Re-Bugging the System: Promoting Adoption of Alternative Pest Management Strategies in Field Crop Systems, 2005-2009

Semiochemical Experiments Data

USER GUIDE

End of Award Report RES-224-25-0093-A

Re-Bugging the System: Promoting Adoption of Alternative Pest Management Strategies in Field Crop Systems.
(Overcoming Market and Technical Obstacles to Alternative Pest Management in Arable Systems)

Background

Weeds, pests and diseases cause serious crop yield and quality losses and consequently less food is available for human consumption. In the context of global population growth, changing diets, increased per capita consumption and competition for land with other uses, it is vital that little potential output is lost.

Pesticides have been effective in limiting crop losses in the recent past. Alongside advances in fertilisers and genetics, pesticides have helped to realise dramatic increases in production over the last 60 years.

Overuse of pesticides leads to pesticide resistance, by creating strong selection pressure among pest biotypes, and can present challenges to the environment. Thus, complementary alternatives are required to prolong the life of effective pesticides and to limit the environmental impact of farming.

Furthermore, some consumers are concerned by both the environmental and potential risks to human health consequences of pesticide use. Some are willing to reveal these preferences by purchasing Organic foods but many more express significant concerns when asked. While certain retailers use contracts to ensure food is free from pesticide residues, and capture demand for 'safe' food, there remains a significant role for policy to reduce threat to biodiversity.

Heightened EU regulations, such as directive EC 91/414, are leading to the withdrawal of many pesticide products currently in use. However, the world has come to rely on relatively secure and plentiful food supplies to sustain large human populations. Thus, there exists a real demand for alternative pest control technologies from a range of stakeholders across the food chain. However, these more benign technologies must provide similar levels of crop protection.

Objectives

A wide range of technologies exist that can reduce farmers' reliance on pesticides. Few have the capability to compete with chemical control on their own. However, when used in combination they are far more effective. This has been long understood and led to the development of Integrated Pest Management (IPM), as applied in a wide variety of agro-ecosystems.

To some degree, all farmers benefit from IPM since natural enemies are always present in the landscape, helping to control pest populations. There are many potential technologies which could be used in IPM approaches. The main techniques currently used in arable crops are:

- cultural means, principally crop rotations and resistant varieties, to minimise the risk of infestation;
- assess pest abundance and apply pesticides only if economic thresholds are exceeded
- conservation biocontrol that seeks to maximise the effects of natural enemies of pests by using selective products and encourage their numbers by providing the required resources.

Most farmers adopt only some of these approaches and are not capitalising on the benefits of a fully integrated approach.

The objective of this research was to assess the reasons why few arable farmers consciously use IPM. We focused on a narrow set of technical approaches to biological control of aphid pests in UK wheat production as our model system. Within this system we aimed to consider the technical efficacy of 2 biocontrol techniques in isolation and when used together. Issues we thought would be fruitful in the technical arena included:

1. the potential benefits of combining technical approaches, specifically those of conservation biocontrol (CBC) and semiochemical push-pull technologies,
2. the effect of uncroped land in the surrounding landscape over a range of scales on control system properties and performance and
3. to consider how best to provide conservation biocontrol services from land use manipulations and vegetative composition on that land.

We further wished to consider the possibility that low levels of commercial interest in biocontrol in general could be blamed on market failure. Here we considered the following aspects:

1. the importance of the external consequences of pesticide use in UK arable agriculture and to consider ways in which these could be taken into account by users of pesticides.
2. how commercial farmers approach the decision, or multiple decisions, to switch there pest control technologies from pesticide based to an IPM system based on an array of biocontrol approaches.
3. the role of risk preferences and perception on commercial technology adoption decisions.

In the interdisciplinary setting, we aimed to develop a set of approaches to the investigation, development and communication of novel crop protection technologies to commercial farmers.

As this award commenced, the UK government introduced a set of policy measures directed at farmers aimed at promoting biodiversity conservation in the farmed landscape. Unlike previous policy initiatives these policies, the Entry Level Scheme (ELS) in particular, were widely targeted rather than aimed at just farmers with land of high biodiversity value. As such, many of our research questions required reformulation as the landscape in which they were to be assessed changed in a rapid and far reaching way. One important example was that field scale and landscape scale trial sites comprising differing habitat complexity became difficult to find and much of our CBC scale research required significant redesign.

As farmers began to take-up their ELS commitments, it became clear that issues in the social science arena also changed. Once farmers were being paid for land use change which had the potential to provide the habitats which can promote beneficials then our technology adoption and risk perception studies became redundant. Our focus changed to that of considering what farmers were doing and what further approaches they may consider for the future, as marginal changes to functioning IPM programmes.

Methods

In order to address these issues, a wide range of experimental and observational research across disciplines of economics, sociology, biochemistry, ecology and entomology was conducted.

Choice experiments – willingness to pay (WTP) for reduced pesticide foods – food safety – environmental safety

Two Choice Experiments (CE) were used to examine consumer preferences for food produced using different quantities of pesticides while accounting for the different threats that pesticides can present. In cereals production the impact of pesticide use is primarily on environmental quality. For horticultural production the potential effect is on consumer health. A survey was distributed to 3000 households drawn from a commercial mailing list stratified by age, income and county of residence. From a response rate of 15.8%, the final number of responses was 420.

Latent class estimators were used to calculate WTP and these were placed in a policy context by calculation of an equivalent pesticide tax. Other novel estimators were applied in an attempt the counter the problem of lexicographic preferences and potential "ya saying" behaviour among respondents.

Farmer Pest management Practice Survey

Following a piloting exercise a pest management focussed farmer survey instrument was developed. The survey asked farmers for information on the area, yield and prices obtained for their most important crops, as organic or conventional, and to report on use of insecticides as a 3 year average. A series of questions designed to elicit their attitudes to a range of aspects of pesticides was included. Data was recorded on their use, and views, of a range of 17 pest management practices. Finally, farmers were asked to report their membership of agri-environmental schemes (AES), of the Voluntary Initiative, the sources they trust for advice and a range of other characteristics data.

Delivery was achieved alongside the Home Grown Cereals Authority newsletter during the 2007 crop year. The survey instrument was sent out to 7,500 randomly selected names from newsletter recipient list. A single mail out strategy with no follow-up was employed. Some 645 surveys were returned which compares favourably with similar work. Following screening of returns for non-participation and incomplete responses the sample fell to 571 useable observations.

The data generated by this survey were subjected to 3 sets of analysis. Firstly, Principle Component Analysis was used to summarise the Pest Management (PM) practice data and to generate factor scores for use in regression analysis to estimate the determinants of IPM adoption and to consider the impact of IPM on insecticide use. Secondly, both parametric and non-parametric count data models were used to estimate the determinants of the adoption of more complex sets of PM practices and finally, Quantile Regression will be used to assess this question from a different angle. This latter work is ongoing.

Interdisciplinary Researchers Interviews

These interviews were conducted between Jan07 to April07 with researchers engaged on this award and with 3 researchers undertaking award RES-224-25-0048 "Biological Alternatives to Chemical Pesticide Inputs in the Food Chain". Each interview was conducted in a semi-structured format and each discussion was digitally recorded for subsequent content analysis using NVivo software. We anticipate that this work will generate a Journal submission late in 2009.

Field scale CBC Trials

Field studies examined the effects of scale of adoption on the effectiveness and sustainability of alternative pest control technologies based on habitat management. Using cereal aphids as a model pest the studies determined:

- the effectiveness and type of pest natural enemies providing cereal aphid control
- how levels of aphid control and natural enemy abundance were affected by landscape features, especially uncropped land and the provision of additional uncropped land created in agri-environment schemes
- the factors effecting the distribution and movement of natural enemies
- the within-field distribution of natural enemies and the use of floral resources

In 2005 the effectiveness and type of pest natural enemies providing cereal aphid biocontrol was determined in exclusion cages previously infested with the grain aphid, *Sitobion avenae*. The following treatments were compared as described in Holland et al. (2008a): E) epigeal (ground-active) predators only; F) flying natural enemies only; A) all natural enemies; N) no natural enemies.

To differentiate the impact on cereal aphids of parasitoids compared to predatory invertebrates, a replicate study was conducted in a field of winter wheat in 2006 and 2007. Exclusion cages were used to create these treatments: no natural enemies, flying predators but no parasitoids, flying natural enemies, all natural enemies. Parasitoids were repelled using the semiochemical *n*-tricosane.

Role of habitats in cereal aphid biocontrol

In 2006, 14 fields were selected on separate farms each with different amounts of grass margins. Natural enemy exclusion cages were established at 80 m from the boundary using the same methodology as in 2005. In 2007, the study was repeated on 12 of the farms, but in different fields owing to crop rotations. Natural enemies were measured in the adjacent crop. Movement of flying predators was measured in 12 of the fields in 2006, using eight cylindrical sticky traps positioned at 40 m from the margin equidistantly around the field. Traps were operated for 10 weeks from the beginning of April. The type and location of all cropped and uncropped land within a 1000 m radius of the natural enemy transect was entered into a GIS system. The effect of type of exclusion was determined using ANOVA. GLMs were conducted to identify whether there were any linear relationships between the type and amount of uncropped land (hedge, linear grass features and flowers-rich areas) and the levels of cereal aphid control achieved by the flying and epigeal predators for buffer zones of 100, 250, 500 and 750 m radius from the exclusion cages. The same approach was used for analysing data on the predatory invertebrates.

Evaluation of floral resource usage
A novel tracking technique was employed to determine usage of floral resources. Rubidium chloride was applied to a floral strip, where it was absorbed by the plant, and subsequently passed to any insect either feeding directly on the plant tissues including the pollen and nectar or indirectly to insects predating those that had previously fed upon the rubidium treated plants. Rubidium was then detected within plant and insect tissues using Flame Emission Atomic Absorption Spectrophotometry.

Pilot studies were conducted to confirm that rubidium could be detected in hoverflies feeding directly upon the pollen and nectar and indirectly to ladybirds predating herbivorous insects.
To assess usage of a flower-rich margin by predatory insects foraging in the adjacent fields a flower-rich margin 10 m wide and 0.5 km long (total area 0.5 ha) was sprayed with Rubidium chloride on the 23 June and 13 July 2008. A grid of 77 sticky traps was established up to 365m into the wheat field and 60 m into the spring barley that bounded the flower-rich margin. . Sticky traps were operated for two four-day periods following spraying. Low numbers of aphid predators were trapped on the first two sampling occasions, therefore yellow sticky traps were also added on the next two trapping occasions. All aphid predators and alate aphids were identified on the sticky traps. Cereal aphids were recorded adjacent to each sticky trap during the first three occasions the sticky traps were active. Owing to high capture of hoverflies on the yellow traps, only 50% of the female hoverflies captured on the third sampling occasion were analysed for rubidium. Flowers and uppermost leaves of the most abundant flower (*Trifolium hybridum*, a known food source for hoverflies) in the flower rich margin were also analysed for rubidium content.

Predator and cereal aphid distribution patterns assessed, using spatially autocorrelation, in SADIE.

Evaluation of Semiochemicals

Semiochemical based pest control approaches are designed to reduce insect colonisation of crops by modifying insect behaviour and development. Using the natural plant activator *cis*-jasmone as a model, studies aimed to:

- Develop effective formulations for field use
- Determine the response of natural enemies to treated plants
- Identify suitable crop varieties
- Investigate effects on pest populations in the field at increasing scales

Release rate properties of different formulations
Volatile semiochemicals are difficult to formulate for slow release on a large scale. We investigated release properties of novel microencapsulated and gum acacia *cis*-jasmone formulations that would be suitable for mass production. Oilseed rape plants were sprayed with test formulations at a rate equivalent to 50g/ha. Release of *cis*-jasmone was then quantified by headspace sampling (Agelopoulos et al. 2000) for 30 minute collection periods 4, 24, 48 and 72 h after the spray treatment.

Foraging Bioassay
Individual female parasitoids (*Aphidius ervi* or *A. rhopalosiphi*) were released onto wheat seedlings and foraging behaviour was observed. Bioassays compared parasitoid behaviour on *cis*-jasmone treated (formulation in Bruce et al 2003) and control plants. Data were analysed using a paired *t*-test (Genstat).

Semi-field arena trial to assess the potential for enhancing CBC
These trials investigated effects of *cis*-jasmone on parasitoids on a larger scale. Two circular arenas (60cm height, 2m diameter) constructed from insect-proof mesh were set up in a polytunnel (Cook et al., 2007). In each replicate 6 pots of wheat seedlings were arranged in a circle inside the arena. One hour prior to the test, pots were infested with 50 *Sitobion avenae.* Ten mated female parasitoids were released at the centre of the arena after 1 hour of acclimatisation and removed after 24h. Plants were kept for 2 weeks after which aphid numbers and percentage parasitism were recorded. These data were analysed with statistical software (Genstat).

Pest colonisation of wheat varieties treated with cis-jasmone
Replicated small plots of winter wheat varieties, Consort, Hereward, Solstice and Welford were either left untreated or treated with *cis*-jasmone released from point sources in the centre of each plot. Visual assessments of cereal aphid populations (*Rhopalosiphum padi, S. avenae* and *Metopolophium dirhodum*) and eggs of the gout fly (*Chlorops pumilionis*) were made on 100 plants/tillers per plot three times in October and once a week in June-July. Larvae of gout fly (25 plants per plot) and orange wheat blossom midge, *Sitodiplosis mosellana* (25 wheat ears/plot) were assessed. Data were subjected to ANOVA.

Field-scale experiments with cis-jasmone
Field plots treated with *cis*-jasmone (50g in 200 litres ha^{-1} formulated with 0.1% EBV or 3% gum acacia) were compared to an untreated control. In the first experiment in wheat cv. Solstice assessments of aphids and their natural enemies were made weekly from May–July (36 samples per plot; 6 replicate plots per treatment). The second experiment consisted of two ~1ha plots of wheat, cv. Solstice, and the third two ~2ha plots of spring peas, cv. Ragtime. In both experiments, 1 plot of each crop was untreated and the other was sprayed with *cis*-jasmone (EBV formulation). Plots were assessed visually for the wheat or by Vortice suction at each sampling point on the peas. Where possible, data were subjected to ANOVA.

Control Cage Abundance and Complexity work

Research at Imperial College examined the role of natural enemy diversity on the biological control of arable crop pests. The community of natural enemies and aphid pests of cereal crops was used as a model system and a series of mesocosm experiments conducted under controlled environment conditions. Using mesocosms we were able to manipulate and monitor precisely the natural enemy and prey compositions, which included species of ladybirds, hoverflies, ground and rove beetles, spiders, parasitoids and up to three species of cereal aphid. Biodiversity experiments such as these are highly factorial, and require considerable replication to overcome the natural variability of the system. To test hypothesis and understand the underlying mechanisms we used a range of models and inference statistics (classical and Bayesian), and also conducted formal comparisons of commonly used experimental designs to improve the interpretation and application of biodiversity experiments. The vast majority of diversity-function studies reported in the scientific literature examine functional changes attributable to alterations in species richness only, but all attributes of diversity contribute to net function in a community including species richness and identity, abundance, evenness and interactions between individuals leading to indirect or non-additive effects within and between species. We conducted a series of experiments to examine how each of these attributes contributes to pest control function and to identify the underlying mechanisms driving these patterns.

Interdisciplinarity

Although the team met twice a year, the research staff teams, each responsible for the different research strands, were employed at different locations. The team envisaged that much of our interdisciplinary understanding, and the spur of our integration, would precipitate from among the staff at Wye. The dismantling of all Interdisciplinary capacity at Wye was a significant blow.

Regular, biannual, research team meetings were held, each over 2 days, provided ample opportunity for both professional and social interaction. In addition, telephone conversations were used to maintain a momentum in that relationship and help steer interdisciplinary collaboration.

At the mid-point of the award, we embarked on an exercise to investigate how our various disciplines, plus some from a sister award, approached the wider framing of our research. A set of semi-structured interviews with 14 diverse researchers were conducted. The main theme of the interviews was to understand how each interviewee would approach the construction of a bio-economic model for pest control. These interdisciplinary researcher interviews were subjected to context analysis in order to highlight the different approaches researchers would consider and to uncover differences in emphasis different disciplines place on system components and on system drivers. This work remains ongoing and we anticipate a journal submission shortly.

Joint Publications

> Griffiths, G.J.K., Holland, J.M., Bailey, A.S. and Thomas, M.B. Efficacy and economics of shelter habitats for conservation biological control. *Biological Control* 45 (2008) 200–209

Joint Presentations

> Holland, J.M. and Bailey, A.S. .”Re-bugging the system: investigating adoption for alternative pest management strategies in field crop systems.”

Theoretical population ecology & practical biocontrol - bridging the gap, Association of Applied Biologists, 5-6 December 2007, Studley Castle, Warwickshire, UK.

Presentations by Economists at Scientific Conferences

Bailey, A.S. "Understanding the adoption of alternative pest management strategies: An economist's view." 41st Annual Meeting of the Society for Invertebrate Pathology and 9th International Conference on Bacillus thuringiensis, August 3-7, 2008 University of Warwick, Coventry, UK.

Results

Consumer Willingness to Pay Study

The application of latent class models for both Choice Experiments (CEs) found evidence to support the presence of preference heterogeneity of respondents' attitudes towards reductions in pesticide categories, with respect to environmental quality and food safety. The latent class analysis identifies the presence of 3 preference groups in the Bread CE and 2 in the Fruits and Vegetables CE. The results suggest that, for consumer health, respondents' WTP for a 100% reduction in pesticide use is £6.85 per week, a 105% increase in a weekly fruit and vegetable bill. For environmental quality, results report a WTP for a 100% reduction in pesticide use equivalent to £0.92 per loaf, a 184% increase in the price of a loaf. These estimates are large, although similar to those published elsewhere. Two equivalent additive pesticide tax rates were computed, one for products used on cereals and another for those used in horticulture. For 'cereals' products, the tax, applied uniformly to all pesticide classes, is £7.07 per kg active ingredient. In the case of those pesticides used in horticulture the additive pesticide tax is £104 per kg active ingredient. Both tax rates are quite small and are unlikely to compromise the industry.

Factor, IPM Portfolio Analysis: What are farmers currently doing or would consider doing?

Most UK conventional farmers, collectively the largest group by area, rely on pesticides for weed, disease and pest control. However, survey results show that many farmers are, or will consider, using practices which can aid crop protection and reduce pesticide use. Figure 1 shows the popularity of a range of technologies which can help protect arable crops within surveyed farms.

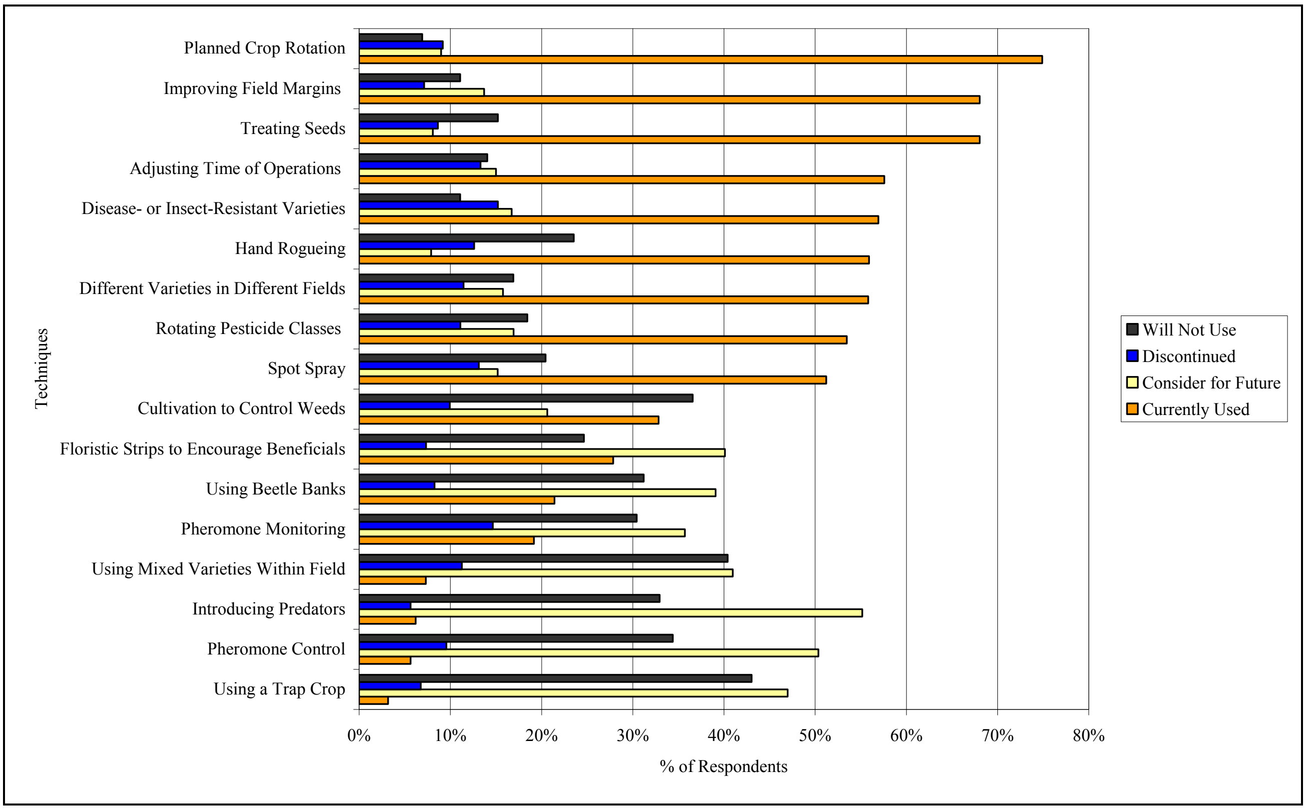

Figure 1: Adoption of pest control methods (percentages)

This survey of practice and attitude also revealed that farmers have combined the practices they adopt into logical IPM "Portfolios".

Portfolio 1 'Intra Crop Bio-controlers'	Portfolio 2 'Chemical "Users" / Conservers'	Portfolio 3 'Extra Crop Conservation Bio-controlers'	Portfolio 4 'Weed Focused Farmers'
Trap Crops	Pheromones	Field Margins	Cultivate Weeds
Mixed Varieties	Different Varieties	Floral Strips	Crop Rotation
Introductions	Resistant Varieties	Beetle Bank	Timing of Operations
Pheromones	Spot Spraying		Hand Rogueing
Different Varieties	Treated Seeds		
	Rotate Pesticide Classes		

Table 1 reports the types of portfolios revealed by the survey data.

Portfolio 1 'Intra Crop Bio-controlers'	Portfolio 2 'Chemical "Users" / Conservers'	Portfolio 3 'Extra Crop Conservation Bio-controlers'	Portfolio 4 'Weed Focused Farmers'
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Different Varieties	Treated Seeds		
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Table 1: IPM Portfolio practices on UK arable farms

Many of the practices considered in this survey are supported by AES in the UK. These include Field Margins, Beetle Banks and Floral Strips but these are usually established for reasons other than IPM and AES objectives down-play IPM promotion.

The survey results report that UK arable farmers are using a range of techniques to control pests, diseases and weeds, and very few respondents appear to rely solely on pesticides. The choice of IPM portfolio differs across the sample and regression analysis suggests that heterogeneity is caused by farm type, tenure and AES engagement while other, unobserved farm characteristics also likely play an important role. Further regression analysis shows that practices which modify the cropped environment, (Portfolio 1) appear to reduce insecticide use. There was no statistical support for a similar affect from Portfolio 3 which should concern advocates of CBC.

Count Data analysis of PM technology adoption

This work focuses on the explanation of the number of technologies employed following Lohr and Park, (2002). Using the farmer survey data collected here, both parametric and non-parametric count data models were estimated. The nonparametric methods of Racine and Li (2004) produced the preferred set of results which also avoided sample splitting and the specification of functional form. This model suggests that full-time, younger arable farmers on larger farms in the southern and eastern parts of the UK employ the largest number of PM technologies. These results suggest that organic farmers do not adopt more complex PM portfolios than conventional farms. Adoption of PM technologies appears to be driven by both farm specific characteristics and agronomic and climatic factors. The spatial interpretation of the results reveals the anomaly that farmers in the South East region (SE) adopted fewer technologies than have their near neighbours, counter to the general result. Possible explanations include; 1. lower regional pest pressure, 2. that spatial network effects limit the returns to or produce psychological barriers to innovation, 3. the Rural Payments Agency implements different AES rules in the SE. Discounting the first explanation, it seems likely that the combined influence of differential policy implementation and farmer to farmer communication could be highly influential in IPM technology adoption.

Field scale CBC Trials

Determining the effectiveness and type of pest natural enemies providing cereal aphid biocontrol
Where flying natural enemies had access (F and A) aphids failed to increase in contrast to where there were only epigeal predators or total exclusion (E and N) (Figure 2). On the final sampling occasion, compared to where all predators were present, flying natural enemies reduced aphids by 90% and 93% in fields with standard and wide field margins respectively, whereas epigeal predators only achieved reductions of 40% and 18%. Aphid parasitism were very low (<3%) in most cages.

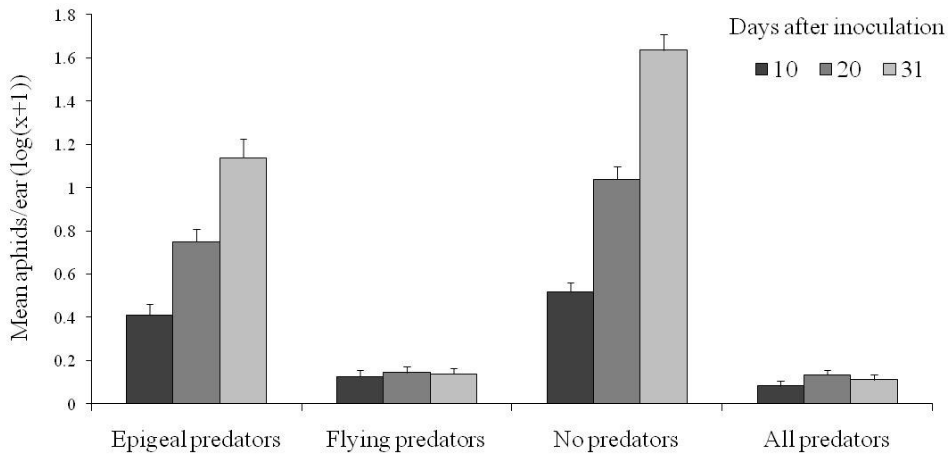

Figure 2: Mean number (± 1 SE) of aphids per ear for each type of exclusion cage at 10, 20 and 31 days after inoculation with *Sitobion avenae*.

83% of invertebrates captured in pitfall traps were predatory but margin width and distance from the field margin had no significant effect on their numbers. Carabid and staphylinid diversity were significantly higher at 20 than 80 m from the field margin Holland et al. (2008a).

Predatory invertebrates captured on the sticky traps were significantly higher in the fields with wider margins, but only in early May. In addition, Cantharidae (soldier beetles) and Tachyporus species (rove beetles) were more abundant in fields with wider margins in early June Oaten et al. (2007).

In both years there was no significant difference between the level of aphid control provided by flying natural enemies with and without parasitoids, but flying predators effectively controlled the cereal aphids.

Role of habitats in cereal aphid biocontrol
Results from the predator exclusion experiments in 2006 and 2007 were consistent with those found in 2005 Holland et al. (2008b).

Aphid control by flying natural enemies increased reciprocally with the area of grass margins within 250, 500 and 750 m of the exclusion cages. In contrast, increasing the area of hedgerow within 100m, 500 and 750 m radii reduced aphid control by the epigeal predators.

Numbers of Cantharidae on sticky traps in the crop declined significantly as the area of margins increased probably because the margins were a more attractive habitat. In contrast, earlier in the year, margins were a source of one natural enemy group, the *Tachyporus* species Oaten et al. (2008).

Evaluation of floral resource usage

Adult hoverflies and ladybirds were successfully marked with rubidium through application to a flower-rich margin. Clover plants retained high concentrations of rubidium for at least seven days after spraying.

Few cereal aphids were found on the wheat plants but high numbers of alate cereal aphids were caught on the clear sticky traps, with clustering into several patches. Empididae (predatory flies) and hoverflies were the most abundant natural enemies. All and female hoverflies were heterogeneously distributed on the third and fourth sampling occasions and with fewer aphids on the third sampling occasion where there were more hoverflies. Empididae were strongly aggregated into patches that coincided with the aphid patches determined from sticky traps.

867 female hoverflies were tested for rubidium, of which only 13 were considered marked. Most of these were captured in close proximity (<150 m) to the flower-rich margin.

In summary, flying predatory invertebrates provided the most effective aphid control the most abundant of which were the predatory flies (Syrphidae, Empididae and Dolichopodidae), predatory beetles (Staphylinidae and Cantharidae) and spiders which balloon. Aphid control improved as the proportion of grass margins increased between 250-750 m of the field, indicating that biocontrol can be improved through habitat manipulation funded by AES. Grass margins benefit natural enemies by providing overwintering and foraging resources. Hoverflies, parasitoids and predatory beetles may benefit from margins providing pollen and nectar. In this study, however, there was little evidence that the hoverflies found within the crop had foraged on the adjacent flower-rich margin. This requires further research making use of the rubidium marking technique that was successfully developed.

Semiochemical Trials

Release rate properties of different formulations

Microencapsulated formulations did not provide sustained release for more than 48h (Fig. 3). The gum acacia formulation had a lower initial release rate but release was sustained for 6 days. The gum acacia formulation was selected for field trials.

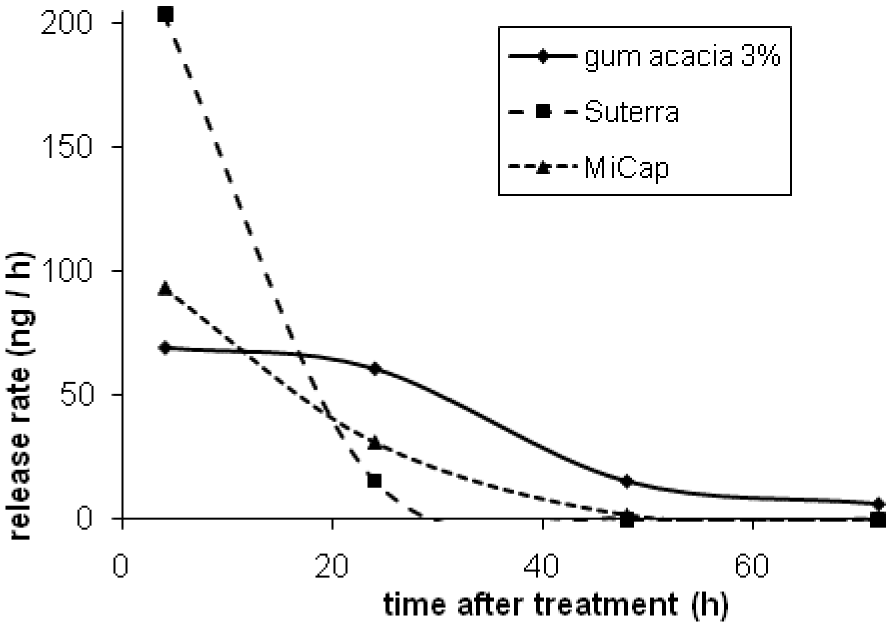

Figure 3: Release rate of *cis*-jasmone from oilseed rape plants treated with different formulations

Foraging Bioassay

Significantly more time (a mean of 16.6 min) was spent by *A. ervi* on *cis*-jasmone induced wheat plants than on control plants (7.6 min).

In contrast, *cis*-jasmone induction had no effect on the foraging behaviour of *A. rhopalosiphi.* Mean time spent on induced and control plants was 12.4 and 14.1 minutes, respectively.

Semi-field arena trial

Performance of *A. ervi* was enhanced by *cis*-jasmone treatment: aphid numbers were significantly reduced and percentage parasitism was significantly higher on induced plants. This finding supports a study with *Arabidopsis* where it was found that *cis*-jasmone treatment made plants more attractive to *A. ervi* (Bruce et al., 2008). It extends the study of *cis*-jasmone on indirect defence and tritrophic interactions to a crop plant and confirms that the interaction is enhanced when aphids are present, helping to explain the reductions in aphid infestations observed in field trials with *cis*-jasmone treated wheat (Bruce et al., 2003). However, as found in the foraging bioassay, *cis*-jasmone did not enhance the performance of *A. rhopalosiphi* (Bruce et al in prep) which probably lies on different cues more specific to its' particular host aphid-plant complex.

Use of natural enemies for CBC is limited in annual field crops by difficulties in maintaining sufficient densities in the crop before levels of insect herbivores become economically damaging (Bradburne & Mithen, 2000). Induction of crop plants with *cis*-jasmone could provide a solution to this by enhancing parasitoid activity. Enhancing favourability of wheat to the generalist parasitoid *A. ervi* becomes particularly relevant when wheat crops are adjacent to more natural vegetation in which the more generalist parasitoids occur.

Pest colonisation of wheat varieties treated with cis-*jasmone*

In the autumn there was a significant reduction in aphid numbers on *cis*-jasmone treated plots (Figure 4). Aphid numbers were also lower on most treated varieties in summer with a statistically significant reduction on cv Solstice (Figure 5). *cis*-Jasmone treated plots had significantly fewer gout fly eggs than the controls, but there was no varietal effect. Numbers of gout fly larvae were not significantly reduced by the treatment, but there were significantly more larvae in Hereward and Welford compared to the other two varieties.

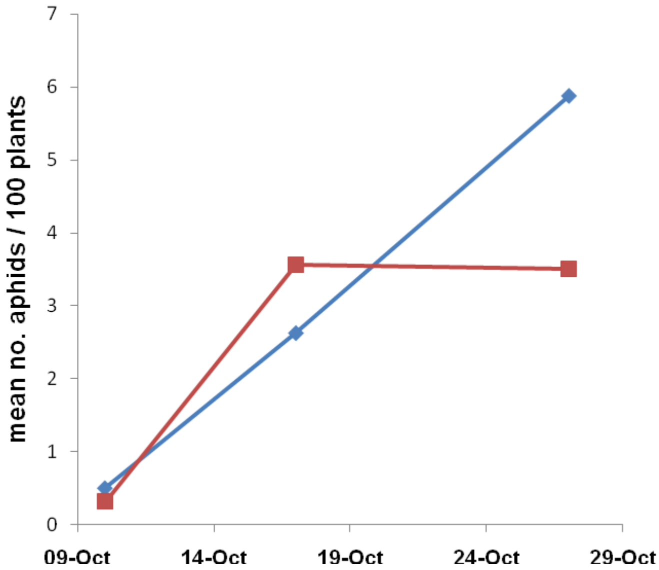

Figure 4: Cereal aphid numbers on *cis*-jasmone treated compared to untreated plots

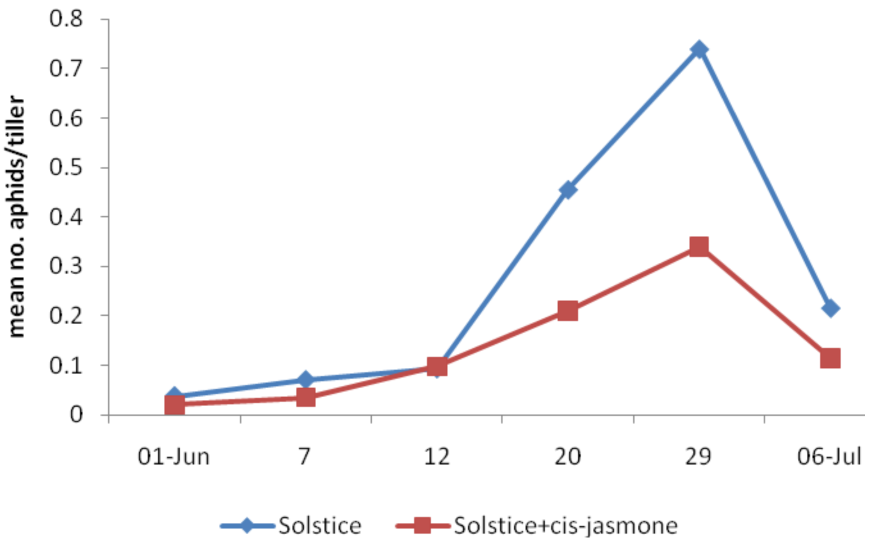

Figure 5 : Numbers of cereal aphids colonising wheat variety Solstice with and without *cis*-jasmone treatment

There was a very low orange wheat blossom midge infestation and no differences between the treatments except for midge-resistant Welford. Numbers of parasitoids and predators were too low for analysis.

Despite low aphid infestations, the *cis*-jasmone treatment produced a consistent trend towards reduction in colonisation and population size. The fact that wheat varieties respond differentially to priming or induction of defence mechanisms by plant signals is a new finding and suggests that control could be improved by using activators in an IPM package where they are combined with appropriate varieties.

Field-scale experiments with cis*-jasmone*
In both years cereal aphid numbers were very low with the main immigration occurring in late June. The most numerous species was *M. dirhodum.* The low aphid numbers meant that no firm conclusions could be drawn from trials 1 and 2.

In trial 3, aphids (mostly *Acyrthosiphon pisum*) arrived early, in large numbers and were fairly evenly distributed across the two pea plots prior to the first application of *cis*-jasmone. Following treatment aphid numbers were significantly lower by 19 June on the *cis*-jasmone plot (Figure 6).

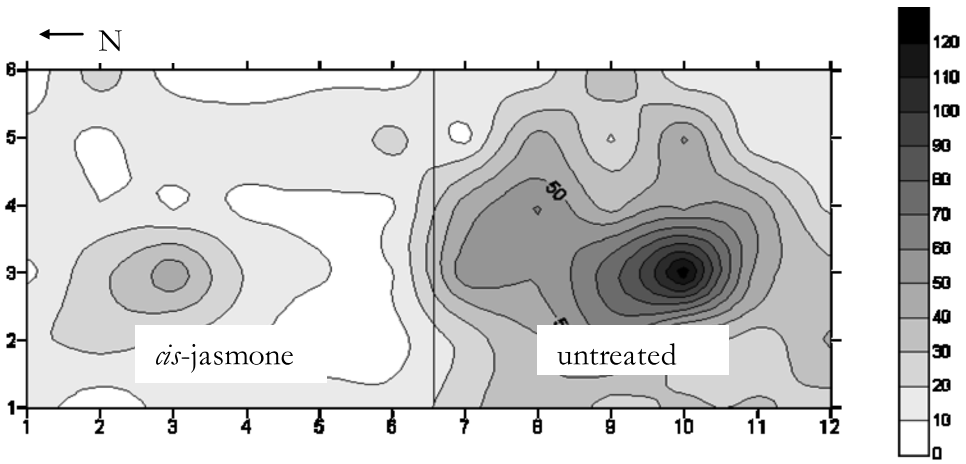

Figure 6: Plot of the distribution of *A. pisum* (aphids/sample) on pea plots on 19/6/08

Although the wheat trials did not produce significant results due to low aphid numbers, the gum acacia formulation was more effective than the wetter and research into formulation will continue. The field trial in peas showed that *cis*-jasmone can be effective at this scale. However, overall the field-scale trials demonstrated the need for replication and also for more consideration of landscape detail.

Control Cage Abundance and Complexity work

Key results from research at Imperial College improve our understanding of diversity-function relationships and how biodiversity may be managed to enhance ecosystem services such as pest control. By manipulating species richness, at different population levels, a positive effect of species richness is found, especially at higher total predator population levels. This is driven by lower levels of intraspecific interference that would depress pest control in species-poor communities, and the positive effects of resource-use differentiation and synergistic interactions among complementary species that improve pest control in species-rich communities (Griffiths et al 2008a).

Natural enemy species were highly idiosyncratic in their predatory potential, and as a consequence, variability in pest control was greatest among species-poor communities. Predator species identity is clearly an important component to consider for maximising pest control function when natural enemy species richness is low. Substantial increases in pest control may be achieved by augmenting populations with single, highly effective species, but these must be selected to minimise the limitations of intraspecific interference. However, where natural enemy populations are intermediate or high, it may be more advantageous to increase diversity to increase representation of functionally complementary species.

Balanced natural enemy assemblages outperformed dominant assemblages, resulting in around 14% higher predation where predator species were evenly represented (Griffiths et al. in review). This pattern was driven by intra- and interspecific interference in dominant assemblages that depress predation levels and a combination of resource-use differentiation and synergistic interactions that enhance predation in balanced communities.

The observed impact of community balance on predation has implications for the design and interpretation of diversity-function studies and management of biodiversity to maximise ecosystem services. Biodiversity experiments typically use an even species-abundance distribution, and as a result may consistently overestimate the frequency of positive or neutral effects for a given species-richness. The data suggest that pest control services may be enhanced by increasing the balance of natural enemy assemblages, with the added benefit of reducing the extinction risk of rare species.

Additionally, measures of variability are particularly important for ecosystem services such as crop protection which tend to have clear biological and economic thresholds, with reliability and risk often important factors for farmers accustomed to the predictability of agrochemicals (Griffiths et al 2008b). As such, it is an important observation that minimum function was greater and more reliably achieved with a species-rich assemblage compared with the more variable species-poor treatments, without any compromise on the maximum function possible. Add to this the fact that the most effective predator is likely to be pest-, crop- and context-dependent and this creates a strong argument for retaining or augmenting a diversity of natural enemies for optimum pest control function.

Overall Implications of the Results

Overall, our results suggest that progress is required on several fronts before the IPM technologies studied here can be considered as an effective substitute to insecticide use in cereals. Significant technical barriers remain and much remains to be done in the development of non species specific, IPM.

The last serious outbreak of cereal aphids in summer in the UK was in the 1970's although these aphids are still a target of much insecticide use in the UK. During this project natural infestation levels were low. It is possible that CBC, generated by AES measures, may have contributed to the decline in cereal aphid populations in the UK although other factors such as changes in rotation, nitrogen fertiliser use, insecticide usage, cultivars and climate have also played a role.

The efficacy of semiochemicals in some of the field trials conducted here was inconclusive because of the low infestation levels. However, in the pea crop there were significant effects and there were promising indications that the wheat variety 'Solstice' responds well to cis-jasmone treatment. The potential for semiochemicals thus requires further evaluation in other crop systems, especially in the horticultural systems where fewer insecticide products will be available due to pesticide revocations. However, speed of action may limit adoption where cosmetic damage is important. Combining CBC and semiochemicals may help to overcome the limitations of both approaches; biocontrol has frequently been demonstrated to be more effective adjacent to field boundaries, but issues regarding the scale of habitat augmentation and the ability of habitats to provide sufficient natural enemies to have an impact need to be addressed. While the literature is full of references to and definitions of IPM which recognise the need for inclusion of a large and diverse range of component technologies, little is known about how these technologies interact.

As for economic barriers to the commercial use of IPM, we have found that policy, as implemented in the UK following the commencement of this research, has made what appears to be a significant breakthrough in what is implemented on farms. We had expected to find that farmers would be reluctant to consider IPM, and that practices which can promote biological control functions would not be found on farms. Reasons for this expectation were; 1. that farmers would capture only a small proportion of the benefits of a change in technology and that they would face large transition costs, 2. insecticides are cheap, to use, and pest control represents a very small proportion of crop production costs, 3. the effectiveness of alternatives had not demonstrated.

However, AES implementation appears to have made a first step toward breaking farmers' dependence on pesticides by compensating them for revenue forgone or cost incurred in the implementation of IPM beneficial land use change. Some of these changes have, in certain combinations yielded measureable reductions in insecticide use. Laboratory studies conducted here demonstrated significant complementarity between natural enemy species shown in improved control and resilience. Further, field scale trials showed that aphid control could be improved with habitat manipulation and therefore, there remains scope to improve CBC in practice. AES is now in place to provide such habitat improvement but these programmes do need to be developed further to fully exploit these gains.

This research award has yielded several significant breakthroughs in our understanding of the functioning of both CBC and semiochemical technologies. Among these is the improved understanding of the relationship between beneficial species diversity, abundance and pest control, which together with our improved understanding of the field-scale habitats likely to promote these populations, will help us make significant improvements to the UKs' AES programmes.

Capacity-Building and Training

Abhijit Sharma completed a course on Programming in MATLAB organized by the Department of Computing and the Department of Maths at the Imperial College in 2006 and in 2006 & 2007 was a Quantitative Methods Tutor in Econometrics for the Open University. In 2007 he completed the advanced training workshops in "*R*". Both he and Marco Bertaglia began their training toward their PGC HEP qualifications. Marco Bertaglia attended training conferences in individual based modelling techniques. Elodie Dourin attended advanced training sessions in GIS at the University of Nottingham in 2008.

Dr Georgianne Griffiths supervised a Masters student project and an undergraduate student on a Professional Training Year to contribute towards a Biology degree. Dr Georgianne Griffiths contributed to a workshop held by the CPB, Kew Gardens and Universiti Malaysia Sabah (funded by the Darwin Initiative) to build research capacity in the design, implementation and analysis of biodiversity experiments in South-East Asia. This included teaching statistical techniques for biodiversity experiments to a broad range of biodiversity researchers and practitioners from the SE Asian region.

Dr John Holland supervised one part-time PhD student, a part-time MPhil student and a full time MSc student. Three undergraduates worked on the project during their year-long placements and one undergraduate volunteered for a 10-week summer placement. Heather Oaten attended the EU funded ENDURE project Summer School "Biodiversity supporting crop protection," in Italy and a 3 week R course and 1-day presentation skills course at Imperial College. Dr Barbara Smith attended a REML course at Rothamsted Research.

Dr Toby Bruce supervised one PhD student with Prof John Pickett. Lesley Smart has supervised work experience students in summer placements on the project.

Outputs and Data

Collaborations with other projects

Collaboration with RES-224-25-0048 on a book entitled: "Biological Control, Integrated Pest Management and the Regulatory Challenge: an Interdisciplinary Approach", CABI.

Academic Presentations

A list of all Academic Presentations arising are attached in an annex 1.

Knowledge Transfer, User Engagement and Impacts

Press Releases

GWCT press release, October 2004: Consumers Demand Less Pesticides - Scientists Respond with a million pound study which will re-bug the system with an army of friendly insects.

GWCT press release, October 2005: Flying predators are top at saving crops.

GWCT press release in June 2009: New study shows that flying predators are top crop savers – but to reap the benefits farmers need to plant flower-rich margins.

Press releases resulted in coverage on BBC TV, Radio and National and local newspapers.

All farmers who participated in this study were provided with a report and list of invertebrates recorded on their farms.

Impacts

Information gained from the project was used to help compile the publication "Beneficials on farmland: identification and management guidelines" written by John Holland and Steve Ellis, published by HGCA and distributed to 25,000 farmers.

Presentations to Stakeholders

Bailey, A.S. (2009) RELU: Re-bugging the System - Promoting Adoption of Alternative Pest Management Strategies in Field Crop Systems. First meeting, 3rd February 2009, The Atrium, Four Millbank, London

Pickett, J. (2008) Seminar at Syngenta, Jealott's Hill, "New approaches to crop protection: letting the plants do the work by activation and priming", 26.3.08

Bailey, A.S. (2006) Project Overview Presentation. Stakeholder range finding exercise, 05-07-06. Confederation House, East of England Showground, Peterborough, PE2 6XE

Pickett, J. (2005) SCI meeting, Plant Signalling: Opportunities for Non-Cidal Pest Control, Belgrave Square, London, "Insights into plant signalling elicited by the plant activator cis-jasmone"; 4.3.08

Bailey, A.S. (2005) RELU: Re-bugging the System - Promoting Adoption of Alternative Pest Management Strategies in Field Crop Systems. Second meeting, 13th September 2005, Terrace Room, Royal Horseguards Hotel, London.

Future Research Priorities

Social Science and Interdisciplinarity

Beyond the work that is planned to continue using both the farmer survey data, there remains scope for further research in three directions. First, more detailed research, using farmer interviews and matched case studies of farm practice, landscape backdrop and background ecology would yield a more detailed picture of the determinants, and patterns, of AES engagement. Secondly, access to "precision farming" GPS data overlayed by ground cover mapping data should be pursued to allow the investigation of both the positive and negative impacts of out-of-field habitat on farm productivity using spatial econometric techniques. These efforts would help us to design in IPM incentive compatibility into AES. Thirdly, ongoing work making use of the interdisciplinary researcher interviews to date suggests that further effort to assess the effect of researcher engagement on interdisciplinary projects could be valuable. A similar investigation of *ex-post* researcher expectation and understanding of complex problems, could be considered within the team.

Natural Science
Research has robustly identified many patterns and mechanisms underlying the relationship between biodiversity and ecosystem services. It is now essential to understand the context-dependence behind these mechanisms within field systems.

The field scale studies demonstrated that effective aphid biocontrol operates in cereal crops and is influenced by the surrounding uncropped landscapes. Such studies need to be extended to other pests and crops if a fully integrated approach is to be developed. The ecology of key pest natural enemies needs further investigation to enable the design of habitats that maximise biocontrol through optimimum resource provision. Their use in conjunction with semiochemicals requires evaluation.

The semiochemical trials showed some promise even though cereal aphid populations were low. Breeding crop plants to respond better to natural plant activators is expected to enhance CBC given the differences between wheat varieties seen here. Other pest targets should be sought for future work and new semiochemical treatments in addition to *cis*-jasmone need to be developed as a matter of urgency given the increasing demand for alternatives to toxic insecticides and ongoing need to protect crops from pests.

Overall, the team recognises a pressing need to widen this research beyond the pest problem considered here. While cereal aphids remain a target for pesticides in the UK, they are by no means the most important cereal pest. In order to achieve high levels of adoption, and to gain the further from pesticide deduction, IPM systems which can control a wider range of pests must be devised.

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ACTIVITIES AND ACHIEVEMENTS QUESTIONNAIRE

1. Non-Technical Summary

A 1000 word (maximum) summary of the main research results, in non-technical language, should be provided below. The summary might be used by the Research Councils to publicise the research. It should cover the aims and objectives of the project, main research results and significant academic achievements, dissemination activities and potential or actual impacts on policy and practice.

The aim of this project was to identify the potential technical and economic barriers to the commercial use of alternative pest management approaches, which could limit the industry's reliance on chemical pesticides, and thereby yield significant benefits to both farmers and the wider public.

Much research in the recent past has demonstrated the potential viability of biologically based measures farmers can use to help control insect pests which could reduce pesticide use in commercial agriculture. Likewise, work across a range of scientific disciplines has drawn attention to the potential harm that pesticides can do, while environmental economists have shown that the public are willing to pay to see threats reduced.

This award marshalled research effort across a range of disciplines, including economics, sociology, entomology, ecology, chemical ecology and biochemistry, to consider the reasons why much of the UK field crop agricultural sector still relies heavily on conventional toxic pesticides for pest management. Two alternative approaches to the control of cereal aphids, a herbivorous pest of wheat crops, were used as a case study of how to conduct Integrated Pest Management Research at a complementary range of scales. Numbers of cereal aphids have been low in recent years but they are still a target of much insecticide use.
The techniques considered were 1; the use of conservation biological control (CBC) to promote predation and parasitism of pest populations and 2; the deployment of non-toxic signalling chemicals (semiochemicals) which can boost levels of bio-control and switch-on plant defence mechanisms in advance of pest attack. Previous research has suggested that both of these techniques can be used by farmers to boost the effect of natural population control mechanisms and limit aphid pest infestations. The techniques work in differing ways, CBC is said to boost populations of beneficial control organisms in the farmed landscape, while semiochemicals have been shown to help farmers direct naturally occurring beneficial organisms toward infested cropped areas.

Research conducted under this award has shown that CBC can, and is, providing background control of cereal aphids but this function can be improved in several ways. Field studies and control cage studies have shown that the complexity of beneficial insect ecology can produce significant complementarity and resilience in pest control function. Landscape manipulations required to boost ecological complexity have been identified. Semiochemicals can attract natural enemies into crops and reduce pest populations. These effects were hard to measure in this study because of the very low levels of aphids present. A field trial into control of aphids in pea crops showed that semiochemicals aid

the biological control of aphids in pea crops and demonstrates the ability of these products to help to harmonise levels of biocontrol across field transects. A valuable new finding is that certain wheat varieties respond better to plant activator treatments than others.

Work to address the economic barriers to commercial use of these, and other, pest management techniques has highlighted the importance of government policy in the adoption process. This is particularly important when considering the adoption of technologies, which can present either costs or benefits to both those making the adoption decision and to the wider populace. In these cases, suboptimal choices can be made when the decision maker shares or does not see all of the consequences of the decision. This situation is present in the decision to adopt alternative pest management. There are significant gains to those outside the farm as consumers can benefit from reduced risk of pesticide contamination or as consumers of improve ecosystems, such as increased levels of farmland birds, and our research shows that the population does value these aspects highly. The research conducted here reacted to concurrent policy changes in the UK which saw farmers implement a wide range of landscape changes on their farms. While these Agri-environment Scheme (AES) programmes are not specifically aimed to promote biocontrol of pests, AES options can produce habitats conducive to the promotion of biocontrol, although the removal of explicit reference to crop management with the withdrawal of Crop Protection Management Plans (CPMPs) is a setback. We discovered that farmers do appear to be implementing a high proportion of practices and land uses which can be beneficial for biocontrol. We also found that farmers appeared to be combining these practices in coherent ways which could considered as functioning IPM portfolios. Further, one of the portfolios we identified does appear to be associated with lower rates of insecticide use and so could be helping to promote lower levels of insect pests in crops.

One important outcome of the joint work conducted in this project and our improved understanding of biocontrol processes and functions, and farmer adoption incentives is that we are now better placed to help reshape AES so that it explicitly promotes IPM. The AES presents a practical incentive structure capable of internalising the benefits of IPM adoption, accruing to consumers and the public at large from reduction in pesticide use, to farmers. We will now produce an interdisciplinary review of all the work conducted here with a view to proposing a set of changes to the way in which AES options are rewarded, in order to improve the public benefits of the AESs, to DEFRA over the coming months and a RELU Policy and Practice Note outlining our approach to the promotion of wider IPM adoption will be published soon.

Research: Rebugging the System

Project overview

The technical aspect of this project involves two important biological control technologies.

One of these technologies is **habitat management for natural enemies.** This is achieved through the creation of features such as *beetle banks* and *grass margins*, and it is a technique currently being driven into British agriculture via agri-environmental schemes. Habitat management represents the only broad-scale "biological control technology" currently in use (and being extended) in UK arable agriculture. However, though some of these techniques have been evaluated, e.g. beetle banks by The Game Conservancy Trust, their technical success and economic viability (in the absence of subsidies) has never been evaluated at the farm scale.

The second technology is the newest and most innovative approach to broad scale biological control. It involves the use of **semiochemicals** and the spatial distribution of crops and pests to encourage and direct natural enemy action. This technology is called " **push-pull" technology.** It has been developed by Rothamsted Research and has been successfully applied in African agricultural systems, where it has won international acclaim. In a UK context, its future application depends crucially on the balance of technical feasibility and economic viability.

This project will refine and study the implementation of these two technologies. The aim is to understand the technical and economic constraints to the broad adoption of biological control in arable cropping systems. By choosing an 'established' and a new technology, this programme of technical and economic research can look backward and forward in developing effective tools to evaluate and promote the adoption of biological control technology into UK agricultural systems. Our approach will focus on arable crops, particularly cereals, both as a model system and also because of (a) their dominance in the UK farming landscape, (b) the extent of background knowledge available on this ecosystem and (c) the fact that they are a major, long-standing target for conventional pesticide use.

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Research: Rebugging the System

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Rationale

Natural and social science research highlight the potential negative environmental effects of pesticides on biodiversity and water quality. In addition, certain retailers have set out objectives to supply produce completely free from pesticide residues. Heightened EU regulations are leading to withdrawal of many pesticide products currently in use. Thus, there exists a real demand for alternative pest control technologies from a range of stakeholders across the food chain.

The development of biological alternatives to chemical pest control has been an area of intensive research for some decades. A few of these have achieved high levels of adoption (e.g. augmentative introductions of predators and parasitoids for biocontrol of pests in protected tomatoes) but most have not. Indeed, on a global scale, the penetration of biological control technology into agriculture has been minimal - less than 1% of global pest control sales of $30b involve biological methods. In particular, the virtual failure of biologically-based pest control in annual arable crop systems is striking, and largely accounts for its poor UK and global impact.

This failure raises two fundamental questions: is the success of biological control in broad scale agriculture limited by inadequate technology, unfavourable economics, or a complex interplay of both aspects? Further, can economists and natural scientists, working together, enhance the impact and adoption of biocontrol techniques in UK field crop production?

This project aims to address these questions by combining recent research developments in the economics of technology adoption with novel natural science research in the development and evaluation of two potentially complementary biocontrol technologies. This interdisciplinary approach will be further complemented by socio-economic studies considering the feasibility for revenue enhancement of pesticide reduced foods and the potential for retailer led supply chain governance, to overcome barriers to adoption of alternative technologies.

Issues of policy design and implementation will be critically important in the adoption of a set of potentially viable biological alternatives to chemical pest control. To facilitate uptake of biological control in arable farming it is essential that we examine issues of policy design and implementation from a jointly scientific and economic viewpoint.

The emergence of a viable alternative pest control technologies has profound implications for both existing and future agricultural and agri-environmental policy.

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Project outline

Economics of technology adoption and replacement

From an economic perspective, the present failure of biological control in modern agriculture could be attributed to:

1. Differential cost structures of pesticide and biological control technologies

Chemical pesticide utilization is backed up by much information and experience, and the fixed costs faced by users of this technology are a small fraction of the total costs of pest control. It has been argued (Cowen 1991; Cowen & Gunby 1996) that this is a consequence of the technology (farmers need only limited information to ensure that control is effective, if not economic) and is a product of past dynamic gains from adoption. In contrast, existing biological control and integrated pest management (IPM) technologies are very dependent on local information and skills, such that this technology has large fixed costs of adoption. However, these fixed costs may deliver a self-renewing form of pest management, and are likely to diminish as these technologies gain more widespread use.

2. Differential risk preferences of producers

The much more limited body of research data and practical experience with biological control and IPM adds to the degree of uncertainty surrounding the efficacy and economic viability of the techniques (Cowen & Gunby 1996; Abadi et al. 1999; Pannell 2003) and acts as a barrier to adoption. Furthermore, farmers heterogeneous, and potentially averse, risk preferences are likely to result in a less than uniform, and likely sub-optimal, adoption pattern of uncertain technologies (see Cowen & Gunby 1996; Yaron et al. 1992; Antle 1987). Potential risk aversion adds to the problem if expectations of the efficacy of alternative strategies based on bio-control are skewed toward the 'down-side' (Antle 1987).

3. Jointness caused by allocatable fixed factors (Shumway et al. 1984)

Jointness in the control of a range of pests, plant pathogens and weeds using conventional chemical control techniques, caused by use of common shared fixed assets, presents a potential barrier to the adoption of alternative bio-control techniques. The broader the range of bio-control approaches integrated into alternative strategies the greater the potential gains to adopters. As such, a more integrated approach to bio-control research is likely to be important.

All of these factors are likely contributors toward 'Path Dependency' or 'Lock-in' of current pesticide technologies. The economic analysis of the technology adoption process recognises the importance of the 'public good' aspect of Government action. Potential 'Path Dependency', researchers argue, suggests that farmers are not irrational in choosing to continue to use an existing but sub-optimal technology. However, society as a whole may be considered to be irrational if the public good provision required to change to a socially more optimal path is not committed.

Habitat management and the functioning of natural enemies

Over recent years, considerable attention has been paid to the concept of "conservation biological control" as an important component of IPM strategies for pests, such as aphids, in arable field crops (e.g. see Landis et al. 2000; Gurr et al. 2003). This approach is based on installation and management of semi-natural habitats in the agroecosystem to provide resources, such as food and overwintering shelter, for natural populations of the key predators, parasitoids and pathogens of pests.

Conservation biological control can benefit enormously from the habitat diversification options promoted by current agri-environment schemes, especially options in the arable and countryside stewardship schemes (see Landis et al. 2000 and references therein). These include the establishment of flower-rich field margins that provide essential nectar and pollen sources for many insect parasitoids and predators, such as hoverflies, and the installation grass margins and "beetle banks" across large fields to act as reservoirs of carabid beetles and other ground-dwelling predators and to aid their timely dispersal into crops in the spring.

It is certain that opportunities for the expansion of such habitat manipulation within the farming community will continue to increase through further agri-environmental initiatives and set-aside options stimulated by CAP reform. However, our understanding of the relationship between biodiversity (as affected by these habitat manipulations) and pest control functioning remains poor, and the mechanisms through which natural enemies interact to determine the extent and stability of pest control, are unclear.

For example, in a recent study of the effect of landscape, habitat diversity and management on species diversity in cereal systems, Weibull et al. (2003) revealed that there was no straightforward relationship between species richness of carabids, rove beetles, and spiders, at either the farm level or in individual cereal fields, and biological control. They concluded that species richness in itself is not as important as a high diversity of different guilds of predators, such as ground and foliage predators, spring and summer breeders, day and night active species, for the overall efficiency of biological control. That is, the key to effective natural control is in maximizing functional complementarity among the natural enemies of pest species.

Unfortunately, our understanding of complementarity and the factors determining the emergent properties of multi-species predator assemblages is limited (Schmidt et al. 2003). While there is evidence that there is significant niche partitioning across microhabitats and functional complementarity among spider species (Sunderland 1999), for example, few other studies have shown significant complementarity among natural enemies (Snyder & Wise 1999). Similarly, whilst examples of synergistic interactions between predators exist (e.g. foliar predators eliciting dropping responses in aphid prey which increases their vulnerability to ground-foraging predators (Lossey & Denno 1998)), processes such as intraguild predation can severely disrupt biological control (Rosenheim et al. 1995; Snyder & Ives 2001). Work at Rothamsted has demonstrated lethal effects of fungal infections of the host on parasitoid larvae developing in aphids (Powell et al. 1986). Although developing parasitoids are also potentially vulnerable to predation of their hosts, evidence is emerging that such intraguild predation is mitigated by semiochemical-mediated, intraguild predator avoidance (Nakashima et al. submitted). Other work has demonstrated the potential of ladybirds for increasing the rate of infectivity and spread of fungal entomopathogens within aphid populations (Roy et al. 2001). Thus, one of the key ecological aims of this project is to evaluate conservation biocontrol by determining the major axes of complementarity among common natural enemy species in limiting population growth of cereal pests and elucidate whether positive or negative emergent properties predominate in the functioning of these natural enemy assemblages. This research is essential as a baseline evaluation to identify what combination of natural enemies (both predators and parasitoids) is most effective and, hence, define the ultimate goals and targets of habitat manipulation (and other complementary interventions) and whether these are achieved.

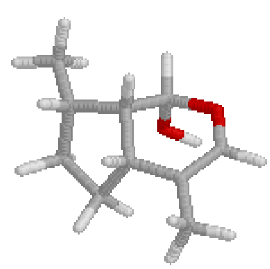
A further challenge in evaluating biocontrol relates to effects of scale of adoption. That is, although it can be shown that the installation and management of semi-natural habitats, such as field margins and beetle banks, can significantly increase the density of insect predators and parasitoids, it is not yet kn own whether these habitats are actually increasing populations of these beneficial insects within the whole ecosystem, or simply affecting their local distribution. If the latter is the case, then it could be hypothesised that the pest management benefi ts of habitat diversification (or semiochemical technologies which also modify spatial distribution) on arable farms will reduce as the scale of its implementation in the landscape increases. That is, if the initial positive effects of an intervention demonstrated at the single field level (the usual scale in developmental research) derive from local redistribution, then not only might this be at the 'expense' of natural pest control in adjacent fields (generally not tested), but the effect will saturate out when the scale of adoption exceeds the ecological scale over which the redistribution occurs. On the other hand, a contrasting scenario is also possible whereby the effectiveness of a technology could increase with increased adoption due to synergistic effects arising in the move from field to farm to landscape scales. Such synergies are most likely if population size is affected, though not necessarily exclusively so. Thus, a second ecological research aim is to evaluate empirically the effects of scale, to determine how effectiveness of pest control technologies alters with scale of adoption. This evaluation of scale is a highly innovative aspect of this proposal with important implications for the economics of adoption and the design, implementation and adoption of future pest control (and conservation) strategies. Placed in the technology adoption context discussed above, these two research aims are essential to test the efficacy and potential of habitat management as a biological control technology for broad scale agriculture in UK. They will also serve as a basis for socio-economic analysis of constraints on adoption, involving differential cost structures, scale effects, and risk preferences of producers.

Semiochemicals

As a consequence of recent developments (see below) semiochemicals, i.e. chemical signals that control pest or natural enemy behaviour and development or act to switch on defence in plants, now have considerable potential as alternatives to conventional pesticides. By influencing the colonisation of crops by pests, and their subsequent population dynamics, semiochemicals can be used to direct pests away from the crop and attract them to areas where they can be controlled, as well as attract their natural enemies (the "push-pull" strategy). Semiochemicals act through non-toxic mechanisms and thus offer benign means of crop protection with which to minimise, supplement, or in the long-term replace, use of broad-spectrum pesticides in IPM. In lower input systems, including organic farming, the use of semiochemicals facilitates the management and thereby greater exploitation of biological control agents.

Considerable knowledge already exists of the nature of semiochemicals, particularly pheromones, and practical uses continue to develop (Howse et al. 1997). Rothamsted Research has played a world-leading role in the identification and strategic deployment of semiochemicals (Pickett et al. 1997; Agelopolous et al. 1999; Chamberlain et al. 2000; Powell and Pickett 2003). Although world use of semiochemical-based pest control currently represents only ca 1% of expenditure on insecticides, some major commercially successful projects are extant. In Mexico, a sustainable IPM strategy based on pheromone deployment has been developed for control of lepidoterous pests on fresh tomatoes with considerably better effectiveness than deployment of conventional pesticides (Trumble & Alvarado-Rodriguez 1993; Trumble 1997).

The push-pull strategy functions through the manipulation of a variety of semiochemical cues in conjunction with habitat management. The principles and potential of this approach have already been proven in other projects co-ordinated by Rothamsted, such as the highly successful project in E. Africa, particularly Kenya, to control stem borers in maize and sorghum (Tsanuo et al. 2003; Khan et al. 2000; Khan et al. 2001; Khan et al. 2001; Khan et al. 2002). Whilst the E. African project, which is aimed specifically at resource-poor farmers, utilises selected trap crops and intercrops to produce the



appropriate semiochemicals for pest and beneficial insect manipulation, the overall strategy can be made more cost effective for first world agriculture by selective deployment of a balance of key semiochemicals to achieve effective push and pull components.

Although the major industrial effort is still committed to research into toxicants, there is a global effort, increasingly exploited by SMEs, directed at this science and technology because of the essentially benign nature of semiochemicals. They act at very low levels to cause natural behavioural or developmental changes, and are perceived as a means of answering a global demand for the reduction of toxic, and potentially neurotoxic, materials in the environment. The European Union incorporates many regions having similar crop pest problems to the United Kingdom, and there are a number of national and EC-funded research programmes on identifying and developing semiochemicals. Indeed, Germany has established a new Chemical Ecology Institute at Jena as a clear statement of its support for these approaches.

It has been established that, where semiochemicals can be produced directly from raw materials or obtained from plants grown for the purpose, substantial reductions in cost can be made over normal synthesis from oil-based starting materials. This has been carried forward to initial commercialisation, for example, in the production of aphid sex pheromone components by a LINK programme (Competitive Industrial Materials for Non-Food Crops). This is now being followed by a new LINK project: "New semiochemical opportunities from Nepeta spp. as a non-food crop" to cover wider use of aphid sex pheromone components and related products attracting a wider range of insects, including predators and parasitoids of aphids. From a "sustainability" viewpoint, these approaches create additional industrial crops for agricultural and horticultural development. Plant-based semiochemical production systems can be cheaper than oil-based production and more sustainable because renewable plant resources provide the semiochemicals or their precursors.

Delivery of semiochemicals is more demanding than conventional toxicant pesticides but the absence of pesticide residues and the demands of the public and food retailers for minimum and even zero use of pesticides makes deployment of semiochemicals attractive. Use and delivery on arable crops presents a serious challenge in providing the means by which the required release rate can be established over an extensive and often diffuse cropping area with appropriate persistence. However, this problem may be solved by exploiting the discovery that certain semiochemicals produced by plants, specifically when infested by pests, cause subsequent "switching on" or "activation" of plant defence in nearby healthy plants, which then remains in place even when the signal has dispersed. This forms a basis for greater use of natural plant activators.

The spatial and temporal scale of effects on the pest and efficacy in stimulating attraction of natural enemies need to be quantified, and potential effects on non-target species, including other pests and their natural enemies need to be assessed to improve understanding and utilisation of push-pull strategies. An innovative aspect of the proposal will be the development of new semiochemical-based strategies, and prediction of the effects of their widespread implementation based on knowledge gained by the complementary studies of the effects of scale on insect manipulation via hab itat diversification and management. An additional innovative dimension will be to consider the potential synergistic interactio n between the existing and expanding approach to conventional pest control in arable production systems (i.e. conservation biocontrol through habitat management) with an exciting developing technology (semiochemicals) that is likely to be implemented within the next 20 years.

Two important questions, one scientific and one socio-economic, apply to both approaches to non-pesticide pest management on widespread arable crops:

1. what will be the implications of widespread adoption of these pest management strategies on their effectiveness
2. what are the socio-economic constraints, from both the farming and public perspective, that would hinder widespread adoption?

The demand-side and biocontrol adoption

Consumer perceptions regarding biocontrol might be considered to harvesting a pheromone-producing plant

have two important impacts on successful adoption. First, consumers and the wider society may have health or environmental concerns about the manipulation of natural predators and pathogens and the use of semiochemicals. Work is required to assess the degree and nature of these concerns and the extent to which these groups are prepared to trade these off against benefits of pesticide reduction. Second, the determination of whether a market of viable scale exists for 'pesticide-reduced' food products derived from arable sector outputs. For the farmer, the adoption of novel pest control strategies may not be cost neutral, at least during the early phase of technology adoption. Assessing ex-ante consumers willingness to pay for 'pesticide reduced' foods provides a further means of exploring the potential for adopters of these technologies to maintain or enhance their competitive position, nationally and internationally.

In addition, consumer perceptions and willingness to pay for reduced pesticide foods products which include cereals in differing proportions, the attitudes of food retailers are critical in determining the nature and scope of the market for pesticide-reduced foods. These issues are handled within a choice modelling setting which can easily cope with the complexities introduced by changes in the attributes of primary components of processed food and drink products by careful design of the choice sets presented to survey respondents.

Competition for supermarket shelf-space is intense and the case for new product introductions needs to be extremely persuasive if retailers are to replace an existing line with a new one and the supply chain encouraged to treat reduced pesticide products in a segregated way. Lessons learnt from the introduction of products containing organic cereals and organic cereals themselves may be valuable in this case. Given the lack of research conducted thus far on consumer and retailers attitudes towards pesticide-reduced foods, there is a clear need for an assessment of how participants in the food chain are likely to view these products and how they might be positioned with respect to distinct consumer segments for different supermarket chains.

The potential for retailer governance to direct technology adoption by their food chain partners, following the example of Tesco 'Pine Broilers' chicken developed by the Food Animal Initiative, will be explored.

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Specific objectives

The specific objectives of the project are to:

1. Quantify the marginal social benefits of a reduction in the use of pesticides in UK cereal systems and compare these to existing estimates of the marginal costs of pesticide applications made by farmers;
2. Evaluate the constraints to, and incentives for, adoption of non-insecticidal pest management technologies, and the relative effects of social, economic and environmental/technical factors in the current level of pesticide lock in;
3. Evaluate the relative importance of natural enemy diversity and abundance in providing effective pest control in cereal-based systems;
4. Evaluate the effects of scale of adoption on the effectiveness and sustainability of alternative pest control technologies;
5. Advance understanding of the roles of semiochemicals and identify new opportunities for practical exploitation;
6. Develop new strategies for non-insecticidal pest control;
7. Develop a framework for the future development of alternative pest control technologies which integrates scientific and socioeconomic research;
8. Estimate the likely private costs of the adoption of bio-control techniques as adoption rates increase;
9. Consider the role of agri-environmental policy on the promotion of biological control technologies;
10. Consider the consumer demand for differentiated 'pesticide-reduced' food products and the feasibility of passing such a price signal to the farm gate;
11. Consider the potential for retailer led initiatives to promote adoption of biological control;
12. Develop a fully integrated bio-economic model of pest control.

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Interdisciplinarity

The project integrates economic and scientific work to explore the constraints and incentives to the adoption of novel crop protection practices in commercial agriculture.

We consider technical issues of evaluation (natural enemy diversity and scaling effects) and development (semiochemicals from lab to field), coupled with economic (path dependency and the technology adoption process) and social science (societal benefits and stated preferences) analysis.

Researchers from the social and natural science disciplines are working closely together in order to elicit the maximum information, economic and technical, from adopter and potential adopter case-study work. They will also consider questions of optimal information and service delivery to adopter farmers, the design of optimal extension and project dissemination and optimal agricultural and agri-environmental policy design.

Interdisciplinary cooperation in the construction of a fully integrated bioeconomic model of pest control is a key activity in this project. This component will prove central to the pooling of our understanding of the interaction of the relevant natural, economic and social systems, provide a means of assessing the impact of biological pest control across a range of temporal and spatial scales and will subsequently provide the basis of a decision support system for future practitioners and adopters.

The integrated research will provide input into the design of potential Government action to promote widespread commercial adoption of biocontrol technologies and contribute toward the provision of knowledge required by potential adopters.

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Methodology and approach

Habitat management

(a) Evaluating natural enemy complementarity and functional diversity

We are conducting a series of **controlled experiments** to monitor mortality rates of representative prey species exposed to different combinations of predators and parasitoids.

In these experiments, **natural enemy species** will be selected from those reported to have significant impact on pest populations in UK cereal-based systems (Wratten & Powell 1991; Holland et al. 1996; Symondson et al. 2002). These will include species from several arthropod groups including beetles (Carabidae, Coccinellidae, Staphylinidae), spiders (Linyphiidae and Lycosidae), hoverfly larvae (Syrphidae), hymenopteran parasitoids (e.g. Aphidius spp), together with entomopathogenic fungi (such as Pandora neoaphidis).

(b) Evaluating effects of scale of adoption

The **effects of scale of adoption** of habitat enhancement on the diversity, abundance and functioning of natural enemies will be evaluated using existing gradients of uptake from arable and countryside stewardship schemes, ranging from minimal adoption at the single field level, through to area-wide/landscape scale implementation.

Our approach will be to examine processes within single fields embedded in landscapes covering four levels of uptake.

Within each field to be monitored, the functional impact of ground and crop active predators and parasitoids on cereal aphids will be measured using an exclusion technique developed by Schmidt et al. (2003).Measures of both abundance and diversity will complement the investigations into natural enemy complexity. Parasitism will be measured by rearing aphids to adulthood and adult parasitoid activity will be monitored.

Directional window traps will be employed within the study areas to quantify the extent of immigration and emigration according to the scale of the habitat manipulations and temporal dynamics of the pest species.

Semiochemicals

Laboratory, semi-field and small scale field studies will be used to identify and **elucidate the roles of key semiochemicals** in (a) intraguild natural enemy interactions identified in the complementarity experiments detailed above and (b) habitat location by key pests and their natural enemies. Volatiles from each relevant ecological situation will be isolated by air entrainment techniques (Agelopoulos et al. 1999) and the physiologically active components in these samples located by coupled gas chromatography-electrophysiology (Wadhams 1996) and identified by coupled GC-mass spec (Pickett 1990).

Recent studies on the location of host plants by pests and the avoidance of unsuitable plants have identified **a new volatile plant activator, cis-jasmone** (Birkett et al. 2000). Application of this plant activator to cereals results in the induction of stress related volatile semiochemicals that not only deter pest colonisation but also attract the predators and parasitoids that attack the pests (Bruce et al. 2003).

In order to fully exploit plant-plant signalling as a method of semiochemical delivery, laboratory studies using chimney cages, whereby the effects of plant volatiles on neighbouring plants can be measured (Pettersson et al. 1999), will be used to identify cereal cultivars that produce the highest levels of stress induced activators and those showing greatest response to activators by turning on their defence systems.

Previous work at Rothamsted has demonstrated that female aphid parasitoids respond strongly to aphid sex pheromones when actively foraging for hosts. This pheromone is currently under commercial production but its effectiveness when deployed over much larger spatial scales needs to be investigated, especially when integrated with habitat manipulation strategies. Thus, semiochemicals will be incorporated into the 'scale of adoption' field trials outlined above.

Bio-Economic modelling

Pest management incorporates important **feed-back mechanisms between natural and social systems**. Any theory or argument about how pest control can be implemented, improved upon and scaled-up requires an implicit or explicit quantitative model which embeds both the natural and socio-economic drivers.

The **modelling** in this project has two main functions. First, it will facilitate an obvious avenue of research that requires ongoing and closing interaction between economics and science. Second, the bio-economic modelling will be used to examine issues of scale, providing a tactical tool combining economic and ecological metrics aimed at optimising semiochemical and habitat management strategies for pest control.

Socio-Economics

The socio-economics work will use key results from the natural science field studies in the characterisation of the **problem faced by adopters during technology roll-out** in order to quantify the private costs of adoption. Key results from the field studies will also be used to design the choice sets offered to survey respondents in all of the proposed choice modelling exercises.

The work will then consider the requirement for action off-farm to promote on-farm adoption. We will also use results from the scaling field studies to consider the dynamics of this requirement by considering the potential that private costs of adoption might fall as adoption rates increase.

The social science research component within this project will perform four important functions. The **first** of these is to provide a **conceptual model of the technology adoption process** specific to the case of the commercial replacement of pesticide technologies with alternative biocontrol techniques. **Secondly**, primary research will be conducted to **characterise and identify potential early adopters of bio-control**, to quantify the potential benefits to society of the widespread adoption of biocontrol and to identify the private costs, and the structure of these costs, of adoption at different phases of technology roll-out. **Thirdly**, in combination with appropriate natural scientific input, the **design of**

appropriate policies to promote wide-scale commercial adoption of biological control will be considered. **Fourthly**, we will assess the **feasibility of marketing reduced-pesticide food products** to achieve a domestic price premium as a signal to potential adopters of biological control. Output from each of these modules will provide input into the bio-economic modelling component discussed above.

(a) Technology Adoption

The **technology adoption** study will be accomplished using an extensive **review of the literature** on the economics of technology adoption and technology replacement. This review will be used **in combination with Case Studies** of adopters of biocontrol in protected glasshouse systems. The output of this component of the work will be **a conceptual model** to identify the likely key barriers to adoption that must be addressed before widespread commercial adoption is perceived to be viable by farmers. This conceptual model will then be used to **steer the nature of the scientific research required** to promote commercial adoption of bio-control technologies.

(b) Experimental Economics

Experimental economics, using **Choice Modelling**, will be used to assess the importance of potential impediments t o the adoption of bio-co ntrol faced by potenti al adopters. Attributes of specific interest here include farmer attitudes to risk related to pest control inputs, to production and market risk, operator heath risks, and aspects of optimal knowledge assimilation mechanisms required for successful implementation of bio-control.

In addition, **Antle's (1987) methodology** for the assessment of farmer **risk preferences** will be applied to verify some of the above results. Research into the risk preferences of farmers will allow the scientific community to target potential commercial early adopters. Such controlled piloting of bio-control technologies in a commercial setting is likely to prove fruitful in driving down the fixed costs faced by subsequent adopters as a new technology is rolled-out, thus generating dynamic gains to adoption.

We also intend to consider the possible impact of such schemes as the Environmental Stewardship Entry Level Scheme (DEFRA) as a vehicle for reducing farm revenue volatility in combination with conservation bio-control techniques. Where necessary we would envisage submitting suggestions to DEFRA to modify such schemes in the light of our analysis.

(c) Market Research

The Centre for Food Chain Research (CFCR), Imperial College London, will be responsible for conducting the market research with consumers and retailers, using a **combination of qualitative and quantitative research**. Qualitative research will take the form of **semi-structured interviews** with representatives of the major food retailers and **focus groups** with consumers. Quantitative research will take the form of **a consumer survey**, using a nationwide panel of food consumer, to identify the stated preferences of different consumer segments (male/female, older/younger richer/poorer) for reduced-pesticide foods. These **stated preferences** will be compared with revealed preference information collected through a series of **store trials**, in which actual purchasing behaviour is recorded.

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2008/R/PES/801
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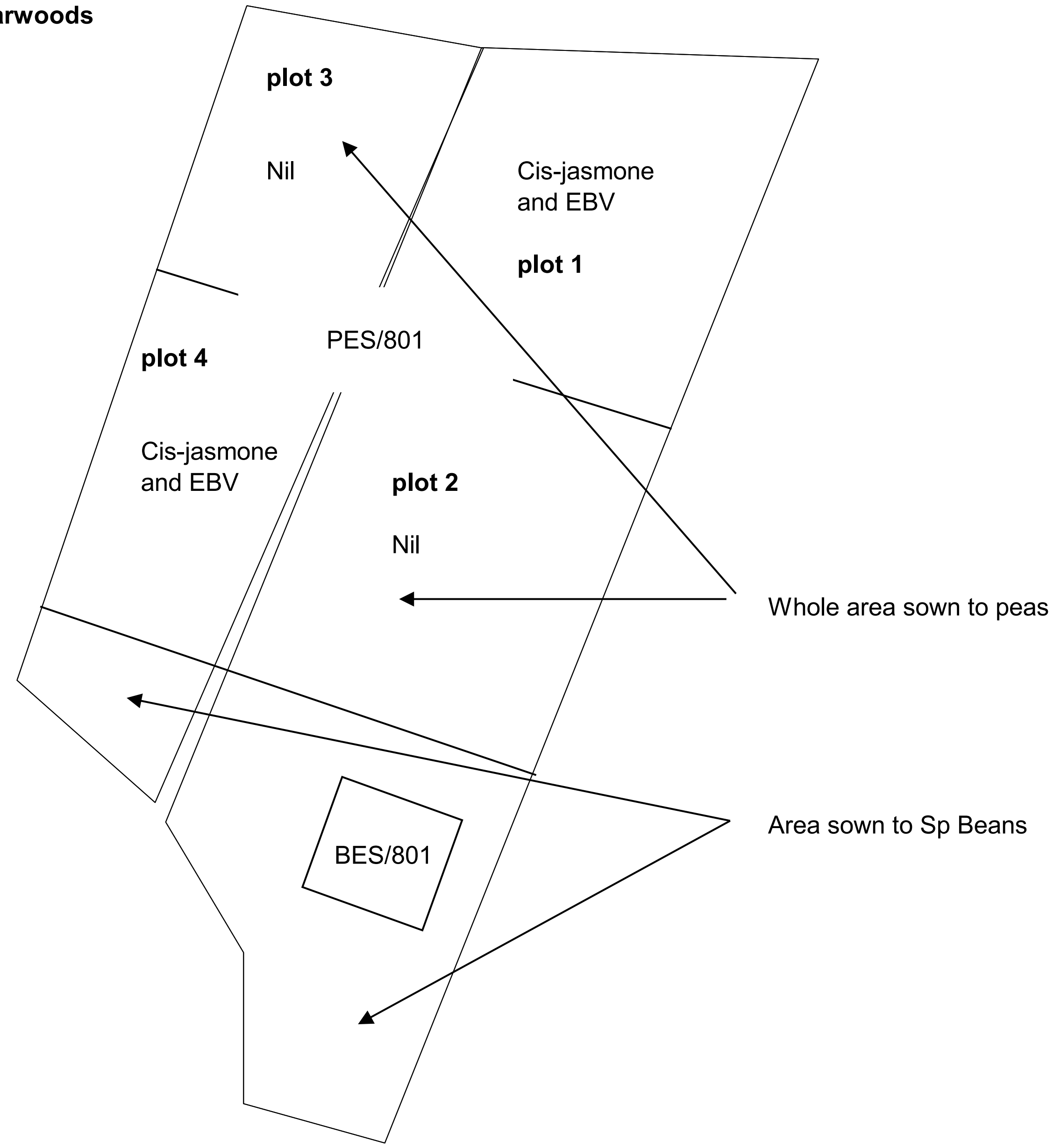

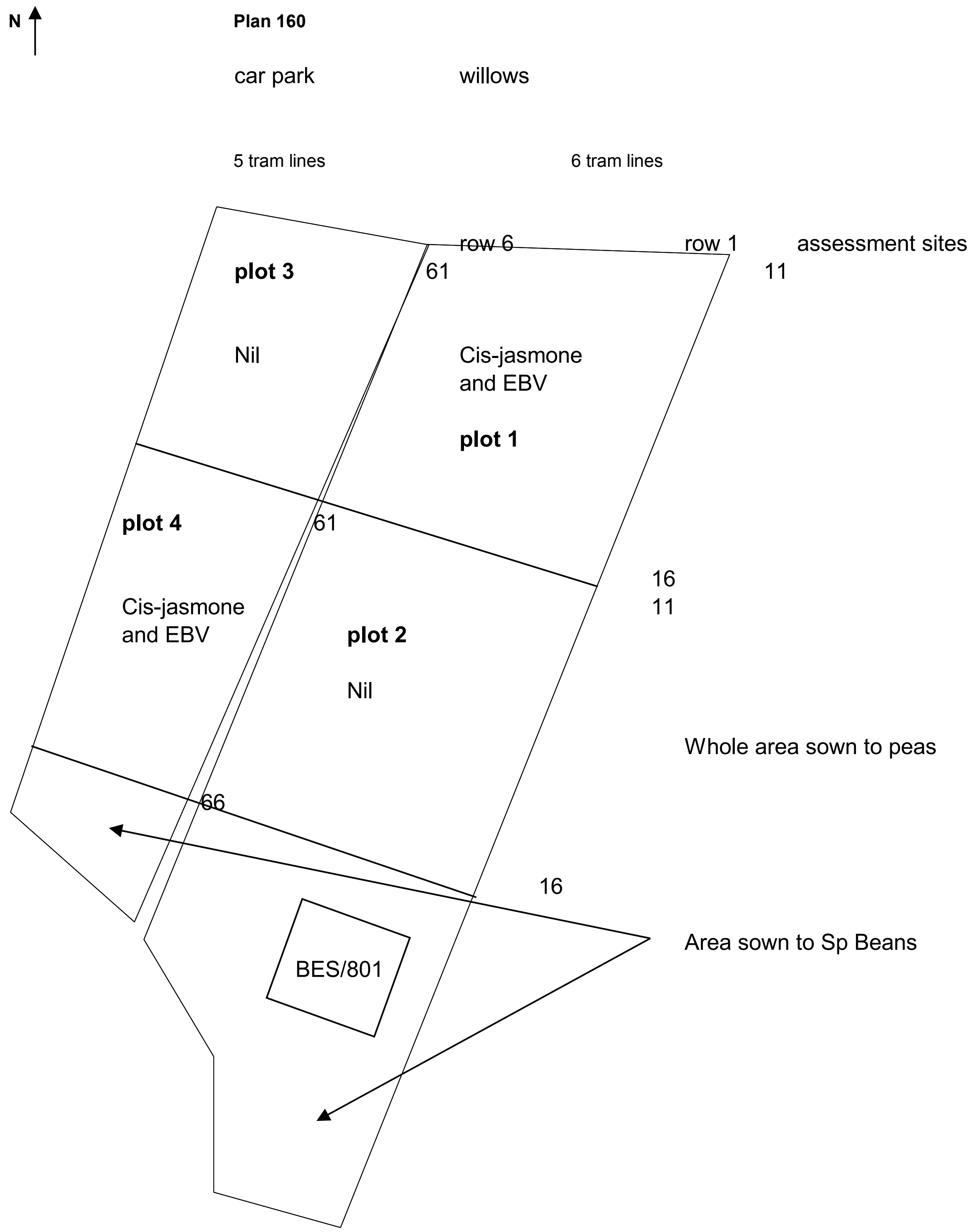

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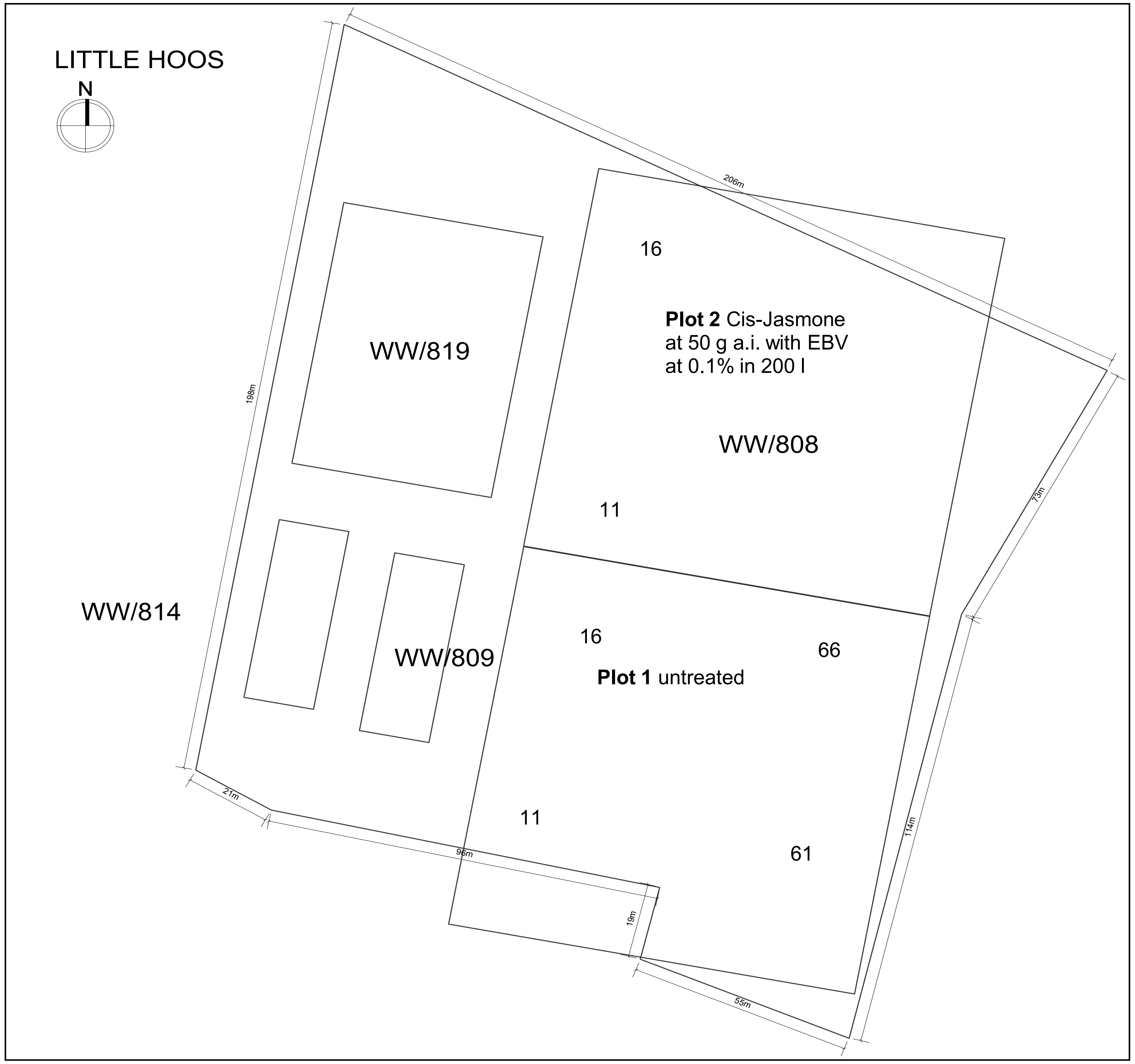
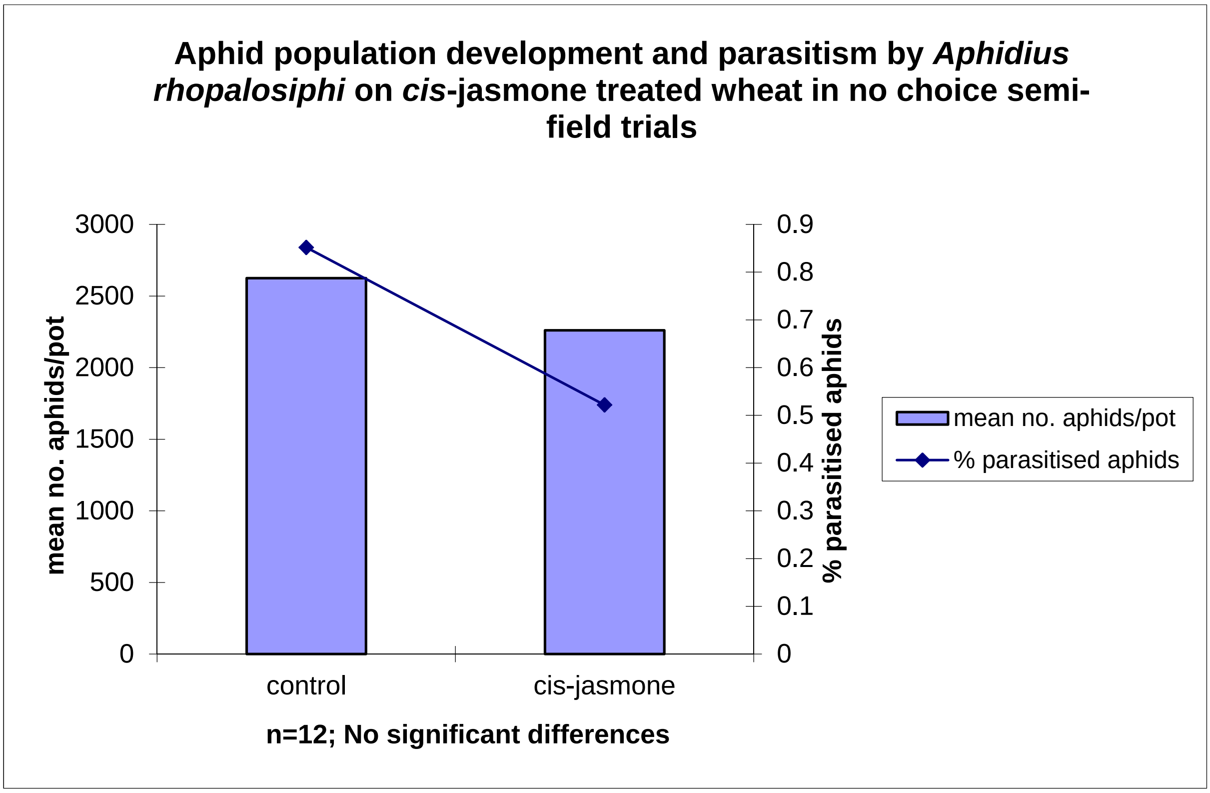
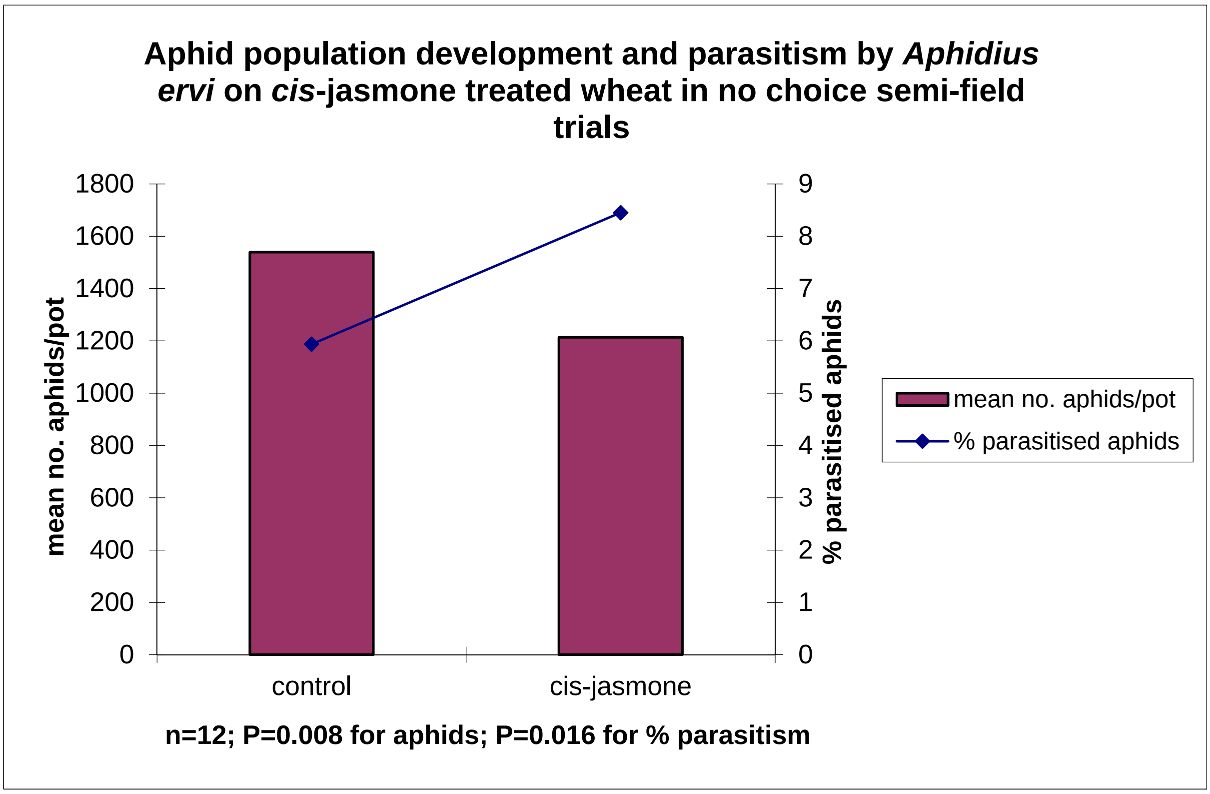


6x6 grid of sampling sites in each plot
ca 12m apart following tram lines

11 = row 1 site 1 for sampling

From arena_trials.xls (sheet 3)





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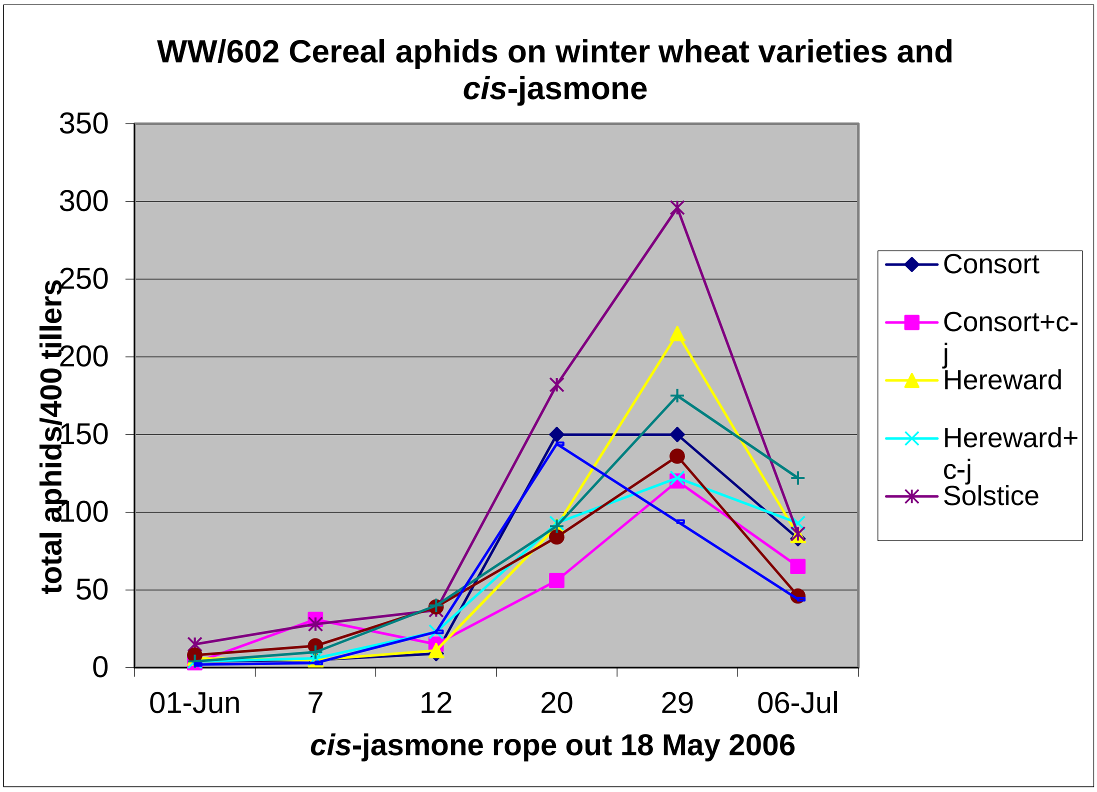

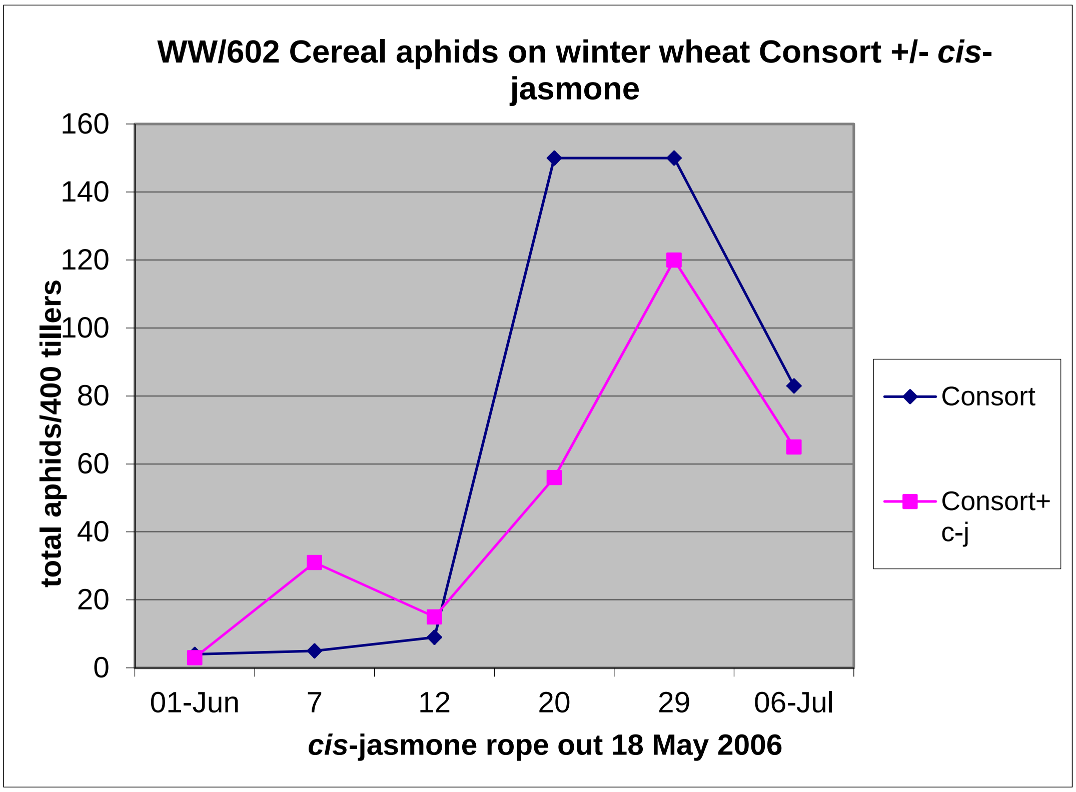

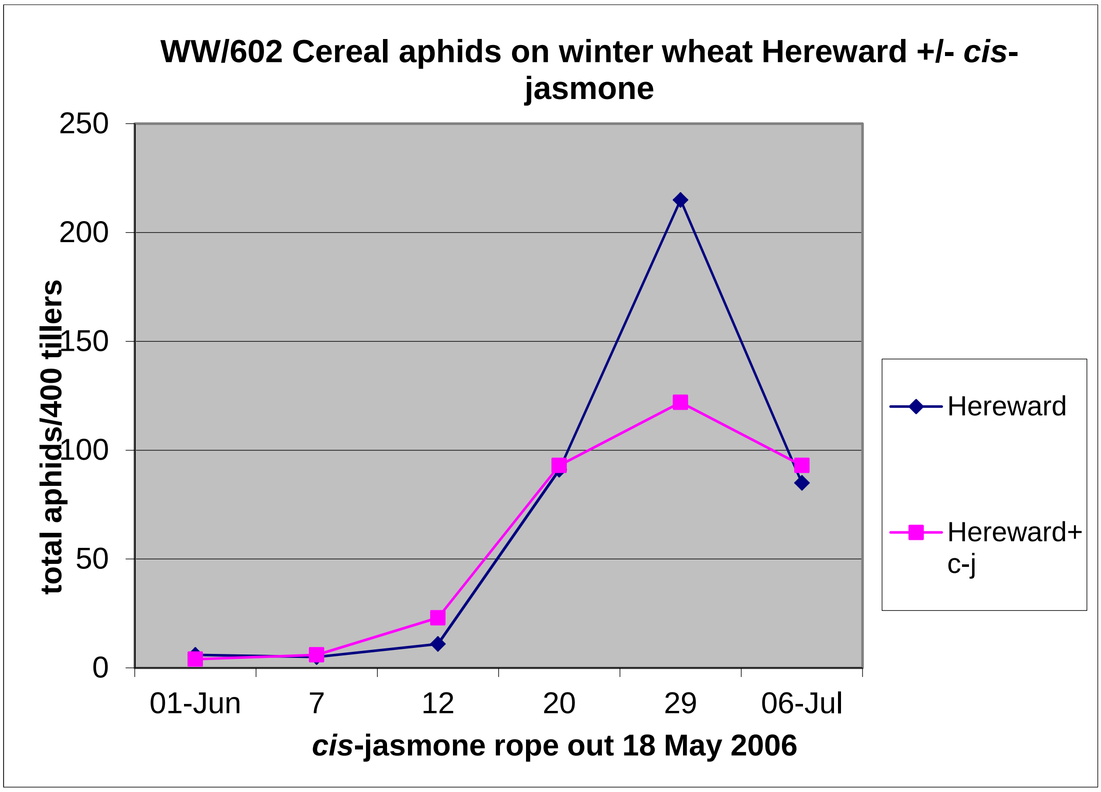
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06-Jul
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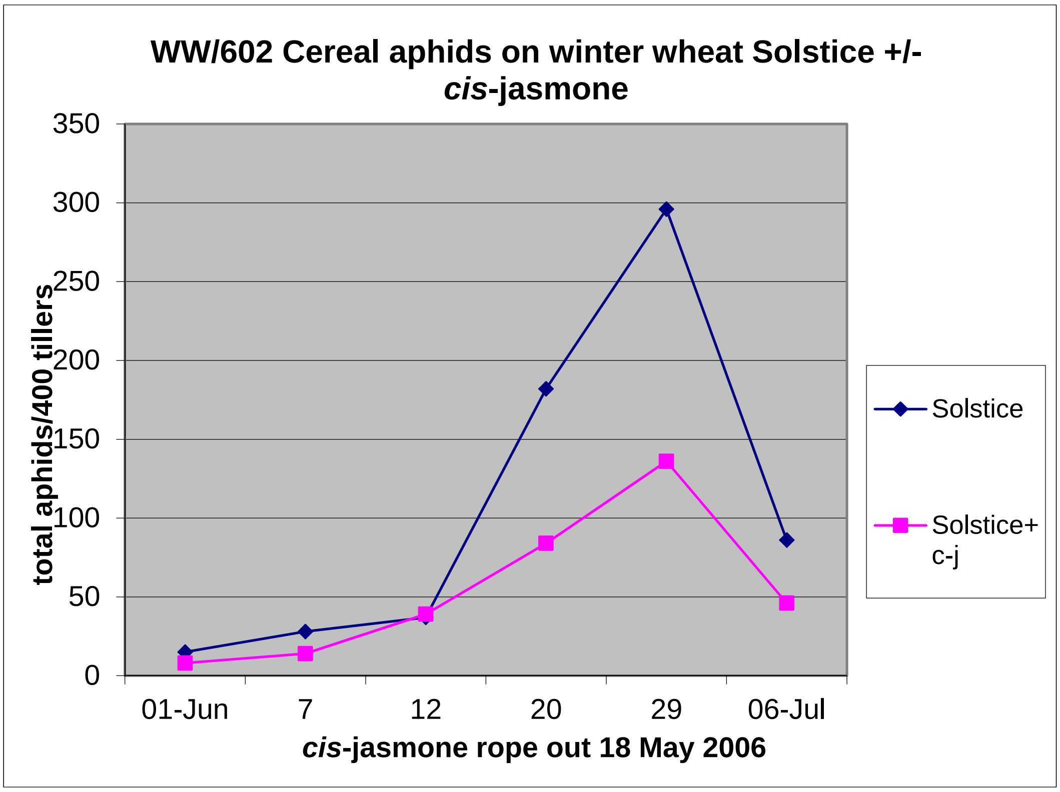
Hereward
Hereward+ c-j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06-Jul
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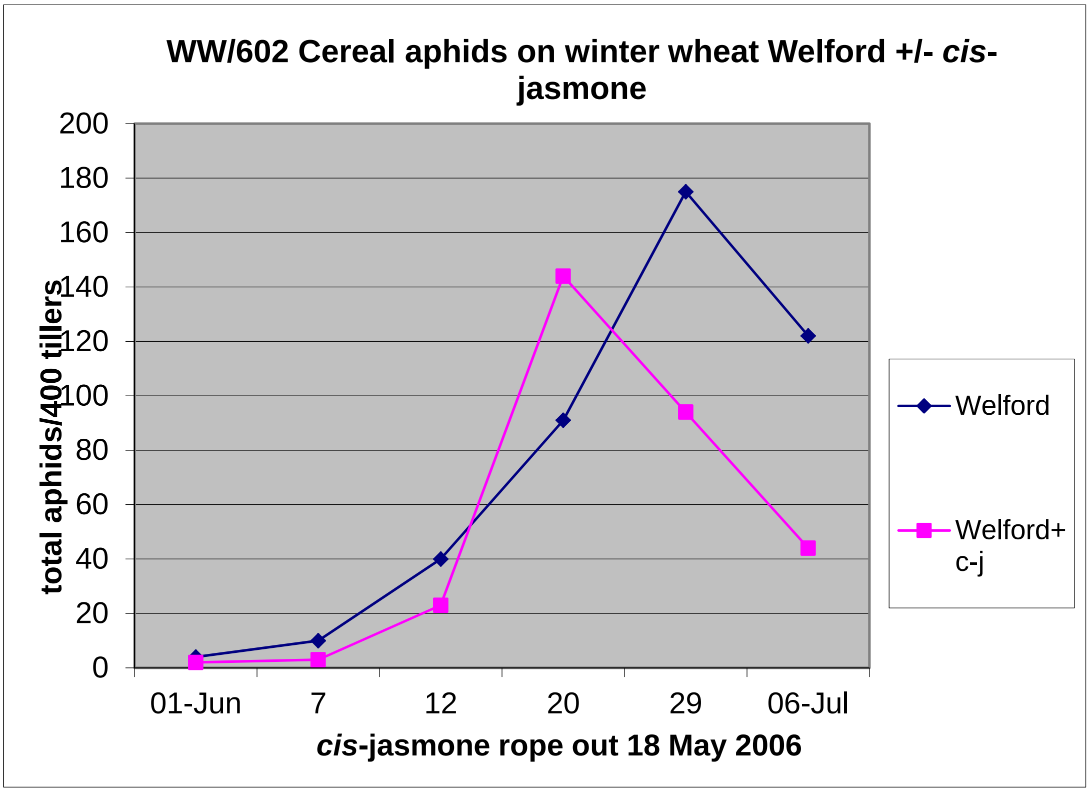
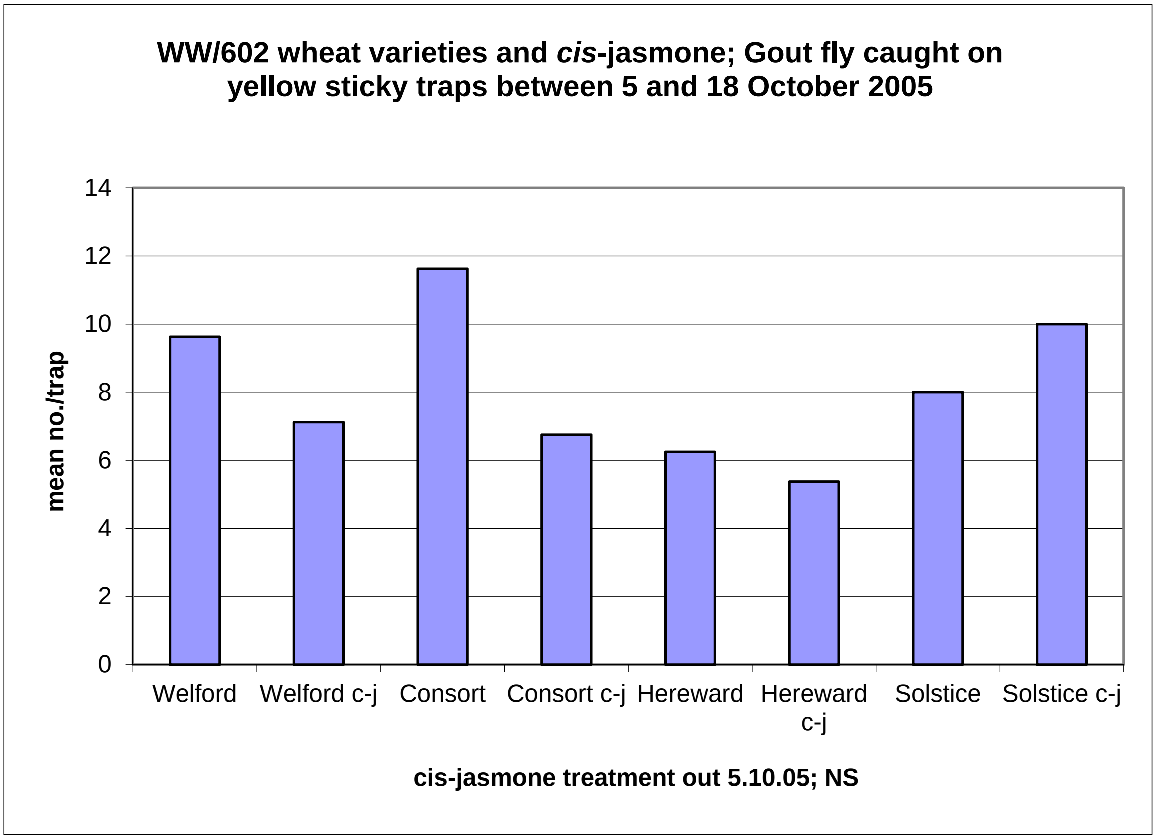
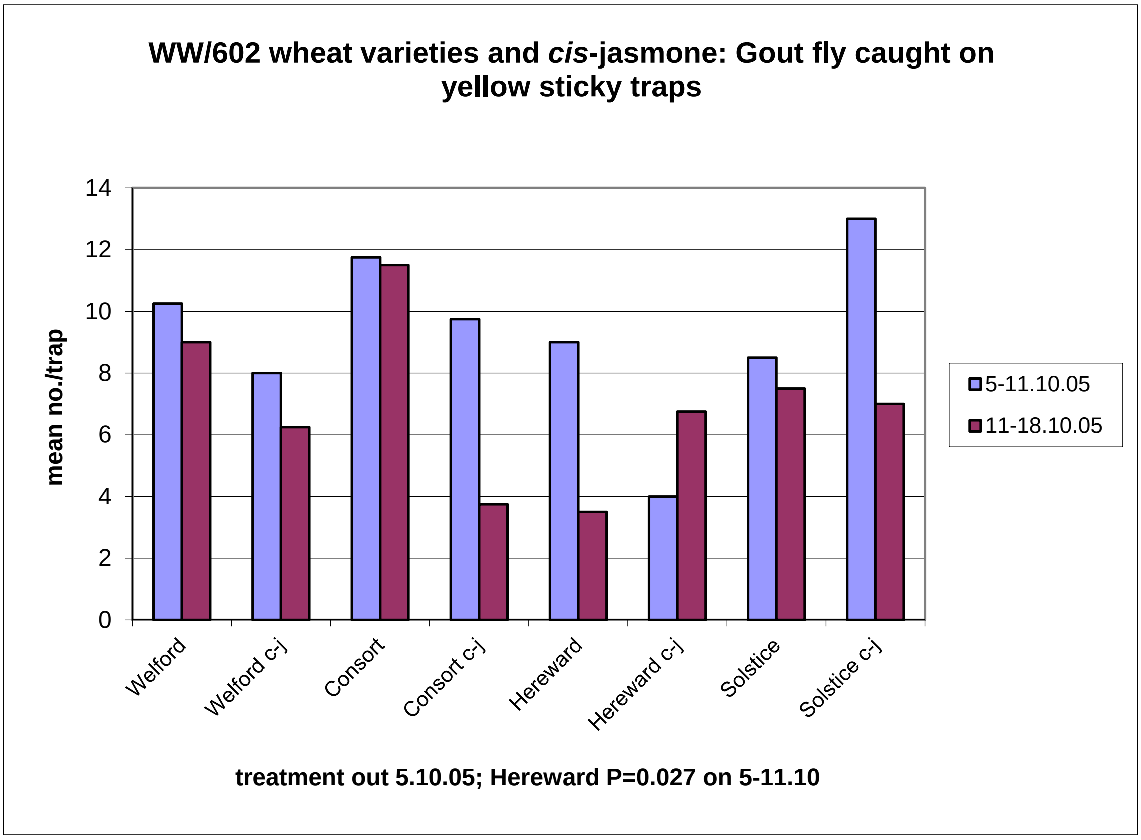
Solstice
Solstice+ c-j



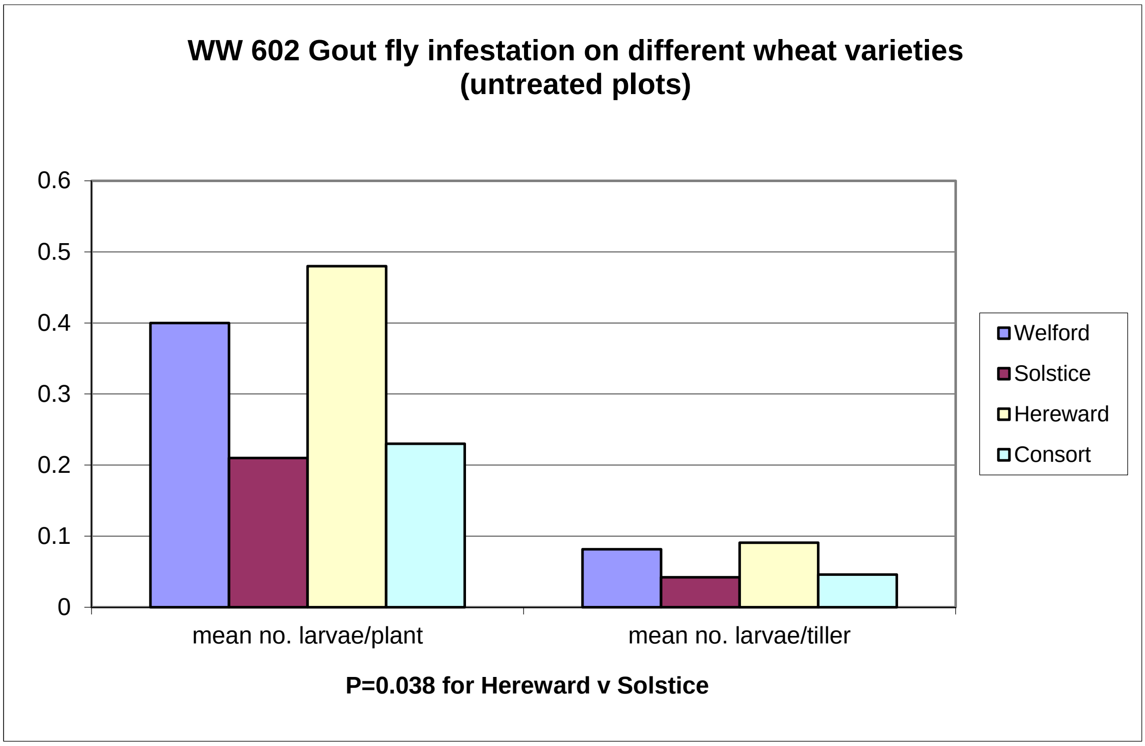
WW/602 Cereal aphids on winter wheat Welford +/- cis-jasmone
total aphids/400 tillers
200
180
160
140
120
100
80
60
40
20
0
01-Jun
7
12
20
29
06-Jul
cis-jasmone rope out 18 May 2006
Welford
Welford+ c-j

From field_trial_2006_cis-jasmone_varieties_06ww602.xls (sticky traps)

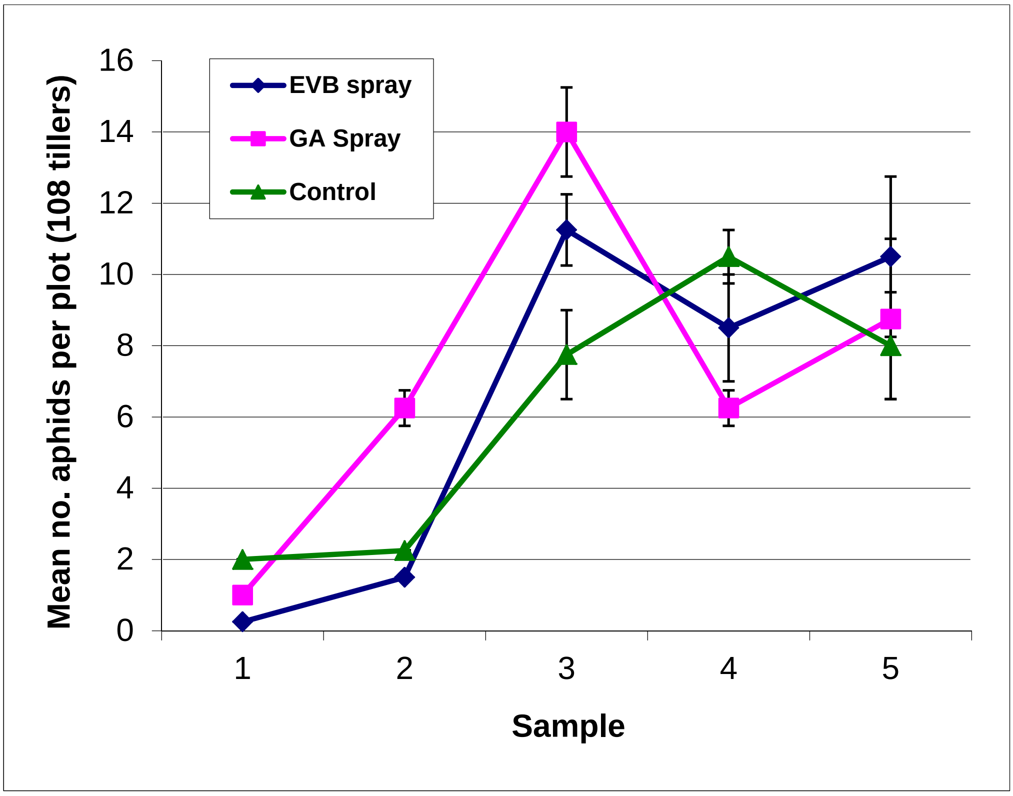


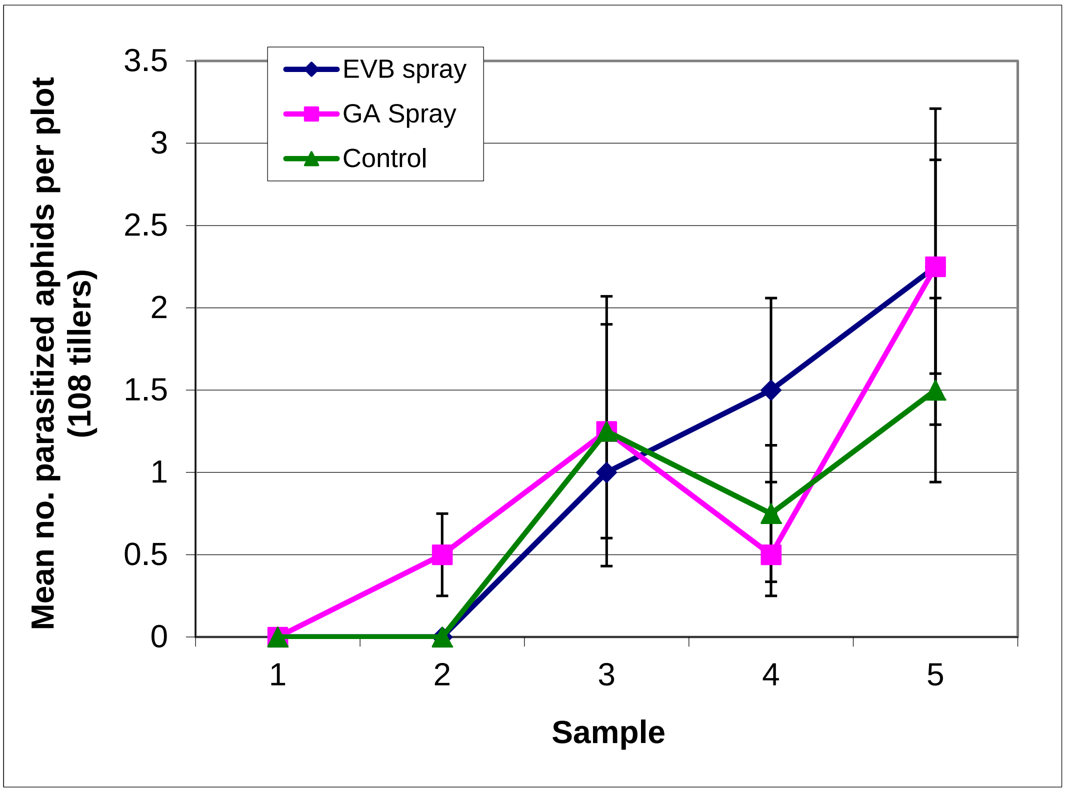


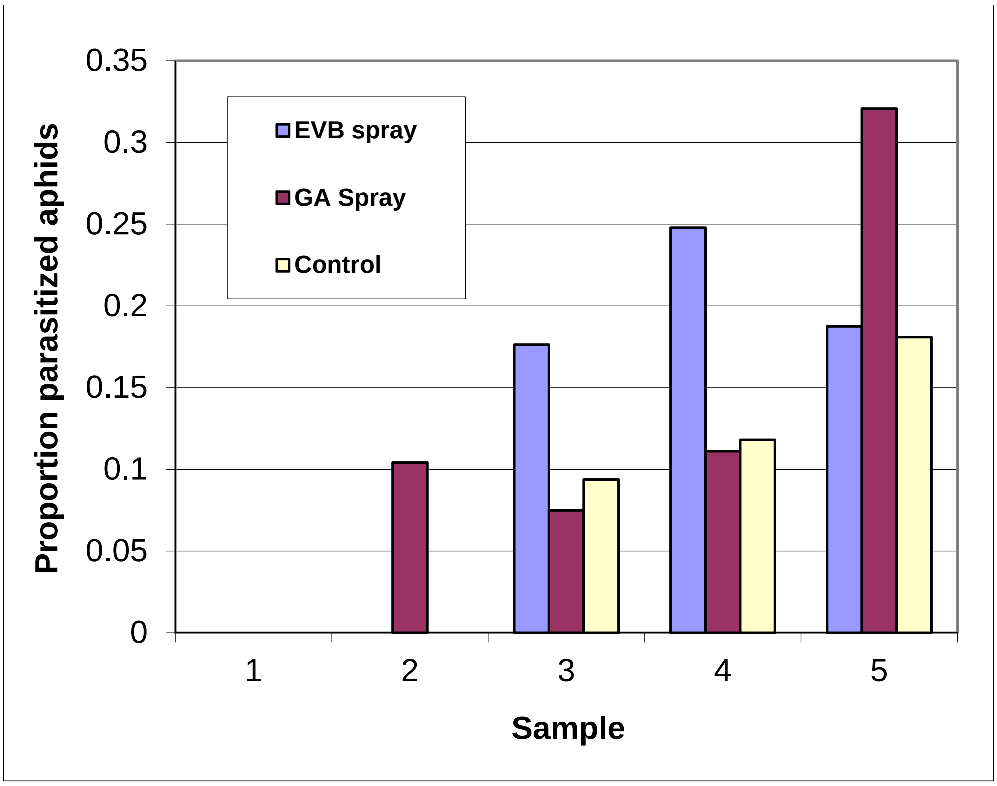
From field_trial_2006_cis-jasmone_varieties_06ww602.xls (gout fly)



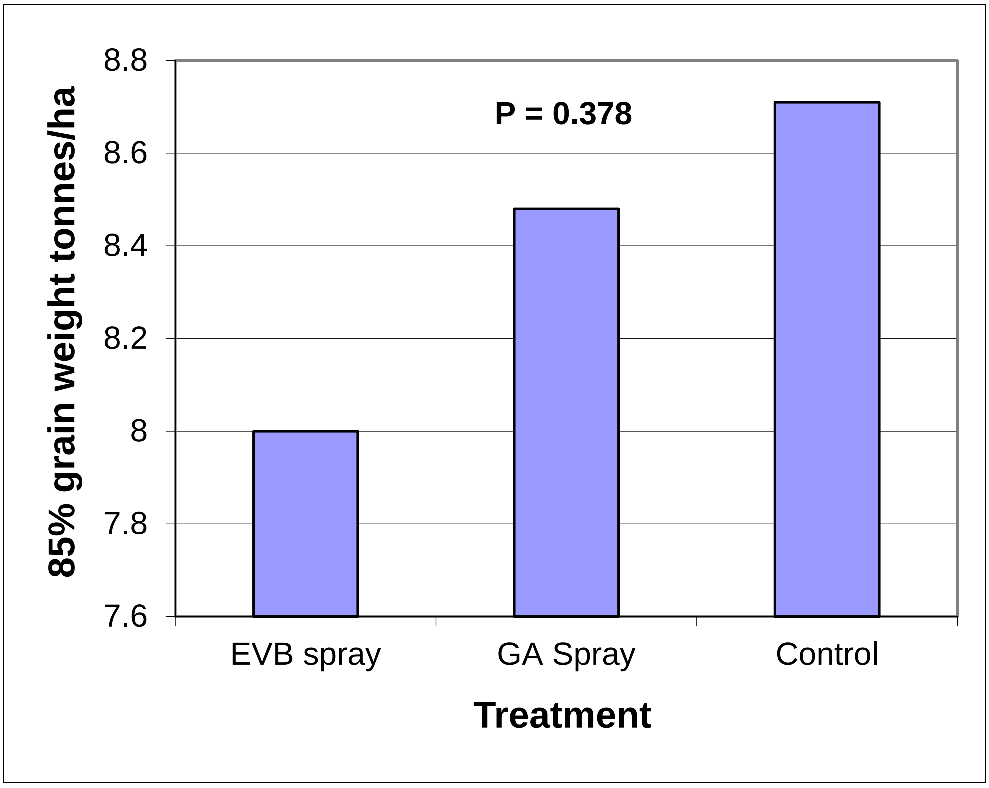
From field_trial_2007_cis-jasmone_adjuvents_07_r_ww_714.xls (summary)





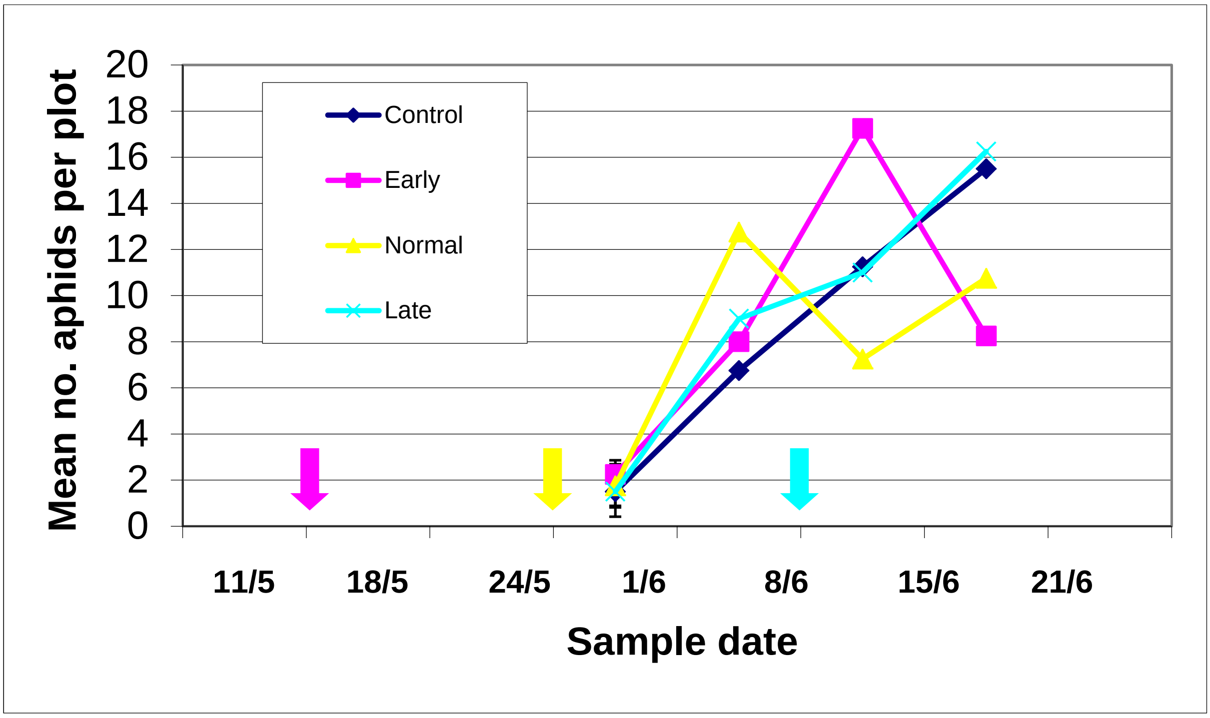


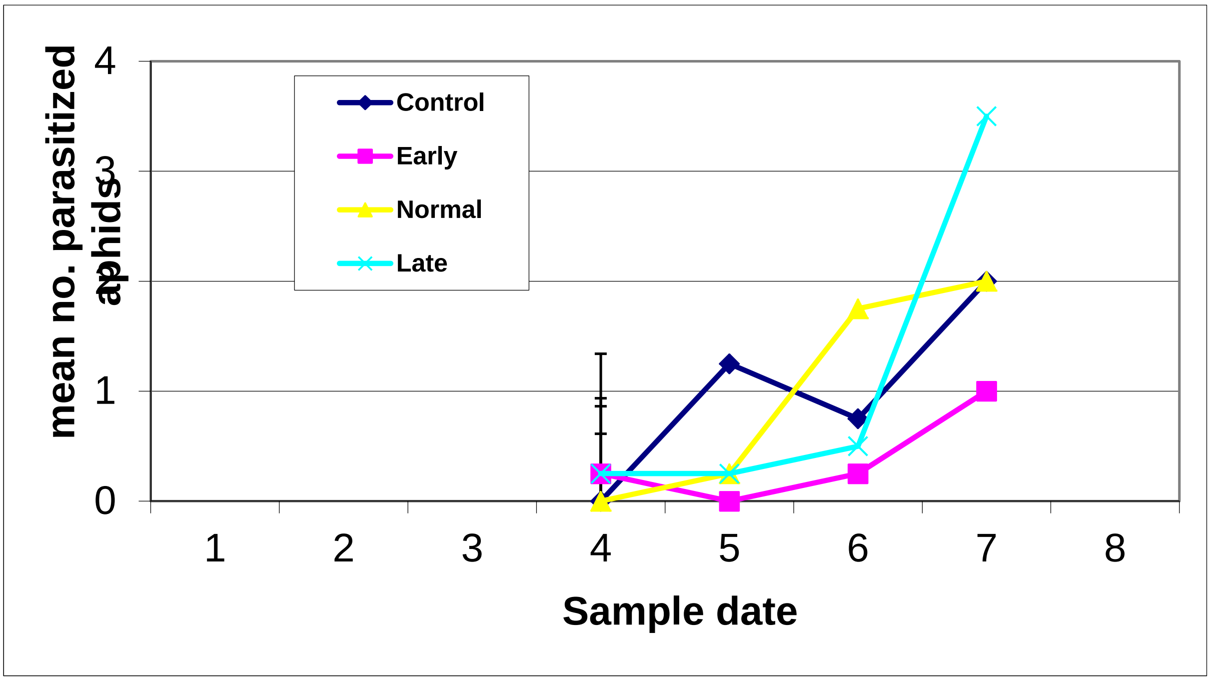
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Proportion parasitized aphids
EVB spray
GA Spray
Control
1
2
3
4
5
Sample

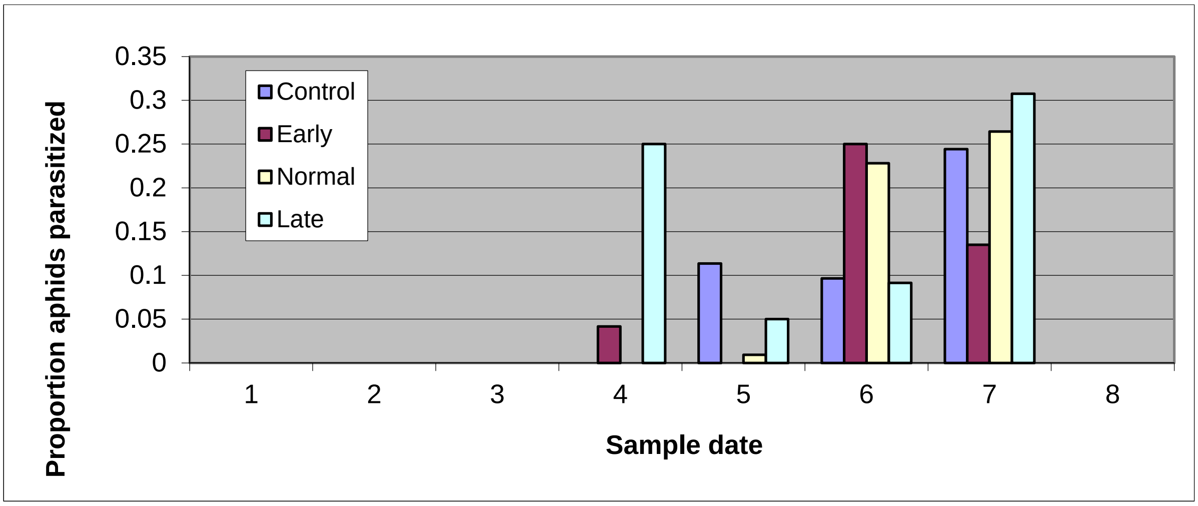


8.8
8.6
8.4
8.2
8
7.8
7.6
85% grain weight tonnes/ha
P = 0.378
EVB spray
GA Spray
Control
Treatment

From field_trial_2007_nepetalactone_timing_07_r_ww_715.xls (summary)

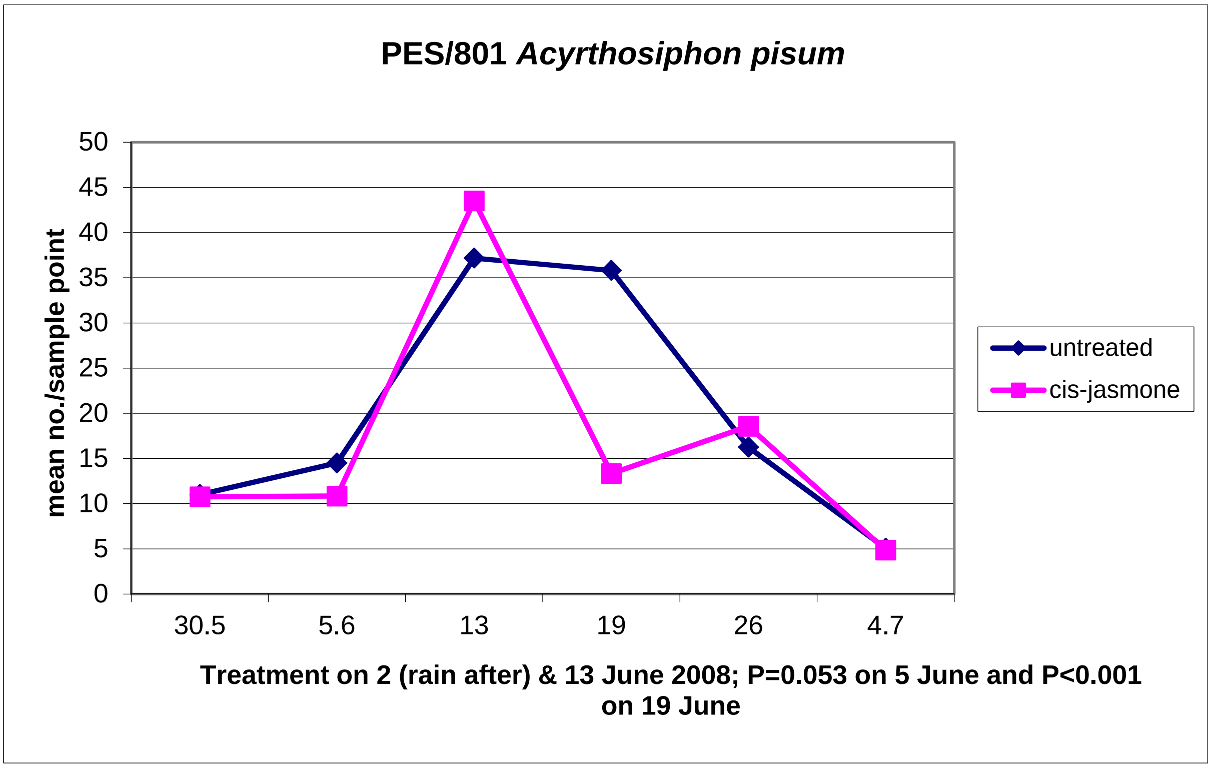


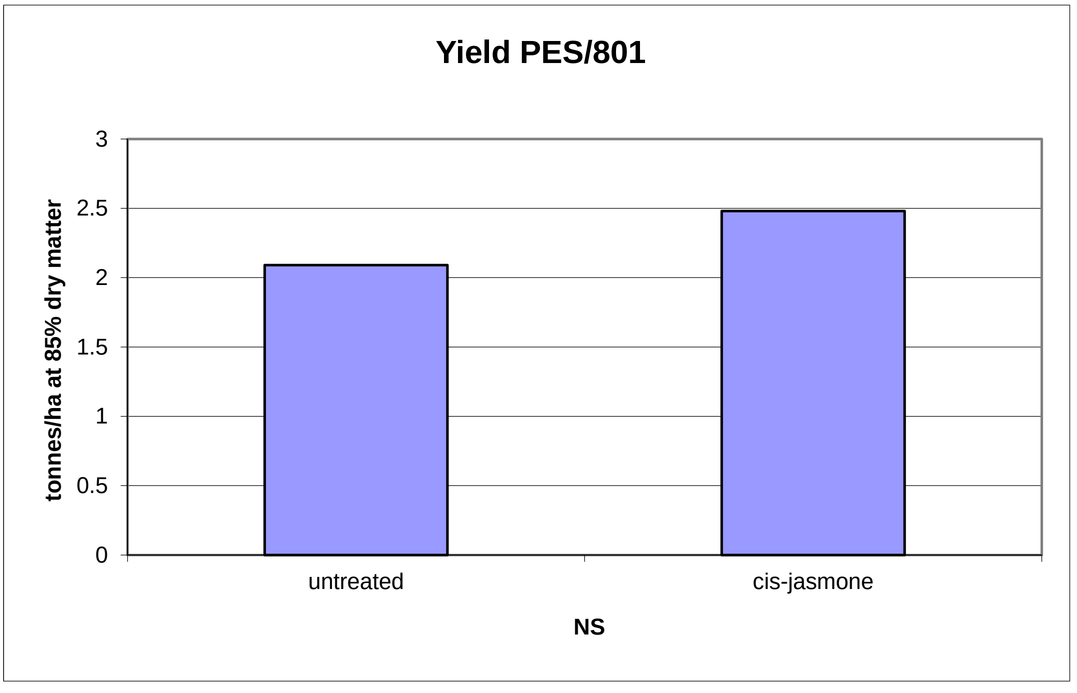




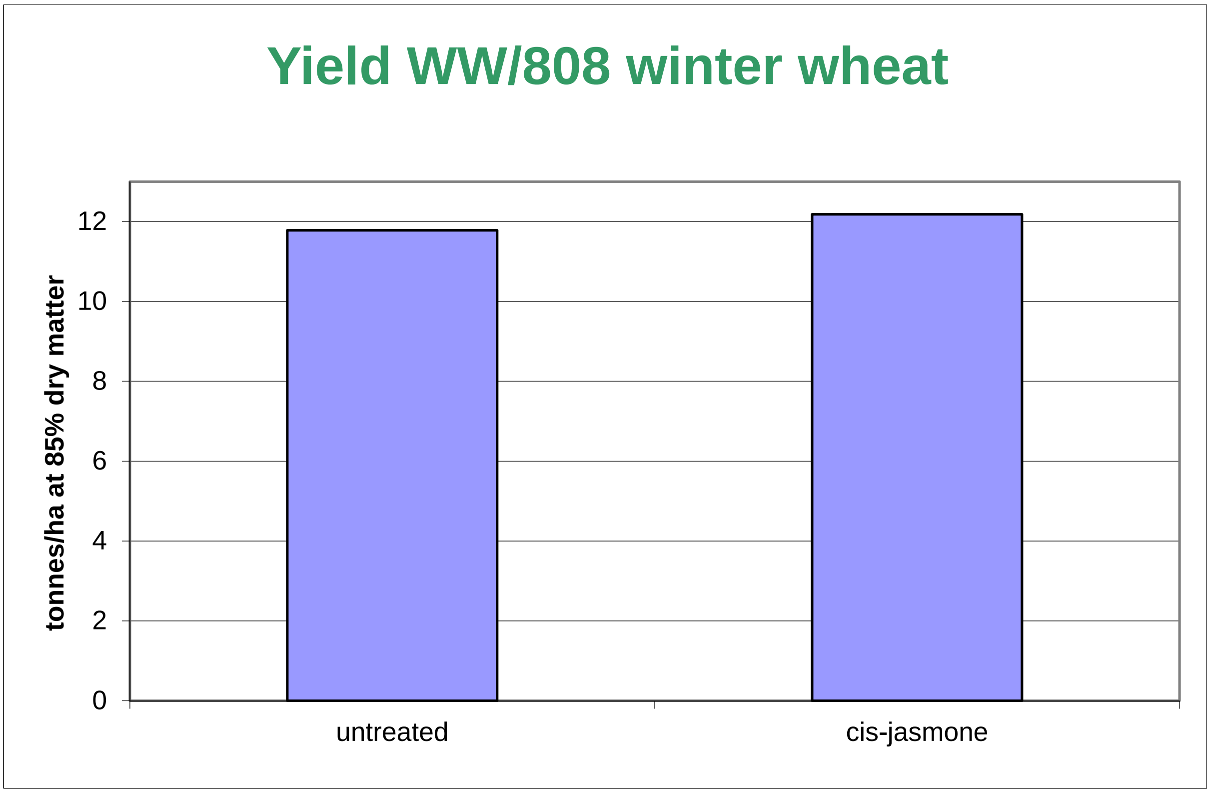
Proportion aphids parasitized
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Control
Early
Normal
Late
1
2
3
4
5
6
7
8
Sample date

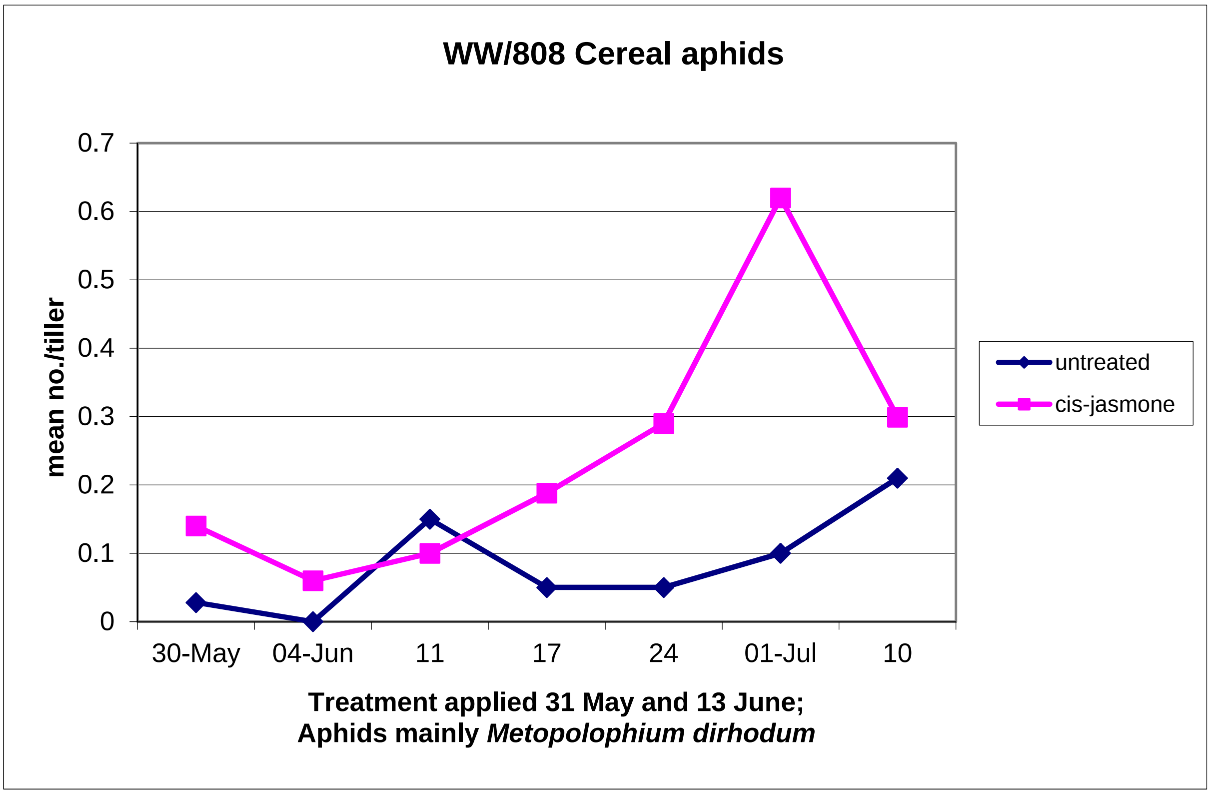
From field_trial_2008_cis-jasmone_and_peas_pes801.xls (graphs)

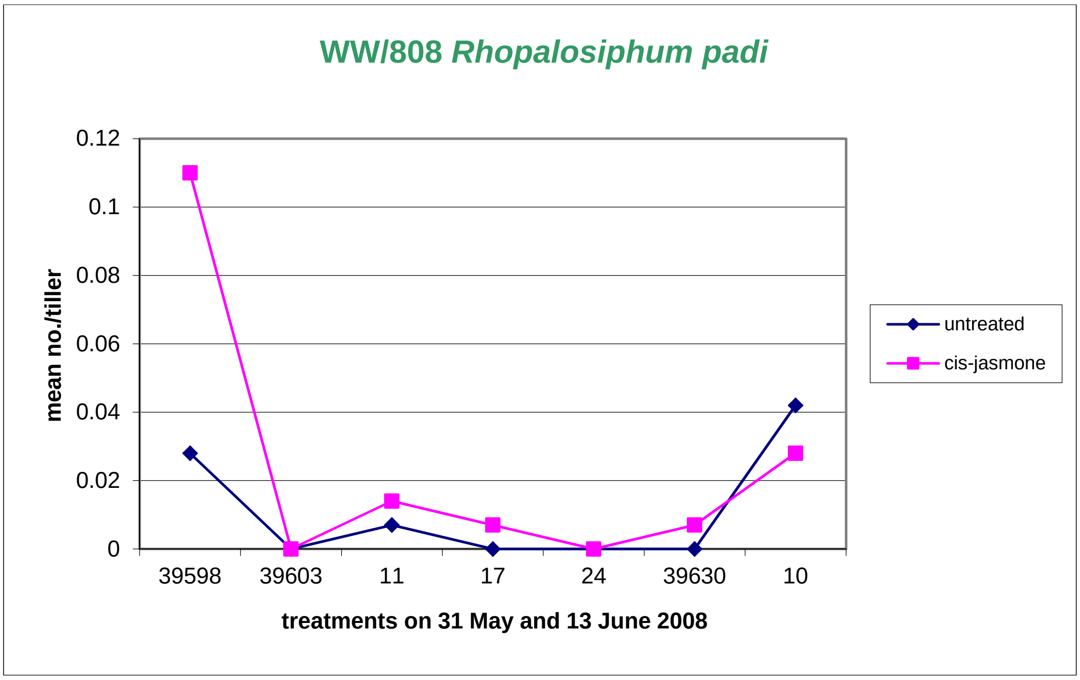


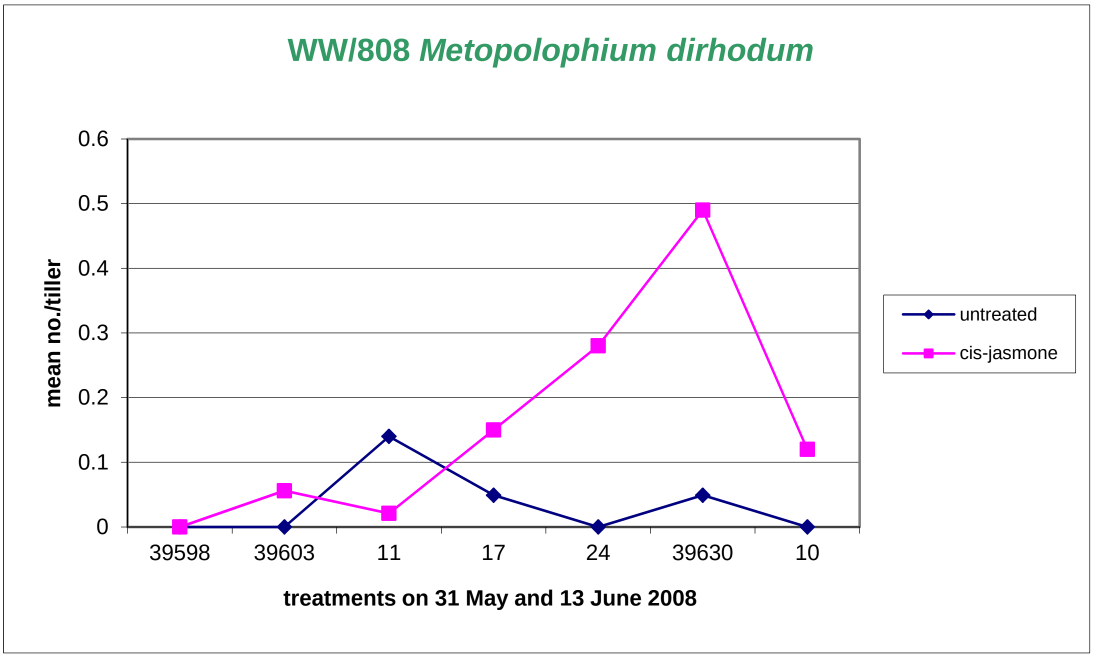


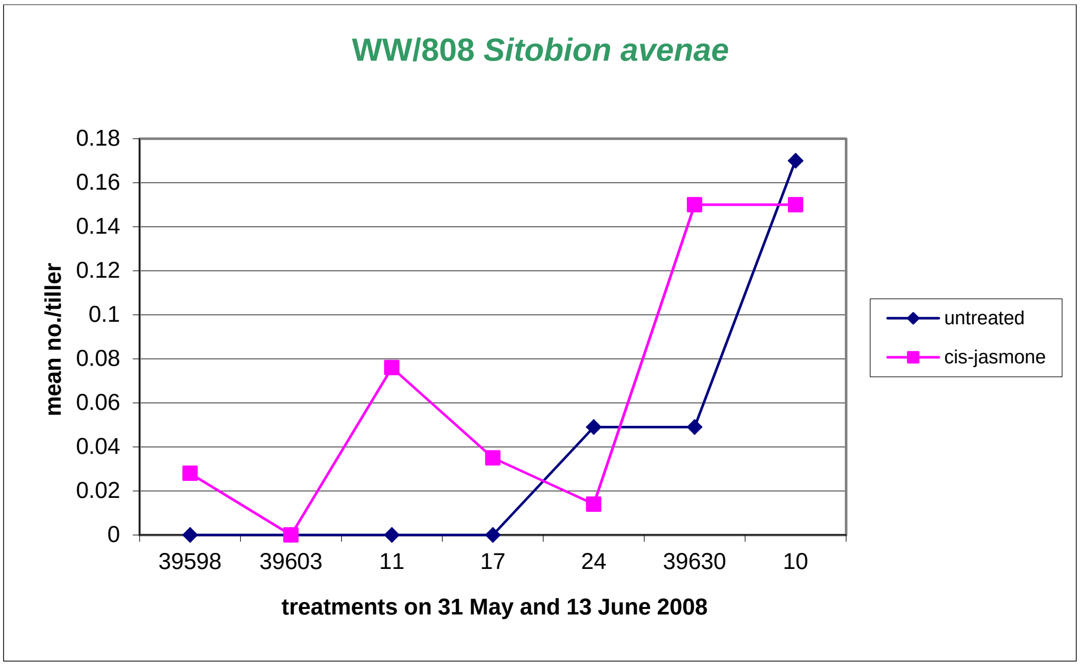
From field_trial_2008_cis-jasmone_and_wheat_ww808.xls (count 10.7.08)






WW/808 Rhopalosiphum padi
mean no./tiller
0.12
0.1
0.08
0.06
0.04
0.02
0
39598
39603
11
17
24
39630
10
treatments on 31 May and 13 June 2008
untreated
cis-jasmone


WW/808 Metopolophium dirhodum
mean no./tiller
0.6
0.5
0.4
0.3
0.2
0.1
0
39598
39603
11
17
24
39630
10
treatments on 31 May and 13 June 2008
untreated
cis-jasmone


WW/808 Sitobion avenae
mean no./tiller
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
39598
39603
11
17
24
39630
10
treatments on 31 May and 13 June 2008
untreated
cis-jasmone

From parasitoid_foraging_trial.xls