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Localised insecticide treatment for the control of vine weevil larvae (*Otiorhynchus sulcatus*) on field-grown strawberry

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Three field experiments at Horticulture Research International (HRI), Efford, in 1992, 1994 and 1995, showed that the incorporation of controlled-release chlorpyrifos granules (78–208 g a.i. m^{-3}) into the compost of the propagation modules of strawberry plants gave significant control of vine weevil larvae in the field. Better control (approximately 90%) was achieved when field planting was in early August so that the root system was small at the time of egg infestation, than following planting in mid-May (approximately 50% control) where a much larger root system had grown. Control was as good where the treated modules had a compost volume of 80 ml as where the volume was 230 ml. Better control occurred when eggs used for artificial infestation were placed close to the crown of the plant than when placed 15 cm away. In a replicated field experiment at Hinton Admiral, Hampshire, in 1994, pre-planting spot, band or whole-bed soil treatment of raised-bed, polythene-mulched plants (planted as bare-root runners) with the chlorpyrifos granules (at 52 or 104 g a.i. m^{-3}) did not reduce the numbers of larvae significantly. In a further field experiment at HRI East Malling in 1994, treatment of a 15 cm diameter by 15 cm deep cylinder of soil round each plant (at 104 g a.i. m^{-3}) did not significantly affect larval numbers. Pre-planting spot treatment with imidacloprid granules (125 g a.i. ha^{-1}) or a curative drench (at the same dose) was not efficacious, though good control was achieved with a standard curative drench of chlorpyrifos (13.1 kg a.i. ha^{-1}).

The survival of vine weevil eggs and of young larvae was low (less than 9%), circumstantial evidence pointing to soil type and condition as being important determining factors. Lighter soils with a structure allowing easy movement of larvae appeared to be more favourable for the survival of the pest. Where adults were caged round strawberry plants with the surrounding surface soil replaced by sand in the field, most eggs (more than 79%) occurred in the top 0–1 cm of sand, 50% being found on or close to the surface (0–0.2 cm depth) in one experiment. Eggs were aggregated weakly round a single non-mulched plant, but there was little evidence of such aggregation round plants grown in polythene-mulched, raised beds. Survival to the semi-mature larval stage from eggs placed on, or 2 cm below, the soil surface 15 cm from the crown of the plant was as great as for eggs placed on, or 2 cm below, the surface adjacent to the crown. Larvae were shown to migrate towards the crown of the plant during their development. Implications for the optimum placement of insecticide granules are discussed. © 1997 Elsevier Science Ltd

Keywords: chlorpyrifos; imidacloprid; *Metarhizium anisopliae*; *Steinernema*; *Heterorhabditis*; granule; controlled-release formulation; oviposition distribution

Introduction

Vine weevil, *Otiorhynchus sulcatus* Fabricius, a damaging pest of protected and field-grown strawberry crops, has increased in importance in the UK in recent years. Damage is caused principally by larvae feeding on the root system and crowns of the plant. Depending on the degree of infestation, damaged plants may be stunted, may fail to grow, fruit poorly and prematurely, and, if severely damaged, collapse and die. The biology of the pest and descriptions of the damage it causes to crops are given by Smith (1932), Anonymous (1992) and Moorhouse *et al.* (1992a), amongst others. However, oviposition behaviour, the spatial and temporal distribution of egg deposition, and larval movement have not been studied adequately in the field.

Changes in cultural practices and in the range and types of insecticides available in commercial strawberry production in the UK have led to the increase in the occurrence and intensity of crop damage

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caused by this pest. A large proportion of crops grown for the production of high-quality fruit are now on polythene-mulched, raised beds. The beds, typically 1 m wide and spaced 1.5 m apart, are each planted with a double (zig-zag) row of plants at densities of approximately 30,000 plants ha^{-1} through 10 cm diameter circular holes in the polythene. Cold-stored, bare-rooted runners are used for planting most often, though mist-propagated shoot tips rooted in peat modules are used for planting a small (about 15%) but increasing proportion of crops. The soil is sterilised normally, usually with methyl bromide, as the beds are made and mulched. Soil sterilisation is principally for the control of soil-borne diseases and weeds. However, a wide range of soil flora and fauna are killed, probably including vine weevil and its natural enemies. The protected, warm environment of the polythene-mulched, raised beds provides even more favourable conditions for vine weevil than traditional non-mulched field crops grown in matted rows (Stenseth and Vik, 1979). Furthermore, access to water supplies necessary for trickle-irrigation of the beds greatly restricts the opportunity for crop rotation. On intensive strawberry production farms, individual fields are often in continuous strawberry cropping, providing continuously a favoured host for the pest.

However, the main reason for the increased prevalence of vine weevil on strawberry is the current lack of effective, easily applied, soil insecticides. Until the 1970s, the pest was controlled easily and very effectively with persistent organochlorine insecticides, especially aldrin and DDT, incorporated in the soil before planting. It has long been known that neonate and young larvae are much more susceptible to insecticides than are more mature larvae. The pre-planting incorporation of these low-cost, persistent insecticides into the entire rooting medium of the plant ensured that neonate larvae came immediately into contact with an insecticide residue. However, such insecticides were withdrawn from use on strawberry in the UK in the early 1970s, and totally from use in the UK in 1989. Equivalent alternatives have not been available since. Current insecticidal control relies on curative soil drenching with chlorpyrifos in the autumn or spring, or late summer or early autumn application of carbofuran 5% granules. The application of curative soil drenches is laborious and costly (approximately 15,000 l of water and 30 l of chlorpyrifos 480 g l^{-1} emulsifiable concentrate (EC) costing approximately £300 are required per hectare) and often only partially effective, as it is difficult to penetrate the rooting zone and crown of the plant thoroughly, especially on heavier soils and where the soil is dry. Spot application of carbofuran granules, though somewhat less laborious, is only partially effective, and can only be done once in the life of a crop, the maximum allowed by the statutory conditions of its use in the UK. Enhanced degradation by soil microflora may also limit its effectiveness. Adults have also proved difficult to control with currently available organophosphorus or pyrethroid insecticides, even by repeated foliar applications at night.

Biological control provides an alternative control option. Several species of entomopathogenic nematode (*Steinernema* and *Heterorhabditis* spp.) have been developed commercially for control of vine weevil larvae, mainly on protected ornamental plants. However, they are costly and not well adapted to the lower soil temperatures that occur in the field. Kakouli *et al.* (1993) reported success with application of *Steinernema carpocapse* to container-grown strawberry plants and through the trickle-irrigation system to field-grown strawberry. However, many growers have tried them with poor results. The entomopathogenic fungus *Metarhizium anisopliae* has also been shown to be effective on hardy ornamental nursery stock (Moorhouse *et al.*, 1993). However, this biological control agent has not been exploited for commercial reasons.

There is, thus, a current need for effective treatments for control of this pest. In view of the successful control achieved previously by soil incorporation of persistent organochlorine insecticides, an option worthy of exploration is the use of granular or controlled-release formulations of less persistent insecticides, that are acceptable environmentally, with a view to increasing greatly their effective persistence. This strategy has proved successful on container-grown hardy nursery stock where previous research (Buxton *et al.*, 1992; Cross *et al.*, 1995) identified a controlled-release granular formulation of chlorpyrifos (suSCon Green) to be effective. Incorporation of the granules into compost has now become standard practice in commercial hardy ornamental nursery stock production in the UK.

This paper reports a series of field experiments which aimed to identify effective soil treatments for control of vine weevil larvae on field-grown strawberry, especially on crops grown on raised, polythene-mulched beds. Controlled-release granular formulation of insecticides is costly and the incorporation of such granules into the entire rooting zone of the plant is likely to be uneconomic. Therefore, the experiments aimed to identify whether localised treatments could be effective and, by studying the spatial distribution of oviposition round the plant and subsequent larval movement, aimed to gain a better understanding of the optimum distribution of insecticide required so that the dose could be minimised.

Materials and methods

Spatial distribution of eggs around strawberry plants

In August 1994, the spatial distribution of eggs round a single, non-mulched strawberry plant was examined. A 70 cm × 70 cm metal-sided cage with a fine mesh gauze roof was placed over a single established strawberry plant (cv. Elsanta) in the field at Horticulture Research International (HRI) East Malling. The surface soil round the plant was removed to a depth of 3–4 cm and replaced with sand. The sand was used because a preliminary laboratory test showed that organic matter in soil renders the recovery of eggs from soil samples very difficult and prone to error, as eggs cannot be separated easily from fine organic matter by the usual elutriation, sieving and flotation

techniques. The preliminary tests showed that a high proportion of eggs (more than 90%) could be recovered from sand. Fifty vine weevil adults that had just started laying eggs were collected from an infested blackcurrant plantation and released into the cage. Ten days later, using a sampling trowel especially constructed for the purpose, the surface of the sand was divided into 10 cm × 10 cm quadrats and sampled to two depths, 0–1 cm and 1–2 cm. In this way, 49 samples each of 100 cm^3 of sand were taken at each depth, removing the entire layer of sand at each depth. The samples were stored in polythene bags and transported to the laboratory. Each sample was then poured into a 20 cm diameter Petri dish and a saturated aqueous solution of magnesium sulphate 7-hydrate added until the sample was submerged completely. Gentle stirring allowed any eggs present to float to the surface. The solution was then decanted into a fine sieve to retain the eggs. The sieve was half immersed in a weak solution of magnesium sulphate 7-hydrate to disperse eggs evenly so that they were easily visible. The number of eggs recovered from each sample was recorded.

In August 1995, the spatial distribution of eggs around groups of plants in a polythene-mulched, raised-bed field crop at Rocks Farm, HRI East Malling, was examined similarly. The surface soil across the entire bed around two seven-plant lengths of double zig-zag row was removed to a depth of 3–4 cm and replaced by sand, and the polythene mulch restored. A gauze cage was placed over each group of plants and 100 adult vine weevils were released into each cage in the same way as in 1994.

After 10 days, the sand was sampled in 10 cm × 10 cm quadrats around three adjacent strawberry plants across the entire surface of the bed in a similar way to the initial experiment in 1994. For one of the beds, samples were taken to two depths, 0–1.0 cm and 1.0–2.0 cm. For the other bed, the sand was sampled to three depths, 0–0.2 cm, 0.2–1.2 cm and 1.2–2.2 cm. The eggs were extracted from the samples and counted in the same way as in 1994.

To test whether vine weevil eggs tended to be aggregated around the plant(s) the mean number of eggs in quadrats adjacent to the plant(s) was compared with values obtained from other sets of random locations in the grid using a Monte Carlo test (Hope, 1968).

Efficacy of insecticidal treatment of module-propagated plants

Three replicated field experiments were done at HRI Efford, Lymington, Hampshire, between 1992 and 1996 to examine the efficacy of pre-planting treatment of the module compost of module-propagated plants for preventive control of larvae on the June-bearer strawberry cultivar Elsanta grown in polythene-mulched, raised beds. Plants were initially mist propagated from shoot tip cuttings inserted in small peat compost modules (medium Irish Shamrock peat+2.2 kg m^{-3} magnesium limestone+4.5 kg m^{-3} Osmocote Plus controlled-release fertiliser) in cell trays for approximately 4 weeks to root before planting in the field from May to August. The treatments tested, except for two localised soil treatments with imidacloprid granules in the third experiment, were applied to the modules before planting in the field. In all three experiments, randomised complete block designs with five replicates were used. Plots consisted of six (first experiment) or 10 (second and third experiments) treated and assessed plants in a double (zig-zag) row on a polythene-mulched, raised, bed with 0.4 m spacing between rows and 0.4 cm spacing between plants in the row. There were guard plants at the ends of the rows in each plot.

Each plant was infested artificially with vine weevil eggs obtained from laboratory cultures on a number of occasions in August and September. The method of culture was similar to that of Moorhouse *et al.* (1992b). Egg viability was checked by keeping 50–100 eggs on moist filter paper at 20°C and observing the proportion which emerged.

In the field experiments, the subsequent survival of the pest after treatment was assessed by sampling a large core of soil round each plant in November–March the following winter, and counting in the laboratory the number of larvae present. In the first experiment, 25 cm diameter by 15 cm deep cylindrical soil cores were taken and larvae were extracted by washing the soil through sieves and separating the collected larvae and organic matter by flotation in saturated magnesium sulphate 7-hydrate solution. In the second and third experiments, cores (20 cm × 20 cm area by 15 cm deep) were taken with a pair of spades and larvae were collected by direct visual searching of the soil in the laboratory as it was broken away from the plant roots.

The first experiment was planted on 6–7 August 1992. Module compost incorporation treatments (*Table 1*) were applied on 9 July 1992 immediately before the modules were made up in QP54 trays (consisting of a 13 × 8 rectangular array of modules each of 80 ml compost volume with a total surface area of 0.2 m^2). The surface drench treatments (*Table 1*) were applied in a volume of 0.5 l water per tray followed by 0.5 l water per tray to rinse off leaves to the surface of the module trays on 5 August 1992, 1–2 days before planting. Each of the six central plants in each plot was infested artificially with 20 vine weevil eggs on 19 August and again on 4 September. The eggs were placed in a shallow depression in the soil adjacent to the crown of each plant and were covered with soil. After determining the number of surviving larvae and excluding data from treatments where no, or very few, larvae were recorded (chlorpyrifos granule and *M. anisopliae* treatments), analysis of variance was done on the counts after appropriate $\log_{10}(x+1)$ transformation.

The second field experiment, planted in 1994, aimed to evaluate further the efficacy of module incorporation of the controlled-release chlorpyrifos granules (suSCon Green) which had been identified as most promising in the initial experiment, but at three rates and on three module system–planting time combinations, reflecting the range used commonly in commercial practice (*Table 2*). Treatments were a factorial comparison of all three

Table 1. Treatments tested in the first module treatment experiment at HRI Efford in 1992 and mean numbers (x) and mean $\log_{10}(x+1)$ transformed numbers of larvae surviving per plot

Treatment	Product	Method of application to modules[a]	Dose applied to module compost	Mean no. larvae per 6 plant plot in January 1993	
				x	$\log_{10}(x+1)$
1. chlorpyrifos 480 g l^{-1} EC	Dursban 4	surface drench	12.5 g a.i. m^{-2}	0.8	0.18
2. chlorpyrifos 10.4% w/w GR	suSCon Green	compost incorporated	104 g a.i. m^{-3}	0.2	—
3. chlorpyrifos 10.4% w/w GR	suSCon Green	compost incorporated	156 g a.i. m^{-3}	0.2	—
4. chlorpyrifos 10.4% w/w GR	suSCon green	compost incorporated	208 g a.i. m^{-3}	0	—
5. *Steinernema feltiae*	Nemasys	surface drench	2.5×10^6 nematodes m^{-2}	3.0	0.54
6. *Steinernema capocapsae*	Bio Safe	surface drench	7.5×10^5 nematodes m^{-2}	2.8	0.56
7. *Heterorhabditis* sp.	Fightagrub	surface drench	6.7×10^5 nematodes m^{-2}	1.0	0.28
8. *Metarhizium anisopliae*	[b]	compost incorporated	2.32×10^{13} spores m^{-3}	0.2	—
9. untreated control	—	—	—	3.8	0.59
SED (21 d.f.) comparisons of treatments 1, 5, 6, 7 with control					0.153

[a]Treatments incorporated into compost on 9 July 1992, surface drenches applied to module trays on 5 August 1992.
[b]Laboratory prepared, spore-impregnated cereal grain.
EC = emulsifiable concentrate; GR = granules.

module systems at each of the three rates with the nil dose treatment of the April-planted runner module system doubly replicated. Each of 10 central plants in each plot was infested artificially with an average of five weevil eggs per plant on 19 July, six eggs per plant on 17 August, seven eggs per plant on 6 September and 20 eggs per plant on 15 September 1994 (a total of 38 eggs per plant). Laboratory tests showed that approximately 85% of eggs were viable. The method of artificial infestation differed from that used in the first experiment. The total number of eggs used for artificial infestation on a particular date was collected from laboratory cultures of adults and counted. The eggs were then mixed with fine grade peat compost, 5 ml for each plant to be infested artificially. Even mixing was ensured by spreading the compost out in a thin layer on a tray and sprinkling the eggs over the surface as evenly as possible. The compost was then collected together and placed in a bag with further gentle stirring to aid mixing. Each plant was infested by spooning 5 ml of the compost with eggs onto the surface of the soil adjacent to the crown of the plant. In January 1995, the number of vine weevil larvae infesting each plant was determined. A generalised linear model with Poisson errors was fitted to the counts of larvae, providing estimated means and approximate standard errors.

In the third experiment, in 1995, treatments consisted of module incorporation of the slow-release chlorpyrifos granules or of a pre-planting spot soil treatment with imidacloprid granules (*Table 3*). The silt loam soil was improved by incorporating peat and grit, to favour the survival of vine weevil. Two locations of placement of the vine weevil eggs used for artificial infestation were compared, namely, adjacent to the plant vs 15 cm from the plant. Runner cuttings were inserted in compost in QP54 (80 ml per cell) module trays on 28 June 1995 and planted on 27–28 July. Immediately before planting, the imidacloprid granules were pre-mixed with fine sand (2 ml per plant) to aid handling and application. They were then applied as a spot treatment to the surface of the bed through the 10 cm diameter holes in the polythene mulch and incorporated to a depth of 10 cm using a slowly rotating auger driven by a cordless, electric hand-drill. This resulted in an approximately 800 ml cylinder of soil being treated. Each plant was infested artificially with an average of 8.7, 17.0, 9.5 and 24.8 (a total of 60 eggs per plant) eggs on 9 August, and 6, 12 and 19 September 1995, respectively. Tests in the laboratory indicated that an average of 60% of these eggs were viable. Eggs (mixed with 5 ml of peat compost as in the second experiment) were placed on the surface of the soil immediately adjacent to the crown of the plant or on the surface of the soil 15 cm from the edge of the crown. In the latter case, small slits were made in the polythene mulch through which the eggs were inserted before resealing with tape. The surviving vine weevil larvae were counted in January and

Table 2. Mean number of vine weevil larvae recorded per plant in January 1995 and, in parenthesis, the approximate standard error (d.f. = 37) in the second module treatment experiment planted at HRI Efford in 1994

Module system	Rate of incorporation of chlorpyrifos 10.4% w/w GR into module compost		
	0	78 g a.i. m^{-3}	156 g a.i. m^{-3}
Runners potted in 230 ml (7 cm) Optipot 8F pots on 7–8 April and planted on 16 May 1994	3.22 (0.303)	1.79 (0.319)	1.74 (0.315)
Cuttings inserted in 230 ml (7 cm) modules on 27–28 June, mist-propagated, then planted on 2 August 1994	3.12 (0.421)	0.28 (0.126)	0.36 (0.143)
Cuttings inserted in 80 ml modules on 27–28 June and planted on 3 August 1994	2.26 (0.359)	0.22 (0.112)	0.38 (0.147)

SED = $(SE_1^2+SE_2^2)^{1/2}$.

Table 3. Mean (x) and mean $\log_{10}(x+1)$ transformed number of larvae recorded per plant in January–February 1996 in the third module treatment experiment at HRI Efford planted in July 1995

Treatment	Dose (g a.i. ha^{-1})	Egg placement	Mean number of larvae per plant in January–February 1996	
			x	$\log_{10}(x+1)$
1. chlorpyrifos 10.4% w/w GR incorp. into module	227	surface adjacent to crowns	1.33	0.284
2. imidacloprid 5% w/w GR soil spot	125	surface adjacent to crowns	2.25	0.404
3. untreated control	—	surface adjacent to crowns	3.25	0.559
4. chlorpyrifos 10.4% w/w GR incorp. into module	227	surface 15 cm from crowns	3.42	0.558
5. imidacloprid 5% w/w GR soil spot	125	surface 15 cm from crowns	2.63	0.392
6. untreated control	—	surface 15 cm from crowns	2.48	0.445
SED (33 d.f.)				0.125

GR = granules.

February 1996 and analysis of variance was done after appropriate $\log_{10}(x+1)$ transformation of the data.

Soil treatment with insecticides and survival of eggs placed at different locations

A replicated field experiment was planted with bare-rooted, cold-stored runners on a commercial farm at Hinton Admiral, Hampshire, on 25 June 1994 to test the efficacy of a range of pre-planting localised soil treatments with the controlled-release chlorpyrifos granules (suSCon Green) for preventive control of vine weevil on strawberries (cv. Elsanta) grown on polythene-mulched, raised beds.

Treatments consisted of a factorial comparison of three methods of placement of the granules each at two concentrations of soil incorporation with double replicated untreated controls (*Table 4*). The placement methods were (1) a band of full bed width incorporated to 0.2 m depth; (2) a band of 0.1 m width incorporated to 0.2 m depth centred on each row of plants; (3) spot treatment (0.1 m diameter) to the surface of the soil incorporated to a depth of 0.2 m. The band treatments were applied to the surface of the soil after the bed had been raised (before mulching with polythene) and the granules were incorporated into the soil by making a second pass over the bed with the bed-making machine before mulching with polythene. Care was taken to ensure the rows of plants were aligned with the centres of the treated bands. The spot treatments were applied to the surface of the soil through the 10 cm diameter holes in the polythene mulch through which the runners were planted after the beds were made up. The granules were incorporated with a 10 cm soil auger in the same way as described for the third module experiment. Each of the 10 central plants in each plot was infested artificially with an average of five vine weevil eggs on 19 July, six eggs on 17 August, seven eggs on 6 September and 20 eggs on 15 September 1994 (a total of 38 eggs per plant) in the same way as in the second module experiment described above. Laboratory tests showed that an average of 85% of eggs were viable. In March 1995, a core (20 cm × 20 cm area by 15 cm deep) of soil containing each artificially infested plant was sampled and the vine weevil larvae present on the roots were counted in the laboratory. Analysis of variance was done on the data after appropriate $\log_{10}(x+1)$ transformation.

A further replicated field experiment at HRI East Malling in 1994 examined the survival of vine weevil eggs placed adjacent to or 10 cm away from the crown of strawberry plants (cv. Elsanta) grown in a heavy clay loam soil in the field, spot treated with the controlled-release chlorpyrifos granules, or untreated. The spot treatment consisted of a 15 cm diameter × 15 cm deep cylindrical core of soil in which a bare-root runner was planted centrally, and into which the controlled-release chlorpyrifos granules were incorporated at a concentration of

Table 4. Mean number of vine weevil larvae (x) recorded per 10 plant plot and $\log_{10}(x+1)$ transformed number in February–March 1995 in the soil treatment experiment planted on 25 June 1994 at Hinton Admiral, Hampshire

Treatment[a]	Rate of chlorpyrifos 10.4% w/w GR		No. larvae per 10 plant plot	
	Dose (kg a.i. ha^{-1})	Conc. in soil (g a.i. m^{-3})	x	$\log_{10}(x+1)$
full bed	55	52	10.8	0.93
full bed	110	104	10.4	1.04
narrow band	14	52	6.2	0.82
narrow band	28	104	7.6	0.84
spot	2.7	52	6.0	0.78
spot	5.4	104	3.0	0.48
untreated control	—	—	7.1	0.70
SED (29 d.f.)	comparisons with control			0.184
	other comparisons			0.213

[a]Artificially infested with 5, 6, 7 and 20 eggs per plant on 19 July, 17 August, 6 September and 15 September 1994, respectively.

104 g a.i. m^{-3}. The treatment was applied accurately by forcing a 15 cm length of 15 cm diameter plastic pipe into the soil, removing the soil from inside the pipe with a trowel into a bucket, and adding and mixing in the granules thoroughly. The pipe was then carefully removed from the soil, the hole was refilled with the treated soil and the strawberry runner was planted. Two treatment and planting times (5 May vs 21 July 1994) and two locations of vine weevil egg placement were compared in a factorial comparison (±insecticide, eggs adjacent to crown vs eggs 15 cm from crown, 5 May vs 21 July planted). A randomised complete block design with five replicates was used. Plots consisted of two adjacent rows of seven plants, 0.7 m apart with a 0.7 m spacing between plants in the row. The 10 central plants in each plot were treated and assessed. The plants at the ends of the row were used as guards. Each plant was infested artificially with an average of 10, 20 and 20 eggs (a total of 50 eggs per plant) on 17 July, 15 August and 5 September 1994, respectively. Laboratory tests showed that an average of 85% of eggs were viable. Eggs, pre-mixed with peat and compost as described previously, were placed on the soil surface. In late November and December 1994 the number of vine weevil larvae surviving in the central core and in the soil round the periphery was assessed. The plastic pipe was forced into the soil again and the cylindrical soil core and central plant were removed. The soil in a 10 cm wide annulus round the periphery was also sampled separately to a depth of 15 cm. The number of larvae in each sample was recorded.

A further replicated field experiment at HRI Efford in 1995 evaluated the efficacy of soil drenches with an aqueous solution of chlorpyrifos (Dursban 4) or of imidacloprid (Admire) (*Table 5*). The survival of eggs placed in different locations relative to the plant was also examined, namely, eggs placed on the surface adjacent to crowns, on the surface 15 cm from crowns, buried to approximately 2 cm depth by crowns, buried to approximately 2 cm depth 15 cm from crowns. Cold-stored, bare-rooted runners were planted in polythene-mulched, raised beds on 10 May 1995. Drenches were applied in 500 ml of water per plant on 12 October 1995. The number of surviving vine weevils was determined in January and February 1996, and analysis of variance of the data done after $\log_{10}(x+1)$ transformation of the data.

Results

Spatial distribution of eggs round strawberry plants

A total of 689 eggs were recovered from the samples around the single plant in 1994 (*Figure 1*). Of these, 79% were from the top 1 cm of sand. However, only 49% were found within a radius of 15 cm of the centre of the plant; 35% were 25–35 cm from the centre. The eggs were significantly ($P<0.05$) aggregated round the plant.

An average of 1282 eggs were recovered from the samples around the three adjacent plants in the polythene-mulched, raised beds. In the first plot, sampled to two depths, 92% of eggs were found in the top 0–1 cm and 8% at a depth of 1–2 cm. In the second plot (*Figure 2*), sampled to three depths, 50% were found on or close to the surface (the top 0.2 cm), 41% at 0.2–1.2 cm and 9% at 1.2–2.2 cm. Although the eggs were not distributed randomly, the Monte Carlo tests showed that there was no significant aggregation around the base of the plants.

Efficacy of insecticidal treatments of module-propagated plants

Survival of vine weevil from eggs to semi-mature larvae in the first experiment in 1992 was poor and variable, even on the untreated control plots (*Table 1*). The mean number of larvae recorded on the untreated control plots (3.8 per plot) was only 1.6% of the number of eggs with which each plot had been infested artificially (240 per plot). The *M. anisopliae* and the controlled-release chlorpyrifos granule treatments reduced the mean number of surviving larvae to near zero or, for the highest dose chlorpyrifos treatment, to zero. The surface drench with chlorpyrifos also significantly ($P\leq0.05$) reduced the numbers of larvae compared with the control, but the surface drenches with nematodes did not.

Egg survival was much better in the second module treatment experiment (*Table 3*). However, the mean number of larvae recorded on the untreated controls (2.9 per plant) was only 9.0% of the number of viable eggs with which each plant had been infested artificially (on average 32.3 per plant). Incorporation of the controlled-release chlorpyrifos granules reduced the numbers of larvae by approximately 50% for the 16 May planted modules, but by

Table 5. Mean (x) and mean $\log_{10}(x+1)$ transformed number of larvae recorded per plant in January and February 1996 in the curative drench treatment and egg survival experiment at HRI Efford planted in May 1995

Treatment	Dose (a.i. ha^{-1})	Egg placement[a]	Mean number of larvae per plant in January–February 1996	
			x	$\log_{10}(x+1)$
1. chlorpyrifos 480 g l^{-1} EC drench	13.1 kg	surface by crowns	0.04	—
2. imidacloprid 70% w/w WDG drench	125 g	surface by crowns	2.92	0.473
3. untreated	—	surface by crowns	3.73	0.516
4. untreated	—	2 cm deep by crowns	3.67	0.493
5. untreated	—	surface, 15 cm from crowns	2.42	0.410
6. untreated	—	2 cm deep, 15 cm from crowns	2.31	0.418
SED (33 d.f.)				0.125

WDG = water dispensible granules; EC = emulsifiable concentrate.

0-1.0 cm depth

7	15	5	1	9	5	12
3	3	5	4	5	4	10
3	4	7	14	29	22	7
1	14	119	**66**	18	4	14
2	3	2	14	5	3	3
4	1	2	7	2	1	18
4	10	3	2	2	11	15

Total = 541

1.0 - 2.0 cm depth

0	2	0	2	0	0	1
0	1	1	1	0	2	1
1	0	3	9	2	4	6
0	1	17	**27**	4	1	4
0	0	0	1	1	0	3
0	1	0	1	1	2	26
0	1	1	9	2	1	8

Total = 148

Grand total = 689

Figure 1. Number of vine weevil eggs recovered in 10 cm × 10 cm quadrats of sand round a central strawberry plant in 1994

approximately 90% for those planted on 2–3 August 1994. There were no significant differences between the doses of granule incorporation. The mean number of larvae recorded in the untreated 230 ml modules (3.17 per plant) was not significantly ($P<0.05$) greater than in the untreated 80 ml modules (2.26 per plant).

In the third module treatment experiment, the mean number of larvae recorded on the untreated controls (2.9 per plant) was only 6.3% of the number of viable eggs with which each plant had been infested artificially (an average of 46 per plant) (*Table 3*). On the untreated controls, the mean number of larvae where eggs were placed adjacent to the crowns (3.25 per plant) did not differ significantly from the mean where eggs were placed 15 cm from the crowns (2.48 per plant). Where eggs were placed adjacent to the crowns, the controlled-release chlorpyrifos granules significantly ($P<0.05$) reduced the numbers of larvae by approximately 60%, but there were no significant differences where eggs were placed 15 cm from the crowns. The spot treatments with the granular formulation of imidacloprid did not reduce the numbers of larvae significantly compared with the control.

Soil treatments with insecticides and survival of eggs placed at different locations

Egg survival was poor in the experiment evaluating localised soil treatments with the controlled-release chlorpyrifos granules at Hinton Admiral in 1994 (*Table 4*). The mean number of larvae recorded on the untreated control plots averaged 7.1 per plot of 10 plants, only 2.2% of the 323 viable eggs with which each plot had been infested artificially. However, the number of larvae present was sufficient to test the efficacy of the treatments, none of which reduced the number of larvae significantly compared with the untreated control.

Egg survival in the experiment evaluating the incorporation of controlled-release chlorpyrifos granules into soil cylinders at HRI East Malling in 1994 was very poor (0.4%) and erratic; for this reason, the mean values are not tabulated here. All but three of the 41 larvae recorded were in the central core soil samples. There was no evidence of any effect of the controlled-release chlorpyrifos treatments. A total of 27 larvae were recovered from treated plants, a total of 14 larvae were recovered from untreated plants, and 12 larvae were recovered in the central core samples feeding on the crowns of the plant where eggs had been placed 15 cm away.

In the experiment at HRI Efford in 1995 evaluating drench treatments and survival of eggs placed in

0-0.2 cm depth

4	3	17	4	1	1	0	1
4	3	25	4	2	0	0	0
8	19	12	6	10	9	3	6
7	24	40	5	7	0	2	8
33	43	13	8	25	12	11	0
14	10	0	3	27	25	4	9
7	3	11	8	17	34	2	17
1	2	4	4	20	7	0	3

Total = 612

0.2 - 1.2 cm depth

7	3	4	8	3	0	0	1
6	5	11	4	2	1	0	0
6	10	5	10	4	0	5	1
8	18	35	4	3	2	4	9
32	44	12	8	6	3	20	6
4	24	0	15	25	5	5	4
5	3	6	3	4	39	15	16
5	0	2	1	4	0	1	2

Total = 498

1.2 - 2.2 cm depth

2	0	1	3	1	0	0	0
1	0	0	1	1	0	0	0
2	2	4	7	0	1	0	0
5	0	5	0	0	1	0	2
11	8	1	1	0	1	3	0
2	3	1	1	3	2	0	1
1	0	2	1	0	6	3	4
3	2	1	1	0	1	0	0

● = location of strawberry plant

Total = 102

Grand total = 1212

Figure 2. Number of vine weevil eggs recovered in 10 cm × 10 cm quadrats of sand from the surface of a raised, polythene-mulched strawberry bed in 1995

different locations relative to the plant, overall egg survival was similar to that in the third module treatment experiment. The chlorpyrifos drench almost eliminated the larvae but the other treatments did not differ significantly (*Table 5*). There were no significant differences between the locations of egg placement.

Discussion

Egg and larval survival

The survival of eggs and/or young larvae appears to be a crucial factor in determining the abundance of vine weevil. Though laboratory tests showed that a large proportion of eggs obtained from cultures in these experiments were viable, only a very small proportion developed to semi-maturity. Circumstantial evidence (including the results of two other field experiments on contrasting soil types not reported here) indicated that soil type and structure were important factors, very poor survival occurring on heavier or more compact soils. Survival was better on lighter, well-structured soils, and appeared to be improved by the peat compost contained in modules. Vine weevil is more frequently a damaging pest of crops grown in lighter soils. It may be speculated that larvae, especially neonates, are less able to move through heavy, compacted soil. Smith (1932) reported death of neonate larvae in soils where there was a hard crust. Soil moisture content may also be critical. Neonate larvae are susceptible to moisture levels and survival can be reduced greatly where the relative humidity falls below 85% (Shanks and Finnigan, 1973). High temperatures leading to desiccation are, thus, likely to be unfavourable for the pest. We have observed a high mortality of adults to occur when they are kept at high temperatures (higher than 30°C) in a container for periods of more than 1 h. However, adults seek shelter in the soil or close to the crown of the plant during the day. Other possible causes or contributory factors to high mortality are predators and/or cannibalism. Adults and larvae of carabid beetles are believed to predate vine weevil (Crook and Solomon, 1996) and are common in agricultural soils. Their high mobility allows them to re-colonise sterilised strawberry beds rapidly. However, it seems unlikely that they were the major cause of mortality. No evidence of predation was apparent in the experiments. P. Richardson (personal communication) and Kakouli *et al.* (1993) have suggested that cannibalism is an important factor, reporting better survival on container-grown plants infested artificially with fewer eggs than on plants infested artificially with numerous eggs. Cannibalism has not been observed directly, either in these experiments or by other workers, but cannot be excluded.

Oviposition behaviour and the spatial distribution of eggs

Accounts of oviposition behaviour by vine weevil are contradictory. Neiswander (1953) and Breakey (1959) reported that no specialised behaviour occurs, eggs being ejected at random from the feeding sites. The other view is that females actively seek suitable oviposition sites in soil close to the plant where the chances of survival are maximised. Garth and Shanks (1978) reported that most eggs were laid at varying depths in the soil underneath foliage on field-grown strawberry. During the laboratory work to develop and pre-test methods for determining the spatial distribution of egg deposition around strawberry plants, adult weevils were observed to bury themselves to a depth of 1–2 cm in the sand. Eggs were recovered in small numbers in samples taken from the places where the sand had been disturbed by such behaviour, none from places where the sand was not disturbed. This behaviour was not observed in the field experiments.

The experiments reported here investigating the spatial distribution of eggs around strawberry plants were artificial and not wholly representative of normal field conditions. The structure of soils in which strawberries are grown varies enormously. Sand, with no structure, represents one extreme. The texture, gap-structure and fissuring of other soils are likely to affect the distribution of eggs by the way they affect adult movement and sedimentation of eggs. The method of caging large numbers of adults round plants in these experiments was artificial and may also have affected egg distribution. However, the distributions determined are probably representative of those which occur in sandy soils in the field. Most eggs were on the surface or in the top 0–2 cm of soil. On non-mulched plants, they were aggregated round the crowns of the plant. They were not aggregated round polythene-mulched plants in raised beds.

Larval movement

Though vine weevil larvae do not have legs, movement in soil is essential to their survival. The first task of neonate larvae is to move to roots to feed. In the experiments at HRI Efford in 1995 where the silt loam soil structure had been improved by the incorporation of peat and grit, survival was as great for eggs placed on the surface of the soil as for eggs buried to a depth of 2 cm, and as great for eggs placed close to the crown of the plant as 15 cm away. However, the proximity of neonate larvae to their food source is probably an important factor in some soil types. As semi-mature larvae often occur close to, or in, the crown of the plant, it is clear that larvae tend to move towards the crown of the plant during their development. This is confirmed by the results of the experiment at HRI East Malling in 1994. Movement may occur not immediately, but gradually, as larvae move to new feeding sites.

Optimum placement of insecticide granules

As neonate larvae are most susceptible to insecticides, it may be concluded that the optimum distribution of insecticide incorporation should coincide with that of eggs, i.e. in the top 0–2 cm of soil and over the entire surface of the bed. Oakley (1994) tested soil surface applications of the controlled-release chlorpyrifos granules with poor results, concluding that they had not been incorporated adequately.

However, the work reported here indicates that the granules did not work well in soil whatever the distribution (see below). It may also be concluded that localised spot or band treatment is only likely to be fully effective if the insecticide used is active against more mature larvae.

Insecticidal control

The first module experiment identified module incorporation of the controlled-release chlorpyrifos granules (suSCon Green) as a promising control method. The entomopathogenic nematodes were ineffective, possibly because their persistence was too short. Though *M. anisopliae* gave promising results, confirming work on other crops (Moorhouse *et al.*, 1993), there are no current plans for commercial development because of the high cost of registration of microbial biological control agents (compared with the costs of registering other biological control agents, e.g. nematodes). The manufacturers' specification for the controlled-release chlorpyrifos granules indicated that the insecticide was released from the molecular matrix of the granule over a 2–3 year period, the rate of release being dependent on temperature. The efficacy of these granules for long-term preventive control of vine weevil in container-grown nursery stock had previously been demonstrated (Cross *et al.*, 1995). The second module treatment experiment confirmed the results of the first. However, it also showed that the degree of efficacy was reduced when the root system of the plant was large in comparison with the size of the module, as occurred with the early planting time. However, even in this situation, where the root system (about 50 cm diameter) was massive in comparison with the module, a useful degree of efficacy was achieved. This experiment led to the conclusion that second-season effects of the granules were likely to be small. Experimental investigation of such effects was not pursued therefore. The third module experiment further validated the finding and showed that better efficacy was achieved when eggs were placed near to the crowns. The results with the spot treatments with imidacloprid were disappointing, as were those with a drench. However, this insecticide was tested at very low doses, the maximum for which environmental safety data for registration purposes are available currently.

Whereas the controlled-release chlorpyrifos granules were, at least partially, effective when incorporated into module compost, poor results were achieved when they were incorporated directly into soil, even when incorporated throughout the entire rooting zone at high dose. Dolmans and van Tol (1996) reported the same difficulty with hardy nursery stock, with the controlled-release chlorpyrifos granules and with other insecticides. It may be speculated that the mobility of chlorpyrifos, an insecticide comparatively insoluble in water, is too low in soil. The granules (size approximately 1 mm) are well separated in the soil and the resulting distribution of insecticides may be poor. Further work investigating their performance in soil is currently in progress at HRI East Malling. Controlled-release granular formulation of a more mobile insecticide may be more effective.

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