Research Review No. 64

June 2007

Price: £6.50

Importance of arthropod pests and their natural enemies in relation to recent farming practice changes in the UK

by

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This is the final report of a four month project which started in September 2006. The work was funded by a contract for £19,017 from the Home-Grown Cereals Authority (Project No. RD-2006-3302).

The Home-Grown Cereals Authority (HGCA) has provided funding for this project but has not conducted the research or written this report. While the authors have worked on the best information available to them, neither HGCA nor the authors shall in any event be liable for any loss, damage or injury howsoever suffered directly or indirectly in relation to the report or the research on which it is based.

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Abstract

Pressure to reduce insecticide use and increase farmland diversity is encouraging farmers to employ a range of approaches to reduce the impact of insect pests on crop yield and quality. Insecticide applications are often still required to prevent significant damage but these interact with other approaches and can undermine efforts to sustain functionally significant populations of beneficial insects. Populations of beneficial and pest insects are also influenced by a range of other factors including cultivations, climate, landscapes and rotations. Consequently, the population dynamics of beneficial and pest insects in arable agriculture are complex. In this review the economically important pests and beneficial arthropods in arable crops were assessed in the context of recent changes in farming practice.

Pests

The current and future status of the more important and potentially important pests of cereals and oilseed rape was reviewed. Information on incidence was drawn from specific surveys of incidence, where conducted, and reports from agronomists and farmers. The reasons for changing status were reviewed, with particular emphasis on any changes linked to climate change, changing farming practice and landscape issues. Milder winters have increased the importance of those pests active during the winter, especially aphid virus vectors transmitting BYDV and oilseed rape viruses. Warmer spring and summer temperatures have resulted in outbreaks of other pests such as orange wheat blossom midge and turnip sawfly. Warmer autumn weather favoured pests such as gout fly and cabbage stem flea beetle. The provision of larger areas of grass margins favoured the traditional ley pests and pests such as the cereal ground beetle.

Natural enemies of cereal and oilseed pests

A list of all the natural enemies of cereal and oilseed rape pests was compiled from the literature. References on their biology and ecology were reviewed, along with opinions of relevant experts and a subjective scoring system devised to identify important gaps in knowledge. This revealed large discrepancies in the level of knowledge for different families and even orders of insects. Long-term trends in the abundance of natural enemies were reviewed using data from The Game Conservancy Trust Sussex study. Polyphagous predators showed consistent long-term declines, unlike the aphid-specific predators. These may be more vulnerable to intensive farming practices because many species are relatively immobile. Parasitica were probably responding to the trends in their hosts, but as they are not identified to species, this relationship could not be examined.

The options available under the Environmental Stewardship scheme, along with minimum tillage and Integrated Pest Management, were assessed to identify the types of natural enemies that they can support and for their potential to improve biocontrol. A subjective score was determined that indicated the potential of each habitat type for natural enemies. Overall well-managed hedgerows comprised a substantial shrubby component with a 2m wide floristically diverse hedgebase providing most resources. Relatively few of the options allow for manipulation of the cropped area even though this is important for some of the most abundant natural enemies (Carabidae, Linyphiidae and some parasitoids). Pest control using insecticide/molluscicide was considered by a panel of experts to remain the mainstay in the future, however alongside the use of natural enemies. To achieve such a balance would require further information and the use of reduced doses was seen as one possible way forward. Suggestions for future research are provided.

1. Introduction

Insect pest of cereals and oilseed rape show considerable variation in incidence from year-to-year due to climatic and agronomic factors. These fluctuations can make it difficult to identify trends in incidence due to other factors.

Fluctuations in temperature are particularly influential on cold blooded insect pests, affecting their rate of development, fecundity, longevity and ability to fly. A trend to warmer temperatures has been evident since 1989. This has directly increased the importance of certain pests, such as the orange wheat blossom midge, which are very sensitive to temperature at critical stages in their life cycles.

Climatic factors also have an indirect effect through their influence on crop establishment and growth.

Other factors affecting pest incidence include the rotation, both in terms of succeeding crops and intensity of cropping, cultivation, the time of sowing, the varieties grown, overall pesticide usage and the impact of natural enemies. Long distance migration can introduce new pest problems to an area.

One issue considered in this review is whether changes to the agricultural landscape may enhance the survival of particular pest by providing alternative host plant reservoirs, hibernation sites and adult food sources.

Each year ADAS collates information on pest incidence on behalf of PSD, continuing a series of such observations which started in 1917 (Anon, 1918). An extract of these reports back to 1993 before the current warm phase is at Appendix 1. These records have been examined to establish whether any pests are changing in status. Possible causes for increasing numbers are examined.

Natural enemies with specific hosts are dependent on the presence of the host for their survival. High mortality of the natural enemies will result if the all of the available food supply is eaten. Preserving a low population of pests in a natural habitat could help to stabilise natural enemy numbers. Other natural enemies are more general feeders and could benefit from the provision of alternative prey within marginal habitats.

Agri-environment schemes offer a range of options for creating wildlife habitats on farmland. Substantial areas of farmland are now devoted to such schemes and this is expected to increase further with the introduction of Entry Level and Higher Level Stewardship schemes in 2005. Many of these habitats can support substantial populations of arthropods, including pests and their natural enemies.

The options available under Entry Level Stewardship, Organic Entry Level Stewardship and Higher Level Stewardship schemes were appraised to identify the types of natural enemies that they can support and for their potential to improve biocontrol.

Studies of the invertebrate natural enemies of cereal and oilseed rape pests are extensive but usually conducted as isolated studies of individual species or guilds. A comprehensive list of the known invertebrate natural enemies was compiled.

Aims

- To identify important gaps in knowledge regarding the biology and ecology of economically important pests and their invertebrate natural enemies in arable crops.

- To review the impacts of changes in farming practice, for example agri-environment schemes, tillage, rotations on the dynamics between pests and their natural enemies.

Objectives

- Define a list of target species of pests and their invertebrate natural enemies.
- Review published literature and recent/ongoing projects in the UK and overseas on the biology and ecology of existing and emerging pests.
- Identify changes in the prevalence of different pests.
- Review relevant changes in crop production, for example Environmental Stewardship schemes, tillage and rotations.
- Assemble a list of researchers working in this area.

2. Review of cereal pests

Table 1. Current status of pests

Common name	Scientific name	Status
Rose-grain aphid	*Rhopalosiphum padi*	Increasing due to warm autumns / mild winters
Grain aphid	*Sitobion avenae*	Increasing due to warm autumns / mild winters
Green bug*	*Schizaphis graminum*	Increasing in France, occasionally recorded in UK
Leatherjackets	*Tipula* spp.	Fluctuating with autumn rainfall
Orange wheat blossom midge	*Sitodiplosis mosellana*	Increased incidence since 1993
Yellow wheat blossom midge	*Contarinia tritici*	Increasing since 2005.
Frit fly	*Oscinella frit*	Fluctuating.
Gout fly	*Chlorops pumilionis*	Increased from 1989.
Yellow cereal fly	*Opomyza florum*	Caused problems in the early 1980's, then declined
Wheat bulb fly	*Delia coarctata*	Fluctuating according to wet weather around harvest
Cereal ground beetle	*Zabrus tenebriodes*	Increasing slowly on affected farms
Wireworm	*Agriotes* spp.	Increasing in arable rotations
Wessex flea beetle	*Psylliodes luteola*	Spreading rapidly from original centre
Cereal stem sawfly	*Cephus cinctus*	Increasing generally
Cabbage aphid	*Brevicoryne brassicae*	A problem after mild winters.
Peach-potato aphid	*Myzus persicae*	A problem spreading virus during mild winters but less so due to widespread insecticide use.
Brassica pod midge	*Dasineura brassicae*	Static, highly visible damage on headlands, but of no consequence
Cabbage root fly	*Delia radicum*	Incidence related to time of sowing and speed of emergence, more seen in autumn 2006.
Cabbage stem flea beetle	*Psylliodes chrysocephala*	Spreading N and W. Incidence

		higher in ‘new’ areas.
Rape winter weevil	*Ceutorhynchus picitarsis*	Incidence increasing
Seed weevil	*Ceutorhynchus assimilis*	Incidence low and remaining so.
Cabbage stem weevil	*Ceutorhynchus pallidactus (quadridens)*	Static
Rape stem weevil*	*Ceutorhynchus napi*	A major pest on the continent, not yet in UK.
Pollen beetle	*Meligethes aeneus*	Insecticide usage greatly increased in UK, may lead to resistance problems as on Continent
Turnip sawfly	*Athalia rosae*	Large migration to UK in 2006 after long absence, problems may now persist.

2.1 Bird cherry aphid and grain aphid as BYDV vectors

The bird cherry aphid is important only as a vector of BYDV. A form of the aphid has evolved that overwinters on cereal. Harrington (2003) has demonstrated that a mean winter temperature in excess of 4.6ºC is required for this strain to overwinter successfully and pose a threat in the following autumn.

The grain aphid first emerged as a significant overwinter vector of BYDV in the very mild winter of 1988/89. The effect was to overturn a forecast of low BYDV incidence following a cold wet autumn and result in widespread BYDV infection. A similarly mild winter followed in 1989/90 resulting in the adoption of a prophylactic approach to autumn aphid control on cereals that continues to the present day. Oakley & Young (2000) demonstrated that a similar mean winter temperature of around 5ºC applied to the development of BYDV spread by grain aphid.

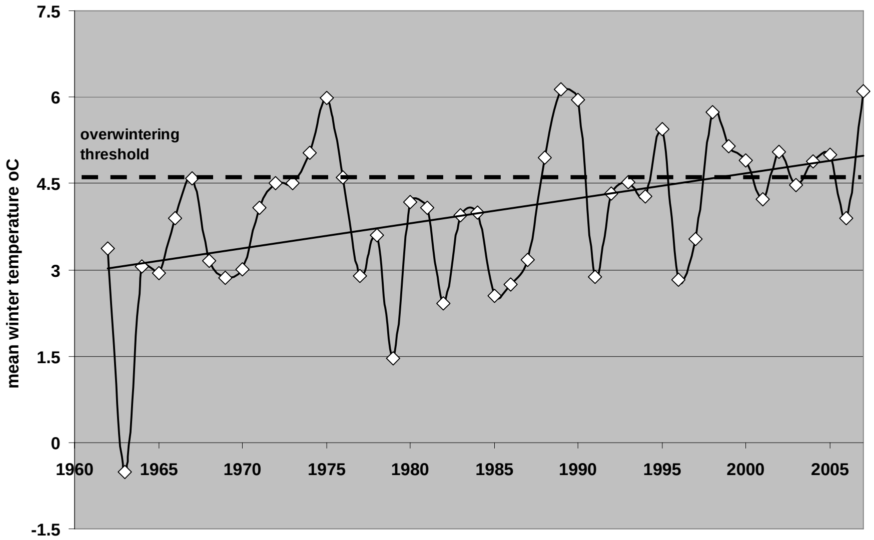

Figure 1. Mean winter temperatures in England and Wales 1961-2007 (Meteorological Office).

The prevalence of mild winters has increased to the point that a prophylactic approach may now be justified (Fig. 1); however the widespread pesticide use prevents the collection of any data on whether it is indeed needed.

Possible implications of landscape factors

Autumn migrations of cereal aphids come from grasses which bridge the gap between cereal crop maturity in the summer and the emergence of winter crops. Perennial grasses also act as a reservoir of BYDV. In arable areas the addition of grassed margins could significantly increase the availability of such reservoirs. Local reservoirs of infested aphids may allow late spread by short flights of winged aphids and by walking wingless aphids, increasing the possibility of re-infestation after treatment.

2.2 Summer aphid problems

Summer aphid problems are usually caused by the grain aphid. The last widespread outbreak was in 1975 when initially low numbers of aphids increased rapidly in favourable weather with few natural enemies to restrain them. This may have been due to widespread spraying against orange wheat blossom midge in 1974 which eliminated many natural enemies. The increase in spraying to prevent BYDV spread has reduced the incidence of overwintered infestations causing problems in the summer and most grain aphid infestations probably originate from aphids migrating from grasses.

Potential damage can be caused by the rose-grain aphid. This species overwinters as eggs on roses but usually arrives on cereal crops after grain aphid. This aphid is usually well controlled by natural enemies attracted to the crop by the presence of grain aphids.

Should temperatures continue to rise, the green bug could become a problem in the UK. Numbers caught in suction traps are increasing (Harrington, pers. comm.) and the species has occasionally been recorded on wheat crops in the SE. The EURAPHID suction trap network provides a suitable means of monitoring the spread of this aphid.

2.3 Leatherjackets (*Tipula paludosa* and *T. oleracea*)

Leatherjacket numbers fluctuate according to rainfall in the autumn, the eggs and young larvae being susceptible to dry conditions.

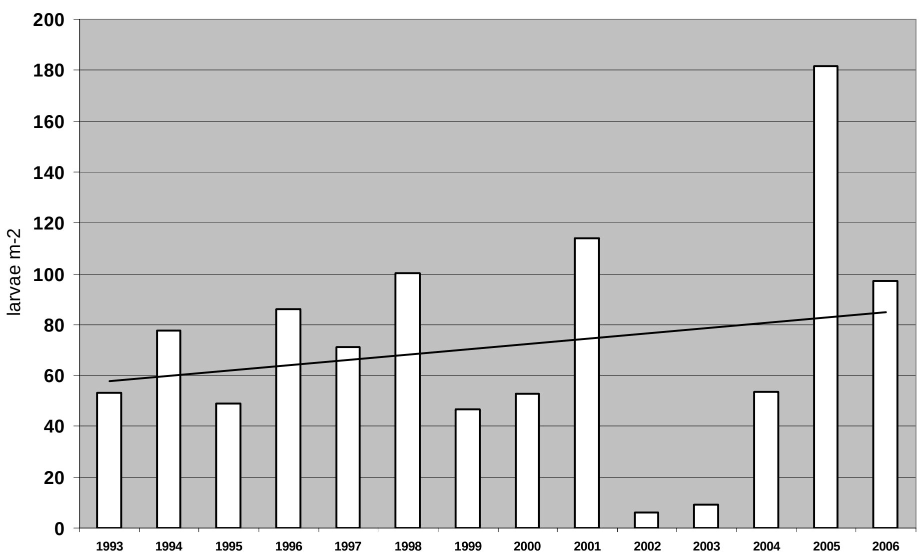

Figure 2. Mean annual leatherjacket numbers in grassland (1993-2006).

Numbers recorded in grassland between 1992 and 2006 (Fig. 2) suggest that there may be a trend for populations to increase when, unlike 2002 and 2003, weather conditions favoured low mortality.

Leatherjackets are a typical ‘ley’ pest affecting crops sown after grass leys are ploughed up. They may also be found after oilseed rape crops sown after a ley where the canopy prevents the adults from escaping

(Blackshaw & Coll, 1999). It is unlikely that marginal grass strips would affect population dynamics on the mixed farms where they occur as they would not add significantly to the grassed area.

2.4 Orange wheat blossom midge

The current orange wheat blossom midge (owbm) outbreak was first noticed in 1993 when half of UK wheat crops were damaged sufficiently for quality to be reduced and 21% of crops suffered significant yield reduction. A heavy insecticide usage in 1994 reduced numbers, but these recovered progressively from 1996 to cause a further major outbreak in 2004. Insecticide usage and the introduction or resistant varieties grown in 20% of fields reduced numbers in 2005 and 2006. Incidence also increased over the same period in France, Belgium, Denmark and Germany due to similar climatic factors.

As the larvae hibernate in the soil of infested fields and the adults don't feed it is unlikely that landscape factors will influence incidence. Further outbreaks remain probable whenever and wherever soil temperatures and moisture in late May and early June induce a hatch of adult midges coinciding with the susceptible ear emergence stages of crops. The use of resistant varieties could help to reduce population recovery and stabilise the situation.

2.5 Yellow wheat blossom midge

The yellow wheat blossom midge (ywbm) is favoured by the same climatic conditions as owbm. Numbers are now increasing to give noticeable infestations in many crops. The ywbm can attack owbm resistant varieties so could benefit if their use replaces insecticides as the main form of control.

2.6 Frit fly

The frit fly is a 'ley' pest attacking crops sown after ryegrass leys. Direct egg lay may also occur on volunteer cereal plants and early sown crops. Other grass species are poor hosts so the avoidance of ryegrass in grass margins would prevent them acting as reservoirs for infestations.

2.7 Gout fly

Gout fly has increased greatly in numbers thanks mainly to the early sowing of winter wheat crops. It has two generations per year and the summer generation, feeding mainly in the flag leaf sheaf causes more yield loss than the winter generation which causes swollen shoots. A project funded by the HGCA confirmed that crops recovered well from winter damage (Bryson *et al*. 2005)

Adult gout flies hatch from crops in late July and feed on flowers, mainly Umbelliferae to maintain themselves and mature eggs that they start to lay in October. The provision of wildflower strips with species flowering in August and September could aid survival and retain populations close to fields. The parasitoids attacking gout fly utilise the same flowers to feed.

2.8 Yellow cereal fly

The yellow cereal fly caused a lot of concern in the early 1980's when early sowing encouraged the pest, which lays its eggs in the autumn to increase. Some varieties, particularly Maris Freeman, were prone to overcompensate for damage and produce a second tier of small, late, secondary tillers in response to damage. Current varieties tend not to do this and recover well from attacks.

2.9 Wheat bulb fly

Adult wheat bulb fly hatch in June and feed on saprophytic fungi and wildflower pollen to mature eggs laid from the end of July. They tend to do better when July and early August are wet encouraging the growth of saprophytic fungi and delaying the harvest of wheat crops in which they rest and feed. Numbers vary considerably from year to year, but in recent years there has been a trend towards more fields having populations above the economic threshold (Fig. 3).

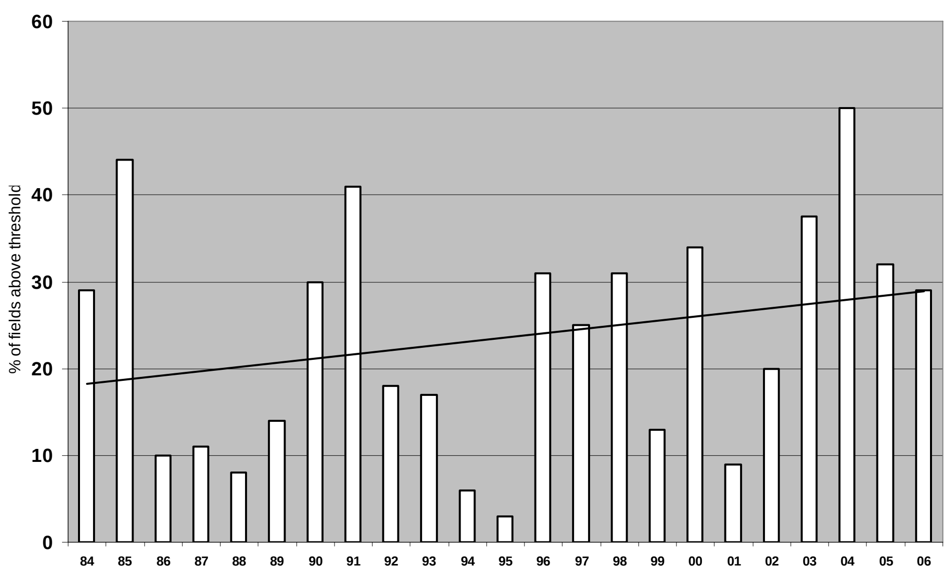

Figure 3. The percentage of fields sampled in England each year with egg numbers above the economic threshold of 250 eggs m^{-2}.

Couch grass is an alternative host of wheat bulb fly. Small populations are maintained on most farms on couch grass but development of these into problem levels is dependent on the adoption of a suitable rotation. This involves growing wheat after a crop providing an egg laying site such as set-aside vining peas or root crops on at least 10% of the farm area. Where this situation occurs on 25% of the farm area regular wheat bulb fly problems tend to develop (Young & Ellis, 1996).

An increase in areas prone to couch grass infestation would be insufficient to increase populations to damaging levels.

2.10 Cereal ground beetle

Problems associated with cereal ground beetle first appeared in the 1980's on certain farms in the south of England in the 1980's and have slowly developed on these farms subsequently. The pest is slow to spread and quite rare generally so that newly infested farms have tended to be those adjoining previously infested areas.

As it colonises new fields quite slowly the pest is dependent on the provision of a rotation dominated by cereals and grasses to maintain damaging levels. Growing a broad-leaved crop cuts numbers back severely and it usually takes 3-4 years for numbers to return to damaging levels. Ploughing also tends to provide some control. Increased problems have occurred on farms with wide grass margins which provide a reservoir for infestations; here populations have recovered much more quickly after a break crop has reduced numbers.

2.11 Wireworms (*Agriotes* spp.)

Wireworm numbers have tended to increase gradually on many farms growing arable rotations. The causes of this increase have not been studied, but it is suspected that it is due to a switch to mainly winter cropping providing a year round food supply for the larvae. As with cereal ground beetle the provision of grassed field margins provides a reservoir for infestations that can spread into cultivated fields (Parker & Howard, 2001).

2.12 'Wessex' flea beetle (*Psylliodes luteola*)

The 'Wessex' flea beetle has continued to spread out from the herbage seed growing farms on the Hampshire/Wiltshire border on which it was first noted in 1994. Infestations have now been recorded as far north as the Wash. Nothing is known of the biology of the species other than that very large numbers of adult beetles appear in the early autumn and feed on germinating seeds of cereals, grass and oilseed rape. It is presumed that the unknown larvae may feed on grasses in which case grass margins may provide reservoirs of infestation.

2.13 Cereal stem sawfly (*Cephus cinctus*)

The cereal stem sawfly is an 'old' pest that had virtually disappeared from the UK for many years. The larva feeds in the stem of wheat plants from mid-June onwards interfering with grain filling and weakening the stem. The damage is easily overlooked and it is only the increasing frequency of adult sawflies in the crop that has drawn attention to the pest. The adult sawflies feed on wildflowers and the presence of wildflower strips could attract more sawflies to a field and increase their longevity and fecundity.

3. Review of oilseed pests

3.1 Cabbage aphid

The cabbage aphid overwinters on brassica plants. When warm autumn encourage colonisation of oilseed rape crops patches of infestation may break out in the spring causing considerable damage. These infestations re usually controlled by parasitoids and seem to have become less frequent as autumn insecticide usage and seed treatment has increased. As with all the oilseed rape pests the inclusion of other brassicas, such as kale in wild bird seed mixes could provide an alternative host plant, maintaining a reservoir of cabbage aphids. However, this should also maintain a reservoir of parasitoids.

3.2 Peach-potato aphid

Peach-potato aphid is mainly important as a vector of TSWV. As with cabbage aphid problems appear to have declined with increasing pesticide usage.

3.3 Brassica pod midge

The damage caused by brassica pod midge larvae is mainly restricted to the headland. The damage is extremely visible so that the pest's importance tends to be over rated. There is no evidence that the loss of some pods results in significant yield depression or of increased levels of damage.

3.4 Cabbage root fly

Cabbage root fly larvae frequently attack early sown oilseed rape crops in the autumn, particularly those crops which emerge before the end of September. There are insufficient records of incidence to detect any trends.

Cabbage root fly attack all brassica crops and incidence could be increased by the growing of kale and stubble turnips in the absence of vegetable brassicas. The adult flies feed on flowers and would benefit from wildflower mixes, especially those containing umbellifers.

3.5 Cabbage stem flea beetle

The area affected by cabbage stem flea beetle has continued to spread northwards following an earlier spread across all of southern England from the original haunts of East Anglia. Within newly infested areas numbers tend to increase until regular insecticide treatment is adopted (Figure 5).

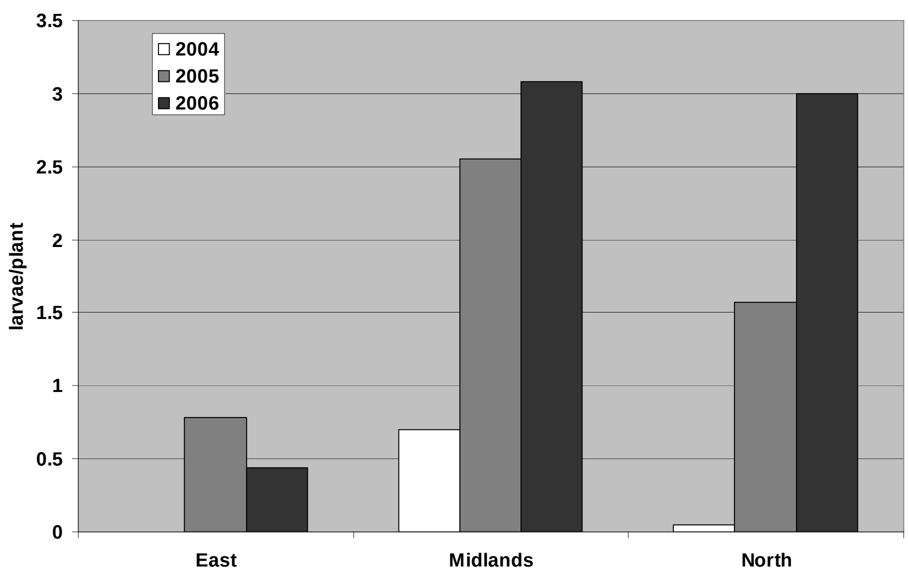

Figure 4. Mean csfb larval infestation by region 2004-06.

Cabbage stem flea beetles hatch at around harvest time and aestivate in field boundaries before starting to feed and lay their eggs from early September. The presence of suitable field boundary habitats could aid retention of csfb by previous crops where volunteer oilseed rape plants would provide an early food source.

3.6 Rape winter stem weevil

Numbers of rape winter stem weevil are currently increasing in the infested areas of the Midlands and East Anglia. It is suspected that use of insecticide sprays may have declined with the adoption of Chinook seed treatment, which does not control this pest. This beetle also aestivates in the summer and could be favoured by suitable field margin habitats.

3.7 Cabbage seed weevil

The cabbage seed weevil is generally well controlled by its parasitoid and numbers well below threshold. Searching plants to count adult weevils is unpopular resulting in considerable over treatment with the opportunity being taken to include an insecticide with Sclerotinia sprays.

Cabbage seed weevil’s hibernation behaviour is poorly understood, but appears to be dispersed and unlikely to be enhanced by field margin management.

3.8 Pollen beetle

Pollen beetle numbers during the green to yellow bud stages are more important those found feeding on open flowers later. These tend to be highest in seasons when warm spells in March reach the flight threshold of 15ºC allowing for early migration to crops.

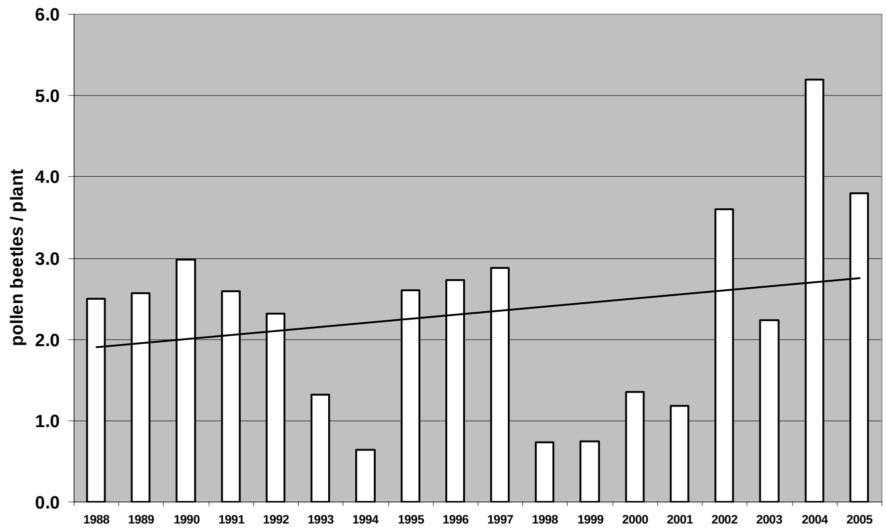

Figure 5. Numbers of pollen beetles per plant at green/yellow bud stages 1998-2005. (CSL Pest Monitoring Scheme data).

Numbers were particularly high in 2004 (Northing pers. comm., Fig. 5) when 58% of oilseed rape crops were sprayed against pollen beetle (Garthwaite *et. al.* 2005). This is a considerable increase in previous spray usage. It would appear that most of these applications are against relatively low numbers of the pest. Insecticide resistant pollen beetle are now a serious problem on the Continent and over use of insecticides in the UK could lead to selection of resistant beetles here.

The hibernation sites used by pollen beetles are poorly understood. The beetles disperse before harvest and feed on a range of flowering plants before hibernating in lighter soils in woodland or grassland. Widlflower strips by fields can attract large numbers of pollen beetles, but whether they then remain on the farm to hibernate is unknown. Where the beetles disperse prior to hibernation it seems unlikely that the provision of additional hibernation sites on farms will have any great effect on risk, although beetles from sources close to crops could disperse to them when conditions do not favour longer range flight.

3.9 Turnip sawfly

Following hot summer weather in France a large scale migration of turnip sawflies invaded England in late August and September. An outbreak of this scale had not been recorded since the 1830s. Outbreaks tend to persist until a severe winter kills the hibernating larvae. It is anticipated that the larvae will have overwintered well and will cause further trouble in summer 2007.

Turnip sawfly has three generations per year, feeding on oilseed rape, turnips, kale and charlock. The adult sawflies feed on wildflowers to increase longevity and fecundity and fuel long distance migration.

4. Review of cereal pest natural enemies

4.1 Pest natural enemy community composition

A list of all the natural enemies of cereal and oilseed rape pests was compiled from the literature, internet searches and project reports (Tables 2 & 3). Pest populations may also be regulated by other organisms including entomopathogenic fungi, nematodes and other microorganisms but these were not appraised here. For cereals the list of natural enemies of cereal aphids was the most comprehensive as these have been much investigated, in part because aphid infestations can be artificially created, their remains are detectable in gut analyses and molecular techniques have been developed to confirm feeding. The parasitoids of the most common cereal aphid species are listed (Table 2) although others exist, especially for those aphids that sometimes occur in the UK but have not yet become serious pests, e.g. green bug and Russian wheat aphid. These two species are the most important cereal aphid species in North America. Their biological control using plant resistance and habitat manipulation was reviewed recently (Brewer & Elliott, 2004). Less detailed information was found for the predators of dipteran pests, especially gout fly and for cereal leafhoppers. No predators were found for the cereal ground beetle. A comprehensive list of the predators and parasitoids of oilseed rape pests was compiled as part of the EU-funded Concerted Action BORIS.

Table 2. Cereal pests and their natural enemies.

Pest name	Pest stage attacked	Natural enemies			
		Species	**Synonym**	**Order**	**Family**
		Predators			
Leatherjackets	Larvae	*Pterostichus melanarius*		Coleoptera	Carabidae
		Cantharis spp. (larvae)		Coleoptera	Cantharidae
	Larvae	*Talpa europaea* L. (moles)		Mammalia	Talpidae
	Larvae	*Sorex* spp., *Crocidura* spp. (Shrews)		Mammalia	Soricidae
	Larvae	*Vanellus vanellus* L. (Lapwing)		Chordata	Charadriidae
	Larvae	*Sturnus vulgaris* L.(Starling)		Chordata	Sturnidae
	Larvae	*Corvus frugilegus* (Rook)		Chordata	Corvidae
	Adults	Many		Chordata	
		Parasitoids			
	egg	*Anaphes* sp.		Hymenoptera	Mymaridae
	larvae	*Phaonia signata* (Mg.)		Diptera	Muscidae
		Predators			
Cereal aphids	Adult/Nymph	*Pardosa agrestis, Pardosa prativaga*		Arachnida	Lycosidae
Grain aphid				Arachnida	Opiliones
Sitobion avenae		*Oedothorax apicatus, Lepthyphantes tenuis, Erigone atra, Erigone dentipalpus*		Arachnida	Linyphiidae
Rose-grain aphid		Many species		Coleoptera	Carabidae
Metopolophium dirhodum		*Tachyporus spp., Philonthus cognatus*		Coleoptera	Staphylinidae
Bird cherry-oat aphid		*Cantharis* spp. (L)		Coleoptera	Cantharidae
Rhopalosiphum padi		*Coccinella septempunctata, Propylea quattuordecimpunctata*		Coleoptera (Beetles)	Coccinelidae
Russian wheat aphid		*Platypalpus* spp., *Hilara* spp., *Tachydromia* spp.		Diptera	Empididae
Diuraphis noxia		*Scathophaga stercoraria*		Diptera	Scathophagidae
Green bug		e.g. *Dolichopus* spp.		Diptera	Dolichopodidae
Schizaphis graminum		e.g. *Aphidoletes aphidimyza*		Diptera	Cecidomyiidae

		e.g. Anthocoris nemorum		Heteroptera	Anthocoridae
		Nabis spp.		Heteroptera	Nabidae
		e.g. *Calocoris spp.*		Heteroptera	Miridae
		Forficula spp. (earwig)		Dermaptera	Forficulidae
		Episyrphus balteatus		Diptera	Syrphidae
		Chrysoperla carnea		Neuroptera	Chrysopidae
		Parasitoids			
		Aphidius rhopalosiphi		Hymenoptera	Braconidae
		A. ervi		Hymenoptera	Braconidae
		A. picipes		Hymenoptera	Braconidae
		Praon volucre		Hymenoptera	Braconidae
		P. gallicum		Hymenoptera	Braconidae
		Ephedrus plagiator		Hymenoptera	Braconidae
		Toxares deltiger		Hymenoptera	Braconidae
		Aphelinus abdominalis		Hymenoptera	Aphelinidae
		Predators			
Orange wheat blossom midge	Adult/Larva	many		Arachnida	Linyphiidae
Sitodiplosis mosellana	Larva/Pupa	many		Coleoptera	Carabidae
	Larva/Pupa	many		Coleoptera	Staphylinidae
	Adult	unknown		Diptera	Predatory flies
		Parasitoids			
	Egg-Larva	*Platygaster tuberosula*		Hymenoptera	Platygastridae
	Egg-Larva	*Macroglenes penetrans*	*Pirene penetrans, Ichneumon penetrans*	Hymenoptera	Pteromalidae
	Egg-Larva	*Euxestonotus error*	*Platygaster error, Anopedias error*	Hymenoptera	Chalcidae
	Egg-Larva	*Inostemma mosellanae*			
		Predators			
Yellow wheat blossom	Adult/Larva			Arachnida	Linyphiidae

midge				
Contarinia tritici	Larva/Pupa		Coleoptera	Carabidae
	Larva/Pupa		Coleoptera	Staphylinidae
	Adult		Diptera	Predatory flies
		Parasitoids		
	Egg-Larva	*Piestopleura* spp.	Hymenoptera	Platygastridae
	Larva	*Leptacis tipulae*		
	Egg-Larva	*Isostasius punctiger*		
		Predators		
Frit fly	Adult		Arachnida	Araneae
Oscinella frit	Adult		Diptera	Empididae
	Egg/Pupa	*Tachyporus* spp., *Philonthus* spp.	Coleoptera	Staphylinidae
	Egg/Larva/Pupa		Coleoptera	Carabidae
		Parasitoids		
		91 species		
	Larva	*Rhoptromeris heptoma*		
	Larva	*Chasmodon apterus*		
		Parasitoids		
Gout fly		*Stenomalus micans*		
Chlorops pumilionis		*Coelinus niger*		
		Predators	Arachnida	Araneae
Yellow Cereal Fly	Pupa	*Coccinella 7-punctata*	Coleoptera	Coccinelidae
Delia coarctata	Pupa	*Cantharis fusca*	Coleoptera	Cantharidae
		Poecillus cupreus	Coleoptera	Carabidae
		Predators		
Wheat bulb fly	Adult		Arachnida	Araneae
	Egg	*Trechus quadristriatus*	Coleoptera	Carabidae

	Larvae	*Agonum dorsale, Notiophilus biguttatus, Bembidion spp*.& others	Coleoptera	Carabidae
		Parasitoids		
	Pupa	*Aleochara bipustulata* and *A. laevigata*		
		Parasitoids		
Saddle gall midge		*Chrysocharis seiuncta*	Hymenoptera	Eulophidae
Haplodiposis marginata		*Platygaster taras*	Hymenoptera	Platygastridae
		Parasitoids		
Cereal stem sawfly		Many species		
Cephus cinctus		*Bracon cephi*	Hymenoptera	Braconidae
		B. lissogaster	Hymenoptera	Braconidae
		Predators		
Cereal leafhoppers			Arachnida	Araneae
Macrosteles cristatus				
M. laevis				
Psammotettix alienus [*P. striatus]*				
Delphacodes (Javasella) pellucida				
Dicranotropis hamata				
Megadelphax sordidula				
J. pellucida				
J. obscurella				
		Predators		
Cereal leaf beetle	Egg/Larva	*Chrysoperla carnea*	Neuroptera	Chrysopidae
Lema melanopus	Pupa	*Coccinella 7-punctata*	Coleoptera	Coccinelidae
		Cantharis fusca	Coleoptera	Cantharidae
		Staphylinus caesareus	Coleoptera	Staphylinidae
		Poecillus cupreus	Coleoptera	Carabidae

		Parasitoids		
	Larva	*Tetrastichus julis*		
	Larva	*Diaparsis carinifer*	Hymenoptera	Ichneumodidae
	Larva	*Lemophagus curtus*		
Cereal ground beetle		No info		
Zabrus tenebrioides				
		Predators		
Wireworm	Adult	Many	Chordata	Many
Agriotes lineatus	Larva		Diptera	Therivae
A. obscurus				
		Predators		
Slugs	Egg/Juvenille	*Abax spp., Carabus spp.,* Pterostichus *spp.*	Coleoptera	Carabidae
Field grey slug		*Scaphinotus striatopunctatus, Scaphinotus interruptus*	Coleoptera	Cychrinidae
Deroceras reticulatum		*Staphylinus olens* *Ocypus olens*	Coleoptera	Staphylinidae
Round backed slugs		*Phasmarhabditis hermaphrodita*	Nematoda	Rhabditidae
Arion spp.			Amphibia	
Keeled slugs		Many	Chordata	Birds
Milax, Tandonia and Boettgerilla spp.		*Erinaceus europaeus* Hedgehog	Insectivora	Erinaceidae
		Many	Mammalia	
		Parasitoids		
		Tetanocera spp.(L)	Diptera	Sciomyzidae
		Riccardoella limacum	Arachnida	Acarina
		Predators		
Cereal thrips		*Anystis baccarum*	Arachnida	Mesostigmata
Limnothrips cerealium	Larva		Arachnida	Araneae
L. denticollis	Egg	*Coccinella septempunctata*	Coleoptera	Coccinelidae

	Adult	*Stilpon nubila, Platypalpus spp.*	Diptera	Empididae
	Larva	*Chrysoperla carnea*	Neuroptera	Chrysopidae
			Diptera	Dolichopodidae

Table 2. Cereal pests and their natural enemies.

(*=key species, S=spring sown, W=winter sown)

Pest name	**Pest stage attacked**	**Natural enemies**			
		Species	**Synonym**	**Order**	**Family**
		Predators			
Cabbage aphid	adult/nymph	Many		Diptera	Syrphidae
Brevicoryne brassicae		*Theridion impressum*		Arachnida	Araneae (web forming)
		Many		Coleoptera	Carabidae
		Many		Coleoptera	Staphylinidae
	Adult	*Platypalpus pallidicornis*		Diptera	Hybotidae
		P. pallidiventris		Diptera	Hybotidae
		P. interstinctus		Diptera	Hybotidae
		P. articulatoides		Diptera	Hybotidae
	Adult			Diptera	Empididae
	Adult	*Dolichopus acuticornis*		Diptera	Dolichopodidae
		Medetera micacea		Diptera	Dolichopodidae
	adult/nymph	*Episyrphus balteatus*		Diptera	Syrphidae
	adult/nymph	*Chrysoperla carnea*		Neuroptera	Chrysopidae
		Parasitoids			
		Diaretiella rapae		Hymenoptera	Braconidae
		Praon spp.		Hymenoptera	Aphididae
		Aphidius colemani		Hymenoptera	Braconidae
		Predators			
Peach-potato aphid		Many		Coleoptera	Coccinelidae

Myzus persicae			Coleoptera	Cantharidae larvae
		Many	Diptera	Syrphidae
		Theridion impressum	Arachnida	Araneae (web forming)
		Many	Coleoptera	Carabidae
		Many	Coleoptera	Staphylinidae
	Adult	*Platypalpus pallidicornis*	Diptera	Hybotidae
		P. pallidiventris	Diptera	Hybotidae
		P. interstinctus	Diptera	Hybotidae
		P. articulatoides	Diptera	Hybotidae
	Adult		Diptera	Empididae
	Adult	*Dolichopus acuticornis*	Diptera	Dolichopodidae
		Medetera micacea	Diptera	Dolichopodidae
	adult/nymph	*Episyrphus balteatus*	Diptera	Syrphidae
	adult/nymph	*Chrysoperla carnea*	Neuroptera	Chrysopidae
		Parasitoids		
		Diaeretiella rapae	Hymenoptera	Braconidae
		Aphidius colemani	Hymenoptera	Braconidae
		Predators		
Brassica pod midge	Larva/Pupa	Many	Coleoptera	Carabidae
Dasineura brassicae	Larva/Pupa	Many	Coleoptera	Staphylinidae
	Adult/Larva	*Theridion impressum*	Arachnida	Araneae (web forming)
	Larva		Arachnida	Araneae (hunting)
	Adult	*Platypalpus pallidicornis*	Diptera	Hybotidae
		P. pallidiventris	Diptera	Hybotidae
		P. interstinctus	Diptera	Hybotidae
		P. articulatoides	Diptera	Hybotidae
	Adult		Diptera	Empididae
	Adult	*Dolichopus acuticornis*	Diptera	Dolichopodidae
		Medetera micacea	Diptera	Dolichopodidae
	Adult	*Episyrphus balteatus*	Neuroptera	Syrphidae

		Parasitoids			
	Egg/Larva	*Amblyapsis sp.*		Hymenoptera	Platygastridae
		Aphanogmus abdominalis	*Calliceras abdominalis*	Hymenoptera	Ceraphronidae
		Ceraphron insularis	*Calliceras insularis*	Hymenoptera	Ceraphronidae
		Ceraphron pallipes		Hymenoptera	Ceraphronidae
		Ceraphron serraticornis		Hymenoptera	Ceraphronidae
		Ceraphron tenuicornis	*Calliceras tenuicornis*	Hymenoptera	Ceraphronidae
		Ceraphron xanthosoma	*Calliceras xanthosoma*	Hymenoptera	Ceraphronidae
		Conostigmus rufescens		Hymenoptera	Megaspilidae
		Inostemma boscii		Hymenoptera	Platygastridae
		Inostemma nov. sp. pr. reticulatum		Hymenoptera	Platygastridae
		Inostemma sp.		Hymenoptera	Platygastridae
		Inostemma walkeri		Hymenoptera	Platygastridae
		Neochrysocharis		Hymenoptera	Eulophidae
		*Omphale clypealis**	*Secodes clypealis*	Hymenoptera	Eulophidae
		Piestopleura sp.		Hymenoptera	Platygastridae
		Platygaster boscii		Hymenoptera	Platygastridae
		Platygaster niger		Hymenoptera	Platygastridae
		Platygaster oebalus	*Prosactogaster oebalus*	Hymenoptera	Platygastridae
		Platygaster sp.	*Prosactogaster sp.*	Hymenoptera	Platygastridae
		*Platygaster subuliformis**		Hymenoptera	Platygastridae
		Prosactogaster tisias		Hymenoptera	Platygastridae
		Synopeas sp.		Hymenoptera	Platygastridae
		Synopeas thomsonii	*Piestopleuro thomsoni*	Hymenoptera	Platygastridae
		Tetrastichus brevicornis	*Geniocerus brevicornis*	Hymenoptera	Eulophidae
		Tetrastichus sp.	*Syntomsophyrum sp.*	Hymenoptera	Eulophidae
	Larva	*Pseudotorymus brassicae*			
		Predators			
Cabbage root fly	Egg	Many		Coleoptera	Carabidae

Delia radicum	Egg/Larva/Pupa	Many		Coleoptera	Staphylinidae
(Delia brassicae)	Larva/Pupa			Arachnida	Araneae
	Larva/Pupa	*Aleochara bilineata/A. bipustulata*		Coleoptera	Aleocharinae
	Larva/Pupa	*Phaonia trimaculata*		Diptera	Muscidae
	Larva/Pupa	*Coenosia tigrina*		Diptera	Muscidae
		Parasitoids			
	Larva	*Tersilochus microgaster*		Hymenoptera	Ichneumonidae
	Larva	*Trybliographa rapae*		Hymenoptera	Figitidae
		Predator			
Cabbage stem flea beetle	Adult/Larva	*Centromerita bicolor*		Arachnida	Araneae
Psylliodes chrysocephala	Egg/Larva/Pupa			Coleoptera	Carabidae
	Egg/Larva/Pupa			Coleoptera	Staphylinidae
		Parasitoids			
		Tersilochus microgaster	*Isurgus microgaster*	Hymenoptera	Ichneumonidae
		Aneuclis melanarius	*Thersilochius melanarius*	Hymenoptera	Ichneumonidae
		Diospilus oleraceus		Hymenoptera	Braconidae
		Diospilus morosus		Hymenoptera	Braconidae
	Adult	*Microctonus sp.*		Hymenoptera	Braconidae
		Microctonus melanopus	*Perilitus melanopus*	Hymenoptera	Braconidae
		Predators			
Cabbage flea beetle	Egg			Coleoptera	Carabidae
Phyllotrea spp.	Egg			Coleoptera	Staphylinidae
		Parasitoids			
	Larva	*Diospilus morosus*		Hymenoptera	Braconidae
	Larva	*Eulophus sp.*		Hymenoptera	Eurytomidae
	Adult	*Howardula phyllotretae*		Hymenoptera	Allantonematidae
	Adult	*Townesiltus bicolor*	*Microtonus bicolor*	Hymenoptera	Braconidae
		Predators			

Rape winter stem weevil	Larva/Pupa			Coleoptera	Carabidae
Ceutorhynchus picitarsis				Coleoptera	Staphylinidae
		Parasitoids			
	Larva	*Diospilus oleraceus**		Hymenoptera	Braconidae
		Sigalphus obscurellus		Hymenoptera	Braconidae
		*Tersilochus spp.**		Hymenoptera	Ichneumonidae
	Adult	*Microctonus melanopus*		Hymenoptera	Braconidae
		Predators			
Seed weevil	Larva/Pupa			Coleoptera	Carabidae
Ceutorhynchus assimilis		**Parasitoids**			
(Ceutorhynchus obstrictus)	Egg	*Mymar autumnalis*		Hymenoptera	Myrmaridae
		Potasson brachygaster		Hymenoptera	Myrmaridae
		Potasson declinata	*Antoniella declinata*	Hymenoptera	Myrmaridae
	Larva	*Anisopteromalus calandrae*	*Aplastomorpha calandra*	Hymenoptera	Pteromalidae
		Bracon fulvipes		Hymenoptera	Braconidae
		Bracon variator	*Bracon discoideus; Bracon maculiger*	Hymenoptera	Braconidae
		Chlorocytus diversus		Hymenoptera	Pteromalidae
		Eulophus hegemon		Hymenoptera	Eurytomidae
		Eurytoma curculionum		Hymenoptera	Eurytomidae
		Habrocytus semotus		Hymenoptera	Pteromalidae
		*Mesopolobus morys**	*Xenocrepis pura*	Hymenoptera	Pteromalidae
		Necremnus sp.		Hymenoptera	Eurytomidae
		*Stenomalina gracilis**		Hymenoptera	Pteromalidae
		Tetrastichus galectobus		Hymenoptera	Eurytomidae
		*Trichomalus perfectus**	*Trichomalus fasciatus*	Hymenoptera	Pteromalidae
	Larva	*Aneuclis melanarius*	*Tersilochus melanarius*	Hymenoptera	Ichneumonidae
		Diospilus morosus		Hymenoptera	Braconidae

		Diospilus oleraceus		Hymenoptera	Braconidae
		Sigalphus obscurellus		Hymenoptera	Braconidae
	Adult	*Microctonus melanopus*	*Perilitus melanopus*	Hymenoptera	Braconidae
		Microctonus sp.		Hymenoptera	Braconidae
		Predators			
Cabbage stem weevil	Larva/Pupa			Coleoptera	Carabidae
Ceutorhynchus pallidactus	Larva/Pupa			Coleoptera	Staphylinidae
(*Ceutorhynchus quadridens*)	Larva/Pupa			Arachnida	Araneae
	Adult	*Muscina stabulans*		Diptera	Muscidae
	Larva/Pupa	*Phaonia trimaculata*		Diptera	Muscidae
		Parasitoids			
	Adult	*Microctonus melanopus*		Hymenoptera	Braconidae
	Egg	No info			
	Larva	*Tersilochus obscurator**		Hymenoptera	Ichneumonidae
		Tersilochus sp.		Hymenoptera	Ichneumonidae
		Predators			
Rape stem weevil	Larva/Pupa			Coleoptera	Carabidae
Ceutorhynchus napi	Larva/Pupa			Coleoptera	Staphylinidae
	Larva/Pupa			Arachnida	Araneae
	Larva/Pupa	*Phaonia trimaculata*		Diptera	Muscidae
		Parasitoids			
		Tersilochus fulvipes	*Porizon fulvipes*	Hymenoptera	Ichneumonidae
		Predators			
Pollen beetle	Larva/Pupa			Coleoptera	Carabidae
Meligethes aeneus	Larva/Pupa			Coleoptera	Staphylinidae
	Larva			Arachnida	Araneae (hunting)
	Larva			Coleoptera	Coccinelidae

		Parasitoids			
Meligethes species	Larva	*Aneuclis incidens*		Hymenoptera	Ichneumonidae
		*Blacus nigricornis**[S]		Hymenoptera	Braconidae
		*Brachyserphus parvulus**[S]	*Codus parvulus*	Hymenoptera	Proctotrupidae
		Calyptus sigalphoides		Hymenoptera	Braconidae
		*Diospilus capito**[S]		Hymenoptera	Braconidae
		*Phradis interstitialis**[W]	*Isurgus interstitialis*	Hymenoptera	Ichneumonidae
		*Phradis morionellus**[SW]	*Isurgus morionellus*	Hymenoptera	Ichneumonidae
		*Tersilochus heterocerus**[W]	*Isurgus heterocerus*	Hymenoptera	Ichneumonidae
		Zeteticontus planiscutellum		Hymenoptera	Encyrtidae
		Parasitoids			
Turnip sawfly	Larva	*Perilissus lutescens*		Hymenoptera	Ichneumonidae
Athalia rosae	Larva	*Meigenia bisignata*		Diptera	Tachinidae
		Predators			
Slugs	Egg/Juvenille	*Pterostichus melanarius*		Coleoptera	Carabidae
Field grey slug				Coleoptera	Cantharidae
Deroceras reticulatum		*Phasmarhabditis hermaphrodita*		Nematoda	Rhabditidae
Round backed slugs					
Arion spp.					
Keeled slugs					
Milax, Tandonia and Boettgerilla spp.					

(Biocontrol of Oilseed Rape Insect pests) and the list of parasitoids is available on the internet, although this contains a few inaccuracies (http://boris.csl.gov.uk/index.html). The publication that arose from this project, edited by Alford (2003), includes chapters describing the parasitoids of the main oilseed rape pests, their predators and their potential to control pests. The taxonomy of oilseed rape parasitoids has been further refined in the MASTER project (Appendix 4, Project no. 39).

Details regarding the lifestage of the pest that was attacked by a particular species are not always provided although this can usually be discerned from the predators feeding habits. For the generalist and aphid-specific predators of cereals and oilseed rape, individual species are sometimes listed, but the list is unlikely to be comprehensive as in many studies investigations are restricted to a limited number of species and therefore these in some cases can only be considered as examples.

There was considerable overlap in the groups of generalist predators contributing towards the control of cereal and oilseed pests and consequently when summarising aspects of their biology they are all listed together (Table 4). On the whole predatory natural enemies are opportunistic feeders, but if given the choice show preferences for particular prey types with aphids often being the least preferred. Moreover, for some species, an aphid only diet inhibited development and a diverse diet was often optimum, indicating that the presence of alternative prey is needed if natural enemy development and fecundity is to be achieved (reviewed for Carabidae by Toft & Bilde, 2002; and for arthropods by Toft, 1996). However, the presence of alternative prey may also reduce the consumption of pests. This concept and whether biocontrol of cereal pests can be enhanced by augmenting the abundance and diversity of predatory natural enemies was explored in a recent Defra project (Appendix 4, Project no. 21). Natural enemy and alternative prey abundance and diversity were enhanced using spent mushroom compost. Significantly fewer aphids occurred where the compost was applied.

The evaluation of predator diet is an important component in the development of IPM, however, appropriate techniques must be used. Predatory invertebrates may also scavenge dead pests and as a consequence this can provide false positives in dietary studies of field collected specimens (Calder *et al*., 2005). A comprehensive dietary list for carabids inhabiting arable land was compiled by Sunderland (2002) and for Staphylinidae (Good & Giller, 1991). For other taxa there is sometimes scant information, especially for crop inhabiting species. Likewise overwintering locations are known for Carabidae, Staphylinidae and some Arachnida but is sparse for other taxa. Not all of the species within each family will overwinter as adults and larva but in one life form. Information on dispersal ability is often lacking because of the difficulty in marking and tracking species, especially those capable of flight beyond the field scale.

Research to identify pest natural enemies continues and techniques are continually being modified, led by researchers at Cardiff University. Such research may highlight influential natural enemies that may require further investigation of their biology and from this ways to manipulate their effectiveness may be developed. It is important that a diverse and abundant natural enemy community is maintained to ensure that pests are attacked throughout their lifecycle and by a wide variety of natural enemies (Waage & Mills, 1992). Thus if any particular natural enemy of group thereof become scarce, as commonly occurs, then another will take over. This is likely to occur because many generalist predators have diverse diets and are opportunistic in their feeding habits. Some degree of synergism may also occur, especially between different guilds of predators. For example, foliage foraging predators are known to increase the falling off rate of aphids, thereby increasing predation by ground-active generalist predators (Evans, 1991; Losey & Denno, 1998). Alternatively, natural enemies may compete for the same resources or consume each other (Sunderland *et al*., 1997; Dinter, 1998). Some studies have examined predation and inter- and intra-species interactions, normally within closed systems with a limited number of natural enemies (Lang, 2003). Such studies can provide some indication of the relationships that occur, but given the diverse complexity of species that reside within arable ecosystems, they cannot replicate what occurs in practice and are of more theoretical interest.

Table 4. Key aspects of natural enemy biology.

Family	**Diet**	**Phenology**	**Overwintering location**	**Mobility of adults**
Adults (Ad)	Aphidophagous (A)	(number of generations/year)		
Larva (La)	Fungivorous (F)			
	Parasitic (Pa)			
	Phytophagous (Ph)			
	Pollen/nectar (PN)			
	Polyphagous (Po)			
	Predatory (Pr)			
Arachnida				
Acari	Pr / Pa	5+	Margins/Grassland/Soil	Field
Araneae	Pr	>1	Margins/Grassland	Landscape
Opiliones	Po	1	Margins	Field/Farm
Coleoptera				
Carabidae (Ad)	Po	1	Margins/Grasslands/Soil	Between-field
Carabidae (La)	Po		Soil	
Cantharidae (Ad)	PN / Pr	1	Margins/Grassland	Farm
Cantharidae (La)	Po / Ph		Soil	
Coccinellidae (Ad)	A / Pr / PN		Margins/Woodland/Crevices	Landscape
Coccinellidae (La)	A / Pr			
Staphylinidae (Ad)	Po / F	1	Margins/Grassland/Soil	Farm/field
Staphylinidae (La)	Po / Pa		Soil	
Diptera				
Dolichopodidae (Ad)	Pr / PN	?		Farm/Landscape?

Dolichopodidae (La)			Damp areas/Soil/under bark	
Empididae (Ad)	Pr / PN	?		Farm/Landscape?
Empididae (La)	Pr		Soil/decaying vegetation	
Hybotidae (Ad)	Pr / PN	?		Farm/Landscape?
Hybotidae (La)	Pr		Soil/decaying vegetation	
Phoridae (Ad)	Po / Pa	?		Field/Farm
Phoridae (La)	Pr / Pa		?	
Syrphidae (Ad)	PN	>1		Landscape
Syrphidae (La)	Pr / Po / A	?		
Asilidae (Ad)	Pr (not A)	1		Farm/Landscape
Asilidae (La)	Pr		Soil/decaying wood	
Scathophagidae (Ad)	Pr-Po (possibly A)	?		Farm/Landscape
Scathophagidae (La)	Ph / Pr		Dung/plants/water	
Hemiptera				
Anthocoridae (Ad)	Pr/PN	?	Margins ?	Field/Farm
Lygaeidae (Ad)	Ph - few Pr	?	Margins ?	Field/Farm
Microphysidae (Ad)	Pr	?	Margins ?	Field/Farm
Miridae (Ad)	Ph - few Pr	?	Margins ?	Field/Farm
Miridae (La)	Ph - few Pr		Margins ?	
Pentatomidae (Ad)	Ph - few Pr	?	Margins ?	Field/Farm
Pentatomidae (La)	Ph - few Pr			
Reduviidae (Ad)	Pr	?	Margins ?	Field/Farm
Nabidae (Ad)	Pr	?	Margins ?	Field/Farm
Hymenoptera				
Braconidae	Pa/PN	>1	Host	Field/Landscape (within host)
Ichneumonidae	Pa/PN	>1	Host	Field/Landscape (within host)
Neuroptera				
Chrysopidae (Ad)	PN/Pr			Farm/Landscape?
Chrysopidae (La)	Pr			
Hemerobiidae (Ad)	Pr			Farm/Landscape?
Hemerobiidae (La)	Pr			

Not all predators contribute to the control of pests during the current growing season, because the pest is for example, inaccessible whilst feeding on the crop, instead they contribute to the overall regulation of the pests population by feeding on the pest during other periods. On the whole, the impact of natural enemies during these periods is less well understood because their impact cannot be so easily measured. In oilseed rape especially, many of the generalist predators predate on dipteran larvae but only after they have dropped to the ground prior to pupation. Likewise, predation of orange wheat blossom midge larvae by ground-active invertebrates occurred after feeding on the crop (Holland *et al*., 1996). Consequently, with sporadic pests that are long lived, the extent of predation is not only important during the current crops growing season but for the pests lifetime.

4.2 Natural enemy attributes and their potential to control pests

The literature pertaining to the biology of natural enemies, their abundance in arable crops, impact on pests and potential for manipulation is extensive. To provide a condensed synopsis, a subjective scoring system was applied for each of the main families of predators and for parasitoids of the main pest species that described the level of knowledge for a range of key factors (Table 5). The scoring was then appraised by experts attending the project workshop and further revised. This information was then used to identify gaps in the knowledge. In addition, to provide further indication as to the amount of information currently available, a literature search of the database “Web of Science” was conducted using the terms “cereal or oilseed” and each predator and parasitoid family. For predators this confirmed that there were most publications on Carabidae (137), almost a third less on Coccinellidae, Staphylinidae, Syrphidae and Linyphiidae and relatively few on any other family (Figure 6). To a large extent these results reflect the ease by which the families can be collected and studied in the field rather than their relative abundance. Many of the predators are confined to field margins and consequently their contribution to pest control is limited (Table 4), however, of the widely dispersed and abundant predators, least information exist for the predatory flies, notably the Dolichopodidae and Empididae. A similar search was conducted for publications relating to parasitoids of cereal and oilseed rape pests. There were 87 publications on Braconidae, 12 for Ichneumonidae and less than five for any other parasitoid family (Figure 7).

Of the predators most information exists for the Carabidae, Syrphidae and for Linyphiidae. Within these families there have been studies of individual species inhabiting arable crops, their impact on pests has been investigated and as a consequence there have been attempts to increase their abundance, predominantly using habitat manipulation (Table 4). The biology, role in pest control and effectiveness as natural enemies is well understood and has been reviewed for Carabidae (Luff, 1987; Kromp, 1999; Holland & Luff, 2000; Holland, 2002; Sunderland, 2002), Araneae (Sunderland & Samu, 2000; Nyffeler & Sunderland, 2003; Riechert & Lockley, 1984; Riechert, 1998) and natural enemies *per se*. (Sunderland *et al*., 1997; Symondson *et al*., 2002). Nevertheless, there have been surprisingly few attempts to manipulate the number or

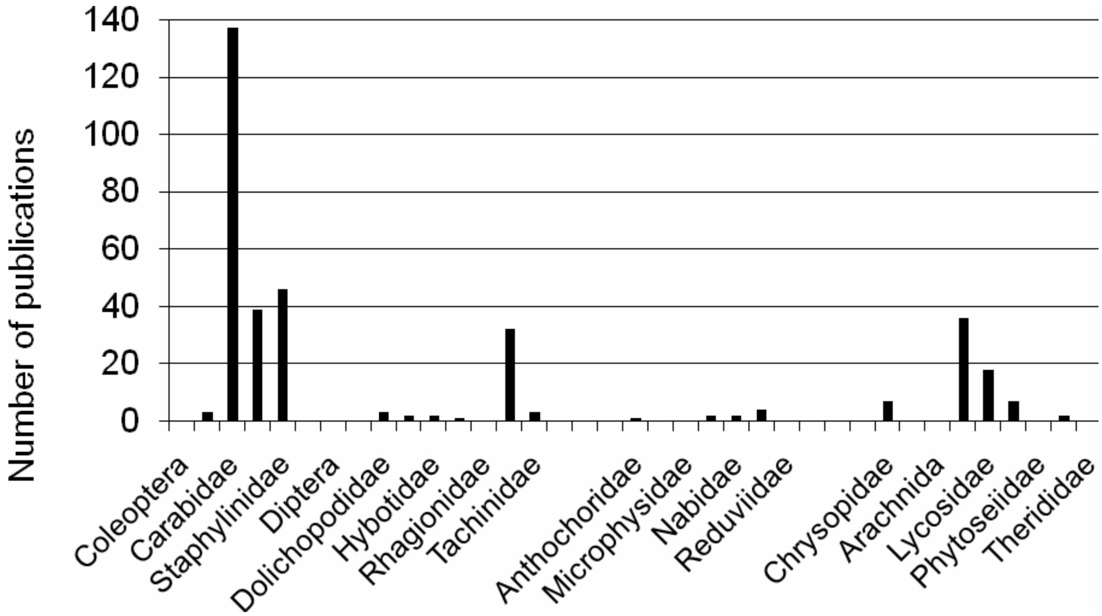

Figure 6. Number of publications 1970-2007 relating to predatory natural enemy families occurring in cereal or oilseed rape crops.

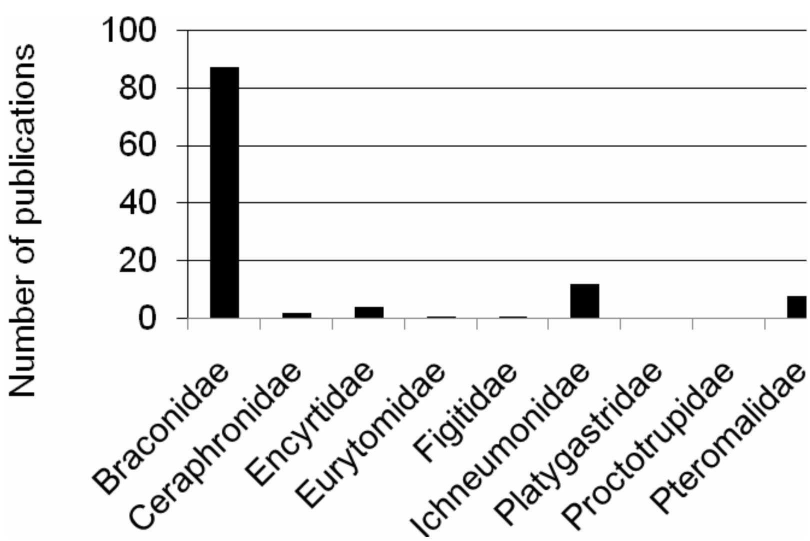

Figure 7. Number of publications 1970-2007 relating to parasitoids occurring in cereal or oilseed rape crops.

distribution of these most abundant predators within crops, as outlined below. Predatory flies are also widespread and abundant but little is known about their biology with the exception of Syrphidae. They were identified in the RELU project "Re-bugging the system" as potentially important predators of cereal aphids"

Table 5. Key aspects of the biology of pest natural enemies and the potential for manipulation.

(**Abundance in arable crops**: 1=more present at edges, 2=present throughout field, 3=more common at edges, 4=common throughout fields, 5=more abundant at edges, 6=abundant throughout fields. **Knowledge of biology**: 1=none, 2=basic, 3=some for individual species, 4=some for arable inhabiting species. **Impact on pests**: 1=Unlikely, 2=Biological possibility, 3=Experimental demonstration, 4=Dietary information only, 5=Some impact-diet and experimental manipulation, 6=High impact demonstrated-diet and experimental manipulation. **Potential to manipulate:** 1=Unlikely, 2=Unknown, 3=Biological possibility, 4=Some evidence, 5=Strongly demonstrated; **using Environmental Stewardship**: 1=Unlikely, 2=Unknown, 3=Biological possibility, 4=Some evidence, 5=Strongly demonstrated; **using cultural practices**: 1=Unlikely, 2=Unknown, 3=Biological possibility, 4=Some evidence, 5=Strongly demonstrated; **using semiochemicals**: E=Electophysiology, L=Laboratory bioassays, F=Field experiments, U=Investigations underway. **Landscape effect**: 1=Not investigated, 2=No effect, 3=Confirmed.

Predators	Number species (important)	Abundance in arable crops	Knowledge of biology	Impact on pests	Potential to manipulate	Potential to manipulate using: Environmental stewardship	Cultural practices	Semio-chemicals	Landscape effect
Coleoptera									
Cantharidae (Soldier beetles)	5 (3)	3	2	4	3	3	2		
Carabidae (Ground beetles)	20-30 (5-10)	5 & 6	4	6	5	5	4		3
Coccinelidae (Ladybirds)	5	4	4	5	4	4	2	L	
Staphylinidae (Rove beetles)	40-50 (5-10)	5 & 6	4	6	5	5	4		
Diptera									
Asilidae (Robber flies)	2	1	2	2	2				
Dolichopodidae (Long-legged flies)	6	3	2	2	3				
Empididae	6	3	2	2	3	4	3		
Hybotidae (Dance flies)	3	1	2	2	3				
Muscidae (Muscid flies)	6	1	2	2	3				
Rhagionidae (Snipe flies)	3	1	2	2	3				
Syrphidae (Hoverflies)	6 (2)	3	4	6	4	4	2		1

Therevidae (Stiletto flies)	2	1	2	2	3				
Heteroptera									
Anthorochoridae (Flower (pirate) bugs)	1	1	3	2	3	3	2		1
Geocoridae	2	1	2	2	3	3	2		1
Microphysidae	2	1	2		2	3	2		1
Miridae	12	3	3	2	3	3	2		1
Nabidae	2	3	3	2	3	3	2		1
Pentomidae	3	1	2	2	3	3	2		1
Reduviidae	2	1	2		2	3	2		1
Saldidae	1	1	2	2	3	3	2		1
Neuroptera									
Chrysopidae (Lacewings)	3 (1)	2	3	4	4	4	2	F	1
Arachnida									
Linyphiidae (Money spiders)	40-50 (10)	6	4	5	4	4	4		3
Lycosidae (Wolf spiders)	12 (2)	5	3	5	1	1	1		2
Opiliones (Harvestmen)	3	2	2	2	2	1	2		1
Phytoseiidae (Predatory mites)		2	2	2	2	2	2		1
Tetragnathidae (Long-jawed spiders)	4	1		1	2	1	2		1
Theridiidae (House spiders)	6	1		1	2	1	2		1
Thomisidae (Crab spiders)	4	1	3	2	2	1	2		1
Parasitoids & parasites of:									
Cereal pests									
Cereal aphids	8	6	4	6	4	4	3	E, L , F	3
Orange wheat blossom midge	4 (3)	6	4	5			4	E, L , F	

Yellow wheat blossom midge	3			5			4		
Frit fly	91 (2)	6	3	5	4	2	4		
Gout fly	2	4	2	2	2	2	2		
Yellow Cereal Fly	0								
Wheat bulb fly	2	4	2	2	2	2	2		
Cereal leaf beetle	3								
Cereal ground beetle	?								
Wireworm	?								
Cereal stem sawfly	2						4		
Leatherjackets	2								
Slugs	10-20								
Oilseed rape pests									
Cabbage aphid	3	6	4	5	4	3	2	E, L, F	1
Peach-potato aphid	2	6	4	5	4	3	2	U	1
Brassica pod midge	>20 (2)	4 & 5	4	5 to 6	4	3	4		1
Cabbage root fly	2								
Cabbage stem flea beetle	8 (1)	4	4	5	4	3	4		1
Cabbage flea beetle	4								
Rape winter stem weevil	4 (2)								
Seed weevil	>20 (3)	4	4	6	3	3			1
Cabbage stem weevil	6 (1)	4	4	6	4	3	5		1
Rape stem weevil	3 (1)								
Pollen beetle	9 (3)	3, 4 or 6	4	6	4	4	5		3
Turnip sawfly	2								
Slugs	10-20								

and further work to examine their diet is planned. Their abundance and distribution may be manipulated because they utilise floral resources, however, because they on the whole are generalist predators such diverse habitats that provide an abundance of prey may equally retain them. Relatively little is known about the predatory Heteroptera inhabiting arable fields (Moreby, pers. comm.). Their diversity is lower than for some of the other Orders and they are usually most abundant at field edges, consequently they may be less effective as biocontrol agents. However, most studies of invertebrates have been conducted at field edges or involve the use of pitfall traps and consequently the distribution of predatory Heteroptera within fields is poorly understood. Only one species of Neuroptera is considered to be important in arable fields and this feeds predominantly on aphids. It has been shown to respond to chemical cues and is a potential candidate for manipulation using semiochemicals.

The ability of predators to withstand starvation is another key attribute that improves their survival and effectiveness as biocontrol agents. Indeed, spiders have become physiologically adapted to survive long periods without food (Wise, 1993) and carabids have also been shown to be food limited within cereal fields (Bilde & Toft, 1998).

The parasitoids of the more serious pests have been well studied and their potential to control the pest quantified. Parasitoids are able to find their hosts wherever they may be within a field and consequently their distribution is linked to that of their host, although they may make use of floral resources along field boundaries. Of the cereal pests, the parasitoids of cereal aphids have been the most intensively studied and their manipulation using semiochemicals is a real possibility, as demonstrated in the 3D Farming project (Powell *et al*., 2004). Further research on their manipulation using semiochemicals is underway or has been recently completed (Appendix 4, Project nos. 5, 18, 23, 24, 31). Enhancement of other parasitoids is recommended through the judicious use of insecticides using treatment thresholds and cultural measures. Their manipulation using habitat manipulation for arable pest control has seldom been explored. In the MASTER project (Appendix 4, Project no. 39) ways to conserve and enhance the 11 key parasitoids of oilseed rape pests (and other natural enemies) are being explored in order to construct, develop, evaluate and promote an IPM system (Williams *et al*., 2005). Techniques include the manipulation of row spacings, seed rates, seed mixes and insecticide inputs alongside different cultivation methods.

4.3 Long-term changes in pest natural enemy populations

The only long-term monitoring of arable pest natural enemies is of those taxa collected by the Game Conservancy Trust in the Sussex study. The abundance of insects and spiders is measured in approximately one hundred cereal fields during the third week in June each year using a Dvac suction sampler. Sampling started in 1970. The study area is comprised of five farms, of which four are now primarily all arable and one remains as a mixed farm. The data from the study for the period 1970-2005 was analysed recently for The Leverhulme Trust (Potts, Ewald and Moreby, 2006). Of the natural enemies the trends of the following groups were analysed: aphid-specific predators, polyphagous (generalist) predators and parasitoids. Within these groups there was some further differentiation into families.

4.3.1 Aphid-specific predators

Across all farms combined there was no significant change in the abundance of aphid-specific predators and no difference between the farms. None of the four components of the group (Coccinellidae, Cantharidae, Neuroptera and Syrphidae) showed any long-term trends, with the exception of Syrphidae which appeared to have been on the increase since the mid 1980's.

4.3.2 Polyphagous predators

There was a decline in the abundance of polyphagous predators across all farms combined and on one farm. Of the components of the group (Araneae, Opiliones, Carabidae, Dermaptera, Staphylinidae, Tachyporus, Staphylinidae minus Tachyporus) all but the Opiliones showed declines over time but not always of each farm.

4.3.3 Parasitica

There was no change across all farms combined but of the six components, two have shown a significant increase (Chalcidae and Ichneumonidae) while two have decreased (Braconidae and Proctrupoidae).

Overall there is some cause for concern of the long-term trends in pest natural enemies, particularly the polyphagous predators. These may be more vulnerable to intensive farming practices because they are on the whole, less mobile than the aphid-specific predators. The parasitica are most likely responding to the trends in their hosts but as they are not identified to species this relationship could not be examined.

4.4 Manipulation of natural enemies

The recent extension of agri-environment funding may create a more diverse arable landscape with a greater proportion of non-crop habitats that can support natural enemies. This may help to reverse some of these long-term declines. Evidence from landscape studies indicate that more consistent and higher levels of biocontrol are achieved in diverse as opposed to simple landscapes (Ostman *et al*., 2001; Thies *et al*., 2003, 2005). To ascertain whether this is likely to occur, the options available under the new Environmental Stewardship scheme were appraised for their potential to encourage natural enemies and whether there evidence for an associated increase in pest control. The effect of non-inversion tillage was also included because this practice is also becoming widespread and can impact on pest and natural enemy abundances.

Of the other farming practices likely to affect natural enemies, the application of insecticides can be substantial because the majority of products (organophosphates and pyrethroids) have a broad spectrum of activity (Moreby *et al*., 2001). Molluscicides are also toxic to non-target species including Carabidae (Purvis & Bannon, 1992). However, the effects of an insecticide on the natural enemy population and the subsequent rate of repopulation depends on many complex and interacting factors including the susceptibility of the each species, the spatial extent of the application in conjunction with the natural enemies mobility and the proportion that remained unaffected in the landscape. Integrated Pest Management guidelines include many suggestions on how to reduce the effects of insecticides and these are reviewed below.

4.5 Impact of habitat manipulation on pest natural enemies

In this section of the review the potential to enhance levels of pest control using habitat manipulation was examined with an emphasis on those habitats that can be created using Environmental Stewardship (ES) schemes. The focus is on those schemes currently being funded. Other approaches that aim to enhance natural enemies exist but have been adequately reviewed in the existing literature and most apply to crops other than cereals or oilseed rape (Landis *et al*., 2000; Wäckers *et al*. Eds, 2005; Gurr & Wratten, Eds, 2000).

The suite of ES schemes introduced in 2005 have a number of aims, but, like their predecessors, the improvement of biological control (biocontrol) of insect pests is only considered for beetle banks. Nevertheless, our understanding of the ecology of pest natural enemies is sufficient to conclude that many of the habitats created under Entry Level Stewardship (ELS), Organic Entry Level Stewardship (OELS) or Higher Level Stewardship (HLS) have the potential to enhance or support populations of pest natural enemies (Holland, 2007). To achieve the most effective pest control it is necessary to provide the following:

- Resources must be sufficient to ensure the survival and reproductive capacity of natural enemies is maintained or improved.
- The farmed landscape must permit movement between non-crop habitats and crops or between crops ensuring an even distribution of natural enemies during the pest infestation.
- A diversity of natural enemies with a range of phenologies and feeding habitats must be present to ensure that the pest is attacked throughout its lifetime and by a variety of ways.
- In the case of parasitic species, it may be necessary to allow the pest to survive outside of the crop ensuring that the parasites survive in the locality.

Overall the contribution that the ES options make towards achieving the first of the above is best understood. The biology and consequently resources required by natural enemies were investigated for many of the more common taxa and consequently inferences about how the ES options will contribute to their survival can be determined. These essential resources include:

1) Pollen and nectar. Floral resources are utilised by a broad range of predators and parasitoids because they provide energy and can act as an alternative food source (Wäckers, 2005). For parasitoids a source of non-host food can influence many facets of their biology that ultimately affect the levels of biocontrol achieved

for example, longevity, mortality rates and fecundity while locating these adjacent to the crop improves searching efficiency (Olson *et al*., 2005).

2) Above-ground overwintering habitats. Predators that overwinter outside of the cropped area benefit from the provision of habitats that create the correct environmental conditions, protect them from predation and damaging farming operations. Grassy margins associated with field boundaries have been shown to support a range of Coleoptera and Araneae, and the woody structure of hedgerows and woods may also provide suitable conditions for the more widely dispersing species, although this has been less well studied. In addition, such habitats may also allow pests and their parasitoids to survive the winter, ensuring their supply in the following season.

3) Alternative prey. Pests may not be present throughout the natural enemies foraging lifetime and therefore a source of alternative prey or hosts are needed to ensure survival and to maximise reproductive potential. These may be present within non-crop habitats or a crop.

4) Refuges from disturbance. Pesticides and some other farming operations e.g. tillage, can directly and indirectly reduce the abundance and diversity of natural enemies. Reinvasion of the affected areas will occur, but the speed with which this is achieved will depend upon the scale and timing of the treatment and for each species will also depend upon behavioural, ecological and toxicological factors (Jepson, 1989). The impact on local populations will be governed by extent of their distribution in relation to the proportion of area affected. Non-crop habitats and untreated cropped land can act as refuges from which treated fields can be repopulated.

5) Uncultivated land. A range of important natural enemies including beetle larvae, parasitoids and spiders overwinter within the soil. Intensive tillage can destroy natural enemies; however, the impact will vary according to the vulnerability of life stage present and the timing of cultivations.

Whether ES options can provide a suitable environment to achieve the other requirements has not been specifically investigated although there is published information available that can assist with this deduction. The potential of each ES option to promote biocontrol was therefore appraised according to the predatory and parasitic species supported (Tables 6 & 7). Where there was no direct information available the option was judged according to the type of habitat created and the likely resources that would be provided.

Table 6. Resources provided for natural enemies by Environmental Stewardship

ES Option	Pollen & nectar	Overwintering	Alternative prey	Refuge	Uncultivated soil
Hedgerow management	*** ?	***	***	***	*
Protection/creation of uncultivated ground flora	*	*** ?	***	*** ?	* ?
Wild bird seed mixture	* ?	* ?	** ?	* ?	* ?
Flower rich habitats	***	** ?	***	***	* ?
Overwintered stubbles		*		?	
Beetle banks	N	***	***	***	* ?
Skylark and fallow plots	*	N	* ?	?	?
Reduced or no herbicide inputs	**	N	***	***	N
Undersown spring cereals	N	***	**	**	***
Uncropped, cultivated margins	**	N	** ?	*	N
Non-inversion tillage	N	***	**	N	***

N=No; ? = assumed but not tested

5. Review of Entry Level Stewardship (ELS) & Organic Entry Level Stewardship (OELS) options

5.1 Hedgerow management (EB1-EB5; OB1-OB5; HB12)

These options entail maintaining hedgerows at a height of at least 1.5 m, protecting them from agricultural inputs, and reducing cutting frequency to alternate years (EB1-2) or once every three years (EB3). Only hedgerows/banks with no more than 20% of gaps are permitted in the option. It is hoped that such management will provide hedges in a variety of growth stages and therefore flowers should be present in a proportion of the hedges every year. Overall, the impact of hedgerow cutting on invertebrates is poorly understood and conflicting evidence exists. Wild hedges were found to support more invertebrates compared to cut hedges (Van Emden, 1963). Likewise invertebrate abundance was higher on uncut compared to recently cut hedges, but diversity showed the opposite trend (Sotherton *et al*., 1981). The timing of cutting may also be important; invertebrate diversity was lower when Cornish hedgerows were cut in summer as opposed to the autumn (Meneer, 1994).

Table 7. Extent to which natural enemies are supported within Environmental Stewardship habitats.

ES Option	**Evidence that natural enemies supported within habitat**
Hedgerow management	*** (A,C,D,He,Hy)
Protection/creation of uncultivated ground flora	** (A, C, D, He, Hy)
Wild bird seed mixture	* (A, C, D, He, Hy)
Flower rich habitats	*** (D, Hy)
Overwintered stubbles	* (A,C)
Beetle banks	*** (A,C)
Fallow plots	?
Reduced or no herbicide inputs	* (A,C, D)
Undersown spring cereals	** (C)
Uncropped, cultivated margins	** (A,C)
Non-inversion tillage	** (C,D, Hy)

Regular cutting was found to have a negative effect on the abundance of highly mobile invertebrates, Hymeoptera and Diptera (Maudsley *et al*., 2000). Further research is needed to determine the extent to which the hedge shape, frequency and time of cutting affects the abundance and diversity of natural enemies.

The floristic composition of the hedgerow also has an impact on the diversity and abundance of natural enemies, because the two are positively correlated (Pollard *et al.*, 1974). The number of arthropod species associated with individual plant species found within hedges can vary enormously. For example, hawthorn

(*Crateagus mongyna*) supported 209 invertebrate species whereas holly (*Ilex aquifolium*) only supported 10 (Kennedy & Southwood, 1984). Floristically diverse hedges in southern England supported 51 families in 13 orders, all within the Phylum Arthropoda. Five orders accounted for 90% of all arthropods: Araneae, Coleoptera, Diptera, Hemiptera and Hymenoptera. The predators accounted for 31% and parasitic species 6% of the total sample (Pollard & Holland, 2006). Individual species were seldom identified in this study therefore it was not possible to identify the component that was comprised of known cereal and oilseed pests or their natural enemies. The proportion of predatory and parasitic taxa was relatively high compared to that found in other permanent vegetation, such as broad-leaf trees where it was only 20%, indicating that shrubby component of hedgerows is a valuable source of natural enemies.

The hedgebase which is also protected by these options, for up to 2m from the hedge centre, is known to harbour a range of natural enemies but is especially favoured as an overwintering site (Lipkow, 1966; D'Hulster & Desender, 1982; Sotherton, 1985; Maudsley, 2002). The abundance of predatory carabids and staphylinids showed a positive relationship with the amount of dead leaf litter, while carabids were also correlated with the biomass of dicotyledonous vegetation (Maudsley *et al*., 2002). In the same study, some carabid species were associated with a drier soil moisture, this being important because they overwinter in the soil beneath the leaf litter. The shrubby component also creates sheltered conditions with higher temperatures and humidity, encouraging particular invertebrates and plants (Lewis, 1969a,b). The climate within the hedgebase is also modified. The hedgebase has been confirmed in many studies to be an important source of natural enemies and is discussed in further detail in the following section.

Potential to improve biocontrol

The extent to which the shrubby hedgerow component contributes to pest control in neighbouring crops or act as a source of pests is unknown. In Canada woody borders did not affect insect densities within alfalfa fields, but increased insect family richness (Holland & Fahrig, 2000). Hedgerows may influence pests and natural enemies in a variety of ways: a) by providing resources that affect survival and fecundity and thereby populations within arable landscapes, b) by effecting the distribution of ground and aerially dispersing species; hedgerows alter air currents creating eddies that deposit airborne pests and natural enemies within fields (Lewis, 1969a). On the other hand, insect pests dispersing by flight may be inhibited from dispersing outside of the field by high structures leading to a population increase within the field (Bach, 1988). For ground dispersing species hedgerows may have a negative effect on biocontrol by inhibiting the movement of natural enemies (Frampton *et al*., 1995; Mauemootoo *et al*., 1995; Thomas *et al*., 1998; Fernández García *et al*., 2000; Holland *et al*., 2004a), the extent to which this occurs depending on the vegetation structure and species in question (Duelli *et al*., 1990). Such movement is necessary if reinvasion is to occur following events that reduce the natural enemy population within a field. The way in which hedgerows affect the distribution of pests and natural enemies requires further investigation. The movement of airborne invertebrates is being investigated in the "Re-bugging the system" project and this will provide some information as to how hedgerows are effecting the distribution of natural enemies within fields (Oaten *et al*., 2007).

5.2 Protection/creation of uncultivated ground flora (EB/OB1-10, EC/OC1, EC/OC4, ED/OD2, EE/OE1-6, EE/OE8, EF/OF1; HC6, HD7)

Many of the options available in ELS and OELS protect from cultivation the ground flora areas associated with particular landscape features including hedgerows, ditches, in-field trees and archaeological sites. Likewise buffer strips on cultivated land are likely to support a similar floral composition, which is most likely to be a grass dominated sward. The exact botanical composition and structure will vary according to the method of creation, whether this is from natural regeneration or a preparatory seed mix. Such areas provide suitable microclimatic conditions for overwintering and aestivation, as foraging sites in winter and summer and for breeding. The complexity of the habitat structure and the plant species composition will determine the range of niches and hosts available and consequently the diversity and abundance of beneficial arthropods that they support (Morris & Webb, 1987). The degree of shelter provided and the amount of nectar, pollen, host or prey availability are key determinants of the natural enemy community. They also act as refuges from inclement field conditions and the perturbations of farming practices, thereby facilitating reinvasion of areas where population reductions have occurred (Lee *et al*., 2001; Holland *et al*., 2000).

Overwintering sites

Invertebrates seeking overwintering sites are especially attracted to tussocky grass swards in field boundaries because they provide stable and dry microclimatic conditions (Luff, 1966; Sotherton, 1985; Thomas *et al*., 1992; Maudsley *et al*., 2002). Temperature and the extent to which it fluctuates were shown to influence the survival of a carabid, staphylinid and coccinellid species, with survival being higher under lower and more stable temperatures (Dennis *et al*., 1995). The shrubby component of the hedgerow can also provide additional protection of the ground vegetation. The abundance of alternative prey within the margin habitat is also important because prior to overwintering the insects build-up fat reserves by feeding within the shelter habitat rather than in the crop (Leather *et al*., 1993). There is a limit to the duration that insects can overwinter which depends on the levels of fat reserves and environmental conditions, while its physiological condition on emergence in early spring will determine subsequent mortality during this period, this often being high (Thomas *et al*., 1992; Dennis *et al*., 1994). Climate change may have an impact on overwinter survival. The lack of prey in early spring was considered a determining factor in post-overwintering mortality. Generalist predators may also feed during the winter and survival was improved where food was available (Thomas *et al*., 1992; Dennis *et al*., 1994).

Studies of ground flora associated with hedgerows have shown that they support a diverse and abundant range of natural enemies through the winter (Sotherton, 1984, 1985; Andersen, 1997; Collins *et al*., 2003a; Maudsley *et al*., 2002). Carabidae and Staphylinidae were the most abundant natural enemies but their densities varied enormously between different studies (margins), ranging from 880 m^{-2} (Thomas *et al*., 2000) to 3305 m^{-2} (Collins *et al*., 2003a). Considerable variation along the same hedgerow also occurs and some component of the variation is a consequence of insufficient replication when sampling (Maudsley *et al*., 2002). Considerable yearly variation in overwintering numbers may also be expected (MacLeod *et al*., 2004). Strips of tussocky grasses may also occur along fencelines and although these are poorer in their botanical diversity, they supported higher densities of Staphylinidae (Griffiths *et al*., 2007). At the farm-scale, because the diversity and abundance of invertebrates in field boundaries is determined by plant diversity, its structure and the amount of leaf litter (Altieri & Letourneau, 1982; Dennis *et al*., 1994; Maudsley *et al*., 2002), the maximum invertebrate diversity will be achieved by having a range of different habitats (Griffiths *et al*., 2007). The propensity of other similar habitats (e.g. buffer zones) that may be created under Environmental Stewardship to support overwintering natural enemies has not been evaluated, but if they are comprised of tussocky grasses they will have some value as overwintering sites. This may, however, not be as great that provided by a hedgebase because there would be less leaf litter and dicotyledonous vegetation biomass, while soil moisture levels may not be a s favourable as those found in a raised bank, these all being key determinants of overwintering habitat suitability (Maudsley *et al*., 2002). Areas that are left to naturally regenerate usually develop a flora that is similar to that in adjacent uncultivated areas. The seed mixes that are promoted for use in field margins typically contain a mix of fine and tussock forming grasses that will provide overwintering cover for invertebrates, although the tussock forming species usually become dominant (MacLeod *et al*., 2004).

Summer usage

The invertebrates supported by uncultivated field margins during the summer have been widely investigated and natural enemies are often recorded within them, but pest species are seldom identified. Uncropped headlands that had been allowed to naturally regenerate supported almost twice as many carabid beetles as a conventional managed wheat crop (Cardwell *et al*., 1994). In contrast, naturally regenerating margins supported less Araneae than the adjacent established margins for the first four years and cutting reduced abundance and species richness (Baines *et al*., 1998). Cutting mid-summer had a greater impact than if conducted in the spring or autumn. Margins sown with a flower rich grass mix supported a greater abundance and to a lesser extent diversity of Araneae compared to those that regenerated naturally (Baines *et al*., 1998), although Linyphiidae showed no difference (Bell *et al*., 2002). There were few differences in the abundance or diversity of Carabidae, Opiliones (harvestmen), Dermaptera (earwigs) or Araneae in margins created by natural regeneration or sown with either tussocky grasses, grasses and wildflowers or strips of both adjacent to each other but were lower in the crop (Meek *et al*., 2002). However, it may take time for the number and diversity of invertebrates to build-up, distinct differences were found between one and six-year old margins (Denys & Tscharntke, 2002). In some cases individual species preferred certain margin types and this may be expected if they have particular environmental, structural or dietary preferences. As a consequence there may be little exchange between the margin and the cropped area and species preferring the margins may not benefit pest control directly within the field, although they may reduce pests utilising margins. Araneae especially were shown to have different species composition in margins compared to the crop (Kromp & Steinberger, 1992) while some carabid species, especially spermophagous species, remain strongly associated with margins (Cardwell *et al*., 1994; Holland *et al*.,1999; Thomas *et al*., 2001;). Further information on the species composition of sown margins and the impact of cutting, scarification and herbicides will be gained from the SAFFIE project.

The establishment of grassy margins is one the most widely adopted ES options (Boatman, *et al*., 2007), but their value for natural enemies has received only limited attention in the UK. In the Arable Stewardship Pilot Scheme, the abundance and species richness of carabids was the same grassy margins, beetle banks and the open field, however, the community composition differed reflecting the differences in the environmental conditions and preferences of individual taxa (Gardner *et al*., 1999). Grassy margins were recommended as a way of enhancing carabid diversity in cereal dominated landscapes (Anon, 2001). The margins were, however, relatively new at the time of sampling and further changes in their invertebrate composition would be expected (Thomas & Marshall, 1999). In the Netherlands, emergence traps placed in grassy margins revealed that during the growing season the fauna was comprised mostly of dipteran flies, followed by parasitic wasps, spiders, carabid beetles and staphylinid beetles (Canters & Tamis, 1999). Numbers of Staphylinidae abd Carabidae were higher in the winter showing that they were used as an overwintering site. Mowing lead to increases in parasitic wasps, hoverflies and Staphylinidae, but also aphids. Spiders were reduced by mowing.

Potential to improve biocontrol

Most biocontrol related research on uncultivated habitats has focussed on determining whether natural enemies were enhanced in the adjacent crop rather than the impact on the pest. Furthermore, because the relationship between the level of predation and abundance of natural enemies remains unquantified, knowing the abundance of natural enemies does not allow their impact to be determined.

Natural enemies overwintering in field margins were shown to move outwards from field margins in two ways. For those species that walked a wave of dispersal was identified, but those that flew achieved rapid coverage across the whole field (Coombes & Sotherton, 1986; Kromp & Nitzlader, 1995). Even so the distribution of natural enemies across fields is rarely even, with most showing some degree of aggregation into patches (Holland *et al*., 1999, 2004b, 2005). Moreover, as the ratio of edge to field will decrease as field size increases, so the impact of boundary overwintering natural enemies would be expected to diminish. When the distribution of boundary overwintering ground-active predators (Carabidae, Staphylinidae and Lycosidae) was examined in the 3D Farming project, they were found throughout the smaller study fields during May and June where the distance to the field centre from the boundary was no more than 150 m. However, they did not penetrate the larger fields and most patches were located within 100 m of the field boundary. By July, most were located within 60 m of the field boundary (Powell *et al*., 2004; Holland *et al*., in prep). Likewise other studies of natural enemy distributions have found strong evidence of aggregation into patches the size and stability of the patches, varying between the families and species (Ericson, 1978; Hengeveld, 1979; Thomas *et al*., 1998; Holland *et al*., 1999; Bohan *et al*., 2000; Thomas *et al*., 2006; Fernández-García *et al*. 2000; Thomas *et al*., 2001; Holland *et al*. 2004a, b, 2005). For Carabidae, some species remain associated with field margins throughout their lives, especially spermophagous species or those typically found in woodland. In contrast, other taxa that may use grassy field margins for overwintering (e.g. Linyphiidae) disperse beyond the adjacent fields and consequently their distribution is largely unaffected by the margins (Holland *et al*., 1999, 2004). Field overwintering species may use the margins as a foraging resource and overwinter within them either as adults or larvae as the soil remains undisturbed, but the number that do so compared to those within the field is relatively small (Holland *et al*., 2005).

Whether increasing the relative proportion of boundary habitat to crop consequently increases natural enemy densities within the adjacent fields has not been determined, although there may be other limiting factors that control densities within fields. Whether wider field margins enhance the levels of cereal aphid control is the one of the subjects currently being investigated in the RELU funded “Re-bugging the system” project. Initial findings revealed that the presence of 6m wide margins did not improve the levels of cereal aphid control, although almost 100% control of artificial aphid infestations was achieved in all fields (Holland *et al*., 2006). Further studies are underway as part this project to determine whether there is a relationship between the proportion and type of uncropped land in the surrounding landscape, and the level of cereal aphid control. Further discussion of the landscape impact is given below.

Not all ground-active natural enemies overwinter in field boundaries and the numerically most dominant species of Carabidae overwinter as larvae within fields. When the density of these two groups was estimated, the contribution of the field overwintering species far outweighed that of the boundary overwinters, except using the highest estimate of natural enemy abundance and fields surrounded by 6m margins (Holland *et al*., 2006). However, field overwintering species peak in abundance during July whereas boundary overwintering species peak in May to June. Therefore, even the overall contribution of boundary overwintering species may be smaller, this may occur at a more critical time when pests populations are starting to increase, as was demonstrated with carabids and cereal aphids (Edwards *et al*., 1979).

Exclusion techniques are often employed to quantify predation and isolate the impact of different guilds of natural enemies. The earliest studies of cereal aphid predation revealed that ground-active natural enemies reduced the number of cereal aphids and that these were most effective when aphid numbers built up slowly (Edwards *et al*., 1978, 1979; Sunderland *et al*., 1980; Chambers *et al*., 1983; DeClerq & Pietraszko, 1983; Chiverton, 1986; Collins *et al*., 2002) contributing most during the early stages of an aphid infestation (Edwards *et al*., 1979; Chiverton, 1986). However, sometimes the ground-active natural enemies were ineffective and did not prevent aphids reaching the spray threshold (Burn, 1992; Holland *et al*., 1997). More recently, exclusion studies indicated that the contribution made by ground-active predators is relatively small compared to flying natural enemies and therefore the provision of additional margins may not increase the overall natural enemy community sufficiently to have an impact on pest control (Schmidt *et al*., 2004; Holland *et al*., 2006). As part of the RELU project “Re-bugging the system,” exclusion cages infested with grain aphids were used to assess the impact of different guilds of natural enemies on the aphids, at different distances from 2 or 6m wide grass dominated margins. Almost 100% control of the aphids was achieved where all natural enemies and just flying ones had access, regardless of distance from the margin or the width of the margin (Holland *et al*., 2006). Ground-active natural enemies alone had less impact, even so sufficient amounts of overwintering habitats may already have been available. The wider margins probably had no effect because of immigration by aerially dispersing natural enemies from outside the study area. In a similar exclusion study, aphid densities were higher next to grassy field margins but lower adjacent to flower rich ones (Flückiger & Schmidt, 2006). Flying natural enemies were again identified as being the most important.

Carabidae and Staphylinidae are known to consume orange wheat blossom midge (OWBM) larvae and pupae on or in the soil (Floate *et al*., 1990; Holland *et al*., 1996) while spiders may prey upon eggs and adults (Barnes, 1956). Consequently, because uncultivated areas enhance these types of predators they may be expected to improve biocontrol of OWBM but this is most likely to occur when larvae drop to the ground to pupate (Holland *et al*., 1996) so preventing populations of OWBM building up within the soil. They were not shown to have any impact during the year of infestation (Holland *et al*., 1996).

In oilseed rape the impact of ground-based natural enemies is poorly understood for most pests (Büchs, 2003). Mortality of pollen beetle larvae caused by ground-based natural enemies was estimated to be 39% (Basedow, 1973) and 51% (Golterman, 1995) in Germany. In Switzerland, mortality due to predators was 16-27% and from parasitoids 2% (Büchi, 2002), although the type of predators was not identified. Predation in these cases was occurring after crops had been damaged, but this contributed to overall population regulation. Adult emergence was reduced by ground-active predators and reached 51% for cabbage seed weevil, 56% for pollen beetle, 58% for brassica pod midge and 82% for cabbage stem weevil (Büchs & Nuss, 2000). Estimates of the contribution to total mortality made by these predators was small in some cases (4% for pollen beetle, 10% brassica pod midge, 52% cabbage seed weevil) but this may be sufficient to ensure outbreaks are prevented (Büchs, 2003).

The predators responsible for control have not been confirmed through dietary analysis, although a good correlation between the peak of the carabid beetle (*Poecilus cupreus*) population and the dropping of pollen beetle larvae indicated that this species may be contributing to their control (Büchs & Nuss, 2000). This is a field overwintering species that peaks in mid-June, along with some other highly abundant field overwintering beetles (Holland *et al*., 2007). In the LINK Integrated Farming Systems project, the abundance and diversity of Carabidae, Staphylinidae and Linyphiidae was as high or higher in oilseed rape crops compared to other cereal crops (Holland *et al*., 1998; Holland, 2000). The carabid species composition is similar to that of other arable crops (Büchs & Alford, 2003), although a greater proportion of spermophagous species was found, attracted by the weedy understorey (Gardner *et al*., 1999). Details of the staphylinid species composition have not been published for the UK although the data exists in the LINK IFS database. Details of other groups of predators found in oilseed rape are described by Büchs & Alford, 2003; of these Diptera and Aranaeae are considered valuable, but the contribution they make towards biocontrol remains unquantified.

Whether margin enhancement encourages the natural enemies of oilseed rape pests overwintering in field boundaries has not been examined to any great extent, although further information could be gained from further interpretation of the LINK IFS data. Migration into oilseed rape was inhibited and slower compared to winter wheat where enhanced margins were present (Goltermann, 1994). Oilseed rape creates cooler and more shaded conditions and consequently attracts or deters some species, as identified by Goltermann (1994). Overall, the value of margins for enhancing the ground-active natural enemies of oilseed rape pests cannot be confirmed and there have been no studies to examine the relationship between these, the amount of margin habitat and the levels of oilseed rape pests. In Switzerland, the flower rich strips encourage ground-active predators (Carabidae and Araneae) in the adjacent crop (Frank, 1996), but they rapidly declined in abundance and diversity with distance from the margin (Frank, 1996). As few predators occur in the canopy where the pests are prevalent (Hausamann, 1996) they are overall not considered to be important in the prevention of crop damage during an infestation.

Parasitoids are, however, considered to be more important in the regulation of oilseed rape pest populations. Parasitism was higher in field centres in the presence of six year old, but not one year old field margin strips and was also higher at the edge adjacent to six year old strips (Thies & Tscharntke, 1999). Parasitoids are known to overwinter in soil following a rape crop but 75% were killed by ploughing and harrowing (Nilsson, 1985). The older field margin strips were considered important in the parasitoids survival, allowing populations to build (Thies & Tscharntke, 1999). Even higher levels of parasitism were recorded in fields adjacent to large fallows, and the authors concluded that the size and age of uncultivated land were key factors in the biocontrol of pollen beetle. Indeed when the landscape was taken into consideration, parasitism increased with landscape heterogeneity. The rate of parasitism did not decrease as the area of rape grown increased. A combination of measures is recommended to maximise biocontrol in oilseed rape (Williams, 2004) alongside the judicious use of insecticides, host plant resistance and crop husbandry.

Negative effects

Uncultivated areas may also have some negative effects on natural enemies. To ensure sufficient numbers of natural enemies are present within a field, some degree of movement between fields is necessary because crops are rotated and therefore the requirement for pest control may differ. The natural enemies may also prefer the environmental conditions created by particular crops and therefore will redistribute accordingly.

Such a process was found to occur with Carabidae, although the whole process took several months (Thomas *et al*., 2006). In addition, agricultural operations (e.g. insecticides or intensive tillage) or natural population regulation (disease, parasitism) may reduce existing natural enemies within a field or part thereof, necessitating the need for immigration. However, uncultivated areas although acting as a reservoir of natural enemies, may inhibit the movement of ground-active invertebrates, the permeability of the feature depending on the vegetation structure and the species physical attributes (Jepson, 1994). Even one of the most mobile carabid species (*Pterostichus melanarius*), only 6% were found to have moved through a 5 m wide hedgerow (Thomas *et al*., 1998). Likewise in the 3D Farming project, use of mark-release-recapture revealed that the movement of two carabid species was restricted by the hedgerows, although the extent to which this occurred varied between the species (Holland *et al*., 2004b). In a study of individual marked beetles, none were recaptured beyond the field's boundaries (Winder *et al*., 2005). All of the above studies used beetle species that were large enough to be marked. Whether smaller species are also confined by field boundaries is not known. In the RELU project "Re-bugging the system," the movement of natural enemies dispersing by flight within fields is being investigated in conjunction with assessments of cereal aphid control. These studies are being conducted in landscapes with varying areas devoted to ES schemes so that this component can be appraised.

Further research is needed to determine whether the enhancement of field boundaries is restricting movement of natural enemies within the landscape and thereby increasing the risk of extinction, changing the community composition and increasing the risk of pest outbreaks. Jepson (1994) proposed that landscapes models could be used to investigate such factors incorporating factors such as permeability and land use for a variety of predator guilds.

Uncultivated areas, if more attractive than the crop to natural enemies may also act as sink habitats, lowering numbers in the adjacent crop. Indeed, a large proportion of those invertebrates overwintering in boundaries remain within or in close association with them during the summer and so contribute little to pest control. Approximately a third of the Carabidae and half the Staphylinidae measured during the winter remained within field boundaries during the summer (Thomas *et al*., 2000) with individual species showing different distribution patterns (Wallin, 1989). Likewise, other natural enemies may be attracted to non-crop habitats if they provide more suitable resources than the crop and with more land being devoted to ES options, depletion as well as augmentation of natural enemies within crops is a possibility.

The resources provided by uncultivated areas may also encouraged the natural enemies own controlling agents, parasitoids in particular may benefit from floral resources, but this remains an unknown quantity.

5.3 Wild bird seed mixture (EF/OF2, EF/OF3; HF12)

Wildbird cover can develop a rich understorey of weeds, especially if retained for more than one year. Such uncultivated areas may become attractive to natural enemies but this has rarely been examined. In the 3D Farming project, the abundance of cereal and pea aphids and their natural enemies was assessed in fields with and without 24 m strip of wildbird cover. In one year, cereal aphids on wheat were higher at 10 and 30 m from the strips compared to the field boundary indicating that strips were encouraging biological control. The strips contained a high proportion of flowering plants at this time, including sown species such as *Phacelia tanacetifolia* that may not normally be sown as part of a wild bird seed mix and flowering weeds, and thus may have boosted numbers of hoverflies and parasitic wasps leading to higher levels of aphid predation or parasitism. There was some evidence that predatory invertebrates were encouraged by the strips, possibly through a diversification of food resources and overwinter cover. However in the second year the reverse effect on aphids was found, but some key natural enemy groups were not appraised, parasitoids and hoverflies, and there was some evidence that the strips were acting as a sink habitat for Staphylinidae. In the pea fields the set-aside strips had no effect on the abundance of pea aphids, but there was some evidence that the strips were acting as a sink for Staphylinidae.

Unpublished data held by the Game Conservancy Trust indicates that wild bird cover contains high numbers of Diptera and Parasitica, along with Araneae and predatory Coleoptera. Further identification of invertebrate samples would be needed to find the proportion of predators and parasites that contribute to the control of cereal and oilseed pests.

5.4 Flower rich habitats (EF/OF4-5; HE10)

These options encourage the establishment of a sward containing at least three pollen and nectar rich plants (EF4, EF5) along with non-aggressive grasses to aid establishment. Besides providing a source of pollen and nectar these habitats may also provide some overwintering and breeding cover and alternative food supplies, while also acting as refuges from agricultural operations. Studies evaluating the use of wildflowers by invertebrates have focussed on species of conservation concern (e.g. bees and butterflies) and to a lesser extent the natural enemies. Instead, studies investigating the value of floral resources for natural enemies have concentrated on using stands of a single flowering species to determine whether improved biocontrol can demonstrated. Plant species that have been tested include *Phacelia tanacetifolia*, buckwheat and coriander (Hodgson & Lovei, 1993; Hickman & Wratten, 1996; Macleod *et al*., 1999). Recent studies have also indicated that even supposedly unattractive flowers such as those of legumes are utilised by natural enemies (W. Powell, pers. comm.) The development of a technique to identify the presence and identity of sugars in the guts of adult parasitoids in the field will further aid our understanding of floral resources and their manipulation (Heimpel *et al*., 2004).

An extensive literature exists describing the mechanism by which flowering plants encourage natural enemies, the practicalities of the technique and results for a range of flowering plants and mixtures. The literature has been extensively reviewed recently (Gurr *et al*., 2000; Wäckers *et al*. Eds, 2005) and will not be considered here except the key conclusions. Instead, only findings relating directly to cereals/oilseeds and for habitats similar to those likely to be established under ES are reviewed.

Key conclusions for flower rich habitats

- Floral resources are utilised by a wide range of natural enemies.
- Plant species differ in the resources they provide, their accessibility and flowering period, all of which need to be considered when designing biocontrol enhancing seed mixtures, thereby ensuring a diverse natural enemy community is supported.
- For some species there is a positive relationship between the provision of floral resources and increase longevity, fecundity and ability to disperse (parasitoids, hoverflies)
- Floral resources may be utilised as an alternative food supply, aiding survival.
- Pests species, particularly Diptera may utilise floral resources and appropriate plants must be selected.

Uncertainties

- The time frame over which floral resources must be available.
- The proportion of the landscapes which must be devoted to the provision of floral resources.
- The spatial arrangement of flower resources within the landscape.
- Whether their use by pests can lead to an increase in their population or crop damage.

Potential to improve biocontrol

The value of floristically rich grass margins comprised of flowering species known to be preferred by natural enemies were investigated as components of the 3D Farming project and to a lesser extent the SAFFIE project.

In the 3D Farming project, the plant species most used by foraging aphidophagous hoverflies were determined (Powell *et al*., 2004) and margins rich in such species were established. The most preferred species were species yarrow, white campion, cornflower, common knapweed, rough hawkbit, field scabious and lady’s bedstraw. The least preferred group included *Phacelia tanacetifolia*, ragged robin, red dead-nettle, cowslip and ox-eye daisy. Fecundity was improved by feeding on the preferred species indicating that females select species with appropriate nutrients. The abundance of hoverflies and cereal aphids within and at 10m, 30m and 100m from these flower rich margins was compared to that of un-enhanced field margins. There was no evidence that the numbers of adult hoverflies, adult parasitoids or carabid beetles was enhanced in the fields with flower rich margins, however, numbers of cereal aphids were significantly reduced in seven site-years out of twelve.

Within the SAFFIE project the impact of the flower rich grass margins on aphids within the adjacent crop was measured, however, there were no significant differences in the number of cereal aphids found in fields with and without 6m floristically enhanced grass margins (Douglas, 2004). The study was, however, conducted one year after establishment when the margins had not become fully colonised. Detailed investigations into the distribution of invertebrates within fields with and without the floristically enhanced margins were conducted during years 3-5. The abundance and distribution of ground-active predatory natural enemies within winter wheat fields was unaffected by the presence of floristically rich 6m wide margins. Further analysis of the data would be required to determine whether crop active predators were affected.

In Switzerland, damage by slugs was reported adjacent to wildflower strips (Frank, 1996) but there was no increase in oilseed rape insect pests (Hausammann, 1996). The strips harboured high numbers of natural enemies but augmentation of the adjacent crop was limited and a spacing of 24m apart was recommended (Nentwig *et al*., 1998). Predation of pollen beetle larvae was 20% and 35% higher at 3 and 30m from the wildflower strip, and parasitism by one species was higher (Büchi, 2002).

5.5 Overwintered stubbles (EF/OF6; EG/OG4-5 HF15, HF19)

In contrast, to fields that are cultivated prior to autumn drilling, this option will allow ground-active invertebrates time to return to field boundaries and increase, but whether this results in higher numbers the following year has not been quantified. The survival of larvae in the soil would also be expected to improve in the absence of cultivation but because the overwintered stubble can be followed by a spring crop there may be no net benefit if the crop is established using intensive soil cultivations. In the Arable Stewardship Pilot Scheme ecological evaluation more carabid larvae were found in the stubbles during the autumn and spring, but adult abundance the following year was no higher even when followed by spring/summer fallow (Gardner *et al*., 1999). The species composition of carabid beetles may change because according to their phenology, vulnerability to the timing of cultivation differs (reviewed by Holland & Luff, 2000).

Potential to improve biocontrol

No previous investigations. The survival of natural enemies overwintering within the field will depend on the intensity of soil cultivations in the spring.

5.6 Beetle banks (EF/OF7)

This is the only option designed to encourage natural enemies although in practice farmers were found to choose this option in order to demark large fields or for game management rather than biocontrol (Thomas, 2000). High numbers of natural enemies (Carabidae, Staphylinidae, Araneae) were found overwintering within the ground vegetation of hedgerows (Sotherton, 1984, 1985). Raised areas that were less prone to water-logging and were preferred by overwintering beetles and this led to the development of "beetle banks", raised banks of approximately 40 cm height and 1.5 m wide covered by tussocky grasses. Initially a combination of Dactylis glomerata L. and Holcus lanatus L. was recommended (Thomas *et al*., 1991; 1992), the former was subsequently found to support Carabidae while *H. lanatus* (Yorkshire fog) was favoured by Staphylinidae (MacLeod *et al*., 2004). However, *D. glomerata* (Cock's foot) was found to rapidly out competed *H. lanatus* whose seed was expensive and difficult to obtain (Collins, 1999). In a comparison of six grass species, *D. glomerata* supported the highest densities of Carabidae and *Arrhenatherum elatius* L. (False oat grass) those of Staphylinidae and Araneae, therefore this combination is now recommended (Collins *et al*., 2003a). Mixes of grasses also increase the structural diversity of the vegetation and thereby that of the beneficial arthropods (Baines *et al*., 1998). Web-building spiders prefer a close structure, although litter depth was also considered an important determinant of spider community composition (Bultman & Uetz, 1982). Tussocky grasses provide both a close structure and abundance of dead leaf material.

The value of beetle banks as overwintering habitat was not found to deteriorate with successional changes in the vegetation and those over 10 years old had a similar diversity to that of a hedge bank (Thomas *et al*., 2002). Moreover, the abundance and diversity of beneficial arthropods did not decline with age (MacLeod *et al*., 2004). Indeed when compared to established hedge banks, beetle banks supported similar densities of beneficial arthropods even though their numbers fluctuated to a greater extent between years (Collins *et al*., 2003b; Macleod *et al*., 2004). The hedgerow was considered to provide additional shelter so buffering environmental conditions, whilst the soil within the hedgebank was also more organic and better drained compared to the clay soil of the beetle bank (Collins *et al*., 2003b). Overwinter survival is higher where there is lower soil moisture (Dennis *et al*., 1994).

Potential for biocontrol

Based upon the dispersal distances of invertebrates overwintering within the banks, the deployment of beetle banks through the centre of fields greater than 16 ha was recommended (Thomas *et al*., 1991). However, an impact on pests (cereal aphids) attributed to generalist predators originating from the beetle bank was only detected up to 58 m from the beetle bank (Collins *et al*., 2002).

5.7 Skylark and fallow plots (EF/OF8; HF13, HF16, HF17, HF20)

Skylark plots were found to support few extra invertebrates compared to the adjacent crop (Smith & Jones, 2007). No information regarding the invertebrate fauna of fallow plots was found although species composition is most likely to depend on the composition and abundance of weeds.

Potential for biocontrol

Owing to the relatively small area occupied by these two options, they would not be expected to have any value for biocontrol.

5.8 Reduced or no herbicide inputs (EF9-10, EF11; HF14, HF15, HF18, HF19, HG7)

Within the crop modern herbicide regimes prevent the survival of all but the hardiest or herbicide resistant weeds. Unsprayed headlands were originally conceived as a means of protecting the native arable flora from herbicides (Schumacher, 1987). They were trialled and adopted as Conservation Headlands in the UK as means to increasing food resources for gamebirds because many of the key chick food insects were dependent on weeds (Sotherton, 1991). More latterly in the UK they have been promoted as a method to preserve and encourage rare arable plants and farmland birds *per se* and the approach can be also implemented within fields in some ES options. Their use by predatory arthropods has also been widely examined, because besides creating a suitable habitat the enriched invertebrate community should be a source of alternative food for polyphagous species. In addition, the flowers of arable plants can provide some pollen and nectar while the seeds are also consumed by polyphagous predators.

Whether unsprayed crop headlands enhanced non-target arthropods within arable fields was reviewed by Frampton (2003) for Defra (PN0939). In total, 31 research studies were reviewed and of the 25 frequently monitored groups of arthropods, 19 exhibited significantly higher abundance and/or species number in the unsprayed edges and only three were significantly lower. Phytophagous invertebrates benefitted most, utilising the higher weed levels found within Conservation Headlands. It was concluded that there would be no increase in invertebrates within the adjacent sprayed crop. Of the predatory arthropods, there was no benefit for Carabidae as also found in the Arable Stewardship Pilot Scheme ecological evaluation (Gardner *et al*., 1999). Carabid beetles were, however, shown to be better fecund more fecund in conservation headlands compared to conventional cereals (Chiverton, 1984). Overall, only a marginal increase was found for Coccinellidae, Syrphidae and Araneae although in the Netherlands 3-4 times more invertebrates were collected from the upper canopy of unsprayed winter wheat margins compared to conventionally sprayed (De Snoo, 1999). The increase was attributed to higher numbers of flower visiting species (Syrphidae) and aphid predators (Coccinellidae). Syrphidae, especially *Episyrphus balteatus* were shown to utilise the floral resources provided by the arable weeds in Conservation Headlands (Cowgill *et al*., 1993; De Snoo, 1999). Aphids were only significantly more abundant in the unsprayed margins (Cowgill *et al*., 1993) but they did not spread into the adjacent crop (De Snoo & De Leeuw, 1996).

Where plots or fields with reduced herbicide inputs are created within fields, natural enemies may increase. If this occurs whether these subsequently survive into the following year in sufficient numbers to have an impact on pests in the same or neighbouring fields is not known. Alternatively the fields may act as a sink for natural enemies within the landscape.

Potential for biocontrol

Enhancement of Syrphidae using Conservation Headlands did not lead to higher numbers of their eggs on the adjacent wheat crop (Cowgill *et al*., 1993).

5.9 Undersown spring cereals (EG/OG1)

This option should improve the survival of those natural enemies overwintering in the soil because the soil remains undisturbed from drilling until 15 July the following year. The emergence of Carabidae was twice as high in undersown barley compared to barley (Vickerman, 1978). Likewise in Sweden, the emergence rates of carabid beetles was increased by an average of 50% and by up to 100% for *Bembidion* species (Carabidae) in spring cereals undersown with clover or ryegrass (Helenius *et al*., 1995). The increase was attributed to preferential selection of the undersown crop or improved larval survival. Although there may be some yield loss, the undersowing may help prevent soil erosion, nitrate leaching and improve soil structure (Helenius, 1998). The undersown vegetation may also create different environmental conditions and host alternative prey for natural enemies if sufficient a sward develops. Indeed, the abundance of Araneae and Opiliones, Hymenoptera, Coleoptera and Diptera was higher in undersown barley compared to barley (Vickerman, 1978). However, in the ASPS there was no difference in the abundance or diversity of Carabidae between undersown and conventional crops during this period (Gardner *et al*., 1999).

Potential for biocontrol

In two of the three study years 60% more cereal aphids were found in barley compared to undersown barley, and this was attributed to increased predation in the undersown crop (Vickerman, 1978). Undersown fields may act as either a sink or source of natural enemies in the landscape.

5.10 Uncropped, cultivated margins (EF11)

This option was primarily designed to protect rare arable plants. When their usage by arthropods was examined, the diversity and abundance of Carabidae captured using pitfall traps within uncropped headlands was higher than either Conservation Headlands or sprayed headlands (Cardwell *et al*., 1994; Hawthorne & Hassall, 1994, 1995) and that the diversity of spiders showed the same trend (White & Hassall, 1994).

Carabid abundance was higher 8m into the crop adjacent to the uncropped headlands (Hawthorne & Hassall, 1994, 1995).

Potential for biocontrol

Uncropped headlands were recommended as a tool for enhancing aphid control (White & Hassall, 1994) but no evidence of their impact on aphids was presented. The habitat created using this option may be extremely attractive to natural enemies having an abundance of weeds and phytophagous arthropods, whilst also being structural diverse and consequently their may be little incentive for them to disperse into the adjacent crop. When the movement of *Agonum dorsale* between the field boundary and the centre of the crop, traversing the uncropped headland was examined there was no evidence that this species was retained in the uncropped headland (Hawthorne *et al*., 1998). In addition the headland acted as a source of another carabid, *Bembidion lampros*. In a detailed study of cereal aphids in wheat up to 64m from the adjacent unsprayed headlands, Conservation Headlands and a fully sprayed crop, there was no consistent effect of the latter two treatments on aphids. They were lower next to the unsprayed headland but only early in the season (Hawthorne & Hassall, 1994). The floral resources provided by the annual weeds may be utilised but there is no evidence that this has any impact on the subsequent effectiveness of the natural enemies.

5.11 Minimum or non-inversion tillage (ED/OD3; HD6)

Mimimum tillage (MT) is now practised upon 50% of arable farms () and has the potential to dramatically alter the arthropod fauna. No funding is available except where annual crops are established over archaeological features. A wide diversity of natural enemies overwinter buried within the field, predominantly from the Coleoptera, Diptera and Hymenoptera while some Arachnida survive year round on the surface. As a consequence they are vulnerable to cultivation. Cultivation may effect survival directly by causing mortality whilst also having indirect effects by modifying habitat and the availability of prey. In the longer-term, MT encourages grass weeds and retains organic matter on the soil surface, thereby increasing saprophytic and detritus feeding species upon which these predators depend. Many studies have been conducted on different tillage systems but the results for natural enemies are largely inconsistent (Holland, 2004). Partly this is because ground-active arthropods were monitored using pitfall traps which have many limitations, the most important being that capture is related to activity (Adis, 1979). In addition, studies of tillage were often conducted as part of farming systems experiments and interactions often occurred with the cropping system, the latter often exerting a greater effect (Hance, 2002).

The effects of cultivation on carabid beetles were summarised by Kromp (1999), Holland and Luff (2000) and Hance (2002). Of the 47 taxa listed by Holland and Luff (2000), 20 had been shown to favour ploughed crops, 21 favoured minimum tillage, with six shown to favour both types of cultivation. They concluded that because different species respond according to their phenology; changing cultivation practices selects for those species best adapted to the new regime, and as a consequence, overall abundance may not differ but the species assemblage may change. Firmer conclusions can be drawn where arthropod density was estimated using emergence traps (Purvis and Fadl, 1996; Holland and Reynolds, 2003). These studies indicated that ploughing adversely affected the survival of many carabid species. A few species of rove beetle (Coleoptera: Staphylinidae) overwinter as larvae within fields. Greater numbers of two species were found in MT compared to autumn ploughed plots (Andersen, 1999), however, no effect of ploughing was found by Holland and Reynolds (2003). Spiders are usually the most abundant arthropods within arable fields and some groups e.g. wolf spiders (Araneae: Lycosidae) are relatively sensitive to disturbance (Holland and Reynolds, 2003). On the contrary, money spiders (Linyphiidae) were considered able to survive ploughing (Duffey, 1978), although this was not found by Holland and Reynolds (2003). It would be expected that spiders would readily colonise MT fields because they prefer an architecturally complex environment and this is better created by MT because there is a more complex litter layer, possibly higher weed densities and more stable soil conditions (Rypstra *et al*., 1999).

Potential for biocontrol

Aphid infestations in the autumn and consequently the incidence of BYDV were lower where minimum tillage was used (Kendall *et al*., 1991). This was attributed to either lower initial infestations or higher high predation. With minimum tillage a greater proportion of the previous crops residues remains on the soil surface and this was considered enough to alter the appearance of the field sufficiently to deter aphids. Larger numbers of ground-based predators were also present helping to reduce aphid survival and prevent the secondary spread of the virus.

5.12 Crop protection management plan (EM4)

The recommended actions that should be undertaken for this option are based upon those developed in studies of integrated farming or integrated crop management. There is clear evidence that the adoption of an integrated approach to crop protection is associated with lower pesticide inputs. A 39% reduction in the overall amount of active ingredient most toxic to arthropods (insecticides, nematicides and molluscicides) was achieved across nine sites (Ogilvy, ed., 2000). In a further review of 11 European studies, insecticide/molluscicide use was reduced by 55% compared with conventional management (Berry *et al*., 2004).

Potential to improve biocontrol

Beneficial arthropods were measured in 10 of the 11 European studies and an increase was reported in eight with no increase in the other two. There was however, considerable variation between studies and taxa in their response to the different farming systems.

6. Conclusions on potential of Environmental Stewardship to encourage biocontrol

6.1 Utilising Environmental stewardship for pest control

The potential of each habitat manipulation approach to provide the key resources for natural enemies is summarised in Table 5. The scoring was considered and revised at the project workshop. Overall well managed hedgerows comprised a substantial shrubby component with a 2m wide floristically diverse hedgebase provide most resources. Current cross-compliance regulations stipulate that the ground flora must be preserved for 2m from the hedge centre, however, where a wide shrubby component occurs the herbaceous strip at the hedgebase may exist beyond this distance. Given the importance of this area for natural enemies and wildlife, some refinement of the rules is needed to ensure that this strip is preserved. Uncultivated margin strips/buffer zones also provide an appropriate ground flora, although their value will depend on whether a herbaceous component exists. Relatively few of the options allow for manipulation of the cropped area even though this is important for some of the most abundant natural enemies (Carabidae, Linyphiidae and some parasitoids). A considerable number of uncertainties exist as indicated in table .

The types of natural enemies supported by each option are summarised in table 6. Hedgerows, field margin strips and beetle banks were considered the best, although whether natural enemies occurring within hedgerows then populate adjacent fields has not been examined in any great detail. Of the within field habitats, the effects of non-inversion tillage warrants further investigation especially as it is now becoming widespread.

Whether habitat enhancement subsequently leads to an increase in pest control, remains on the whole uncertain (Table 8). The effects on cereal aphids have been most studied and the emphasis of the current research on parasitoids is to combine habitat enhancement with semiochemicals in a push-pull approach (Appendix 4: Project nos. 18 & 31) as tried in the 3D Farming project (Powell *et al*., 2004). For other natural enemies, the effectiveness of the habitat enhancement depends on there being adequate dispersal of the natural enemies between these habitats and the crop, and in sufficient numbers to change the natural enemy:pest ratio in favour of the natural enemies. The alternative approach is to improve the environment for natural enemies within the field by, for example, increasing plant diversity and reducing the impact of tillage. This may be achieved by adopting minimum tillage, undersowing or manipulating herbicide inputs but few options are available for this under ES. The two approaches may complement each other. For example, when the number of ground-active natural enemies overwintering in the margins was estimated and the number that they provide per unit area of crop in the following year estimated and compared to that of field overwintering species, it was apparent that except in the smallest field (5ha), their contribution was always smaller than that of the field overwintering taxa (Holland *et al*., 2006). However, the boundary overwintering taxa were more active earlier in the year and consequently if pressure on the pests is to be maintained season long, measures to encourage both aggregrated and dispersed diversity are needed. Many other flying natural enemies also make use of non-crop habitats but these were excluded in these calculations and so the value of the margins was underestimated. Even so, they may remain within the margins or move elsewhere if the crop environment does not provide suitable food or hosts. Further research is needed to develop more options to enhance dispersed diversity. Options to increase the suitability of the crop for natural enemies that may be acceptable to farmers and maintain profitability are limited. Minimum tillage has shown to be acceptable, with 50% of farms now adopting this practice (SMI). The level of weed cover may also strongly influence the abundance and diversity of natural enemies (Powell *et al*., 1985). Certain carabid species are known to favour weedier areas (Powell *et al*., 1985) and in the 3D Farming

Table 8. Potential for Environmental Stewardship habitats to improve biocontrol in cereal and oilseed rape crops and whether they support pests.

ES Option	**Potential for biocontrol in cereals**	**Potential to support cereal pests**	**Potential for biocontrol in OSR**	**Potential to support OSR pests**
Hedgerow management	*** ?	*	***	*
Protection/creation of uncultivated ground flora	** ?	***	* ?	***
Wild bird seed mixture	?	*	?	***
Flower rich habitats	***	**	*	***
Overwintered stubbles	*	*	** ?	*
Beetle banks	**	*	** ?	*
Fallow plots		no	* ?	no
Reduced or no herbicide inputs	*	no	?	*
Undersown spring cereals		**	* ?	no

project, carabids were found to be most abundant with 10-14% weed cover (Powell *et al*., 2004). The impact on other natural enemies is less well understood. The manipulation of weed cover using different herbicide regimes, harrowing and row spacing was investigated as part of the SAFFIE project (Jones & Smith, 2007).

Where no noxious weeds or volunteers were present it was possible to reduce herbicide inputs and allow the more desirable weeds to survive, without compromising yield. Analyses are currently underway to determine whether the strength of the relationship between natural enemies and weed cover, and whether an optimum level can be identified.

A diverse cropping system may also be used to achieve dispersed plant diversity. Rotations, are recommended in ICM and their impact is better understood for pests than natural enemies. However, the spatial arrangement of crops in the rotation may also affect natural enemies and pests, but has received less attention. Studies of intercropping or strip cropping go some way towards helping understand these issues but these techniques are rarely used in western Europe. Where practised they can successfully enhance natural enemies and reduce pests (Parajulee *et al*., 1999). The development of such techniques relies on a full understanding of the natural enemies and pest's biology if these are to be exploited. In the UK, there is a move towards more block cropping to reduce costs but whether this will effect pests and their natural enemies remains uncertain. Some evidence already exists indicating that the spatial arrangement of crops is important. Pollen beetle parasitoids are poor dispersers and rely on their being a suitable crop nearby when they emerge (Hokkanen, 1989). There is also some evidence that other predators make use of the floral resources provided by oilseed rape (Bowie *et al*., 1995). On the other hand, some pests are poor dispersers (e.g. orange wheat blossom midge) and would be equally favoured by spatially diverse cropping.

Intercropping oats and faba bean was examined in Finland, but although some natural enemies (Carabidae) were enhanced, others were unaffected (Coccinellidae and parasitoids) and the overall cereal aphid densitity was the same because the aphids were concentrated on fewer plants.

6.2 Integrated Pest Management (IPM)

The principles of IPM have been widely publicised to farmers and agronomists and guidelines periodically produced over the last 20 years, most recently by HGCA (Oakley, 2003). In addition, these principles have been incorporated into the BASIS courses in Crop Protection and Integrated Crop Management. Effective pest control in arable crops relies on four main principles (Oakley, 2003):

1. Minimise the risk of infestation using cultural means (e.g. rotations and resistant varieties)

2. Assess pest abundance before treatment

3. Only use treatments if economically justified

4. Maximise the effects of natural enemies by using selective products and habitat manipulation.

In 1996, British farmers were surveyed to determine the level of awareness and use of Integrated Crop Management and IPM techniques. This survey was repeated in 2002 to gauge whether there any been any changes (Bradshaw & Scott, 2002). Farmers were classified according to the crops produced and this included a combinable crops category. Understanding of the principles of IPM was highest amongst fruit and vegetable producers, probably because the research focus and consequently developments were initially made in this sector. Of the cereal farmers many were aware of and used ICM and to a lesser extent IPM principles, although only 22% had a clear understanding, an improvement of 10% since 1996. A large proportion of cereal farmers were using some of the above principles, but the survey did not differentiate whether they were used for insect pest control alone, instead grouping them for weeds, pests and diseases. Crop monitoring was the most widely used and perceived as the most effective IPM technique. Crop rotations, thresholds, products compatible with natural enemies and reduced rates were also commonly used. With respect to alternative methods of production, 88% of the cereal farmers agreed that there was insufficient information on non-pesticide control methods, although the same proportion would not consider switching to organic methods. This indicated that a large proportion of farmers were interested in reducing pesticide usage and indeed the survey revealed that they were feeling some degree of public pressure to adopt alternatives. Environmental considerations had also moved up their list of business priorities. Overall the survey suggests that farmers have and are willing to change their methods of production but it is likely that of the ICM/IPM techniques adopted, many were most likely to have been used in disease control. Similar detailed information on how to reduce insecticide/molluscicide inputs are likely to be well received although they must remain robust and not compromise profitability.

At the project workshop there was discussion relating to IPM. Thresholds were not considered to be widely used in pest control because of the time required and difficulty in obtaining meaningful assessments. Pollen beetle and orange wheat blossom midge meet these criteria. Indeed, the abundance of cereal aphids (Winder *et al*., 1999) and oilseed rape pests (Ferguson *et al*., 2000, 2003, 2006; Warner *et al*., 2003) were shown to be highly variability within fields, with some showing distinct preferences for field edges. Consequently, the methodology used to assess their overall abundance can affect the subsequent result; random counts or line transects were the most accurate (Alexander *et al*., 2005). However, such detailed assessments of abundance are very time consuming and the presence/absence of pests in the locality is often used as a guideline for a treatment recommendation, especially for those pests known to regularly occur. A requirement for simpler and quicker monitoring methods was identified and the use of pheromone traps for pea aphid control was highlighted as an example of a highly desirable approach. Alternatively a greater understanding of pest's distribution patterns within and between fields may allow simpler monitoring methods to be developed and indicate the number of fields that require assessment within a locality.

Pest control using insecticide/molluscicide was also perceived to be the mainstay in the future alongside the use of natural enemies. To achieve such a balance would require further information and the use of reduced doses was seen as one possible way forward. This would necessitate not only identifying the key natural enemies and their response but also that of the pests. Selectivity may also be achieved using application technology, ensuring minimal contamination of non-target areas. Such studies, however, cannot be conducted in isolation because of the complexity of the agroecosystem and therefore an understanding of the whole system is also needed. For example, natural enemies may recover following an insecticide treatment but the extent and speed by which this occurs depends on the lifecycle of the organism, its mobility and the availability of recolonisers in the surrounding landscape. Further work on recovery following insecticide treatments was identified as a requirement but needs to be conducted on a larger scale than previously tried (e.g. SCARAB) because of new knowledge relating to the importance of the wider landscape in pest regulation. Whatever the approach, an economic costing would be needed for any new method if it is to be adapted. The social and economic reasons that inhibit the adoption of alternative pest management practices is currently being investigated by Kent University as part of the RELU funded project "Re-bugging the system." No results are available at present; the project will report fully in 2008.

Some treatments that were considered to be particularly damaging or were implemented prophylactically and should be a priority to reduce; these included:

1. Application of organophosphate insecticides for control of orange wheat blossom midge. Further work on the development of pheromone trap monitoring system is underway.

2. Insecticides applied mid-flowering in oilseed rape. Research on resistant varieties, an alternative flower colour and petaless flowers is in the pipeline. Resistance by pollen beetle to pyrethoid insecticides may provide a further impetus to reduce insecticide applications.

Further development of an integrated approach to oilseed rape pest control continues in the MASTER project (Appendix 4: Project no. 39) from which short papers from the projects first workshop provide further detail (Various, 2006). In addition, the optimising biocontrol through manipulation of crop husbandry is currently being investigated in a Defra funded project (Appendix 4: Project no. 16).

7. Future work

7.1 Habitat manipulation

1. Determine the extent to which habitat manipulation can improve the level and reliability of pest control and how this is influenced by the complexity of surrounding landscapes - specifically, to identify how much non-crop habtat is needed and its spatial arrangement on-farm to maximise levels of biocontrol. Some answers may be gained from four current projects (nos 17, 25, 27, 31, Table).

2. Examine to what extent non-crop habitats encourage or inhibit the movement and distribution of natural enemies and pests. In particular, the extent to which they also affect reinvasion of fields following insecticide treatment.

3. Determine whether habitats under ES are harbouring pest populations and whether these are subsequently increasing the risk of crop losses.

7.2 Natural enemies

1. Investigate the biology and especially diet of some of the more abundant natural enemies about which little is known. Specifically:

a. diet/prey selection of beetle larvae and their predation of pests, especially the overwintering stages.

b. diet of predatory flies e.g. Histeridae, Hybotidae, Dolichopodidae and Emididae

c. Identify those natural enemies that contribute to the control of those pests most frequently requiring insecticide treatments e.g. pollen beetle.

d. Using information above to then identify ways to enhance the most efficient natural enemies.

2. Examine the movement of natural enemies, especially following insecticide applications and for those species (especially parasitoids) emerging in unsuitable crops.

7.3 IPM

1. Investigate the use of reduced insecticide dosages to preserve natural enemies in conjunction with the impact on reliability and persistence of pest control.

2. Investigate the potential to reduce insecticide impacts using application technology.

3. Examine the recovery of natural enemies following insecticide applications, the impact of scale of treatment and importance of the surrounding landscape.

4. Compare the effects of different cultivation systems on pests overwintering within the soil and the survival of their parasitoids.

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Appendix 1. Annual reports of pest incidence - Crop agronomy

Winter cereals

Harvest year	
2007	Early or timely drilling. Warmer than average autumn and winter. Rapid establishment of wheat and barley, forward, well-tillered crops by late December.
2006	Early or timely drilling. Warmer than average autumn. Near normal winter temperatures but colder than average in March 2006. Initially rapid crop establishment, forward, well-tillered wheat and barley crops by late December. Development checked by colder weather in late winter making crops relatively backward compared with previous year. Ear emergence in wheat at normal timings (late May to mid June (north). July was the hottest on record leading to premature senescence and early start to harvest.
2005	Later drilling on completion of delayed harvest. Drilling progress then rapid. Favourable autumn-spraying conditions. Warmer than average winter. Ear emergence wheat from end of May to mid June (north) – typical timings.
2004	Normal drilling dates but dry autumn (<50% of average rainfall in eastern England in Sept and Oct) – delayed cereal emergence. Crops in east relatively 'backward' in winter (impact on wbf). Warmer than average winter. W.wheat GS 59 late May to mid June (north). Wet weather in August substantially delayed wheat harvest with impact on next cropping year.
2003	Most first wheat crops drilled mid-late September (wet conditions delayed start of drilling campaign). Patchy emergence in subsequent dry conditions in mid October. Relatively backward crops overwinter due to late emergence (impact on wbf). Ear emergence wheat late May – typical timing.
2002	Rapid drilling progress. Rapid establishment. December 2001 colder (-0.5 to 1.5°C) than average, then mild esp. Feb 2002. More late Aug drilling than normal (response to problems with drilling in previous year). Few late drilled crops except after roots. Ear emergence wheat late may to mid June (north).

2001	More late August drilled winter wheat crops than usual (follow on effect from harvest year 2000). Autumn rainfall above average. Extended drilling period and ultimately it became too late to drill winter cereals prompting a switch to spring cereals (winter wheat area down by 21%, winter barley 12% lower, spring barley area up by 86% compared with previous year). Too wet to roll effectively. Oct, Jan, March, April slightly colder than average. Ear emergence wheat from early June (a week later than usual).
2000	Rapid drilling progress. Most winter cereals drilled by late October. Wet October – early return to field capacity. Delayed drilling of later sowings (WBF impact). Mild winter notably Jan and Feb (2 C above normal). Ear emergence wheat late May to early June. Most spring cereals drilled by late March.
1999	Early start to drilling followed by wet weather in late September and October. 10-20% winter cereal crops remained undrilled in mid Feb. Cereal area down by 9% compared with previous year (set-aside requirement increased from 5% to 10%). Winter cereal drillings not completed until February. Ear emergence wheat from late May or early June (majority of wheat crops).
1998	Favourable conditions for autumn drilling. Mild winter. Winter wheat ear emergence early (third week of May).
1997	Timely drilling, dry seedbeds delayed emergence of winter cereals esp. east and south. Ear emergence in wheat from late May.
1996	Seedbeds dry after hot, dry summer. Wheat crops in the east slow to establish. Colder than average winter slowed crop establishment (impact on wbf).
1995	Wet weather early autumn delayed drilling. 10-20% winter wheat drilled by end September. Most winter barley drilled later than usual in late September. June very dry; August was the hottest on record; also dry with early crop senescence and harvest.
1994	Wet autumn – late drilling of winter wheat
1993	Wetter than average September in Midlands and east. Some drilling delays. .

Winter oilseed rape

Harvest year	
2007	Most crops drilled mid-late August, remainder during early September. Favourable conditions in late August for rapid emergence and good establishment, although patchy in straw swaths. Dry start to September delayed establishment of later drillings esp. in east. Typically vigorous crops with 12+ leaves by late December.
2006	Timely drilling; mainly latter half of August. Warmer than average autumn. Rapid crop establishment, forward, well-leafed crops by late December. Development checked by colder than average March making crops relatively backward compared with previous year. Late start to flowering in mid-late April. July was the hottest on record leading to premature senescence and early start to harvest.
2005	Rapid drilling progress from 30 August after completion of delayed harvest. Milder than average winter, strong canopy development. Flowering from late March/early April.
2004	Normal drilling dates but patchy establishment in dry seedbeds esp. in east where drier than average in Sept/Oct. Later development than previous year; flowering from early-mid April. Many crops remained ‘backward’.
2003	Dry soils in September delayed emergence until mid-September rains. Two crop categories – normal and backward. Slower start to spring growth than previous year. Flowering from late March or early April.
2002	Rapid drilling progress and good establishment. Exceptionally early season. Forward crops flowering in late March.
2001	Most crops drilled at normal timings (mid Aug to early Sept). Extended drilling period of any later crops due to wet autumn and problems with establishment (slugs). Late start to flowering typically from mid April.
2000	Rapid drilling progress. Flowering from late March to early April.
1999	Most wosr crops drilled by 10 September in all areas. Temperatures above normal during winter. Rapid crop development; flowering from late March or early April.

1998	August drillings emerged rapidly. September-drilled crops established slowly from drier seedbeds. Flowering late March or early April.
1997	Timely drilling. Rapid emergence of August drilled wosr. Dry seedbeds in September delayed establishment of later drilling. Flowering from early April.
1996	Dry seedbeds in autumn (following hot, dry summer) delayed establishment especially in east. Few crops emerged before mid September. Backward crops after colder winter. Late April start to flowering.
1995	Initially slow establishment; more rapid after wetter than average weather in September. June very dry; August was the hottest on record; also dry.
1994	Wetter than average autumn – slug impact. Many crops re-drilled.
1993	Rapid establishment of wosr in wetter than average September (impact on slugs)

Appendix 2. Pest highlights of current year to date

Winter cereals

Harvest year	Review – pest highlights of current year to date
2007	**Aphids/BYDV.** Grain aphids flying until mid November in most arable areas and until late November in south. Warm autumn favourable for flights into crops and some rapid increases in populations in winter cereals. Frosts in early November temporarily checked bird-cherry aphid increases but subsequent conditions favourable for aphid survival. Symptoms of BYDV reported from Wales in late February. Concerns that follow up sprays will be needed pre GS 31.
	Wheat bulb fly. Autumn 2006. 29% of fields with >250 eggs/m2 (lower than previous year). Warmer than average autumn and winter probably extended diapause period for eggs. Slow egg hatch progress in January; rapid hatch and plant invasion after cold period in early February 2007. Deadhearts evident from mid February as second instars developed. Longer than expected period for egg hatch spraying but wet soils prevented field access before early February.
	Leatherjackets. Mean populations were overall 47% lower (46 sites) than in the previous year in the Midlands and north (but higher in south) probably due to desiccation of eggs in hot, dry weather in September 2006. Damaging populations in some fields (61% fields with >50 leatherjackets/m2). Damage symptoms seen in late winter in grass in northern England and wheat after grass in western Midlands. Potential risk of damage to susceptible spring crops.

Oilseed rape

Harvest year	Review – pest highlights of current year to date
2007	**Cabbage stem flea beetle**: Continued increase in beetle activity during autumn, esp. in Midlands and northern England. Low activity in eastern England. Early-mid October start of larval invasion. Larval numbers higher than previous year. Obvious damage in Chinook-treated crops (as in previous year). **Turnip sawfly**: Notable resurgence of pest previously considered of low importance. Severe canopy damage in wosr in September and early October – many crops sprayed. Larvae have high potential to cause damage – 1-2 larvae per plant justified spraying but often applied too late when damage was at a peak.

Appendix 3. Cereal pest incidence 1992-2007

Wheat bulb fly

Variable incidence – often no clear trend. Significant weather-related and agronomic factors in harvest years 2002, 2003, 2004, 2006. Low incidence in 1994 and 1995 due to unfavourable weather in late summer for maturation of female wbf and egg laying. Strong agronomic factor if high proportions of crops are drilled later than planned and cold weather overwinter restricts crop growth – more crops then at susceptible single shoot stages during egg hatch and larval invasion periods. Egg population surveys helpful but more sites needed. Model predictions gave uncertain information but accuracy improved by actual field studies. Little or no recent information on oviposition timing and progress of egg lay.

Harvest year 2007: 29% of fields with >250 eggs/m² (slightly lower than previous year). Warmer than average autumn and winter probably extended diapause period for eggs. Slow egg hatch progress in January; rapid hatch and plant invasion after cold period in early February 2007. Deadhearts evident from mid February as second instars developed. Longer than expected period for egg hatch spraying but wet soils prevented field access before early February. Well-tillered crops (after warmer and wetter than average winter) likely to minimise effect on most crops but improved conditions for larval development and survival.

Harvest year 2006:

Overall 32% of fields (combined total for east and north) with >250 eggs/m². Favourable conditions for crop establishment, although checked by colder than average weather in March 2006 making crops relatively backward compared with recent seasons. Slow progress with egg hatch and larval invasion (not peaking until late March). Poorer than expected control from Evict seed treatment as many crops well-tillered when main period of larval invasion occurred. Lengthy hatch period led to reported poorer than expected damage reductions from chlorpyrifos egg hatch sprays applied in late January. Soil temps <5 ºC also reduced activity of chlorpyrifos.

Harvest year 2005:

High populations especially in beet and potato rotations. Mean 336 eggs/m² and 50% of fields with >250 eggs/m². Harvest 2004 was delayed by wet weather in August leading to fungal development on ears (favourable to female wbf adults prior to oviposition). Also delayed drilling of winter cereals but mild winter favoured rapid crop development and tillering which reduced impact of wbf in potentially high-risk year. Damage overall was less severe than had been expected.

Harvest year 2004. Significant agronomic factor (contrasting reason with previous season). Dry autumn delayed winter cereal emergence in eastern England leading to some relatively backward (more crops at single shoot stages) crops in east during wbf egg hatch and larval invasion period. Mean 280 eggs/m^2 and 37.5% of fields with >250 eggs/m^2 (Figure 1).

Harvest year 2003. Recovery of egg numbers to near normal values 20% of fields with >250 eggs/m^2 (compared with 9% in previous year). As in previous year, some damaging attacks. Damage potential was favoured agronomically as a wetter than average autumn delayed drilling progress and led to a higher proportion of winter wheat crops at single shoot sates during egg hatch and larval invasion.

Harvest year 2002. Mean egg numbers 50% lower than previous year. 9% of fields in high-risk infestation category (>250 eggs/m2). Low risk overall to crops mitigated by early drilling and rapid crop establishment. Very few late-drilled crops except after roots.

Harvest year 2001. Higher egg numbers than previous year (34% fields >250 eggs/m2)– highest since 1991 (Figure 1). Strong agronomic effect with more late-drilled crops than usual (33% of winter cereal crops remained undrilled in mid November). Mean egg counts in east and north were 220 and 230 eggs/m2 respectively.

Harvest year 2000.
Agronomic effect with locally severe damage mainly on late-drilled crops.

Harvest year 1999.
Wet autumn delayed wheat drilling, some crops not drilled until February. Severe damage in later-drilled crops. *Localised damage in NW England (south Lancashire*) following damage in previous year in this area (outside normal main wbf range in east and north).

Harvest year 1998
Mild winter reduced damage impact – predominantly well tillered crops during larval invasion period.

Harvest year 1997
Risk high with 31% of fields with >250 eggs/m2 (highest percentage of sampled fields since 1991). *Much higher egg counts than previous two years.* Shows how rapidly populations can recover with suitable conditions

in August for maturation of female wbf. Severe damage on late-drilled crops; economically-important damage seen in Lancashire and in south as far west as Hampshire and Glos.

Harvest year 1996.
Low incidence of egg laying in autumn 1995 after hot, dry August. Low damage predictions but late expression of symptoms – concerns that damage was locally more severe than had been expected.

Harvest year 1995.
Low incidence of damage following low egg numbers.

Harvest year 1992. High egg counts in previous autumn but damage not severe – crops well tillered during larval invasion.

Leatherjackets

Steady increase in populations from 1995 to a peak in winter 1997/98. Fluctuating numbers until substantial crash in numbers in harvest year 2003 (only 2% of fields with >50/m²). During two autumns that favoured survival of eggs and small larvae, substantial recoveries in numbers were recorded (Dow surveys, 45+ sites per year) in harvest years 2005 and especially 2006. In 2006, mean populations in the Midlands and in northern England were the highest on record. Changes in population status are strongly influenced by autumn rainfall. Population crash in West and South Yorkshire in 1996 following hot, dry weather in August 1995) but less effect in other survey regions despite similarly hot, dry weather in August (mean max 26C and monthly rainfall only 4mm (Oxford).

Harvest year 2007. Mean population (46 sites) was 97/m² which was above the long-term mean (1992-2006) of 70/m2 and lower than in the previous year (mean 182/m2), probably due to desiccation of eggs in warm/very warm, dry weather in September 2006. Damaging populations in some fields (61% fields with >50 leatherjackets/m2). Damage symptoms were seen in late winter in grass in northern England and wheat after grass in western Midlands. Potential risk of damage to susceptible spring crops.

Harvest year 2006. Favourable conditions in autumn 2005 for further substantial recovery in numbers. Mean numbers in Midlands, north and south were x3 higher than in previous year. 83% fields with >50/m2. Mean number (all sites) 182/m2 compared with 68/m2 for period 1991-2005. Severe damage to spring crops after grass esp. in northern England.

Harvest year 2005. Substantial recovery in mean numbers. Wet soils in early autumn after wetter than average August, but drier than average September. Autumn rainfall overall close to or slightly above normal. x5 increase in mean numbers in Midlands and north. Overall 34% fields with >50/m2.

Harvest year 2004. As in previous year, very low numbers in harvest year 2004 for second year running (only 2% fields with >50/m2). Second year with unsuitable conditions in autumn (drier than average Sept and Oct) for egg/larval survival. Higher numbers in Scotland where 50% of fields with >60/m2.

Harvest year 2003. Unsuitable conditions in England for egg and larval survival in autumn – hot, dry conditions from 17 Sept to 8 October 2002. Only 2% of fields (from 49 sampled) with >50/m2. No leatherjackets at all extracted from samples from southern sites. No damage reported to cereals or grass reported from any area.

Harvest year 2002. Upward trend reversed in next harvest year due to adverse weather in autumn.

Harvest years 1992-2001. Rising trend 1995 – 1998 but some annual variations.

Harvest year 1996. *Notable due to population crashes in West and South Yorkshire* ,following hot, dry weather in late summer 2005 (comparable with the 1955 and 1959 crashes in leatherjacket populations recorded in NE England. In these years, dry weather extended from August into September). The downward trend in harvest year 1996 was not so marked elsewhere, despite apparently similar weather conditions. Reasons speculative.

Frit fly

Fluctuating activity for reporting period with strong agronomic factor in harvest year 2001. Typically only localised damage seen in period 1992-2006 in winter wheat after grass especially in crops in the western Midlands and northern England.

In harvest year 2001, third generation activity was high in late summer (2000) and harvest year 2001 overall was a higher than average risk year. As a follow-on effect from the previous season, a few winter wheat crops were drilled exceptionally early in late August and were emerging in early September when adult frit fly activity remained high. Indications of direct egg laying onto winter wheat with damage showing in non-grass rotations.

Aphids/BYDV

Good strategic research progress leading to improved decision making (good industry uptake of risk definition based on accumulated day degrees above 3C). Incidence of BYDV strongly influenced by agronomic and *weather factors in autumn/winter with impacts on drilling dates, timeliness of autumn spray treatments. Need improved knowledge of overwinter mortality which impacts on need for late winter sprays or follow-up sprays pre GS 30/31. Need for follow-up sprays after use of seed treatments now defined. Reasons for limited or no build-up and limited secondary spread overwinter still poorly defined. Effect of wet weather – uncertain effects on aphid survival and build. High incidence years show evidence of aphid increases in crops in late autumn or winter (Harvest year 2007 possibly – to be confirmed, harvest year 1998 notable). Most years only low incidence of BYDV (but most crops at risk sprayed given suitable conditions in autumn for field access).*

Majority of winters in period were considered mild (some very mild) during the reporting period 1992-2007 (exceptions were 1996 and 1997). But in most years there was only limited or no build-up of aphids overwinter. Poor understanding of aphid build-up under actual field conditions. Perhaps a tendency for DSS models to overestimate risk and need for follow-up sprays (risk-aversion approach at farm level with cheap and effective aphicides available). No evidence of resistance in grain aphid or bird-cherry aphid to pyrethroids.

Harvest year 2007 – *potentially high-risk year*. Grain aphids flying until mid November in most arable areas and until late November in south. Warm autumn favourable for flights into crops and some rapid increases in populations in winter cereals. Frosts in early November temporarily checked bird-cherry aphid increases but subsequent conditions favourable for aphid survival. Symptoms of BYDV reported from Wales in late February. Cereal aphids building in barley ex Rosemaund; re-invasion of crops post spraying reported from Holderness. Concerns that follow up sprays will be needed pre GS 30/31. Clothianidin (Deter) seed treatment launched in 2006 by Bayer – offers longer (around 8 week protection period from crop emergence compared with 6 weeks from Secur).

Harvest year 2006. Favourable weather until frosts in late November (2005) for flights of grain aphids and bird-cherry aphids into crops. Early but limited build of populations in wheat and especially barley until aphid development was checked by cold weather. Low overwinter survival (colder than average March). BYDV infection at low incidence in most crops, typically at trace or low levels with <1% crop areas affected from autumn spread. Foliar symptoms not apparent until flag leaf emergence stages.

Harvest year 2005. Agronomic impacts on risk. Later drilling and later emergence of winter cereals after late completion of harvest 2004. Infection risks reduced but not eliminated as favourable weather for migration into crops and overall warmer than average autumn, winter and spring (esp. January 2ºC above average in England and Wales). Drier than average November enabled timely applications of planned aphicide sprays to be applied. Good spray timing possible. Low incidence of BYDV in spring but most crops at risk were sprayed or received imidacloprid seed treatment.

Harvest years 2004 and 2003. Limited overwinter build and spread leading to overall low BYDV incidence in spring. Relatively late drilling and delayed emergence of winter cereals in harvest year 2003 with impact on infection incidence.

Harvest year 2002. Favourable conditions for early drilling and autumn colonisation of winter cereals by cereal aphids. Typically good conditions for autumn spraying effectively mitigated risk. Very few untreated crops. Warmer than average January and February with mean temps. up to 3 ºC above average. Aphid survived anholocyclically in winter cereal crops. Direct transfer a problem in south-west England. Severe infection (80% infection with severe stunting) in unsprayed winter barely (early October drilled) in unsprayed trial plots of winter barley in Devon.

Harvest year 2001. Noticeable agronomic impact on risk as the wet autumn led to considerable delays to drilling winter cereals and difficulties with application of aphicide sprays. Not possible to drill all planned crops, prompting large switch to spring cereals. Noticeable agronomic impact on risk. Reduced aphid migration pressure and little or no overwinter build-up, with colder than average October, January, March and April. Low incidence of BYDV infection in spring 2001.

Harvest year 2000. Early drilling of early-drilled winter cereals. Late drilling and emergence (wet autumn) of later drillings. Late end to aphid migration. Mild winter (esp. Jan and Feb) but no evidence of overwinter build-up of aphids in winter cereals. Late expression of BYDV symptoms but not severe, despite apparently favourable conditions for secondary spread.

Harvest year 1999. Late migration (perhaps the norm?). Warm winter but little overwinter build and secondary spread. Estimated 20% of crops at risk not sprayed due to wet autumn and restricted field access. No/limited overwinter build.

Harvest year 1998. *Significant BYDV in spring and early summer with marked stunting in early-drilled cereals esp. barley; wheat to lesser extent wheat*. Lengthy autumn migration (norm again?). Mild winter. Evidence for increasing numbers in crops from November. Need for pre GS 30/31 sprays applied in response to aphid build overwinter.

Harvest year 1997. Secondary spread prevented by frosts in Dec/Jan (mean min. January <0C (Oxford). Most crops at risk sprayed preventatively.

Harvest year 1996. No/limited overwinter build. Cold February (mean min <0C Oxford).

Harvest year 1995. Migration into mid November. Limited secondary spread. Low and patchy incidence of BYDV esp. Midlands and south.

Harvest year 1994. Low autumn populations of aphids in crops. Little overwinter increase in populations in crops. Low incidence of BYDV in spring.

Harvest year 1993. Delayed drilling and crop emergence (wet autumn). Low aphid numbers. Low incidence BYDV in spring.

Harvest year 1992. BYDV incidence described as 'lowest for years'. Low overwinter survival.

Cereal aphids summer

Most years only sub threshold populations during flowering. Late build-up occurred in some years esp. in eastern and northern England. Evidence of rapid overwinter increases e.g. 1998 but populations did not continue to develop. Outbreak years 1992-1995 (esp. 1994 and 1995), 1999 and 2001. Evidence that in outbreak years, most crops at risk are sprayed too late. Logistical problems at farm level with crop monitoring and taking effective action, in time, where necessary. In recent years, treatments also applied (esp. south, Midlands and east) at ear emergence to winter wheat for owbm control providing incidental aphid control. tendency to record late increases (late flowering/early grain fill period of winter wheat) in aphids in northern England.

Harvest year 2006. Little or very limited overwinter build-up in winter cereal crops. Colder than average March (mean temps in England and Wales in w/e 7 and 14 March were 1.7 and 4.5 ºC (4.3 and 1.5 ºC respectively below normal) with impact on survival of anholocyclic populations of aphids. Slow increases in populations in crops from ear emergence. Main build-up occurred at end of flowering period after migration (RIS trap records) in June. Few control thresholds reached and very hot weather (>32ºC) in July checked population development. Early crop senescence induced by drought stress reduced green leaf area during early grain filling period. Post pyrethroid spraying, evidence for a substantial increase in rose-grain aphid on remaining leaves but too late for effective control. Differences recorded between pyrethroids tested - variable effects against beneficials perhaps (Moreby *et al*., 2001).

Harvest year 2005. Low numbers of overwintered aphids in crops, limited build in spring, populations remained below control thresholds in most wheat crops.

Harvest year 2004. Limited overwinter increases in aphids and low populations in winter wheat before ear emergence followed by steady increases during flowering (5-10% ears infested at GS 59 rising to mean of 40% ears infested at GS 71). Control thresholds reached in Midlands and in eastern England. Hot, dry weather in early-mid June favoured migration into crops. Increased incidence of alate grain aphids on ears of winter wheat with colony development on leaves. Incidental impact of sprays applied to control owbm in early June, which effectively controlled aphids also just as populations were starting to increase.

Harvest year 2003. Limited overwinter increase in cereal aphids in winter wheat crops. Higher populations than in previous year. Relatively late build-up in crops peaking at GS 71 (mean 26% tillers infested at GS 71 compared with means of 15% at GS 61 and 6% at GS 59 (31 fields monitored in Midlands, north and south-east). Increased evidence of parasitised aphids and hoverfly larvae at GS 71.

Harvest year 2002. Mild winter (January and February) enabled aphids to overwinter in crops (see also aphids – BYDV section). Populations building in late winter (from mid February in Midlands) prompting some late winter spraying pre GS 31/31. Early (April) start of grain aphid migrations (RIS traps) increasing during May. But only limited increases in crops due to obvious beneficial activity and fungosed aphids by mid June. Mean 4%, 5% and 7% tillers infested at GS 59, 61 and 71 respectively (60 sites). Few thresholds reached despite early spring build-up in winter wheat crops.

Harvest year 2001. Mean 11%, 22% and 33% tillers infested at GS 59, 61 and 71 respectively. Evidence that populations were increasing at GS 59 followed by rapid increases in late June and early July. In the Midlands*, infestations were the highest for many years; some crops with 100% tillers infested at GS 71-73.* Threshold for control (66% tillers infested) was reached at 31% of sites in the Midlands. Due to the late and very rapid build-up, it was logistically difficult to spray wheat crops,; some of which were sprayed too late to prevent yield losses.

Harvest year 2000. Low overwintered popualtions. Main build during late flowering period in winter wheat. Mean 2%, 7% and 12% ears infested at GS 59, 61 and 71 respectively

Harvest year 1999. *An outbreak year.* Low overwintered populations with few beneficials. Rapid increases in winter wheat crops from ear emergence. Thresholds for control reached esp. Midlands. Late increases in N and NE.

Harvest year 1998. *Overwinter increase (obvious BYDV infection in spring). Potentially high-risk season.* Steady increases in populations during March/April (similar to 1990) until checked by cool, wet weather in June.

Harvest year 1997. Low incidence overall, localised thresholds reached.

Harvest year 1996. Many winter cereal crops emerged late (dry autumn seedbeds). Autumn spraying delayed (herb+ins). Cold weather overwinter (esp Feb mean min <0C Oxford).

Harvest year 1995. *Very high incidence.* Initially only low overwintered populations (mainly low incidence BYDV). Rapid increases during flowering period of winter wheat. Threshold for control widely reached - logistical problems with monitoring and so many wheat crops in a short period. Mean 18.2 grain aphids per tiller at GS 71 in winter wheat (25 sites). Exceptionally high populations reported from eastern England. Some re-invasion in east with follow-up treatments required.

Harvest year 1994. *Large increases in grain aphid numbers during winter wheat flowering period.* Populations initially low at GS 45. Late and rapid build. Large areas treated (wheat and oats).

Harvest year 1993. Localised thresholds reached in Midlands and northern England.

Harvest year 1992. Late increases in grain aphids esp. in eastern England where described as severe locally.

Orange Wheat Blossom Midge

Incidence determined by suitability of soil conditions in May for pupation to occur and for adult flushes to appear when winter wheat crops are at susceptible ear emerging to emerged stages (coincidence effect). Consider effect of resistant wheat varieties. Remains a major challenge to farmers and agronomists – logistical problem with responding in time to risk factors. Excellent results from collaborative research, backed by pupation tracking studies – but limited number of sites. Improved benefits from collaborative approach from industry. Future monitoring partly dependent on outcome of chlorpyrifos review. First recorded outbreaks (1992-2007 period) were in 1993; severe damage also in 1994. Lower incidence 1995-1997 followed by steady increases in period 1998-2001. Locally severe outbreaks continued to occur 2003-2005 esp. 2004. Lower incidence overall with hot spots in 2006.

Harvest year 2006. Moderate to high numbers in soil in fields where damage occurred in 2005. Slow and late advance into pupal stages – mean 11% in late May compared with a mean of 26% in 2005. First adult emergence in late May in southern England and south Midlands; early June in western Midlands and in mid June in northern England (Yorkshire Wolds). First flushes of adults in south coincided with susceptible growth stages of winter wheat but in Midlands, crops were flowering when delayed midge emergence occurred. Main emergence on Wolds occurred at GS 57-59 near the end of period of risk (before bulk of crop flowering) and weather precluded application of some planned sprays of chlorpyrifos. Smaller area with resistant varieties in 2006 (19% of winter wheat area compared with 34% of wheat area sown with resistant varieties in harvest year 2005). Robigus was the most frequently grown resistant variety followed by Glasgow.

Harvest year 2005. Widespread and locally severe attacks on winter wheat although overwintered populations in soil were lower than the previous two years (mean 6.7/kg soil compared with 21.5/kg in 2004 and 9.3/kg in 2003. In 2005, only 4% pupation in mid May (32% in previous year). Variation in pupation and more patchy emergence made crop monitoring difficult. Emergence (from late May) coincided with susceptible ear emergence stages in east, Midlands and north.

Harvest year 2004. High overwintered populations in soil and favourable conditions in May for pupation. *Severe attacks in most arable areas from North Yorkshire through to the southern counties.* Supplies of chlorpyrifos ran out due to high demand.

Harvest year 2003. Locally severe attacks. Favourable conditions for pupation, advancing from 12% in late May to 33% in mid June.

Harvest year 2002. Damage more sporadic and less severe overall than previous year.

Harvest year 2001. *Widespread damage, locally severe*. Variable pupation in May, especially in drier soils in the Midlands. Lengthy period of adult emergence coinciding with susceptible growth stages in wheat crops. Many crops were at relatively 'backward' growth stages on account of late drilling dates. Hot spots for activity in the south Midlands, eastern England, Yorkshire Wolds. Many crops sprayed – logistical difficulties.

Harvest year 2000.
More widespread and severe than previous year. Many thresholds

Harvest year 1999.

Described (for second year running) as the most severe since the 1993 outbreak year. First adult emergence in late May, large flushes 8-11 June. Many wheat crops drilled late with main period of ear emergence occurring in early June leading to improved coincidence of ear emergence and adult flushes.

Harvest year 1998. Higher incidence than previous year. Described as worst since 1993 (see also 1999 comments)

Harvest year 1997. Slight overall, a few hot spots in S and SW, locally in Midlands. First adult emergence was in early June which was 10-14 days later than in 1996.

Harvest year 1996. Populations in soil (limited monitoring) lower than previous year. Not a major problem overall but localised control thresholds in Hampshire, south Midlands and Shropshire. Adult emergence in mid June when most winter wheat crops were flowering.

Harvest year 1995. Low incidence overall, lower than previous year. Localised hot spots only.

Harvest year 1994. *Severe infestations leading to major losses (estimated at £20 million).* First adult emergence in early June coinciding with ear emergence stages of winter wheat (many crops drilled later than planned due to wet autumn).

Harvest year 1993. *Reported to have been unexpected and widespread.* Most severe in SE and east Anglia. 10% yield reductions in some wheat crops. Grain rejections by millers.

Harvest year 1992. No reports.

Gout fly

Damage mainly confined to southern counties in period 1994-1996 with evidence of northwards spread into the south Midlands in 1997 and 1999. Continued spread and more severe and widespread outbreaks in 2000. Severe and widespread attacks in all arable areas in harvest years 2001 and 2002, more locally in 2003. Trend towards lower incidence in period 2004-2006. Increased incidence with obvious (but localised) damage showing in February 2007. In 2001, major effect of spring generation on late-drilled winter wheat crops in which ears failed to emerge normally.

Harvest year 2007 (to date). Increased incidence compared with previous year. Locally severe attacks (e.g. Midlands and northern England). Early expression of damage symptoms (by end of 2006). Egg laying favoured by early drilling and warmer than average autumn. Feb 2007 – severe damage (patches of crop killed out) in September-drilled winter wheat in Vale of York. Pyrethroids applied for BYDV control (earliest sprays in first week of October) probably too late for effective reduction of gout fly before start of significant egg hatch.

Harvest year 2006. Generally low incidence.

Harvest year 2005 lower incidence than 2004. Late emergence of spring generation with few eggs on winter wheat.

Harvest year 2004. Agronomic factor – egg laying favoured by early drilling but incidence lower than 2003. In the east, dry seedbeds delayed crop emergence and provided an incidental reduction in damage. Decision making influenced by presentations of results from ADAS/Velcourt spray-timing trials and fewer crops were sprayed to control gout fly. Clear advice available on spray timing.

Harvest year 2003. Widespread and locally widespread attacks but not as severe as in harvest years 2002 and 2001. High incidence of egg laying on early-drilled winter cereals – up to 90% of plants in September-emerged crops infested with eggs in many arable areas. Low incidence of egg laying in crops emerging from 15 October. In 2003, damage occurred as far north as Lancashire and Yorkshire.

Harvest year 2002. *Severe and widespread damage in main arable areas.* More severe than 2001 when damage also obvious. Strong agronomic (time of drilling) effect. Damage obvious in February and March, large patches in some fields prompting crop destruction and re-drilling with spring cereals. Follow-on spring cereals drilled as early as practicable to minimise risk from spring generation.

Harvest year 2001. Continued trend towards increased incidence. *Strong agronomic effects impacting on autumn and spring generations*. Attacks more widespread and severe than in harvest year 2000. Two distinct risk phases – early drilled crops (higher proportion of wheat crops drilled in late August) were affected by a high egg laying incidence and developed severe symptoms of damage overwinter. Extended wheat drilling period (wet autumn) and many wheat crops were drilled exceptionally late (wet autumn) with some not being drilled until February. *Obvious effects on ears which failed to emerge normally due to attack by spring generation (active from late May). Late-drilled winter wheat crops in the Midlands had up to 50% of ears that failed to emerge normally*.

Harvest year 2000. More widespread and severe than previous year. Many early-drilled crops.

Harvest year 1999. Obvious attacks in southern England and south Midlands (as far north as Oxfordshire) following trend towards increased incidence in 1997 and 1998.

Harvest year 1998. Localised outbreaks confined to southern England (Hampshire, Berkshire).

Harvest year 1997. Localised attacks in southern counties and in south Midlands.

Harvest year 1996, 1995, 1994. Localised in south, occasional slight damage in Midlands (south Midlands in 1994 and unusually (at that time) in south Staffordshire).

Harvest year 1993, 1992. No gout fly reports.

Wessex flea beetle (Psylliodes luteola)

Harvest year 2001. Continued outwards spread from herbage seed growing areas in Hampshire, Dorset and Wiltshire.

Harvest year 1999. Damage to winter wheat in Hampshire. *P. luteola* previously recorded as rare in the UK. Similar cases of damage in Dorset and Wiltshire in 1995 and 1996.

Appendix 4. Current and recent completely research projects relating to pest control in cereal and oilseed crops

Project Number	Title	Lead research organisation	Start date	End date
	BBSRC funded projects - current			
1	Enemies reunited - understanding the behaviour of parasitic nematodes in soil systems	University of Abertay Dundee	04/10/2004	03/10/2007
2	Genomic analysis of adaptive biodiversity in Aphidius ervi parasitoids	Rothamsted Research	16/08/2004	15/08/2007
3	Developing the potential of Phasmarhabditis hermaphrodita as a biological control agent of slugs (PhD)	University of Aberdeen	02/10/2006	01/10/2009
4	Sustainable pest control - comparing tritrophic interactions in organic and conventional production systems	University of Southampton	01/04/2006	31/03/2009
5	Chemical mediation of contest behaviour in parasitoid wasps	University of Nottingham	18/10/2004	17/10/2007
6	Parasitoid webs in organic and conventional farming systems: structure, sustainability and exploitation	University of Bristol	01/06/2004	31/05/2007
7	Dynamic responses of predators to biodiversity in sustainable agriculture: spatial and molecular analyses	Cardiff University	01/09/2005	31/08/2008
8	Chemical enhancement of plant resistance to aphids	Imperial College London	01/05/2006	30/04/2009
9	Role of foraging behaviour in parasitoid ecology and population structure	Rothamsted Research	01/04/1999	31/03/2007
10	Biodiversity on farms: a complex systems approach	University of Bristol	01/08/2006	31/07/2009
	BBSRC funded projects - recently completed			
11	Effects of biodiversity on the dynamics of predation in low- input arable systems: molecular approaches	Cardiff University	01/05/2001	21/05/2004

12	New semiochemical opportunities from Nepeta spp. as a non- food crop	Rothamsted Research	02/06/2003	01/12/2006
13	Predicting the success of biological control using a slug- pathogenic nematode against pest slugs	Rothamsted Research	01/04/2000	30/09/2004
14	Utilising ecological profiling to evaluate the significance of predator biodiversity for sustainable pest regulation	Cardiff University	01/07/2003	30/06/2006
15	Individual-based spatio-temporal predator-prey dynamics	Rothamsted Research	29/08/2002	29/08/2005
	Defra funded Projects - current			
16	Oilseed rape crop ecology: optimising crop husbandry for conservation biological control and greater biodiversity (AR0316)	Rothamsted Research	01/04/2004	31/03/2008
17	Habitat diversification and aphid-specific natural enemies in arable ecosystems: optimising crop protection and environmental benefits (AR0318)	Rothamsted Research	01/04/2004	31/03/2007
18	Further development of a framework for practical application of semiochemicals in field crops. (PS2113)	Rothamsted Research	01/04/2006	15/05/2009
	Defra funded Projects - recently completed			
19	Utilising populations of natural enemies for control of cereal aphids (AR0305)	Rothamsted Research	01/04/2000	31/03/2004
20	Natural enemies of arable pests - study of movement and host preference using molecular markers (AR0303)	Rothamsted Research	01/04/2000	31/03/2004
21	Natural enemies for enhanced biocontrol of cereal pests (AR0301)	Horticulture Research International	01/04/2000	31/03/2004
22	Integrating management of pest and beneficial insects on oilseed rape. (AR0302	Rothamsted Research	01/04/2000	31/03/2004
23	Delivery of semiochemicals within plant-pest-natural enemy systems. (PS2105)	Rothamsted Research	01/04/2003	31/03/2006
24	A framework for the practical use of semiochemicals in field crops. (PS2107)	Rothamsted Research	01/04/2003	31/03/2006

	LINK funded projects - current			
25	Managing uncropped land in order to enhance biodiversity benefits of the arable farmed landscape (LK0971)	The Game Conservancy Trust	01/08/2005	28/02/2010
26	Assessment of wheat blossom midge risk and exploitation of resistant and tolerant varieties - LK0969		2005	2008
27	Sustainable Arable Farming For an Improved Environment (SAFFIE)	ADAS	01/01/2002	31/12/2006
	LINK funded projects - recently completed			
28	3D Farming - making biodiversity work for the farmer (LK0915)	Rothamsted Research	01/04/2000	31/03/2004
29	Integrated control of slugs in arable crops (LK0925)		01/09/2001	31/08/2005
30	Integrated control of wheat blossom midge: Variety choice, use of pheromone traps and treatment thresholds		01/10/2001	28/02/2005
	RELU Funded - current			
31	Overcoming Market and Technical Obstacles to Alternative Pest Management in Arable Systems	Kent University	01/01/2005	31/11/2008
32	Improving the Success of Agri-Environment Schemes	CEH		
	HGCA funded projects - current			
33	Novel Approaches to the Control and Management of the Field Slug, Deroceras reticulatum (PhD)	SAC	01/10/2006	30/09/2009
34	Autumn survey of wheat bulb fly incidence	ADAS	01/07/2005	31/12/2007
35	Revised thresholds for cabbage stem flea beetle	ADAS	01-Aug-04	31-Oct-07
36	Enhancing management of wheat bulb fly via the use of lure and kill and assessment of egg numbers	SAC	01-Sep-07	31-Aug-10

	HGCA funded projects - recently completed			
37	Plant-insect interactions in oilseed rape (PhD)	University of Nottingham	01-Oct-02	30-Sep-05
38	Development of guidelines for improved control of gout fly	Velcourt, ADAS	01-Sep-02	31-Dec-04
	EU funded projects			
39	Integrated pest management strategies incorporating biocontrol for European rape pests (MASTER)	Rothamsted Research in UK	01/12/2001	30/11/2005
	SAC			
40	Determining nematode damage thresholds in cereals and potatoes	SAC	2006	2007
	SEERAD			
41	Effects of climate change on the distribution of pests of arable crops	SAC	2006	2007

Appendix 5. List of British researchers working on biocontrol or aspects of pest control in cereal and oilseed crops.

Name	Organisation
Dr James Bell	Rothamsted Research
Dr Anthony Biddle	PGRO
Prof Rod Blackshaw	Plymouth University
Dr Dave Bohan	Rothamsted Research
Mr David Brooks	Rothamsted Research
Dr Toby Bruce	Rothamsted Research
Dr Dave Chandler	University of Warwick HRI
Dr Sam Cook	Rothamsted Research
Dr Ian Denholm	Rothamsted Research
Dr Andy Evans	SAC
Dr Jason Chapman	Rothamsted Research
Mr Andrew Ferguson	Rothamsted Research
Dr Stephen Foster	Rothamsted Research
Dr Geoff Frampton	University of Southampton
Dr Georgianne Griffiths	Imperial College London
Dr Cathy Hawes	SCRI
Dr Richard Harrington	Rothamsted Research
Dr Pat Haydock	Harper Adams
Dr John Holland	The Game Conservancy Trust
Dr Simon Leather	Imperial College London
Dr Alice Mauchline	University of Reading
Dr Jane Memmott	University of Bristol
Mr Steve Moreby	The Game Conservancy Trust
Dr Sean Murphy	CABI
Dr Phil Northing	CSL
Dr Jon Oakley	ADAS
Dr Bill Parker	ADAS
Dr Judith Pell	Rothamsted Research
Prof John Pickett	Rothamsted Research
Dr Jon Pickup	SASA - Edinburgh
Prof Guy Poppy	University of Southampton
Dr Simon Potts	University of Reading
Prof Wilf Powell	Rothamsted Research
Dr Dave Skirvin	University of Warwick HRI
Dr Barbara Smith	The Game Conservancy Trust
Dr Bill Symondson	Cardiff University
Prof Felix Wackers	University of Lancaster

Dr Keith Walters	CSL
Dr Andrew Wilby	University of Reading
Dr Ingrid Williams	Rothamsted Research
Dr Ben Woodcock	University of Reading
Mr Ian Woiwood	Rothamsted Research
Prof Denis Wright	Imperial College London