This field guide, also produced as Shona and Ndebele language versions, aims to help extension workers and agricultural trainers to recognise the most important groups of natural enemies of arthropod pests of vegetables ('farmers' friends').

It also provides information about the conservation and augmentation of these groups, from a variety of cultural practices to the selective use of pesticides. Multi-lingual posters intended for farmers have been produced to compliment the field guides.

Collaborating Organisations

Imperial College of Science, Technology & Medicine, UK

Plant Protection Research Institute, Zimbabwe

African Farmers for Research & Training, Zimbabwe

Natural Resources Institute, UK

Kenya Agricultural Research Institute, Kenya

CABI Bioscience, Africa Regional Centre and UK Centre

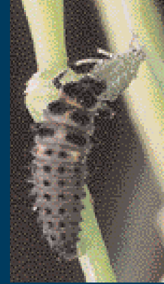
Participatory Ecological Land Use Management Association, Zimbabwe

University of Zimbabwe

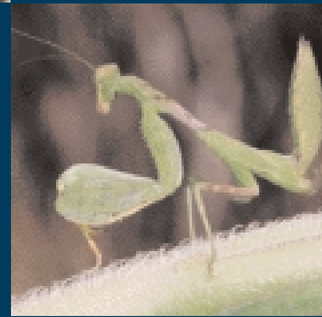
ISBN: 0-9540132-0-4

Farmers' Friends

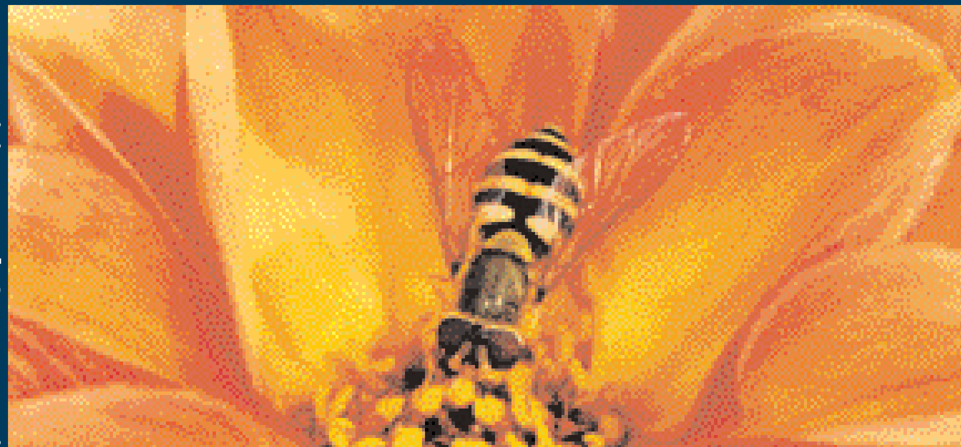
Recognition and Conservation



Farmers' Friends



Recognition and conservation of natural enemies of vegetable pests in Zimbabwe



A field guide for extension workers and trainers

A collaborative project

FARMERS' FRIENDS

Recognition and conservation of natural enemies of vegetable pests

A field guide for extension staff and trainers in Zimbabwe

This Field Guide is dedicated to the memory of Jason Ong'aro, a researcher, co-editor and team member, who passed away during the course of this project.

Published by:

Department of Biology, Imperial College of Science, Technology & Medicine,
University of London SW7 2AZ

ISBN 0-9540132-0-4

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This publication is an output from a research project funded by the Department for International Development of the United Kingdom (DFID project code R7587, Crop Protection Programme). However, the Department for International Development can accept no responsibility for any information provided or views expressed.

For information about the DFID Crop Protection Programme, visit www.nrinternational.co.uk (see also Natural Resources International, *Contacts*, p. 109).

Shona and Ndebele language versions of this guide and posters (Shona, Ndebele and English language versions) have also been produced as part of this project.

Photographs by R.H.J. Verkerk unless otherwise stated.

Design by deepblue,
First Floor, 91a Rivington Street, London EC2A 3AY.

Printing by Fontline, Harare.

Contents

I are indebted to the vegetable farmers, trainers, extension personnel and scientists in Zimbabwe and Kenya whose input and enthusiastic cooperation made the compilation of this natural enemy field guide, associated posters and training programme possible.

In Zimbabwe, we would like to extend particular thanks to the staff from the Plant Protection Research Institute (Department of Research & Specialist Services) and the non-governmental organisation African Farmers' Organic Research and Training (AfFOResT) for their dedication to the project and translation of the text to local languages (Shona and Ndebele). We are also grateful to AGRITEX, the IPPM Working Group (Food and Agricultural Organization of the United Nations), Peter Wilkinson (Xylocopa Systems, Harare) and the PELUM Association (Harare) who provided valuable input during the production of the materials.

Part of the research and development for this guide and its associated project was carried out in Kenya (1998-1999), the work being made possible by the invaluable contributions of our colleagues from the Kenya Agricultural Research Institute (KARI) and CABI Bioscience (Africa Regional Centre).

Dr Denis Wright (Imperial College, University of London) was responsible for the overall management of the project, and Hans Dobson (Natural Resources Institute, UK) provided essential support and input throughout. Thanks are also due to Tony Little (CABI Bioscience, UK Centre) who helped collate some of the data on side effects of pesticides on natural enemies (Part 3.2). Catherine Pinch (Imperial College, University of London) and Max Barclay (Natural History Museum, London) provided useful input to the section on carabid beetles. Tony Russell-Smith (Natural Resources Institute, UK) kindly identified the spiders shown in the guide. Further thanks are offered to Graham Matthews (Imperial College, University of London) and Hans Dobson for their useful suggestions on selective pesticide application in Part 3.

I would like to thank Andrew Jones and Mick Tomlinson from deepblue (London) for their work on the design and layout of the guide and associated posters.

Hans Dobson, Denis Wright and Misha Verkerk proof-read the manuscript and I am very grateful for their useful suggestions. I offer heartfelt thanks to my family, especially Ellie, Misha, Greta and Hannah, for all their support and encouragement throughout the course of this project.

Finally, I am grateful to the Department for International Development (DFID) of the United Kingdom (Crop Protection Programme) for providing financial support and advice.

Robert Verkerk, Ascot, January 2001

Introducing this field guide

This field guide and its associated posters and 'natural enemy flip-cards' (available in English, Shona and Ndebele languages) are the result of collaboration between Imperial College (University of London), Plant Protection Research Institute (Department of Research & Specialist Services, Harare), African Farmers' Organic Research and Training (AfFOResT, Harare), National Agricultural Research Laboratories of the Kenya Agricultural Research Institute (NARL/KARI, Nairobi), CABI Bioscience (Africa Regional Centre, Nairobi, and UK Centre) and Natural Resources Institute (University of Greenwich, Chatham, UK).

The purpose of the guide and its associated outputs is to help extension staff and farmers recognise and conserve important groups of natural enemies by raising awareness of the presence, abundance, diversity and benefits of natural enemies on smallholder farms in Zimbabwe. Nearly all of the photographs within this guide were taken in the field during surveys in Zimbabwe and Kenya in October 1998, and in Zimbabwe in May and October 2000.

During the October 1998 field surveys in Zimbabwe and Kenya, interviews with small-scale farmers were also undertaken. The interviews showed generally that little information on natural enemies was available at the farm-level. However, it was also clear that farmers were very interested and enthusiastic about gaining more knowledge to help them recognise natural enemies and distinguish them from pests and other plant-feeding insects. Farmers were particularly keen to learn about conservation methods that could be used to encourage natural enemies on farms.

Learning about ways of improving the effectiveness of natural enemies on small-scale, tropical, vegetable production systems is likely to become increasingly important to many farmers as the cost of inputs such as pesticides and fertilisers continues to increase. In addition, many farmers are becoming more concerned over the possible human health and environmental risks of pesticides. There is also a growing worldwide interest in 'organic' production where the use of synthetic pesticides (and fertilisers) is not permitted.

The English language version of this guide is divided into three parts. **Part 1** provides a general background to natural enemies and biological control, while **Part 2**, the main body of the guide, considers in turn each of the major groups of natural enemies and important methods for their conservation. **Part 3** is subdivided into three sub-sections, **Part 3.1** being an introduction to the evaluation of natural enemy effectiveness, emphasising common pitfalls to frequently used methods. **Part 3.2** contains information about the side effects of commonly used pesticides on natural enemies, and it includes a table and cross references to websites aimed to help readers assess the relative hazards of different products to important natural enemies. The final part, **Part 3.3**, presents various approaches to selective application of pesticides that can be used to minimise harm to natural enemies.

The Shona and Ndebele versions are essentially similar to the English language version, except for Part 3. In these versions, Part 3.1 has been omitted, and the remaining two sub-parts are reduced slightly in scope and length.

Introduction

1

Feeding levels in natural and agricultural systems

Natural systems, such as forests and savannahs, support a wide range of plants and animals. The plants provide food for plant-eating animals such as antelopes and many insects, while the plant-eating animals are consumed by a wide range of carnivorous animals from lions to predatory and parasitic insects. Even carnivorous animals generally have natural enemies. These four feeding levels of life (see Table 1) exist in all stable natural and agricultural habitats. When a particular type of plant-eating animal consumes too much of a crop or a commodity that we as humans value, we often call it a *pest*, while those animals which feed on plant-eating animals are commonly referred to as *natural enemies* and should be considered *farmers' friends.*

In most natural systems, the numbers of animals from these different groups are kept in check by complicated interactions between the organisms present. This is why the leaves of most trees, shrubs and grasses in most natural systems remain more or less intact most of the time. In stable agricultural systems this is also the case, with plant-eating organisms causing only a small amount of damage to crops. The presence of some of these plant-eating organisms (so-called pest species) is often important to make sure that there is a food source available to allow establishment of natural enemies that in turn will help to prevent the development of pest outbreaks.

Frequently in agricultural systems, and very occasionally in natural ecosystems, the natural balances between these four feeding levels is upset and pest numbers increase rapidly resulting in pest outbreaks. Outbreaks are most common in intensive agricultural systems. Three important reasons for this are considered below.

Table 1: *Four feeding levels common to natural and agricultural habitats*

FEEDING LEVEL	Type of Organism	Example from a NATURAL habitat	Example 1 from an AGRICULTURAL habitat	Example 2 from an AGRICULTURAL habitat
1	Plant	Grasses	Tomato (crop)	Cabbage (crop)
2	Plant-eating animal	Antelope	Caterpillar (pest)	Aphid (pest)
3	Predatory or parasitic animal	Lion	Parasitic wasp (natural enemy)	Hover fly larva (natural enemy)
4	Predatory or parasitic animal	Tick	Hyperparasitoid wasp (natural enemy of natural enemy)	Parasitic wasp (natural enemy of natural enemy)

Some problems caused by intensive agriculture

Poorly adapted crop cultivars

Many plant cultivars grown as food crops in tropical countries have originated from Europe or other temperate latitudes. They may have been bred to enhance particular qualities such as size, colour or water content. They often have little natural resistance to pests and diseases and have effectively been 'designed' for high input agriculture that is dependent on high fertiliser and pesticide inputs. The resistance that is expressed by a given crop cultivar in temperate regions has been shown to break down sometimes in the tropics (Picture 1).

1. A cabbage variety (Minicole F_1) which has partial resistance to cabbage aphid under European conditions, but has been shown to be highly susceptible to aphid pests when grown in Kenya

Monocultures

Intensive agriculture often involves the planting of large tracts of land to a single crop type, this being referred to as a *monoculture* (Picture 2). This makes it easier for pest species to find the crop and once found, the pest can develop very quickly as its food source is plentiful and closely spaced. Monocultures usually contain few suitable refuges or adult food sources for natural enemies (e.g., nectar and pollen from flowers). If they are heavily and regularly sprayed with insecticides (Picture 2), there is also a high chance that resistance to the insecticide will develop (see below).

2. A broad bean monoculture, showing serious damage by leaf miner fly larvae despite frequent spraying with insecticides

Use of pesticides

There is a large variety of pesticides that can be used against insect, mite and nematode pests, plant diseases and weeds. However, in practice, it is the insecticides and acaricides that are the most harmful to natural enemies. This is because most natural enemies, like the targets of insecticides and acaricides, are either insects or closely related groups such as predatory mites or spiders. All these groups are *arthropods*. That is, they have jointed appendages and external skeletons.

Some of the general problems that may arise from indiscriminate use of pesticides (particularly broad-spectrum insecticides or acaricides) are:

a) Death or harm to natural enemies

Pesticides may affect the physiology (e.g., egg-laying rate, developmental period) or behaviour (e.g., host location, walking speed) of natural enemies, and can cause lethal or sublethal effects.

3. Adult hover fly dead on leaf after contacting a recently sprayed crop

Natural enemies are generally more sensitive to pesticides than pests. This is partly because they spend more time searching for potential hosts and prey, so risking contact with residues. They are often also smaller and more physiologically sensitive, and many important groups such as parasitoid wasps preen themselves regularly so consuming residues they may have picked up on their legs and antennae. If natural enemies are harmed or killed (Picture 3), pests multiply much more quickly, causing *pest resurgence*.

b) Pests may develop resistance or tolerance to pesticides

Pesticide resistance or *tolerance* often occurs when farmers spray more and more frequently, often with increasing doses of pesticide, with little impact on the pest populations (Picture 4). This is because the surviving populations contain a specific version of a gene (an allele) that allows them to be less sensitive to the pesticide in some way (e.g., detoxification, altered target site). Increased frequency of spraying with broad spectrum pesticides, which often accompanies resistance or tolerance, also increases the harm to natural enemies.

4. *"I've been spraying once a week for the last month and the crop is being destroyed by pests. What is going on?"*

c) Pesticides may be harmful to humans and the environment

Exposure of operators is very common during application. Most pesticides are readily absorbed through the skin and the eyes, and droplets may be inhaled. Harmful levels of pesticides can also be consumed on produce if pre-harvest intervals are not followed carefully. Pesticides may move in groundwater and contaminate drinking water supplies. They may contaminate water following the inappropriate disposal of pesticide concentrate containers (Picture 5). Pesticides may harm pollinators and a wide range of other beneficial or non-target organisms.

Introduction

WHAT ARE NATURAL CONTROLS?

Nature provides two basic lines of defence for plants against plant-eating organisms (potential pests).

These are:

5. Pesticides can contaminate water supplies

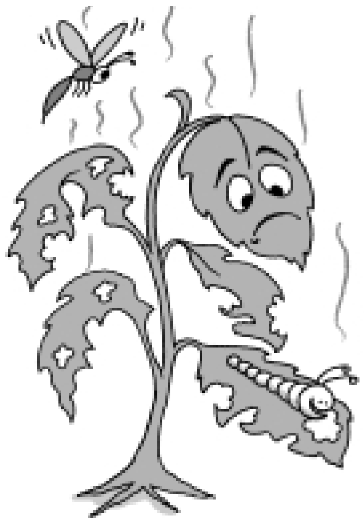
■ **Plant defences**

Plants possess a wide range of mechanisms that allow them to resist damage by most plant-eating organisms. They may contain chemicals that make them distasteful or poisonous to certain organisms (Picture 6), they may produce toxic secretions following attack, or they might have hairs on their leaves that make it difficult for potential plant-eaters to settle and feed. This sort of *plant resistance* may be *complete* (making it impossible for a plant-eater to develop successfully on the plant) or it may be *partial* (where a plant-eater can develop, but it does so more slowly or produces fewer offspring than on a susceptible plant). A degree of *partial plant resistance* is often very helpful in low input crop production systems, as long as this resistance does not interfere with the performance of natural enemies.

6. *"This plant tastes bad and is making me sick"*

■ **Defence via natural enemies**

Natural enemies provide a very important means of controlling the abundance of plant-eating organisms. Crop plants under attack by pests have been shown to 'cry for help' by releasing particular chemicals that are attractive to specific natural enemies (Picture 7).



7. A plant 'crying for help' after being attacked by caterpillars

In agricultural situations where crop losses need to be kept to a minimum, every effort should be made to ensure that these natural controls work as well as possible before consideration is given to more interventionist methods of pest control, such as the application of pesticides.

TYPES OF NATURAL ENEMY

Natural enemies of insect and mite pests can be divided into three main groups:

■ **Predators** (see Part 2, pages 26-63)

These are organisms that prey on and feed on other organisms. Each predator generally kills several prey during its lifetime. Immature and/or adult stages can be predatory. Some predators feed on a wide range of species (*generalists*), while others are more specialised in their choice of prey, feeding on only one or a few species (*specialists*).

Examples: ladybird beetles; ground beetles; mantids; dragonflies; predatory mites; predatory wasps; spiders.

■ **Parasitoids** (see Part 2, pages 64-77)

Parasitoids are organisms that during their immature (larval) stages feed on and eventually kill a single arthropod, and in their adult stage with very few exceptions are free-living. About 8.5% of insect species described to-date (i.e., approximately 85,000 species) are parasitoids. They are nearly all wasps or flies, but include a relatively small number of beetles and very occasionally other groups. The adults of most agriculturally important parasitoids species feed on sugary substances such as the nectar of flowers or aphid honeydew. The larvae may feed from within or outside the body of their host. Many species are regarded as *solitary* with only one parasitoid developing per host, or they may be *gregarious* with many larvae (sometimes hundreds) developing per host. Most parasitoids are highly or relatively specific (that is, are *specialists*), selecting only a single host species or narrow range of species as targets. Natural enemies including parasitoids are themselves also susceptible to attack by other parasitoids (and other natural enemies (see Table 1).

Examples: parasitoid wasps and flies

■ **Pathogens** (see Part 2, pages 78-82)

Pathogens are disease organisms. They can be important in controlling the growth of pest populations in agricultural systems. They include fungi, bacteria, viruses, nematode worms and microsporidia. Many pathogens tend to be found more commonly where pest populations are large or during rainy seasons.

Examples: *Metarhizium*, *Zoophthora*, *Entomophthora* (entomopathogenic fungi); GV (granulosis virus); NPV (nuclear polyhedrosis virus); *Bacillus thuringiensis* (bacterium); EPNs (entomopathogenic nematodes)

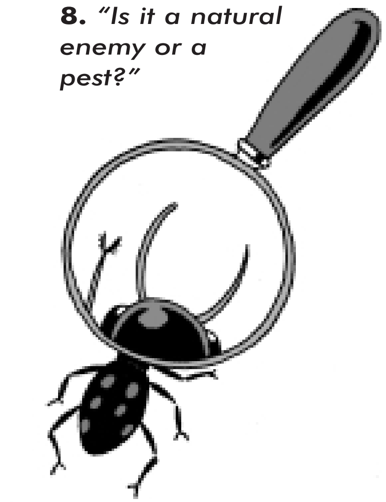
BIOLOGICAL CONTROL
Biological control refers to the process of pest management achieved through the use of living organisms, namely predators, parasitoids or pathogens. To be effective, cropping systems need to be designed and managed in such a way to enhance the function of natural enemies that immigrate naturally into and multiply within the crop. This approach to biological control is called *conservation* and it has particular relevance for smallholder farmers in the tropics. In some cases, where a particular natural enemy species or group of natural enemies is missing from a crop or a specific region, these can be introduced from other areas (*introduction*, *inoculation* or *augmentation*). In other cases, particular natural enemies can be reared in large numbers in special facilities and released into the crop at intervals (*inundation*).

FOUR STEPS FOR IMPROVING BIOLOGICAL CONTROL OF PESTS
This field guide is intended to help extension staff and field staff provide support to farmers so that biological control can be improved. In simple terms, four important steps are generally required.

STEP 1

■ **Find out which natural enemies are present** (see Part 2 of the guide)

In most cropping systems, natural enemies will either be present already or be close by and therefore do not need to be introduced. It is critical that pests and natural enemies on a crop can be recognised (Picture 8). This field guide aims to help trainers recognise the most important groups of natural enemies and in turn share this information with farmers. Farmers can be encouraged to set up 'insect zoos' where groups of suspected pests and natural enemies are kept together in ventilated jars or other small containers with a portion of the crop and are maintained until all the animals go through their complete development. This will allow the farmer to see who is eating who or what. It will also allow the effects of parasitism to be observed if it has occurred.

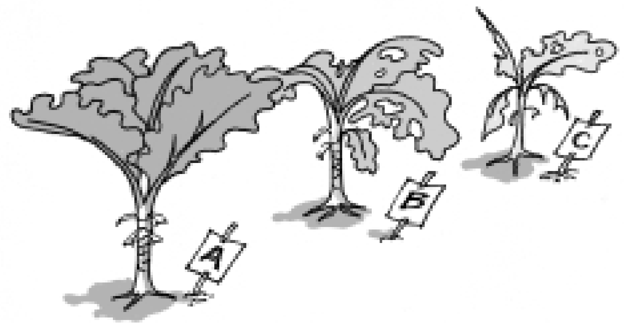


8. ***"Is it a natural enemy or a pest?"***

STEP 2

■ **Select the most appropriate crop cultivars**

It is important to choose crop cultivars that are not highly susceptible to pests (and diseases), as discussed on p. 12 (Picture 9). Information on the relative susceptibility of particular crops can often be obtained by talking to other farmers, relevant research institutes, extension staff or seed retailers. If data on cultivar tolerance or resistance are not available for a specific region, it may even be useful to run on-farm trials between different cultivars.

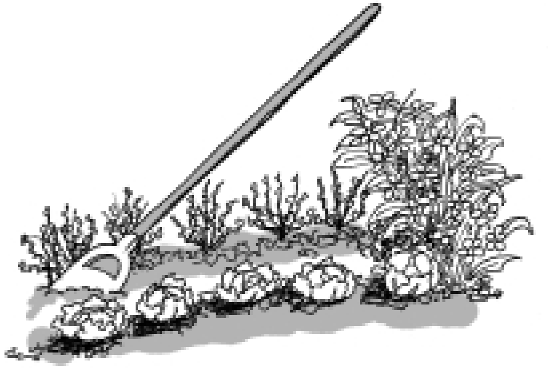


9. Kale variety A has been damaged much less by caterpillars than the other two varieties

STEP 3

■ **Conserve natural enemies by cultural means** (see Part 2 of the guide)

There are many things that can be done on individual farms to help encourage natural enemies and improve their effectiveness (Picture 10). Some relevant techniques and information are given in Part 2 of the guide under the subheading *Conservation*. Important methods of conservation include providing adult food sources such as flowering plants (e.g., fennel, thistles, coriander, Indian mustard and other flowering brassicas) within or close to the crop, mixed cropping or interplanting, providing live fences (trees, hedges) and shelters, using mulches, and providing water sources for important predators with aquatic life stages.



10. *"Can I grow some flowering plants to provide adult food sources and refuges for my natural enemies?"*

STEP 4

■ **Ensure that pest management practices are not disruptive to natural enemies** (see Part 3 of the guide)

The reader can use the information given in Part 3.2 of the guide as a starting point to help identify those pesticide products available in Zimbabwe that are likely to be less harmful to natural enemies (Picture 11). Part 3.3 offers some suggestions on ways of applying pesticides that minimise the risk of side effects on natural enemies. Obviously there are many more pesticides available than those given in Part 3.2, but the list given includes all the main pesticides used by the smallholder sector during surveys conducted between 1998 and 2000. Bear in mind that many pesticides have not been tested in a rigorous way against natural enemies and the side effects of most botanical pesticides have not been tested at all (see *Note on use of botanical pesticides*, pp. 101–102).

11. *"Is this spray going to kill my natural enemies?"*

Development and metamorphosis of insects and other arthropods

Most natural enemies that have a major influence on pest abundance are arthropods. Of these, the vast majority are insects (see Part 2). Insects can be broadly classified into two types according to the way they develop. The process of development is often referred to as metamorphosis. These types are:

■ **Simple metamorphosis**

These include those insects (and other arthropods) whose immature stages appear similar in basic form to the adults, varying mainly in size. Immature insects that undergo simple (or incomplete) metamorphosis are referred to as *nymphs*.

Adults arise following the last moult of the nymphs – there is no pupal stage. Insects that undergo simple metamorphosis are regarded as being more primitive than those that go through complete metamorphosis. If wings are present in the adult form, these develop externally, and may be seen in nymphs as wing buds. Other arthropods, such as mites and spiders, also undergo simple metamorphosis.

EGG → NYMPHS, several growth stages (instars) ► ADULT

Examples:

IMMATURE FORMS		ADULT FORMS
Insects		
Mantid nymph	→	Mantid
Pirate bug nymph	→	Pirate bug
Other arthropods		
Mite nymph	→	Mite
Spiderling or nymph	→	Spider

Complete metamorphosis

This group includes insects whose immature forms (larvae and pupae) appear very different, often live in different habitats and have different habits, compared with the adults of the same species. Examples include maggots, which turn into flies; grubs, which turn into beetles; and caterpillars, which turn into moths or butterflies. The earlier immature stages (instars) of these insects are called *larvae* (singular = *larva*) and their principle function is feeding. If wings are present in adults of a given species, these develop internally. Each larva sheds its skin (moults) at intervals to allow growth, and then undergoes pupation, from which the adult emerges. The pupa is inactive and does not feed, but during this stage, a very large amount of change occurs as seen by the differences between larvae and adults of the same species. All parasitoids and many predators undergo complete metamorphosis.

EGG → LARVAE, several growth stages (instars) ► PUPA ► ADULT

Examples:

LARVAL FORMS		ADULT FORMS
Caterpillar	→	Moth
Maggot	→	Fly
Aphid-lion	→	Lacewing
Wasp larva	→	Wasp
Ladybird beetle larva	→	Ladybird

Not all insects can readily be categorised as undergoing either simple or complete metamorphosis. Insects such as whiteflies, thrips and male scale insects are sometimes said to undergo *intermediate* metamorphosis, as they have gone well down the path towards the development of complete metamorphosis.

Important natural enemies of vegetable pests

2

Page

Predators

Parasitoids

Pathogens

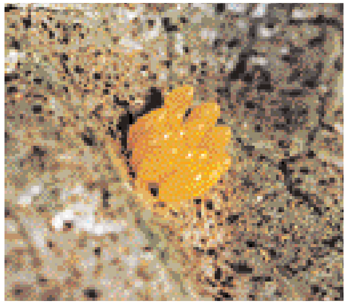
Type: Predator (larvae and adults)
Immatures: Different from adults (complete metamorphosis)
Main prey: Aphids, mites, thrips, small caterpillars, insect eggs
Crops: Vegetables, particularly brassicas, tomato, potato, beans
Group: Insect, beetle, ladybird beetle (Coleoptera: Coccinelidae)
Common names: Ladybird, 'Volkswagen', coccinelid

APPEARANCE

Eggs: Usually yellow to orange in colour, and laid in groups near aphid colonies (Picture 12).

Larvae: Crocodile-like, and can grow up to about 1 cm before pupation (Picture 13).

Pupae: Seen less often than the other stages, oval-shaped and spiny (Picture 14).



12. A typical cluster of ladybird beetle eggs (*Hippodamia variegata*)

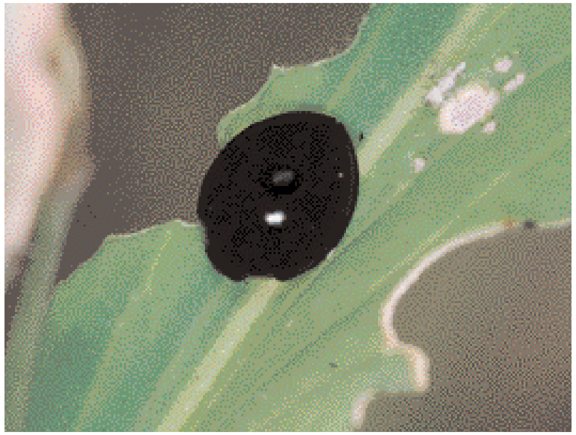
13. Ladybird beetle larva (*Hippodamia variegata*)

14. Ladybird beetle pupa (*Coccinella septempunctata*)

15. Adult ladybird beetle (*Hippodamia variegata*)

16. Adult ladybird beetle (*Cheilomenes* sp.)

Adults: Easy to recognise, dome-shaped bodies, wing covers may be red or orange with black markings (Pictures 15 and 16), or more or less completely brown or black (Picture 17). Adults may often be seen mating (Picture 18).



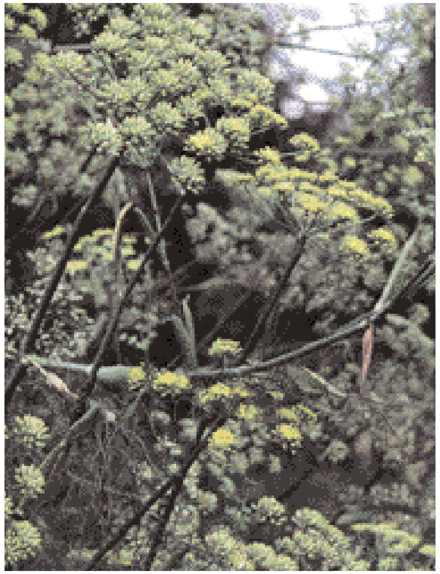
17. Adult ladybird beetle (*Exochomus* sp.)

18. Adult ladybird beetles mating (*Hippodamia variegata*)

PEST LADYBIRD BEETLES

Note that there are several species of plant-feeding ladybird beetles (notably, *Epilachna* and *Henosepilachna* spp.) that are often regarded as pests because of the damage they can cause to solanaceous crops (such as tomato and potato) and curcurbits (such as cucumber and marrow). These species are commonly referred to as *melon beetles*. Both the adults and the larvae eat leaves or damage fruits. The larvae are pale yellowish in colour and are covered in delicate spines. The adult wing cases are covered in fine hairs giving them a non-glossy or matt appearance (Picture 19).

19. Plant-feeding melon beetles (*Henosepilachna* sp.). Note fine hairs on wing cases



20. Fennel in a vegetable plot to help support natural enemies (such as ladybird beetles and hover flies) and pollinators (such as bees and hover flies)

EFFECTS ON PESTS

The larvae eat more pests (particularly aphids) than the adults. Usually, they are most abundant when aphid populations are large. A single ladybird beetle might consume 200-300 aphids over its lifetime of 1-3 months. Ladybird beetle larvae tend to be more active at night than by day so their activity is often underestimated.

CONSERVATION

- Grow strips or groups of non-crop flowering plants (sometimes thought of as 'weeds') that support non-pest aphid species within and around the crop, such as fennel (Picture 20), coriander (Picture 21), thistles (Picture 22) and milkweed. These provide food sources and refuge sites for beneficial insects like ladybird beetles and they allow populations of the natural enemies to build-up and suppress the development of pest aphids on the crop.
- Avoid spraying pesticides unless absolutely necessary. Should spraying be considered necessary, use a product and application method that is least harmful to key natural enemies (see Parts 3.2 and 3.3 of this guide).

21. Adult ladybird beetles and other beneficial insects are attracted to coriander (and many other flowering plants), which can be grown as strips between crop rows

22. Thistles growing among brassicas to help support aphid predators like ladybird beetles

Type: Predator (larvae and adults)
Immatures: Different from adults (complete metamorphosis)
Main prey: Eggs and immature insects in or on soil
Crops: Most, particularly on mixed crops and near natural vegetation and where mulches are present
Group: Insect, beetle, ground beetle (Coleoptera: Carabidae)
Common names: Ground beetle, carabid

APPEARANCE

Eggs: In soil and not often seen.

Larvae: In soil, not seen unless soil is disturbed; elongated, clearly segmented bodies, tapered towards the end, with 3 pairs of legs. Head and thorax are usually darker in colour than the bodies that vary in colour from whitish to brown. Mandibulate mouthparts ('jaws') can be seen readily (Picture 23).

23. Ground beetle larva (*Pterostichus* sp.)

Pupae: In soil and rarely seen.

Adults: Most species are mainly active at night (*nocturnal*), so are not often seen by day unless hiding places such as rocks, leaves on ground or mulches are disturbed. Adults vary in size (3 – 30 mm in length), are often brown or black in colour and

24. Ground beetle adult (*Chlaenius* sp.)

have distinctive ridges on their wing cases (Picture 24). Some species may have a metallic sheen to their wing cases (Picture 24), these often being more active by day (*diurnal*) than by night. The legs are well developed allowing them to run fast and catch prey. The antennae are long and thread-like (Picture 24). Most species of ground beetle are unable to fly.

EFFECTS ON PESTS

Adult and larval ground beetles are often important *generalist* predators (see p. 16) and are usually more abundant in diversified (mixed) crop environments, where mulches are present and soils are kept humid, or in crops close to natural areas that are themselves diverse (e.g., scrub or forest). As generalists, ground beetles eat a wide range of insects of all life stages (eggs through to adults) usually in or on the soil. Thus, they may be important in helping to control a broad range of pests including cutworms, beanflies and aphids. Although ground beetles do not climb up plants, they consume aphids that have fallen from plants and would otherwise climb back up the plant and resume feeding.

CONSERVATION

- It is important to develop refuges for soil-dwelling beneficial insects like carabid beetles. For example, rocks, stones and logs close to cropping areas can provide useful harbourages for adult beetles.

25. Live fences around a vegetable cropping area

26. Mulch around crop plants (in this case, rape) provides an attractive environment for carabid beetles and other ground-dwelling predators

- Promote diversity in the cropping area, using crop and non-crop plants, including use of live fences (trees or hedges around or between crops) (Picture 25).
- Use mulches to provide harbourages and maintain soil humidity (Picture 26).
- Avoid spraying pesticides unless absolutely necessary. Should spraying be considered necessary, use a product and application method that is the least harmful to key natural enemies (see Parts 3.2 and 3.3 of this guide).

Type: Adults and larvae mainly predators; a few species are parasitoids
Immatures: Different from adults (complete metamorphosis). Free-ranging or parasitic larvae
Main Prey: Eggs, mites, aphids, scale insects, other small insects (including immatures, e.g., larvae and pupae)
Crops: Most, may be seen on plants or on soil
Group: Insect, beetle, rove beetle (Coleoptera: Staphylinidae)
Common names: Rove beetle, staphylinid

27. An adult, generalist rove (staphylinid) beetle (*Philonthus* sp.) searching for prey on a leaf

APPEARANCE

Eggs: Not often seen.

Larvae: These may be free-ranging, having distinctive segmented, and, relative to the adults, long, narrow bodies and well developed legs and mandibles ('jaws'), while some species are parasitic and feed within insect host pupae. Size is extremely variable.

Pupae: Not often seen.

Adults: May be earwig-like, but lack the well-developed 'pincers' at the end of the abdomen (although smaller appendages or *cerci* may be clearly visible). The distinctive short wing cases (Picture 27) of adults do not conceal the segments of the abdomen. The abdomen may be raised in

a threatening posture (like scorpions) when disturbed. Rove beetles are often reddish-brown, brown or black. The wing cases may be coloured differently from the rest of the body (Picture 27). They are very variable in size, ranging from about 1 mm to 20 mm in length. The smallest ones are difficult to identify with the naked eye but often become more obvious, owing to their increased abundance, during heavy red spider (tetranychid) mite infestations. During the surveys undertaken for the present work, one genus of very small staphylinid (*Oligata* sp., adult about 1mm in length) was found to be common and predatory on red spider mites in both Zimbabwe and Kenya.

EFFECTS ON PESTS

Some species of rove beetles, both as adults and larvae, are important *generalist* predators, and are usually more abundant in cropped areas that have a diverse range of vegetation or are close to natural areas that are themselves diverse (e.g., scrub or forest). These generalist species eat a wide range of insects of all life stages (eggs through to adults) in the soil or on foliage. They may be important in helping to control pests such as cutworms, beanflies, spider mites and scale insects, although more studies are needed to assess their importance more fully. Other species are parasitic; individual young larvae typically search the soil for suitable host cocoons (containing pupae of fly pests, for example), and they emerge from the host cocoon some time later as adults, having consumed the pupa.

Rove Beetles

CONSERVATION

- It is important to develop refuges for soil-dwelling rove beetles and other ground-dwelling predators like carabid beetles. This might be by promoting diversity (crop and non-crop plants) in and around crop plots, using mulches and leaving or importing stones, logs or other items that provide harbourage areas (see also *Conservation*, *Ground Beetles*, p. 31)

- Avoid spraying pesticides unless absolutely necessary. Should spraying be considered necessary, use a product and application method that is the least harmful to key natural enemies (see Parts 3.2 and 3.3 of this guide).

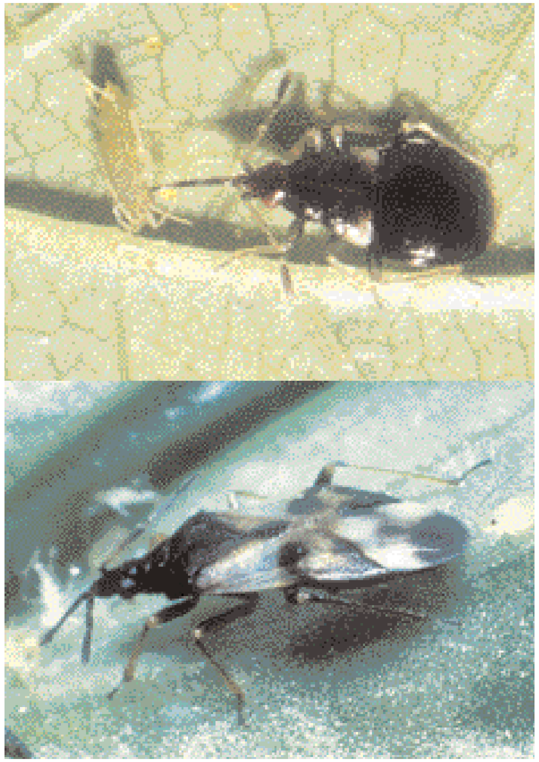
Pirate Bugs

Type: Predator (nymphs and adults)
Immatures: Similar to adult (incomplete metamorphosis)
Main prey: Thrips, mites, aphids, insect eggs, small caterpillars
Crops: Beans, potatoes, tomatoes, others crops (rarely brassicas)
Group: Insect, anthocorid (Hemiptera: Anthocoridae)
Common names: *Orius* bug, anthocorid

APPEARANCE

Eggs: Not often seen. Generally laid in plant tissue.
Nymphs: The nymphs are minute (less than 2 mm in length) and are tear-drop-shaped (similar to adults); often brown, black or orange in colour.

Adults: Pirate bugs are tiny insects (true bugs), the adults being no larger than 2-3 mm (Picture 28). The most common genus on vegetable (or flower) crops (*Orius* and *Anthocoris* spp.) have black and white patches on their wings. Adults move rapidly and can be



28. Above: Pirate bug nymph (*Anthocoris* sp.) **Below**: adult (Photographs courtesy of Horticulture Research International, UK) found hunting prey on leaves and flowers. They suck the body contents of their prey with their piercing/sucking mouthparts. Adults can feed on pollen and plant juices when prey are not available (Picture 28).

EFFECT ON PESTS

Pirate bugs can be very important predators of spider mites, thrips and aphids but will attack various stages (e.g., eggs, larvae and nymphs) of a wide range of other small arthropods. An anthocorid nymph may consume up to about 30 spider mites per day. They are particularly common on legume and solanaceous crops. There are many native anthocorid species in Africa and their relative effectiveness has yet to be adequately determined.

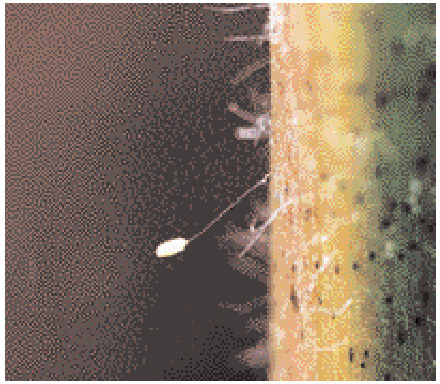
CONSERVATION

- Planting or maintaining flowering plants (including weeds) near the crop can help to sustain adult pirate bugs when their primary prey (mites, thrips and aphids) are not available.
- Avoid spraying pesticides unless absolutely necessary. Should spraying be considered necessary, use a product and application method that is the least harmful to key natural enemies (see Parts 3.2 and 3.3 of this guide).

Type: Predator (larvae only)
Immatures: Larvae ('ant-lions' or 'aphid-lions') different in form to adults (lacewings) (complete metamorphosis)
Main Prey: Aphids, other plant-feeding bugs, small caterpillars, insect eggs
Crops: Beans, potatoes, tomatoes, others crops (rarely brassicas)
Group: Insect, lacewing (Neuroptera: Chrysopidae)
Common names: Lacewing larva, aphid-lion, ant-lion, chrysopid

APPEARANCE

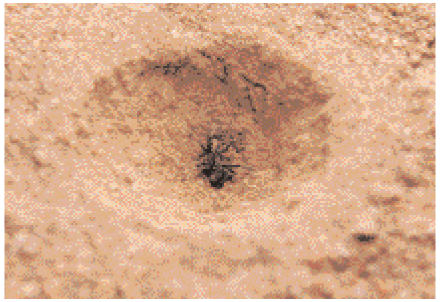
Eggs: Eggs are laid on characteristic fine silk stalks (Picture 29).



29. A lacewing egg supported on a silk stalk from a leaf

Larvae: Lacewing larvae are among the fiercest predators in the insect world! There are two main types of larvae, these being commonly known as 'aphid-lions' (Picture 30) and 'ant-lions' (Picture 31). Aphid-lions are usually brown and crocodile-like (Picture 30) and possess large pincer-type 'jaws'. They are very mobile and can be found in large numbers on some crops (particularly cotton and coffee). They can sometimes be found on vegetable crops. Ant-lions reside just beneath the soil surface in characteristic pits, with only their relatively huge pincer-like 'jaws' visible above the surface in the ground. Ants are attacked on falling in the pit (Picture 31).

30. A lacewing larva (aphid-lion type) (*Chrysoperla carnea*) searching for prey on a leaf



31. An ant-lion seizes an ant within its in-ground pit

32. A green lacewing adult (*Chrysoperla carnea*)

Pupae: These are whitish and spherical, but are not often seen on vegetable crops. They can sometimes be confused with spider egg sacs.

Adults: The adults, commonly known as 'lacewings', are often seen indoors, near lights in the evenings, or feeding from flowers. They can readily be distinguished by their finely veined, net-like wings, large eyes and rather fragile-looking bodies (Picture 32). The adults only feed on nectar from flowers and other sugary substances like aphid honeydew.

EFFECT ON PESTS

The effectiveness of lacewing larvae as predators on crops has been well documented on cotton and coffee where large numbers of larvae (*Chrysoperla* spp.) can 'clean up' a wide range of pests (e.g., aphids and eggs of moth pests). In vegetable crops, which often have a relatively short growing season, lacewing larvae appear not to be as common and their effectiveness has yet to be evaluated adequately. Lacewing larvae are available commercially in many countries for inoculation or augmentation, and are used widely on covered crops.

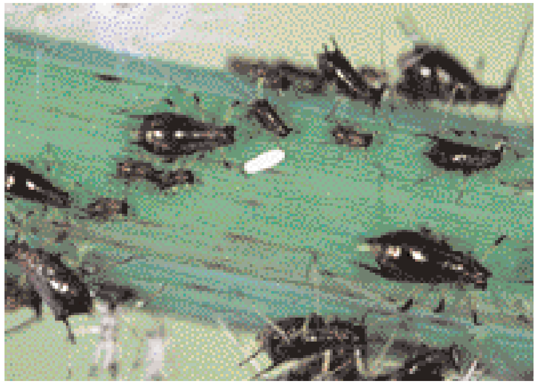
CONSERVATION

- Ensure flowers are present within or close to the crop to provide a food supply for adult lacewings.
- Populations can be maintained on non-pest species of aphids and other alternative hosts on non-crop (weedy) areas around field margins, between crop cycles.
- Avoid spraying pesticides unless absolutely necessary. Should spraying be considered necessary, use a product and application method that is the least harmful to key natural enemies (see Parts 3.2 and 3.3 of this guide).

Type: Predator (larvae only)
Immatures: Different from adults (complete metamorphosis)
Main Prey: Aphids
Crops: Most where aphids are common, especially brassicas
Group: Insect, fly, hover fly (Diptera: Syrphidae)
Common names: Hover fly larvae, hover fly maggots, syrphid larvae, aphidophagous syrphids, 'helicopter' flies

APPEARANCE

Eggs: The eggs, despite their small size, are often easy to see on the leaves of plants, particularly where aphids are common. They are white, cylindrical and about 1-2 mm long. Some species lay their eggs singly, close to aphid colonies (Picture 33), while others lay eggs randomly on plants in batches (of often 2-5 eggs) (Picture 34), even on plants that are more or less un-infested by aphids. The first larva to hatch from one of these egg batches can survive by eating the larvae within the unhatched eggs. Close examination of the egg will reveal whether the larvae have hatched.



33. A single hover fly egg adjacent to an aphid colony (non-pest species on thistle)

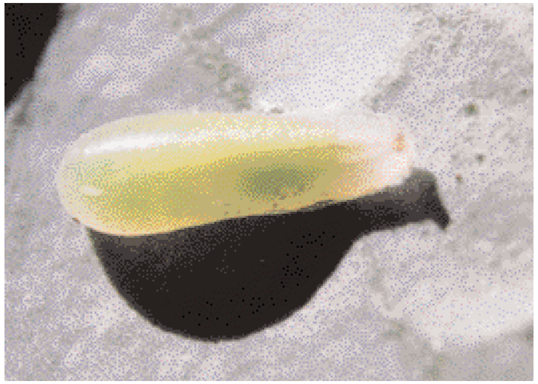
Larvae: The larvae are often mistaken for caterpillars but on close examination they are easily distinguished by their slug-like, tapered bodies and pointed heads (mouthparts retract into the

34. A batch of hover fly eggs (one egg has already hatched)

35. Last instar hover fly larva feeding on cabbage aphids

36. Last instar hover fly larva (13mm length) just before pupation. Note fat stripe along top of body

tip) (Pictures 35 and 36). This contrasts with the well-defined head, chewing mouthparts and prolegs of caterpillars. The bodies of hover fly larvae, like all fly larvae, also lack the *prolegs* (short, stumpy, appendages used for 'walking') of moth and butterfly caterpillars, and sawfly larvae. They may be translucent, green, or brown in colour, depending on species and prey consumed, and the bodies may be slimy-looking or



37. Hover fly pupae attached to leaf

38. Parasitised hover fly pupa

'bristly' in appearance. Some common species are greenish and marked with one to three whitish (fat-containing) stripes along the length of their bodies (Pictures 35 and 36). The first instar larvae are tiny (1-2 mm) and may not be visible if feeding within aphid colonies, while the last (third) instar (Picture 36) may grow up to 15 mm before pupating. However, overall size depends both on the species and the amount and quality of food that larvae are able to consume during their development.

Pupae: Pupae are pear-shaped and may be green (Pictures 37) or brown; they are either attached to leaves or develop in the soil. They can sometimes be attacked by parasitoid wasps (e.g., *Diplazon* sp.) that pupate within the hover fly pupa, turning the pupal case dark brown (Picture 38).

Adults: The adult flies owe their common name to the ability of the males (in particular) to hover, helicopter-like (Picture 39). They are often seen on or close to flowers that provide nectar and pollen as essential adult food sources, required for the production of viable eggs (Picture 40). The abdomen of adult aphid-eating hover flies is often striped yellow (Picture 39 and 41), amber (Picture 40) or grey on black and is always rather flat when viewed from the side (Picture 42). When at rest, adults often raise and lower their abdomens, to assist in 'breathing'. The adults are sometimes confused with wasps and bees, which belong to a different insect group (Order Hymenoptera). However, two common characteristics set all flies apart from the bees and wasps: flies have only one pair of wings, while wasps have two pairs; and flies have very short, stumpy antennae that originate from between large compound eyes (forming a 'V' shape) (Picture 41), while bees and wasps have longer antennae.

39. Adult hover fly 'hovering'

40. Hover fly adult (*Betasyrphus adligatus*) feeding on nectar and pollen within kale flower

41. Hover fly adult feeding from a flower. Note single pair of wings and short antennae typical of all adult flies

EFFECT ON PESTS

Hover fly larvae feed on a wide range of food sources, but the group which is most important to crop production are the aphid-eating (*aphidophagous*) hover fly larvae. In many situations hover fly larvae are the most important group of aphid predators. The larvae are particularly active at night and are extremely voracious – a single larva can eat well over 400 aphids in about the two weeks before it turns into a pupa! Most of this eating is done in the final (third) instar. Some species only become abundant when aphid numbers are

42. Hover fly adult female searching for egg-laying site on leaf

large and their beneficial effect may be regarded by some farmers as arriving too late. Others (e.g., *Melanostoma* and *Platycheirus* spp. that lay their eggs in characteristic batches) are well adapted to dealing with low densities of aphids. Both groups should be regarded as complementary from a pest management viewpoint. In addition, the adults, like bees, are very important pollinators.

CONSERVATION

- Flowering plants (such as fennel, thistles, milkweed, sunnhemp, flowering brassica crops or 'weeds') must be grown within or at least around crop plots to provide an adult food source (Picture 43). This increases immigration of adults to the plots, and because adult females must feed on pollen and nectar before they can lay viable eggs, it also prevents 'loss' of adults that emerge from pupae from within the crop. These flowering plants may also support aphids (often of non-pest species; Picture 33), which provide an on-going food supply to help maintain hover fly populations in the vicinity of the crop.
- Live fences can contain flowering plants (see above) and also reduce wind speed that might otherwise disturb the egg-laying activities of gravid female hover flies.
- Avoid spraying pesticides unless absolutely necessary. Should spraying be considered necessary, use a product and application method that is the least harmful to key natural enemies (see Parts 3.2 and 3.3 of this guide).

43. Abundance of flowering plants (including flowering kale pictured) provides plentiful food sources (nectar and pollen) for adult hover flies

Type: Predator
Immatures: Similar to adults (early stages with only three pairs of legs) (incomplete metamorphosis)
Main Prey: Plant-feeding mites (e.g., red spider mite), thrips, insect eggs
Crops: Crops susceptible to spider mites and thrips (e.g., tomatoes, egg plant, beans)
Group: Mite, phytoseiid (Acarina: Phytoseiidae)
Common names: Mites, phytoseiids

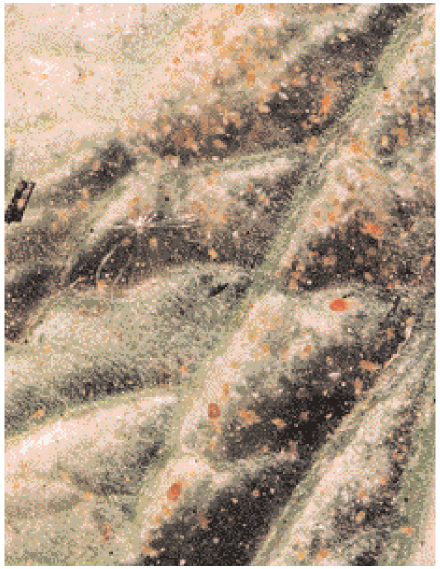
APPEARANCE

Eggs: Laid on plants, round or oval in shape, too small to be seen with the naked eye.

Nymphs: Similar but smaller than adults, the early instars with only three pairs of legs, compared with the four pairs of older nymphal (and adult) stages.

Adults: Mites are so small that they can barely be seen with the naked eye. They are not insects and are more closely related to spiders and are even closer relatives of ticks. As such, the adults have four pairs of legs and two body segments rather than the three of insects. They can often be found on plants where plant-feeding tetranychid mites (red spider mites) are present (Picture 44). They are about the same size (less than 1 mm in length) as spider mites but they move much more rapidly, have longer legs and more oval (pear-shaped) bodies (Picture 45). They may be red in colour, dark or even translucent in colour, depending on species and growth stage. Unlike spider mites, predatory mites can also move backwards. Red spider mites are often distinguished by the presence of two dark spots on the body, and characteristic webbing which they produce on infested plant parts. Predatory mites such as *Phytoseiulus*, as with the plant feeding spider mites are variable

44. Tomato leaves showing symptoms of heavy red spider mite infestation. Although predatory mites can often be found on such heavily damaged plants, they probably arrived too late from the farmer's viewpoint



45. Predatory mites (Phytoseiidae) among large colonies of red spider mites (*Tetranychus* sp.)

in colour, depending on their growth stage (Picture 45). Therefore, colour must not be used as the only way of separating these mite types!

EFFECT ON PESTS

Predatory mites (e.g., *Amblyseius*, *Phytoseiulus* spp.) can be one of the most effective natural enemies of spider mites. They can search out spider mite colonies effectively and can reach areas that are difficult to target with pesticides. The most serious spider mite problems are often found on crops that are sprayed regularly with acaricides or insecticides, pest resurgence being caused by the pesticide killing predatory mites and other key predators (e.g., predatory thrips, rove beetles) (see also pp. 13–14). If predatory mites are not found on a crop being damaged by spider mites, they can be introduced (*inoculated*). They can readily be reared for this purpose and in an increasing number of countries they are commercially available as biological control agents. However, most common species of predatory mites will starve and die if they run out of food, so they should only be introduced to crops where primary prey such as spider mites or thrips are already present. Some species (e.g., *Typhlodromus* spp.) are able to survive on pollen and fungal spores in the absence of prey. Predatory mites can also be very effective against thrips.

CONSERVATION

- Predatory mites may be sustained in culture on potted plants deliberately infested with spider mites, ready for introduction as and when spider mite or thrips problems arise. They are available commercially in many countries for inoculation purposes.

- There tends to be an association between the degree of hairiness of crop leaves and abundance of predatory mites. The reasons for this are not fully understood but cultivars with hairy leaves might help to reduce high temperatures, increase humidity, provide protection from predators and help to capture other food items such as pollen and fungal spores.

- Maintain irrigation of crops to avoid dusty conditions which often contribute to spider mite outbreaks as they are harmful to predatory mites.

- Predatory mites are common on trees, shrubs and other perennial plants, so the presence of these plants near vegetable crops will often enhance the immigration rate of predatory mites into seasonal crops such as vegetables.

- Avoid spraying pesticides unless absolutely necessary. Should spraying be considered necessary, use a product and application method that is the least harmful to key natural enemies (see Parts 3.2 and 3.3 of this guide).

Type: Predator
Immatures: Different from adults (complete metamorphosis)
Main prey: Caterpillars, sawfly larvae, heteropteran bugs
Crops: Any crops on which caterpillars, sawfly larvae, bugs and other prey are present
Group: Insect, wasp (Hymenoptera: Polistinae, Sphecidae and Vespidae)

APPEARANCE

Eggs: These are not seen as they are laid within wasp nests that may be in the ground, in or on trees and other vegetation, or even around buildings and other structures.

Larvae and pupae: Wasp larvae and pupae are also not seen unless nests are opened up.

Adults: These are large wasps, often 12–30 mm in length, generally with some form of striped marking on the abdomen (Pictures 46 and 47). They may be solitary or they may live in groups (*eusocial*). They include the paper (polistine) wasps (Hymenoptera: Polistinae; Picture 46) that form characteristic ‘papery’ and honeycombed nests

46. A paper wasp (*Polistes* sp.) collecting prey for its young

Predatory wasps

47. A sphecid wasp (*Sphex* sp.) in search of prey, heteropteran bugs in particular

often found suspended by a stalk from the leaves of trees or sides of buildings, and the sphecid wasps (Hymenoptera: Sphecidae; Picture 47) that can exceed 40 mm in length.

EFFECTS ON PESTS

On crops where caterpillars, sawfly larvae or other prey are abundant, predatory wasp adult females can be seen repeatedly on 'sorties' in search of prey. Prey are stung, paralysed and taken back to the nest to provide a food source for developing larvae. Nests may be in the ground, in natural cavities within trees, stumps, or they may be constructed of mud or 'paper'. Although the predatory habit of members of these wasp families is often highly conspicuous, their impact on pest populations has not been well studied and therefore is poorly understood.

CONSERVATION

- Avoid destroying nesting sites, unless the presence of the wasps poses a threat to humans, especially young children, who could be stung.

- Avoid spraying pesticides unless absolutely necessary. Should spraying be considered necessary, use a product and application method that is the least harmful to key natural enemies (see Parts 3.2 and 3.3 of this guide).

Mantids

Type: Predator (nymphs and adults)
Immatures: Similar to adult (incomplete metamorphosis)
Main prey: Moths, flies, crickets, small spiders
Crops: Various
Group: Insect, mantid (Order Mantodea)
Common names: Praying mantis, mantis

APPEARANCE

Eggs: Females lay these in a sac containing hardened foam.

Nymphs: Form and function similar to adults, although smaller in size.

Adults: Mantids have characteristic forelegs that assume a 'praying posture' when at rest, hence the common name, *praying mantis* (Picture 48). Mantids wait motionless, often well camouflaged within foliage until prey come within their grasp. Then they will suddenly pounce, grasping their prey with their powerful forelegs – and the feast begins! The adults are strong flyers so can disperse widely.

48. A praying mantis adult in resting pose on a sunflower plant close to a vegetable plot

EFFECTS ON PESTS

Although the praying mantis is one of the most well-known insect predators, the extent of its value as a natural enemy of agricultural pests has not been well evaluated. Since mantids are rather indiscriminate feeders, eating natural enemies (e.g., beneficial flies and spiders) as well as pest insects (e.g., some moths and flies), their beneficial role may in some situations be partially offset by negative impacts on other natural enemies. However, their presence is often an indication that indiscriminate use of broad spectrum insecticides or acaricides is not occurring.

CONSERVATION

- Avoid spraying pesticides unless absolutely necessary. Should spraying be considered necessary, use a product and application method that is the least harmful to key natural enemies (see Parts 3.2 and 3.3 of this guide).

Type: Predator
Immatures: Similar to adults (incomplete metamorphosis)
Main prey: Flies (e.g., leaf miners), moths, small caterpillars, mites, aphids
Crops: Most
Group: Spider (Arachnida: Araneae)

APPEARANCE

Eggs: Egg sacs of spiders are usually spherical in shape and covered in whitish-coloured silk. The eggs within the sac hatch to release several or sometimes even hundreds of tiny spider nymphs that are sometimes called *spiderlings*.

49. Webbing spider and sheet web (Family Linyphiidae)

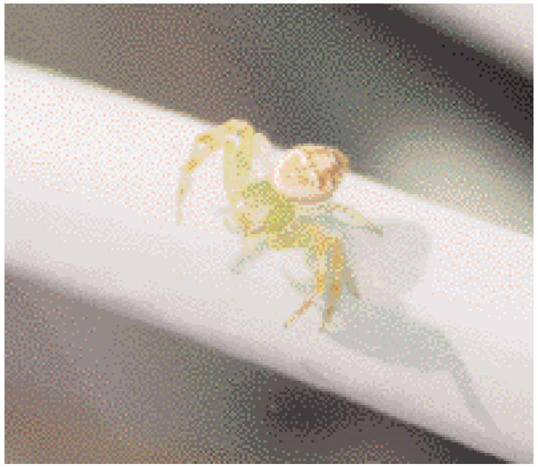
Nymphs: These appear very similar to the adults, except in size. Small, young spiders can produce threads of silk that aid their dispersal by wind currents. This behaviour is called 'ballooning' or 'parachuting'.

Adults: Spiders are recognised by everyone! Like mites, they are not insects. They have two body segments and four pairs of legs. They feed by sucking the body fluids from their arthropod prey. Many species trap their prey in nets or webs, while others forage actively or lie in wait before pouncing on their prey. Spiders from various families may be found on vegetable crops, including sheet webbing spiders (Linyphiidae, Picture 49), crab spiders (Thomisidae; Picture 50), lynx spiders (Oxyopidae; Picture 51), wolf or ground spiders (Lycosidae), jumping spiders (Salticidae) and orb weavers (Araneidae).

EFFECT ON PESTS

Although spiders or their webs may sometimes be regarded as a nuisance around the home, spiders can be very important predators on agricultural crops including vegetables. Spiders found on crops can be divided broadly into two groups according to how they hunt their prey: *webbing spiders* (Picture 49), such as sheet web spiders, which spin webs that in turn trap prey, and *hunting spiders* (Pictures 50 and 51), such as crab, jumping or wolf spiders, that rely on their ability to pounce on and overpower their prey. In some agricultural systems, such as rice in Asia, spiders, particularly wolf spiders, can be the dominant natural enemy of key pests. However, as generalist feeders, they may sometimes prey on natural enemy as well as pest species.

50. Crab spider (Family Thomisidae)



CONSERVATION

- Do not remove spider webbing or egg sacs from plants.
- Avoid spraying insecticides or acaricides unless absolutely necessary. Should spraying be considered necessary, use a product and application method that is the least harmful to key natural enemies (see Parts 3.2 and 3.3 of this guide).

51. Lynx spider (*Peucetia* sp., Family Oxyopidae)

There are many other types of predator, representing a diverse range of animal groups, that can prey on pests of vegetable crops. Some of these other predators are considered below.

OTHER INSECT PREDATORS

Although the predatory role of particular life-stages of the following insects is well known, the importance of each group in tropical vegetable cropping systems is presently not well understood.

Ants

Ants (Hymenoptera: Formicidae), like all bees and many wasps, are social insects and so have a division of labour between different groups (i.e., workers, soldiers and reproductives) within each colony. The worker ants, comprised of sexually undeveloped females, are responsible for food collection and hence are the caste encountered most commonly (Pictures 52 and 53). Worker ants generally use trails as a means of searching for and collecting food. Larvae and pupae, which are whitish in colour and grub-like, are maintained in below- or above-ground nests that can be some distance from foraging sites. Some species of ants can be important predators, while others, referred to as 'attendant ants', can protect aphids and

52. Ants removing a caterpillar from a bean pod

53. 'Safari' ants carrying a diamondback moth caterpillar after clearing it from a kale plant

other sucking pests from attack by natural enemies as a means of securing their supply of honeydew (the sticky, sugar-based secretion produced by sucking pests).

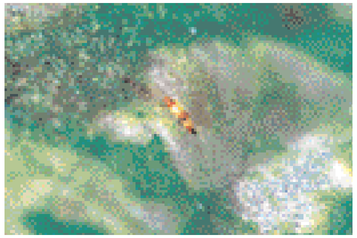
Predatory bugs

These include three important predatory groups of true bug (Order Hemiptera): minute pirate bugs (Hemiptera: Anthocoridae; p. 37), nabid bugs (Hemiptera: Nabidae) and assassin bugs (Hemiptera: Reduviidae). Other families of true bug that include many plant-eating members, such as lygaeid bugs (Lygaeidae), mirid bugs (Miridae) and shield bugs (Pentatomidae) also contain species that are predatory. Assassin bugs (Picture 54) are the largest in size, with adults typically being 30 – 40 mm in length. They all undergo incomplete metamorphosis, so the nymphs are similar in basic form to the adults (although colours may vary substantially) and they feed by sucking body fluids from their prey.

54. Assassin bug; note beak used for sucking body fluids of prey

Predatory thrips

Thrips (Order Thysanoptera), some of which are important plant-sucking pests, undergo metamorphosis which is intermediate, with immatures which look essentially similar to the adults, although the first two instars, often referred to as larvae, never show wings externally. Wings, when present and fully developed, are four in number, and are long, narrow and fringed with long hairs, giving them a feathery appearance when viewed under magnification. The final two instars (usually the third and fourth) do not feed and are often referred to as the pre-pupal and pupal stages respectively. The pupae may be enclosed in a cocoon. Most thrips are plant feeders, attacking flowers, leaves, fruits and buds. However, a small number of species are predatory on other small arthropods. These appear rather similar to plant-feeding thrips, being very small (often 1-3 mm in length) with characteristic bullet-shaped bodies. Their colour may be uniform varying from opaque to black, while others may appear banded (Picture 55) or have spot markings on their 'feathery' wings. They can at times be abundant and important natural enemies of mites and many small insects, including leaf miner larvae.



55. A predatory thrips within a leaf mine on broad bean

Dragonflies and Damselflies

These insects (Order Odonata) both have aquatic immature (nymph) life stages, so they are particularly common in crops near ponds, streams, rivers and irrigation canals. The fast-flying adults are often seen resting on plants (Pictures 56 and 57) between bouts of searching for insect prey on vegetable and other crops. Most of the adult prey, which include a wide range of small flying insects such as flies and moths, are caught and often eaten while the adults are in flight.

56. A dragonfly (Suborder Anisoptera) adult resting on a non-crop plant near a vegetable crop

57. A damselfly (Suborder Zygoptera) adult at rest on reeds near water

58. Tree frog in axil of banana plant, also found foraging for insect pests on nearby organically-grown brassica crops

FROGS AND TOADS

Amphibians such as frogs and toads have a healthy appetite for insects, although they may eat pests as well as natural enemies. Small 'tree frogs', about 20–30 mm in length (Picture 58), are not uncommon on unsprayed vegetable crops where they can feed on a wide range of insects including aphids and caterpillars. They need water in which to lay eggs and allow development of tadpoles, but this may be in any area where small quantities of water accumulate, such as the axils of plants (Picture 58).

REPTILES

Chameleons (Picture 59) and lizards (Picture 60) are frequently found in vegetable crops, particularly those where broad spectrum pesticides are not used. They feed on a wide range of insects and other arthropods, but because pests tend to be less mobile than natural enemies, pests are often a more important food component.

59. A chameleon searching for food sources, notably aphids, on kale plants on an organic kale crop

60. A lizard searching for prey in a mixed organic crop

BIRDS

Many bird species, such as shrikes, can forage for insects and other animals in vegetable crops. However, birds may also damage leaves and fruits.

MAMMALS

Rats are not uncommon visitors to vegetable crops, and although they may feed on certain insects present, they may also cause serious damage to crops. Humans can be natural enemies too! Particular life stages of pests can be removed selectively by hand (Picture 61).

61. Humans as predators: hand-picking bollworm (*Helicoverpa* sp.) pupae from cabbage plants on an organic farm

Type: Parasitoid
Immatures: Different from adults
Main prey: All pest insects, including caterpillars (moth larvae), aphids, bugs, fly larvae, insect eggs, beetle and fly larvae, insect pupae
Crops: All
Group: Insect, wasp (Hymenoptera: Braconidae [incl. Aphidiinae], Ichneumonidae, Chalcidae, Eulophidae, Trichogrammatidae, and others)
Other common names: Parasitoid, parasitic wasp, parasite, wasp

APPEARANCE AND BIOLOGY

There are about 50,000 described species of parasitoid wasp and many of them are so small that they go unnoticed. To the untrained eye, these wasps look rather like small flies or flying ants (see Pictures 65 and 66 on pp. 67-68). Some, notably egg and leaf miner parasitoids, are so small they often require magnification to be distinguished as wasps. Unlike the much larger predatory wasps (pp. 51-52), which have the ability to inflict a painful sting on unwary humans, parasitoid wasps, with very few exceptions, cannot sting any animal other than their insect host. In parasitoids, stinging by females is the process by which eggs are laid (*oviposition*). In many crop/pest situations, parasitoid wasps are the single most important group of natural enemy, although their impact can be hard to evaluate without detailed study (see Part 3.1 of this guide).

Parasitoid wasps comprise a very diverse group with complex and variable biologies, spread across a large number of families within the Order Hymenoptera. Parasitoids also exist within the fly (Diptera: Tachinidae, p. 76) and beetle (e.g., Coleoptera: Staphylinidae, p. 34) families. Parasitoid wasps nearly always lay their eggs within or on the body of their host (prey) and the eggs hatch into larvae that feed on the host. After pupation within or outside the host's body, the adult parasitoid wasp emerges, usually as a small, dark-coloured, winged wasp (typically 1- 6 mm in length). Some species of parasitoid wasps have wingless adults that appear ant-like. The prime purpose of the adult stage is dispersal and reproduction, although some adults are predaceous and may *host feed*, killing pests (and potential hosts) in the process. Host feeding is common in adult parasitoid wasps that attack leaf miner larvae (p. 70). Adults locate mates and, following mating and fertilisation, the females lay eggs, the cycle beginning once again.

There may be few or no outward symptoms of a larval parasitoid's presence within its insect host. In other cases, the host insect may become swollen or permanently paralysed after being 'stung'. Parasitoid wasps may pupate within or outside the host's body. Field collection and rearing of immature stages of pests, to check if any adult parasitoids emerge, is often a useful method for determining whether parasitism has occurred (see Part 3.1 of this guide). In vegetable crops, parasitoid wasps that attack aphids (pp. 65-66), moth pests (caterpillars and eggs) (pp. 68-70), leaf miners (pp. 70-71) and whiteflies (p. 72) are particularly important.

APHID PARASITOIDS

The first obvious indication of aphid parasitism is usually the presence of *aphid mummies* (Pictures 62 - 63). Mummified aphids have been killed by the wasp larva, which will have consumed the aphid's body contents, leaving only the aphid's cuticle (skin) as the parasitoid's cocoon. The cuticle changes colour, often becoming brown, golden, pinkish or black, depending on the particular parasitoid wasp and aphid species attacked. With many species, following pupation within the

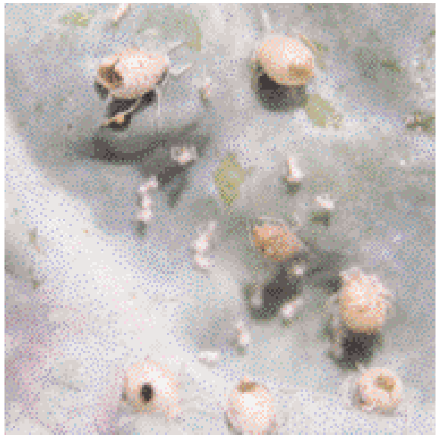
62. Cabbage aphid colony showing mummified (brown) and un-mummified (grey) aphids

63. Aphid colony (*Myzus persicae*) with mummified aphid in centre

aphid, the newly-formed adult parasitoid wasp chews a circular exit hole through the dead aphid's cuticle (normally towards the back of the aphid) (Picture 64) and emerges. Some aphid parasitoids emerge as late stage larvae and spin their cocoons beneath the dead aphid's body. Adult aphid parasitoids (Picture 65) are very small (2 - 3 mm in length), dark coloured and have rather long antennae. The careful observer will be able to watch adult females 'stinging' aphids, in the process laying eggs, usually only one per aphid. Only a single parasitoid develops within each host aphid. Each female will typically lay between 50 and 100 eggs during her lifetime. Many species of parasitoid are specific to only a single host or a very narrow range of host species (*specialists*), while others have a wider host range (*generalists*).

Counts of aphid mummies compared with unparasitised aphids (often expressed as a percentage) will normally significantly underestimate the amount of parasitism, since these counts do not take into account parasitism of aphids that have yet to

become 'mummified' (see Part 3.1 of this guide). It is not possible to tell visually whether un-mummified aphids have already been parasitised as mummification does not occur until the parasitoid reaches the pupal stage within its host aphid.

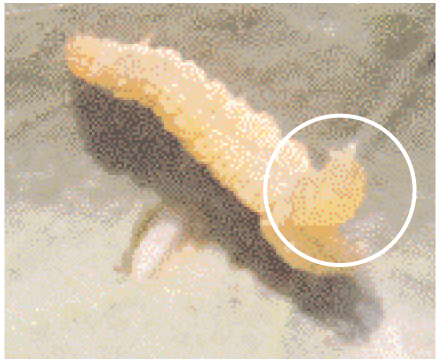


64. Cabbage aphid mummies with exit holes, indicating that adult parasitoid wasps have pupated and emerged

65. An adult aphid parasitoid, *Diaeretiella rapae* (Braconidae: Aphidiinae), one of the most important parasitoids of aphids on brassicas

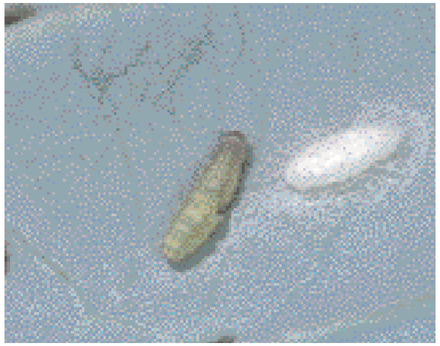
PARASITOID WASPS OF CATERPILLARS

66. *Cotesia* sp., a braconid parasitoid wasp and key endoparasitoid of diamondback moth



67. A braconid larva (*Cotesia* sp.) emerging through the side of a final instar diamondback moth larva, prior to spinning its cocoon

The larvae of these parasitoids may feed from within (*endoparasitoids*) or outside (*exoparasitoids*) their host's body. However, it is usually the former group that are more important as natural enemies of caterpillars on vegetable crops (Pictures 66 to 72). Depending largely on the species of parasitoid, either a single wasp, a small number or a large number of wasps (sometimes more than 100) will develop within each caterpillar. Late stage parasitoid larvae may emerge from their host, attaching their cocoon either to the dying caterpillar's body or to the plant surface (as in *Cotesia* sp., Pictures 67 to 69) or they may consume the bulk of the caterpillar before pupation (as in *Diadegma* sp., Pictures 70 to 72). Parasitoid wasp cocoons (pupal cases) may be covered in white silk spun by the parasitoid itself (Pictures 68 and 69) or they may be contained within the host's own pupal sheath (Pictures 71 and 72).



68. *Right*: The silk-covered cocoon containing the pupa of a braconid parasitoid (*Cotesia* sp.) of diamondback moth larvae. *Left*: The mortally wounded host larva, showing the hole to the right side of its body from which the parasitoid larva emerged before spinning its cocoon

69. A *Cotesia* sp. cocoon on a leaf. The neat cap on the left side shows that an adult has already chewed its way out and emerged

70. *Diadegma* sp., an ichneumonid parasitoid wasp, and key endolarval parasitoid of the diamondback moth

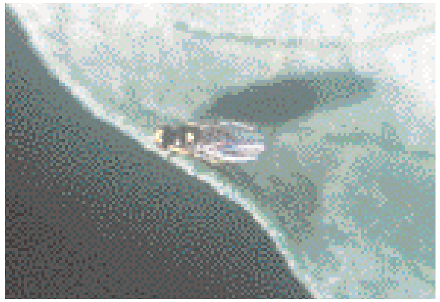
71. *Left*: A *Diadegma* sp. cocoon within a silken sheath of a diamondback moth prepupa. *Right*: an unparasitised diamondback moth pupa within its sheath

72. As for *Picture 71*, but the silk sheaths of the diamondback moth have been removed to show more clearly the differences between the parasitoid cocoon (*left*) and diamondback moth pupa (*right*)

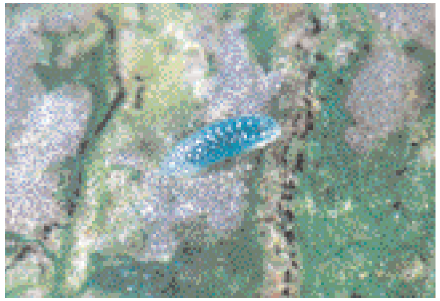
LEAF MINER PARASITOIDS

Black-coloured, tiny parasitoid wasps (around 1 mm in length) can be very important in the control of leaf miner flies (Diptera: Agromyzidae), particularly in situations where broad spectrum insecticides are used regularly. However, leaf miners can become a huge, induced problem where indiscriminate spraying occurs. This is because they readily become resistant to many insecticides and their key natural enemies that include various parasitoids and predatory thrips species are killed. If leaf miners are allowed to establish in a younger crop by avoiding applications of broad spectrum insecticides, it is often found that their abundance diminishes in response to increasing numbers of leaf miner parasitoids over the cropping period.

Two genera of leaf miner parasitoids are commonly found in Zimbabwe, these being *Meruana* and *Diglyphus*, although they can usually only be separated by specialist taxonomists. These wasps should not be confused with the slightly larger leaf miner flies. The most common leaf miner flies belong to the genus *Liriomyza*, and these adults are distinguished by a yellow spot on their thorax (Picture 73). Eggs are laid by adult female wasps within leaf miner larvae through the leaf epidermis, larvae develop within the body of the host (Picture 74) and pupation occurs in the mine (Picture 75).



73. An adult leaf miner fly (*Liriomyza huidobrensis*) on a bean leaf



74. A leaf miner parasitoid larva visible within the body of a leaf miner (*Liriomyza huidobrensis*), exposed after peeling away the lower epidermis of a bean leaf

75. A leaf miner parasitoid pupa found within a leaf mine

WHITEFLY PARASITOIDS

These are tiny parasitoids (Family Aphelinidae e.g., *Encarsia formosa*, less than 1 mm in length, available commercially in some countries for release on covered crops) and their presence is often noticed in the field when parasitised whitefly nymphs turn black or brown (Picture 76). Apart from mortality caused by parasitism (larval feeding within the nymphs), adult wasps also host feed, killing more whitefly in the process.

76. Parasitised (dark-coloured) and unparasitised (opaque) whitefly nymphs on the underside of a leaf

EGG PARASITOIDS

This is another important group of tiny parasitoids (Family Trichogrammatidae), the adults often being less than 0.5 mm in length. The adults generally have bright red eyes, short antennae and their bodies may be coloured black and yellow, or yellow. They lay their eggs (one or several per host egg) within moth eggs on a wide range of vegetables and other crops. Moth eggs turn black when the wasp pupates within the egg, this characteristic being a useful trait for recognition.

FIELD INTRODUCTIONS

If an important parasitoid often associated with a particular pest in other parts of the country or region is not present, it may be possible to establish it locally by introducing a small group of the parasitoid (perhaps 50 –1000, both sexes) in the vicinity of appropriate hosts. This process is sometimes referred to as *introduction* or *inoculation* (see also p. 18). This type of introduction may be appropriate in some smallholder systems, for example, a small highland plot isolated from other vegetable growing areas.

CONSERVATION

Conservation techniques that provide parasitoids with adequate food sources, shelter and means of reproduction on the farm are required to ensure efficient population growth. Some key methods are considered below:

- Ensure ample numbers of flowers, containing nectar, are provided as adult food sources for parasitoids and other adult natural enemies. This might include the growing of fennel (Picture 77), coriander, nasturtiums (Picture 78), flowering crucifers or sunnhemp close to, between, and/or around the crop. The use of marigolds by organic farmers (Picture 79) is thought to repel certain pests more than it attracts natural enemies.

77. Fennel (and many other flowering plants) provide a useful nectar resource for adult parasitoids and other natural enemies

78. Nasturtiums growing within a smallholder plot, used as a food source both for natural enemies and humans

79. Marigolds growing adjacent to kale plants, used more to repel pests than attract natural enemies

80. A smallholder organic farm, including mixed cropping, livestock and use of compost

- Encourage habitat, plant and animal diversity in cropping areas (Pictures 80 and 81); develop a mixed cropping system and include non-crop plants (sometimes thought of as 'weeds') that provide nectar sources and alternative hosts for parasitoids.

- Provide shelter and shade for parasitoids by growing live fences (Picture 82) around plots.

- Grow trap crops that can allow some build-up of plant-feeding

81. A diverse habitat for natural enemies, based on mixed cropping and provision of flowering plants

82. A live fence bordering a vegetable growing area on an organic farm

83. Sweet sorghum, a trap crop for bollworms (*Helicoverpa* and *Diparopsis* spp.), used here in a smallholder organic cotton/vegetable mixed crop (Photograph by Meg Davies)

insects (that may be alternative hosts or pests) and their natural enemies, which can in turn provide early suppression of pests on the nearby principle crop (Picture 83).

- Avoid spraying pesticides unless absolutely necessary. Should spraying be considered necessary, use a product and application method that is the least harmful to key natural enemies (see Parts 3.2 and 3.3 of this guide).

Type: Parasitoid
Immatures: Different from adults (complete metamorphosis)
Main prey: Cutworms, caterpillars, beetle larvae, fly larvae, bugs
Crops: Brassicas, potatoes, cucurbits, maize and others
Group: Insect, parasitic fly (Diptera: Tachinidae, and some other Families)
Other common names: Tachinid, parasitoid, parasitic fly, parasite, fly

APPEARANCE

Eggs: The eggs of tachinids, the most important group of parasitoid flies, can sometimes be seen with the naked eye on their hosts such as caterpillars and beetle larvae. The eggs are tiny (less than 1 mm in length), white or off-white in colour and oval in shape. Some tachinids lay their eggs on leaves rather than directly on the host body.

Larvae and pupae: Eggs normally hatch on the host body and larvae then burrow through the body and feed internally. With species that lay their eggs on foliage, eggs or young flattened larvae (called *planidia*) are ingested by caterpillars or other pests whose body contents provide a food source for the developing larvae. Parasitism nearly always results in death of the host insect. Pupation occurs either within or outside the body of their hosts. Some species pupate in the soil.

Adults: The adult flies look rather similar to common flies such as house flies, flesh flies or blow flies, but they are more robust and hairy (or bristly) than house flies, typically being between 8 – 12 mm in length. Their most identifiable feature are the long and short bristles usually clearly visible on the abdomen (Picture 84). Their bodies are often grey in colour, with markings (Picture 84). Being flies, they only have a single pair of wings (which may also possess markings and be less translucent than those of a house fly) and these are often held slightly or partially out-spread when at rest.

84. Adult tachinid (parasitoid) fly. Note bristles on abdomen and single pair of wings.

EFFECT ON PESTS

Tachinids make up a very large family of flies, containing both highly specialised types which attack only a single or narrow range of species, as well as generalists which attack a much wider range of species. As with parasitoid wasps, it is the larval stages of parasitoid flies that attack other insects (and occasionally other arthropods) and it is difficult to evaluate their population impact without detailed study. Generally, parasitoid flies have not been as well studied as parasitoid wasps. However, their short generation time means that populations can build-up rapidly. On farms where these flies are found to be numerous, it is likely that they are exerting important regulatory pressure on pest populations.

CONSERVATION

- Ensure adequate, sugar-containing food sources are available for adults, such as flowers, plant sap or honeydew.
- Encourage habitat diversity, as for parasitoid wasps (see *Parasitoid Wasps*; *Conservation*: p. 73).
- Avoid spraying pesticides unless absolutely necessary. Should spraying be considered necessary, use a product and application method that is the least harmful to key natural enemies (see Parts 3.2 and 3.3 of this guide).

The most important naturally-occurring disease causing pathogens of vegetable pests are generally fungi and viruses. These disease organisms tend to be more common during rainy seasons, are difficult to manipulate and they may be unpredictable as to their presence or effect. However, on occasions, disease outbreaks will occur and over a very short period, can cause complete collapse of pest populations. Many pathogens (e.g., granulosis viruses, certain bacteria and fungi) are highly specific to particular pests. The primary pathogens which attack insects are specific to insects and closely related arthropods and cannot cause disease in unrelated organisms such as humans.

Entomopathogenic fungi

Fungi, when sporulating, usually cause their insect host to become covered in a cream-coloured (Picture 85), green, red or grey coloured mould. Aphids, caterpillars and a wide range of other pests may be found infected by fungi. Spores are transferred on insect bodies, in rainwater or in the wind, and hyphae (fungal strands) enter the insect body via openings (e.g., breathing holes, anus). The fungal hyphae or mycelia develop and consume the insect from the inside. Signs of infection tend to be quite easy to find during sustained wet or humid conditions, such as those found during rainy seasons. Considerable research is on-going to develop biological pesticides based on fungal pathogens, particularly *Metarhizium* *anisopliae*. At particular times of year, other genera of fungi such as *Zoophthora* and *Entomophthora* can be readily encountered in the field infecting pests such as caterpillars and aphids.

85. *Left*: Fungal infected diamondback moth caterpillar (Zoophthora sp.). *Right*: healthy caterpillar

Baculoviruses

A wide range of viruses specific to insects, known as baculoviruses, have been identified in wild populations of insects and some have been multiplied in sufficient quantity to be used as 'biological pesticides'. Virus-infected insects, notably caterpillars, tend to be found more commonly in heavy infestations, particularly during prolonged wet seasons. The two most common types of baculovirus encountered are species-specific granulosis viruses (GVs) and nuclear polyhedrosis viruses (NPVs). Recent investigations in Kenya have been carried out to assess the potential for using a GV specific to the diamondback moth (PxGV) in brassica crops. Infected larvae typically appear pale and swollen (Picture 86), and the development of the final instar is delayed considerably. Infected insects usually die prior to adulthood and turn brown or black after death owing to secondary infection by bacteria. NPVs, such as the soya-bean

86. *Left*: A healthy diamondback moth larva (fourth and final larval instar). *Right*: a fourth instar diamonback moth larva in the late stages of infection by PxGV semi-looper virus used in Zimbabwe, often cause the caterpillar's cuticle (skin) to become flaccid (weak and soft), and heavily infected or dead caterpillars tend to be found hanging from leaves, the body contents having turned to liquid, charged with virus particles (Picture 87).

87. A semi-looper caterpillar on soya, killed by a Nuclear Polyhedrosis Virus (NPV) (Photograph courtesy of Natural Resources Institute, UK)

Viruses need to be consumed (unlike fungi) in order to enter and replicate within the insect body. One of the main constraints to the sustainable use of viruses as 'biological pesticides', which can be applied to infected crops much in the same way as conventional pesticides, is the cost of small-scale or commercial virus production.

Bacteria

Insects such as caterpillars infected by bacteria can sometimes be found in the field. Following infection, they generally turn brown or black and die. *Bacillus thuringiensis* (Bt) is a naturally occurring bacterium, found both in the soil and on plants, and is the most well-known bacterial pathogen of insects.

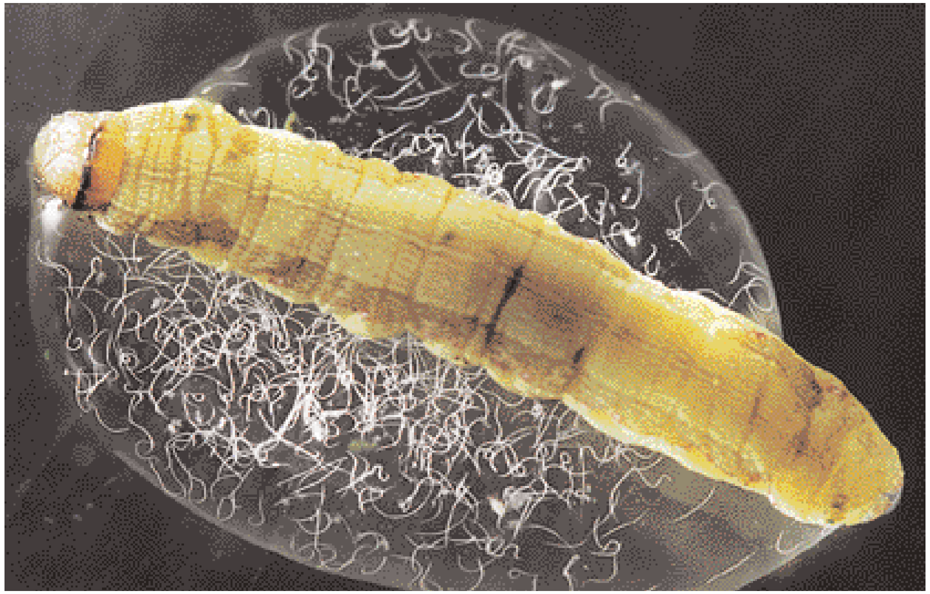
Several formulations of various Bt products are available commercially for use against caterpillar pests of vegetables such as diamondback moth (*Plutella xylostella*) and African bollworm (*Helicoverpa armigera*). These products tend to be highly effective against their target pests and have little or no

effect on natural enemies. Although a caterpillar may take several days to die after ingesting the product, it stops feeding shortly after exposure, so dramatically reducing crop damage.

Bt products can be applied with spraying equipment in the same variety of ways as conventional insecticides. However, they cannot be regarded properly as biological agents since either the bacterial cells themselves are not present within the formulation, or if present, they are not living. These insecticides are some of the least harmful to other arthropods and natural enemies (see Part 3.2, p. 91). The often highly specific insecticidal effect is caused by toxic proteins (endotoxins) produced by various subspecies of the bacterium.

Entomopathogenic nematodes (EPNs)

EPNs are found in soils all over the world, particularly in lighter soils and in coastal areas. They are small, long, thin roundworms that can usually only be seen under a microscope. Recent surveys have been carried out in both Zimbabwe and Kenya, with the purpose of finding virulent isolates. EPNs belong to two genera: *Steinernema* (Picture 88) and *Heterorhabditis*. The insect host is actively infected in the soil by a specialised third stage juvenile (about 1 mm in length), known as a *dauer larva* (or *infective juveniles*). EPNs have a symbiotic (mutually beneficial) relationship with particular species of bacteria: *Steinernema* with *Xenorhabdus* species and *Heterorhabditis* with *Photorhabdus* species. Infection by these bacteria often provides a useful clue to the genus of nematode: the bodies of insects killed by *Xenorhabdus* are typically yellow to orange in colour while those killed by *Photorhabdus* species can be bright red. These bacteria are released from the nematode into the body cavity of the insect,



88. Entomopathogenic nematodes [infective juveniles] (*Steinernema carpocapsae*) emerging from their dead *Spodoptera* caterpillar host in search of new hosts

multiply rapidly and kill the host within 48 hours by septicaemia. The nematodes feed on the bacterial cells and host tissues, develop and reproduce. When food supplies run out, nematode development stops at the dauer larva stage and these escape into the soil to find new hosts.

The role of EPNs in regulating insect populations in soils is not well understood. However, EPNs can be mass produced on a commercial scale on solid or liquid media and in a number of countries around the world are now used as ‘biological insecticides’ against a variety of insect pests (especially caterpillars and beetles). EPNs are regarded widely as being very environmentally friendly with no adverse side effects reported.

Evaluation of natural enemies, and pesticide selectivity

3

Page

An introduction to natural enemy evaluation

Background

Being able to distinguish natural enemies from pests and then counting the numbers in each of the two categories will not provide you with enough information to be able to make meaningful judgements on the effectiveness of different natural enemies on specific pests. The whole subject of natural enemy evaluation is complex and one that has only recently become a major focus for researchers working in the field of biological control of pests. This part of the guide aims to outline some of the important principles that need to be borne in mind when carrying out evaluations or interpreting data that has already been collected. It serves particularly to provide information on some common shortcomings of evaluations.

Principles of field evaluation

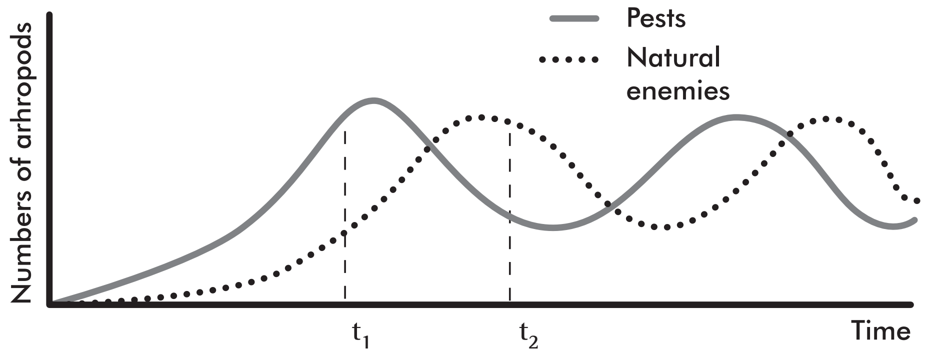
Many of the methods now being used by researchers to assess natural enemy effectiveness involve studies of natural enemy egg production, consumption rates, lifespan, development time, movement rates and numerous other factors. These methods require detailed laboratory and field investigations by highly specialised personnel over long periods of time, and are not appropriate for the extension worker or farmer. Nevertheless, some important principles of this type of work are relevant to those involved in pest management decisions at the farm-level and it is to these that we now turn.

Evaluations of abundance in the field

Counts of natural enemies (and pests) are often the starting point of an evaluation. However, there are numerous problems with how the count data are then interpreted. Some of the major reasons why the numbers of natural enemies found on plants vary from one assessment to the next are considered below:

a) **Population fluctuations.** Natural enemy numbers vary over time because many populations follow a similar pattern of fluctuation as their hosts or prey (i.e., pests). However, since many natural enemies multiply in response to the availability of food, there is often a 'time lag' between pest and natural enemy population fluctuations. This is shown graphically in Figure 1. Therefore, if only a single assessment was undertaken and this was carried out at time 1 (t_1), a very different picture of natural enemy abundance would be observed compared with a later assessment at time 2 (t_2).

Figure 1. Typical fluctuations of pest and natural enemy abundance over time



This demonstrates the need to evaluate natural enemies and pests throughout the cropping season. In detailed studies, this is often carried out at weekly or two weekly intervals. Management practices, which may include applications of pesticides or cultural manipulations, will also tend to contribute to fluctuations of pest and natural enemy abundance, so the role of these must be taken into account during evaluations.

b) **Assessments at different times of the day.** If an assessment of natural enemy numbers is undertaken at 8.00 am one day, 12.00 midday on another and 6.00 pm on yet another, differences in number of natural enemies between assessments could well be attributed to the different times of day rather than to genuine differences in abundance. This is because natural enemies are more visible, or search for prey or hosts at specific times of day or night. For example, larvae of many species of hover fly and ladybird beetle are particularly active at night so assessments made in the middle of the day will tend to vastly underestimate numbers. Natural enemies are also affected by other factors such as weather conditions, temperatures and condition of the plants. Adult parasitoids, for instance, are generally most active on mornings and afternoons and may be deterred by high midday temperatures or strong winds. Generally, assessments of most natural enemies are often best undertaken under calm conditions in the early morning or late afternoon. If the intention is to assess relative numbers over time, it is important to aim to carry out assessments at the same time of each day.

c) **Effects of crop growth stage.** As a crop grows and matures, it can become progressively more difficult to locate natural enemies both because the surface area of the plant becomes much larger, but also because there is a greater possibility of natural enemies being hidden in plant parts of older rather than younger plants.

d) **Bias from assessors.** There can be substantial variation in the accuracy of data collected by different individuals. This means that, as far as possible, the same individual or group of individuals with known identification skills and track records for accurate assessments, should be selected for each of a series of assessments on a given crop. Also different techniques are required for different organisms; for example, visual counts may be useful for parasitoid cocoons or aphid 'mummies', while pitfall trapping is commonly used for ground-dwelling predators.

e) **Concealed life stages.** Some life stages of natural enemies, notably parasitoids and pathogens, can be concealed within the bodies of their hosts that show no outward sign of attack until the later stages of parasitism or infection. For example, aphids or caterpillars which are attacked by endoparasitoids (p. 68), do not show any obvious evidence of parasitism until the parasitoids reach the pupal stage. In the case of parasitised aphids, there are no outward signs until each aphid becomes mummified, while with caterpillars, no evidence of attack is revealed until parasitoid larvae emerge from or consume their hosts just prior to pupation.

f) **Variable durations of exposure to natural enemies.** A method commonly used for assessment of parasitism is by collecting potential hosts from the field and then rearing through in the laboratory or other controlled environment. With such methods, it is critical that the hosts that are removed from the field (and therefore from exposure to parasitoids) have had the same period of susceptibility to parasitoids. For example, diamondback moth caterpillars are particularly susceptible to endoparasitism in their second and third instars and are rarely parasitised in the first or final (fourth) instar. Therefore, if caterpillars are collected from the field these must not be of mixed ages (instars), otherwise there will be variations in the amount of time that each will have been susceptible to parasitism. Accordingly, it is more appropriate to collect only fourth instar caterpillars and determine the proportion of these that are killed by parasitoids when reared through in the laboratory. This type of assessment is normally carried out at regular intervals (e.g., two-weekly) throughout the cropping cycle. This principle applies to all hosts and parasitoids. In addition, care must be taken to not include remnants of previous life stages in assessments. For example, when assessing numbers of hover fly or lacewing eggs laid on a crop over time, hatched eggs should not be included in the assessments, or, when evaluating aphid parasitism by periodic assessments of mummified aphids compared with un-mummified aphids, mummified aphids from which wasps have already emerged should also be excluded from counts.

Counts of arthropod natural enemies alone, even when the above factors have been taken into account, do not provide an indication of the relative effectiveness of a range of natural enemies. This is because of the very great variations in life cycle parameters between different natural enemies species, and within species at different times and places. One of the most important parameters is *voracity* (the number of hosts or prey consumed by the natural enemy), this being demonstrated by a generalised example given below.

The importance of voracity: a generalised example

An aphid pest, Species X, is preyed on by two key species of natural enemy, these being designated as A and B. Species A is a parasitoid wasp, while Species B is a hover fly predator. Each adult, fertilised female wasp of A can lay up to 50 viable eggs during its adult lifespan, each being laid within an individual host aphid. This means that each female has a 'killing potential' of 50 aphids.

Species B on the other hand, although having the same lifespan (about 30 days), lays twice the number of eggs compared with Species A (i.e., 100) on leaves close to the colonies of Species X. The hatch rate from these eggs is 75%, and each of these larvae has the capacity to consume 400 aphids during its average 12-day larval period. The 'killing potential' of one fertilised female of Species B is therefore 30,000 (75 x 400), which is 600 times greater than that of Species A.

There are many other factors that can be important in assessments of natural enemy effectiveness. Some of these are difficult to measure in the field and have been poorly studied, but this does not necessarily detract from their importance in biological control. Many of the most important life cycle parameters (which must be determined both for the natural enemy and its hosts or prey) are listed in Table 2.

Table 2. Important life cycle parameters in relation to natural enemies

EGG OR PREY (PEST) PARAMETERS	NATURAL ENEMY PARAMETERS
Immigration rate	Immigration rate
Emigration rate	Emigration rate
Fecundity	Voracity (consumption rate)
Development time	Development time
Juvenile mortality	Fecundity
Adult mortality	Egg mortality
	Juvenile mortality
	Adult mortality

Finally, and certainly not least, the size of the area (scale) over which natural enemies are evaluated will have a very important bearing on the results. There are many reasons for this, one being that natural enemies are often highly mobile so can readily move in or out of the study area. If a small area is sprayed with a broad spectrum pesticide and is then evaluated, the natural enemies may appear relatively unharmed because species that are killed are likely to be replaced relatively quickly by those that immigrate from nearby untreated areas. As a result, 'recovery' of natural enemy populations will tend to be considerably more rapid than when relatively large areas are sprayed.

Conclusions

There are a large number of factors that relate to the biology of natural enemies and their hosts or prey, as well as to the influence of climate, prevailing weather and other specific environmental factors, which need to be considered before appropriate methods of evaluation can be developed and implemented. The range of methodologies that have been used for given crop-pest-natural enemy combinations is beyond the scope of this section. However, it is hoped that some of the principles given here might be helpful at the farm-level so that some information on the relative value of natural enemies can be obtained or inferred.

It is anticipated that in the future, some practical methods, presently under development, will provide the basis for farmer-participatory evaluation of the effectiveness of key natural enemies.

In the meantime, taking into account some of the potential pitfalls as considered above, recognising which natural enemy types are present and evaluating their *relative* numbers at several points during the cropping cycle should provide useful information on the relative abundance of each natural enemy over time. Different management practices will tend to have different impacts on natural enemies, and the nature of these impacts, particularly whether they are positive or negative, can be assessed in general terms in this way. As with any experimental technique, it is essential that appropriate 'controls' are included in these studies. These control areas should be comparable to the 'treatment' areas in every way except that they do not include the specific 'treatment' or manipulation under investigation.

Lethal and sublethal effects of pesticides

It is often thought that a pesticide that does not kill a natural enemy must then be harmless to the natural enemy. This is not necessarily true. By analogy to a human example, a product surely could not be described as harmless, if when swallowed accidentally it then makes a person ill and prevents them from working. Such a product is most certainly harmful, but its effect does not lead directly to death. These effects are referred to as being sublethal, and they are common with pesticide exposure of natural enemies as well as other animals, including humans. It is therefore important to appreciate the differences between *lethal* and *sublethal* effects, between *direct* and *indirect* effects and understand something about the possible routes of exposure.

Pesticides may kill or harm natural enemies following exposure by contact, ingestion or, less commonly by respiration. They may also affect natural enemies indirectly by killing or contaminating their hosts or prey. Natural enemies are usually more susceptible to the effects of pesticides than their plant-feeding hosts or prey owing to their generally smaller size, searching habits, usually less-developed enzyme-based detoxification systems and preening behaviour (notably in parasitoids). Although the effects of pesticides on natural enemies are often negative, pesticides can sometimes enhance natural enemy function (see Figure 2) particularly if they are selective against the pests or are used at low dosages.

For a given population of natural enemies exposed to a pesticide over a range of doses, some natural enemies will generally die within a relatively short period (e.g., 48 hours) while others may survive beyond that period. Sublethal effects are those effects that occur in the pesticide-exposed survivors. The behavioural or physiological nature of sublethal effects on natural enemies tends to be fundamentally similar, although less severe, compared with that of lethal effects.

In field studies that attempt to assess pesticide impact on natural enemies (at the population or community level), it is often not possible to separate lethal from sublethal effects, or even indirect from direct effects. As such, pesticides may give rise to a continuum of effects that affect natural enemy populations positively or negatively or sometimes apparently not at all (Figure 2). Factors such as the inherent toxicity of the pesticide to a given natural enemy, the pesticide's persistence in the environment and the natural enemy's exposure will influence the severity of the effect.

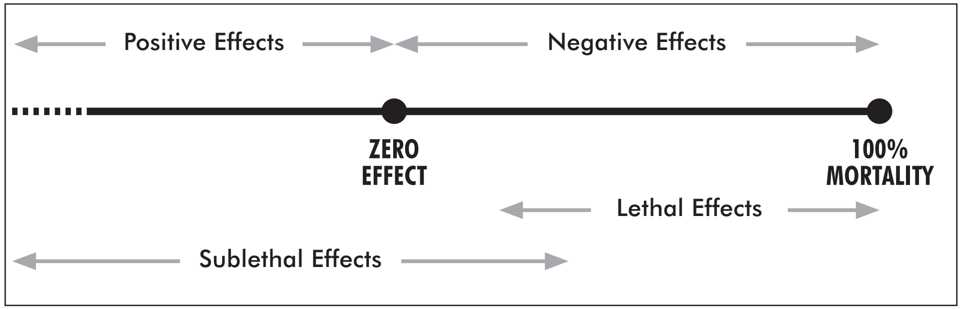


Figure 2. Continuum of possible pesticide effects on natural enemies

As mentioned above, sublethal effects may be generally sub-divided into two groups: behavioural and physiological effects (Table 3). Such effects may be measured in the laboratory but because a wide range of experimental protocols are used by different researchers, comparisons between species are often difficult. Where sublethal effects occur in the field, they will give rise to effects on natural enemy populations which will in turn affect the capacity of natural enemies to limit the abundance of hosts or prey (i.e., pests).

Table 3. Spectrum of sublethal effects on natural enemies caused by pesticides[1]

BEHAVIOURAL EFFECTS	PHYSIOLOGICAL EFFECTS
Communication	Development time
Locomotion	Voracity/Consumption/Parasitism
Consumption	Deformation
Repellency	Longevity
Foraging/Parasitism	Vigour
• searching	Reproduction
• oviposition	• fecundity
• handling time	• fertility

It should also be borne in mind that biological control agents, such as entomopathogenic fungi used to target pest populations, have the potential to cause negative side effects on other biological control agents.

[1] Adapted from: Wright, D.J. & Verkerk, R.H.J. (1995) Review - Integration of chemical and biological control systems for arthropods: evaluation in a multitrophic context. *Pesticide Science,* **44:** 207-218.

Pesticide exposure

Insects and other natural enemies can either be exposed *directly*, with the natural enemy coming into contact with droplets or particles of the pesticide, or they can be exposed *indirectly* (Figure 3). In the case of indirect exposure, the pesticide is either accumulated from residual deposits, for example on leaves, or it is consumed via treated hosts or prey. Another form of indirect effect results from impacts that a pesticide might have on pest (prey or host) populations. If these populations are depleted or eliminated by pesticide application, the change in the amount of food available for natural enemies can have profound effects on predators and parasitoids (Figure 3).

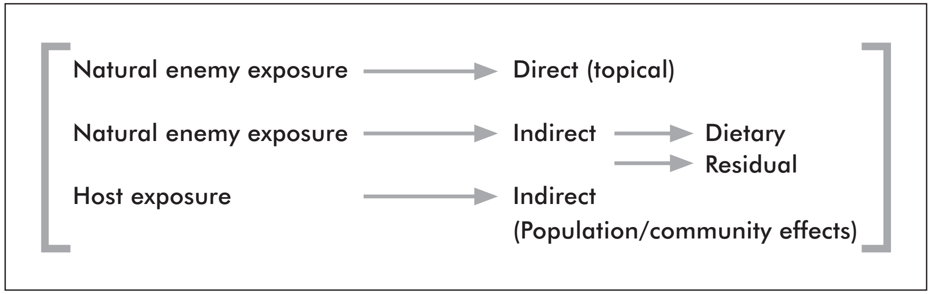


Figure 3. Important types of natural enemy exposure to pesticides

Finally, it is important to bear in mind that the impact of pesticides on pest and natural enemy populations within agro-ecological communities may have long-term consequences and may occur on large spatial scales. This means that pesticide impacts may not be detectable on individual farms sampled only occasionally.

Risk

When evaluating the impact of pesticides, we need to consider the *risk* of using a pesticide under the particular range of conditions under which it is used. These conditions, which include both living and non-living elements, are likely to vary considerably with both time and scale. For example, application of a broad-spectrum (non-selective) insecticide during a time when the adult stage of an important parasitoid species is abundant may result in resurgence of pest populations caused by suppression of the natural enemy. On the other hand, although the pesticide may have localised impacts on natural enemies, if it is sprayed selectively (e.g., spot or barrier application), the negative impact of the spray on the natural enemy might be relatively unimportant on a larger scale.

In its simplest form, *risk* should be seen as a function of both *exposure* and *susceptibility* of the target organism. Looked at from the point of view of the natural enemy, *hazard* is basically a function of its *exposure* to the pesticide and the pesticide's *toxicity* to the natural enemy in question. These relationships are shown by the following two simple formulae:

$$\text{Risk} = f\,(\text{exposure} + \text{susceptibility})$$

$$\text{Hazard} = f\,(\text{exposure} + \text{toxicity})$$

However, there are often substantial differences between *short-term* and *long-term* risks. Short-term risks include the amount that a natural enemy population is depleted after the application of a pesticide, but following this depletion there will be a recovery phase. Recovery will depend on such factors as the persistence of the pesticide in the environment and the rate of immigration of the natural enemy. As a result, the ranking of risk for a given pesticide application in a particular agro-ecosystem will often be different when comparing the short-term and long-term impacts.

There are very few data generally available on short- or long-term risks, and most farmers or pest managers are usually forced to use one or more of a limited range of products that are available to them commercially. This section of the field guide aims to help extension staff and trainers decide which pesticides might be less hazardous to natural enemies. The data on which this information are based is taken largely from laboratory experiments, not field studies.

The advantage of standardised laboratory experiments, as used by the International Organisation of Biological Control (IOBC) (see pp. 98-99), is that they allow the relative toxicity of specific pesticides to be tested under standardised conditions against a range of organisms from the most important natural enemy groups. The pesticides are used at the maximum recommended field rates under conditions where exposure is considerably greater than those usually encountered in the field. Data from any table of pesticide side effects on natural enemies, such as the one given in this guide (pp. 98-99) or those produced by some pesticide manufacturers (e.g., p. 100), should therefore be interpreted with caution. It should be appreciated that these data reflect effects following much higher exposure rates than those normally encountered in the field, and they give no indication of possible long-term or large-scale risks. However, if properly conducted tests (such as those following the IOBC protocols) show a product to be 'harmless' to a range of natural enemies under these laboratory conditions, the likelihood is that the product will also be 'harmless' to the same natural enemies under field conditions.

Introducing the Table of Pesticide Side Effects on Natural Enemies

The table overleaf aims to provide some information on the relative toxicity to a range of natural enemies of some commonly used insecticides and fungicides. The table also includes a few newerhproducts that are known to be relatively harmless to many species of natural enemies. The table includes all the main pesticides found to be used in Zimbabwe or Kenya during surveys carried out for the present work.

The data aim to demonstrate both the variability of response to pesticides by a range of key natural enemies as well as showing differences between the pesticides. Although the data provide useful information on *relative* toxicity of different pesticides to specific natural enemies, as discussed above, they do not provide data on risk or hazard of these pesticides in use. This type of information is generally much harder to come by and is not available for many pest/natural enemy/crop situations. Where data are available they are contained in scientific journals. An attempt to collate this published work has been made by workers at Oregon State University in the USA, in the form of the SELCTV database (see *SELCTV Database*, p. 100).

Products that have different intrinsic toxicities to pests compared with natural enemies are referred to as selective products (e.g., *Bacillus thuringiensis* [Bt] based products). However, even products that are classified as 'harmless' are very rarely harmless to all non-target organisms. All pesticides should be used judiciously (see *Conservation* under each natural enemy group in Part 2), as over-use can lead to other unforeseen problems including insecticide resistance (see p. 14).

Apart from the intrinsic selectivity of a given product, some additional selectivity can be achieved by selective and judicious pesticide application (Part 3.3).

3.2 Side Effects of Pesticides

INSECTICIDES AND ACARACIDES | **FUNGICIDES**

			Actellic (*Piriniphosmethyl*)	**Ambush** (*permethrin*)	**Applaud** (*bupofrezin*)	**Basudin** (*diazinon*)	**Dipel** (*Bacillus thuringiensis*)	**Cymbush** (*cypermethrin*)	**Decis** (*deltamethrin*)	**Folithion, Sumithion** (*fenitrothion*)	**Karate** (*lambda cyhalothrin*)	**Kelthane** (*dicofol*)	**Mitac** (*amitraz*)	**Pirimor** (*pirimicarb*)	**Rogor** (*dimethoate*)	**Sevin** (*carbaryl*)	**Sumicidin** (*fenvalerate*)	**Thiodan** (*endosulfan*)	**Trigard** (*cyromazine*)	**Antracol** (*propineb*)	**Dithane M45** (*mancozeb*)	**Neviken** (*lime-sulphur*)	**Thiovit** (*sulphur*)	**Vitrigran** (*copper oxychloride*)
Parasitoid Wasps	Egg Parasitoid	*Trichogramma cacoeciae*	Harmful	Harmful	Harmless	Harmful	Harmless	Harmful	Harmful	Harmful	Harmful	Moderately harmful	Harmful	Harmful	Harmful	Harmful	Harmful	Harmful	Harmless	Slightly harmful	Slightly harmful	Harmful	Harmful	Harmless
	Larval Parasitoid	*Encarsia formosa*	Harmful	Harmful	Harmless	Harmful	Harmless	Harmful	Harmful	Harmful	?	Moderately harmful	Harmful	Harmful	Harmful	Moderately harmful	Harmful	Harmful	Harmless	?	Harmless	Harmful	Harmful	?
	Larval Parasitoid	*Leptomastix dactylopii*	Harmful	Harmful	Harmless	Moderately harmful	Harmless	Harmful	Harmful	Harmful	?	Harmful	Harmless	Slightly harmful	Harmful	Harmful	Harmful	Slightly harmful	Harmful	Harmless	Harmless	?	Harmless	Harmless
Predators	Mite	*Phytoseiulus persimilis*	Harmful	Harmful	Harmless	Harmless	?	Harmful	Harmful	Harmless	Harmful	Harmful	Harmful	Slightly harmful ●	Harmful	Harmless	Harmful	?	Harmful	Moderately harmful	Harmless	Harmful	Harmless	Harmless
	Spider	*Chiracanthium mildei*	?	?	Harmless	Harmful	?	Moderately harmful	?	?	?	?	?	?	Slightly harmful	?	?	?	Harmless	Harmless	?	Harmless	Harmless	Harmless
	Lacewing	*Chrysoperla carnea*	Harmful	Harmful	Harmless	Harmful	Harmless	Slightly harmful	Moderately harmful	Harmful	Harmful	Harmless	Harmless	Harmless	Harmful	Harmful	Moderately harmful	Harmless	Harmful	Harmless	Harmless	Harmful	Harmless	Moderately harmful
	Hoverfly	*Syrphus vitripennis*	Moderately harmful	Harmful	?	Harmful	Moderately harmful	Harmful	Harmful	Harmful	?	Harmful	Moderately harmful	Moderately harmful	Harmful	Harmful	Harmful	Harmful	?	?	Harmless	?	Slightly harmful	Harmless
	Ground beetle	*Pterostichus melanarius*	Moderately harmful	?	Harmless	Harmful	Harmless	Harmful	Slightly harmful	Harmful	Harmless	?	Harmless	Harmless ●	Slightly harmful	Harmless	?	Harmless	Harmless	Harmless	Harmless	Harmless	?	Harmless
	Rove beetle	*Aleochara bilineata*	Moderately harmful	?	Harmless	?	Moderately harmful	?	Harmful	Harmful	Harmful	?	Moderately harmful	?	?	Harmful	?	Harmless	Harmless	Harmless	Harmless	Harmless	?	Harmless
	Pirate bug	*Anthocoris nemoralis*	Harmless	Harmful	Harmless	Harmless	Moderately harmful	Harmful	Harmful	Harmful	Harmful	?	Harmless	Slightly harmful ●	Moderately harmful	?	Harmful	Slightly harmful	Slightly harmful	Harmless	?	Harmful	Harmless	Harmless
Pathogens	Fungi	*Verticilium lecanii*	Slightly harmful	?	Harmless	Harmless	Harmless	Harmless	Harmless	Moderately harmful	Harmless	?	Slightly harmful	?	Harmless	Harmless	?	?	Harmless	Slightly harmful	Harmful	?	?	Harmful

● Estimations made from data available in SELCTV database

Harmful (adverse effects* in 99% tested).
Moderately harmful (adverse effects* in 80-99% tested).
Slightly harmful (adverse effects* in 50-79% tested).
? No test results available
Harmless (adverse effects* in less than 50% tested).

*In most cases the tests only measure mortality (death rate).

These data are based on laboratory tests carried out according to International Organisation for Biological Control (IOBC) protocols between 1983 and 1998. Laboratory testing exposes the test organism to higher levels of pesticide than would normally be experienced in the field. The tests consider the impact of each pesticide on mortality (death rate) and sometimes include a range of sublethal effects such as effects on egg production. The effects of mixtures of pesticides are not tested. The IOBC supports a sequential testing system that includes up to three basic levels of testing: laboratory, semi-field and field. The basic assumption made is that since exposure is highest in the laboratory and least in the field, if a pesticide is shown to be 'harmless' in the laboratory, it is likely to be harmless in the field. If it is shown to be 'slightly harmful', 'moderately harmful' or 'harmful' following one test, further testing is required, at the next successive level of exposure (i.e., extended laboratory test, semi-field test or field test).

Koppert Side Effects Database

Koppert is one of the leading companies involved in the production of biological control agents and pollinators. Koppert's headquarters and principal research base is in the Netherlands, but the company also has offices in England, France, Italy, Spain, the USA, Canada, Mexico, Turkey and New Zealand. It has developed a very useful Side Effects Database which is accessible on the Internet at the following website:

http://www.koppert.nl/english/service/index.html

You can access the database free of charge, but you need to go through a simple registration process the first time you use it. The database allows you to select from a wide range of insecticides, acaricides and fungicides and compare their toxicity and persistence against a range of important natural enemies (and bumblebees). Data are provided for immature as well as adult insects and include estimates of the persistence of each product. The information is based on the results of the IOBC Working Group 'Pesticides and Beneficial Organisms', other published research, as well as Koppert's own research and experience. More than one hundred scientific publications were included in the comparative literature study.

SELCTV Database

Also requiring access to the Internet is a comprehensive database dealing with side effects of pesticides on arthropod natural enemies. Access is again free. It is known as the SELCTV (pronounced *selective*) database and it is based on published literature, including the results of many field experiments. The website for the database is:

http://www.ent3.orst.edu/Phosure/database/selctv/selctv.htm

Development of the database began in 1986/87 in the Department of Entomology at Oregon State University, Corvallis (Oregon, USA.). The database represents a relatively comprehensive compilation of the literature published worldwide, from approximately 12,500 data records describing pesticide effects on non-target arthropods. Records date from 1921 to 1994, although at the time of writing the majority of the records originate from the pre-1986 literature. It is thus particularly useful for older pesticides, many of which are still widely used. Each record in the output table represents the effects of a pesticide on one natural enemy taxon under conditions described in the source publication.

An 'average toxicity rating' system is used (1 = no effect, 2 = <10% response, 3 = 10-30% response, 4 = 30-90% response, 5 = >90% response). Links are provided to the published sources for the data. The database allows you to insert the pesticide, crop, country and other criteria of your choice before a search is run.

The database developers aim to create a self-funding, continuously updated, unbiased, international resource useful for both research and decision-making in pest management. For more information contact: Dr Phil Heneghan *Department of Entomology, Oregon State University, 2046 Cordley Hall, Corvallis, Oregon 97331-2907, U.S.A; email: heneghap@bcc.orst.edu.*

Note on Use of Botanical Pesticides

About 20 pesticides extracted from plants are used widely by some smallholder or organic growers in different parts of Zimbabwe. Some of these products are derived from plants indigenous to the region (e.g., *Schwartzia madagascariensis*, snake beans), while others are from exotic plants now growing in Zimbabwe (e.g., tobacco) or from imported plant parts or extracts (e.g., many pyrethrum products).

Although there is some evidence that some botanical products might be quite selective against pests and relatively harmless to natural enemies, the data on which these conclusions are based are on the whole very limited. This is because, as yet, botanical pesticides, which are often extracted from botanical products on-farm, have not been scrutinised by registration authorities or researchers in the same way as synthetically-produced pesticides. From the available data, we do know that some botanical pesticides (e.g., nicotine extracted from tobacco leaves) may be much more broadly toxic, to humans and other mammals as well as to arthropods, than many synthetic pesticides.

Until reliable data are available on the side effects of botanical pesticides against both mammals and other non-target organisms, including natural enemies, these pesticides should be treated as being of unknown hazard. Unless, there is a good body of evidence demonstrating the harmlessness of specific botanical pesticides to natural enemies and other non-target organisms, their use should be avoided.

Selective pesticide application

Apart from selecting pesticides that are likely to be less harmful to natural enemies (Part 3.1) and other non-target organisms such as pollinators, further selectivity can be gained by judicious pesticide application.

There are five important aspects of pesticide application that can be manipulated to help reduce non-target effects. Further information on this subject can be found in a companion manual entitled 'Integrated Vegetable Pest Management in Zimbabwe' (authored by Hans Dobson, Jerry Cooper, Walter Manyangarirwa, Joshua Karuma and Wilfred Chiimba).

■ Target the spray carefully on to the pest

If the pest (in any of its life stages) cannot be exposed to the required dose of an insecticide, for example because the pest is concealed within stems or fruits or hidden within curled leaves, application may be ineffective, wasteful and may simply disrupt natural enemies that may otherwise be able to 'search out' prey. Many pests are present on the underside of leaves, so spraying the upper surface of leaves may result in insufficient exposure of the pest, or to be effective, may require use of excessive doses. In addition, such treatments will be harmful to natural enemies, which often search all parts of plants. Careful targeting of spray requires a thorough knowledge of the habits of the pest, an experienced applicator, a good quality, calibrated sprayer, and appropriate nozzles.

■ Minimise the volume application rate

By careful targeting and use of good quality, calibrated sprayers and nozzles, volumes of pesticides used can be minimised. For control of most vegetable pests and diseases in smallholder, tropical vegetable systems, operators should ideally apply water-based sprays at rates between 200 and 400 l/ha (even less for small or young crops), in the range known as

Medium Volume spraying. In contrast, many spraying operations actually use High Volumes of over 1000 l/ha. This is wasteful and may cause greater exposure of natural enemies than lower volume applications – the excess liquid drips from plants and adversely affects a wide range of natural enemies that are ground-dwelling or have a soil-based life stage. Also, since tank concentrations are usually calculated on the assumption of lower volume application rates, High Volume spraying means the operator is often applying many times the required dose of the pesticide itself. The droplet size of the spray is very important for efficient application and needs to be varied according to the type of application. A significant proportion of very fine droplets (less than 100 μm [microns] in diameter) in a spray may lead to pesticide drift which is wasteful, prevents much of the pesticide being deposited on the target and can lead to undesirable impacts on natural enemies and other non-target organisms. The most efficient coverage for most applications targeting vegetable pests on foliage involves deposition of small discrete droplets and does not involve spraying to the point of run-off. For many situations, 5 –15 small droplets of around 100 – 300 μm in diameter of an appropriate formulation on each square centimetre of infested foliage provides reliable control. Knapsack sprayers fitted with a small hollow cone nozzle are capable of achieving this, but it is difficult to achieve with flat fan and other types of nozzle. Although the sprayer may be calibrated to apply a rate of between 200 and 400 l/ha, the actual volume application rate per hectare of crop can be reduced considerably by selective spraying techniques. These techniques include spot spraying (i.e., targeting areas of substantial pest infestation only) or strip spraying (i.e., applying bands of treatment through a crop, the width of the sprayed and untreated bands being dependent on factors such as the severity of the infestation and prevalence of natural enemies).

Timing of pesticide application

If it is decided that spraying must occur, make sure it is carried out at a time of the day or even season when there is the lowest chance of adversely affecting natural enemies. Some natural enemies like hover fly and ladybird beetle larvae are most active at night, so spraying at dawn might expose more to the pesticide. Other natural enemies, such as parasitoids, are more likely to be searching plants during the daytime, sometimes avoiding the hottest times of day. However, other factors must also be taken into account. Conditions must be selected to avoid the risk of pesticide drift caused by very small droplets being carried by wind, or scorching of foliage by intense sunshine that can occur by magnification of the sunlight through pesticide/water droplets. Optimum weather conditions for spraying are usually most likely to occur in the early morning or late afternoon.

Minimise the pesticide concentration

Use the minimum concentration recommended on the product label (or less, if it still gives adequate control). Not all pesticides kill pests quickly so a slow result does not mean a poor result. In some cases, using a low concentration may give a better long-term result because it will suppress the pest numbers without killing the natural enemies – the natural enemies can then control most of the remaining pests. By spraying at the right time for example against more susceptible immature stages of a pest (e.g., small, early instars of a caterpillar pest), it is often possible to use a low dosage. Once the pests have grown to a larger size (e.g., large, late instar caterpillars), they are often much more difficult to kill as their tolerance to many pesticides increases. This tolerance is usually caused by the presence of enzyme-based detoxification systems within the pest that have evolved to cope with secondary plant products, which make most plants toxic to most plant-eating arthropods.

Reduce the frequency of application

Apply pesticides as infrequently as possible, and only when there is clear evidence that natural enemies are providing inadequate levels of control. This might involve the need for only a single application that either reduces the numbers of pests or slows their rate of development. Combined with appropriate conservation practices, natural enemies should then be able to provide sustainable control of pests.

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Species List 1: Predators

The following genera and species of predators (List 1) and parasitoids (List 2) have been identified, mainly between 1998 and 2000, on vegetable crops in Zimbabwe and Kenya. This is by no means on exhaustive list but it does contain some of the most common natural enemies likely to be encountered.

Order	Family	Genus/species
Coleoptera	Coccinellidae	*Hippodamia variegata*
		Cheilomenes spp., including *C. lunata*, *C. propinqua* and *C. sulphurea* *Exochomus* spp., including *E. troberti* and *E. ventralis*
	Carabidae	*Calosoma* spp. *Chlaenius* sp. *Passlidius fortipes* *Harpalus agilis* *Microlestes* sp. *Stenethmus* sp.
	Staphylinidae	*Philonthus* sp. *Oligata* (*Holobus*) sp.
	Anthicidae	*Anthicus biplagiatus* *Formicomus rubricollis*
	Nitidulidae	*Cybocephalus* sp.
Hemiptera	Anthocoridae Reduviidae	*Orius* spp. *Harpactor* sp.
Neuroptera	Chrysopidae	*Chrysoperla* spp.
Diptera	Syrphidae	*Metasyrphus corollae* *Syritta flaviventris* *Ischiodon aegyptius* *Betasyrphus adligatus* *Melanostoma annulipes* *Allobaccha sapphirina* *Paragus* sp.
Mantodea	Mantidae	*Sphodromantis* spp.
Hymenoptera	Vespidae Sphecidae	*Polistes* sp. *Sphex* sp.
Acari	Phytoseiidae	*Amblyseius* spp., including A. teke and A. tutsi *Phytoseiulus* spp. *Typhlodromus* spp.
Arachnida	Lycosidae Linyphiidae Oxyopidae	*Pardosa* spp. *Microlinyphia* spp. *Peucetia* spp.

Species List 2: Parasitoids

Order	Family	Genus/species
Hymenoptera	Braconidae	*Meteorus* sp. *Apanteles* sp. *Cotesia* spp., including *C. ruficrus* and *C. plutellae* *Glyptapanteles maculitarsis* *Microchelonus curvimaculatus*
	Braconidae: Aphidiinae	*Diaeretiella rapae* *Aphidius* spp., including *A. colemani*
	Ichneumonidae	*Diadegma* sp. *Charops* sp. *Diplazon laetorius*
	Eulophidae	*Diglyphus* spp., including *D. isaea* *Meruana liriomyzae* *Neochrysocharis* sp. *Oomyzus sokolowskii*
	Scelionidae Chalcididae Encyrtidae	*Telenomus* sp. *Brachymeria* sp. *Syrphophagus africanus*
Diptera	Tachinidae	*Gonia bimaculata* *Nemoraea rubellana* *Palexorista* spp., including *P. laxa* *Periscepsia carbonaria* *Nemorilla* sp.
	Bombyliidae Calliphoridae	*Bombylius* sp. *Isomyia dubiosa*

Notes