THE EFFECTS OF PESTICIDES ON CARABIDAE (INSECTA: COLEOPTERA), PREDATORS OF SLUGS (MOLLUSCA: GASTROPODA): LITERATURE REVIEW

R.F. VAN TOOR

Crop & Food Research, Private Bag 4704, Christchurch, New Zealand

Corresponding author: vantoorr@crop.cri.nz

ABSTRACT

Predation of slugs by Carabidae may contribute significantly to slug control in an integrated approach in pasture and arable crops. Carabidae are susceptible to many insecticides used in field crops and to the molluscicide, methiocarb, but populations tend to recover within 1 month through migration from adjacent areas. However, in the long-term repeated insecticide and molluscicide treatments may affect carabid numbers and diversity in agricultural habitats. The effect of pesticides on carabid populations can be reduced in soils rich in organic matter, and recovery enhanced by establishment of beetle refugia in conservation headlands and winter cover crops, and by avoiding deep and frequent soil cultivation.
Keywords: slugs, molluscs, insecticides, molluscicides, slug predators, Carabidae.

INTRODUCTION

Slugs are important pests in many agricultural crops worldwide. All pestiferous slug species found in pastures and crops in New Zealand are introduced from Europe. Of these, *Deroceras reticulatum*, *D. panormitanum* and *Arion* spp. are the most significant (Barker 2002). Predators of slugs have been investigated by several authors as potential alternatives to molluscicides and predaceous arthropods are common in many agricultural crops. For example, Sivasubramaniam et al. (1997) in Canterbury carrot fields found spiders (Linyphiidae, Lycosidae), rove beetles (Staphylinidae), harvestmen (Phalangiidae) and ground beetles (Carabidae) comprised 68, 13, 11 and 2.6% of the pitfall trap catches of predators at Lincoln, and 77, 8.5, 0.7 and 6.5% at Killinchy, respectively. In the same study pesticides used to control carrot rust fly caused a decline in predator numbers. Carabidae are the most studied group of invertebrate predators. This review focuses on the effects of molluscicides and insecticides commonly used in pasture, arable and vegetable crops on Carabidae mainly in the UK and Europe, and relating this information for use in integrated slug control in New Zealand.

CARABIDAE AS SLUG PREDATORS

Most Carabidae are polyphagous predators, feeding on invertebrates such as aphids, Diptera, Lepidoptera and slugs (Kromp 1999). No carabid species feeds exclusively on gastropods (Symondson 2004), although carabids such as *Pterostichus melanarius* have been found to aggregate to areas of high slug numbers implying preferential feeding on slugs (Symondson et al. 1996). This polyphagy can be a useful attribute in biological or integrated control systems as it enhances survival and persistence in the crop if populations of the pest invertebrate are reduced. It allows for carabids to be effective predators of slugs in field crops. In the UK, slug populations have been controlled by several carabid beetle species common in fields of oilseed rape and winter wheat (Ayre & Port 1996; Symondson et al. 1996), by *Pterostichus niger* and *P. melanarius* in winter wheat (McKemey et al. 2003), by *P. melanarius* in pasture establishment (Buckland & Grime 2000) and by *Abax parallelepipedus* and *Pterostichus madidus* in a grass/clover sward (Asteraki 1993). Larvae of *P. melanarius* reduced numbers of *D. reticulatum* and *Arion intermedius* in field plots of winter wheat (Thomas 2002). Moreover, provided large numbers of alternative prey are available, long-term control of slugs is possible. For example, predation by high densities of *P. melanarius* was credited with preventing slug populations reaching pest status in arable fields for several years (Symondson et al. 2002). Slugs of all sizes were attacked by this species (McKemey et al. 2003). Earthworms were shown to provide an alternative prey for *P. melanarius*, helping to sustain its population when pest numbers were low (Symondson et al. 2000). *Abax parallelepipedus* has also been shown to have potential for use in biological control of slugs (Ayre 1995) and is amenable to mass culturing (Symondson 1994).

The New Zealand carabid fauna consists of 424 described species and 14 subspecies (Larochelle & Lariviere 2001), some of which prey on pestiferous slugs. For *D. reticulatum,* mortality from carabid predation has been shown to be inversely related to initial slug density and associated with *Plocamostethus planiusculus, Holcaspis mucronata* and *Ctenognathus bidens* density (Barker 1991). Chapman et al. (1997) found that in caged (1 m^2) field plots of lettuce *Megadromus antarcticus* on average preyed on 0.5 slugs (*D. panormitanum* or *D. reticulatum*) per day, and caused a reduction in slug numbers.

PESTICIDE EFFECTS ON CARABIDAE

Generally, herbicides (Brust & House 1990; Zhang et al. 1997) and fungicides (Sotherton & Moreby 1984) are not acutely toxic to Carabidae, although they may indirectly influence survival through removal of food items and habitat modification. However, there is growing evidence that pesticides can dramatically depress populations of non-target organisms including predatory beetles.

Molluscicides

Metaldehyde, methiocarb and thiodicarb are currently registered for control of slugs in New Zealand (NZ Agrichemical Manual 2005). Data on the effects on Carabidae are available from Europe for baits containing the first two ingredients.

Metaldehyde bait pellets broadcast at the label rate onto winter cereals in the UK had no significant effect on numbers of carabid beetles in two trials (Wiltshire & Glen 1989). This result was supported by Bieri et al. (1989) who found no or negligible toxic effects on carabid populations in fields, even at 10 times the product label rate of 30 kg/ha. In field tests, four metaldehyde formulations had no effect on *P. melanarius, Poecilus cupreus* [*Pterostichus cupreus*] or *Harpalus rufipes*, but caused a slight reduction in numbers of *Carabus granulatus* (Buchs et al. 1989). These findings were similar to those of Samsoe-Peterson et al. (1992) who found no or negligible effects from metaldehyde on these carabid species.

Methiocarb formulated as a bran-based pellet bait is broadly insecticidal (Murray & Spackman 1983). It also kills worms (Barker 1982; Samsoe-Petersen et al. 1992) and carabids through secondary poisoning. Methiocarb residues in *D. reticulatum* killed *P. melanarius* carabid beetles in laboratory tests (Langan et al. 2004), but not all carabid species are affected to the same extent. In laboratory tests, methiocarb baits were shown to be toxic to *P. cupreus*, *P. melanarius*, *C. granulatus* and *H. rufipes*, although in field tests some of these species were repelled while others were attracted by the baits (Samsoe-Petersen et al. 1992). In other field tests, methiocarb pellets killed 66-100% of *P. cupreus*, *C. granulatus* and *H. rufipes*, but only up to 25% of *P. melanarius* (Buchs et al. 1989). Methiocarb bait pellets broadcast at the label rate onto winter cereals in the UK reduced numbers of carabid beetles in one trial but not in another (Wiltshire & Glen 1989). In Irish fields of wheat or barley, four annual autumn applications of methiocarb-based slug pellets had minimal effect on the activity of the carabids *N. brevicollis* and *Trechus quadristriatus,* their populations recovering by each subsequent year, but the activity of *Bembidion obtusum* remained suppressed at the end of the trials (Purvis 1992). The effect of methiocarb appears to be affected by beetle activity. In a paddock containing 27 carabid species (mainly *Bembidion aeneum* and *B. obtusum*), Purvis & Bannan (1992) found that total carabid activity following broadcast and drilled applications of methiocarb pellets in autumn was reduced to less than 5% and to 10-15%, respectively. However, species not active at the time of application were largely unaffected, and all species showed a gradual recovery to normal levels of activity in the following season.

The responses of carabids to slugs that consumed molluscicides can also influence the dose of a molluscicide they receive by ingestion. Ayre (2001) found that smaller slugs are more readily preyed upon by larger beetles, with *P. madidus* and *N. brevicollis* consuming only small, live slugs (<110 mg) or, if the slugs were larger, scavenging on dead slugs in preference to feeding on injured or healthy slugs (Mair & Port 2001b). This implies that in a treated field, large carabids, rather than small ones, would receive a toxic dose of methiocarb through consuming methiocarb-contaminated slugs regardless of slug size. Mair & Port (2001a) also found that carabid beetles often attacked other prey in preference to adult slugs, only feeding on slugs of all sizes when carabid density was high or other prey slugs were unavailable. Beetle avoidance of slugs containing methiocarb (Langan et al. 2004) and re-invasion of paddocks by carabids, as indicated by recovery of carabid populations within a generation following pesticide use (Purvis 1996), both contribute to an overall low impact of methiocarb on carabid populations. Kelly & Curry (1985) concluded that a single application of methiocarb for the control of slugs in winter wheat had no adverse effect on surface-dwelling Coleoptera.

Insecticides

Insecticides from several chemical classes are regularly applied to pasture, arable crops and vegetable crops where slugs are present. For example, a survey on insecticide use in 84 cereal paddocks within 26 farms in New Zealand during 2003 showed that the pyrethroid lambda-cyhalothrin, the chloronicotinyl imidacloprid, the organophosphates diazinon and dimethoate and the pyrethroid taufluvalinate were foliar-applied in 54, 25, 12, 2 and 2% of paddocks respectively (D.I. Hedderley, unpubl. data). Temporary effects on carabids from field applications of all of these insecticides have been reported.

Chloronicotinyls. Topical, dietary or turfgrass-residue exposure of the carabid *Harpalus pennsylvanicus* to imidacloprid has caused neurotoxic effects, making them highly vulnerable to predation (Kunkel et al. 2001). But imidacloprid seed treatment at label rates did not significantly affect numbers of Carabidae caught in pitfall traps in maize crops over 5 years in Spain (Albajes et al. 2003), on sugarbeet in Germany (Schwalbe 1997; Epperlein & Schmidt 2001), or in the UK, where other chloronicotinyls, clothianidin and thiamethoxam, also had no observable effect (Baker et al. 2002).

Organophosphates. Mauchline et al. (2004) found in feeding tests that *P. madidus*, *P. melanarius* and *N. brevicollis* showed no avoidance behaviour and consumed enough aphid prey contaminated with dimethoate, at concentrations similar to field exposure, to cause significant levels of mortality. Heimbach et al. (2002) estimated that LD_{50} values for larvae of *P. cupreus* exposed to dimethoate applied to a standardised sandy soil ranged between 26.3 and 54.2 g dimethoate/ha. Dimethoate sprayed at label rates in UK winter wheat fields temporarily reduced numbers of *P. madidus* and *P. melanarius*, although declines in number of five other carabid species were similar to seasonal population fluctuations (Holland et al. 2000). Kennedy et al. (2001) also found treatment with dimethoate in cereal fields led to significant short-term reductions in pitfall catches of Carabidae, and in field trials in Finland, similar effects lasted 2-4 weeks (Huusela-Veistola 2000). In Switzerland, fonofos and dimethoate applied to a cabbage crop did not fundamentally alter the species composition of carabids (mainly *Bembidion quadrimaculatum*), although numbers were reduced (Freuler et al. 2003). In New Zealand, diazinon sprayed topically to field plots had less effect on numbers of the carabid *Rhytisternus miser* than fensulfothion and isazofos (Robertson et al. 1986). The abundance of carabids was greatly reduced by recommended rates of phorate in field plots in two carrot fields in Canterbury, but numbers of most of the predatory carabid species had recovered by 40 days after treatment (Sivasubramaniam & Wratten 1995).

Pyrethroids. In Germany, lambda-cyhalothrin applied to winter wheat reduced activity and densities of carabids, but the effects disappeared in the following year (Wick & Freier 2000). In Finland harmful effects of deltamethrin on Carabidae were shown to last only 2-4 weeks (Huusela-Veistola 2000). In a white cabbage field in Switzerland, cypermethrin did not fundamentally modify the species composition of carabids (35) although numbers, particularly of *Bembidion quadrimaculatum*, were reduced (Freuler et al. 2003).

***Moulting hormones*.** Diflubenzuron is commonly used on pasture in New Zealand, for control of early instar porina (*Wiseana* spp.) caterpillars. Although no reports of the effect of diflubenzuron on carabids have been published, Abdelgader & Heimbach (1992) found that the chitin-synthesis inhibitors hexaflumuron and buprofezin and the juvenile hormone analogues pyriproxyfen and fenoxycarb at field rates had minimal adverse effects on 1st-instar larvae of *Poecilus cupreusi* carabids. Diflubenzuron is unlikely to have any direct effect on adult carabids.

Factors influencing insecticidal activity

Insecticide effect is influenced by the insecticide type, soil type and carabid species. The greater the percentage of clay, silt or organic matter in the soil, the lesser the effects of endosulfan, lindane and parathion on *Pardosa* sp, and of pyrazophos, chlorpyrifos and methamidophos on *P. cupreus*, with soil type having a lesser effect on the impact of fenvalerate and lambda-cyhalothrin (Heimbach et al. 1992). Similar trends were observed for adults and larvae of *P. cupreus* (Heimbach et al. 1995). Post-treatment temperatures also affect activity, as shown by the negative correlation between temperature and the insecticidal effects of lambda-cyhalothrin, fenvalerate and pyrazophos on *P. cupreus* (Heimbach & Baloch 1994). The time of insecticide application and seasonal activity of carabid species also influence the effect of the insecticide. Gyldenkaerne et al. (2000) observed dimethoate applied in midsummer reduced oviposition by *Bembidion lampros* and *B. obtusum* but had less effect when applied in autumn.

General impact of pesticides

In studies of modern farming systems in Europe, short-term reductions were common for some carabid species following insecticide applications (Buchs et al. 1997; Huusela-Veistola 2000). Monitoring the spatial and temporal distribution of arthropods after an application of dimethoate revealed that re-invasion by carabids across a 16 ha field can occur within 1 month (Holland et al. 2000) and even accumulated drift deposition of insecticides in field margins had little effect on carabid numbers when lambda-cyhalothrin was sprayed in a wheat field for 3 years (Freier et al. 2002). Holland & Luff (2000) concluded that insecticides have only a localised and short-term effect because many carabids rapidly re-invade sprayed crops. But they considered the long-term effect of pesticide usage at a landscape scale was more difficult to predict, and may have contributed to the observed decline in carabid diversity in the wider countryside. Herbicides and fungicides, while not toxic on carabids, were considered to reduce their survival through habitat modification or food removal.

The abundance and diversity of Carabidae in Europe appear to be in decline since farming intensification began in the 1950s. Basedow (1987) found an 81% decrease in trapping rates and a 90% decrease in carabid biomass between 1971-74 and 1978-83 in Germany. The decline in carabid numbers was attributed to seasonal applications of parathion. There was a shift in the dominance of carabid species, with fewer species making up a greater proportion of the total occurrence in 1952 than in 1986 (Croy 1987), with species with the poorest dispersal power having declined the most (Turin & Den Boer 1988). Loss of habitats appeared to be primarily responsible for the decrease of many species in parts of Europe since 1950 (Desender & Turin 1989). These trends highlight the importance of conserving populations of carabids by enhancing carabid habitats rather than focusing on reducing the use of molluscicides or insecticides, which appear to have a temporary impact on carabid populations. These conclusions have relevance in New Zealand through implementation of integrated pest control systems.

INTEGRATED CONTROL OF SLUGS

In New Zealand, Ferguson (1990) suggested that native carabids *Mecodema rectolineatum* and *Megadromus vagans*, which ate 1-2.5 slugs/day in a feeding study after collection from compost heaps in South and Central Otago, could be suitable for control of slugs in glasshouses at a rate of $2/m^2$. Chapman et al. (1997) concluded that although carabids such as *Megadromus antarcticus* can reduce slug numbers by predation in small 1 × 1 m plots of lettuce, carabids were unlikely to be useful biological control agents for slugs in intensive field crops because naturally occurring populations required augmentation and large inundative releases of carabids would be needed. *Megadromus antarcticus* (25-35 mm), *Metaglymma moniliferum* (15-20 mm) and *Holcaspis angustula* (12-16 mm) were regularly found in pitfall traps set in transects within three cereal fields in Canterbury, but in laboratory tests only *M. antarcticus* aggressively consumed slugs of all sizes, with the smaller species only eating freshly-hatched slugs, but no eggs (A. Horrocks, pers comm.). Manipulation of the cropping environment to maintain populations of the larger carabids at high enough densities for effective control of slugs would potentially increase the effectiveness of carabids as control agents and this remains the largest challenge to using carabids as biocontrol agents. Keesing & Wratten (1997) reported that unlike in Europe where nature reserves exist surrounded by a farmland matrix, New Zealand agro-ecosystems are more rarely punctuated by pockets of semi-native ecosystems. Of the carabids, only *Megadromus* spp. have adapted to pastoral and cropping landscapes. Thus the ecologically depauperate communities of New Zealand farmland requires more proactive measures to return diversity into the landscape.

Kromp (1999) reported that carabid numbers were enhanced by reduced tillage systems, green manuring, intercropping and the presence of perennial field margins in agro-ecosystems of the temperate Northern hemisphere, although on a field scale there was no evidence that increasing numbers of Carabidae-reduced pest populations. A key element to improving the environment for Carabidae is organic matter in and on the soil, which provides shelter, increases alternative food sources, buffers weather variations (Hance 2002), and reduces the effects of insecticide on carabids (Heimbach et al. 1995; Heise et al. 2005). The impact of non-selective insecticides and molluscicides (Purvis & Bannon 1992) can be minimised if they are not applied during the main activity periods of carabid beetles. Cultivation of cereals in the autumn may favour higher populations of carabids than cultivation in spring when carabids are more active (Fadl & Purvis 1998). Applying natural refugia, such as grass strips in the middle of fields ("beetle banks"), may provide stable over-wintering sites and assist in maintaining high numbers of carabids within paddocks. In the UK, such refugia increase numbers of carabids within arable fields and the speed with which they can penetrate and re-establish in the crop in spring (Thomas et al. 1992; Thomas et al. 2001). Similar strips of the grasses *Agrostis stolonifera, Dactylis glomerata* and *Holcus lanatus* provided an effective overwintering habitat for carabids, increasing their numbers and species diversity compared to areas outside the strips during a 7-year study in New Zealand (MacLeod et al. 2004). Maintaining pesticide-free grass strips in field margins provides refugia from adverse agricultural operations and enhances breeding by carabids over winter, although the extent to which they influence distributions of carabids within a field and the impact on effective slug control has not been established (Holland & Luff 2000).

Management practices such as those discussed may increase the populations of Carabidae in crops and help minimise the negative impact of molluscicides and insecticides and are promoted in Europe as doing just that. However, there needs to be a clear demonstration that carabids in New Zealand agricultural and horticultural landscapes can contribute significantly to the control of slugs and if so, the effect of pesticide use on carabids should be further investigated.

ACKNOWLEDGEMENTS

Funding came from the New Zealand Foundation for Research, Science and Technology LINX0304. Bruce Chapman and Steve Wratten, Lincoln University, and Nicholas Martin at Crop & Food Research advised on and critiqued this manuscript.

REFERENCES

Abdelgader H, Heimbach U 1992. The effect of some insect growth regulators (IGRs) on first instar larvae of the carabid beetle *Poecilus cupreus* (Coleoptera: Carabidae) using different application methods. Aspects of Applied Biology 31: 171-177.

Albajes R, Lopez C, Pons X 2003. Predatory fauna in cornfields and response to imidacloprid seed treatment. Journal of Economic Entomology 96(6): 1805-1813.

Asteraki EJ 1993. The potential of carabid beetles to control slugs in grass/clover swards. Entomophaga 38(2): 193-198.

Ayre K 1995. Evaluation of carabids as predators of slugs in arable land. PhD thesis, University of Newcastle upon Tyne, England.

Ayre K 2001. Effect of predator size and temperature on the predation of *Deroceras reticulatum* (Muller) (Mollusca) by carabid beetles. Journal of Applied Entomology 125(7): 389-395.

Ayre K, Port GR 1996. Carabid beetles recorded feeding on slugs in arable fields using ELISA. Slug & snail pests in agriculture. Proceedings of a Symposium, University of Kent, Canterbury, UK. Pp. 411-418.

Baker P, Haylock LA, Garner BH, Sands RJN, Dewar AM 2002. The effects of insecticide seed treatments on beneficial invertebrates in sugar beet. The BCPC Conference: Pests and diseases, Volumes 1 and 2. Proceedings of an international conference, Brighton, UK. Pp. 653-658.

Barker GM 1982. Short-term effects of methiocarb formulations on pasture earthworms (Oligochaeta:Lumbricidae). New Zealand Journal of Experimental Agriculture 10(3): 309-311.

Barker GM 1991. Biology of slugs (Agriolimacidae and Arionidae: Mollusca) in New Zealand hill country pastures. Oecologia 85(4): 581-595.

Barker GM 2002. Gastropods as pests in New Zealand pastoral agriculture, with emphasis on Agriolimacidae, Arionidae and Milacidae. Molluscs as crop pests. CABI Publishing, Wallingford, UK. Pp. 361-421.

Basedow T 1987. The effect of increased intensity of cereal growing on ground beetles (Coleoptera, Carabidae). Investigations from 1971 to 1984. Mitteilungen aus der Biologischen Bundesanstalt fur Land- und Forstwirtschaft Berlin-Dahlem (No. 235). 123 pp.

Bieri M, Schweizer H, Christensen K 1989. The effect of metaldehyde and methiocarb slug pellets on surface dwelling organisms in grassland. Monograph - British Crop Protection Council 41. Pp. 391-392.

Brust GE, House GJ 1990. Effects of soil moisture, no-tillage and predators on southern corn rootworm (*Diabrotica undecimpunctata howardi*) survival in corn agroecosystems. Agriculture, Ecosystems & Environment 31(3): 199-215.

Buchs W, Heimbach U, Czarnecki E 1989. Effects of snail baits on non-target carabid beetles. Monograph - British Crop Protection Council (No. 41). Pp. 245-252.

Buchs W, Harenberg A, Zimmermann J 1997. The invertebrate ecology of farmland as a mirror of the intensity of the impact of man? – An approach to interpreting results of field experiments carried out in different crop management intensities of a sugar beet and an oil seed rape rotation including set-aside. Biological Agriculture & Horticulture 15(1-4): 83-107.

Buckland SM, Grime JP 2000. The effects of trophic structure and soil fertility on the assembly of plant communities: a microcosm experiment. Oikos 91(2): 336-352.

Chapman RB, Simeonidis AS, Smith JT 1997. Evaluation of metallic green ground beetle as a predator of slugs. Proceedings of the 50th New Zealand Plant Protection Conference: 51-55.
Croy P 1987. Faunistic-ecological investigations of the carabids in the surroundings of an industrial centre. Entomologische Nachrichten und Berichte 31(1): 1-9.
Desender K, Turin H 1989. Loss of habitats and changes in the composition of the ground and tiger beetle fauna in four West European countries since 1950 (Coleoptera: Carabidae, Cicindelidae). Biological Conservation 48(4): 277-294.
Epperlein K, Schmidt HW 2001. Effects of pelleting sugarbeet seed with Gaucho(R) (imidacloprid) on associated fauna in the agricultural ecosystem. Pflanzenschutz-Nachrichten Bayer 54(3): 369-398.
Fadl A, Purvis G 1998. Field observations on the lifecycles and seasonal activity patterns of temperate carabid beetles (Coleoptera: Carabidae) inhabiting arable land. Pedobiologia 42(2): 171-183.
Ferguson CM 1990. Slug control. Hort News 12(6): 3.
Freier B, Kuhne S, Kaul P, Baier B, Moll E, Juttersonke B, Forster R 2002. Three-year study of the effects of Karate(R) applications in wheat on arthropod communities in a field margin: results and the problem of small numbers. Bulletin OILB/SROP 25(11): 115-120.
Freuler J, Blandenier G, Meyer H, Pignon P 2003. Effects of chemical control programs against cabbage pests on ground dwelling fauna. Bulletin OILB/SROP 26(3): 371.
Gyldenkaerne S, Ravn HP, Halling-Sorensen B 2000. The effect of dimethoate and cypermethrin on soil-dwelling beetles under semi-field conditions. Chemosphere 41(7): 1045-1057.
Hance T 2002. Impact of cultivation and crop husbandry practices. In: Holland JM ed. The agroecology of Carabid beetles. Intercept Limited, Hampshire, UK. Pp. 231-260.
Heimbach U, Baloch AA 1994. Effects of three pesticides on *Poecilus cupreus* (Coleoptera: Carabidae) at different post-treatment temperatures. Environmental Toxicology and Chemistry 13(2): 317-324.
Heimbach U, Abel C, Siebers J, Wehling A 1992. Influence of different soils on the effects of pesticides on carabids and spiders. Aspects of Applied Biology 31: 49-59.
Heimbach U, Wehling A, Metge K, Siebers J, Kula H 1995. Bioavailability of pesticides in different soils on carabid beetles, spiders and earthworms. Gesunde Pflanzen 47(2): 64-69.
Heimbach U, Baier B, Barth M, Blumel S, Geuijen I, Jackel B, Maus C, Nienstedt KM, Schmitzer S, Stabler P and others 2002. First ring test results of a laboratory method to evaluate effects of plant protection products on larvae of *Poecilus cupreus* (Coleoptera: Carabidae). Bulletin OILB/SROP 25(11): 19-26.
Heise J, Heimbach U, Schrader S 2005. Influence of soil organic carbon on acute and chronic toxicity of plant protection products to *Poecilus cupreus* (Coleoptera, Carabidae) larvae. Journal of Soils and Sediments 5(3): 139-142.
Holland JM, Luff ML 2000. The effects of agricultural practices on Carabidae in temperate agroecosystems. Integrated Pest Management Reviews 5(2): 109-129.
Holland JM, Winder L, Perry JN 2000. The impact of dimethoate on the spatial distribution of beneficial arthropods in winter wheat. Annals of Applied Biology 136(2): 93-105.
Huusela-Veistola E 2000. Effects of pesticide use on non-target arthropods in a Finnish cereal field. Aspects of Applied Biology 62: 67-72.
Keesing V, Wratten SD 1997. Integrating plant and insect conservation. In: Maxted N, Ford-Lloyd BV, Hawkes JG ed. Plant genetic conservation: the *in situ* approach. Chapman & Hall, London, UK. Pp. xxiv + 446 pp.
Kelly MT, Curry JP 1985. Studies on the arthropod fauna of a winter wheat crop and its response to the pesticide methiocarb. Pedobiologia 28(6): 413-421.

Kennedy PJ, Conrad KF, Perry JN, Powell D, Aegerter J, Todd AD, Walters KFA, Powell W 2001. Comparison of two field-scale approaches for the study of effects of insecticides on polyphagous predators in cereals. Applied Soil Ecology 17(3): 253-266.

Kromp B 1999. Carabid beetles in sustainable agriculture: a review on pest control efficacy, cultivation impacts and enhancement. Agriculture, Ecosystems & Environment 74(1/3): 187-228.

Kunkel BA, Held DW, Potter DA 2001. Lethal and sublethal effects of bendiocarb, halofenozide, and imidacloprid on *Harpalus pennsylvanicus* (Coleoptera: Carabidae) following different modes of exposure in turfgrass. Journal of Economic Entomology 94(1): 60-67.

Langan AM, Taylor A, Wheater CP 2004. Effects of metaldehyde and methiocarb on feeding preferences and survival of a slug predator (*Pterostichus melanarius* (F.): Carabidae, Pterostichini). Journal of Applied Entomology 128(1): 51-55.

Larochelle A, Lariviere MC 2001. Carabidae (Insecta: Coleoptera): catalogue. Fauna of New Zealand No.43. 285 pp.

MacLeod A, Wratten SD, Sotherton NW, Thomas MB 2004. 'Beetle banks' as refuges for beneficial arthropods in farmland: long-term changes in predator communities and habitat. Agricultural and Forest Entomology 6(2).

Mair J, Port GR 2001a. Predation by the carabid beetles *Pterostichus madidus* and *Nebria brevicollis* is affected by size and condition of the prey slug *Deroceras reticulatum*. Agricultural and Forest Entomology 3(2): 99-106.

Mair J, Port GR 2001b. Predation on the slug *Deroceras reticulatum* by the carabid beetles *Pterostichus madidus* and *Nebria brevicollis* in the presence of alternative prey. Agricultural and Forest Entomology 3(3): 169-174.

Mauchline AL, Osborne JL, Powell W 2004. Feeding responses of carabid beetles to dimethoate-contaminated prey. Agricultural and Forest Entomology 6(2): 99-104.

McKemey AR, Symondson WOC, Glen DM 2003. Predation and prey size choice by the carabid beetle *Pterostichus melanarius* (Coleoptera: Carabidae): the dangers of extrapolating from laboratory to field. Bulletin of Entomological Research 93(3): 227-234.

Murray D, Spackman G 1983. Application of baits for soil insect control. Queensland Agricultural Journal 109(1): 47-48.

NZ Agrichemical Manual 2005. New Zealand Agrichemical Manual. Young S ed. Agri Media Ltd, Christchurch, New Zealand. 634 pp.

Purvis G 1992. A long-term study of the impact of methiocarb molluscicide on carabid populations and case history for interpretation of non-target pesticide effects in the field. Aspects of Applied Biology 31: 97-104.

Purvis G 1996. The hazard posed by methiocarb slug pellets to carabid beetles: understanding population effects in the field. Slug & snail pests in agriculture. Proceedings of a Symposium, University of Kent, Canterbury, UK. Pp. 189-196.

Purvis G, Bannon JW 1992. Non-target effects of repeated methiocarb slug pellet application on carabid beetle (Coleoptera: Carabidae) activity in winter-sown cereals. Annals of Applied Biology 121(2): 401-422.

Robertson LN, Wrenn NR, Barker GM 1986. Effects of diazinon, fensulfothion and isazophos on predatory invertebrates in pasture. Proceedings of the 39th New Zealand Weed and Pest Control Conference: 117-121.

Samsoe-Petersen L, Bieri M, Buchs W 1992. Interpretation of laboratory measured effects of slug pellets on soil dwelling invertebrates. Aspects of Applied Biology 31: 87-96.

Schwalbe R 1997. Results of a five year study on the carabid fauna in sugarbeet fields in the drier areas of central Germany. Mitteilungen der Deutschen Gesellschaft fur allgemeine und angewandte Entomologie 11(1/6): 103-106.

Sivasubramaniam W, Wratten SD 1995. Effects of insecticides on the abundance of arthropod predators in carrots in Canterbury, New Zealand. Proceedings of the 48th New Zealand Plant Protection Conference: 302-307.

Sivasubramaniam W, Wratten SD, Klimaszewski J 1997. Species composition, abundance, and activity of predatory arthropods in carrot fields, Canterbury, New Zealand. New Zealand Journal of Zoology 24(3): 205-212.

Sotherton NW, Moreby SJ 1984. Contact toxicity of some foliar fungicide sprays to three species of polyphagous predators found in cereal fields. Annals of Applied Biology 104 (Suppl.): 16-17.

Symondson WOC 1994. The potential of *Abax parallelepipedus* (Col: Carabidae) for mass breeding as a biological control agent against slugs. Entomophaga 39(3/4): 323-333.

Symondson WOC 2004. Coleoptera (Carabidae, Staphylinidae, Lampyridae, Drilidae and Silphidae) as predators of terrestrial gastropods. Natural enemies of terrestrial molluscs. Pp. 34-86.

Symondson WOC, Glen DM, Wiltshire CW, Langdon CJ, Liddell JE 1996. Effects of cultivation techniques and methods of straw disposal on predation by *Pterostichus melanarius* (Coleoptera: Carabidae) upon slugs (Gastropoda: Pulmonata) in an arable field. Journal of Applied Ecology 33(4): 741-753.

Symondson WOC, Glen DM, Erickson ML, Liddell JE, Langdon CJ 2000. Do earthworms help to sustain the slug predator *Pterostichus melanarius* (Coleoptera: Carabidae) within crops? Investigations using monoclonal antibodies. Molecular Ecology 9(9): 1279-1292.

Symondson WOC, Glen DM, Ives AR, Langdon CJ, Wiltshire CW 2002. Dynamics of the relationship between a generalist predator and slugs over five years. Ecology 83: 137-147.

Thomas MB, Sotherton NW, Coombes DS, Wratten SD 1992. Habitat factors influencing the distribution of polyphagous predatory insects between field boundaries. Annals of Applied Biology 120(2): 197-202.

Thomas RS 2002. An immunological and behavioural study of the role of carabid beetle larvae as pest control agents in cereal crops. PhD thesis, Cardiff University, Cardiff.

Thomas SR, Goulson D, Holland JM 2001. Resource provision for farmland gamebirds: the value of beetle banks. Annals of Applied Biology 139(1): 111-118.

Turin H, Den Boer PJ 1988. Changes in the distribution of carabid beetles in The Netherlands since 1880, II. Isolation of habitats and long-term time trends in the occurrence of carabid species with different powers of dispersal (Coleoptera, Carabidae). Biological Conservation 44: 179-200.

Wick M, Freier B 2000. Long-term effects of an insecticide application on non-target arthropods in winter wheat – a field study over 2 seasons. Anzeiger fur Schadlingskunde 73(3): 61-69.

Wiltshire CW, Glen DM 1989. Effects of molluscicides on slugs and soil arthropods in winter cereal crops. Monograph – British Crop Protection Council (No. 41). Pp. 399-406.

Zhang J, Drummond FA, Liebman M, Hartke A 1997. Phenology and dispersal of *Harpalus rufipes* DeGeer (Coleoptera: Carabidae) in agroecosystems in Maine. Journal of Agricultural Entomology 14(2): 171-186.