Root Weevil (Coleoptera: Curculionidae) and Ground Beetle (Coleoptera: Carabidae) Immigration into Strawberry Plots Protected by Fence or Portable Trench Barriers

MICHAEL K. BOMFORD and ROBERT S. VERNON[1]

Pacific Agri-Food Research Centre, Agriculture and Agri-Food Canada, Box 1000, Agassiz, BC, Canada V0M 1A0

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ABSTRACT Physical exclusion shows some potential as a novel root weevil control strategy, but barriers to root weevil immigration may also exclude beneficial insects, such as ground beetles. A field study was undertaken in 1997 to assess the impact of two physical barriers—portable plastic trenches and aluminum fences with Teflon tape—on root weevil and ground beetle immigration into plots of strawberry, *Fragaria* x *ananassa* (Duchesne). *Barypeithes pellucidus* (Boheman) and *Nemocestes incomptus* (Horn), each comprised 43% of the root weevils caught at the site. Most (86%) of the ground beetles caught in control plots were longer than 1 cm, the width of the gap in the portable trench top. Trenches excluded 75 and 63% of *B. pellucidus* and *N. incomptus*, respectively, without significantly reducing immigration of large (<1 cm) ground beetles. Fences excluded 65, 84, and 99% of *B. pellucidus*, *N. incomptus*, and large ground beetles, respectively. Adding diatomaceous earth to trenches did not increase their efficacy, and fences without Teflon tape excluded ground beetles but not root weevils. The reduction in the population of root weevils and other strawberry pests caused by the use of barriers reduced damage to strawberry plant leaves and increased strawberry plant survival relative to unprotected control plots. Advantages and disadvantages of these physical control tools are discussed with a view to creating superior tools for root weevil exclusion, compatible with an integrated pest management approach. Portable trenches may offer a means of selectively excluding root weevils but not ground beetles.

KEY WORDS *Barypeithes pellucidus, Nemocestes incomptus,* physical control, Teflon

Weevils (Coleoptera: Curculionidae) that feed on roots as larvae and leaves as adults are collectively termed root weevils. Species of economic importance in the Pacific temperate rainforest bioregion include the black vine weevil, *Otiorhynchus sulcatus* (Fabricius); clay colored weevil, *O. singularis* L.; obscure root weevil, *Sciopithes obscurus* (Horn); rough strawberry root weevil, *O. rugosostriatus* (Goeze); strawberry root weevil, *O. ovatus* L.; and woods weevil, *Nemocestes incomptus* (Horn) (Cram and Neilson 1975, Warner and Negley 1976, Antonelli and Campbell 2001). Adults of these species are wingless and range in size from 5 to 9 mm long. A smaller (3–5 mm) wingless weevil, *Barypeithes pellucidus* (Boheman), might also be included in this group. It is abundant in northern North America, can cause severe damage to nursery crops, and is thought to feed on roots in its larval stages (Galford 1987, Balsbaugh 1988).

These species all leave characteristic notches on leaf margins, but larval feeding on roots is more often responsible for economic injury by species other than *B. pellucidus* (Galford 1987, Moorehouse et al. 1992, Antonelli and Campbell 2001). Root weevils feed on >100 crops (Masaki et al. 1984), and the attrition of effective insecticides, changing husbandry practices, and an increase in host crop acreage have contributed to a general increase in their economic impact (Masaki et al. 1984, Moorehouse et al. 1992). In the lower Fraser valley of British Columbia, damage by root weevils is particularly widespread in the expanding nursery and small fruit industries.

The search for alternatives to insecticides for root weevil control has led to the adoption of some novel biological and cultural controls, but little recent research has evaluated physical control strategies (Moorehouse et al. 1990, Booth et al. 2002, Vincent et al. 2003). The inability of root weevils to fly should make them particularly susceptible to physical exclusion. Aluminum fences with a band of lithium grease near the upper edge have reduced root weevil invasion of nursery plots, leading one researcher to describe barriers to adult migration as "probably the most underutilized, most common sense tool to combat root weevils" (Cowles 1995). Sticky bands and fluoropolymer (e.g., Teflon) tape on shrub stems are both recommended to reduce adult feeding on leaves (Antonelli and Campbell 2001).

[1] Corresponding author, e-mail: vernonbs@agr.gc.ca.

A plastic portable trench (U.S. patent 5,926,999) that impedes the migration of Colorado potato beetle, *Leptinotarsa decemlineata* (Say), into enclosed tomato fields (Hunt and Vernon 2001) may also have potential for root weevil exclusion. The device works as both a barrier and a trap for Colorado potato beetle, and it is hypothesized that the inclusion of various amendments to the inside of the trench could improve trapping efficacy. For example, the use of fine dusts could reduce insect escapes by clogging their tarsal hairs and making the smooth plastic of the trench more difficult to climb (Boiteau et al. 1994). Abrasive dusts, such as diatomaceous earth, can kill insects by desiccation (Golob 1997, Korunic 1998), potentially increasing the mortality of trapped insects.

Physical barriers to root weevil migration might also affect the movement of nontarget organisms, including ground beetles (Coleoptera: Carabidae) and other natural enemies of root weevils (Holopainen and Varis 1986). Ground beetles have been credited with helping to maintain natural control of root weevils (Feytaud 1918, Evenhuis 1983). In particular, *Pterostichus melanarius* (Illiger) can attack and consume root weevil adults (M. B., personal observation). In the laboratory, two Pterostichinid species, *P. melanarius* and *P. lucublandus,* consumed all life stages of the carrot weevil, *Listronotus oregonensis* (LeConte), destroying ≈10 weevils per carabid per day (Baines et al. 1990). Such control could be compromised if ground beetles are excluded by barriers erected for root weevils.

This study documents the abundance of root weevils and ground beetles in plots of strawberry, *Fragaria* x *ananassa* (Duchesne), enclosed by two physical exclusion devices: aluminum fences with and without Teflon tape and portable trenches with and without diatomaceous earth.

Materials and Methods

The study was conducted in a windbreak consisting of two parallel rows of mature conifer trees separating plantations of raspberry, *Rubus idaeus* L., and kiwi, *Actinidia chinensis* (Planchon), near Abbotsford, 80 km east of Vancouver, Canada. The site had a history of heavy root weevil feeding damage and was relatively secluded from human activity. Undergrowth was cleared from a 150-m corridor between the windbreak rows to make room for five linearly arranged 22 by 5-m blocks, each separated by at least 10 m. Five plots (1 by 2 m) were staked out in each block, with 2-m buffers between plots. A trench (2 by 0.2 by 0.2 m) was dug down the center of each plot. A piece of black woven landscape fabric was used to cover each plot, including the sides and bottom of each trench. Trenches were filled with a commercial potting soil mix consisting of sphagnum peat moss, fertilizer, lime, and a wetting agent (Sunshine Professional Growing mix; SunGro Horticulture, Vancouver, Canada), into which 10 strawberry plants, free of root weevil larvae, were transplanted at 20-cm spacing along the length of each trench. Four pitfall traps were evenly spaced along the center of each trench, flush with the soil surface. Each pitfall trap consisted of two 450-ml plastic cups, one snugly nested inside the other, dusted inside with powdered talc to prevent insect escape. Traps were covered with a plywood roof, supported ≈2 cm above the soil surface, to exclude rain and small rodents but allow the free passage of insects.

Plots within each block were randomly assigned to one of five treatments: (1) unprotected control plots (Control); (2) plots surrounded by the portable plastic exclusion trench (Hunt and Vernon 2001) with the inner edge on top of the landscape fabric, the outer edge buried in soil surrounding the plot perimeter, and corners held together by plastic connector inserts (Trench; Fig. 1); (3) plots surrounded by the portable exclusion trench, as above, with a fine layer of diatomaceous earth coating the inner surfaces (Trench + d.e.); (4) plots surrounded by a single 30-cm wide strip of aluminum flashing, the adjoining ends riveted together, dug 10 cm into the soil surface, with the edge of the landscape fabric tucked between the soil and the aluminum (Fence); and (5) plots surrounded by aluminum flashing, as above, with Teflon-coated aluminum tape (EnviroSafe; Professional Ecological Services, Victoria, Canada) affixed to the top outer edge (Fence + Teflon; Fig. 1).

Pitfall trapping began on 6 May 1997. Traps were checked on 14 and 27 May, 5, 12, and 25 June, 18 July, and 5 and 17 September. The experiment was terminated on 2 October, when a final trap check revealed that most traps had been destroyed by animals. All weevils caught were identified to species in the laboratory and counted. All ground beetles caught on or before 25 June were counted but not identified. Thereafter, they were identified as Amarini, Bembidini, *Notiophilus directus* (Casey), Pterostichini, *Trechus obtusus* (Erichson), or other species, counted, and divided into groups of beetles larger or smaller than 1 cm in length.

On 12 June and 17 September notches characteristic of root weevil feeding were counted on all strawberry leaves, and plant survival and health were noted. On 10 October, all surviving plants were removed, and roots were checked for root weevil larvae and damage. Roots and shoots were weighed separately.

Trap counts were transformed (square root[x + 0.5]) to correct for heterogeneity of variance (Zar 1984). These data, and data on plant mass, survival, and leaf notching, were subjected to two-way analysis of variance (ANOVA; SAS Institute 2001) to test for treatment and replicate effects. Treatment means were separated by the Tukey test (SAS Institute 2001). Least squares mean contrasts (SAS Institute 2001) were conducted to test for differences between fenced plots and control plots; trenched plots and control plots; fences with and without Teflon tape; and trenches with and without diatomaceous earth.

Results

Weevil Catches. Of the 864 root weevils caught in pitfall traps, 43% were *B. pellucidus,* 43% were woods

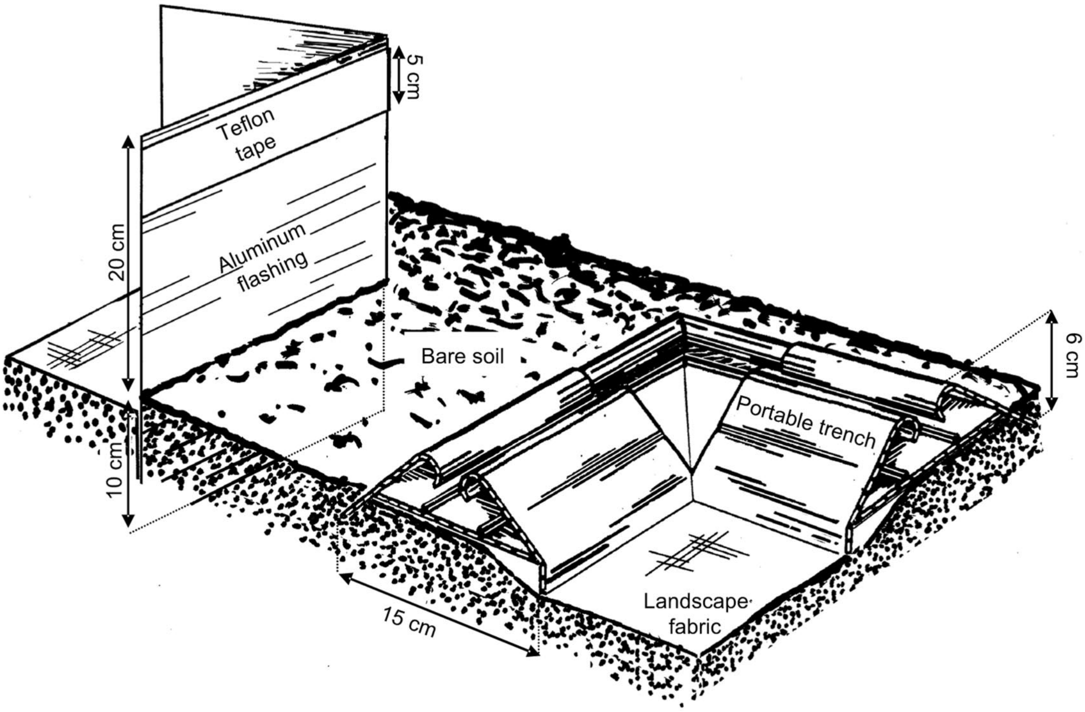

Fig. 1. Corners of enclosures surrounded by barriers of aluminum flashing with Teflon tape (left) and a portable plastic trench (right).

weevils, 10% were obscure root weevils, and 4% were other species, including strawberry root weevil, rough strawberry root weevil, and clay colored weevil. *B. pellucidus* and woods weevil were dominant until mid-July, with the other species becoming more prevalent in September (Fig. 2).

Treatment and replicate both had significant ($P < 0.001$) effects on total root weevil catches (Table 1; Fig. 3). Root weevil catches were higher in control plots than in plots surrounded by plastic trenches or aluminum fences (Table 1). Teflon tape reduced root weevils' ability to enter plots surrounded by aluminum fences (Table 1). The addition of diatomaceous earth to trenches did not reduce the ability of root weevils to escape and enter enclosures, and woods weevil catches were actually higher in plots surrounded by trenches dusted with diatomaceous earth than undusted trenches (Table 1).

Aluminum fences with Teflon tape and plastic trenches without diatomaceous earth offered the highest rates of root weevil exclusion, reducing catches relative to control plots by 67 and 65%, respectively. Similar trends were apparent for woods weevils and *B. pellucidus* when catches were analyzed by species (Table 1; Fig. 3). Fences with Teflon tape excluded the highest proportion (84%) of woods weevils, and trenches without diatomaceous earth excluded the highest proportion (75%) of *B. pellucidus* (Fig. 3).

Ground Beetle Catches. Of the 865 ground beetles caught in pitfall traps over the course of the season, 71% belonged to the Pterostichini subfamily, the most common species being *P. melanarius. Trechus obtusus* and *N. directus* comprised 9% and 3% of the catch, respectively, and representatives of the subfamilies Amarini and Bembidini each comprised 2% of the

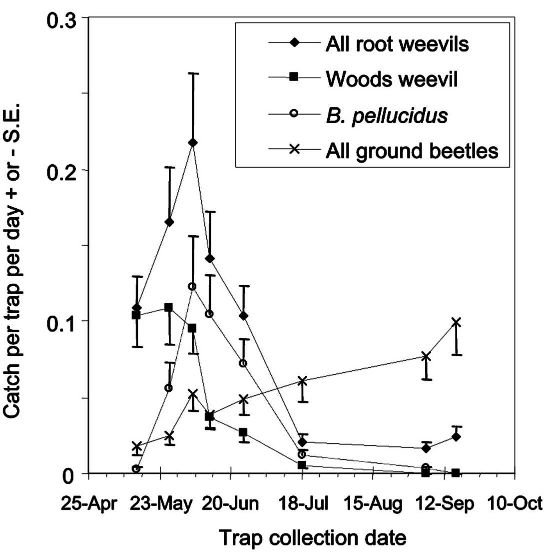

Fig. 2. Mean pitfall trap catches of root weevils and ground beetles in all study plots between 6 May and 17 September 1997.

Table 1. Least squares mean contrasts comparing transformed (square root [x + 0.5]) pitfall trap catches of root weevils and ground beetles across four treatment combinations

Trap catch	Mean difference ± SE (% of control)			
	Fenced versus control	Trenched versus control	Fenced with Teflon versus without	Trenched with d.e. versus without
All root weevils	−0.95 ± 0.28 (−45)[a]	−1.19 ± 0.28 (−55)[a]	−1.16 ± 0.32 (−45)[a]	0.49 ± 0.32 (21)
B. pellucidus	−0.50 ± 0.22 (−43)[a]	−0.71 ± 0.22 (−55)[a]	−0.59 ± 0.25 (−43)[a]	0.57 ± 0.25 (39)[a]
Woods weevil	−1.01 ± 0.23 (−61)[a]	−0.93 ± 0.23 (−60)[a]	−0.92 ± 0.27 (−45)[a]	0.10 ± 0.27 (4)
All ground beetles	−2.61 ± 0.30 (−88)[a]	−1.09 ± 0.30 (−43)[a]	0.22 ± 0.35 (4)	−0.85 ± 0.35 (−33)[a]
Small ground beetles (<1 cm)	−0.34 ± 0.22 (−41)	−0.69 ± 0.22 (−81)[a]	0.23 ± 0.25 (30)	−0.03 ± 0.25 (−2)
Large ground beetles (>1 cm)	−2.84 ± 0.29 (−99)[a]	−0.77 ± 0.29 (−35)[a]	0.01 ± 0.33 (0)	−1.05 ± 0.33 (−46)[a]

Untransformed differences are shown in parentheses as a percentage of control catch.
[a] Significant difference, least squares mean contrast, $\alpha = 0.05$.

catch. The remaining 13% of ground beetles caught were not identified. Most (86%) of the ground beetles caught in control plots were longer than the gap in the portable trench top (1 cm).

Ground beetle catches increased through the season (Fig. 2). Catches varied by treatment ($P < 0.001$) but not replicate. More ground beetles were caught in control plots than in plots surrounded by aluminum fences or plastic trenches (Table 1). The addition of diatomaceous earth to trenches reduced the catch of ground beetles, but the addition of Teflon tape to aluminum fences did not (Table 1; Fig. 4).

Aluminum fences reduced catches of large ground beetles (>1 cm long; chiefly Amarini and Pterostichini subfamilies), but not small ground beetles (<1 cm long; chiefly *Bembidion* spp., *N. directus,* and *T. obtusus*), relative to control plots (Table 1; Fig. 4). Trenches reduced catches of ground beetles relative to control plots, with differences tending to be proportionally greater for small beetles than large (Table 1; Fig. 4). Trenches without diatomaceous earth did not significantly reduce large ground beetle catches relative to control plots (Fig. 4).

Plant Health. Strawberries in plots surrounded by plastic trenches or fences with Teflon tape had fewer feeding notches per leaf than plants in control plots on 12 June, but differences were no longer significant by 17 September (Table 2). The effect of barriers on plant survival became more pronounced as the season progressed (Table 2). By 17 September, fewer plants were alive in the control plots than in the plots surrounded

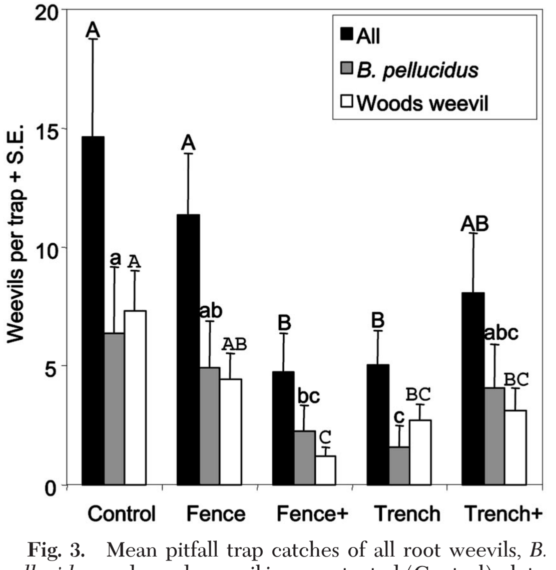

Fig. 3. Mean pitfall trap catches of all root weevils, *B. pellucidus*, and woods weevil in unprotected (Control) plots; plots surrounded by aluminum fences with and without Teflon tape (Fence+ and Fence, respectively); and plots surrounded by trenches with and without diatomaceous earth (Trench+ and Trench, respectively). Bars of the same shade labeled with the same letter do not differ significantly at α = 0.05 (Tukey test).

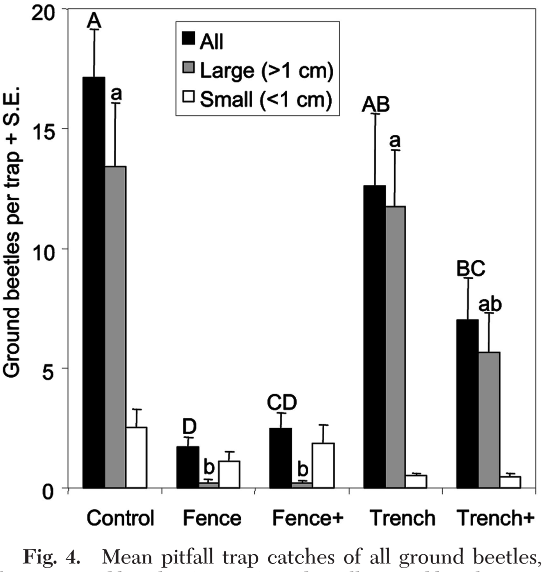

Fig. 4. Mean pitfall trap catches of all ground beetles, large ground beetles (>1 cm), and small ground beetles (<1 cm) in unprotected (Control) plots; plots surrounded by aluminum fences with and without Teflon tape (Fence+ and Fence, respectively); and plots surrounded by trenches with and without diatomaceous earth (Trench+ and Trench, respectively). Bars of the same shade labeled with the same letter do not differ significantly at α = 0.05 (Tukey test). No labels are shown when no significant differences were found.

Table 2. Leaf notching and survival of strawberry plants in unprotected (Control) plots; plots surrounded by trenches with and without diatomaceous earth (Trench+ and Trench, respectively); and plots surrounded by aluminum fences with and without Teflon tape (Fence+ and Fence, respectively)

Treatment	Notches per leaf [(mean ± SE) n = 5]		Surviving plants [(mean ± SE), n = 5]		
	12 June	17 Sept.	12 June	17 Sept.	10 Oct.
Control	1.6 ± 0.4a	1.1 ± 0.2a	9.6 ± 0.2a	4.8 ± 1.0b	4.0 ± 1.0b
Trench	0.6 ± 0.1bc	0.9 ± 0.1a	9.8 ± 0.2a	9.0 ± 0.0a	8.6 ± 0.4a
Trench+	1.0 ± 0.2ab	1.2 ± 0.2a	9.6 ± 0.2a	8.4 ± 0.4a	8.2 ± 0.6a
Fence	0.8 ± 0.1abc	1.3 ± 0.1a	9.6 ± 0.2a	8.0 ± 0.8ab	7.4 ± 1.1a
Fence+	0.1 ± 0.0c	1.4 ± 0.3a	10.0 ± 0.0a	9.2 ± 0.8a	9.2 ± 0.8a

Means followed by the same letter within a column do not differ significantly at $\alpha = 0.05$ (Tukey test).

by trenches or fences with Teflon (Table 2). By 10 October, plant survival was higher in all enclosed plots than in control plots (Table 2).

Leaf counts on 12 June and 17 September, and plant fresh weight measurement on 10 October, showed no significant treatment effects. When plants were removed from the soil on 10 October, no root weevil larvae were found feeding on the roots, and no roots showed evidence of weevil feeding damage.

Discussion

Root Weevil Exclusion. Our results show that low-profile barriers can reduce root weevil immigration and subsequent leaf damage to an enclosed strawberry crop. Woods weevil and *B. pellucidus* adults responded similarly to the physical barriers tested even though individuals of the former species are approximately twice as long, and five times as heavy, as the latter. The results reported here are likely applicable to other economically important flightless root weevil species.

Root weevils are strong climbers. A simple fence constructed of aluminum flashing only reduced weevil immigration when Teflon tape was attached to the outer edge of the barrier. Portable trenches designed for Colorado potato beetle exclusion were as effective as aluminum fences with Teflon tape; both reduced weevil catches inside the plots they enclosed by about two thirds. Although dry dusts have been shown to reduce insects' ability to climb smooth surfaces (Boiteau et al. 1994), diatomaceous earth did not improve the efficacy of trenches as barriers to root weevil immigration and may have actually helped *B. pellucidus* cross the barriers. We suggest that rainfall and other sources of moisture caused the diatomaceous earth to cake to the inner plastic surfaces, giving the insects a means of escape.

Strawberry plants suffered severe damage from leaf browsing in this study, but did not suffer from root weevil larvae feeding on roots. The cool, shady study area within the windbreak had high root weevil pressure, but was not optimal for strawberry production. Under these conditions, strawberry growth was slow, and above-ground feeding by adult root weevils caused easily observed damage (leaf notching), which may have contributed to plant mortality. Browsing by pests not monitored in this study, such as slugs (Gastropoda: Pulmonata), might have also been responsible for strawberry mortality. The high rate of mortality among plants in the control plots toward the end of the season should not be attributed entirely to root weevil browsing, because traps showed little evidence of root weevil activity at this time.

The exclusion rates achieved in this study were sufficient to reduce feeding damage to strawberries in our experimental plots, but were well short of the almost total control once afforded by applications of persistent insecticides. In recommending an aluminum fence and lithium grease barrier for the protection of rhododendrons from black vine weevil, Cowles (1995) commented that "if adults are totally excluded, then other management practices for black vine weevil become unnecessary." The barriers tested in this study might be a useful component of an integrated pest management program, but do not offer the total exclusion required if they are to be used as the sole means of root weevil control.

Ground Beetle Exclusion. Our results suggest that fences exclude most large ground beetles, such as *P. melanarius*, but not small ground beetles, such as *Bembidion* spp., or *T. obtusus* (Fig. 4). This finding reflects the observation of Holopainen and Varis (1986) that enclosing areas with a polyethylene barrier has a much stronger effect on large and medium than on small ground beetles, possibly because many small species are strong fliers and can fly over barriers. Barriers protect small ground beetles from predation by larger ground beetles (Holopainen and Varis 1986). Teflon tape attached to aluminum fences does not affect ground beetle exclusion rates, suggesting that most ground beetles are unable to climb vertical aluminum surfaces.

More large ground beetles (>1 cm long) were caught inside trenched enclosures than fenced enclosures (Fig. 4). The large insects' relative length and crawling speed may have allowed them to crawl over the 1-cm trench opening without falling in. The portable trench's ability to selectively exclude root weevils while allowing larger ground beetles to cross may make it suitable for root weevil management programs that integrate physical exclusion and conservation biological control strategies.

Barrier Design Considerations. The aluminum barriers proved more durable than the portable plastic trenches under the cool, moist conditions at this experimental site. The aluminum maintained its integrity, but the plastic grew brittle over the course of the season. Each trenched enclosure had 12 seams at which cracks could open, whereas a fenced enclosure could be constructed from a single piece of aluminum flashing with a single seam. Rivulets often formed under trenches, but not fences, after heavy rainfall. The comparatively high fence profile prevented field debris from bridging the aluminum barriers, but the narrow trench openings were often bridged by fallen twigs or leaves.

Aluminum fences are currently more practical tools for root weevil exclusion than portable trenches. The flashing is easily bent, allowing seamless corners and curves; it weathers well; and is readily available at most hardware stores (≈$3/m). Such fences must be periodically treated with a product that reduces the ability of root weevils to climb over them. We found that Teflon tape (≈$1.50/m) reduces weevil immigration by about two thirds; Cowles (1995) reported that a strip of white lithium grease is also effective.

A modified version of the portable plastic trench could offer advantages over the aluminum fence. The low profile of the trench could make it more compatible with wheeled farm machinery. The narrow trench gap selectively excludes most of the comparatively small, slow-moving root weevil adults while allowing most of the larger, faster-moving predatory ground beetles to cross. Further studies measuring the impact of ground beetles on root weevil populations would help determine whether the selective exclusion offered by the portable plastic trench represents a sufficient advantage to pursue its development as a practical tool for the physical control of root weevils.

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