The Biology and Control of the Slug *Deroceras laeve* (Gastropoda:Pulmonata:Limacidae) in Manitoba Strawberry Fields

A Thesis

Submitted to the Faculty

of Graduate Studies

The University of Manitoba

By

Brian Dale Prystupa

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science

Department of Entomology

October 1982

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ABSTRACT

Prystupa, Brian Dale, M.Sc., The University of Manitoba, August, 1982

The Biology and Control of the Slug Deroceras laeve (Gastropoda: Pulmonata:Limacidae) in Manitoba Strawberry Fields.

The biology and control of the slug Deroceras laeve was studied in strawberry fields in several locations throughout Manitoba. Slug biology was determined in strawberry fields and adjacent areas using quadrat sampling and bait trapping. Slug phenology was determined using quadrat sampling and local weather information. Overwintering adult Deroceras laeve appeared with the first snow-melt in spring (eggs and immature slugs may also overwinter). Adult slugs fed and reproduced during the first two weeks of July, then they disappeared. Oviposition begins in June, and a new generation can lay eggs into October if weather conditions permit. Peak egg densities occurred in the last week of June (1981) or the first week of July (1980). Peak slug densities occurred in the second week of July in both 1980 and 1981 (mostly immature slugs). The new generation of slugs feed and reproduce until temperatures approach freezing.

Chemical control was tested in field trials using registered and unregistered molluscicides; Methiocarb 2% bait formulation, metaldehyde 50% EC spray formulation, a 'modified' metaldehyde 2.75% bran bait formulation, metaldehyde 2.75% bran bait formulation, copper sulphate-lime powder (1:9 w/w) and Kocide 101 56% WP spray formulation were tested. Three molluscicides were found effective for slug control under the conditions experienced in Manitoba strawberry fields. Methiocarb 2% bait

formulation, metaldehyde 50% EC spray formulation, and a 'modified' metaldehyde 2.75% bran bait formulation were the most effective molluscicides tested (listed most to least significant).

Hedgerow care and composition, the use of ploughed borders around fields, and field renovation were found to be crop management practices which could be used as cultural control methods for slugs. Hedgerows with trees with a shrubby growth form, with branches within 0.5-1.0 m of the ground, with a thick leaf canopy, and which provided a thick leaf litter in fall, were found to be significantly more suitable for slugs. Weedy hedgerows were found to have higher slug densities.

Ploughed field borders reduced slug movement from hedgerows and headlands into strawberry fields; fields which were separated from the adjacent hedgerow or headland, at least 4 m wide, had fewer slugs than fields without ploughed borders. Field borders were more effective when ploughed two or three times throughout the summer.

Renovation was found to modify the environment within the strawberry field; strawberry plants were mowed, and the gaps between plant rows were rototilled. Mowing removed the protective plant cover. Rototilling removed plant debris and straw mulch into the soil between plant rows, and reduced soil moisture. Slug densities were found to be significantly reduced, often to zero, immediately following rotovation.

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ACKNOWLEDGEMENTS

I wish to express my most sincere gratitude to Dr. N.J. Holliday for his patience and guidance throughout the course of this study.

I am very grateful to Waldo Thiessen and the members of the Manitoba Strawberry Growers' Association for cooperation and help with field studies.

I am also indebted to Mrs. M. Funk for the time and care taken in typing this manuscript.

I wish to express a special thanks to Mr. Rob Currie, whose friendship and encouragement made this study more enjoyable.

The time taken by Drs. P.A. MacKay and G.R.B. Webster to review this thesis and their advice concerning improvements was very much appreciated and I thank them for their contributions.

INTRODUCTION

There are approximately 121 ha of strawberries (Fragaria spp.) in Manitoba. This small developing industry has an annual gross income of $1.3 million. The crop is marketed on a U-Pick basis with the major centres of production located in the Portage la Prairie and Altona areas. In 1978, growers in these areas reported that slugs had become a serious pest. Deroceras laeve Müller, a native slug species, was causing direct economic loss by feeding on the ripe strawberries, and was causing indirect loss by discouraging customers from returning once they had picked slug infested berries. This project was set up under an Agro-Man agreement to study the biology and control of the slug D. laeve in Manitoba strawberry fields.

In Manitoba, strawberries are planted in rows 0.75 m wide, with a 0.75 m wide gap between rows. Strawberries are produced over a five year period; berries are not picked the first year, but are picked during the next four years. The field is then ploughed, destroying the plants, and then left fallow for two years.

Manitoba has a fairly low rainfall and strawberries are shallowly rooted so irrigation is essential for consistently high strawberry production. To maximize production, an average of 30 cm of irrigation water is required during the growing season (J. Portree, personal communication). More water may be required for frost protection or if there are above average summer temperatures.

Mulching with wheat and oat straw is used to prevent low temperature injury to crowns and roots. Mulch keeps soil temperatures

more uniform and prevents plants from drying out from cold dry winds. Mulching conserves soil moisture, reduces the number of weeds, and helps keep the berries clean. Straw mulch is removed from the rows to the gaps in the spring before new leaf growth begins. Normally, this takes place during the first two weeks of May. Unless rotovation is used to renovate fields, the straw mulch builds up in the gaps over the five year production period.

Shelterbelts are planted if tree protection is lacking. These reduce wind velocity to reduce the amount of evaporation from plants and soil during the growing season, or during the dormant winter period. In winter, the shelterbelt assists in uniform coverage and distribution of snow as an insulating cover.

Slugs are found where there is plant cover and more or less constant moisture. They are nocturnal, but activity may continue into the early afternoon on days when humidity is high (especially on sunny days following rainfall). Slugs are generalist feeders and accept a wide variety of food materials; fruits and vegetables with a high water content are particularly susceptible to slug attack (Dirzo 1980; Jennings and Barkham 1975). The reproductive capacity of most slug species is high; the hermaphrodidic slugs mate by cross-fertilization to produce about 10-30 eggs per oviposition bout; and each slug may oviposit several times a year (Hunter and Runham 1970).

The molluscicides currently recommended for slug control do not appear to work under the conditions experienced in Manitoba strawberry fields. In this study, registered and unregistered chemicals were tested for their efficacy of control of D. laeve in laboratory and

field trials. The biology of D. laeve was studied to determine whether chemical control could be made more effective by synchronization with slug phenology. Several crop management practices were also tested to determine their affect on the distribution and abundance of slugs in Manitoba strawberry fields.

CHAPTER I

LITERATURE REVIEW

SLUGS OF AGRICULTURAL IMPORTANCE

There are approximately twenty-one slug species of agricultural importance throughout the world. Many of these slugs are of European origin and have been accidentally introduced worldwide through intercontinental and international commerce (Chichester and Getz 1969). Chichester and Getz (1969) have arranged these slugs into three groups of invading species based on habitat characteristics.

The slugs Limax maximus Linnaeus, L. flavus Linnaeus, Lehmania valentiana (Ferussac), Deroceras (Agriolimax) reticulatus (Müller) and Milax gagetes (Draparnaud) have been introduced to Australia, South Africa and South and North America. Slugs from this group are characteristically associated with cultivated areas including active agricultural lands, home gardens, greenhouses and the debris associated with human habitation. This group has the most extensive worldwide distribution.

The second group of invading slug species includes Arion hortensis Ferussac, A. subfuscus (Draparnaud), A. ater (Linnaeus), A. intermedius (Normand), the A. fasciatus complex, and Lehmania marginata (Müller) which are characteristically associated with cultivated areas and natural or bordering habitats. Slugs from this group have been variously introduced to Australia, New Zealand, Tasmania, South Africa and North America. A. hortensis appears to be the most widely distributed slug of this group, being found in all the forementioned locations.

The third group of European slugs includes Geomalacus maculosus (Allman) and Limax cinereoniger (Wolf) and others. Neither of these slugs has achieved intercontinental importation. The former is simply not widely distributed while the latter is restricted to woodlands (and other wild, non-agricultural lands) in the countries where they have been introduced.

In North America, there are fifteen species of European slugs (not including Testacellidae) and three species of native slugs. D. reticulatus, D. agreste (Linnaeus), D. laeve (a native slug), Limax maximus, Lehmania valentiana, A. hortensis, A. ater and A. intermedius are major pests in various parts of North America. Pallifera dorsalis (Binney), Philomycus carolinianus (Bosc), Limax flavus (Linnaeus), Lehmania marginata, Prophysaon andersoni (Cooper), Milax gagates, Arion circumscriptus (Johnston), A. subfuscus, A. fasciatus (Nilsson) and A. silvaticus (Lohmander) are less important agricultural pests in North America. D. reticulatus, D. laeve, A. hortensis, and Limax maximus are the most widely distributed slugs of major agricultural importance. A. circumscriptus, A. fasciatus, A. silvaticus, Limax flavus, Pallifera dorsalis and Philomycus carolinianus are the most widely distributed slugs of minor agricultural importance (Chichester and Getz 1969).

D. reticulatus is the most widely distributed slug throughout Europe and is the most widespread European slug in North America. D. laeve is the most widely distributed native slug of North America. Both of these species are capable of producing large population densities wherever they occur. As well, both of these species are occasional pests in greenhouses (Chichester and Getz 1969).

Importation and Dispersal

In 1822, Thomas Say reported the presence of a European slug in North America (Chichester and Getz 1969). There are now fifteen European slugs in North America, most of which arrived during the period 1850-1920. The earliest reports of European slug importations were from the coastal regions (Chichester and Getz 1969). Two mechanisms of importation have been suggested. Slugs may have arrived in the ballast of ships, since this was dumped on offshore islands or nearby shores. Alternatively slugs may have arrived in nursery supplies or agricultural materials (Chichester and Getz 1969). The wide distribution of some species may be the result of single or multiple importations followed by rapid local dispersal of slugs from the high density populations which are characteristic of those species which are widespread (Howe and Findlay 1972; Platt 1980).

THE BIOLOGY OF SLUGS

The Activity of Slugs

Slugs are found in areas with plant cover and more or less constant moisture. Behavior and activity are influenced by weather conditions. Barnes and Weil (1944, 1945) concluded that activity was controlled by changing combinations of a complex of factors. Temperature and moisture are factors which ultimately determine the presence or absence of slugs, however, the details of day to day variation in population activity are unknown.

Water is lost through the moist, permeable integument and by the

secretion of slime during locomotion. Howes and Welles (1934) stated that an inactive slug can lose 33% (A. ater) to 67% (L. flavus) of its body weight in 24 h if not provided with water. They also stated that an active slug, provided with water, may lose more than 100% of its initial body weight and die in less than 24 h (extrapolated from a one-hour observation).

In damp surroundings (90-100% humidity) slugs can offset the water loss associated with activity by becoming inactive, and absorbing water through the skin until the normal body weight has been re-established. Repetition of this process results in intermittent spurts of activity within the normal activity period (Dainton 1954).

Crawford-Sidebotham (1972) observed the occurrence of activity at various levels of temperature and relative humidity. Activity was found to be a function of temperature and vapour pressure deficit. Vapour pressure deficit is the difference between saturated vapour pressure and the actual vapour pressure. The rate of evaporation from a surface into the air is proportional to the vapour pressure deficit. A high vapour pressure deficit would cause evaporation of moisture from slug and substrate surfaces, thereby reducing slug activity. Furthermore, the vapour pressure deficit is not independant of temperature.

Dainton (1954) found that the activity of slugs is related to the detection of changes in temperature. Activity is induced by falling temperatures between 4^{o} C and 20^{o} C such as often occur at night; rising temperatures in this same range suppress activity. Hence, response to temperature may account for the nocturnal activity and day time inactivity frequently observed in slugs. Daytime rainfall is often associated with

periods of falling temperature (in the 4^{o} C to 20^{o} C range) and can result in daytime slug activity. However, wet periods extending over several days may mask temperature fluctuations such that little slug activity is observed (Dainton 1954). Rising temperatures between 20^{o} C and 30^{o} C induce slug activity, while falling temperatures in this same range suppress activity. Activity is essential when temperatures increase above 21^{o} C. In such a situation, perhaps resulting from sunlight striking an area sheltering slugs, the rising temperature would soon dry out the hiding place and kill the slugs if they were not induced into activity to find a more suitable hiding place (Dainton 1954).

Activity may also be regulated by endogenous cycles. D. caruanae (Pollonera) has an endogenous cycle of activity and inactivity associated with the cycle of feeding and digestion, and affected by humidity, temperature, soil water/rain, food, air currents, copulation/egg laying, and the cycle of night and day (Morton 1970, 1979; Lewis 1969).

Habitat Characteristics

Habitat suitability is determined, primarily, by environmental variables which function to maintain suitable moisture conditions within the slug's microclimate. Soil type determines the moisture-holding capacity of a soil. Plant cover provides shade, shelter from winds, and maintains soil moisture. Debris and stone cover provides moist, temporary shelters. Topography determines rainfall runoff and angle to the sun. In a given area, any of these environmental variables may be the dominant factor determining habitat suitability. This fact has great implications for agriculture, as will be demonstrated in the

section on damage to crops and cultural control of slugs (South 1965; Carrick 1942).

Beyer and Saari (1977) found that slug species are not associated with particular food plant species, but that vegetation does affect the density of slugs through modification of the microclimate. Grime and Blythe (1969) reported similar findings for other molluscs. Barnes (1944) determined that rubbish heaps or heaps of plant debris affected slug density by modifying the microclimate: slug activity, egg survival, and the rate of development increased, and fewer slugs died.

Reproductive Biology

Mating and egg laying normally occur at a species-specific time of the year, but abnormal environmental conditions may alter the timing (Runham and Hunter 1970). Most slug species have either one or two generations per year, depending on species, with egg laying occurring over several weeks. Some species, such as D. laeve, have a life history pattern which may have one or two generations a year depending on environmental conditions (Hunter and Symonds 1971). Alternating generation patterns of this type complicate chemical control of slugs.

Slugs usually lay their eggs in holes or crevices in the ground or under plant debris and other materials. Eggs are laid on or in moist soil in direct contact with the moisture film associated with soil particles. D. reticulatus lays about 500 eggs in batches containing up to 33 eggs while D. laeve, may lay 300 eggs in twenty batches (Hunter and Runham 1970).

The number of eggs laid depends upon the soil moisture conditions.

D. reticulatus lays the maximum number of eggs on soil which is at 75% of the moisture holding capacity. When the soil is only 10% saturated no eggs are laid. The eggs laid at 100% and 25% of the moisture holding capacity of the soil fail to hatch. Eggs are laid deeper in the soil when conditions are dry (Hunter and Runham 1970).

Eggs which are removed from contact with the soil moisture film dessicate at a rate which is dependent upon the humidity of the atmosphere. There are no adaptations of the slug egg to prevent water loss; however, larger, heavier eggs, eggs with older embryos and eggs laid in larger groups generally undergo slower dehydration (Carmicheal and Rivers 1932; Hunter and Runham 1970). Rehydration of dehydrated eggs shows that embryos survive if water loss from the egg does not exceed 85% by weight over short-term periods (Bayne 1969; Carmicheal and Rivers 1969). The survival ability of the embryos is largely due to the greater amount of water loss from the perivitelline fluid relative to that from the embryo proper. D. reticulatus embryos actually lose only 35-40% of their weight when the egg has lost over 65% of its water weight (Bayne 1968). At the opposite extreme, complete immersion of eggs in water for a period of 4 d had little effect on development. Longer periods of immersion considerably reduced hatching success. The behaviour of the slug in selecting an egg laying site is therefore extremely important for egg survival. Both eggs and immature slugs may vary in size and rate of development even if from the same egg batch. This variability can complicate the timing of chemical control measures (Runham and Hunter 1970).

Feeding Biology

Slugs are omnivores and have been found to feed on fungi, mosses, liverworts, lichens, insects, oligochaetes and fresh, senescent or dead plant material (Jennings and Barkham 1975; Richter 1979; Dirzo 1980). There is general agreement that slugs are generalist feeders capable of accepting a wide variety of food materials but showing a distinct order of preference (Dirzo 1980; Jennings and Barkham 1975). Feeding activity of this type enables slugs to select the most nutritious of those foods available in times of food abundance and to have life cycles which are independent of specific host plants or animals (Dirzo 1980).

Dirzo (1980), Pallant (1969), and Jennings and Barkham (1975) have tested the acceptability of approximately 75 plant species to several species of slug. In the summer, during the plant growing season, fresh leaf material from higher plants (dicotyledons) appears to form the largest part of the diet of most slug species. The palatability of a particular plant species depends upon many factors. Leaf texture (soft vs. tough), life-history (annuals vs. biennials and perennials), habitat (natural sites vs. cultivated sites vs. waste sites), and plant chemistry (tannin concentration, etc.) are a few variables of plant palatability measured by Richter (1979) and Dirzo (1980). Leaf texture appears to be the most important factor determining acceptability. Soft-leaved plants are more acceptable than tough-leaved plants. Plants with leaves closer to the ground, and therefore more accessible to slugs, are preferred. Annual plants are more acceptable than either biennials or perennials, possibly because they often grow closer to the ground. Annuals are commonly found in habitats preferred by slugs. It is not

known whether annuals are the most preferred plant in the slugs' habitat, or if the annual plants form the main habitat requirement to which the slugs are attracted (Dirzo 1980).

A number of constraints have been placed upon the aforementioned experiments of Dirzo (1980) and Pallant (1969) which have led to these conclusions. Only a narrow size range of slugs was chosen, however juveniles and adults feed differently. Only leaves were offered as food, leaves were removed from the plants and offered to slugs as cut leaf discs, however cut leaf margins often remove a feeding hinderance. Young and senescent leaves were not used in these experiments. Feeding trials were conducted in petri dishes, rather than in the natural environment (Dirzo 1980).

Jennings and Barkham (1975) used faecal analysis of slugs captured in their natural environment to determine the seasonal food preferences of slugs. Laboratory experiments involving a wider range of food types (fungus, animal material, and senescent and young leaves) were conducted for comparative estimates of food acceptability. In spring A. ater, A. fasciatus, A. hortensis, A. intermedius and A. subfuscus show a large increase in the amount of animal material eaten. Chaetae of earthworms, limbs and parts of the exoskeleton of Collembola and other small arthropods can frequently be observed in the gut of these slugs at this time of year (Jennings and Barkham 1975). It is not known whether these small animals were being eaten dead or alive. Fox and Landis (1973) found that slugs in greenhouses captured and devoured green peach aphids independently of their normal plant feeding activity. In addition to

animal material, any fungi, lichens, algae and/or seedling plants will also be eaten in spring (Boycott 1934).

In autumn there is a significant increase in the amount of fungus material consumed by most slug species. D. reticulatus, D. columbianus Gould, A. ater, A. fasciatus, A. intermedius, Limax maximus, L. tenellus Nilsson, Lehmania marginata feed heavily on a wide range of fungal species. A. circumscriptus and Limax arborum Bouch did not show a preference for the same fungi (Jennings and Barkham 1975; Richter 1979). The widespread use of fungi by slugs in autumn is explainable in terms of the relative decrease in the availability of higher plant material, and more importantly, in the nutritional quality of the food. During late summer (August) tannins build up in higher plants, and in autumn, leaf senescence may cause a sharp reduction in the nutritional value of many plants (affecting nutrients such as N, P, K, Ca and Mg) (Feeny 1970; Richter 1979). Fungi, in contrast, rank high in both caloric and chemical content throughout the year. D. reticulatus preferentially feeds on fungi, when suitable amounts are available, to the exclusion of other available and commonly eaten foods. Fungi are known to be an excellent source of nicotinic acid, riboflavin, niacin, pantothenic acid, and are a good source of vitamins B, C, E and K (Richter 1979).

Climatic conditions may affect feeding such that low temperatures, high winds or other adverse factors may cause slugs to remain low in the leaf litter and feed on the immediate surrounding foods (Jennings and Barkham 1975).

DAMAGE TO AGRICULTURAL SYSTEMS

Slugs cause damage of considerable significance throughout the world and few pests have such a wide geographical distribution or affect such a wide range of crops (Runham and Hunter 1970). Slugs are one of the three most important pests of winter wheat in both England and Wales. They are responsible for the loss of approximately 16,600 ha equivalents of wheat (out of a total of 880,000 ha). In the British Isles, slugs are the third most important pest of potatoes, with losses equivalent to the annual consumption of about 400,000 people (Stephenson 1967; Runham and Hunter 1970; Rayner 1975).

The type of damage caused by slugs, and its severity, vary according to the type of plant, the part of the plant being eaten, the environmental conditions and the suitability of the habitat for slug activity. Though slugs will feed on many types of plants, preference is often shown for one or two parts of any particular plant species (Duthoit 1964). Slugs often chew or rasp the surface of roots, stems, leaves or fruiting bodies. Although only small amounts of plant material are consumed, significant economic losses result if appearance affects saleability. Lange and MacLeod (1941) reported this type of loss when globe artichoke buds were slightly disfigured and discolored from feeding activity of D. agreste and M. gagates.

Damage to stem or leaf surfaces, in some plant species, may result in the death of the plant, thereby greatly decreasing the overall crop productivity. Barry (1969) found that D. reticulatus caused widespread economic damage to field corn by completely destroying the corn

in large sections of fields. Damage resulted from slug feeding activity (grazing, shredding or severing) on the leaves and stem of young corn plants. Damage was greatest if no tillage, minimum tillage, or spring ploughed sod techniques of farm management were employed. Control of the slug pests was complicated by the sporadic nature of the slug infestations. For many plant species feeding damage may also take the form of complete consumption of soft-textured plant parts. Howitt and Cole (1962) reported that entire plantings of newly sprouted corn, beans and brussel sprouts could be consumed by slugs during periods of wet weather. Gould (1961) found that D. reticulatus and A. hortensis could severely damage or completely destroy dry harvesting peas, clover, beans, brassica seed, several lays, and cereals by grain hollowing, shoot grazing or leaf shredding. A large portion of the plant material was consumed in each case.

Lindquist and Krueger (1976) found that D. laeve and D. reticulatus could severely damage both leaves and ripe fruits of a wide range of garden vegetables including tomatoes, lettuce, cabbage, peppers, radishes, carrots and potatoes. Characteristically holes were eaten in foliage or ripe fruits were partly or totally consumed. Control attempts were complicated by changes in species composition and abundance. Both species were abundant in late spring and autumn, however, D. laeve had peak abundance from late June through July, while D. reticulatus had peak abundance from August to October. D. laeve fed more often, but consumed relatively smaller amounts of food material at each feeding. D. reticulatus fed less often, but consumed a great amount of food at each feeding. D. laeve fed by night on surface food materials and then retreated to

suitable surface shelters by day. The slugs remained inactive until the following evening or next period of suitable conditions. D. reticulatus fed by night on the surface food material, or on roots, seeds and other food materials under the soil surface. If D. reticulatus was not already feeding underground, it usually found a suitable protective location for a period of inactivity following feeding, this location was often the top 30-45 cm layer of the soil. Inactive slugs, or slugs feeding underground, may present a problem for chemical control, since the time spent underground may be longer than the time required for pesticide breakdown. Differences in the activity periods, the abundance of slugs and the resting locations of the two slug species can complicate timing and targeting of chemical control efforts (Lindquist and Krueger 1976).

The damage which may be experienced by crops was shown dramatically in a study by Duthoit (1964). The agriculture lands in the study were heavily infested by eight slug species. D. reticulatus, A. fasciatus, A. hortensis, A. ater and A. subfuscus were found to be predominantly surface feeding species, though under different circumstances they may occur as subsurface feeders. Milax gagates, M. budapestensis Hazay and M. sowerbyi Ferussac were found to be predominantly subsurface feeding species. The feeding behaviour of each slug species can result in very different consequences for the crop. Feeding behaviour was tested on oat, wheat and barley seeds and seedling plants. D. reticulatus and A. ater were the most voracious of all the slug species present and constituted the greatest threat to seeds and seedlings. As well, the nature of the damage caused by each species varied; D. reticulatus and A. ater

preferentially attack plant parts such as the germ or the young plumule. The germ and young plumule are vital for plant growth; slug feeding damage to either of these parts is fatal to the plant. A. fasciatus, A. hortensis and M. budapestensis preferentially damage the endosperm which is not as vital and does not often cause plant fatality. Threshold levels for each type of damage are quite different, therefore, the tolerable numbers of slugs for each species are also quite different. Control attempts are made difficult by the presence of both surface and subsurface dwelling species and the complex nature of their feeding behaviour (Duthoit 1964).

The different feeding behaviour of slugs on different plant species can have a profound effect on plant dynamics and can, therefore, have implications for agriculture. Dirzo and Harper (1980) found that the effects of slug grazing activity on two different plant species were quite different if the types of damage to the plants were different. D. caruanae ate whole, or parts of leaves of Capsella sp., but was not found to kill the plants. However, when feeding on Poa sp., D. caruanae chewed through the young shoots at ground level, "felling" but not consuming the leaves or shoots. Plants damaged by this type of feeding activity usually died. The effect of the differential feeding of the slugs was therefore to change the size of plants of Capsella, but not their density, and to change the density of Poa, but not their size (Dirzo and Harper 1980; Cates 1975). Similarly Howitt (1961) reported that in pasture D. agreste and A. ater ate large portions of ladino white clover but little orchard grass. As a result ladino white clover could be replaced in a single season by orchard grass and weeds,

with consequent loss of pasture quality.

The amount of plant material consumed by slugs has been estimated by Pallant (1970) who found that the wet weight of Ranunculus repens (L.) leaf eaten, was 60.9 mg/24 h for slugs averaging 254.6 mg (in woodland). Assimilation efficiency was found to be 78% of food intake. Jennings and Barkham (1976) found the dry weight of food eaten, estimated from mixed plant species, to be 9.34 mg/g live weight/day for mature A. ater, and 20.15 mg/g live weight/day for immature slugs (in woodland). Assimilation efficiency was found to be 70% of food intake for both mature and immature A. ater. Values for food consumption and assimilation efficiency in agricultural systems are not necessarily the same as those from woodland.

CHEMICAL CONTROL OF SLUGS

Early Control Attempts

A large number of inorganic and organic pesticides have been tested for their ability to control slugs. Miles, Wood and Thomas (1931) tested a large number of control substances and repellent substances. Few chemicals were lethal, and these were either toxic to plants or people, or not adequate for slug control in the field. The lethal effects were based on contact toxicity which necessitated both nighttime application and direct contact with slugs. Nighttime chemical applications are unrealistic, especially when only a very small percentage of the slugs would be active and therefore be killed. A number of chemicals were found to be repellent. Trails of these chemicals are often employed as a barrier to slug movement at field edges. However,

field testing has shown that these chemicals are capable of only a 20 to 30% reduction in the number of slugs at best, while requiring excessive amounts of labour and materials.

Lange and MacLeod (1941) tested a variety of newer chemicals in 1940, including a number of aldehydes and calcium arsenate. Calcium arsenate was found to give "satisfactory" control of slugs (no figures given). Metaldehyde was found to give good control of slugs and excellent control of slug eggs, when dusted on them. All other chemicals tested gave no control of slugs.

Chemical Control with Metaldehyde

Metaldehyde has been tested for its ability to control slugs on a variety of agricultural and ornamental plant types. Though total control is not possible, it is possible to reduce slug numbers to levels which cause less appreciable economic loss (Thomas 1948). Slug species known to be susceptible to metaldehyde formulations include D. reticulatus, D. laeve, D. agreste, A. ater, A. hortensis, A. circumscriptus, A. subfuscus, M. gagates, M. budapestensis, Limax maximus and Prophyson andersoni. The percentage mortality varies and depends on environmental conditions, season, and other factors. Metaldehyde formulations are still among the most efficacious known chemical controls for slugs.

Metaldehyde can exert a toxic action on D. reticulatus either by contact as a powder, spray or colloidal suspension, or by stomach poisoning as a bran bait. Toxic effects appear more rapidly in contact treatments, with death occurring after 1 h of contact with metaldehyde concentrations equivalent to 0.0063 mg/cm^2. There is some evidence that

metaldehyde works as a nerve poison. The symtoms of metaldehyde poisoning include immobilization broken by bursts of unco-ordinated muscular activity, and heavy slime secretion. Toxic effects on slugs are greater under conditions of high or rising temperatures. Moderate doses often cause lengthy periods (24 h) of abnormal behaviour and a complete loss of feeding activity (30 h after treatment). However, recovery from moderate doses is possible when slugs are in a saturated or almost saturated atmosphere (Cragg and Vincent 1952).

Barnes and Weil (1942) tested forty-five possible substitutes for bran in metaldehyde bran bait formulations. Only animal foods (concentrates) were significantly better than bran as a bait formulation material. Human foods were found to be slightly better than bran. None of the non-foodstuff materials were significantly better than bran in metaldehyde bait formulations.

Barnes and Weil (1942) concluded that most foodstuffs were significantly more effective than bran in metaldehyde bait formulations. Nutritive foodstuffs such as the animal cakes tested, appeared to be more attractive than roughage foodstuffs such as bran. However, the higher costs of animal foodstuffs were found to reduce the economic feasibility of chemical control, especially on low value, high acreage crops.

Lange and Sciaroni (1953) found that the toxicity of metaldehyde dusts could be significantly increased by the addition of parathion. The mortality of D. reticulatus and M. gagates increased from 66.7% to 86.7% (over six days) when parathion (2%) was added to metaldehyde

(5%) dust. However, mortality was based on direct application of dusts to slugs. The effectiveness of the parathion-metaldehyde mixture was greatly reduced (only 13.3%) when slugs were left to contact the dust on their own, in the course of normal activity.

Ruppel (1959) tested metaldehyde-bran bait plus carbaryl (each at 1.25% conc.), and metaldehyde-bran bait (7.5%) plus calcium-arsenate (2.50% conc.). Slugs placed in petri dishes in direct contact with either chemical mixture died within three days. Ruppel gave no estimate of slug mortality under field conditions. Webley (1962, 1964) found that addition of carbaryl to metaldehyde baits did not always enhance slug mortality, and attributed this variability to differing weather conditions. The addition of endrin, dimethoate or diazinon or of the fungicides dazomet or zineb to metaldehyde-bran baits did not enhance the efficacy of the bait (Webley 1962, 1963).

New Chemicals: Carbamates and Organophosphates

Methiocarb (Bayer 37344) was among the earliest carbamates to be tested and immediately proved to be a superior molluscicide to metaldehyde (Symonds 1975). Methiocarb was significantly better at reducing the number of D. reticulatus when tested against standard metaldehyde-bran baits under dry conditions; under wet conditions, methiocarb gave satisfactory control of slugs, while metaldehyde-bran bait was ineffective. The influence of the environment on slug mortality is not as great with methiocarb bait as it is with metaldehyde baits (Getzin 1965).

Getzin (1965) and Crowell (1967) reported that methiocarb produced

paralysis or loss of muscle tone in test slugs without inducing excessive mucous secretion. Death may take up to 5 d to occur, with most slugs remaining immobile for the entire period. The effectiveness of the carbamate bait is largely governed by the quantity of bait consumed before paralysis sets in, there is an optimal balance between the concentration of active ingredient which produces a sublethal dose and that which is repellent. Getzin (1965) found that methiocarb concentrations of 1% and 2% paralysed slugs, but feeding ceased before a lethal dose of toxicant was ingested so that the slugs eventually recovered. Getzin (1965) and Crowell (1967) found that methiocarb concentrations of 3% and 4% were lethal to slugs.

Crowell (1967) compared metaldehyde bait with several carbamate bait formulations including methiocarb, promecarb, formetanate, methomyl, and several experimental carbamates. All, except methomyl and one experimental carbamate, caused significant slug mortality. Promecarb and formetanate were as toxic to slugs as methiocarb.

Judge (1969), Barry (1969), Hunter and Johnston (1970) and Symonds (1975) have tested a large number of carbamates and organophosphorus pesticides. About 25-30 chemicals were capable of causing adequate slug mortality in the laboratory but only four of these were capable of causing mortality which was adequate for slug control when applied as sprays to field plots. This indicates the importance of the mode of application of each chemical: Crowell (1967) found that aldicarb bait showed little promise as a chemical for slug control, but Judge (1969) found that a granular formulation of aldicarb caused 100% mortality to D. reticulatus on field peas.

Chemicals which were found to be effective in controlling slugs were metaldehyde, methiocarb, aldicarb and phorate (Judge 1969; Barry 1969), and thiocarboxime (Hunter and Johnston 1970; Symonds 1975). Methyl bromide and chloropicrin are fumigants which are very toxic to slugs under laboratory conditions. However, the conditions and procedures necessary for field applications do not appear to be amenable to slug control in the field (Barker et al. 1980, 1981; Kolbezen and Abu-El-Haj 1972).

CHEMICAL CONTROL STRATEGIES

Thomas (1948) and Howitt and Cole (1962) suggested that the conditions required for optimum chemical control results are warm, damp nights, causing high slug activity, followed by warm sunny days, which extend slug activity into the late morning period. Warm, sunny, drying conditions after a rainfall increase slug activity and baits can be effective if not exposed to excess moisture (Thomas 1948). However, the relationship between the effectiveness of a treatment and its timing, relative to slug activity, is not always consistent. It is possible that a highly variable proportion of the active slugs engage in feeding activity and therefore respond to baits (Rayner et al. 1978).

Chemical control attempts are not usually effective when field applications are made after disturbances to the environment. Rayner et al. (1978) working in potatoes, found that chemical control attempts are more effective if treatments are applied when the soil is thoroughly moist and the ground cover is undisturbed and thereby in a condition favourable for slug activity. Applications made in July or early August

are more reliable than those made later, when the ground cover is removed during crop management practices; the moist microclimate favourable for slug activity is destroyed and the effectiveness of the treatment decreases (Rayner et al. 1978). Attempts to reduce overwintering slug populations, or populations throughout the season, should be made prior to any working of the fields or other physical alteration of the environment.

Howitt and Cole (1962) reported that the effectiveness of metaldehyde bait, spray or dust could be increased by placing it under the plant canopy rather than on bare ground. A. hortensis, M. budapestensis and D. reticulatus were reduced to less damaging levels on potato crops and wheat fields when chemical treatments were applied as seed dressings, rather than as surface treatments (Gould 1962; Stephenson 1967).

Webley (1965) and Cragg and Vincent (1952) suggested that the proper chemical treatment to control slugs should include application of molluscicides to slug reservoirs including headlands and adjacent hedges or uncultivated lands. Webley (1965) recommended a control strategy for problem areas with nearby slug reservoirs. Metaldehyde spray formulation should be used for epidemics of slugs to obtain an initial kill of a high percentage of the slugs. Metaldehyde bait formulations could then be used as a long-term control measure to keep down infestations already partially controlled by preventing massive repopulation of an area.

Hunter and Symonds (1970) determined the optimum density of metaldehyde and methiocarb pellets for slug control under field conditions. For D. reticulatus, on lawn, the optimum density of pellets was found

to be between 25 and 100 pellets/m^2 (10-20 cm apart) (Hunter and Symonds 1970).

The rate and number of applications has already been determined for commercially available molluscicides. Higher than recommended rates of chemical application and repeated applications were found to give only a marginally better reduction in slug damage than a single application at the standard rate (Rayner et al. 1978).

Webley (1966) increased the persistence of metaldehyde bran baits by waterproofing the pellets using chlorosilanes, alkoxysilanes, silicone resins and fluids to coat the individual pellets. The process was successful when 1% siloxane gas was passed over metaldehyde-bran pellets: the waterproofed pellets were intact after three months immersion in water. Stephenson (1972) took the waterproofing process a step further. Talcord, an experimental molluscicide, was incorporated into inert photographic grade gelatin as a carrier. Attractant wheat bran was not used as a bait because it is attacked by mould. Rather, the water-soluble, protein rich constituents of wheat bran were formulated into the molluscicide-gelatin mixture. This mixture was able to withstand conditions of excess moisture over extended periods of time, while maintaining its ability to reduce the numbers of D. reticulatus. Hardening the gelatin with formaldehyde greatly increased the durability of the bait in wet weather without significantly reducing the activity of the toxicant. A mixture of hardened and unhardened gelatin discs could eliminate the necessity of repeated chemical applications. An initial quick release of molluscicide would occur from unhardened discs under normal conditions and a second release would occur

when the hardened discs were thoroughly wetted by rainfall (Stephenson 1972).

CULTURAL CONTROL OF SLUGS

Cultivation and Crop Management Practices

One of the most effective methods of decreasing slug habitat suitability is through the use of cultivation before, during and after the growing season (Lewis 1980). Hunter (1967a) found that various cultivation techniques could significantly affect the population levels of D. reticulatus, A. hortensis and M. budapestensis. Three cultivation procedures were tested: soil ploughed once during the winter, soil ploughed three or more times to produce a fine tilth and soil ploughed several times to produce a tilth which was then compacted and sown with grass. All treatments caused a significant reduction in the number of slugs: D. reticulatus, a surface feeder and A. hortensis, a subsurface feeder, were reduced to 25% and 33%, respectively, of their previous population levels when the soil was ploughed once. Multiple ploughing was significantly more effective than single cultivation in controlling all three slug species, and multiple ploughing followed by seeding of grass was the most effective method of slug control. The effectiveness of these treatments appeared to result from the elimination of adequate shelter. Adverse weather conditions kill slugs which cannot find shelter. The absence of soil spaces also inhibited the movement and feeding activity of slugs below the soil surface and reduced the subsurface crop damage (Hunter 1966; Runham and Hunter 1970).

Stephenson (1975a) and Runham and Hunter (1970), found that when

aggregates of fairly dry, medium-coarse soil were broken down and firmed over the seed bed by compaction, winter wheat was less damaged by D. reticulatus. Stephenson (1975b) found that the distribution of D. reticulatus varied in different aggregate fractions of garden loam. Slugs layed more eggs in fine or medium aggregate fractions (3-10 mm). The slugs apparently preferred these fractions because of the protection for the egg-masses offered by the clumps left by cultivation. The finer parts of the soil made for ease of oviposition and possessed better moisture retention characteristics. The spatial distribution and species composition of slugs is affected by the history of cultivation. Populations of D. reticulatus can survive in locations where the soil does not permit access to underground shelter, whereas A. hortensis and M. budapestensis require shelter from drought and frost in loose soil. The use of herbicides for weed control has reduced the number of cultivations required for the growth of agricultural crops. The probability of crop damage by slugs would be expected to increase under these conditions (Hunter 1967b).

It may be impractical to use extra cultivations as a tool for slug control because they are labour and energy intensive; chemicals are usually cheaper and easier to apply. Too many cultivations may cause overcompaction of the soil and reduce plant growth.

Humus, Plant Debris and Compost Heaps

Excess humus in the soil can loosen the soil, increase the capacity of the soil to retain moisture, provide soil spaces to aid slug movement, and provide shelter and winter food for slugs (Barnes 1944). Slugs of all

sizes were more frequently found on compost heaps than anywhere else in gardens, especially late in the growing season. Slug activity persisted near compost heaps when environmental conditions did not permit activity in other parts of the garden. This probably resulted from high moisture and temperature inside the compost heap. The heat of the heap also appeared to affect the surrounding temperature. The microhabitat in the compost heap allowed more frequent activity and feeding, faster rates of growth and development, and extension of the egg laying period than in the rest of the garden. In the compost heap an extra generation of D. reticulatus occurred late in the season. These slugs survived the winter in large numbers and reappeared early in the following season and caused great damage to plants because of their advanced level of development.

Hedgerows and Headlands

Hedgerows and headlands can result in a situation similar to that of the compost heaps. Trees and other vegetation of the hedgerows can act as an isolated, suitable habitat; for instance, providing leaf litter and shade (Beyer and Saari 1977). A. fasciatus and D. laeve are only present in areas where ground vegetation is present and their abundance is affected by the amount of litter and foliage in such areas. Hedgerows with suitable conditions for slug abundance may act as a reservoir from which slugs disperse nightly into field crops. This may cause repopulation of areas which have been treated with molluscicides (Webley 1965; Miles et al. 1931).

Crop History

Gould (1961) found that D. reticulatus and A. hortensis could cause complete failure of winter wheat crops planted after dry harvesting peas, clover and brassica seed crops. The increased numbers of slugs appeared to be due to the ideal breeding conditions experienced under these crops or their residues. However, Miles, et al. (1931) suggested that under normal farming conditions, the practice of crop rotation probably limits slug development. The absence of a crop can cause a temporary elimination of all food except for a limited amount of organic matter in the soil; the alteration of the microhabitat may also reduce the suitability of the habitat.

BIOLOGICAL CONTROL OF SLUGS

Predators, parasites and diseases are among the most important density-dependent mortality factors for most organisms (Runham and Hunter 1970). However, these mortality factors appear to have little effect on slug populations. It seems that the peculiarities of slug biology may make them less liable to depletion by predators and parasites. Slugs are nocturnal and activity is often irregular, so the probability of encounter with predators and parasites is reduced. Slugs often feed, rest and reproduce in a wide variety of habitats or microhabitats, even within a localized area. A large proportion of the total slug population of an area may be concentrated in any one of the many microhabitats typical of the areas slugs inhabit.

Slugs have been found in the crops of a number of bird species, but only as occasional foodstuffs (Blezard 1967; Runham and Hunter 1970).

There also exist reports of slug predation by moles, toads, shrews and hedgehogs (Miles et al. 1931). However, there are very few accounts of observed predation by the forementioned predators and Skaren (1978) found that the least shrew Sorex minutissimus did not eat slugs, even when hungry.

Runham and Hunter (1970) reviewed the many observations of parasitism of slugs by various invertebrates. Normally the relationship between the slug and the organism within is a true parasitic relationship: the parasite does not kill the slug. This seems to be the case whether the parasites are inhabitants of the alimentary canal, the reproductive glands and/or other vital organs (Stephenson and Knutson 1966).

Insects such as carabid, lampyrid and staphylinid beetles are known to eat slugs. However, since only a very small percentage of any slug population is affected by predation, mortality of this type cannot be considered appropriate for the control of slugs in the field (Runham and Hunter 1970). Only three parasites and seven predators are capable of killing even a small percentage of fourteen slug species; no significant biological control of slugs has ever been observed.

CHAPTER II

MATERIALS AND METHODS

SAMPLING METHODS FOR SLUGS

Slugs and eggs were sampled in 1980 and 1981 from strawberry fields and bordering areas in several locations throughout Manitoba. A 0.25 m^2 quadrat was used to sample low slug densities. A 0.10 m^2 quadrat was used to sample high slug densities. Samples were selected with the aid of random number tables. Each sample was searched and the total number of slugs, the number of adult slugs, immature slugs, eggs, egg batches and slug lengths were recorded. Samples were taken from an assortment of second, third, fourth and fifth year strawberry fields in each location. Site, date, field age, field number, sample location within the field, temperature, cloud cover, and the occurrence of rainfall were recorded for all samples.

Slugs and eggs collected during field sampling were placed in 125 mℓ plastic cups with lids with a small amount of moist straw mulch or plant debris. If only dry material was available, distilled water was added to maintain humidity. The cups were placed in a styrofoam cooler with freezer packs for transport to the laboratory.

Periodically, some slugs were killed for dissection by drowning in warm water. Slugs were either stored in a freezer, or preserved in 70% ethanol.

STRAW COVER

In 1980 the amount of straw cover was measured using a graduated 30 ℓ plastic tub. The volume of fresh straw and of decomposing straw mulch from the previous year was measured for a 0.25 m^2 area. Measurements were taken from within the plant rows, and in the gaps between the rows. Samples were taken from fields of different ages at some sample sites, and from different sample sites in the province.

SOIL ANALYSIS

Soil analysis was performed to determine whether or not there was a correlation between various soil factors and the distribution and abundance of slugs in strawberry fields. Soil pH, soil carbonate content, and soil organic matter content were determined for soil samples from fields with heavy slug infestations, and from those fields in which slugs were scarce or absent.

Soil cores 10.5 cm in diameter and 10 cm deep were taken using a soil corer. The soil was placed in polyethylene bags and transported to the laboratory where it was stored at 5^{o} C. Each core was oven dried for 7 h at 105^{o} C. A subsample was taken from the oven-dried soil sample. A mortar and pestle was used to grind the subsample to fine powder.

pH Determination

Soil pH was measured in 0.01 M calcium chloride, as recommended by the Manitoba Provincial Soil Testing Laboratory.

Reagents: 0.01 M Calcium chloride ($CaCl_2$)

The 0.01 M $CaCl_2$ solution was adjusted to pH 5.5 with 4 N HCl.

Procedure: In a 50 mℓ beaker, about 20 mℓ of 0.01 M $CaCl_2$ solution were added to 10 g of soil. This suspension was stirred several times during the next 30 min, and then left to stand for 30 min to allow most of the sediment to settle. A pH meter with a combination electrode was used to measure the pH of the supernatant. The meter was checked against a standard buffer solution after each sample was tested.

Carbonate Determination

Soil carbonates were measured as calcium carbonate equivalent.

Reagents: 4 N Hydrochloric acid

Calcium carbonate

Procedure: 30 mℓ of 4 N HCl were placed in a 700 mℓ wide-mouth reaction bottle. A sample of the oven-dried soil was weighed, then placed in a waxed paper cup, the cup and contents were floated on the HCl in the reaction bottle. Reaction bottles were each stoppered with a 2-hole rubber stopper, and a thermometer and glass tube were inserted into the holes. Reaction bottles were clamped onto a shaker apparatus, the bottles were immersed in an adjacent circulating water bath maintained at 25° C. A mercury manometer was connected via the glass tube of each reaction bottle. The zero reading on the manometer was checked when the temperature of the reaction bottles had attained equilibrium with the temperature of the water bath (25° C). The shaker apparatus was set in motion by hand, dumping the soil into the acid. Readings were taken at frequent intervals until no change in pressure occurred. Calcium carbonate was used as a standard.

Organic Matter Determination

Soil samples were sent to the Manitoba Provincial Soil Testing Laboratory for determination of soil organic matter. The Walkley-Black chromic acid titration method (using $K_2Cr_2O_7$) was used (Peech et al. 1947).

LABORATORY EFFICACY TESTING OF MOLLUSCICIDES

Laboratory Culture of Slugs

Laboratory cultured adult slugs (> 1.0 cm extended length) were placed on a Whatman No. 1 filter paper covering the bottom of a 15 cm plastic petri dish. The filter paper was moistened with distilled water. A maximum of ten slugs were placed in each petri dish. If slugs were to be used for efficacy testing of molluscicides on the day following collection, a small amount of moist leaf litter or straw mulch was added to each petri dish. Slugs kept in the laboratory for more than one day before testing were given fresh lettuce leaves. The petri dishes were kept in an incubator at 10^{o} C, in total darkness.

Laboratory Trials of Molluscicides

Copper sulphate. Copper sulphate stock solution was prepared by dissolving 1 g of copper sulphate ($CuSO_4.5H_2O$ crystals) in 1 ℓ of distilled water. Stock solutions for all trials except the first were stored at room temperature for 2 d to insure total solution of the copper sulphate. Test solutions were prepared by adding enough distilled water to obtain the desired concentration of copper sulphate.

Laboratory cultured slugs were placed on a dry Whatman No. 1 filter

paper placed on the bottom of a 15 cm petri dish. Ten adult slugs (> 1.0 cm long) were placed inside each dish, and 4 mℓ copper sulphate test solution was added. The copper sulphate solution was added such that several drops of solution contacted each slug, and some wetted the filter paper. The petri dishes were placed in an incubator at 10^{o} C, in total darkness. Initial responses of the slugs to chemical treatment, and the responses at several time intervals were recorded. Laboratory trials were conducted using copper sulphate concentrations ranging from 10 to 1,000 mg/ℓ.

Detailed observations on the effects of topical application of 400 mg/ℓ aqueous copper sulphate solutions on slugs were made. The procedure differed from that outlined above in that slugs were treated individually on damp filter paper using a microlitre syringe.

Modified metaldehyde bait formulation. Symonds (1975) found that palatability of bait formulations of molluscicides may be more important than the intrinsic toxicity. In this study, metaldehyde 2.75% bran bait formulation was reformulated in an attempt to increase palatability. A "modified" metaldehyde bait formulation was produced by combining commercial 2.75% metaldehyde bran bait with molasses and strawberry extract (Appendix 1).

In the laboratory, Whatman No. 1 filter papers were placed on the bottom of two 54 cm (l) x 26 cm (w) x 12 cm (h) plastic boxes and saturated with distilled water. In one box, lettuce leaves were placed at one end, and modified metaldehyde bait was placed at the opposite end. The bait consisted of 2.0 g metaldehyde bran bait sprinkled over

8.0 mℓ molasses containing 0.02 mℓ strawberry extract. In the second box, lettuce leaves were placed at one end, and 2.0 g of commercial metaldehyde bran bait were placed at the opposite end. Twenty laboratory cultured adult slugs were placed in the middle of each plastic box. Both boxes were placed in an incubator at 10^{o} C, in continuous darkness. Slug mortality, and the location of the slugs in the boxes were recorded over a 72 h period.

FIELD TRIALS OF MOLLUSCICIDES

Field testing was conducted on strawberry crops (Fragaria spp.) in Altona, Manitoba.

1980 Molluscicide Field Trial

Experimental design. Slugs were sampled in 7 m x 10 m field plots using a 0.10 m^2 quadrat. Three samples were taken from each field plot at 3-4 d intervals. Samples were taken before and after chemical treatment. Four chemical treatments and one untreated control were replicated five times in a randomized block design.

Application of Molluscicides. Methiocarb 2% pelleted bait formulation was provided by Chemagro Ltd. Methiocarb bait was applied by hand broadcasting over both plant rows and gaps at a rate of 0.18 kg a.i./ha. Metaldehyde 2.75% bran bait formulation was applied by hand broadcasting between plant rows at a rate of 1.0 kg a.i./ha. Three applications of metaldehyde were made at weekly intervals. Copper sulphate and lime were mixed (1:9 w/w) as recommended (Anonymous 1977), and applied uniformly over the ground surface at a rate of 65.0 kg/ha.

Kocide 101 56% copper hydroxide wettable powder formulation was applied to both plant rows and gaps using a backpack sprayer at a rate of 0.55 kg a.i./ha in 454 ℓ of water/ha.

1981 Molluscicide Field Trial

Experimental design. Slugs were sampled in 8 m x 10 m field plots using a 0.10 m^2 quadrat. Four samples were taken from each field plot at 3-4 d intervals. Samples were taken before and after chemical treatments. Four chemical treatments and one untreated control were replicated three times in a randomized block design.

Application of Molluscicides. Methiocarb 2% pelleted bait formulation was obtained from Chemagro Ltd. Methiocarb bait was applied by hand broadcasting over both plant rows and gaps at a rate of 0.18 kg a.i./ha. Metaldehyde 50% emulsifiable concentrate spray formulation was applied by spraying the gaps between plant rows using a backpack sprayer at a rate of 10.5 ℓ of EC formulation/ha in 2,200 ℓ of water/ha. Modified metaldehyde bait formulation was applied as bait strips between plant rows (every fourth gap was treated) at a rate of 1.0 kg a.i./ha; 299.4 g of metaldehyde 2.75% bran bait and 3.4 ℓ molasses and 7.3 mℓ strawberry extract were applied to each 8 m x 10 m field plot. Metaldehyde 2.75% bran bait formulation was applied by hand broadcasting between plant rows at a rate of 1.0 kg a.i./ha. A single application of metaldehyde was made in 1981.

Modified Metaldehyde Bait Formulation

On 22 June 1981, modified metaldehyde bait formulation (metaldehyde-

bran-molasses-strawberry extract mixture) was applied to a single 25 m x 25 m field plot in Altona. The modified bait was applied at a rate of 1.0 kg a.i./ha; 2.45 kg 2.75% metaldehyde bran bait, 17.6 ℓ beet molasses and 38 mℓ strawberry extract were applied to the field plot. Modified metaldehyde bait was applied by first mixing the strawberry extract into the molasses. The molasses-strawberry extract mixture was then poured as a 2.5-4.0 cm wide strip along the centre of the gap between rows of strawberry plants. Metaldehyde bait was sprinkled over the strip to cover it lightly. Three strips were prepared within the 25 m x 25 m field plot.

Random samples of slugs were taken using a 0.10 m^2 quadrat. Each sample was searched by hand and the total numbers of slugs, and the numbers of adults, immatures and eggs were recorded for each sample. Samples were taken before and after chemical treatment.

On 29 June 1981, modified metaldehyde bait formulation was applied to a 0.6 ha strawberry field in Altona. The procedure differed from that outlined above in that the rate of application of the molasses-strawberry extract mixture was reduced. An application of 23.5 kg metaldehyde 2.75% bran bait, 122.7 ℓ molasses and 270 mℓ strawberry extract was applied to the field. On 4 July 1981, modified metaldehyde bait formulation was applied to a 0.6 ha strawberry field in Selkirk, Manitoba. The procedure was that outlined for the 25 m x 25 m field plot above. In both Altona and Selkirk, 0.10 m^2 quadrat samples were taken randomly along the length of the bait strip for the first sampling period after chemical treatment, and the numbers of dead slugs were recorded.

METALDEHYDE BREAKDOWN IN THE FIELD

Metaldehyde bait samples were tested to determine whether or not metaldehyde breakdown was responsible for the loss of effectiveness of the bait formulation under field conditions.

Field Methods

Metaldehyde 2.75% bran bait was placed in two locations in each of two strawberry fields in Altona, Manitoba; 50 g of bait was spread over the straw mulch between plant rows. Eight bait samples (5 g) were collected over a 3 wk period. The samples were transported to the laboratory in plastic bags in a cooler with freezer packs and then stored at about -20° C.

Experimental Methods

Metaldehyde extraction. Field samples of metaldehyde bait (1 g) were placed in a stainless steel blender with 50 mℓ of pesticide grade benzene. Samples were extracted into benzene for 5 min. Sample extracts were filtered through silanized glass wool and anhydrous sodium sulphate, and washed twice with 50 mℓ distilled water and 2 mℓ 2% aqueous NaCl. Sample extracts were passed over anhydrous Na_2SO_4 to dry, and analyzed in benzene solution on a Perkin-Elmer 337 spectrophotometer using 0.2 mm NaCl liquid cells.

Preparation of the metaldehyde standard. A fractional crystallization procedure was used to prepare the metaldehyde standard (no standard was available from government agencies). Three grams of metaldehyde 50% EC were placed in a blender with 50 mℓ of pesticide grade

benzene and extracted for 5 min. The sample extract was filtered through silanized glass wool and anhydrous sodium sulphate and washed twice with 50 mℓ of distilled water and 5 mℓ of 2% NaCl. The organic layer was placed in a 125 mℓ Erlenmeyer flask and metaldehyde crystallized from benzene-ethanol. Metaldehyde crystals were washed 3 times with cold ethanol. The infrared spectra of the metaldehyde standards were recorded on a Perkin-Elmer 377 spectrophotometer using 0.2 mm NaCl liquid cells.

Calculation of metaldehyde concentration. Peak height at 1375 cm^{-1} was measured from the nearest well defined baseline shoulder. This measurement was then applied to the baseline at the spectrum origin to give an absorbance reading. The sample absorbance reading gives a metaldehyde concentration reading when measured from a plot of absorbance versus concentration of metaldehyde standard (see results). For the 7 d bait sample, the 19 mm peak at 1375 cm^{-1} gives an absorbance reading of 0.109 at the spectrum origin. An absorbance of 0.109 corresponds to 0.0178 g of metaldehyde/mℓ solvent. The final volumes of both the metaldehyde standard solution and the bait sample solution, used to determine the spectra, were 1 mℓ. Therefore, 0.0178 g of metaldehyde in the 7 d bait sample (1 g extracted) corresponds to a 1.78% concentration.

IMPACT OF MANAGEMENT PRACTICES ON SLUGS

Grower Survey

Slug control questionnaires were circulated to growers through the Strawberry Growers Association of Manitoba. Thirty questions about slug damage, management practices and control attempts were presented (Appendix 2).

Experimental Methods

Hedgerows. Modified metaldehyde bait was placed under 30 cm x 30 cm pieces of 6 mm plywood to form "bait traps". Three bait traps were randomly placed in each of seven hedgerows. Plant species composition or physical characteristics were different in each hedgerow. The numbers of live and dead slugs were recorded for each bait trap on 5 June and 8 June 1981. Slugs were not trapped during the following week. Trapping resumed on 17 June; bait traps were placed in new, randomly selected locations within each hedgerow. The numbers of live and dead slugs were recorded for each bait trap on 20 June and 22 June 1981.

Field borders. Bait traps were used to assess the effect of field borders on slug movement into strawberry fields. The characteristics of the areas between hedgerows and strawberry fields, or of the areas adjacent to strawberry fields, were recorded. Bait traps were placed on top of the straw covered plants within the first six rows. The numbers of live and dead slugs were recorded for each bait trap.

Renovation. Random sampling with a 0.10 m^2 quadrat was used to assess the impact of renovation techniques of crop management on slugs. Samples were taken before and after renovation. In addition, bait traps were used to attract slugs in renovated fields. Quadrat samples and bait traps were searched and the numbers of slugs were recorded.

SAMPLE SITES

Site 1

The Altona site was located 1.6 km west of Altona, Manitoba. Seven separate fields (1980) and nine fields (1981) (15.4 ha) were planted.

Each field was completely bound by hedgerows. Hedgerow composition was usually different on each side of each field. Hedgerows were composed of green ash (Fraxinus pennsylvanica Marsh.), tower poplar (Populus spp.), ornamental apple (Malus spp.), chinese elm (Ulmus spp.), manitoba maple (Acer negundo L.), or combinations of these tree species. Some of the hedgerows were in a weedy condition.

The dominant soils were Orthic black and Rego black chernozemic soils; these soils are fine textured, calcareous, lacustrine, and loam to clay loam in composition. The surrounding environment was mainly flat, cultivated land. There were no rivers, hills, or large areas of uncultivated land in the immediate vicinity. Irrigation water for the strawberry fields came from two small dugouts, located approximately 300 and 500 m from the fields. The dugouts were relatively free of trees and shrubs. Strawberries have been in production, at this site, for about 15 years.

Site 2

The Selkirk site was located between Lockport and East Selkirk, Manitoba. Four separate fields (1980) and five fields (1981) (6.0 ha) were planted. Hedgerows were present on two sides of two fields, the remaining two fields were not bordered by hedgerows. All hedgerows were composed of a single row of saskatoon berry bushes (Amelanchier alnifolia Nutt.).

The dominant soils were gleyed rego black and rego humic gleysol chernozemic soils; these are fine textured, calcareous, lacustrine, clay soils. The surrounding environment was mainly undulating, uncultivated land. The site was adjacent to a large river (Red River) and part of

the site was situated on the sloping flood banks. Irrigation water for the strawberry fields came from the river. Strawberries have been in production at this site for about four years.

Site 3

The Portage (Sosiak) site was located approximately 4.0 km south and 6.4 km east of Portage la Prairie, Manitoba. Five separate fields totalling 8.0 ha were in production in 1980 and 1981. Each field was bound by hedgerows on two sides. Hedgerows bounding all fields were composed of a single row of willow trees (Salix spp.), maintained by removing branches to a height of 0.5-1.0 m from the ground. Leaf litter and weeds were removed from beneath the willows by raking.

The dominant soils were orthic black and rego black chernozemic soils; these soils are calcareous, lacustrine, and loam to clay loam in composition. The surrounding land was mainly flat to undulating, and cultivated. There were several large surrounding areas of uncultivated land and an adjacent small river from which irrigation water was drawn. Strawberries have been in production, at this site, for about 40 years.

Site 4

The Portage (Nazar) site was located approximately 6.4 km south and 4.8 km east of Portage la Prairie, Manitoba. Six separate fields totalling 8.0 ha were in production in 1980 and 1981. Hedgerows were present on one side of two fields, the remaining four fields were not bordered by hedgerows. Hedgerows were composed of an uncultivated strip of land with mixed tree species, grasses, and weeds.

The dominant soils were orthic black and rego black chernozemic soils; these soils are fine textured, calcareous, lacustrine, and loam

to clay loam in composition. The surrounding environment was mainly flat, extensively cultivated land. There was an adjacent small river and several large surrounding areas of uncultivated land. Irrigation water for the strawberry fields came from the small adjacent river. Strawberries have been in production, at this site, for about 40 years.

Site 5

The Portage (Mayfair) site was located on Island Park in the town of Portage la Prairie, Manitoba. Five separate fields totalling 5.7 ha were in production in 1980 and 1981. Fields were not bound by hedgerows.

The dominant soils were orthic black and rego black chernozemic soils; these soils are fine textured, calcareous, lacustrine, and loam to clay loam in composition. The surrounding environment was mainly flat, cultivated land with a large shallow oxbow lake surrounding the area. There were large areas of uncultivated land immediately surrounding the strawberry fields. Irrigation water for the strawberry fields came from the adjacent lake. Strawberries have been in production, at this site, for more than five years.

CHAPTER III

RESULTS

Slug Biology

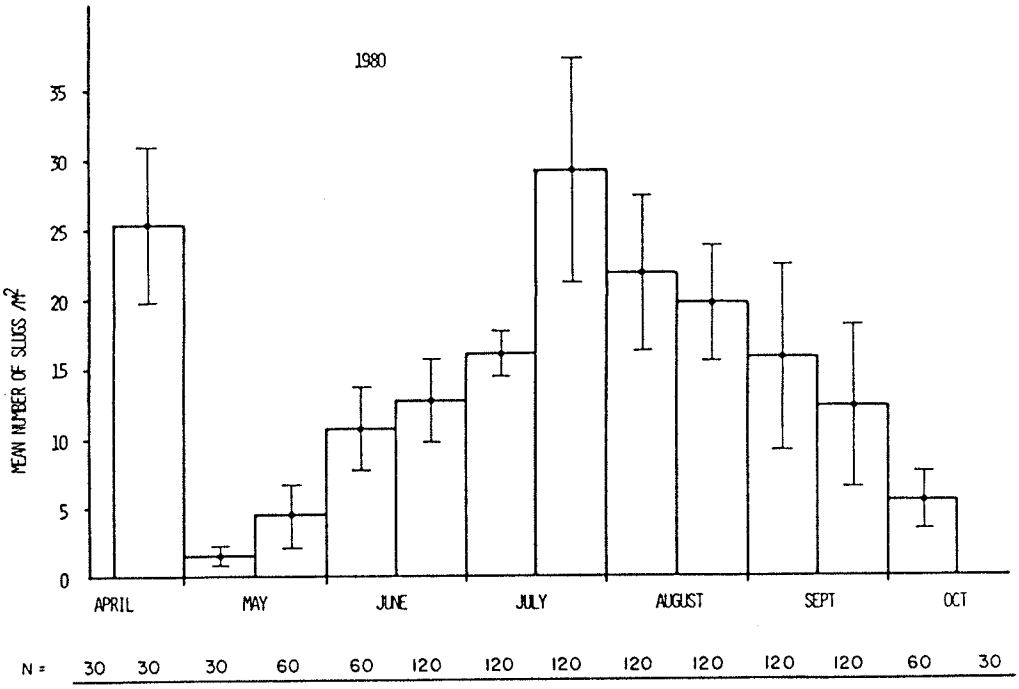
In both 1980 and 1981, Deroceras laeve had two distinct peaks of abundance (Figures 1 and 2). The first peak of abundance occurred in early spring and was 2-3 weeks in duration. In 1980 the peak was larger, and occurred later, than that in 1981. The second peak of abundance of slugs began in early May, with the number of D. laeve increasing through May, June, and July. In both 1980 and 1981, slug numbers peaked in late July. D. laeve was still found on the last sampling period in both years.

The temporal distribution of the eggs of D. laeve in 1980 and 1981 was similar (Figures 3 and 4). Eggs were found from early June to the end of August in 1980, and from early June to early September in 1981. Peak egg densities were similar in 1980 and 1981, but the peak occurred later in 1980.

Immature D. laeve (< 1.0 cm extended length) were found in strawberry fields on 14-21 June, about 2.5 weeks after eggs were found in the same fields in both 1980 and 1981 (Figures 5 and 6). In 1981, immature slugs were also found in late May, about 2-3 weeks after eggs were found in the adjacent hedgerows (Figure 4). Immature slug numbers peaked on 10 July 1980, and on 15 July 1981. Numbers decreased, but immature slugs were still found on the final sampling date (10 October) in 1980; no immature slugs were found on the final sampling date

Figure 1. Mean number of D. laeve per m^2 determined by quadrat sampling in strawberry fields throughout 1980. Means and standard errors are calculated for four and five year fields at Site 1 (Altona) and Sites 3, 4 and 5 (Portage la Prairie). "N" indicates number of samples.

Figure 2. Mean number of D. laeve per m^2 determined by quadrat sampling in strawberry fields throughout 1981. Means and standard errors are calculated for three and five year fields at Site 1 (Altona) and Site 2 (Selkirk). "N" indicates number of samples.


1980
MEAN NUMBER OF SLUGS /M²
0
5
10
15
20
25
30
35
APRIL
MAY
JUNE
JULY
AUGUST
SEPT
OCT
N = 30 30 30 60 60 120 120 120 120 120 120 120 60 30

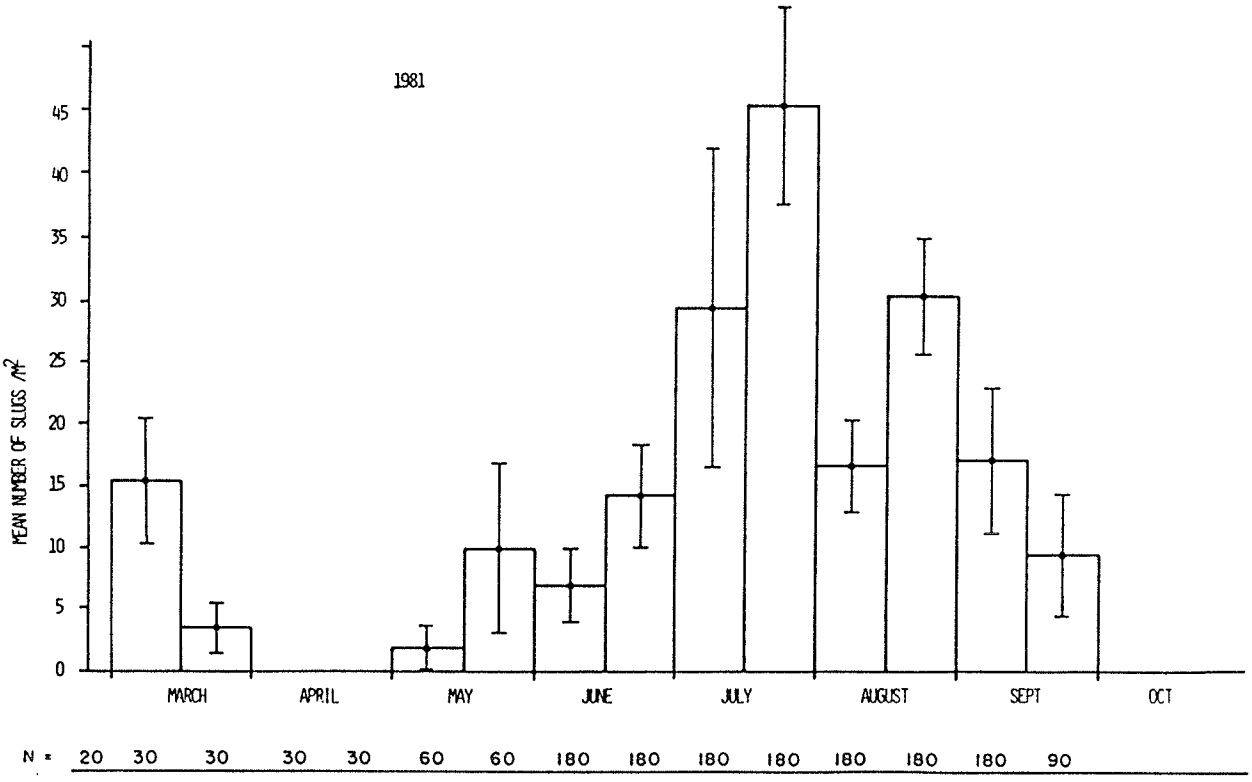
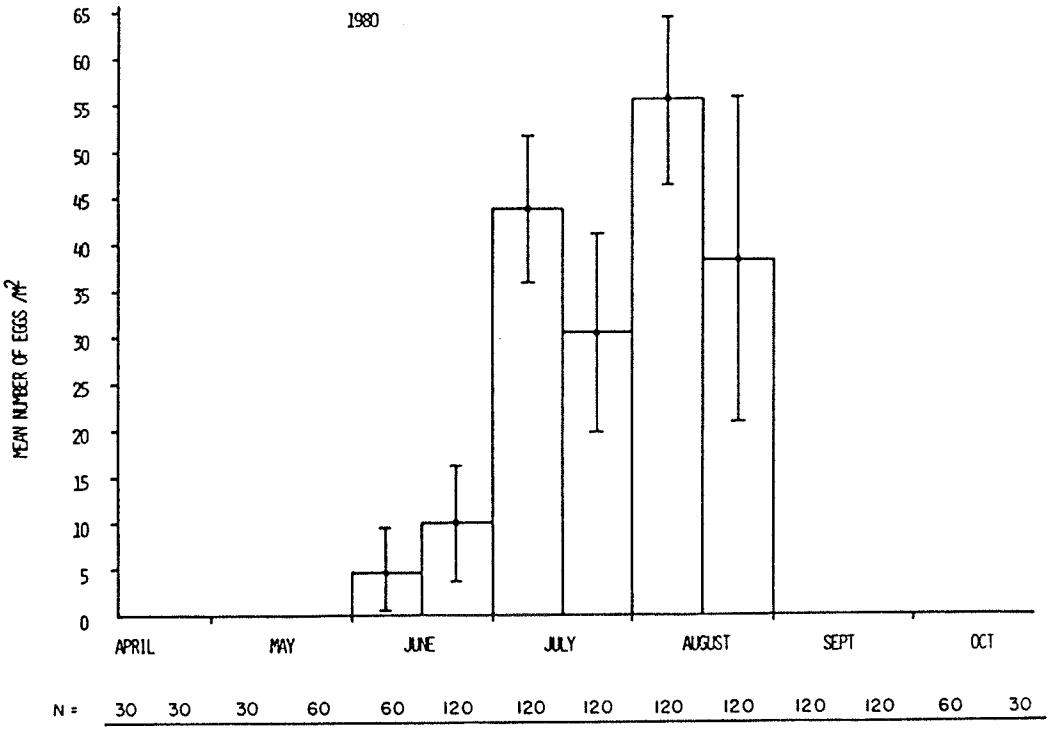

1981
MEAN NUMBER OF SLUGS /M²
0
5
10
15
20
25
30
35
40
45
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPT
OCT
N = 20 30 30 30 30 60 60 180 180 180 180 180 180 180 90

Figure 3. Mean number of D. laeve eggs per m^2 determined by quadrat sampling in strawberry fields throughout 1980. Means and standard errors are calculated for four and five year fields at Site 1 (Altona) and Sites 3,4 and 5 (Portage la prairie).

Figure 4. Mean number of D. laeve eggs per m^2 determined by quadrat sampling in strawberry fields throughout 1981. Means and standard errors are calculated for three and five year fields at Site 1 (Altona) and Site 2 (Selkirk). Dashed bar indicates eggs found in adjacent hedgerows.


1980
MEAN NUMBER OF EGGS /M²
65
60
55
50
45
40
35
30
25
20
15
10
5
0
APRIL
MAY
JUNE
JULY
AUGUST
SEPT
OCT
N = 30 30 30 60 60 120 120 120 120 120 120 120 60 30

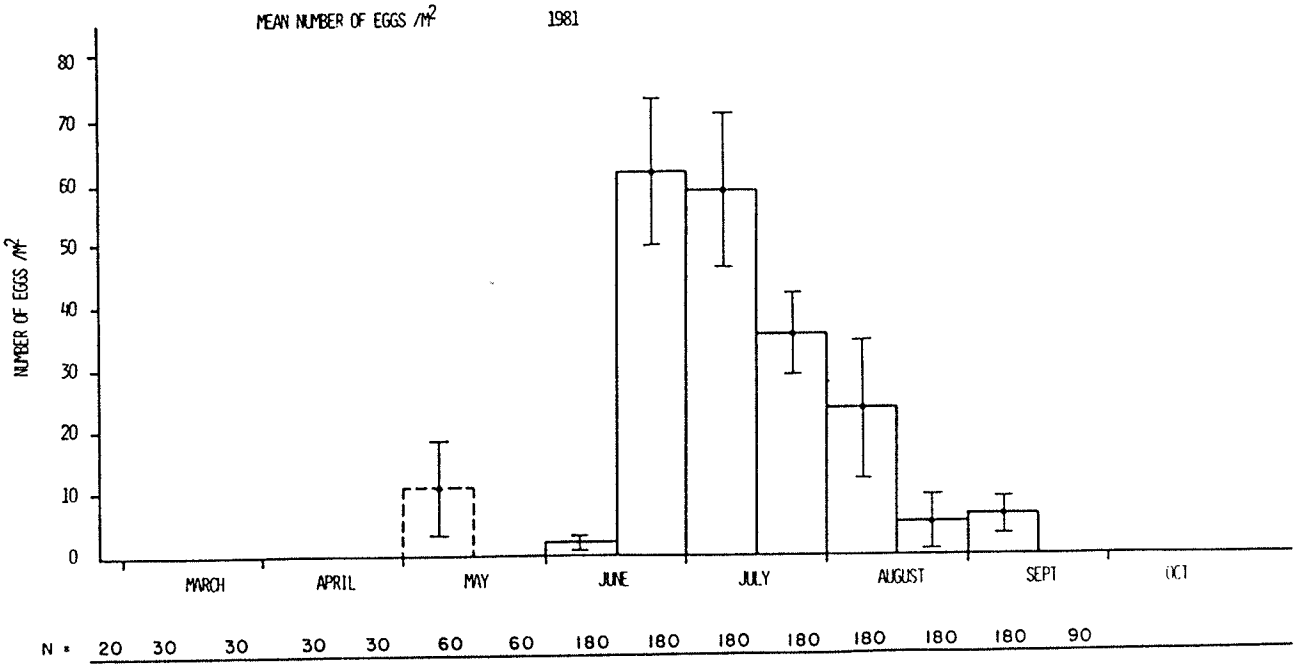
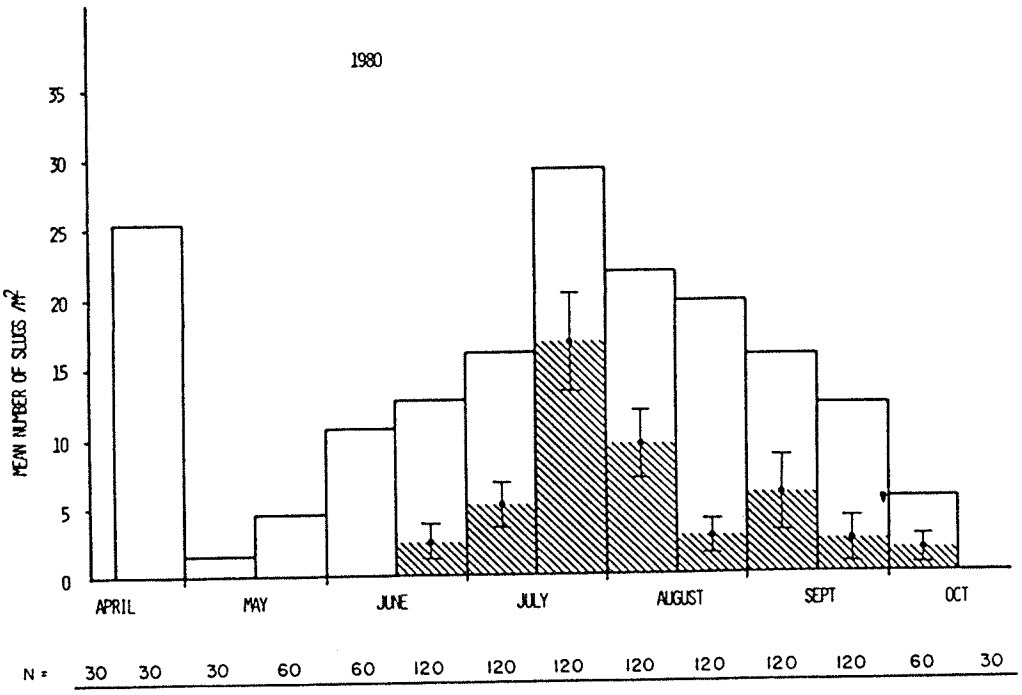
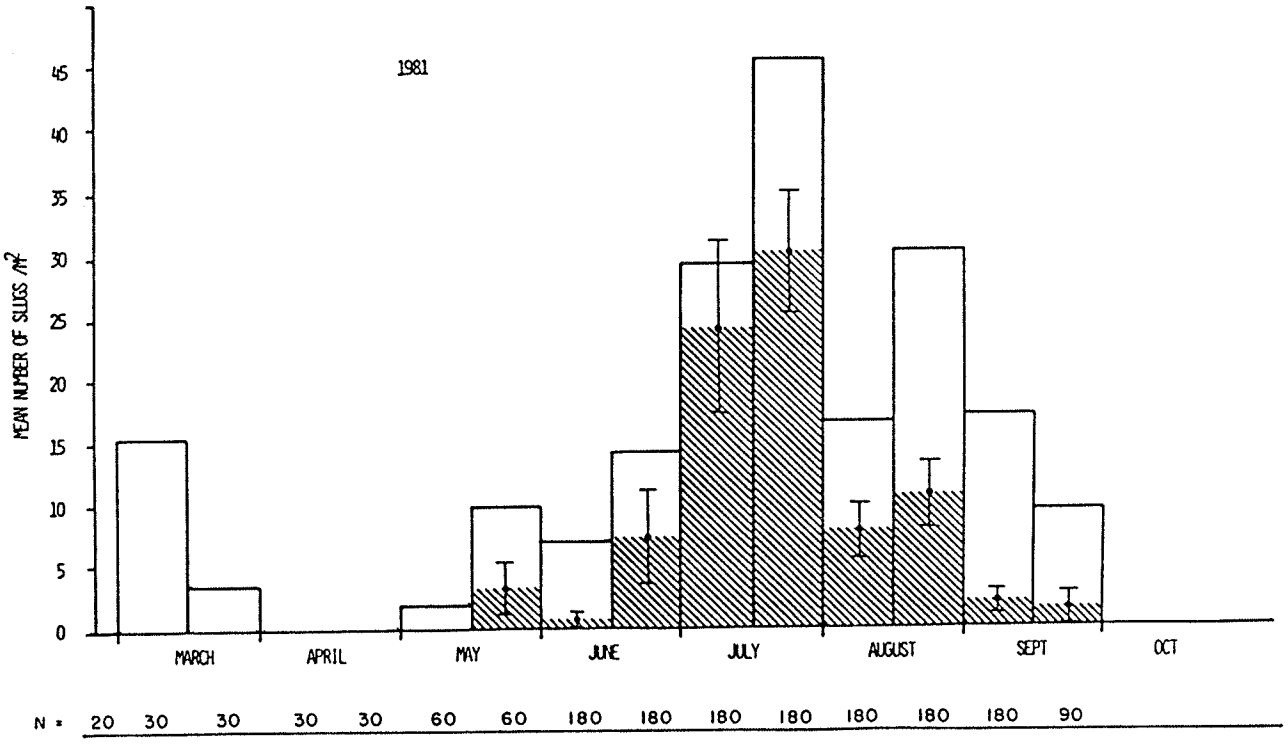

MEAN NUMBER OF EGGS /M²
1981
NUMBER OF EGGS /M²
80
70
60
50
40
30
20
10
0
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPT
OCT
N = 20 30 30 30 30 60 60 180 180 180 180 180 180 180 90

Figure 5. Mean number of immature D. laeve (hatched bars) per m^2 determined by quadrat sampling in strawberry fields throughout 1980. Means and standard errors are calculated for four and five year fields at Site 1 (Altona) and Sites 3, 4 and 5 (Portage la Prairie). Open bars indicate the mean number of adult and immature slugs per m^2.

Figure 6. Mean number of immature D. laeve (hatched bars) per m^2 determined by quadrat sampling in strawberry fields throughout 1981. Means and standard errors are calculated for three and five year fields at Site (Altona) and Site 2 (Selkirk). Open bars indicate the mean number of adult and immature slugs per m^2.


1980
MEAN NUMBER OF SLUGS /M²
0
5
10
15
20
25
30
35
APRIL
MAY
JUNE
JULY
AUGUST
SEPT
OCT
N = 30 30 30 60 60 120 120 120 120 120 120 120 60 30


1981
MEAN NUMBER OF SLUGS /M²
0
5
10
15
20
25
30
35
40
45
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPT
OCT
N = 20 30 30 30 30 60 60 180 180 180 180 180 180 180 90

(27 September) in 1981.

The relationship of phenology of D. laeve to changes in temperature and precipitation are shown in Figures 7 and 8. The spring peak of abundance of D. laeve coincides with the first significant snowmelt when daily maximum temperatures reached 1-5° C. Slugs found at this time were adults which must have overwintered. Slug activity varied with weather conditions; when precipitation was low or absent, slug numbers decreased until no slugs could be found. This occurred in early May 1980, and in April and early May 1981. The summer peak of abundance of D. laeve coincides with the appearance of a new generation of slugs. Slug numbers fluctuated during the summer with fluctuating weather conditions. A correlation of slug numbers with weather conditions was not attempted, because precipitation, temperature, and other climatic factors interact with the slug microhabitat in a complex manner. Slug numbers decreased in fall when temperatures neared 0° C (Figures 7 and 8).

Soil Relationships

The relationship of soil characteristics to the distribution and abundance of D. laeve was determined by analyzing the pH, carbonate content, and organic matter content of soil samples. Soil samples were taken from several locations in the province; some locations had high slug numbers and others had low slug numbers or no slugs.

Soil pH was similar in all fields at a sample site, and varied slightly between sample sites in the province. Soil pH for three sample

Figure 7. Phenology of D. laeve in 1980. Daily maximum temperatures (°C) and daily precipitation (mm) at Altona are plotted against the mean number of slugs (adults and immatures) determined by quadrat sampling at in four and five year fields at Altona.

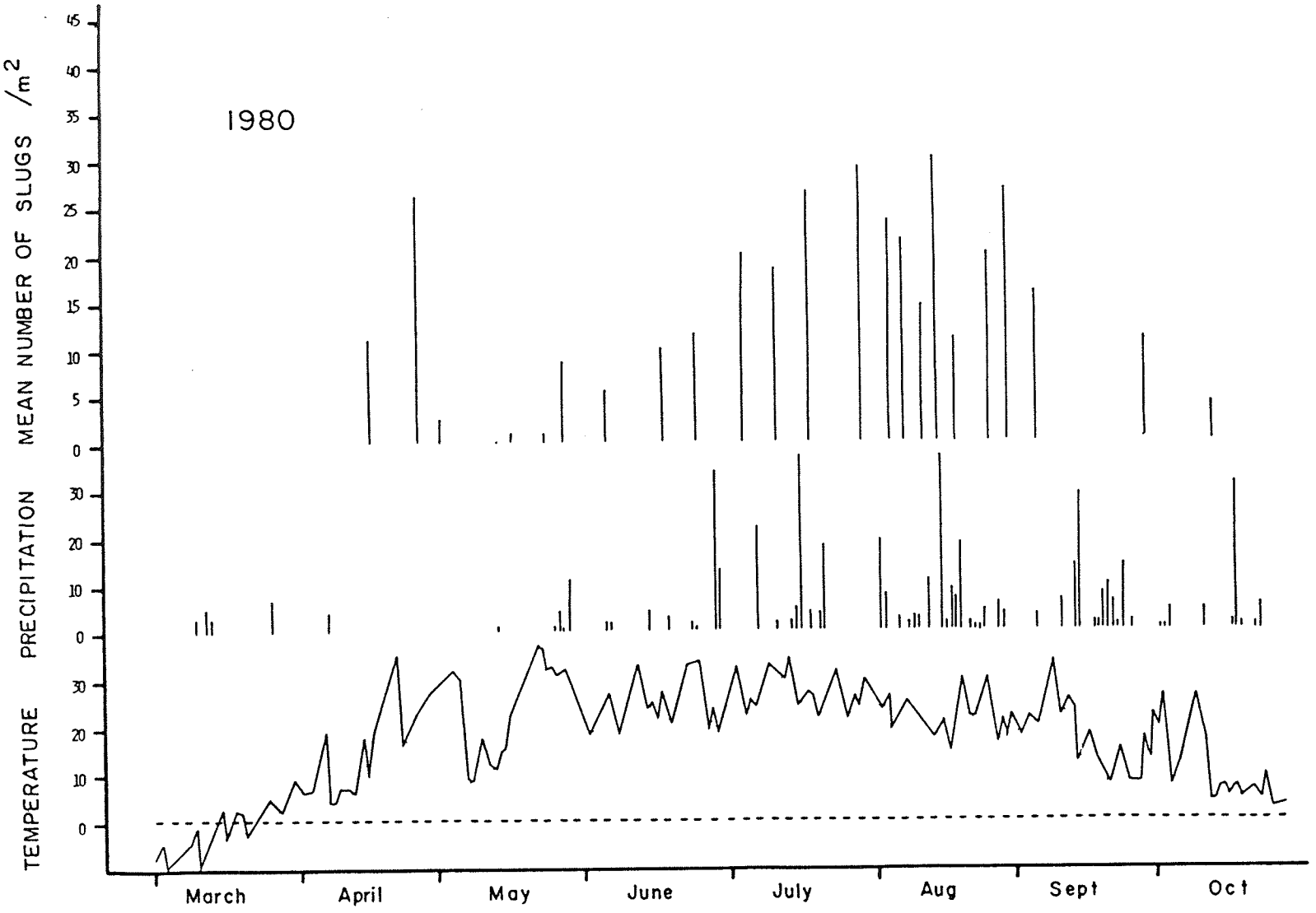
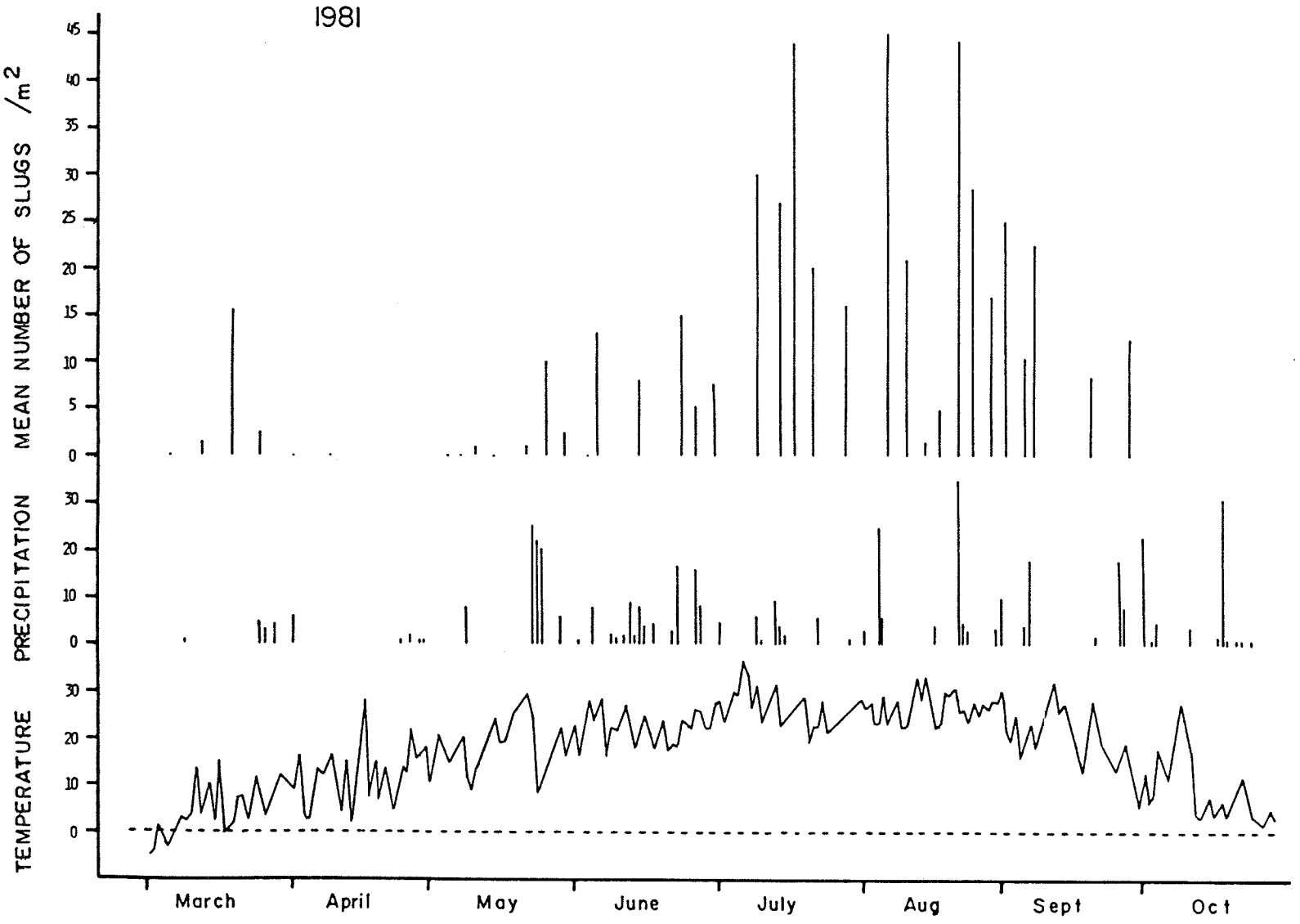

1980
MEAN NUMBER OF SLUGS /m2
PRECIPITATION
TEMPERATURE
March
April
May
June
July
Aug
Sept
Oct

Figure 8. Phenology of D. laeve in 1981. Daily maximum temperatures (°C) and daily precipitation (mm) at Altona are plotted against the mean number of slugs (adults and immatures) determined by quadrat sampling in three and five year fields at Altona.


1981
MEAN NUMBER OF SLUGS /m2
PRECIPITATION
TEMPERATURE
March
April
May
June
July
Aug
Sept
Oct

sites in Portage la Prairie, Manitoba, was 7.0, 7.0 and 7.1. Soil pH for three fields at Altona, Manitoba, was 6.7, 6.6 and 6.8.

Laboratory analysis of soil samples for carbonate content yielded final manometer readings in the range of 0.75 to 1.25 cm of mercury. Accurate soil carbonate determination requires final manometer readings of 2.5 to 8.9 cm of mercury: soil carbonate levels were too low to be accurately measured both in Altona and at three sites in Portage la Prairie. This result was also recorded by the Provincial Soil Testing Laboratory (J. Portree, personal communication).

Soil organic matter content was approximately the same in all fields at a sample site, and between sample sites in the province. Soil organic matter content for three sample sites in Portage la Prairie was found to be 5.7, 5.5 and 8.0% soil dry weight. Soil organic matter content for three fields at a sample site in Altona was found to be 7.4, 7.7 and 6.4%.

Field Age

Quadrat samples were taken from strawberry fields of different ages in several locations throughout the province to determine the affect of field age on the number and distribution of slugs. In 1980, slug numbers were significantly higher ($P<0.05$) in four and five year old strawberry fields than in two and three year old fields in Altona and Portage la Prairie, Manitoba (Table 1). In 1981, slug numbers were significantly higher ($P<0.05$) in three and five year old strawberry fields than in two and four year old fields in Altona and Selkirk, Manitoba.

Table 1. The distribution of Deroceras laeve in strawberry fields at different ages in 1980 and 1981 measured as the mean number of slugs/m^2 (±S.E.) (n = 30).

	1980			1981		
Field Ages	Number of fields	June	July	Number of fields	June	July
2 Year	1	0±0	0±0	4	0.0±0.0	1.40±1.10
3 Year	2	0.50±0.50	2.10±1.10	3	9.64±1.07	48.00±7.55
4 Year	2	7.93±1.37	16.82±3.16	3	2.83±0.60	5.33±1.83
5 Year	2	6.86±1.84	12.76±2.75	3	6.10±1.72	20.19±5.54

Straw Cover

In 1980, the amount of straw cover was measured in four strawberry fields of the same age and three fields of different ages to determine the effect of straw cover on the number and distribution of slugs. Samples were taken from several locations in the province.

Slug numbers were highest in four and five year old fields in Altona and Portage la Prairie (Table 1). The amount of straw cover was measured in three, four and five year old fields at Site 1 (Altona). The amount of fresh straw was slightly higher in four and five year old fields, the amount of straw mulch was 2-3 times higher in four and five year old fields (Table 2). There was considerable variation in the amount of organic, decomposing straw mulch in four year old fields in different sample sites due to differences in renovation methods. The amount of fresh straw cover was less variable between sample sites in the province.

PESTICIDE EFFICACY TRIALS

Laboratory Trials

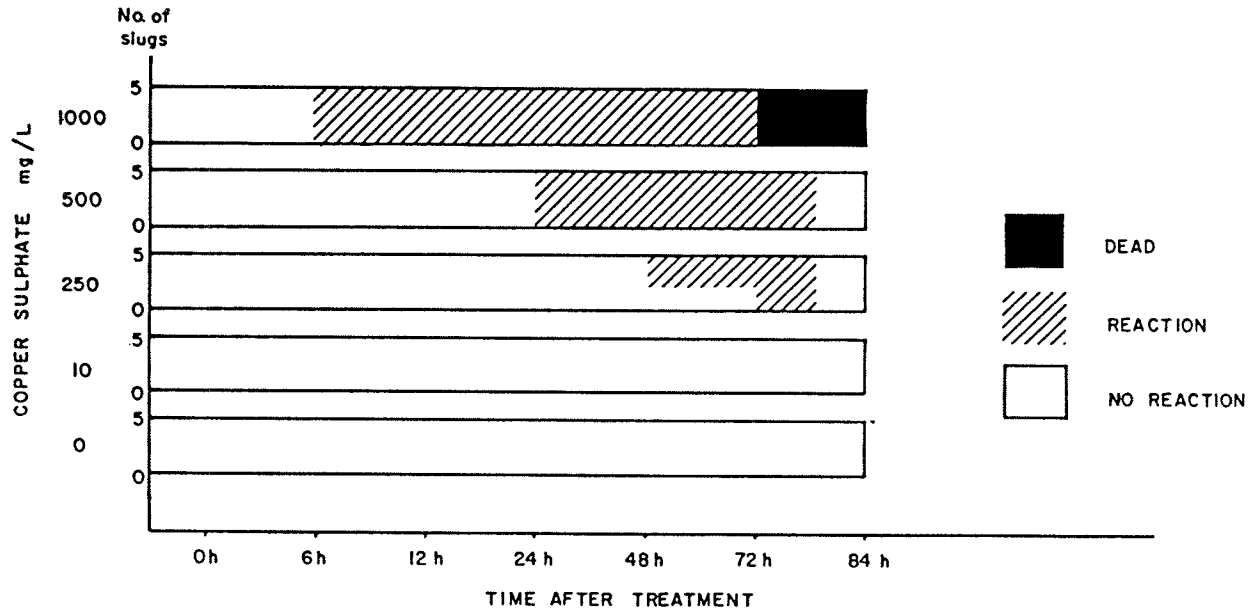
Copper sulphate. Three laboratory trials were conducted using copper sulphate concentrations ranging from 10 to 1,000 mg/ℓ.

In the first trial, a reaction consisting of the onset of heavy slime secretion, the appearance of a dry, wrinkled integument, and inactivity (lack of antennal response to probing) occurred in slugs treated with 250 mg/ℓ or more (Figure 9). The reaction appeared sooner at higher concentrations.

Table 2. The amount of fresh straw and decomposing straw mulch per 0.25 m^2 in strawberry fields of different ages, and in different sample sites in Manitoba.

	Site 1				Site 3				Site 4				Site 5			
	Row		Cap		Row		Cap		Row		Cap		Row		Cap	
Field Age	Fresh Straw	Straw Mulch	Fresh Straw	Straw Mulch	Fresh Straw	Straw Mulch	Fresh Straw	Straw Mulch	Fresh Straw	Straw Mulch	Fresh Straw	Straw Mulch	Fresh Straw	Straw Mulch	Fresh Straw	Straw Mulch
3 Years	0	0	10	4	-	-	-	-	-	-	-	-	-	-	-	-
	1	0.5	12	4	-	-	-	-	-	-	-	-	-	-	-	-
	0	1	14	6	-	-	-	-	-	-	-	-	-	-	-	-
	1	1	7	2	-	-	-	-	-	-	-	-	-	-	-	-
	1	0.5	10	4	-	-	-	-	-	-	-	-	-	-	-	-
4 Years	1	3	27	12	0.5	0	2	0	0.5	0.5	2	2	0.5	0.25	26	0
	1.5	4	28	8	0	0	2	0	0.5	0.5	4	1	0.5	0.25	18	0
	2	3	34	14	0.5	0	1.5	0	0	0.25	0	2	0	0.25	22	0
	2	2	17	6	0.5	0	2	0	0	0.5	4	1	0.5	0.25	24	0
	2	2	35	18	0	0	1.5	0	0	0.25	5	2	0.5	0.5	30	0
	1	2	31	10	-	-	-	-	-	-	-	-	-	-	-	-
5 Years	2	1	16	8	-	-	-	-	-	-	-	-	-	-	-	-
	1	1	14	10	-	-	-	-	-	-	-	-	-	-	-	-
	2	2	17	10	-	-	-	-	-	-	-	-	-	-	-	-
	2	1	8	5	-	-	-	-	-	-	-	-	-	-	-	-
	2	0.5	13	8	-	-	-	-	-	-	-	-	-	-	-	-

Figure 9. Response of D. laeve to treatment with 0, 10, 250, 500, and 1,000 mg/L copper sulphate. Observations were made at 0, 6, 12, 24, 48, 72, and 84 hours after treatment. Five slugs were treated at each concentration.


No. of slugs
COPPER SULPHATE mg/L
1000
500
250
10
0
5
0
Oh
6h
12 h
24 h
48 h
72 h
84 h
TIME AFTER TREATMENT
DEAD
REACTION
NO REACTION

In the second trial, an immediate reaction occurred in all slugs at all concentrations (Figure 10). The reaction was more severe than that observed in the trial above; slugs reacted to chemical treatment with a 2 to 3 min period of writhing, in addition to the reaction above. All slugs at all concentrations were dead 4 h after treatment. This trial differed from that above in that the copper sulphate stock solution was prepared, then left for 2 d before being used in laboratory testing. The storage period allowed complete solution of the copper sulphate.

In the third trial, test solutions with copper sulphate concentrations of 75, 125, 200, 350, 400 and 500 mg/ℓ were applied to slugs. A reaction (without writhing) occurred in some of the slugs treated with concentrations of 75, 125 and 200 mg/ℓ; a toxic reaction with writhing occurred in all slugs treated with concentrations above 200 mg/ℓ (Figure 11). A large proportion of slugs died when concentrations of 200 mg/ℓ, or more, were applied.

To determine the effect of applying a small volume of test solution, 1 µℓ and 2 µℓ of 400 mg/ℓ copper sulphate solution were topically applied to individual slugs with a microlitre syringe. Slugs showed no initial reaction to chemical treatment, however, 1 to 2 h after treatment, a reaction occurred in some slugs at both treatment levels (Figure 12). Slugs treated with 1 µℓ recovered within 24 h of treatment; slugs treated with 2 µℓ recovered within 48 h. An application of 1 µℓ treated only the slug; 2 µℓ treated both slug and substrate.

Modified metaldehyde bait formulation. In a laboratory trial, slugs placed in a plastic box containing modified metaldehyde bait

Figure 10. Response of D. laeve to treatment with 600, 700, 800, 900, and 1,000 mg/L copper sulphate. Observations were made at 0, 2, 4, 6, and 8 hours after treatment. Ten slugs were treated at each concentration. The copper sulphate solution was left for two days before being used in laboratory testing.

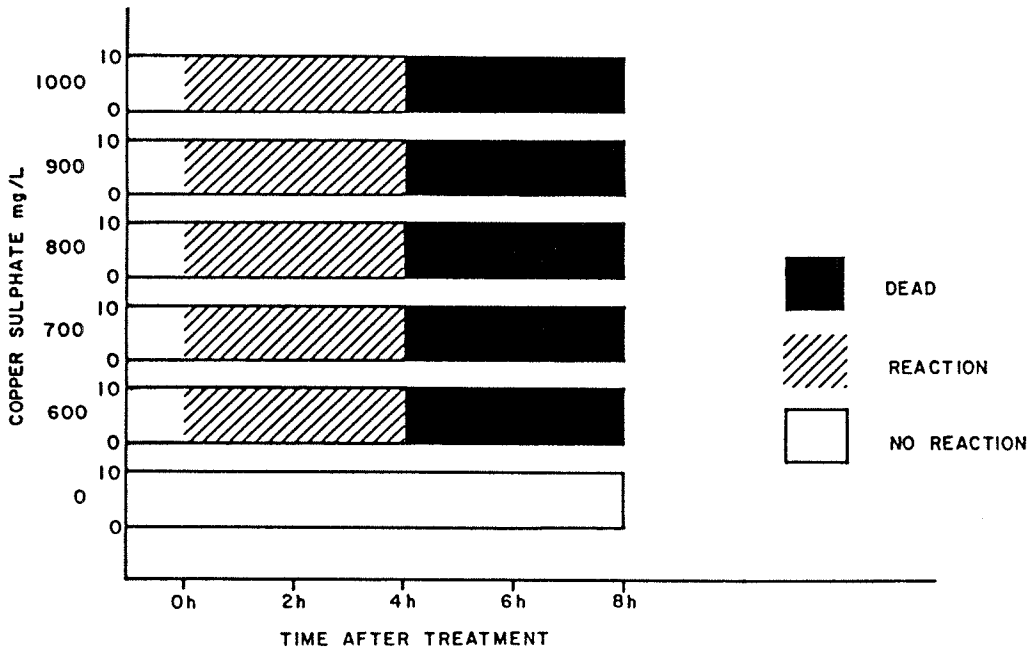

COPPER SULPHATE mg/L
1000
900
800
700
600
0
10
0
0h
2h
4h
6h
8h
TIME AFTER TREATMENT
DEAD
REACTION
NO REACTION

Figure 11. Response of D. laeve to treatment with 75, 125, 200, 300, 350, 400, and 500 mg/L copper sulphate. Observations were made at 0, 2, 4, 6, 8, 12, 24, and 48 hours after treatment. Ten slugs were treated at each concentration. The copper sulphate solution was left for two days before being used in laboratory testing.

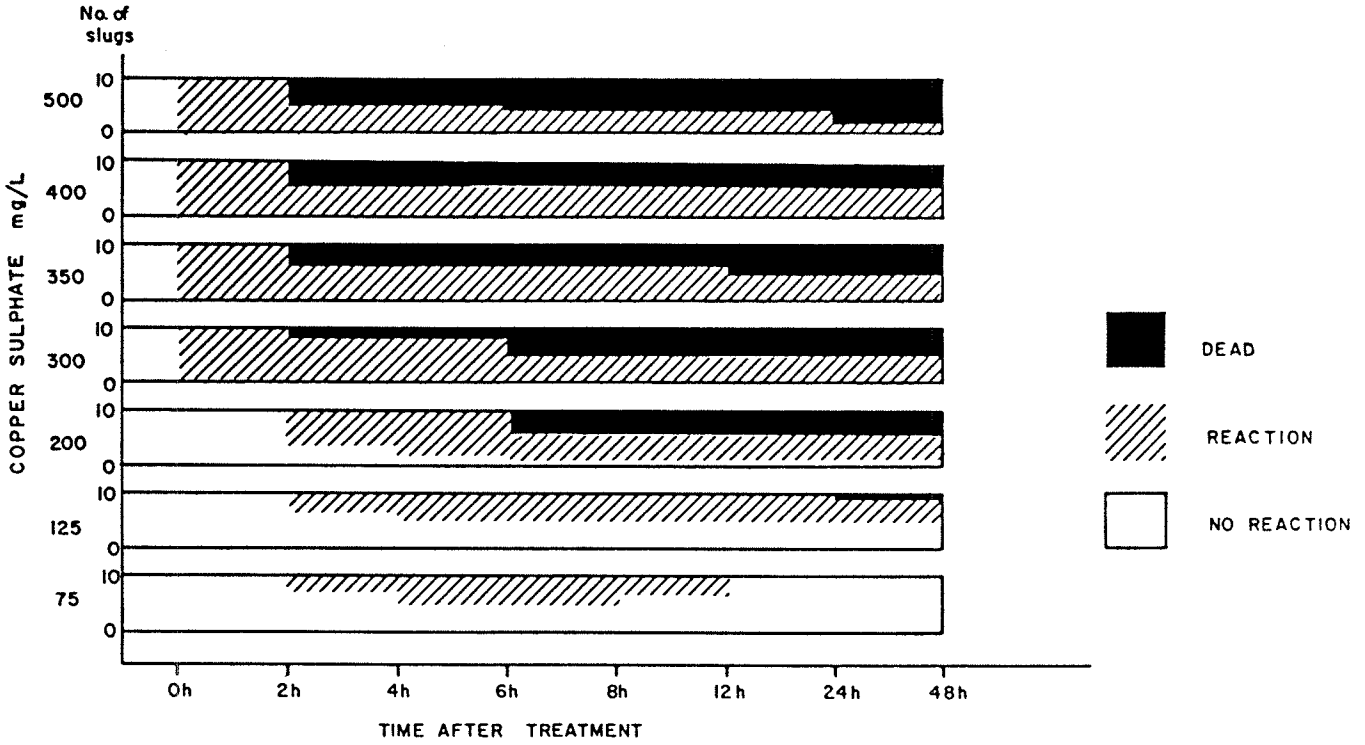
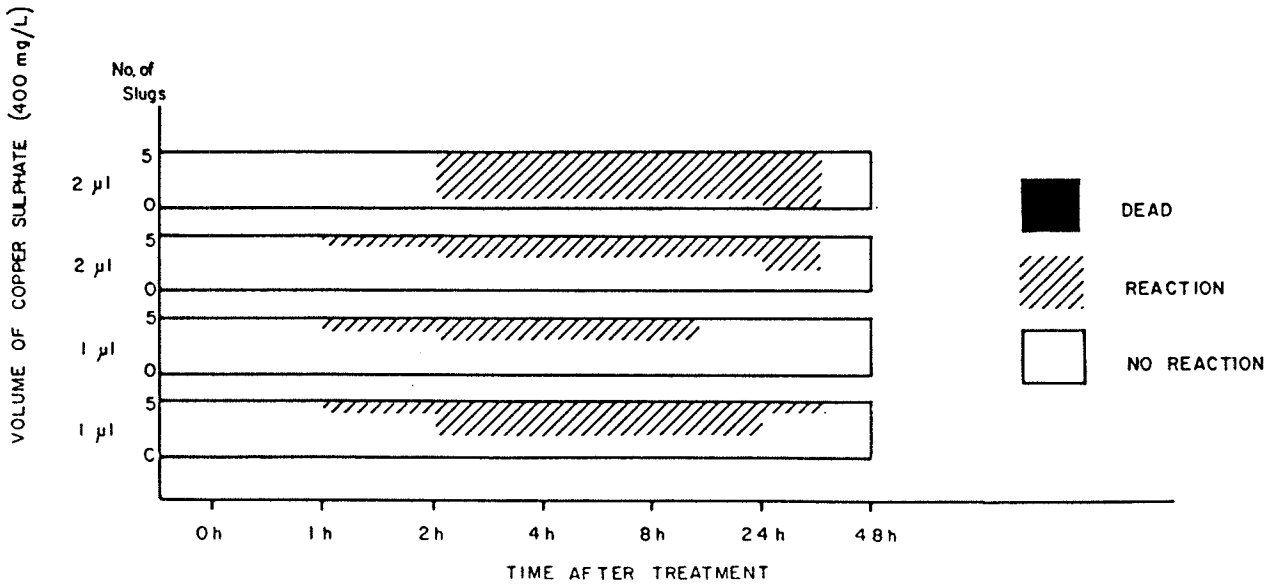

No. of slugs
COPPER SULPHATE mg/L
500
400
350
300
200
125
75
10
0
0h
2h
4h
6h
8h
12h
24h
48h
TIME AFTER TREATMENT
DEAD
REACTION
NO REACTION

Figure 12. Response of D. laeve to treatment with 1 µl and 2 µls of a 400 mg/L copper sulphate solution. Observations were made at 0, 2, 4, 8, 24, and 48 hours after treatment. Five slugs were treated at each dosage level.


VOLUME OF COPPER SULPHATE (400 mg/L)
No. of Slugs
2 µl
5
0
2 µl
5
0
1 µl
5
0
1 µl
5
C
0h
1h
2h
4h
8h
24h
48h
TIME AFTER TREATMENT
DEAD
REACTION
NO REACTION

formulation were found on the bait within 2 h of treatment; many of the slugs died within 72 h of treatment (Table 3).

Field Trials

1980 field trial. Slug numbers before and after treatment are shown in Figures 13 to 17. A factorial analysis of variance was used to analyze the data. Orthogonal contrasts were used to compare treatment means over the test period.

The control versus treatment x before versus after interaction was significant ($P<0.01$) in the methiocarb 2% bait formulation treated plots: slug numbers were significantly reduced by the treatment. The interaction was not significant ($P>0.05$) for metaldehyde 2.75% bran bait formulation, copper sulphate-lime powder (1:9 w/w) and for Kocide 101 56% WP spray formulation: slug numbers were not significantly reduced by treatment with these chemicals ($P>0.05$).

1981 field trial. Slug numbers before and after treatment are shown in Figures 18 to 22. Field data were analyzed with a factorial analysis of variance and orthogonal contrasts, as for the 1980 field trial.

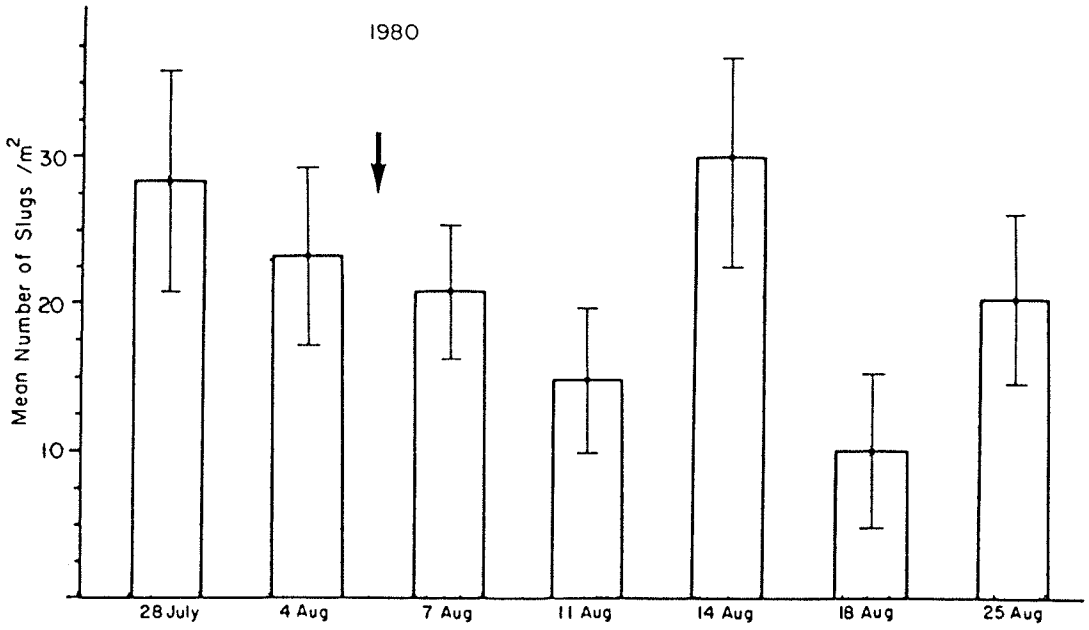
The control versus treatment x before treatment versus after treatment interaction was significant ($P<0.01$) for field plots treated with methiocarb 2% bait formulation, metaldehyde 50% EC spray formulation, and modified metaldehyde bait formulation. Methiocarb 2% bait was significantly more effective ($P<0.01$) in reducing slug numbers than both metaldehyde 50% EC spray formulation, and modified metaldehyde bait formulation. Metaldehyde spray formulation was significantly more effective ($P<0.01$)

Table 3. Reaction of Deroceras laeve to modified metaldehyde bait formulation and standard metaldehyde bait formulation. The number of slugs feeding on bait, or dead, are shown.

Treatment		Time After Treatment						
		2h	4h	6h	12h	24h	28h	72h
Standard Metaldehyde Bait	Feeding On Bait	0	2	3	3	4	2	2
	Dead	0	0	0	0	3	5	5
Modified Metaldehyde Bait	Feeding On Bait	4	6	11	15	6	2	1
	Dead	0	0	0	4	12	16	16

Figure 13. Mean number of slugs/m^2 (±S.E.) (n = 15) in 7 m x 10 m field plots left untreated (control). Arrow indicates date of application of molluscicides in other plots.

Figure 14. Mean number of slugs/m^2 (±S.E.) (n = 15) in 7 m x 10 m field plots before and after treatment with Methiocarb 2% bait. Arrow indicates date of application. Dashed line indicates mean number of slugs in control plots.


1980
Mean Number of Slugs /m²
30
20
10
28 July
4 Aug
7 Aug
11 Aug
14 Aug
18 Aug
25 Aug

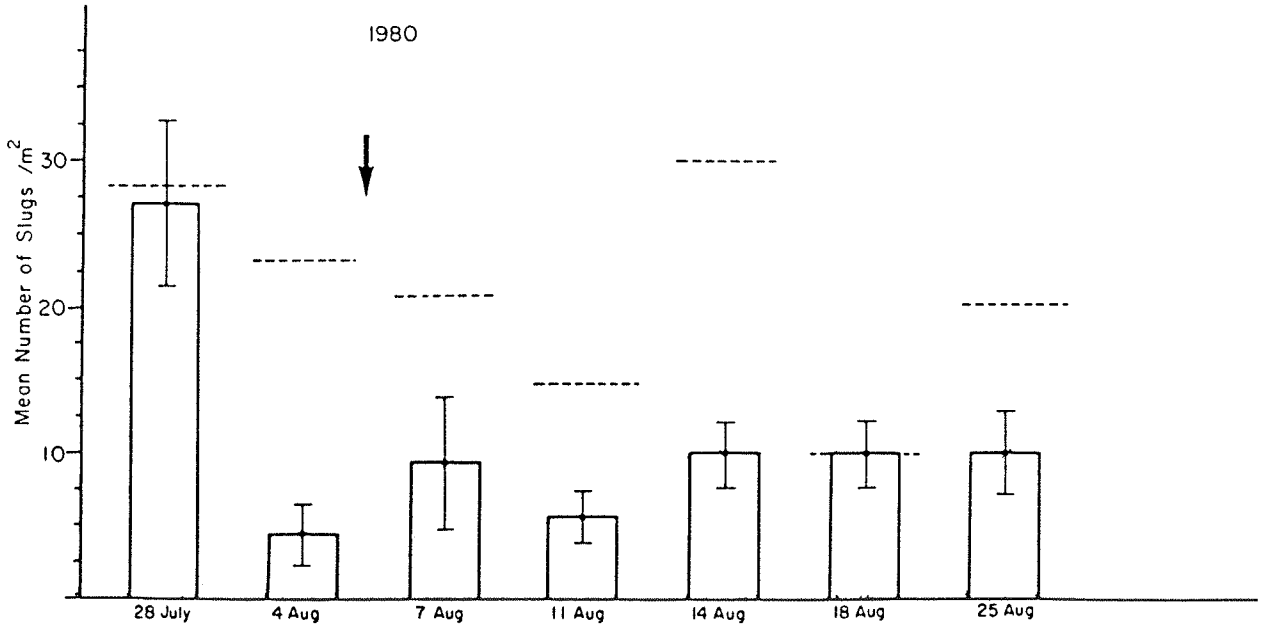
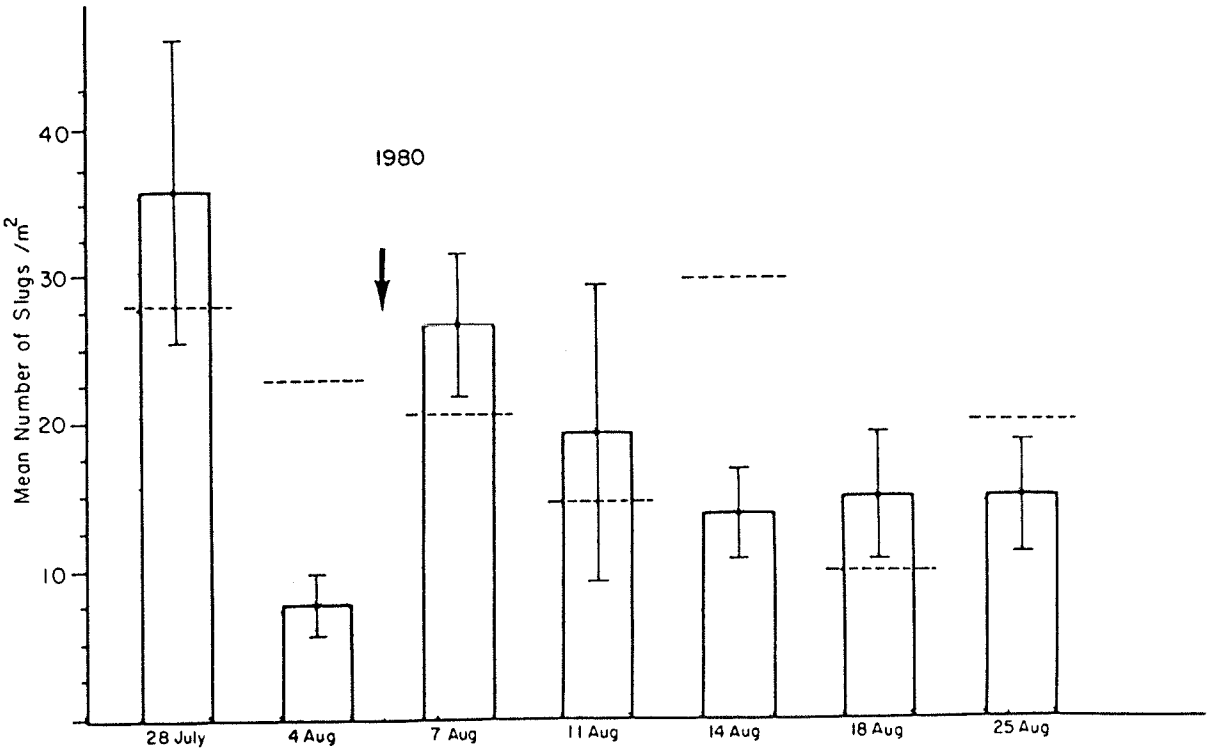

1980
Mean Number of Slugs /m²
30
20
10
28 July
4 Aug
7 Aug
11 Aug
14 Aug
18 Aug
25 Aug

Figure 15. Mean number of slugs/m^2 (±S.E.) (n = 15) in 7 m x 10 m field plots before and after treatment with metaldehyde 2.75% bran bait formulation. Arrow indicates date of application. Dashed line indicates mean number of slugs in control plots.

Figure 16. Mean number of slugs/m^2 (±S.E.) (n = 15) in 7 m x 10 m field plots before and after treatment with copper sulphate-lime powder (1: 9 w/w). Arrow indicates date of application. Dashed line indicates mean number of slugs in control plots.


1980
Mean Number of Slugs /m²
40
30
20
10
28 July
4 Aug
7 Aug
11 Aug
14 Aug
18 Aug
25 Aug

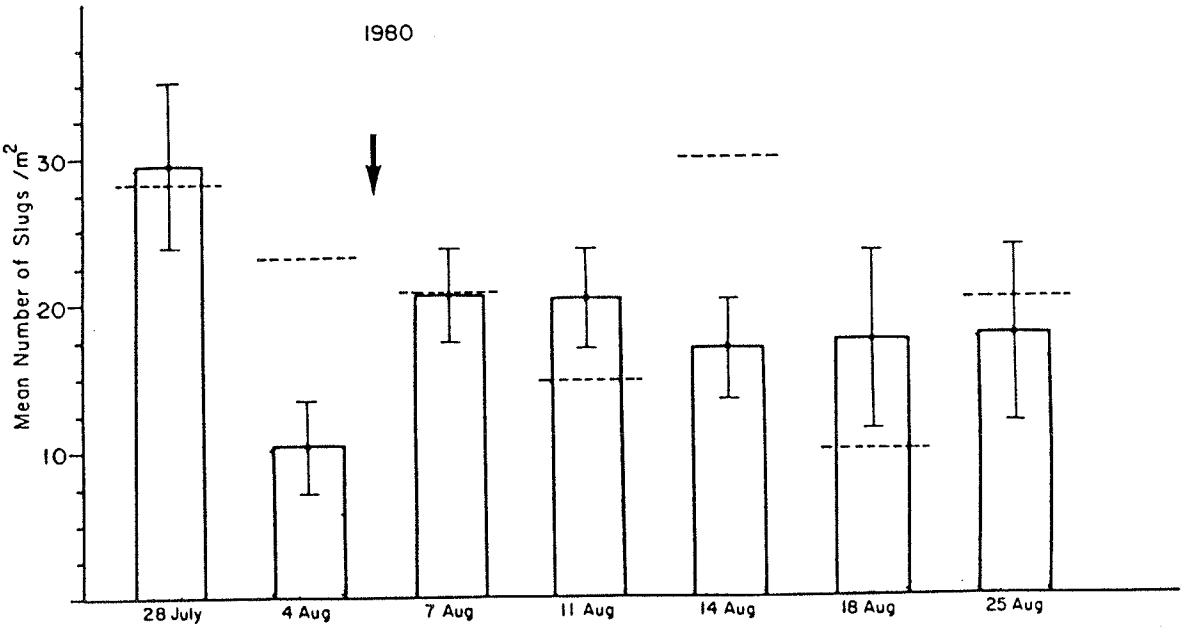

1980
Mean Number of Slugs /m²
30
20
10
28 July
4 Aug
7 Aug
11 Aug
14 Aug
18 Aug
25 Aug

Figure 17. Mean number of slugs/m^2 (±S.E.) (n = 15) in 7 m x 10 m field plots before and after treatment with Kocide 101 56% WP spray formulation. Arrow indicates date of application. Dashed line indicates mean number of slugs in control plots.

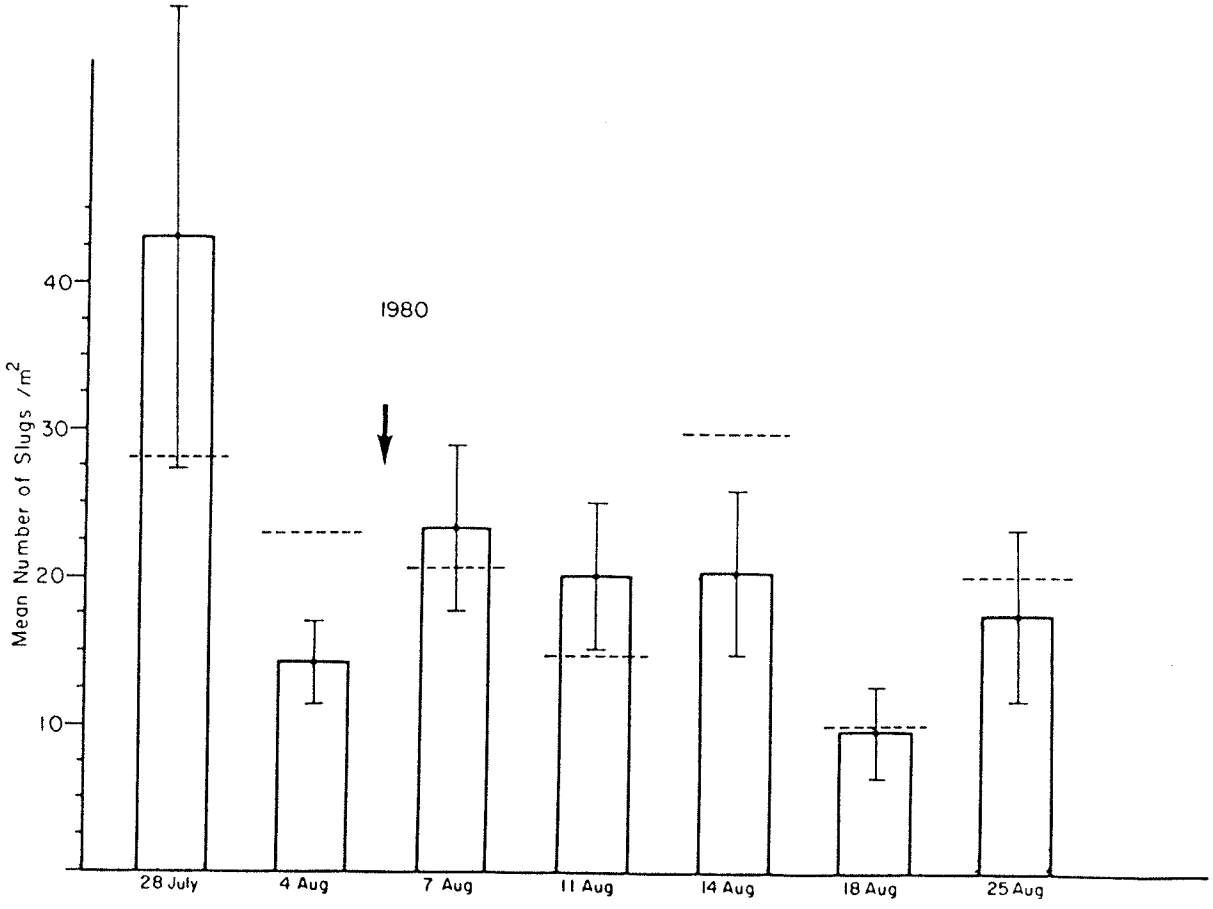
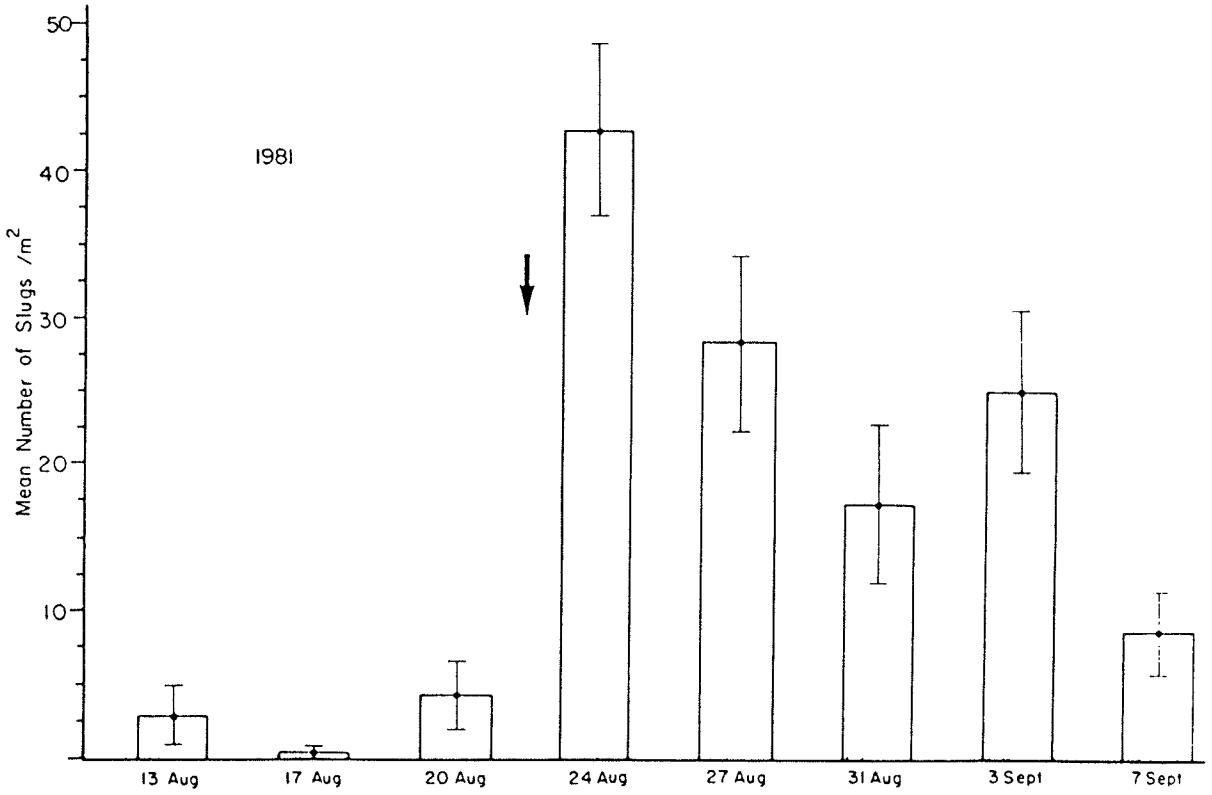

Mean Number of Slugs /m²
40
30
20
10
1980
28 July
4 Aug
7 Aug
11 Aug
14 Aug
18 Aug
25 Aug

Figure 18. Mean number of slugs/m^2 (±S.E.) (n = 12) in 8 m x 10 m field plots left untreated (control). Arrow indicates date of application of molluscicides in other plots.

Figure 19. Mean number of slugs/m^2 (±S.E.) (n = 12) in 8 m x 10 m field plots before and after treatment with Methiocarb 2% bait. Arrow indicates date of application. Dashed line indicates mean number of slugs in control plots.


1981
Mean Number of Slugs /m²
50
40
30
20
10
13 Aug
17 Aug
20 Aug
24 Aug
27 Aug
31 Aug
3 Sept
7 Sept

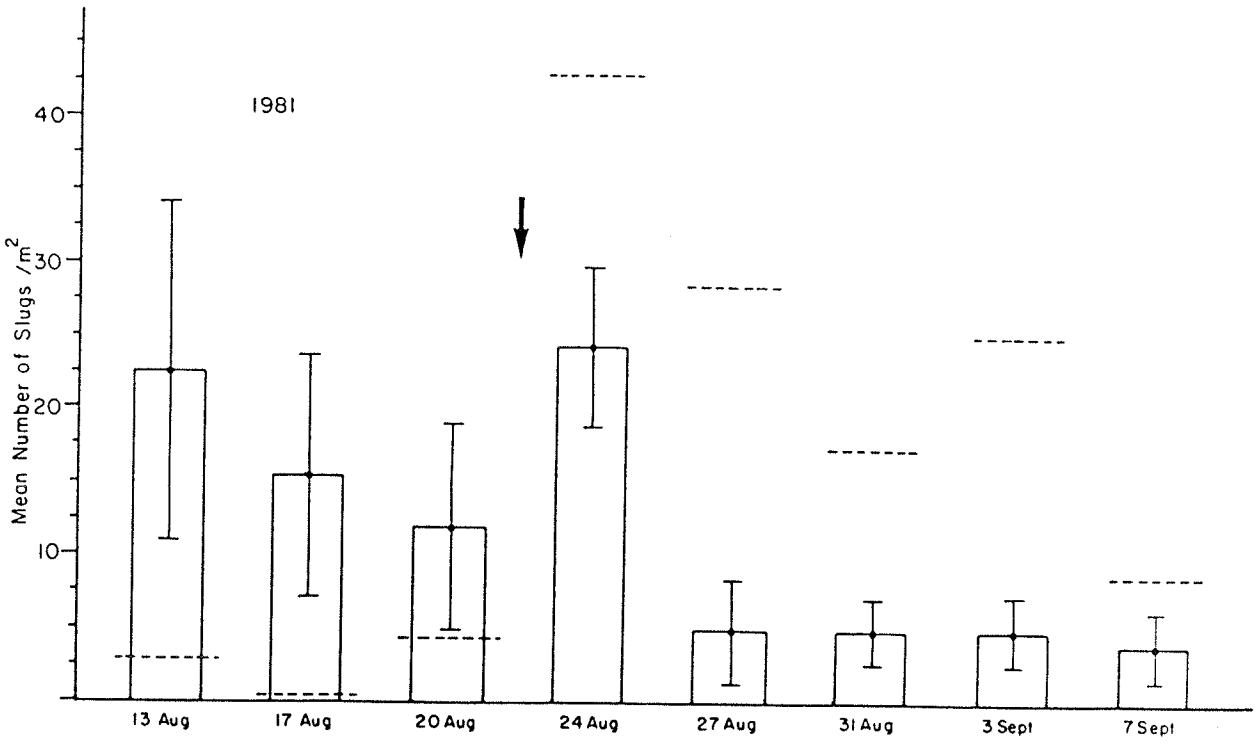
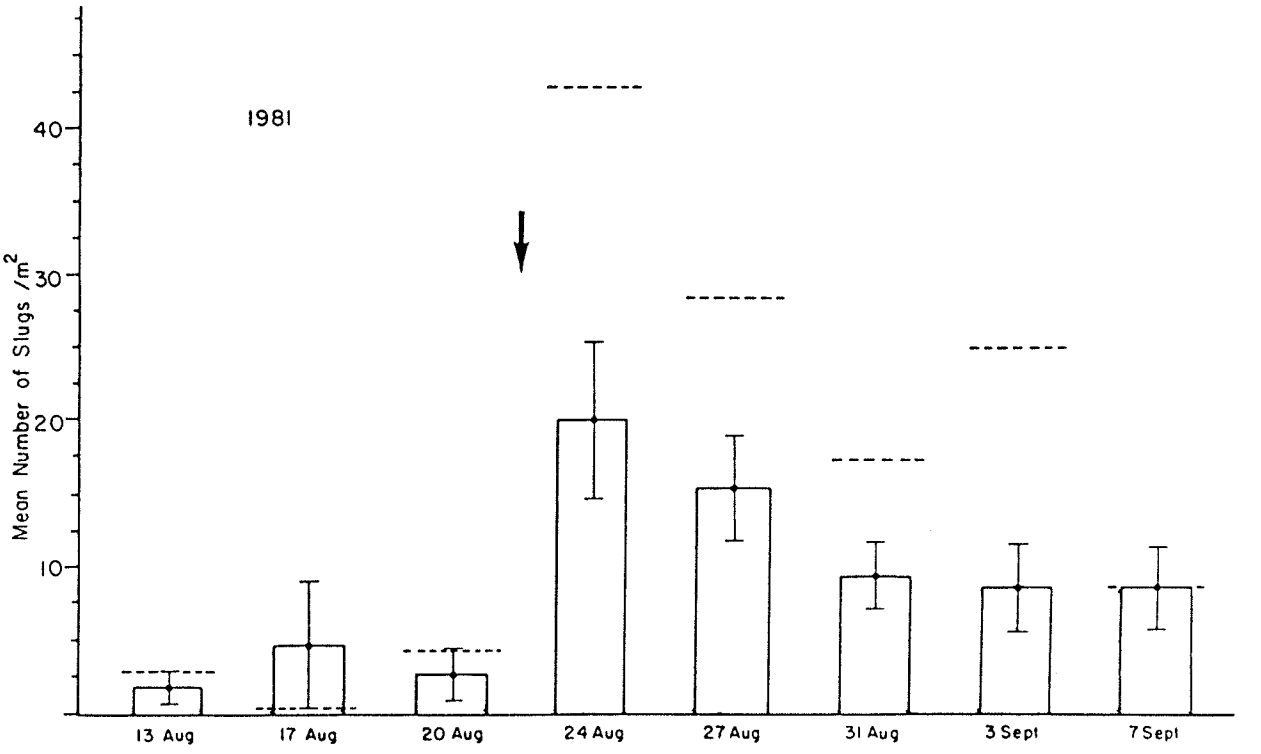

1981
Mean Number of Slugs /m²
40
30
20
10
13 Aug
17 Aug
20 Aug
24 Aug
27 Aug
31 Aug
3 Sept
7 Sept

Figure 20. Mean number of slugs/m^2 (±S.E.) (n = 12) in 8 m x 10 m field plots before and after treatment with metaldehyde 50% EC spray formulation. Arrow indicates date of application. Dashed line indicates mean number of slugs in control plots.

Figure 21. Mean number of slugs/m^2 (±S.E.) (n = 12) in 8 m x 10 m field plots before and after treatment with modified metaldehyde bran bait. Arrows indicate date of application. Dashed line indicates mean number of slugs in control plots.


1981
Mean Number of Slugs /m²
40
30
20
10
13 Aug
17 Aug
20 Aug
24 Aug
27 Aug
31 Aug
3 Sept
7 Sept

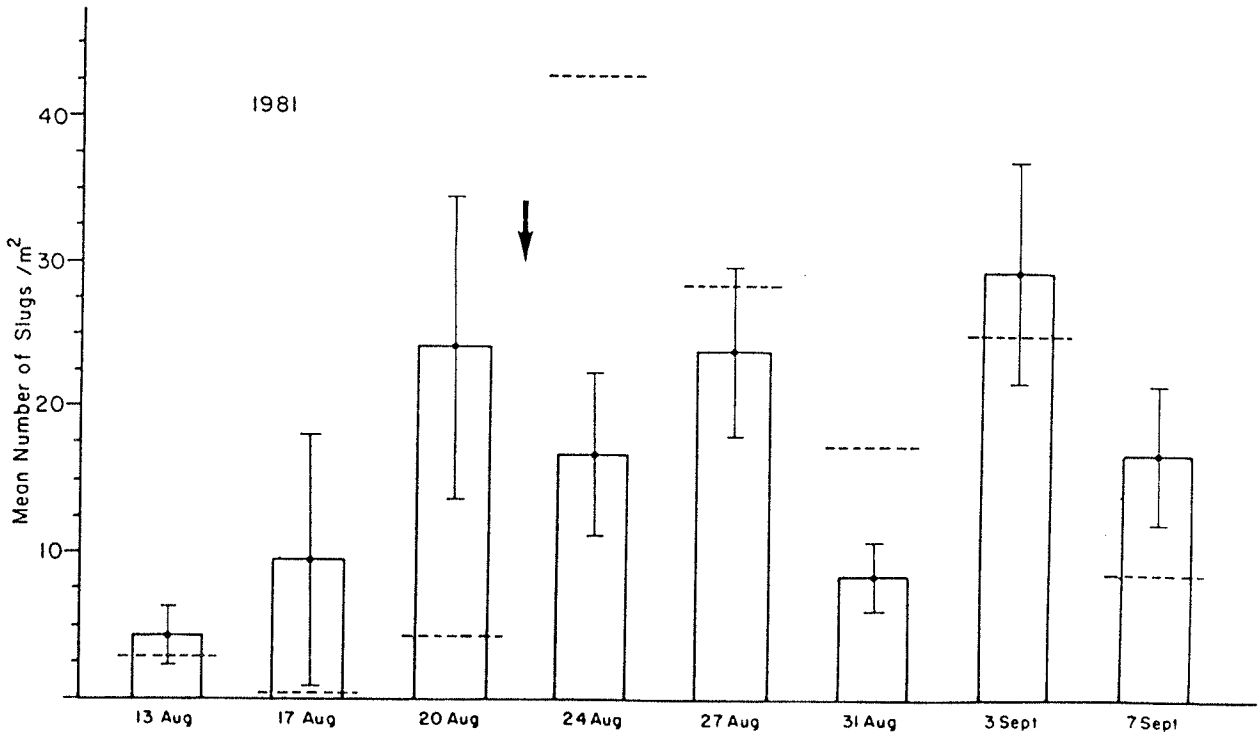
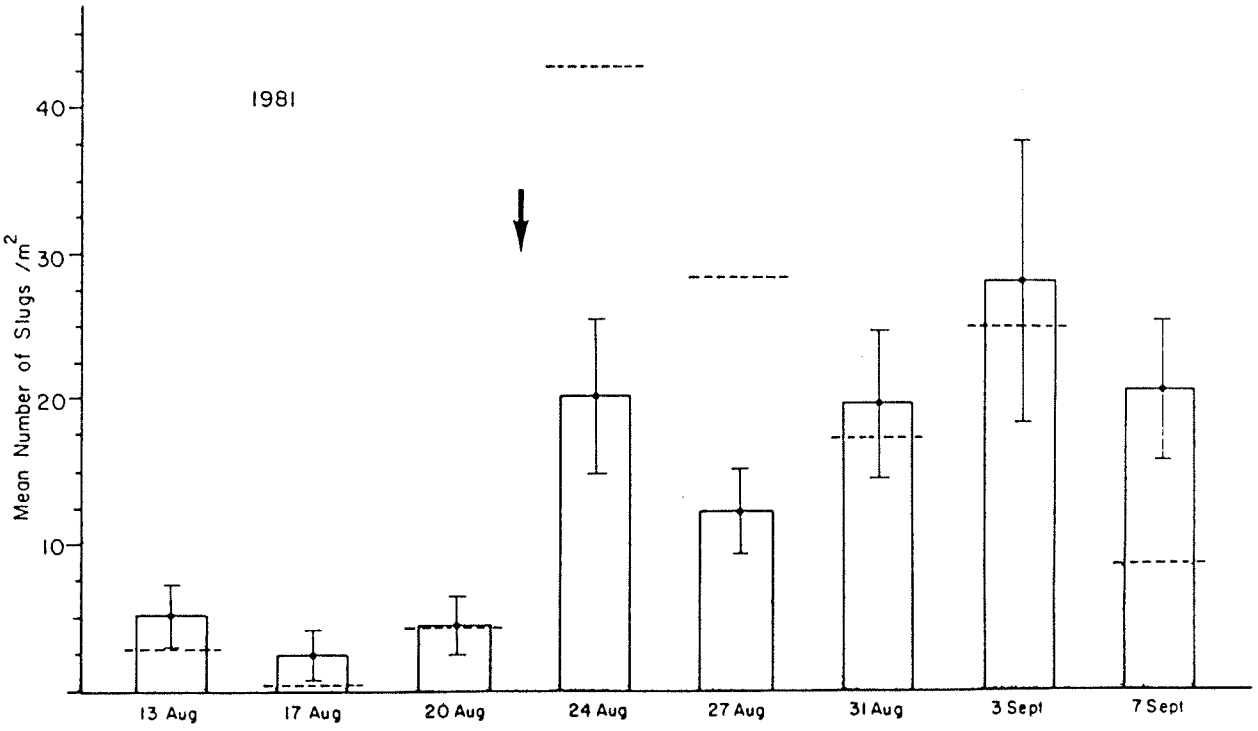

1981
Mean Number of Slugs /m²
40
30
20
10
13 Aug
17 Aug
20 Aug
24 Aug
27 Aug
31 Aug
3 Sept
7 Sept

Figure 22. Mean number of slugs/m^2 (±S.E.) (n = 12) in 8 m x 10 m field plots before and after treatment with metaldehyde 2.75% bran bait formulation. Arrow indicates date of application. Dashed line indicates mean number of slugs in control plots.


1981
Mean Number of Slugs /m²
40
30
20
10
13 Aug
17 Aug
20 Aug
24 Aug
27 Aug
31 Aug
3 Sept
7 Sept

than modified metaldehyde bait formulation. The interaction was not significant ($P>0.05$) for the metaldehyde 2.75% bran bait formulation.

Modified metaldehyde bait formulation. On 22 June 1981 modified metaldehyde bait was applied to a 25 m x 25 m field plot within a 0.6 ha strawberry field known to be infested with Deroceras laeve. Slug numbers before and after treatment are shown in Table 4.

The control versus treatment x before versus after interactions was significant ($P<0.05$); slug numbers were significantly reduced by chemical treatment.

Large scale field testing was conducted on 29 June 1981 in Altona, and on 4 July 1981 in Selkirk. Modified metaldehyde bait was applied to a 0.6 ha strawberry field in each location; slug numbers in treated fields were compared to those in adjacent untreated fields.

In Altona, the control versus treatment x before versus after interaction was not significant ($P>0.05$); slug numbers were not significantly reduced by chemical treatment (Figure 23). However, 135 dead slugs were collected from eighteen 0.10 m^2 quadrat samples randomly selected along the length of the bait strips (samples were taken on the bait strips). Many heavy slime trails were found (indicating a reaction to a toxic substance) leading into the nearby plant rows.

In Selkirk, the control versus treatment x before versus after interaction was significant ($P<0.05$); slug numbers were significantly reduced by treatment with modified metaldehyde bait formulation (Figure 24). One hundred twenty-eight dead slugs were collected from thirty 0.10 m^2 quadrat samples randomly selected along the length of the bait

Table 4. Mean number of *Deroceras laeve* per m^2 (±S.E.) before and after treatment of a 25m x 25m field plot with modified metaldehyde bait formulation.

Treatment	Mean number of slugs	
	Before Treatment	After Treatment
Control	3.75±1.83	5.00±3.07
Modified Metaldehyde bait	13.75±1.88	2.00±1.33

Figure 23. Field efficacy trial of modified metaldehyde bran bait (hatched bars) on a 0.6 ha strawberry field at Altona. An adjacent 0.6 ha field was left untreated for a control. Application was made on 29 June. Mean number of slugs/m^2 (±S.E.) are shown (n = 15).

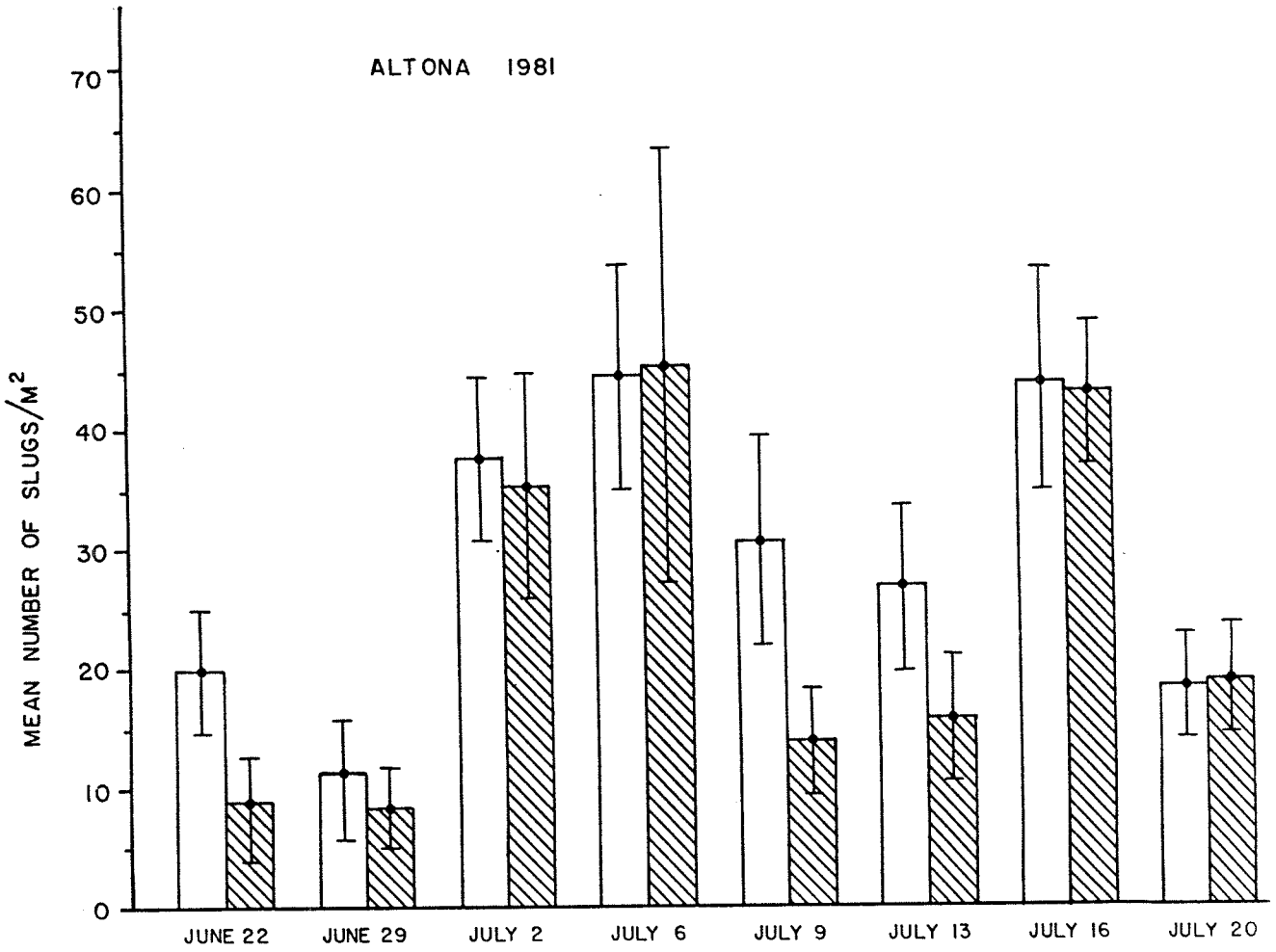
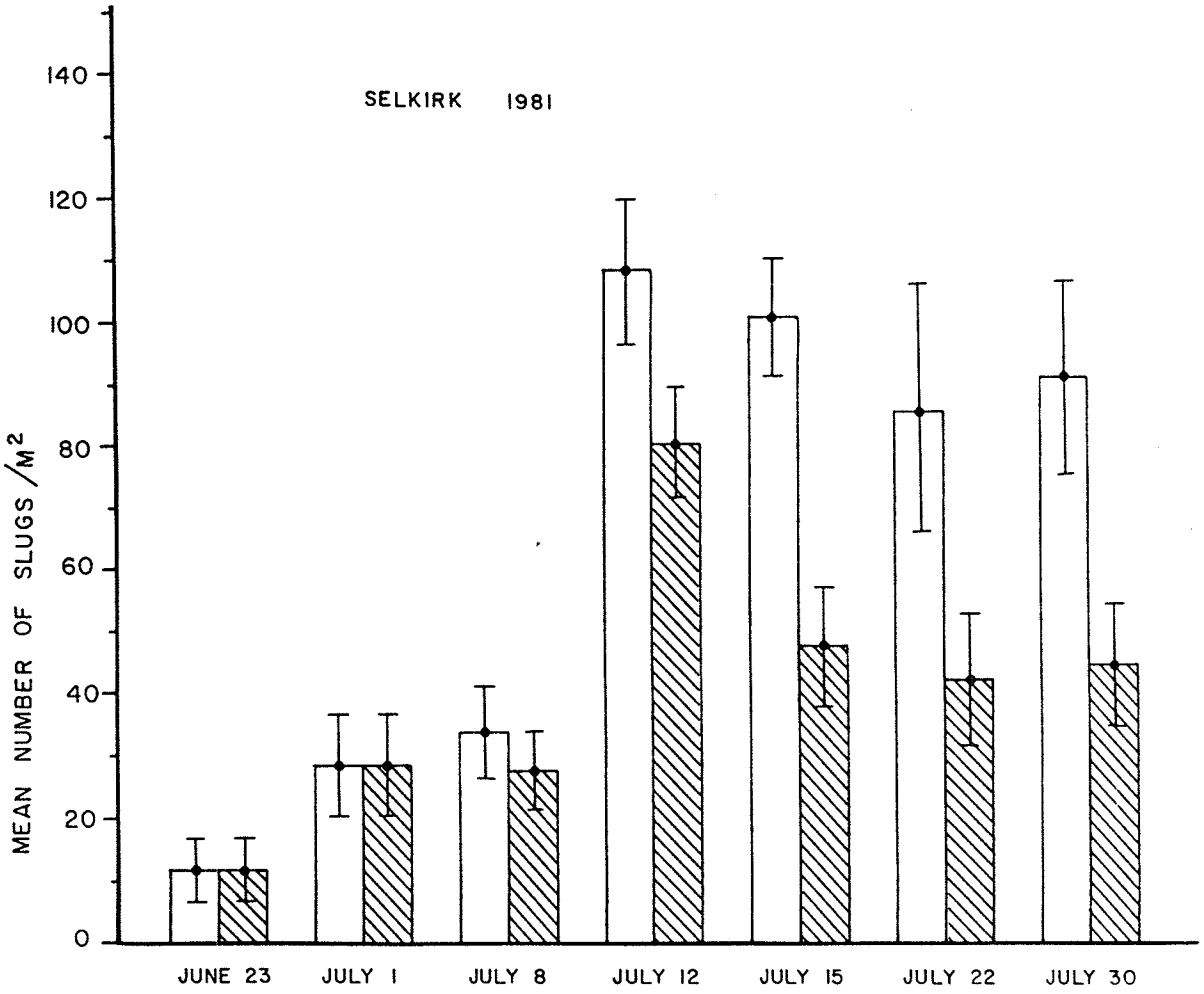

ALTONA 1981
MEAN NUMBER OF SLUGS/M²
0
10
20
30
40
50
60
70
JUNE 22
JUNE 29
JULY 2
JULY 6
JULY 9
JULY 13
JULY 16
JULY 20

Figure 24. Field efficacy trial of modified metaldehyde bran bait (hatched bars) on a 0.6 ha strawberry field at Selkirk. An adjacent 0.6 ha field was left untreated for a control. Application was made on 4 July. Mean number of slugs/m^2 (±S.E.) are shown (n = 15).


SELKIRK 1981
MEAN NUMBER OF SLUGS /M²
0
20
40
60
80
100
120
140
JUNE 23
JULY 1
JULY 8
JULY 12
JULY 15
JULY 22
JULY 30

strips. Few heavy slime trails were found, possibly due to the heavy rain which occurred over the previous two days.

Metaldehyde Breakdown in the Field

Infrared spectra were recorded for metaldehyde 2.75% bran bait formulation samples exposed to field conditions for 6 h, and 3, 7, 9 and 11 d. Bait samples to be collected after 14 and 21 d of field exposure were destroyed by crop management practices. Sample infrared spectra were compared to the infrared spectra from 0.0185 (Figure 25), 0.0103, and 0.0037 g of metaldehyde standard.

The concentration of metaldehyde was determined by measuring the absorbance of each sample at 1375 cm^{-1} on an infrared spectrophotometer. The sample absorbance reading gives a metaldehyde concentration reading when measured from a plot of absorbance versus concentration of metaldehyde standard. The calculation is based on the assumption Beer's law is obeyed and that a linear relationship exists between the absorbance and the concentration of the metaldehyde standard. A linear relationship was found (Figure 26). The concentration of metaldehyde in the bait samples was determined by interpolation.

A single sample of bait was collected after 6 h and 3, 7, 9 and 11 d exposure in the field. The spectrum of 7 d exposed bait is shown in Figure 27. The amount of metaldehyde remaining in all bait samples is shown in Figure 28.

Grower Survey

Thirty-five of the fifty slug control questionnaires distributed

Figure 25. Infrared spectrum of metaldehyde standard (0.0185 g). The absorbance used for the detection of metaldehyde is at 1375 cm^{-1}.

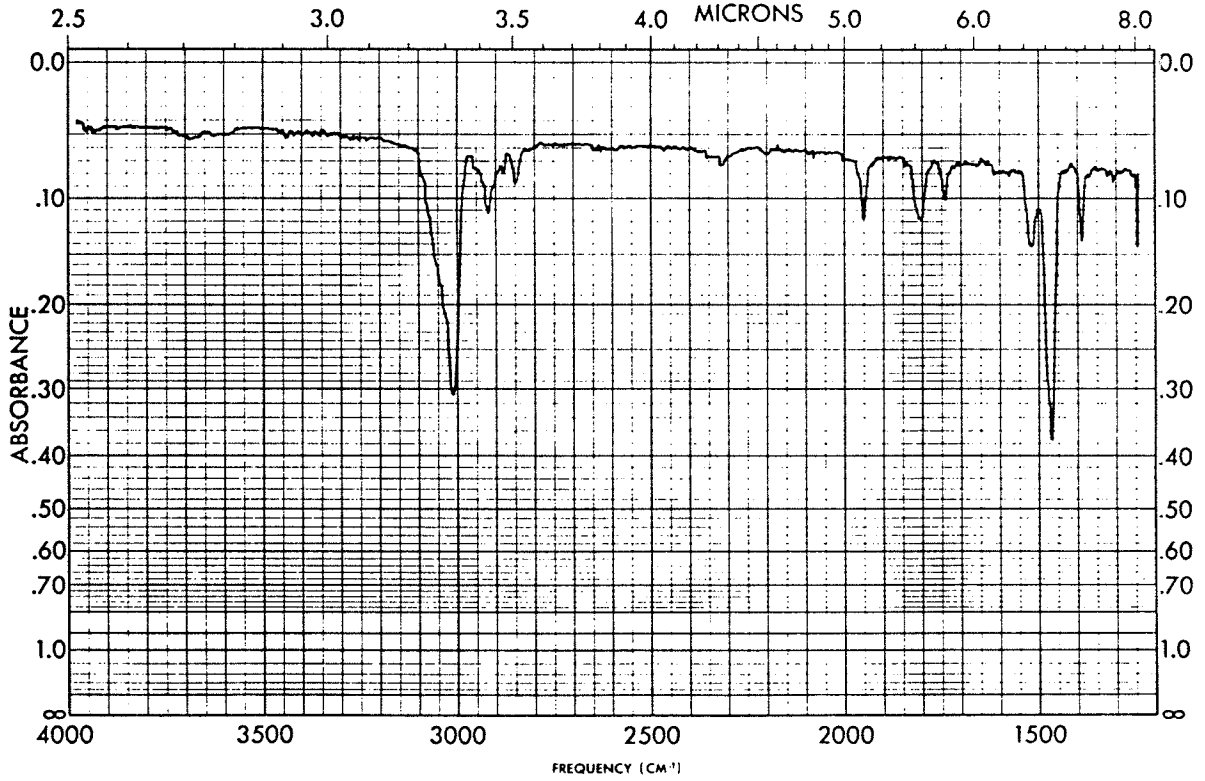

2.5
3.0
3.5
4.0
MICRONS
5.0
6.0
8.0
0.0
.10
.20
.30
.40
.50
.60
.70
1.0
∞
ABSORBANCE
4000
3500
3000
2500
2000
1500
FREQUENCY (CM⁻¹)

Figure 26. Absorbance at 1375 cm^{-1} (from IR spectra) versus concentration of metaldehyde standard (g/mℓ).

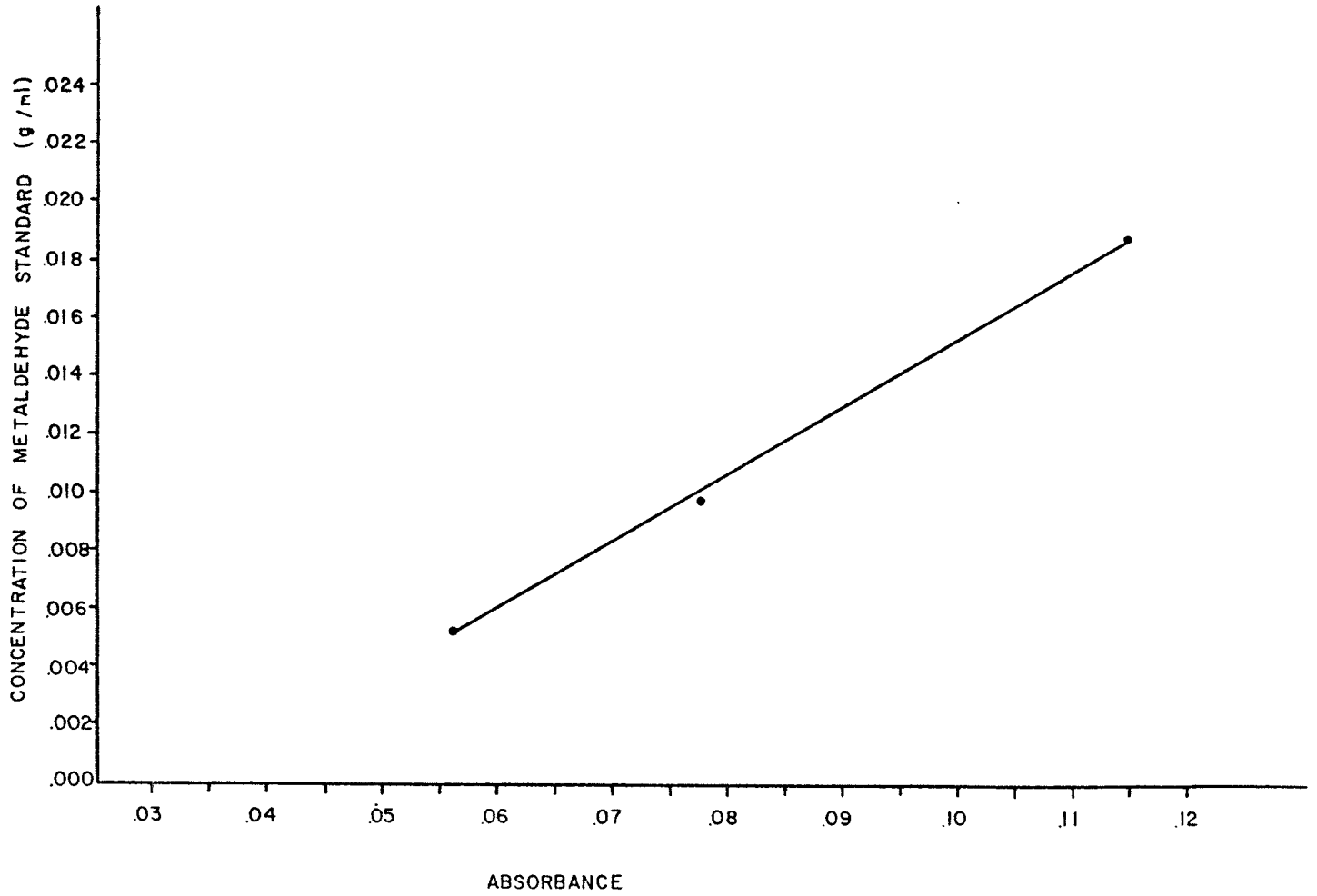

CONCENTRATION OF METALDEHYDE STANDARD (g/ml)
.024
.022
.020
.018
.016
.014
.012
.010
.008
.006
.004
.002
.000
.03
.04
.05
.06
.07
.08
.09
.10
.11
.12
ABSORBANCE

Figure 27. Infrared spectrum of metaldehyde extracted from a field sample (7 day). The absorbance used for the detection of metaldehyde is at 1375 cm^{-1}.

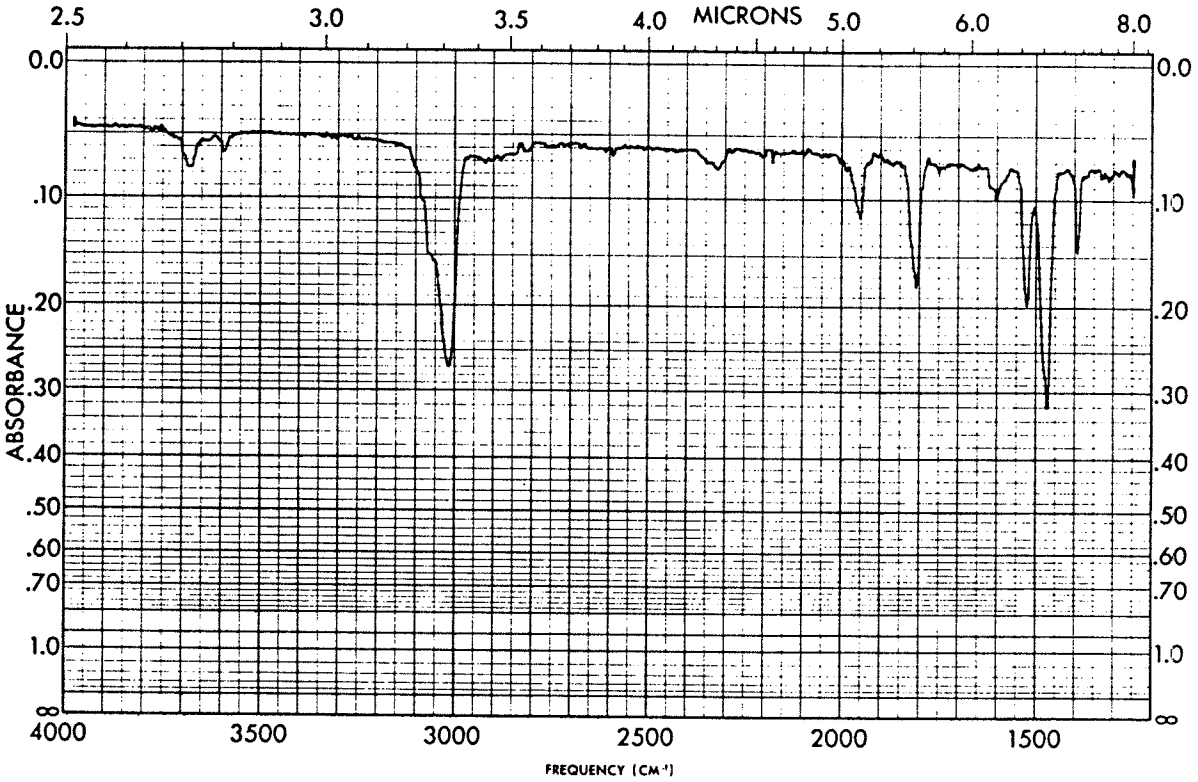
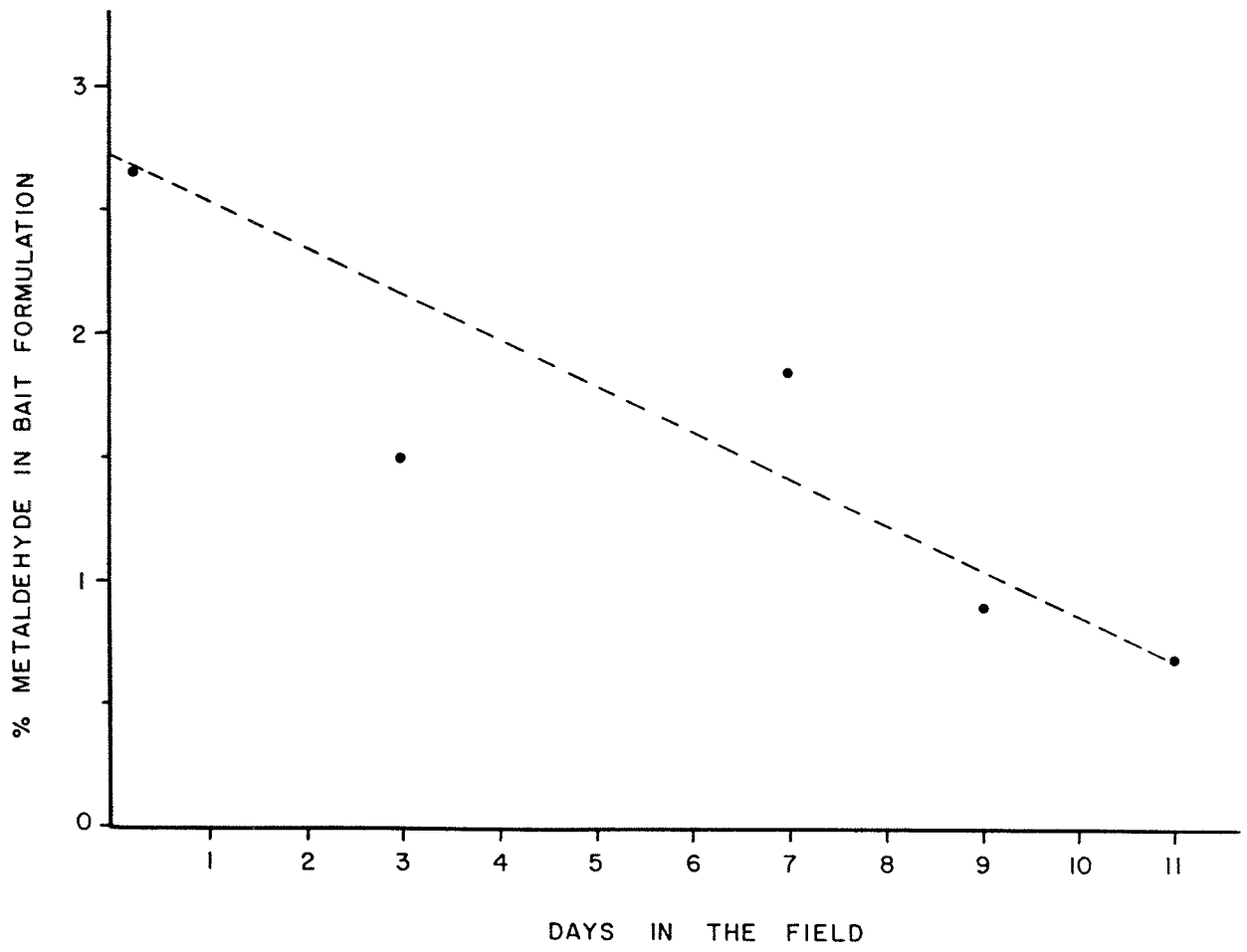

2.5
3.0
3.5
4.0
MICRONS
5.0
6.0
8.0
0.0
.10
.20
.30
.40
.50
.60
.70
1.0
∞
ABSORBANCE
4000
3500
3000
2500
2000
1500
FREQUENCY (CM⁻¹)

Figure 28. Percent metaldehyde (from IR spectra) remaining after exposure to field conditions for 6 h, and 3, 7, 9, and 11 d (n = 1). Line fit by eye.


% METALDEHYDE IN BAIT FORMULATION
3
2
1
0
1
2
3
4
5
6
7
8
9
10
11
DAYS IN THE FIELD

were completed by strawberry growers. In most cases, conclusive evidence could not be drawn from grower responses to questions. Some information was found for questions pertaining to the effect of crop renovation practices, the effect of variable straw cover, and the effect of treatment with some molluscicides.

Twenty-five growers used rotovation as the method of renovating strawberry fields. Slug problems were reported by six of these growers (24%). Slug problems were reported by five of the ten growers who used other methods to renovate strawberry fields (50.0%). Straw cover on strawberry fields ranged between 32 and 101 straw bales per hectare, but there appeared to be no relationship between this amount of straw applied and slug density. Six growers used chemicals to control slugs. Four growers used metaldehyde 2.75% bran bait formulation; three growers reported that slug numbers had not been reduced. The fourth grower treated fields after harvest and did not know if slug numbers had been reduced; slug problems were reported the following year. One grower used metaldehyde 50% EC spray formulation and reported that slug numbers had not been reduced. One grower applied copper sulphate as a spray formulation and reported that slug numbers were reduced by the chemical treatment (the rate of application was not known).

Impact of Management Practices on Slugs

Hedgerows. Slugs were collected in bait traps placed in hedgerows (Table 5). A two-way analysis of variance was performed on the data. Hedgerow type, and date, significantly affected slug numbers in hedgerows ($P<0.01$).

Table 5.

The number of slugs caught in bait traps placed in hedgerows of different tree species.

Date	Control	Tower Poplar	Ornamental Apple A	Ornamental Apple B	Elm-Green Ash A	Elm-Green Ash B	Elm-Green Ash Maple	Elm
	0	0	0	0	4	2	0	0
June 5	0	0	1	0	10	2	0	1
	0	0	0	2	17	1	0	0
	0	2	4	4	8	5	3	0
June 8	1	2	5	3	10	7	3	0
	0	0	0	6	22	6	1	0
	0	0	1	3	15	8	2	0
June 20	1	1	2	6	11	7	2	0
	0	1	0	6	23	13	1	0

Orthogonal contrasts were used to compare the mean numbers of slugs in different hedgerows over the test period. Slug numbers in two elm-ash hedgerows (designated A and B), and in two ornamental apple hedgerows (designated A and B), were significantly higher ($P<0.01$) than slug numbers in other hedgerows. Slug numbers in the two elm-ash hedgerows were significantly higher ($P<0.01$) than slug numbers on the two ornamental apple hedgerows. Slug numbers in elm-ash hedgerow A, and in ornamental apple hedgerow A, were significantly higher ($P<0.01$) than slug numbers in elm-ash hedgerow B and ornamental apple hedgerow B, respectively. Elm-ash hedgerow A, a weedy hedgerow, had the highest number of slugs at all times ($P<0.01$).

Since slug numbers were significantly different ($P<0.01$) in hedgerows having different tree species composition, and in hedgerows having the same tree species composition ($P<0.01$), both tree species and some additional hedgerow characteristics appear to cause differences in slug numbers in hedgerows.

Field borders. Slug numbers in two five year old fields were determined using bait traps. The fields were surrounded by the hedgerows designated elm-ash A, elm, apple B, and elm-ash-maple (Figure 29).

There is some indication that slug numbers were higher where borders between strawberry field and the adjacent hedgerows were not ploughed (Table 6). Slug numbers were also higher in fields where the adjacent hedgerow contained high numbers of slugs.

Rotovation. Densities of 34.0 slugs/m^2 were found in a three year old field on 10 August 1981. Renovation of strawberry fields occurred

Figure 29. Location of hedgerows around strawberry fields, and the location of bait traps used to assess the effect of field borders on slugs.

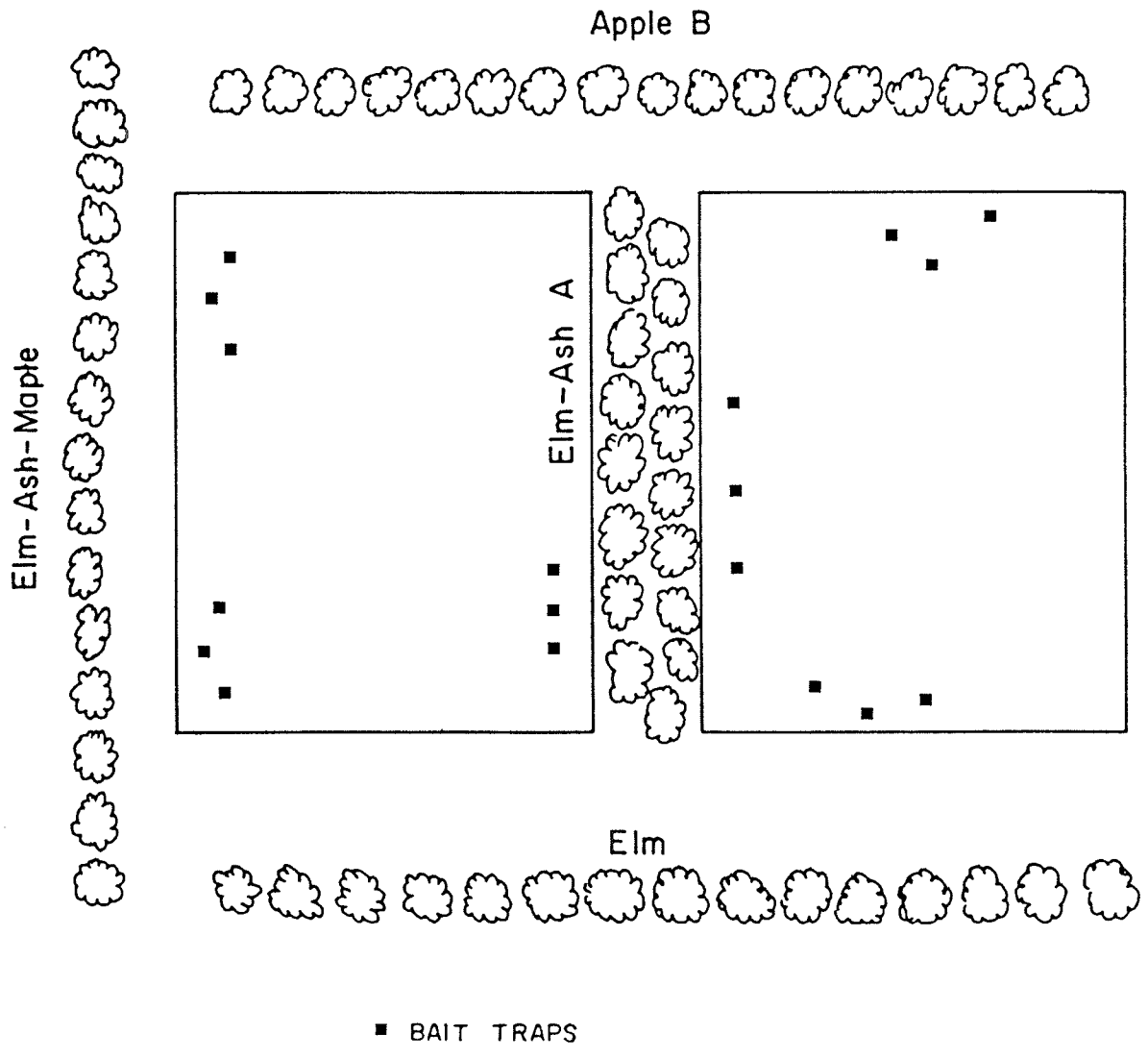

Apple B
Elm-Ash-Maple
Elm-Ash A
Elm
■ BAIT TRAPS

Table 6. Mean number of slugs per m^2 (±S.E.) in strawberry fields with, and without, ploughed borders separating the adjacent hedgerow.

	Mean number of slugs			
	June 4		June 8	
	Strawberry field	Adjacent hedgerow	Strawberry field	Adjacent hedgerow
Field borders not ploughed	1.67±1.20	10.33±3.76	3.00±0.58	13.33±4.37
	1.33±0.67	10.33±3.76	6.33±2.91	13.33±4.37
Field borders ploughed	1.33±0.88	0.67±0.67	0.33±0.33	4.33±0.88
	0±0	0±0	1.00±1.00	2.33±0.67
	0±0	0±0	0±0	2.33±0.67
	0±0	0.33±0.33	0±0	0±0

on 12 August; plant rows were moved, and the plant debris and straw mulch was rotovated into the gaps between plant rows. No slugs were found on 13 August, 17 August, 20 August, and on 24 August using 0.10 m^2 quadrat sampling and bait trap sampling.

CHAPTER IV

DISCUSSION

SAMPLING METHODS

South (1964) reviewed the sampling methods used to determine slug numbers in the field. Sampling has been done with 'traps', including boards, sacking, stones, leaves (Miles et al. 1931); inverted squares of turf (Thomas 1944); and inverted wooden boxes (Howitt 1961) - all laid on the ground. Sampling has been done with uncovered metaldehyde bait (Barnes and Weil 1942; Thomas 1944, 1948) and with baits covered by the 'traps' above (Thomas 1944).

Barnes and Weil (1944, 1945) searched the ground, collecting slugs at night during a 30 min tour. Gould (1962) counted dead slugs, in 30 cm x 30 cm quadrats, on soil treated with molluscicides and compared the results to those of trapping. Miles et al. (1931) and Duthoit (1961) estimated slug activity by measuring slug damage (South 1964).

Surface-searching, hand sorting of 0.3 m cubes of soil, and trapping with poisons have been compared (South 1964). It was found that evening surface-searching exaggerated the relative abundance of some slug species and that hand sorting soil cubes was the most reliable sampling method. Baits were found to have differential attraction for different slug species (Webley 1962; South 1964), Thomas (1944) and Howitt (1961) hand-sorted 10 cm diameter cores and 1.0 m^2 quadrats of soil (to a few cm below the surface), and concluded that hand sorting was subject to

considerable error (South 1964). Rollo and Ellis (1974) washed soil samples in a washing machine; the method was reliable for adult slugs and for eggs, but immature slugs were destroyed as were some dead slugs.

Richter (1976) used freeze-branding to mark slugs. Hunter (1968) compared a mark-release-recapture method with a simultaneous estimate by soil sampling; the mark-recapture method tended to under-estimate population density.

The method of surface-searching quadrats in this study, as with all the methods described above (except soil sorting or washing) depends on slug activities, which are largely governed by weather and factors which modify the microclimate. Therefore, all of the above sampling procedures measure a variable and unknown fraction of the population.

THE BIOLOGY OF DEROCERAS LAEVE

Overwintering adult Deroceras laeve appear in strawberry fields early in spring when the weather becomes warm (1-5^{o} C), and the soil moist. The straw cover on the strawberry fields helps to maintain moist conditions, suitable for slug activity, and provides protection from extremes of temperature.

In both 1980 and 1981 adult slugs fed and dispersed until dry weather of April and May when slugs disappeared into cracks and crevices in the ground, or hid beneath leaf litter. Slugs reappeared during warm, wet weather in May and June, and layed eggs through June and July; a well defined peak period of oviposition occurred over a 7-10 d period in the last week of June or the first week in July.

Adult slug numbers remain approximately constant through June to

mid-July, when adult slugs suddenly disappeared. The disappearance of these adult slugs was partially masked by the appearance of a new adult generation hatching through late June, July and August (Figures 5 and 6). The hatching period for slugs in the field, at 14.5-26.5° C (mean maximum and minimum temperatures for July 1981) was about 10-14 d. The hatching period can be deduced from the time lapse between the appearance of eggs, and the appearance of immature slugs. The 3 week hatching period of slug eggs in the laboratory, at 10° C, is consistent with a 10-14 d hatching period in the field at 14.5-26.5° C.

Adult slugs of the new generation fed, matured, and layed eggs (Figure 3) through August and early September. If weather conditions permit, egg laying may continue through September; immature slugs were found on 10 October 1980. Slug activity fluctuates throughout the summer in response to changes in environmental conditions (Figures 7 and 8). The moist straw cover on the strawberry fields normally helps to maintain suitable conditions for slug activity, but lengthy periods without precipitation can cause the straw mulch to become dry; slug activity was reduced, or absent, when the straw mulch was dry.

Adult slugs, eggs, and possibly immature slugs may overwinter; adult slugs, eggs, and immature slugs have been found on at least two sampling occasions in early spring. Slug eggs in the laboratory hatched at temperatures of 1° C; the time for hatching at this temperature was 6 weeks. This suggests that slug eggs laid in the fall season could hatch later the same fall; the immature slugs would not have time to mature before winter. Since large numbers of eggs and

immature slugs can be found in fall (Figure 4), and since several immature slugs were found on 18 March (1981) (Figure 2), it appears that immature slugs may overwinter with adult slugs in Manitoba. On 11 May (1981) many eggs were found in hedgerows (Figure 4); it is not known whether the eggs overwintered, or if they were laid by adult slugs in the spring. The survival of slugs and eggs depends on the suitability of the habitat, and on weather conditions in both the previous fall and in the spring (Runham and Hunter 1970).

D. laeve prefers uncultivated lands (Runham and Hunter 1970), and can be found in uncultivated land throughout most of the year (Mellanby 1961). In this study adult D. laeve were found in hedgerows and headlands early in the season in several sampling sites in the province. In many cases, slugs were found in hedgerows 1-2 weeks before slugs were found in adjacent strawberry fields. Eggs and immature slugs were also found in hedgerows 1-2 weeks before being found in adjacent strawberry fields (Figure 4). Similar results were found by Rollo (1974). Data from quadrat sampling in strawberry fields and hedgerows suggest that hedgerows are slug reservoirs, from which slugs invade strawberry fields in spring and summer when conditions there become suitable. Miles et al. (1931), Barnes (1944) and Webley (1965) found that slugs in such reservoirs make nightly forays into areas of low slug abundance.

SOIL FACTORS - EFFECTS ON THE DISTRIBUTION AND ABUNDANCE OF SLUGS

Soil pH is thought to be a factor affecting slugs, because at least one slug species (Arion circumscriptus) is known to be more adapted to acidic soils, although this tolerance is not well defined (Carrick

1942). However, most slug species have been shown to be tolerant of a wide range of soil pH (Carrick 1942). Carrick (1942), Barnes and Weil (1945) and Stephenson (1968) have found that there is little correlation between soil acidity (pH) and the density of slugs. In this study soil pH varied little and appeared not to be a major determinant of the distribution and abundance of slugs in Manitoba strawberry fields.

The availability of soluble carbonates in soil is thought to be a factor affecting slugs, since soil carbonates are known to affect the distribution and abundance of snails (both slugs and snails require calcium carbonate for shell formation) (Barnes and Weil 1945). However, Barnes and Weil (1945) and Stephenson (1968) found that the availability of soluble carbonates in soil was not correlated with the abundance of six species of slugs, including the common pest species. In this study soil carbonate content was low and was probably not a major determinant of the distribution and abundance of slugs in Manitoba strawberry fields.

The organic matter content of soils is known to affect the distribution and abundance of slugs through its effect on soil moisture (Miles et al. 1931; Carrick 1942; Barnes and Weil 1945). However, in Manitoba strawberry fields there was no correlation between organic matter content, field age, sample site, or slug levels. Although the organic matter content of soils may affect slug abundance in most field situations (Barnes and Weil 1945), the straw cover on strawberry fields, and irrigation, may have affected soil moisture to a much greater extent. This probably masked any effects which organic matter content may have had on slug abundance.

CHEMICAL CONTROL OF SLUGS

Methiocarb 2% bait formulation

Methiocarb significantly reduced slug numbers in field trials in both 1980 and 1981, and was the most effective molluscicide tested. Similar results have been found in numerous studies since 1965 (Getzin 1965; Crowell 1967; Symonds 1975).

The effectiveness of methiocarb has been attributed to the superiority of the carbamate ingredient, the greater attractiveness of the bait formulation (contains molasses, apple pomace, and amyl acetate), and to increased persistence in the field, due to pelletization (Getzin 1965; Crowell 1967; Symonds 1975). However, perhaps even more important, methiocarb contains mould inhibitors (Symonds 1975). Mould inhibitors are important in maintaining bait effectiveness by prolonging bait palatability (preventing bait souring); the palatability of bait formulations of molluscicides may be more important than the toxicity (Symonds 1975).

Getzin (1965) found that methiocarb was significantly better at reducing slug numbers than commercial metaldehyde bait, under dry conditions; under wet conditions, methiocarb gave satisfactory control (no figures given), while metaldehyde bait was ineffective. It appears that the carbamate ingredient and the attractiveness of the bait formulation make methiocarb better at reducing slug numbers under dry conditions. Under wet conditions, pelletization (which acts as a controlled release formulation), and the addition of mould inhibitors, apparently makes methiocarb satisfactory for slug control.

However, methiocarb may be ineffective for slug control in some situations. Symonds (1975) found that metaldehyde pellets were more effective than methiocarb pellets, particularly in a second week of field trials, when strong winds lowered daytime humidity. A heavy rainfall occurred soon after treatment. No other details were given. Wright and Williams (1980) found that methiocarb bait was ineffective in some field trials, while effective in several others. The trials in which methiocarb was ineffective were not included in the calculation of efficacy due to unusual slug activity, characterized by the absence of feeding.

Metaldehyde 50% EC spray formulation

Cragg and Vincent (1952) found that, metaldehyde was soluble in water (0.02% at 17^{o} C), and water which had been in contact with metaldehyde irritated slugs. The metaldehyde solution could act on slugs either by contact (both direct and residual), or as a "stomach poison" when ingested with food material. Toxic effects appeared more rapidly in contact treatments, with death occurring after 1 h contact with metaldehyde concentrations equivalent to 0.0063 mg/cm^{2}. Slugs became immobilized and secreted thick white slime 1 to 8 min after direct contact with a saturated metaldehyde solution; abnormal behavior lasted for 10-24 h, with many slugs dying from the treatment. Similar results were found when slugs contacted dry filter papers, which had previously been soaked with 2 mℓ of a 0.02% metaldehyde solution (0.0063 mg/cm^{2}) (Cragg and Vincent 1952). Howitt and Cole (1962) found that metaldehyde spray formulation was most effective when applied to the soil surface.

Slugs died after both direct and residual contact with the chemical.

Metaldehyde 50% EC spray formulation was the second most effective molluscicide in the 1981 field trial. The effectiveness of the treatment was probably due to direct and residual contact action, and to the ingestion of coated food material by slugs, as described by Cragg and Vincent (1952).

The effectiveness of the metaldehyde spray formulation, over the entire sampling period, indicates that either the concentration of metaldehyde was adequate for slug control throughout the test period (even though metaldehyde breakdown presumably did occur), or that a high initial kill of slugs was achieved. Even with a residue analysis of the bait formulation, it is not certain which of the above factors was most important to the overall effectiveness of the formulation. The results of Thomas (1948) and Webley (1965) indicate that bioassays are needed to determine the concentrations of metaldehyde that would be effective for slug control under the conditions experienced during field trials. Since bioassays were not performed in this study, the exact reason for the effectiveness of the spray formulation is uncertain.

The effectiveness of the metaldehyde spray formulation might be further increased by modifying the method of application. Since slugs normally remove water from the substrate to maintain their internal water balance (Howes and Welles 1934), it is conceivable both from this work and that of Vincent and Cragg (1952) that metaldehyde may be taken up with substrate moisture. If metaldehyde, in the spray formulation, does enter slugs with substrate water, then the effectiveness of the treatment

might be increased by application to fields after irrigation or light rainfall; slugs would be active, and the flow of substrate water through their bodies should be high. A lethal dose of metaldehyde would be taken up in a short period of time.

Modified metaldehyde bait formulation

Symonds (1975) found that palatability of bait formulations of molluscicides may be more important than their intrinsic toxicity. Several attempts have been made to reformulate commercial metaldehyde bait to a more palatable (more attractive) form. Lange and MacLeod (1941) found that a formulation of black-strap molasses, 5% calcium arsenate, 1.5-2.5% metaldehyde, bran, and water, was significantly more effective than commercial metaldehyde bait in killing slugs (the mixture was not tested without calcium arsenate). Thomas (1948) found that the addition of molasses or crude sugar significantly increased the effectiveness of commercial metaldehyde bait formulation.

Laboratory testing revealed that the modified metaldehyde bait was far more attractive than commercial metaldehyde bait (Table 3); slugs found and fed upon the modified metaldehyde bait in a shorter period of time. A higher proportion of the slugs were killed by the modified metaldehyde bait, apparently as a result of its increased attractiveness. Small scale field testing revealed that modified metaldehyde bait can in some cases significantly reduce slug numbers in the field and may be an effective method of slug control.

However, large scale field testing on a 0.6 ha field in Altona on 29 June 1981 indicated that modified metaldehyde bait was ineffective

(Figure 13). Slug numbers in chemically treated fields increased proportionately to slug numbers in untreated fields (even though many dead slugs were found on the bait strips). The rapid increase in slug numbers at the time of chemical testing was due to the appearance of newly hatched slugs (Figure 6). In the first 2 weeks of July, 80% of all slugs in the field were immature. In an untreated control field, the mean number of immature slugs increased from 16.4 slugs/m^2 on 1 July, to 74.30 slugs/m^2 on 12 July. The lack of slug mortality in the first week of chemical treatment appears to have been because immature slugs did not move to the bait strips. Field sampling has revealed that immature slugs tend to remain aggregated for several days after hatching. Immature slugs disperse from aggregations 1 to 2 weeks after hatching, if weather conditions permit. Runham and Hunter (1970) found similar aggregation and dispersal behavior in immature slugs.

The lack of adult slug mortality probably resulted from a change in feeding behavior at the time of chemical application. The application in Altona was timed, as closely as could be predicted from sampling, to coincide with both the seasonal increase in slug numbers, and the appearance of ripe strawberries in the fields. However, Howitt (1960, in Howitt and Cole 1962) found that, in most cases, slugs presented with a choice between a succulent plant or a bait, preferred to feed on the plant so that the plant was often damaged or destroyed even though the slugs might eventually be killed by taking the bait. This is especially the case when slugs feed on tomatoes and other berries (Lindquist and Krueger 1976). Rayner et al. (1978) found similar results. They attributed the ineffectiveness of methiocarb bait to a change in slug feeding

behavior, which occurred when potato tubers became attractive as the growing season progressed.

Modified metaldehyde bait formulation was effective in reducing slug numbers in the 0.6 ha field in Selkirk (though there was a delayed effect) (Figure 14). Application was made one week after application was made to the 0.6 ha field in Altona. The difference in the date of application could have been a significant factor in chemical treatment. If chemical application had been made 3 weeks earlier, just before egg laying, or 3 weeks later, when immature slugs become active adults, chemical control in both Altona and Selkirk might have been more effective.

Metaldehyde 2.75% bran bait formulation

Metaldehyde has been the most commonly used chemical for controlling slugs since 1940 (Barnes and Weil 1942), but the results of field application have ranged from no control to better than 90% (Barry 1969). The inconsistency has been attributed to environmental conditions, method of application, rate of metaldehyde breakdown, and the bait formulation (Thomas 1944; Cragg and Vincent 1952; Barry 1969).

In both the 1980 and 1981 field trials, environmental conditions, and the method of application, were probably less important factors affecting efficacy than the rate of metaldehyde breakdown and formulation of the bait. Although environmental conditions can reduce slug activity, thereby reducing the probability of slugs contacting the pesticide, the effect of environmental conditions in this study was modified by the presence of a moist straw mulch on the strawberry fields; slug activity

was high at the time of field testing.

The method of application affects placement of the chemical, and can also reduce the probability of slugs contacting the pesticide. However, metaldehyde bran bait was applied by hand broadcasting; hand broadcasting of baits is the most reliable method of control for surface-dwelling slug species, such as D. laeve (Cragg and Vincent 1952).

The rate of metaldehyde breakdown and the bait formulation are often cited as the reason for the observed decrease in effectiveness of the commercial bait formulation 1-4 d after treatment (Barnes and Weil 1942; Howitt and Cole 1962; Symonds 1975). The rate of metaldehyde breakdown was determined by chemical analysis of bait samples exposed to field conditions for various lengths of time. Indeed, metaldehyde breakdown occurred rapidly (Figure 28): the 2.75% bran bait formulation decreased in concentration to 1.50% after 3 d (54% of initial concentration). This more or less agrees with the 1-4 d duration of effectiveness of metaldehyde bait formulation reported in the literature (Barnes and Weil 1942). However, none of the bait samples left in the field were bioassayed in the laboratory to determine their effectiveness on slugs. It is possible that a very small concentration of metaldehyde could still cause slug mortality. Thomas (1948) found that metaldehyde concentrations as low as 0.50% could cause 10 ± 1.8% slug mortality (Milax gracilis, D. reticulatus and Arion hortensis), and a concentration of 0.70%, which was that of 11 d old bait in this study, could cause more than 20 ± 3.1% slug mortality under field conditions. Thomas concluded that decreased bait palatability rather than metaldehyde breakdown in

the field, was the reason for the ineffectiveness of the commercial metaldehyde bait formulation in his field trials.

Webley (1965) found that a high initial kill, and subsequent decrease in the numbers of slugs caught at bait sites, was due to a partial destruction of the local slug population around the baits; subsequent counts were composed of the remnants of the original population, and migrant individuals entering into the immediate vicinity of the baits. The bait was effective over a long period of time, but sharp changes in slug numbers and variable slug activity masked this effectiveness. These findings were confirmed when baits, left out for 7 d, were moved 100 m away for a 7 d interval and then returned to their original location; the number of slugs caught over the next 7 d was similar to that caught with the same bait during the first week (environmental conditions being about the same) (Webley 1965).

Furthermore, Howitt and Cole (1962) found that slugs treated with a sublethal dose of metaldehyde bait formulation ceased to feed for long enough that damaged bean plants were able to recover and attain normal growth; economic damage was reduced without slug mortality. They also found that the residual activity of metaldehyde in the bait formulation was greater when placed under matted rows of strawberry plants, than when placed on the cultivated ground between rows. The increased residual activity was attributed to a slower rate of metaldehyde depolymerization, since the chemical was not exposed to the sun. In this study most of the metaldehyde bait broadcast between plant rows was observed to fall through the straw mulch layer covering the ground.

Thus shaded, the metaldehyde in both the 1980 and 1981 field trials of molluscicides, should have undergone a slower rate of depolymerization. The metaldehyde breakdown trial was in the sun.

In view of the information above, the rate of metaldehyde breakdown may have been a factor reducing the long term effectiveness of the commercial bait formulation in 1980 and 1981 field trials, but metaldehyde breakdown, alone, cannot account for the low initial effectiveness of the bait. In addition, three applications of metaldehyde bait (as prescribed on the label of the package) were made over the 4 week field trial in 1980; it is unlikely that metaldehyde breakdown would be the main factor reducing effectiveness in such a case.

It appears that bait attractiveness may have been a more important factor contributing to the low initial, and long term, effectiveness of the commercial metaldehyde bait formulation. The importance of formulation of the bait, and the affect of bait re-formulation, is apparent from the testing of the modified metaldehyde bait formulation.

Copper sulphate-lime powder (1:10 w/w)

Miles et al. (1931) found that slugs died almost immediately when treated with copper sulphate; a rate of application of 448 kg/ha, or more, was effective in controlling slugs. However, when they applied copper sulphate to fields, at this concentration, the soil acidity increased, and there was a definite risk of injury to crop plants. Miles et al. (1931) recommended the addition of an equal weight of lime to eliminate the problem of increased soil acidity, and added that "application needs care", to reduce the risk of damage to crop plants. Lime

is a non-toxic, dry powder; when lime is directly applied to slugs, it is merely cast off with slime (Thomas 1948).

In the 1980 field trial, copper sulphate-lime powder (1:9 w/w) was applied to fields at a rate of 65 kg/ha as recommended by Anonymous (1977). In the 1:9 w/w mixture, only 6.5 kg/ha of copper sulphate and 58.5 kg/ha of lime were applied to the field plots.

In the 1980 field trial, copper sulphate-lime powder (1:9 w/w) was ineffective in reducing slug numbers. It appears that copper sulphate is not suitable for slug control at the low application rates necessary to reduce the risk of injury to crop plants.

Kocide 101 56% WP spray formulation

Kocide 101 56% WP spray formulation was ineffective in reducing slug numbers in the 1980 field trial. The ineffectiveness of this formulation, as with the copper sulphate-lime powder formulation was probably due to the low recommended rate of application. Only 3.36 kg/ha of Kocide 101 (copper hydroxide) was applied, rather than the 448 kg/ha of copper in the copper sulphate found effective by Miles et al. (1931), above. However, Miles et al. (1931) found that, while copper sulphate killed slugs slmost immediately, copper carbonate and copper sulphocyanide were easily cast off with slime and were ineffective.

IMPACT OF MANAGEMENT PRACTISES

The distribution and abundance of slugs varies among strawberry fields of the same age, among strawberry fields of different ages, and among sample sites in the province. In an attempt to explain the

observed variation, the numbers of slugs in strawberry fields and the adjacent hedgerows were estimated. Slug numbers were also estimated before and after some crop management practises.

Hedgerows. Hedgerows are islands of suitable habitat for slugs (Beyer and Saari 1977). Since slugs have been shown to disperse from high density areas to low density areas (Barnes 1944), strawberry fields adjacent to hedgerows with slugs should also become infested with slugs. Hedgerows would serve as slug reservoirs to reinfest fields which have had slug numbers reduced by chemical treatments (Webley 1965; Miles et al. 1931).

Statistical analysis (2-way analysis of variance) indicates that hedgerow composition varies significantly with slug numbers in hedgerows (Table 5). Beyer and Saari (1977) found that slug species are not limited to one or a few closely related tree species, and are not associated with particular plant species as food plants, but vegetation does affect the distribution of slugs through its modification of the microclimate. It appears that the tree species in the hedgerows at the Altona sampling site modified the microclimate differently. Indeed, the elm-ash hedgerow had tree species with larger leaves, different growth forms, and which created a different soil surface environment than the ornamental apple hedgerows. The larger leaves appeared to be important in forming the thicker leaf litter layer found under the elm-ash hedgerow (5-10 cm thick), as opposed to the very thin (1-3 cm thick) leaf litter layer found under ornamental apple hedgerows. The leaf litter provides shelter, moisture, food, and egg laying sites (Barnes 1944).

The shrubby growth form of the young trees of the elm-ash hedgerows formed a dense leaf canopy, which was also close to the ground. It appears that the leaf canopy reduced air movement near the ground, since the leaf litter was usually found to be quite damp, and the humidity high (Palti 1981). Ornamental apple hedgerows were composed of trees with higher branches and most of the leaf canopy was well away from the tree trunk. It appears that the structure of the canopy allowed air movement so that the leaf litter layer was usually dry. Leaf litter is only effective as a source of food, protection, and egg laying sites for slugs if it is damp (Barnes 1944).

It appears that there were differences in the soil surface microenvironment in the different hedgerows, as evidenced by the complete lack of weeds and annual plants in the ornamental apple hedgerows. Elm-ash hedgerows contained an abundance of weeds. Weeds help maintain high soil moisture, and may offer food and protection to slugs (Carrick 1942; South 1965).

Similarly, the tower poplar, elm, and elm-ash-maple hedgerows modified the microenvironment in a way which apparently decreased their suitability as habitats for slugs (Table 5). All three hedgerows were composed of mature trees more than 6 m high. These hedgerows were composed of orderly rows of trees, with the lowest branches well above the soil surface. All three hedgerows lacked a complete leaf litter layer. Tower poplar dropped an abundance of large leaves; however, tall grass growing beneath the trees and for several metres on either side of the hedgerow broke and lifted the leaf litter

layer. Thus the ground cover was grass, intermixed with a loose layer of leaves, and was often quite dry. A bare, moist soil surface is more suitable for the uptake of soil moisture for slug locomotion, and is necessary for egg laying (Carmichael and Rivers 1932; Runham and Hunter 1970). The elm-ash-maple hedgerow was very narrow, and free of branches at the bases of the trees. The absence of low branches, and the narrowness of the hedgerow, allowed wind to remove all the leaves dropped in fall. Hence, there was no leaf litter, weeds, or plants beneath the trees. Slugs require a vegetative cover or leaf litter layer for protection from extremes of weather (Barnes 1944). The elm hedgerow was tall enough that most branches were too high to prevent drying of the leaf litter and soil surface by the sun. It appears that any slugs in the hedgerow died, or dispersed to a more suitable location.

The significant differences ($P<0.01$) in slug numbers in hedgerows with the same tree species composition further suggests that modification of the microclimate, rather than tree species, effects slug numbers in hedgerows. Ornamental apple A hedgerow (Table 5) was composed of smaller shrubbier trees, with more centrally thickened canopies, than trees of ornamental apple B hedgerow. Elm-ash A hedgerow had a thicker leaf litter layer, and was more weedy than elm ash B hedgerow. Both ornamental apple A hedgerow, and elm-ash A hedgerow had significantly higher numbers of slugs. Beyer and Saari (1977) found that modification of the microclimate affects slug numbers irrespective of the tree species.

The high slug numbers found in the hedgerows and adjacent straw-

berry fields at Sites 1, 2 and 4 are consistent with the experimental results above; the multiple tree species composition, the shrubby growth, and the weedy condition made the hedgerow and headlands at these sites more suitable for slugs. These areas became reservoirs from which slugs subsequently dispersed into adjacent strawberry fields. The low slug numbers found in the hedgerows and adjacent strawberry fields at Sites 3 and 5 are also consistent with the experimental results above; the hedgerows at Site 3 were composed of a single row of mature trees (Salix spp.) which were maintained by the removal of low branches, and by removal of the underlying weeds and plant debris, while the headlands at Site 5 were composed of mature trees with grass growing beneath, and were located 20 to 30 m away from the fields.

Field borders. When ploughed strips of land are used as field borders, the numbers of slugs in strawberry fields appear to be lower (Table 6). The ploughed strip reduces the cover through which slugs may safely disperse from hedgerows; the soil surface presents an effective barrier to slug movement in dry conditions. Lewis (1980) and Hunter (1967b) found similar results, with respect to ploughed surfaces.

Sites 1, 2 and 4 had high slug numbers in some strawberry fields where there was no field border separating the adjacent hedgerow or headland; the slug numbers in the fields appeared to be higher where adjacent hedgerows had higher slug numbers. The low slug numbers, or absence of slugs, found at Sites 3 and 5 appear to have been due to the presence of wide borders of tilled soil around the fields, separating

the adjacent hedgerows or headlands (these borders were usually tilled two or three times over the summer). The way in which hedgerows modified the environment, and the presence of field borders, together, appear to have had a significant effect on slug numbers. Unfortunately the experimental results above did not provide sufficient information to substantiate these observations; further testing is necessary.

Rotovation. The effect of rotovation on the distribution and abundance of slugs was tested in Altona, and observed in several other sites in the province. In every location, the high numbers of slugs found before rotovation were reduced to zero after rotovation. Sample sites in Selkirk and Altona were searched several times over a 3 week period after rotovation and no slugs were found.

Rotovation incorporates the decomposing straw mulch into the soil between plant rows. Rotovation also moves much of the plant debris, from inside plant rows, into the soil between plant rows. The procedure greatly reduces soil moisture in both the plant rows and the gaps. These modifications of the microclimate appear to make the strawberry fields unsuitable for slug survival. Rotovation may also have a direct effect on slugs by physical control. Similar results of tillage were found by Hunter (1967b) and by Lewis (1980).

Slug numbers at Site 1 were among the highest in the province in both 1980 and 1981. This was the only site where rotovation was not used during field renovation. Slug numbers throughout the summer of 1980 and 1981 were usually much lower at Sites 2, 3, 4 and 5, where rotovation was used during field renovation; no slugs were found immediately following rotovation, and for several weeks thereafter. These

observations are consistent with the experimental results above.

Straw cover. Slug numbers seem to be associated with the amount of the decomposing straw mulch component of straw cover, rather than to the total straw cover; higher slug numbers were observed in strawberry fields with larger amounts of straw mulch. Unfortunately, the amount of data gathered (Tables 1 and 2) was not sufficient to substantiate the observed differences; further testing is necessary.

The occurrence of lower slug numbers in fields having smaller amounts of straw mulch, supports the experimental results of field rotovation; rotovation reduces slug numbers by removing the straw mulch component of straw cover. Barnes (1944) found that soil surface plant debris provides a microhabitat that significantly increases slug abundance.

CONCLUSIONS

1) D. laeve has a one year life cycle in Manitoba.
2) Adults, eggs and immature slugs may overwinter in uncultivated land in Manitoba.
3) Adult D. laeve appear in high numbers with the first snowmelt. These slugs subsequently disperse locally from overwintering sites to areas having low slug numbers.
4) The peak period of oviposition occurs during the last week of June to the first week in July, depending on environmental conditions.
5) The peak period of egg hatch occurs during the third to fourth week in July, depending on environmental conditions.
6) Straw mulch appears to modify the microclimate in strawberry fields in a way which is suitable for slugs. Large amounts of mulch are associated with high numbers of slugs.
7) Hedgerows are areas of high slug density from which slugs may invade strawberry fields.
8) Copper sulphate-lime powder (1:19 w/w) and Kocide 101 56% WP spray formulation are ineffective for slug control in Manitoba strawberry fields at the recommended application rates.
9) Metaldehyde 2.75% bran bait formulation is ineffective for slug control under the conditions most often encountered in Manitoba strawberry fields.
10) Metaldehyde 50% EC spray formulation is the only molluscicide, recommended for slug control that is effective in reducing slug numbers in Manitoba strawberry fields.

11) Methiocarb 2% bait formulation was the most effective of the molluscicides tested in 1980 and 1981, but is not registered for use on strawberry fields in Canada.

12) A modified metaldehyde bran bait formulation, an unregistered formulation, was effective in reducing slug numbers in Manitoba. strawberry fields.

13) The efficacy of Methiocarb 2% bait, metaldehyde 50% EC spray, and modified metaldehyde bait may vary with weather conditions, and when synchronized to different aspects of the phenology of D. laeve.

Literature Cited

Abdou, A.H. 1958. Studies on the development of Davainea proglottina in the intermediate host. J. Parasitol. 44:484-488.

Alicata, Joseph E. 1962. Angiostrongylus cantonensis (Nematoda: Metastronylidae) as a Causative Agent of Eosinophilic Meningoencephalitus of Man in Hawaii and Tahiti. Can. J. Zool. 40:5.

Anderson, R.C. 1960. On the Development and Transmission of Cosmocercoides dukae of Terrestrial Molluscs of Ontario. Can. J. Zool. 38:801-825.

Anonymous. 1977. Control of Slugs. Agriculture Canada Pub. 1213.

Barker, Philip S., B.D. Prystupa, N.J. Holliday. 1980. Susceptibility of the Slug Deroceras laeve to Methyl Bromide. Pest Res. Report 1980.

Barker, Philip S., B.D. Prystupa, N.J. Holliday. 1981. Susceptibility of the Marsh Slug Deroceras laeve to Chloropicrin. Pest. Res. Report 1981.

Barnes, H.F. 1944. Proceedings of the Association of Applied Biologists I. Introduction Seasonal Activity os Slugs. Ann. Appl. Biol. 31:160-163.

Barnes, H.F. and J.W. Weil. 1942. Baiting Slugs Using Metaldehyde Mixed with Various Substances. Ann. Appl. Biol. 29:56-68.

Barnes, H.F. and J.W. Weil. 1944. Slugs in Gardens: Their Numbers, Activities and Distribution. Part I. J. Anim. Ecol. 13:140-175.

Barnes, H.F. and J.W. Weil. 1945. Slugs in Gardens: Their Numbers, Activities and Distribution. Part II. J. Anim. Ecol. 14:71-105.

Barry, B.D. 1969. Evaluation of Chemicals for Control of Slugs on Field Corn in Ohio. J. Econ. Ent. 62:1277-1279.

Bayne, C.J. 1968. A Study of the Dessication of Egg Capsules of Eight Gastropod Species. J. Zool. Lond. 155:401.

Bayne, C.J. 1969. Survival of the Embryos of the Grey Field Slug Agriolimax reticulatus, Following Dessication of the Egg. Malacologia 9:391-400.

Bequaert, J. 1925. The Arthropod Enemies of Molluscs, with Description of a New Dipterous Parasite from Brazil. J. of Parasitol. 11:201-212.

Berg, C.O. 1953. Sciomyzid Larvae (Diptera) that Feed on Snails. J. of Parasitol. 39:630-636.

Bett, J.A. 1960. The Breeding Seasons of Slugs on Gardens. Proc. Zool. Soc. Lond. 135:559-568.

Beyer, W.N. and D.M. Saari. 1977. Effect of Tree Species on the Distribution of Slugs. J. Anim. Ecol. 46:497-502.

Boycott, A.E. 1934. The Habitats of the Land Mollusca in Britain. J. Ecol. 22:1-38.

Cappucci, D.T. Jr. 1978. Nematodes in the Alimentary Canal of Terrestrial Slugs. Veliger 21:306-307. (Abstract).

Carmicheal, E.B., T.D. Rivers. 1932. The Effect of Dehydration Upon the Hatchability of Limax flavus Eggs. Ecology 13:375-380.

Carrick, Robert. 1942. The Grey Field Slug Agriolimax agrestis L., and its Environment. Ann. Appl. Biol. 29:43-55.

Cates, Rex G. 1975. The Interface Between Slugs and Wild Ginger: Some Evolutionary Aspects. Ecology 56:391-400.

Chichester, L.F. and L.L. Getz. 1969. The Zoogeography and Ecology of Arionid and Limacid Slugs Introduced into Northeastern North America. Malacologia 7:313-346.

Cragg, J.B. and M.H. Vincent. 1952. The Action of Metaldehyde on the Slug Agriolimax reticulatus. Ann. Appl. Biol. 39:392-406.

Crawford-Sidebotham, T.J. 1972. The Influence of Weather Upon the Activity of Slugs. Oecologia 9:141-154.

Crowell, H.H. 1967. Slug and Snail Control with Experimental Poison Baits. J. Econ. Ent. 60:1048-1050.

Dainton, B.H. 1954. The Activity of Slugs. I. The Induction of Activity by Changing Temperatures. T. Exp. Biol. 31:165-187.

Dirzo, Rudolfo. 1980. Experimental Studies on Slug-Plant Interactions. I. The Acceptability of Thirty Plant Species to the Slug Agriolimax caruanae. J. of Ecol. 68:981-998.

Dirzo, Rudolfo and J.L. Harper. 1980. Experimental Studies on Slug-Plant Interactions. II. The Effect of Grazing by Slugs on High Density Monocultures of Capsell bursa-pastoris and Poa annua. J. of Ecol. 68:999-1011.

Duthoit, C.M.G. 1961. Assessing the Activity of the Field Slug in Cereals. Pl. Pathol. 10:165.

Duthoit, C.M.G. 1964. Slugs and Food Preferences. Pl. Pathol. 13:73-78.

Feeney, P.P. 1970. Seasonal Changes in Oak Leaf Tannins and Nutrients as a Cause of Spring Feeding by Winter Moth Caterpillars. Ecol. 51:565-581.

Fox, Lee and B.J. Landis. 1973. Notes on the Predaceous Habits of the Grey Field Slug, Deroceras laeve. Environmental Entomol. 2:306-307.

Geckler, R.P. 1971. Laboratory Studies of Predation on Snails by Larvae of the Marsh Fly, Sepedon tenuicornis. Can. Entomol. 103:638-649.

Getz, L.L. 1961. An Attempt to Infect Molluscs with Acanthamoeba spp. J. Parasitol. 47:842.

Getzin, L.W. 1965. Control of the Grey Garden Slug with Bait Formulations of a Carbamate Molluscicide. J. Econ. Entomol. 58:158-159.

Gould, H.J. 1961. Observations on Slug Damage to Winter Wheat in East Anglia, 1957-1959. Plant Path. 10:142-146.

Gould, H.J. 1962. Tests with Seed Dressings to Control Grain Hollowing of Winter Wheat by Slugs. Plant Path. 11:147-152.

Grime, G.P. and G.M. Blythe. 1969. An Investigation of the Relationship Between Snails and Vegetation at the Winnats Pass. J. of Ecol. 57-45-66.

Hand, Cadet and Marietta Voge. 1951. Agriolimax columbianus, an Intermediate Host for Brachyleamus virginiana (Dickerson) (Trematoda: Digenea) in California. J. Parasitol. 38:57.

Howe, G.J. and G.M. Findlay. 1972. Distribution of Terrestrial Slug Species in Manitoba. The Manitoba Entomol. 6:46-48.

Howes, N.H. and G.P. Welles. 1934. The Water Relations in Snails and Slugs. II. Weight Rhythm in Arion ater L. and Limax flavus L. J. Exp. Biol. 11:327-343.

Howitt, A.J. 1961. Chemical Control of Slugs in Orchard Grass-Ladino White Clover Pastures in the Pacific Northwest. J. Econ. Entomol. 54:778-781.

Howitt, A.J. and S.C. Cole. 1962. Chemical Control of Slugs Affecting Vegetables and Strawberries in the Pacific Northwest. J. Econ. Entomol. 55:320-325.

Hunter, P.J. 1966. The Distribution and Abundance of Slugs on an Arable Plot in Northumberland. J. Anim. Ecol. 35:543-557.

Hunter, P.J. 1967a. The Effect of Cultivations on Slugs of Arable Ground. Plant Path. 16:153.

Hunter, P.J. 1967b. A Note on Nematodes in the Alimentary Canal of Slugs. Proc. Malac. Soc. Lond. 37:385.

Hunter, P.J. 1968. Studies on Slugs of Arable Ground. II. Life Cycles. Malacologia 6:379-389.

Hunter, P.J. and D.L. Johnston. 1970. Screening Carbamates for Toxicity Against Slugs. J. Econ. Entomol. 63:305-306.

Hunter, P.J. and N.W. Runham. 1970. Some Aspects of Recent Research on Slugs. Proc. Malac. Soc. Lond. 39:235-238.

Hunter, P.J. and B.V. Symonds. 1970. The Distribution of Bait Pellets for Slug Control. Annals of Appl. Biol. 65:1-7.

Hunter, P.J. and B.V. Symonds. 1971. The Leap-frogging Slug. Nature 229:349.

Jennings, T.J. and P.J. Barkham. 1975. Food of Slugs in Mixed Deciduous Woodlands. Oikos 26:211-221.

Jennings, T.J. and J.P. Barkham. 1976. Quantitative Study of Feeding in Woodland by the Slug Arion ater. Oikos 27:168-173.

Judge, F.D. 1969. Preliminary Screening of Candidate Molluscicides. J. Econ. Entomol. 62:1393-1397.

Kolbezen, M.J. and F.J. Abu-El-Haj. 1972. Fumigation with Methyl Bromide II. Equipment and Methods for Sampling and Analyzing Deep Field Soil Atmospheres. Pesticide Sci. 3:73-80.

Lange, W.H. Jr. and G.F. MacLeod. 1941. Metaldehyde and Calcium Arsenate in Slug and Snail Baits. J. Econ. Entomol. 34:321.

Lange, W.H. Jr. and R.H. Sciaroni. 1953. Metaldehyde Dusts for Control of Slugs Affecting Brussel Sprouts in Central California. J. Econ. Entomol. 45:896.

Lewis, R.D. 1969. Studies on the Locomotor Activity of the Slug Arion ater (Linnaeus). Malacologia 7:307-312.

Lewis, T. 1980. Faunal Changes and Potential Pests Associated with Direct Drilling. Bull. Organ. Eur. Mediterr. Prot. Plant 10:187-194.

Lindquist, R.K. and H.R. Krueger. 1976. Slugs: A Tough Problem for Home Gardeners. Ohio Farm Report, March-April: 24-27.

Mellanby, K. 1961. Slugs at Low Temperatures. Nature 189:944.

Miles, H.W., J. Wood and I. Thomas. 1931. On the Ecology and Control of Slugs. Ann. Appl. Biol. 18:370-400.

Morton, B.S. 1970. The Tidal Rhythm and Rhythm of Feeding and Digestion in Cardium edule. J. Mar. Biol. Assoc. U.K. 50:499-512.

Morton, B.S. 1979. The Diurnal Rhythm and the Cycle of Feeding and Digestion in the Slug Deroceras caruanae. J. Zool. (Lond.) 187:135-152.

Pallant, D. 1969. The Food of the Gray Field Slug (Agriolimax reticulatus) in Woodlands. J. Anim. Ecol. 38:391-398.

Pallant, D. 1970. A Quantitative Study of Feeding in Woodland by the Grey Field Slug (Agriolimax reticulatus Muller). Proc. Malacol. Soc. Lond. 39:83-87.

Palti, J. 1981. Cultural Practices and Infectious Crop Diseases. Springer - Verlag, New York.

Peech, M., L.T. Alexander, L.A. Dean and J.F. Reed. 1947. Methods of Soil Analysis for Soil-Fertility Investigations. U.S.D.R. Circ. 757.

Platt, Thomas R. 1980. Observations on the Terrestrial Gastropods in the Vicinity of Jasper, Alberta (Canada). Nautilus 94:18-21.

Rayner, J.M. 1975. Experiments on the Control of Slugs in Potatoes by Means of Molluscicidal Baits. Plant Path. 24:167-171.

Rayner, J.M., A.M. Brock, N. French, H.J. Gould and S. Lewis. 1978. Further Experiments on the Control of Slugs in Potatoes by Means of Molluscicidal Baits. Plant Path. 27:186-193.

Reynolds, B.D. 1936. Colpoda steini, a Facultative Parasite of the Land Slug Agriolimax agreste. J. Parasitol. 22:48.

Reynolds, B.D. 1938. Developmental Stages of Panopistus pricei Sinitsin in Agriolimax agreste. Parasitol. 30:320.

Richter, Klaus, O. 1976. A Method for Individually Marking Slugs. J. Moll. Stud. 42:146-151.

Richter, Klaus, O. 1979. Evolutionary Aspects of Mycophagy in Agriolimax comumbianus and Other Slugs, Proc. of the VII Intern. Soil Zool. Colloq., Syracruse, New York Jul 29-Aug 3 1979.

Rollo, C.D. 1974. Ecology of the Slugs Deroceras reticulatus, D. laeve and Arion fasciatus in Ontario Corn Fields. M.Sc. Thesis, Univ. of Guelph. 173 pp.

Rollo, C.D. and C.R. Ellis. 1974. Sampling Methods for the Slugs Deroceras reticulatus (Muller), and Arion fasciatus Nilsson in Ontario Corn Fields. Proc. Ent. Soc. Ont. 185:89-95.

Rose, J.H. 1960. The Field Slug Agriolimax reticulatus as a Vector of the Lungworm Cystocaulus ocreatus. Nature 185:180.

Runham, N.W. and P.J. Hunter. 1970. Terrestrial Slugs, Hutchinson and Co. Ltd. Publishers, London. 185 pp.

Ruppel, R.F. 1959. Effectiveness of Sevin Against the Gray Garden Slug. J. Econ. Entomol. 52:360.

Skaren, Uolevi. 1978. Feeding Behaviour, Coprophagy and Passage of Foodstuffs in a Captive Least Shrew. Acta Theriol. 23:131-140.

South, A. 1964. Estimation of Slug Populations. Ann. Appl. Biol. 53:251-258.

South, A. 1965. Biology and Ecology of Agriolimax reticulatus (Muller) and Other Slugs: Spatial Distribution. J. Anim. Ecol. 34:403-417.

Stephenson, J.W. 1967. The Distribution of Slugs in a Potato Crop. J. Appl. Ecol. 4:129-135.

Stephenson, J.W. 1968. A Review of the Biology and Ecology of Slugs of Agricultural Importance. Proc. Malac. Soc. Lond. 38:169-178.

Stephenson, J.W. 1972. Gelatin as a Carrier for S^2-Cyanoethyl N-((methylcarbamoyl) oxy) thioacetimidate, An Experimental Molluscicide. Pesticide Sci. 3:81-87.

Stephenson, J.W. 1975a. Laboratory Observations on the Effects of Soil Compaction on Slug Damage to Winter Wheat. Plant Path. 24:9-11.

Stephenson, J.W. 1975b. Laboratory Observations on the Distribution of Agriolimax reticulatus (Mull.) in Different Aggregate Fractions of Garden Loam. Plant Path. 24:12-15.

Stephenson, J.W. and L.V. Knutson. 1966. A 'Resume' of Recent Studies of Invertebrates Associated with Slugs. J. Econ. Entomol. 59:356-360.

Symonds, B.V. 1975. Evaluation of Potential Molluscicides for the Control of the Field Slug Agriolimax reticulatus (Mull). Plant Path. 24:1-9.

Thomas, D.C. 1944. Proceedings of the Association of Applied Biologists. II. Field Sampling for Slugs. Ann. Appl. Biol. 31:163-164.

Thomas, D.C. 1948. The Use of Metaldehyde Against Slugs. Ann. Appl. Biol. 35:207-227.

Webley, D. 1962. Experiments with Slug Baits in South Wales. Ann. Appl. Biol. 50:129-136.

Webley, D. 1963. Experiments with Slug Baits in 1959. Plant Path. 12:19-20.

Webley, D. 1964. Slug Activity in Relation to Weather. Ann. Appl. Biol. 53:407-414.

Webley, D. 1965. Aspects of Trapping Slugs with Metaldehyde and Bran. Ann. Appl. Biol. 56:37-45.

Webley, D. 1966. Waterproofing of Metaldehyde on Bran Baits for Slug Control. Nature 212:320-321.

Wright, A.A. and R. Williams. 1980. The Effect of Molluscicides on the Consumption of Bait by Slugs. J. Moll. Stud. 46:265-281.

APPENDIX 1

Preparation of Modified Metaldehyde Bait Formulation

The mixture consists of commercially available Metaldehyde plus molasses and wild strawberry extract in quantities as recommended below.

39.2 kilograms Metaldehyde bait (2.75%) /hectare
35 pounds/acre

281 liters molasses /hectare
25 gallons/ acre

617 ml wild strawberry extract /hectare
8.8 ounces /acre.

The strawberry extract should be mixed with the molasses. The molasses-extract mixture should then be poured as a 1-1½ inch strip in the centre of a gap between rows. Field testing has shown that one strip of molasses-extract mixture down the length of every seventh gap is effective in reducing slug densities in strawberry fields (based on two field tests). The molasses strips should be kept approximately 5m inside the field edges so that slugs are not attracted into fields from areas outside the treated field. Lightly cover the molasses strips with enough Metaldehyde bait so that they can no longer be seen (while maintaining the proper application rate of Metaldehyde).

This bait formulation will go mouldy if applied to wet areas, or if applied to fields just before rainfall. Application is most effective when made on the morning following rainfall (when slug activity is highest).

APPENDIX 2. Slug Questionnaire

University of Manitoba
Department of Entomology

Slug Control Questionnaire

Name: _____

Address: _____

_____

Phone: _____

Acreage: _____

Have you had any slug problems? _____

If yes, was there fruit damage? _____

Were there customer complaints? _____

If fruit damage, percentage of fruit damage. _____

number of acres damaged. _____

age of fields damaged. _____

year damage occurred. _____

If customer complaints, how many? _____

age of field complaints from? _____

weather at time of picking? _____

year of complaints. _____

Have you ever used slug control chemicals? _____

If so, what? _____

when? (year and season) _____

Was control effective? _____

What brand? _____

What formulation? _____

(i.e. spray, pellets, bran bait)

What concentration? _____
