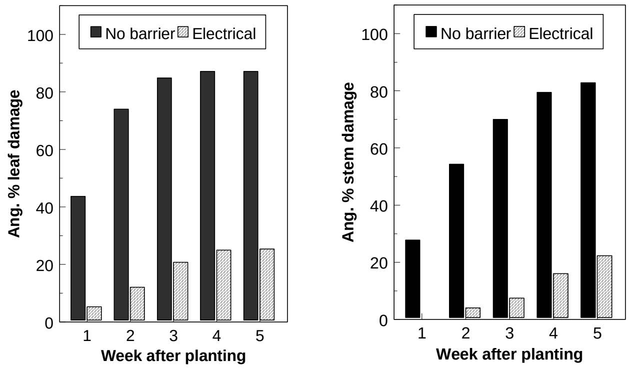

Fig. 1. Slug damage to courgette leaves and stems in the first five weeks after planting, with or without an electrical barrier around each plant.

One interesting observation in this experiment was that very few weeds survived in the areas of each plot not protected by electrical barriers. Only inside the barriers were there significant numbers of weeds (mainly chickweed, *Stellaria media* and *Veronica persica*). This observation suggests that, if plants are protected from slug damage by electrical barriers enclosing a relatively small area around each plant along a crop row, the slugs living in the area outside the barrier could be left without any form of control, thus enabling the farmer to exploit these slugs for weed control. Thus, instead of these slugs being regarded as harmful pests, they could be exploited as valuable biological control agents against weeds. This strategy would, of course, only be effective against weeds that are palatable to slugs.

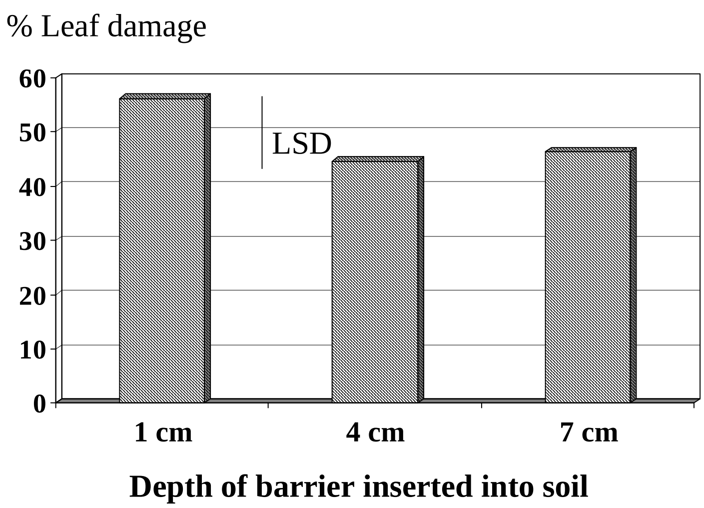

Fig. 2. Mean damage to Chinese cabbage plants inside electrical barriers inserted to different depths in soil.

Two experiments were established in autumn 2000 to further investigate the feasibility of using electrical barriers (Snailaway Ltd), alone or in combination with other treatments. The advanced prototype barriers used in these experiments were 14 cm high, made of plastic, with metal conducting strips. In one experiment (01.056), each barrier enclosed a square area (1.5 m x 1.5 m), containing 25 Chinese cabbage plants. In the other experiment (01.055), each barrier enclosed an elongated area 1.5 m long x 0.15 m wide, which contained a single row of 6 Chinese cabbage plants. In Experiment 01.055, there were three barriers in each experimental plot and each barrier in each plot was inserted to a different depth (1, 4 or 7 cm). This meant that the barriers extended to a height of 13, 10 or 7 cm above soil level, respectively. Damage to leaves of Chinese cabbage seedlings was considerably lower on plants surrounded by electrical barriers than on plants without barriers, as described in detail under Objective 8. Depth of insertion of barriers into soil did not significantly affect damage (Fig. 2), indicating that most slugs responsible for damage were probably moving over or just below the soil surface.

<u>Objective 4. Evaluate the potential for reducing crop damage by slugs by intercropping with attractive or repellent crops, as part of an integrated strategy of control</u>

<u>Objective 4a Intercropping with attractive plants</u>. A field experiment was established to investigate the potential value of intercropping autumn-heading cabbage with different fertility-building crops However, the cabbage crop was quickly suppressed by the intercrops and the experiment was therefore adapted to investigate the effects of different fertility building crops on slug populations (see Objective 5). However, the companion crops were left to grow after cabbage harvest and slug populations in these plots are being followed into summer 2000.

<u>Objective 4b Intercropping with antifeedant plants</u>. An experiment was established in May 1999, to test whether it was possible to reduce the movement of slugs from field margin habitats into a crop of summer cabbage by growing a strip of either coriander or onion as a slug-repellent crop, or by establishing a sterile strip between the crop and field margin. However, because of dry weather conditions, few slugs were recorded and results were inconclusive. A similar experiment, done in wetter weather in 2000, provided valuable results (see objective 7), but the plant chosen did not show the expected beneficial effect.

<u>Objective 5. Assess the potential value of modified crop rotations, to minimise the risk of slug damage</u>

The growth and mortality of the field slug, *Deroceras reticulatum*, fed on legume cultivars (white clover cvs Aran, Donna and Milkanova, red clover cvs Herbiseed '93 and Merviot, vetch cvs Early English and Presta) were measured in the laboratory at 15^{o}C, then analysed and modelled.

Table 5. Estimated parameters of growth in weight of *Deroceras reticulatum* (SE's in parentheses; degrees of freedom range from 17 to 70).

Expt	Food Plant	Asymptotic Final Slug Weight (*C*) (mg)	Relative growth rate (*B*)	Time to 50% weight from start of experiment (t_{50}) (days)	Significance of Lack of Fit
1	White clover Milkanova	258.5 (19.0)	0.57 (0.024)	9.2 (0.32)	0.6
2	White clover Milkanova	302 (21.7)	0.53 (0.019)	9.6 (0.30)	0.3
1	White clover Aran	180 (10.6)	0.33 (0.025)	14.2 (0.84)	0.74
2	White clover Donna	219 (9.83)	0.54 (0.022)	9.0 (0.27)	0.11
1	Red clover Herbiseed 93	239 (28.7)	0.33 (0.023)	15.3 (0.94)	0.83
2	Red clover Merviot	285 (78.0)	0.26 (0.020)	19.3 (1.77)	0.30
1	Vetch Presta	206 (12.2)	0.39 (0.026)	10.9 (0.53)	<0.01
2	Vetch Early English	209 (9.3)	0.21 (0.027)	24.3 (2.86)	0.09

These legumes were chosen on the basis of information from organic growers' organisations and NIAB, and on the known contrasting susceptibility of the two white clover cvs. to slug damage. Legume species and cultivar were found to have significant effects on slug growth and mortality. From the combined predictions for growth (Table 5) and mortality, the expectation was that the white clover cv. Milkanova should give higher *D. reticulatum* abundance and total biomass than the white clover cv. Aran or the Red Clover cv. Merviot.

This expectation was tested in a replicated field experiment (99.052), from April 1999 to May 2000. The abundance and total biomass (Fig. 3) of *D. reticulatum* was almost always highest in plots with white clover cv. Milkanova plots compared to the other five treatments (red clover, cv. Merviot; white clover cv. Arran; vetch, cv. Imported English; lucerne, cv. Diana; no cover crop). By the end of the experiment, however, the abundance and biomass of *D. reticulatum* was not significantly different between the white clover cvs. Milkanova or Aran or the red clover plots. On the vetch plots, slug numbers were similar to those on plots with other legumes until January 2000. By then, the vetch had died and slug numbers in spring 2000 were lower than on vetch plots than on plots with live legume cover. Slug populations on plots with lucerne were consistently lower than on other plots with growing legumes throughout the experiment. However, this difference was less marked by the end of the experiment. The final biomass and abundance of *D. reticulatum* was significantly greater in all legume plots than on the bare earth plots and plots where vetch had died. Thus, over a period of one year, the differences between the legume crops were small when compared to the differences between plots with or without the fertility building crops. However, lucerne appeared to result in a slower increase in *D. reticulatum* populations than the other legume crops tested. Also, an overwinter fallow after vetch significantly reduced slug abundance and biomass by May.

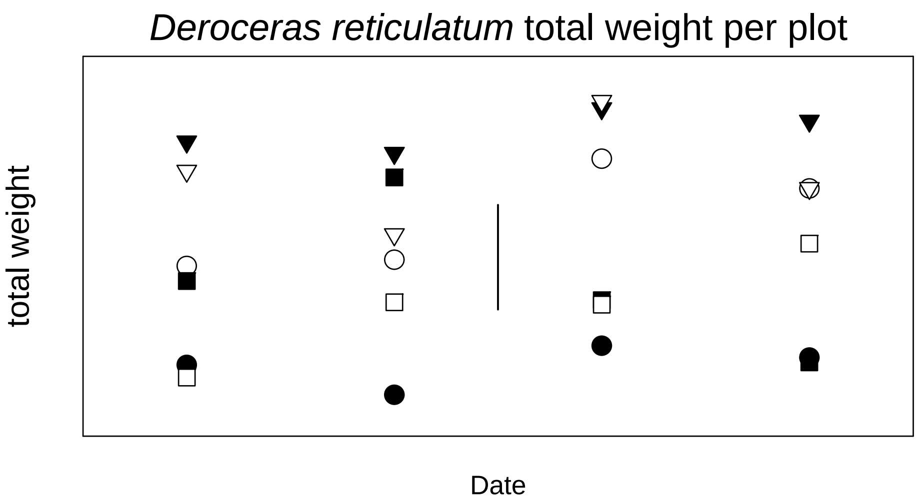

Fig. 3. Total live weight of *Deroceras reticulatum* recorded on plots with different fertility building crops (white clover cv. Milkanova – closed triangles; white clover cv. Aran – open triangles; red clover – open circles; vetch – closed squares; lucerne – open squares; no legume crop – closed circles). The vertical bar shows the least significant difference between treatments (*P* = 0.05). Sampling dates were 17.11.99, 17.01.00, 21.03.00 & 8.05.00.

Table 6. Effect of no cover crop and different cover crops grown in the two months preceding planting Chinese cabbage seedlings, on slug damage to Chinese cabbage seedlings eaten by slugs over the first 6 weeks after planting in Experiment 00.048

Cover crop	**Mean angular % damage by slugs (back-transformed mean)**
No cover crop	23.2
Red clover	28.0
Ryegrass	19.1
Vetch	27.0
Least Significant Difference (*P* = 0.05)	6.3

As noted under Objective 1, a replicated experiment (00.048) was established in two adjacent polytunnels in autumn 1999, to investigate the effect of previous cover cropping on nematode survival. Cover crops were sown on 16 July 1999, cut on 7 and 8 September and the crops were rotovated into the soil on 13 September. Barriers were then replaced, on the same day. Chinese cabbage seedlings were planted on 6 - 7 October 1999 and the crop was harvest in early February 2000. Although the performance of the nematodes was not influenced, the preceding cover crop significantly influenced the mean percentage of leaf tissue removed by slugs during the first six weeks after planting (Table 6, *P* = 0.05). The level of damage was significantly greater following a red clover or vetch cover crop than after ryegrass. Damage was at intermediate levels in plots without any cover crop, and not significantly different from either extreme.

6. Assess whether molluscicidal and slug repellent mulches, have any potential practical uses as part of integrated pest management in organic vegetables

Studies at the Swiss Research Institute for Organic Agriculture (FiBL) have shown (Speiser, 1999; Speiser *et al.*, 2000) strong mollusc-repellent and molluscicidal effects of anaerobically digested organic matter in the laboratory, but the effects were rapidly lost when the material was stored and also after application in the field. For this reason, the effects in the field were rather limited and no further work has been done on this in OF0158.

Objective 7. Determine patterns of slug populations and damage in key vegetable crops

An experiment was established in early June 2000, to test whether it would be possible to reduce the movement of slugs from a field margin into a cabbage crop by creating a 2-m wide edge strip with bare soil or with plants thought to be unsuitable as food for slugs. For the experiment, summer cabbage was planted along a grass/clover field margin. The experiment was divided into 24 plots, each extending along a 6 m length of field margin. Each plot consisted of the field margin plus a 2 m-wide edge strip and an 8 m width planted with cabbage. Six replicates of the following treatments were arranged in a randomised block design: -

A. Cabbage planted up to the field margin
B. 2m-wide sterile (bare soil) edge strip separating cabbage from field margin
C. 2 m-wide edge strip of coriander separating cabbage from field margin
D. 2 m-wide edge strip of tagetes + weeds separating cabbage from field margin (tagetes seeds were slow to germinate and plots were dominated by weeds).

Each plot was separated from the neighbouring plot by a polythene barrier to restrict slug movement between plots, inserted to a depth of 20 cm into the soil, running from 1 m into the field margin across the width of the plot. Slug numbers were sampled from 7 June until 16 August, at 2-week intervals using refuge traps baited with organic chicken layers mash, at five positions across each plot:- 1) 1 m into field margin, 2) middle of 2 m edge strip (cabbage for treatment A), 3) in cabbage, 1 m from edge strip, 4) in cabbage, 2 m from edge strip, 5) in cabbage, 4 m from edge strip. Cabbages were harvested on 17 and 18 August. The numbers of slugs in each of four cabbages harvested from each position were recorded.

Significantly more slugs were recorded in traps in edge strips with coriander or tagetes + weed than in edge strips with cabbage plants or bare soil. The same trend was apparent 1 m into the cabbage from the edge strips. However, no differences between treatments were apparent at greater distances into the crop. In all treatments, there were significantly more slugs in the edge strip than in the main cabbage crop. Numbers of slugs in cabbage heads at harvest are shown in Fig. 4. At harvest, in treatment A, where cabbages were grown in the edge strip, i.e., right up to the field margin, there were significantly more slugs in cabbages sampled from the middle of the edge strip than from all other positions in the crop. Significantly more slugs were present on cabbages harvested 1 m from an edge strip of coriander or tagetes + weeds than 1 m from the cabbage strip or the bare-earth strip. No differences between treatments were found at greater distances from the edge strip.

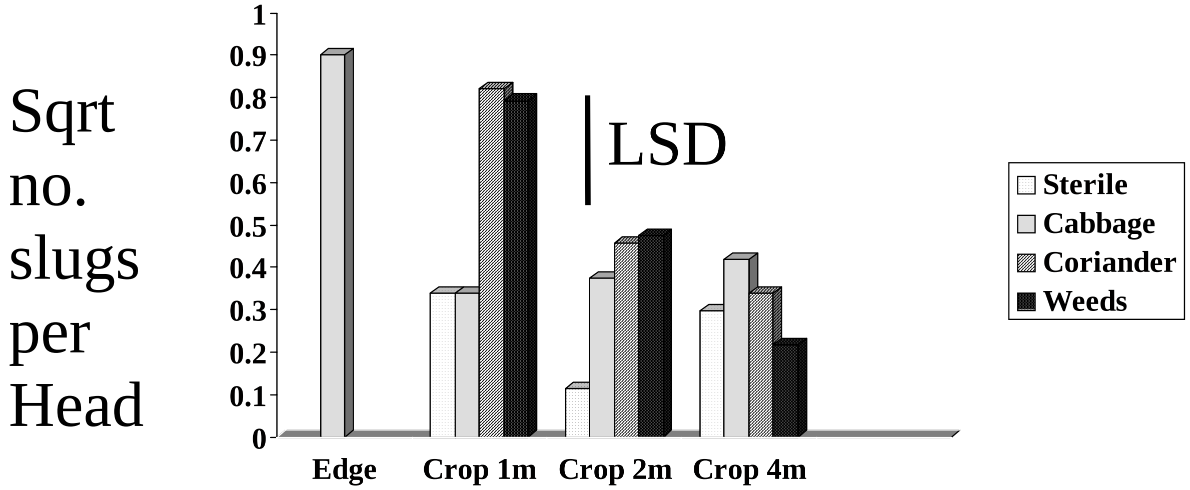

Fig. 4. Number of slugs found in organic cabbage heads at harvest in 2000, in relation to the distance from four different types of 2m wide edge strip separating the crop from a grass field margin. (LSD = Least significant difference, *P* = 0.05).

Thus, 2-m wide edge strips of coriander or tagetes + weeds appeared to encourage increased slug numbers in the strips and increased slug movement into the crop to a distance of at least 1 m but not more than 2 m from the strip, when compared to edge strips of cabbages or bare soil. There appeared to be no advantage in a bare-earth strip at the edge of the crop, compared to cabbages grown right up to the field margin. Admittedly, cabbages grown in the edge strip were contaminated by more slugs than those further from the margin. However, this edge crop was itself a bonus compared to the bare earth or tagetes + weeds treatments. The only other crop crown in the edge strip (coriander) resulted in increased slug numbers both in the coriander strip and in the adjacent cabbages.

<u>Objective 8. Devise and test combinations of control measures to be used in integrated pest management</u>

Experiments in autumn 1998 – winter 1999 indicated no potential benefit for slug control in combining the use of slug-parasitic nematodes with mechanical hoeing between rows (see Objective 1). However, there were clear benefits from using nematodes in combination with electrical barriers for control of slug damage to courgettes (Objective 3).

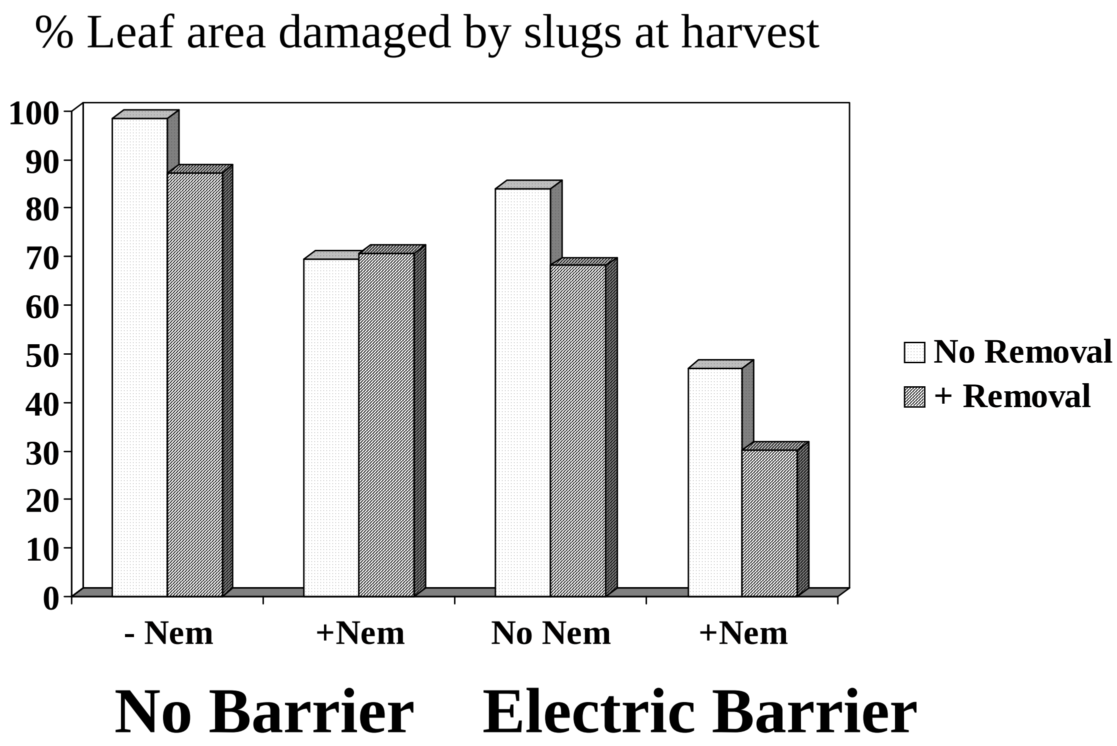

Fig. 5. Slug damage to Chinese cabbage plants (Expt. 01.056) at harvest in plots with no electric barrier (No) or surrounded by an electric barrier (Electric), with or without nematode application and hand-removal of slugs.

In one polytunnel trial (01.056) established in autumn 2000, Chinese cabbage seedlings were planted in plots 1.5 m x 1.5 m to investigate the effects of nematode control with or without electrical barriers and hand removal of slugs at dusk (3 times per week). Thus, there were 8 factorial combinations of treatments, each replicated 4 times in a randomised block design. Nematodes, electrical barriers and hand removal all significantly reduced slug damage to Chinese cabbage and all had additive effects (Fig. 5). Thus, damage was least severe where nematodes were applied and slugs were removed by hand within plots surrounded by electrical barriers. Conversely, without these three treatments damage was most severe and almost all plants were destroyed by slugs.

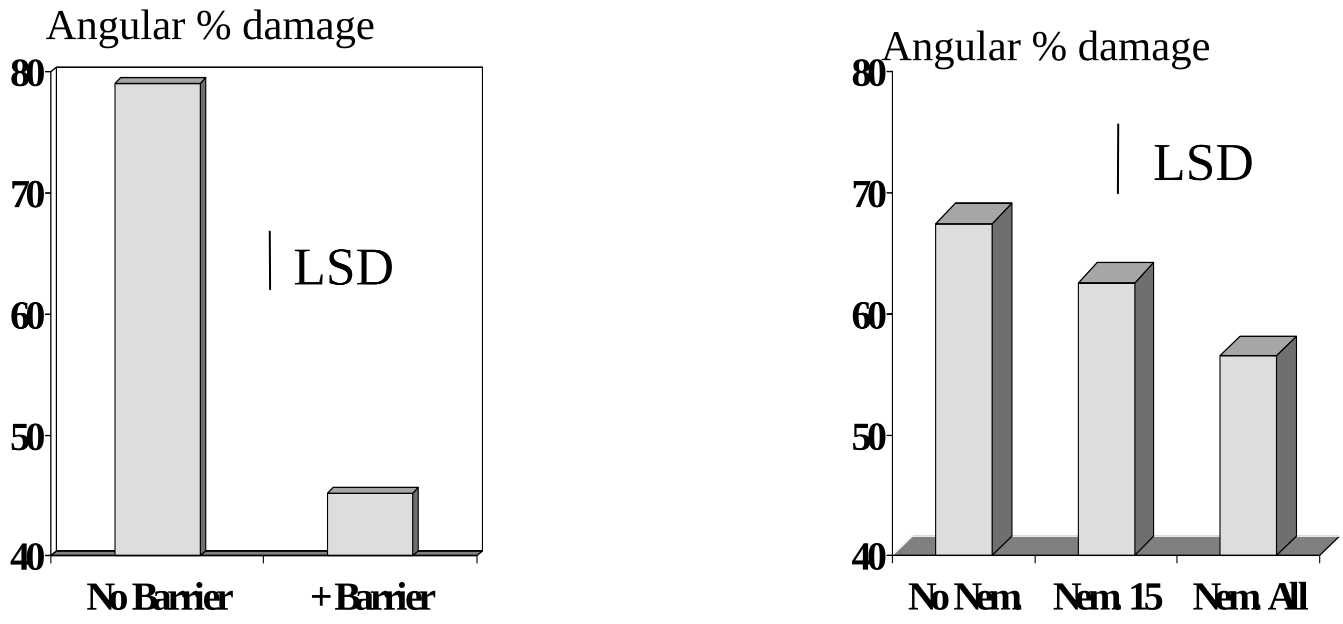

Fig. 6. Damage to Chines cabbage seedlings with or without electrical barriers along the crop rows, and with three different nematode treatments.

In the other polytunnel experiment in autumn 2000 (01.055), the aim was to investigate the potential value of electrical barriers surrounding individual crop rows, alone or in combination with nematodes. Each barrier enclosed only about 30% of the soil surface area in the plot where the crop was grown, thus potentially allowing the area to be treated with nematodes to be reduced by 30%. Plots with or without electrical barriers were laid out in factorial combinations with three nematode treatments: - (1) No nematodes (2) Nematodes applied only in a 15 cm band along each crop row, (3) Nematodes applied as an overall treatment to all the soil in the plot. Thus, there were six combinations of treatments, each replicated six times, in a randomised block design. Each plot was planted with three rows of Chinese cabbage seedlings on 14 November 2000, with each row running from the middle of the tunnel towards the polythene cladding. Each experimental plot with electrical barriers contained three barriers, each of which enclosed an area 1.5 m long x 0.15 m wide centred on a row of Chinese cabbage seedlings .

The effects of nematode treatments and electrical barriers were additive in reducing slug damage over the first 6 weeks after planting (Fig. 6). However, by harvest in plots without barriers, only the overall nematode treatment was effective, whereas in plots with barriers surrounding each crop row, both the nematode treatment along the row and the overall nematode treatment significantly reduced damage, with no significant difference between these two nematode treatments. As noted under Objective 3, depth of insertion of the electrical barrier did not significantly affect damage. In plots without barriers and no nematode treatment, Chinese cabbage plants and weed seedlings were almost completely destroyed.

In addition to the effects on damage to Chinese cabbage, profound effects of nematode treatment and barriers were found on the numbers of weeds (*Veronica persica* and *Stellaria media* together with smaller numbers of *Coronopus squamosus, Equisetum arvense, Taraxacum officionale, Cirsium arvense* and unidentified grasses). Weed numbers along crop rows were significantly greater in the presence of electrical barriers compared to plots without barriers. Weed numbers along the rows were also significantly greater in nematode-treated than untreated plots, with no significant difference between the two nematode treatments. These effects on weed numbers were essentially mirror images of those shown for damage to Chinese cabbage in Fig. 6.

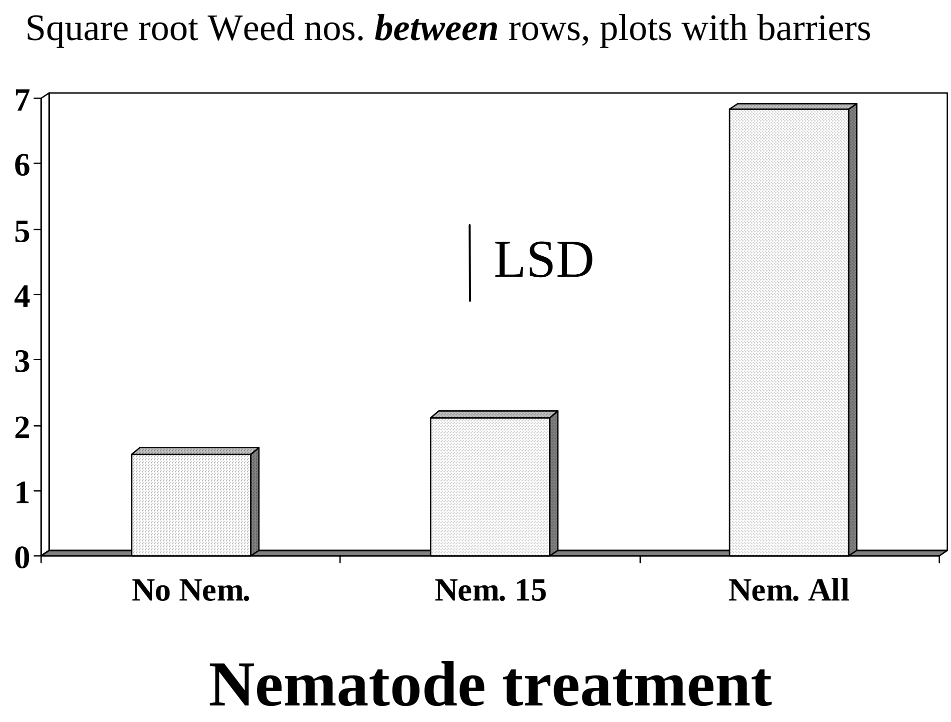

Fig. 7. Weed numbers between rows in plots with electric barriers surrounding each row (Expt. 01.055).

On plots with electrical barriers, nematode treatment significantly affected the numbers of weeds surviving between rows (Fig. 7). In plots where nematodes were applied only within barriers along the crop rows, the surviving slugs outside the barriers greatly reduced the number of weeds, to the same level as that on untreated plots. In contrast, in plots where nematodes were applied as an overall treatment, substantially more weeds survived between the rows as a result of decreased feeding by slugs.

Objective 9. Produce recommendations for best practice in integrated pest management of slugs in organic vegetable production.

Technology Transfer activities were undertaken as shown below

a) events

Welsh Pest Management Forum: The Challenge of pest and Weed Control in Organic Farming, 11 October 2000, Treforest, Wales. Talk on "Integrated Control of Slug Damage in Organic Vegetable Crops: Progress and Prospects

b) reports and publications (include only popular/farming (Times New Roman, Font 10) **press articles, book chapters and refereed publications derived directly from the project being reported)**

Slugging it out against weeds. Article by Martin Warnes, The Grower, 7 December 2000, p.18.

Organic Update. Article by Martin Warnes, Organic Gardening, April 2001, pp. 32-33.

At least four refereed papers will be published based on work already completed: -

1) Growth and mortality of slugs on fertility building leguminous plants
2) Effects of preceding cover crop on slug damage and on the activity of slug-parasitic nematodes
3) Slug control in organic vegetables: integration of biological control using nematodes with mechanical control (electrical barriers, hand removal and mechanical weed control).
4) Slug population distribution in an organic cabbage crop in relation to management of the field edge.

Discussion and Conclusions

This project has established a number of techniques that are suitable for use by organic growers for integrated control of slug damage. Ineffective techniques were also identified. The results clearly indicate that no one method of control will give a sufficient reduction in slug damage where problems are severe. Suitable combinations of control measures are necessary. Key points are summarised below:

- Cover crops: where these are grown for short periods only to prevent nutrient leaching, ryegrass should result in less severe slug problems in a following crop compared to legumes such as red clover or vetch.
- Where a fertility–building leguminous crop is required, lucerne appears to result in slower growth in the slug population than other popular legumes (white clovers, red clover and vetch) .
- A period without a crop over winter, following an annual vetch crop, reduced slug populations to levels similar to those on plots without cover crop, by the following spring.

- Slug-parasitic nematodes (*Phasmarhabditis hermaphrodita*), electrical barriers and hand-picking of slugs can all be effective methods of control. They provide additive effects for slug control and, as an integrated package, they can make the difference between a valuable crop and complete failure due to slug damage.
- Single applications of slug-parasitic nematodes were sometimes ineffective. Work in a recently completed EU project (FAIR5-PL97-3355) indicates that the commercial strain of the nematode is now significantly less effective than new strains isolated at Long Ashton Research Station. This difference in virulence persisted when selected new strains were cultured monoxenically with the same strain of bacterium used for commercial nematode production.
- The carabid beetle, *Pterostichus melanarius*, did not appear to be effective in preventing contamination of cabbages by slugs at harvest in September, even though the crop had been grown in the field throughout the beetles' main period of activity. Numbers of adult *P. melanarius* are thought to be drastically reduced by ploughing and associated cultivations in spring, compared with autumn cultivation (Purves, 1996). This is because ploughing in spring is thought to result in high mortality of the beetle, which is present as pupae in the soil in spring. Since soil is normally cultivated in spring before planting most organic vegetable crops that are grown over the summer, during the period of *P. melanarius* activity, this probably prevents beetles from reaching high numbers in most such crops. However, even in a field experiment where large numbers of beetles were introduced to a summer cabbage crop, *P. melanarius* had no significant effect on the contamination of cabbage heads by slugs. Interestingly, Symondson (1993b) concluded that although a related carabid beetle, *Abax parallelepipedus*, was an effective predator of slugs at soil level, it was incapable of capturing slugs within large lettuce plants. Similarly, in the cabbage experiment in OF0158, slugs may have used the cabbage heads as refuges from beetle predation.
- Mechanical control of weeds (hand hoeing) did not reduce slug damage, even when done as frequently as twice per week.
- Although coriander has been shown to be an antifeedant for slugs (*D. reticulatum*) under laboratory conditions (Dodds *et al.*, 1999), a 2-m wide strip of this herb grown at the edge of a cabbage crop resulted in increased slug numbers within the coriander strip and in the cabbage crop at 1 m from the strip.
- Anaerobically digested compost showed strong mollusc-repellent and molluscicidal effects in laboratory studies in Switzerland, but the effects were rapidly lost when the material was stored and also after application in the field. For this reason, it is unlikely to be suitable as a practical method of slug control.
- Importantly, work in OF0158 has identified the possibility of devising systems of integrated control of slugs and weeds, both of which are the major crop protection problems facing growers of organic vegetables and soft fruit. Further work is warranted in order to develop practical systems for protecting crops from slugs whilst benefiting from their feeding activities in killing weeds.

- Contacts with organic growers have revealed that a number of the methods that are advocated for slug control in organic systems do not appear to be based on any published scientific results. This, of course, does not mean that such methods are ineffective. However, it does indicate that further work should be done to test their validity and to investigate ways to integrate their use with other methods

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