Project title	Organic tomato: Development and implementation of a robust IPM programme
Project number:	PC 240
Project leader:	Dr P Morley, Wight Salads Group Dr R. Jacobson, IPM Consultant.
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Key words:	tomato, organic production, IPM, *Macrolophus caliginosus*, mealybugs (*Pseudococcus viburni*), woodlice, spider mites (*Tetranychus urticae* and *T. cinnabarinus*), glasshouse whiteflies (*Trialeurodes vaporariorum*), leafminers (*Liriomyza bryoniae*), parasitic nematodes, *Atheta* spp., chitin, *Dysdera* spp., garlic, *Diglyphus isaea*, *Dacnusa sibirica*, open rearing systems, natural pyrethrins, Thripstick 2, *Phytoseiulus persimilis*, Ferramol pellets

The results and conclusions in this report are based on investigations conducted over a four-year period. The conditions under which the experiments were carried out and the results have been reported in detail and with accuracy. However, because of the biological nature of the work it must be borne in mind that different circumstances and conditions could produce different results. Therefore, care must be taken with interpretation of the results, especially if they are used as the basis for commercial product recommendations.

AUTHENTICATION

We declare that this work was done under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

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CONTENTS

GROWER SUMMARY

Headlines

- Robust IPM control programme developed for organic tomato crops.
- Overall expenditure on IPM products in organic crops reduced by over 50%.
- *Macrolophus* damage prevented by application of natural pyrethrins.
- New physical methods of preventing mealybug establishment.
- Added value gained by recycling biocontrols.

Background and expected deliverables

The overall aim of the project was to develop and implement a robust integrated pest management (IPM) programme to provide reliable results in large-scale organic tomato crops. The specific objectives were to develop a suite of compatible primary and secondary control measures for each of the following pests: *Macrolophus*, mealybugs, woodlice, spider mites, glasshouse whiteflies, leaf miners and russet mites.

The work plan was designed to make the most cost-effective use of all the resources available. It can be broken down into four categories:

- **Information gathering**: Apart from regular monitoring of the scientific and horticultural literature, the project benefited from the Project Leader's participation in the International Biological Control Organisation, International Biocontrol Manufacturer's Association and Association of Applied Biologists' Biocontrol Subgroup, as well as his involvement in many other related projects.
- **Small-scale preliminary studies:** The Project Leaders tested a wide range of potential control measures in small-scale cost-effective studies before embarking upon more expensive experimentation. This aspect of the work plan remained flexible so that newly reported products / techniques could be quickly drawn into the work programme. Subsequent studies were allowed to evolve to take into account findings as they occurred. Where appropriate, more detailed studies of the biology and behaviour of invertebrates, or biocontrol production systems, were done under tightly controlled conditions by collaborators.
- **Crop-scale evaluations:** There were no experimental glasshouse facilities in the UK dedicated to organic production on the required scale, so the proposed work was done in commercial crops. This created some new challenges in terms of experimental design and analysis of data but these were not insurmountable. Furthermore, there were considerable benefits associated with this approach:

    - It was not necessary to grow crops dedicated to this project, which provided a substantial saving to the overall budget.
    - It was not necessary to have a "further exploitation" phase to transfer the results from the experimental to the commercial situation.
    - Each study was part of a whole organic system, which highlighted any impact on other important aspects of agronomic practice.
    - The crops benefited from the day to day input from specialist organic tomato crop growers and agronomists.
- **"Spin-off" projects:** Where appropriate, the Project Leaders facilitated spin-off projects to generate additional funding to address specific issues that required resources and / or expertise that were not available within the project team.

Summary of the project and main conclusions

General:

A preliminary survey to determine the susceptibility of over 30 speciality tomato cultivars to the major pest species was completed at the start of the project. The cultivars were continually monitored to fine-tune the classification and to guide appropriate adjustments to IPM strategies. In addition, a spin off project was organised to investigate the underlying reasons for the differences in pest development rate on these cultivars (PC 272).

***Macrolophus*:**

- A reliable method of monitoring populations of *Macrolophus caliginosus* was developed to aid decisions on control timings and to enable the control measures under trial to be properly evaluated.
- A new method was developed for reducing the size of the *Macrolophus* population after other pests had been controlled but before plant damage occurred. This was based on natural pyrethrins (as Pyrethrum 5EC), which are extracts from African chrysanthemums (*Chrysanthemum cinerarifolium*). A SOLA was obtained to allow more flexibility in its application to mature organic tomato crops. This method of "culling" the predator population has since been successfully implemented in over 12ha of commercial organic crops and has also been adopted by many conventional tomato growers.
- A novel method was developed for collecting *Macrolophus* from areas of surplus for release elsewhere. It was shown that *Macrolophus* with a value of over £200 could be collected with an expenditure of only £8 on labour. This technique was also built into the new IPM programme for AYR tomato crops (PC 251 / 251a).

Mealybugs:

- Mealybugs have become the most difficult pest to control within the IPM programme for organic tomato crops. More than twenty IPM compatible control measures or combinations of control measures that are acceptable in organic production have been evaluated against mealybugs in this and previous HDC funded projects. Many have shown potential when tested against individual mealybugs in the laboratory but have failed at the population level when trials have been scaled up in commercial crops. This has been due to a combination of the following factors:
    - The cryptic nature of the pests.
    - The protection provided by their waxy filaments.
    - Their resilience in returning to the plants after being knocked off by sprays.
    - The fecundity of survivors, which allows rapid resurgence of populations.
- Control measures based on parasitic nematodes, parasitc wasps and spray applications of Eradicoat T, Savona, steam and natural pyrethrins all proved to be inadequate.
- As there had been so much difficulty in achieving remedial control during the growing season, more emphasis was placed on minimising the numbers of mealybugs that survived between crops and successfully colonised the new plants. A new strategy was designed and successfully evaluated in 3ha of commercial crops. This led to the production of a mealybug control protocol for participating growers which has now been adopted on a much larger scale. In summary:
    - The programme began with a thorough clean-up in the empty glasshouse. This involved removing all crop debris, soaking irrigation pegs / laces in nitric acid, power washing irrigation lines and flaming the glasshouse structure with a hand lance.
    - The soil was completely covered with black-backed plastic to prevent light penetration and growth of volunteer tomato seedlings. The overlaps between plastic sheets were offset so that they were to the side of the bed rather than directly under the plants and all joints were sealed with Thripstick 2 (60% polyisobutylene).
    - Thripstick 2 was diluted with water (2:1) and applied to the concrete dollies, metal posts to a height of about 2.1m, dwarf walls around the periphery of the crop and the edge of the central concrete roadway. After the floor plastic had been positioned and sealed at the joints, a 300mm wide band of Thripstick 2 was sprayed down the centre of each bed.
    - The plants were stood out on plastic saucers immediately above the Thripstick 2 barrier. At planting, which varied from four to six weeks later, the hole cut in the plastic to receive the plant pot was kept to the absolute minimum size so that the treated plastic was still touching it. Lower leaves were removed as soon as possible

to reduce opportunities for mealybugs to find a green bridge across the sticky barrier. This was also important to aid monitoring and detection of the pest.

Woodlice:

- Several prophylactic methods of controlling woodlice were evaluated between 2005 and 2007. Chitin compost additives, a silicon-based desiccant dust, three species of parasitic nematodes (*Steinernema feltiae*, *S. carpocapsae*, *Heterorhabditis megidis*) and the predatory beetles, *Atheta* spp., all showed some potential in small-scale experiments but failed to provide adequate protection for commercial crops.
- A spin off project investigated the soil fauna in the glasshouses with particular emphasis on possible natural enemies of woodlice. While this provided valuable information, particularly about *Dysdera* spp. spiders, there were no immediate leads towards effective control measures.
- Small scale experiments in 2007 began to explore the potential of ferric phosphate pellets (Ferramol) to protect young plants from woodlice. These pellets are sold in various formulations for slug control in amateur and commercial organic crops. Larger scale trials in 2008 demonstrated that this was an effective control measure and the technique has now been adopted by commercial growers.

Spider mites:

- Studies compared the establishment of *Amblyseius andersoni* with standard and tomato pre-conditioned *Phytoseiulus persimilis* on tomato crops. A. andersoni and P. persimilis are both predatory mites that feed on red spider mites. One of the attractions of *A. andersoni* was its availability in culture packs, which offered potential for establishment before the pest was found. Unfortunately, the results indicated that *A. andersoni* was not suitable for use as a biological control agent on tomato plants.
- A desk study evaluated the cost-effectiveness of *Feltiella acarisuga* (a predatory midge which is a natural enemy of spider mites) on tomato crops. There seemed little doubt that natural migrations into tomato crops during the summer could make a significant contribution to the overall control of spider mites. However, the information collected showed inconsistencies in the results obtained with this predator when it was released earlier in the season. Furthermore, it is not compatible with *M. caliginosus (prey on whiteflies)*, which has since become an important component of the whole IPM package. Overall, there was little evidence to support expenditure on inundative releases of this predator in organic tomato crops.
- A new method was developed of collecting *Phytoseiulus* from areas of surplus in commercial tomato crops for release elsewhere. This enabled large numbers of high value tomato-reared *Phytoseiulus* to be collected with minimal labour input.

- A study in 2008 compared the cost-effectiveness of standard bean-reared *Phytoseiulus* and the more expensive tomato-conditioned product with the *Phytoseiulus* collected from areas of surplus. Given similar expenditure, the results indicated that the tomato-conditioned product would provide 4% more offspring than the standard bean-reared product after two generations. However, the population growth of the *Phytoseiulus* harvested from commercial tomato crops far exceeded both of these products. For example, it was calculated that after two generations the harvested *Phytoseiulus* would give rise to 70% more offspring than the tomato conditioned product.
- Our whole approach to IPM of spider mites could change to accommodate these findings. For example, the first releases of natural enemies in each season could not only be aimed at controlling those specific pest infestations but also be used to establish biocontrol cultures that can be harvested at a later date. On this basis, growers could greatly increase the numbers of *Phytoseiulus* released at the start of the season in the knowledge that their investment will provide savings at a later date.

Leafminers

- The leaf miner monitoring system and early season release strategies for *Diglyphus isaea* developed in LINK Project CSA2921 were re-assessed in the light of acquired experience and re-evaluated at the start of the 2006 growing season. The studies were successful and the number of *Diglyphus* released was substantially reduced compared to recent seasons. However, there was still unacceptable foliar damage to the more susceptible cultivars such as Piccolo and Campari.
- The final flush of leaf miner activity before control is achieved with *Diglyphus* consistently causes an unacceptable amount of foliar damage in the more vulnerable cultivars. Several means of either slowing down leaf miner development or speeding up *Diglyphus* establishment in these crops, were given consideration:
    - **Entomopathogenic nematodes** - When used as a second line of defence to support *Diglyphus*, *Steinernema feltiae*, contributed about 10-20% control of the leaf miners. The cost-effectiveness of this control measure within the overall IPM programme remains debatable and is unlikely to be widely adopted.
    - **Sterile insect technique** – Previous studies in the USA have indicated that this could be an appropriate technique to use against leafminers on tomato. Two spin off projects were initiated with MSc students at Imperial College to investigate the possibility of slowing down leaf miner establishment by releasing sterile males in the glasshouse at the start of the season. These projects paved the way for an HDC sponsored PhD studentship (CP53), which began in June 2008.
    - ***Diglyphus* open rearing systems** – The development of open rearing systems to enhance *Diglyphus* establishment was fraught with problems due to the difficulty in

keeping the leafminer / parasitoid cultures free of contamination on the commercial nursery. The work was terminated due to the successful outcome of other studies.

- ***Macrolophus* as a supplementary biocontrol** – *Macrolophus* couldn't previously be used against leaf miners due to the risk of serious damage being caused to the plants after the predator had controlled the pest. However, with the development of the IPM compatible remedial treatment for *Macrolophus*, it became possible to place greater emphasis on this predator as a component of the leaf miner control programme. Studies involving the release of purchased *Macrolophus* began in 2007 and were completed in 2008.
- ***Diglyphus* release strategy –** One obvious method of speeding up *Diglyphus* establishment is to release larger numbers at the correct time. The current release rates have been restrained by economics and there is an understandable reluctance by growers to spend more. However, it may be cheaper to do this than to suffer other consequences in the more susceptible cultivars. Furthermore, a new method was developed of collecting *Diglyphus* from areas of surplus for release elsewhere. This has enabled growers to recover their additional early season outlay on *Diglyphus* products.
- **An IPM programme** which utilised 1-2 *Diglyphus* per m^2 and 1-2 *Macrolophus* per m^2 was evaluated in 10,000m^2 of vulnerable tomato cultivars in 2008. This approach greatly reduced foliar damage by leafminers and there were additional benefits in terms of reduced expenditure on spider mite control.

Financial benefits

- The project has developed cost-effective solutions to the most important pest problems in organic tomato crops.
- Effective measures to control *Macrolophus* and mealybugs have already been successfully implemented in 12ha of commercial crops and the financial benefits, in terms of reduced crop loss, have exceeded £0.6m per annum.
- The biocontrol recycling techniques have yielded vast numbers of prime quality natural enemies, at very low cost, for redistribution elsewhere. For example, immediately after controlling a leafminer population, a 1000m^2 tomato crop may contain over £20k worth of *Diglyphus* for redistribution.
- The benefits of the new and refined control measures, combined with the novel methods of harvesting / redistributing biocontrols, reduced overall expenditure on IPM products in commercial organic crops by over 50%. This brought the costs in line with conventional tomato production.
- These benefits will be sustained and increased each year as the technologies become

more widely implemented.

- The new developments have made a major contribution to the economic viability of organic tomatoes in the UK and will help British suppliers satisfy the increasing demand from retailers for top quality organic products.
- The results are also having knock-on benefits to conventional tomato production.

Action points for growers

The new developments within this project have already been proven in commercial crops. By following the described techniques, growers should be able to make substantial savings. In particular:

- Damage by *Macrolophus* can be avoided by culling populations with a high volume spray of Pyrethrum 5EC (1 litre per 1000 litres of water) applied to the upper half of the plant canopy. Repeat sprays may be required at 4-5 week intervals.
- Mealybug plant invasion can be prevented at the start of the season by adopting a programme of complementary physical control measures. A protocol is available but growers may benefit from discussing the techniques with one of the project team who has first hand experience of the techniques.
- Young plants may be protected from woodlice with ferric phosphate pellets (Ferramol).
- Foliar damage by leafminers can be reduced in vulnerable cultivars such as Piccolo by timely release of a combination of 1-2 *Diglyphus* per m^2 and 1-2 *Macrolophus* per m^2.
- Growers should consider obtaining added value from their biocontrols by using new methods of collecting *Diglyphus*, *Macrolophus* and *Phytoseiulus* from areas of surplus for redistribution elsewhere. This can be particularly beneficial with *Phytoseiulus*, which are already fully adapted to tomato plants and may produce 70% more offspring than purchased products over the first two generations.

SCIENCE SECTION

Introduction

Background

Integrated Pest Management (IPM) is highly advanced in conventional tomato crops in the UK (Jacobson, 2004). The programme has been developed over 30 years and includes primary and secondary control measures that can be employed against over 10 individual species of pests. The primary measures are usually biological and suppress the pest's population growth throughout the season. The secondary measures are commonly target specific chemicals that can be used to redress the balance between the pest and beneficial populations at times when the pest damage approaches the economic damage threshold. The use of IPM compatible chemicals has been a major factor in the success of the overall programme in conventional tomato production. The availability of such chemicals reduces the pressure on busy crop managers by providing a "safety net" that should eliminate the risk of complete failure.

With so many control measures being used simultaneously, the overall programme is complex and can be difficult to manage successfully. If just one of the control measures fails and it becomes necessary to use a persistent non-specific insecticide, the whole programme will be disrupted.

IPM programmes for organic tomato crops have benefited from the research and development work that has previously been done for conventional crops. However, there are two important differences:

- There are no synthetic chemicals that can be used as a second line of defence in organic systems. This removes the "safety net" and increases the pressure on organic growers to "get it right first time". This has proved very difficult when operating on a large scale and has resulted in such organic growers suffering unacceptable levels of pest damage.
- Conventional crops are grown hydroponically while organic crops are grown in the soil. The latter provides opportunities for pests that do not exist in conventional production systems.

In addition, the organic market focuses on speciality cultivars, many of which are particularly susceptible to pests (Jacobson & Morley, 2008). Pests are therefore a major constraint to profitable organic tomato production on the scale that is required to satisfy the demands of the major retail outlets.

To become more successful, IPM in organic tomato crops has to depend on more sophisticated methods of manipulating the populations of both pest and beneficial invertebrate populations. This requires an improved knowledge of the tritrophic interactions between the plants grown in the organic system, the pests and the beneficial organisms. Experience has shown that any action taken within this three-way system is likely to impact on other components of the IPM programme and / or other routine agronomic practice. It was therefore important that these studies were done within a whole organic system. It was agreed at the outset that this “systems approach” should remain flexible, with studies being allowed to evolve to take into account findings as they occurred.

The approach

The work plan was designed to make the most cost-effective use of all the resources available. It was broken down into four categories:

- **Information gathering**: Apart from regular monitoring of the scientific and horticultural literature, the project benefited from the Project Leader’s participation in the International Biological Control Organisation, the International Biocontrol Manufacturer’s Association and the Association of Applied Biologists’ Biocontrol Subgroup, as well as his participation in many other related R&D projects.
- **Small-scale preliminary studies:** The project team tested a wide range of potential control measures in small-scale cost-effective studies before embarking upon more expensive experimentation. This aspect of the work plan remained flexible so that newly reported products / techniques could be quickly drawn into the work programme. Subsequent studies were allowed to evolve to take into account findings as they occurred. Where appropriate, more detailed studies of the biology and behaviour of invertebrates, or biocontrol production systems, were done under more tightly controlled conditions by collaborators.
- **Crop-scale evaluations:** As the aim of this project was to implement the pest control measures, it was important that the studies were done on a relevant commercial scale. There were no medium-large experimental organic glasshouse crop facilities in the UK and so it was necessary to use commercial crops. WSG provided access to their crops on the Isle of Wight within the limitations of sensible pest and disease precautions. This had considerable benefits to the work programme. For example:
    - It wasn’t necessary to grow crops dedicated to this project, which provided a substantial saving to the overall budget.
    - It wasn’t necessary to have a “further exploitation” phase to transfer the results from the experimental to the commercial situation.
    - Each study was part of a whole organic system, which immediately highlighted any

impact on other important aspects of agronomic practice.

  - o The trials benefited from the day to day input from specialist organic tomato crop growers and agronomists.

- **"Spin-off" projects:** Where appropriate, the Project Leaders facilitated "spin-off" projects to generate additional funding to address specific issues that required resources and / or expertise that weren't available within the project team.

It was known at the outset that there would be some disadvantages to working in commercial crops but these were not considered to be insurmountable. One disadvantage was that it was not possible to allow untreated control plots to become a threat to production on the rest of the site. However, this did not restrict activities because the main comparisons were made with "current best practice" rather than completely untreated plants. In fact, the biometrics community has moved away from insistence on 'negative' controls in crop protection trials for exactly the reason that such controls may act as foci of infection / infestation and may be totally unrealistic (Fenlon, pers.com, 2005). The other main disadvantage was that it was often impossible to have adequate replication to allow conventional statistical analysis. However, it must be remembered that this project sought major improvements in pest control rather than fine-tuning. If statistical analysis had been required to determine whether improvements were real, then those differences were probably inadequate in terms of commercial control. Nevertheless, some measure of natural variability was required and the team utilised statistical techniques that allowed within-treatment variation to be used as a proxy measure of experimental variation (e.g. Jacobson, Croft, & Fenlon, 2001).

Overall aim and specific objectives:

The overall aim of the project was to develop and implement a robust IPM programme that would provide reliable results in large-scale organic tomato crops in the UK. The specific objectives were to develop a suite of compatible primary and secondary control measures for each of the following pests:

1. *Macrolophus caliginosus*.
2. Mealybugs (*Pseudococcus viburni*)
3. Woodlice
4. Spider mites (*Tetranychus urticae* and *T. cinnabarinus*).
5. Leafminers (*Liriomyza bryoniae*).
6. Glasshouse whiteflies (*Trialeurodes vaporariorum*).
7. Russet mites (*Aculus lycopersica*)

Summary of all completed work

Much of the work during the first few months of the project (*i.e.* July – December 2005) was preparatory, involving information gathering and small scale experimentation to aid trial design with agronomists and the statistician. There followed trials during three full growing seasons, which began in December 2005, December 2006 and December 2007. In addition, the project was extended through the winter of 2008/09 to allow further evaluation of new mealybug control strategies. The following notes summarise the completed actions for each original milestone and for additional topics that were given consideration during the course of the project. References are provided to the previous project reports and / or to other sections of this report where full details of the experimentation can be found.

General:

- Dr Jacobson attended the IOBC Conferences in 2005 and 2008 as independently funded exercises. At the 2008 event, he organised and Chaired the session entitled “Pest Management in Organic Production”.
- The monitoring of scientific and horticultural literature was continuous throughout the project.
- A preliminary survey to determine the susceptibility of over 30 speciality tomato cultivars to the major pest species was completed in Autumn 2005 (Jacobson & Morley, 2006; Appendix 1). The cultivars were continually monitored to fine-tune the classification and to guide appropriate adjustments to IPM strategies. In addition, a spin off project was organised to investigate the underlying reasons for the differences in pest development rate on these cultivars (HDC Project PC 272; Jacobson & Morley, 2008).

Macrolophus:

- A cost effective method of monitoring populations of *Macrolophus caliginosus* was developed to aid decisions on control timings and to enable control measures under trial to be evaluated (Jacobson & Morley, 2006; Jacobson & Morley, 2006a).
- Two approaches to the management of *M. caliginosus* populations were considered:
    - o The first approach involved restraining *M. caliginosus* population growth by keeping populations of its invertebrate prey as small as possible. It was concluded that the management of this predator by manipulation of its invertebrate prey was very complicated and fraught with potential problems (Jacobson & Morley, 2006a; Jacobson & Morley, 2007).
    - o The second approach involved using an IPM compatible control agent as a remedial treatment to reduce the size of the *M. caliginosus* population after pests had been controlled. A remedial treatment based on pyrethrins (as Pyrethrum 5EC), which are

naturally occurring extracts from African chrysanthemums (*Chrysanthemum cinerarifolium*), was tested successfully against *M. caliginosus* in 2006 and a SOLA was obtained to allow more flexibility in its application to mature organic tomato crops (Jacobson & Morley, 2006). The method of "culling" the predator population was further refined in 2007 (Jacobson & Morley, 2007) and the technique has now been successfully implemented in over 12ha of commercial organic crops. The technique was also adapted for all year round (AYR) tomato production in HDC project PC 251 / 251a and this has allowed the successful implementation of a new IPM programme based on this predator (Jacobson, 2008).

- Studies to determine the feasibility of the proposed "disturb and catch" technique, with adults being disturbed during the twisting-in operation (or similar) and then caught by a suction device (or sticky trap) mounted on the trolley were initially stalled by engineering difficulties. However, the need for this method has now been superseded by the successful development of natural pyrethrins as a management tool.
- A new method was developed of collecting *M. caliginosus* from areas of surplus for release elsewhere (Jacobson & Morley, 2007). It was shown that *M. caliginosus* with a value of over £200 could be collected with an expenditure of only £8 on labour. This technique was built into the overall organic IPM programme in 2008 and into the new IPM programme for AYR tomato crops via HDC project PC 251 / 251a (Jacobson, 2008).

Mealybugs:

- Mealybugs (*Pseudococcus viburni*) have become the most difficult pest to control within the IPM programme for organic tomato crops. More than twenty IPM compatible control measures or combinations of control measures that are acceptable in organic production have been evaluated against mealybugs in this and previous HDC funded projects (Jacobson & Croft, 2002; Croft & Jacobson, 2007; Jacobson & Morley, 2006; Jacobson & Morley, 2006a). Many have shown potential when tested against individual mealybugs in the laboratory but have failed at the population level when trials have been scaled up in commercial crops. This has been due to a combination of the following factors:
    - The cryptic nature of the pests.
    - The protection provided by their waxy filaments.
    - Their resilience in returning to the plants after being knocked off by sprays.
    - The fecundity of survivors, which allows rapid resurgence of populations.
- Control measures based on spray applications of Eradicoat T, Savona, steam and natural pyrethrins have been found to be only partially effective.
- Trials in HDC project PC 215 showed that the parasitoids, *Leptomastix epona* and *Pseudaphycus maculipennis*, were capable of locating, attacking and completing their development in most life cycle stages of *P. viburni*. However, the parasitoids were unable

to suppress the rapid population growth of their host and it was concluded that both were more likely to coexist with the pest than to control it.

- In collaboration with Becker Underwood, three species of nematodes (*Steinernema feltiae*, *S. carpocapsae*, *Heterorhabditis megidis*) were tested against mealybugs in the laboratory and in crop scale experiments. There was no apparent reduction in the population growth of the mealybugs compared to untreated controls.
- As there had been so much difficulty in achieving remedial control during the growing season, more emphasis was placed on minimising the numbers of mealybugs that survived between crops and successfully colonised the new plants:
    - o Clean-up treatments between crops with a tractor mounted flame gun and hand-held flame lance were partially successful and some elements were incorporated into a larger package of control measures that were evaluated in November 2006 during the crop turn round (Jacobson & Morley, 2006)
    - o A strategy based on the use of sticky barriers and early season sprays of pyrethrins / soft chemicals was evaluated in 3ha of crops in 2007 (Jacobson & Morley, 2007). The sticky barriers were successful without additional sprays.
    - o Additional physical methods of control were found to be successful during cropping and replaced the previous spray-based control measures (Jacobson & Morley, 2007).
    - o A control programme based on the sticky barriers and new physical methods of remedial control were evaluated in full commercial production in 2007/08 and further refined for 2008/09. A protocol and a summary of the successful results are provided in Sections 3.6 and 3.8 of this report respectively.

Woodlice:

- Work started in 2005 to develop a prophylactic control method for woodlice based on *Atheta* spp. (Jacobson & Morley, 2006). Preliminary results indicated some predation of the smallest woodlice but not of the medium or larger individuals. However, further studies showed that the effect was marginal and not significantly different from the untreated controls. Overall, the results indicated that *A. coriaria* was not a voracious predator of this pest and the studies were terminated.
- The efficacy of chitin compost additives against woodlice was investigated in the laboratory in 2005 with disappointing results (Jacobson & Morley, 2006).
- An alternative compost additive consisting of a silicon-based desiccant dust was evaluated against woodlice in 2006 (Jacobson & Morley, 2006). Although this was very effective against woodlice, they were able to escape the treatments by burrowing into the growing medium.
- A spin off project undertaken by an MSc student at Imperial College investigated the soil

fauna in the glasshouses with particular emphasis on possible natural enemies of woodlice (Stewart, 2006). While this provided valuable information, particularly about *Dysdera* spp. spiders, there were no immediate leads towards effective control measures.

- In collaboration with Becker Underwood, three species of parasitic nematodes (*Steinernema feltiae*, *S. carpocapsae*, *Heterorhabditis megidis*) were evaluated against woodlice in the laboratory (Jacobson & Morley, 2006) and in the spin off student project (Stewart, 2006). There were mixed results and it was concluded that the nematodes were too unreliable for the control of woodlice in commercial crops. Further work in 2007 began to investigate the potential to enhance their efficacy by use in association with attractive baits but this was ineffective and the studies were terminated.
- Small scale experiments in 2007 began to explore the potential of ferric phosphate pellets (Ferramol) to protect young plants from woodlice (Jacobson & Morley, 2007). These pellets are sold in various formulations for slug control in amateur and commercial organic crops. Larger scale trials in 2008 demonstrated that this was an effective control measure (Section 4 of this report).

Spider mites:

- In 2006, studies compared the establishment of *Amblyseius andersoni* with standard and tomato pre-conditioned *Phytoseiulus persimilis* on tomato crops (Jacobson & Morley, 2006). One of the attractions of *A. andersoni* was their availability in culture packs, offering the potential for establishment before the pest was found. Unfortunately, the results from the first series of experiments indicated that *A. andersoni* was not suitable for use as a biological control agent on tomato plants.
- A new source of *P. persimilis*, which were claimed to be considerably more fecund than bean-reared products, was compared to both standard bean-reared and tomato conditioned products. Unfortunately, they did not establish on tomato plants. However, the tomato conditioned *P. persimilis* performed very well in these trials and the cost-effectiveness of this product was further evaluated in 2008 (Jacobson & Morley, 2007).
- A desk study evaluated the cost-effectiveness of *Feltiella acarisuga* on tomato crops (Jacobson & Morley, 2006). There seemed little doubt that natural migrations into tomato crops during the summer could make a significant contribution to the overall control of spider mites. However, the information collected showed inconsistencies in the results obtained with this predator when it was released earlier in the season. Furthermore, it is not compatible with *M. caliginosus*, which has since become an important component of the whole IPM package. Overall, there was little evidence to support expenditure on inundative releases of this predator in organic tomato crops.

- The possibility of conducting commercial trials with *Beauveria bassiana* in 2006 was investigated with Certis UK Ltd and PSD. We were unable to obtain an Extrapolated Experimental Approval based on the Dutch label because this did not include tomatoes. However, there is now a strong possibility that *B. bassiana* will be approved in the UK as Naturalis-L and trials are planned within a recently proposed HDC funded project (HDC Project PC 299).
- A collaboration was formed with Plant Physiologists at Lancaster University to seek funding for a "spin-off" project to investigate methods of reducing the impact of hyper-necrotic spider mite damage. The concept was strongly supported by the TGA Technical Committee and a draft proposal was prepared and submitted to HortLINK. Our consortium was initially given encouragement to further develop the proposal but it was later abandoned due to changes in Defra research priorities. It is unclear how we can proceed with these important investigations.
- A "spin-off" project to evaluate the effect of garlic through the irrigation system on the establishment of leaf miners and spider mites was initiated at Stockbridge Technology Centre Ltd with Garlic Farms Ltd. Although there was no significant effect on establishment of either species, there appeared to be some degree of repellancy with leafminers in a choice situation (Jacobson & Morley, 2006). It wasn't considered appropriate to pursue this topic any further within this project.
- A new method was developed of collecting *P. persimilis* from areas of surplus in commercial tomato crops for release elsewhere. This enabled large numbers of high value tomato-reared *P. persimilis* to be collected with minimal labour input (Jacobson & Morley, 2007).
- A study in 2008 compared the cost-effectiveness of standard bean-reared *Phytoseiulus* and the more expensive tomato-conditioned product with the *P. persimilis* collected from areas of surplus. Given similar expenditure, the results indicated that the tomato-conditioned product would provide 4% more offspring than the standard bean-reared product after two generations. However, the population growth of the *Phytoseiulus* harvested from commercial tomato crops far exceeded both of these products. For example, it was calculated that after two generations the harvested *Phytoseiulus* would give rise to 70% more offspring than the tomato conditioned product (Section 5 of this report).

Leafminers

- A survey has been completed to categorise the susceptibility of over 30 commonly grown cultivars of speciality tomatoes (Appendix 1 of this report). The leaf miner monitoring strategy and *Diglyphus isaea* release strategies have been revised for the more susceptible cultivars.

- The leaf miner monitoring system and early season release strategies for *D. isaea* developed in LINK Project CSA2921 were re-assessed in the light of acquired experience and re-evaluated at the start of the 2006 growing season. The studies were successful and the number of *D. isaea* released was substantially reduced compared to recent seasons (Jacobson & Morley, 2006). However, there was still unacceptable foliar damage to the more susceptible cultivars.
- A trial to explore the value of increased rates of release of *D. isaea* was delayed until mid-season 2006 due to the late arrival of leaf miners in the set of six similar glasshouses / crops which were most suitable for the study. The results demonstrated that *M. caliginosus* was a more important control agent than *D. isaea* at that time of the year (Jacobson & Morley, 2006).
- The final flush of leaf miner activity before control is achieved with *D. isaea* consistently causes an unacceptable amount of foliar damage in the more vulnerable cultivars (*eg* cvs Piccolo and Campari). Several means of either slowing down leaf miner development or speeding up *D. isaea* establishment in these crops, have been given consideration (Jacobson & Morley, 2006):
    - o **Entomopathogenic nematodes** - When used as a second line of defence to support *D. isaea*, *Steinernema feltiae*, contributed about 10-20% control of the leaf miners. The cost-effectiveness of this control measure within the overall IPM programme remains debatable and is unlikely to be widely adopted.
    - o **Garlic extract** – A trial has investigated the potential of slowing down leafminer establishment by circulating garlic extract through the irrigation system. (See Section 2.5).
    - o **Sterile insect technique** – Previous studies have indicated that this could be an appropriate technique to use against leafminers on tomato (Kaspi & Parella, 2003; Kaspi & Parella, 2006). Two spin off projects were initiated with MSc students at Imperial College (Jacobson & Morley, 2007) to investigate the possibility of slowing down leaf miner establishment by releasing sterile males in the glasshouse at the start of the season. These projects paved the way for an HDC sponsored PhD studentship, which began in September 2007.
    - o ***Diglyphus* open rearing systems** – The development of open rearing systems to enhance *Diglyphus* establishment has been fraught with problems due to the difficulty in keeping the leafminer / parasitoid cultures free of contamination on the commercial nursery. Further development of this system would require a significant investment in more sophisticated rearing facilities. The work was terminated due to the successful outcome of other studies.
    - o ***Macrolophus* as a supplementary biocontrol** – *Macrolophus caliginosus* could not previously be used against leaf miners due to the risk of serious damage being

caused to the plants after the predator had controlled the pest. However, with the development of an IPM compatible remedial treatment for *M. caliginosus*, it became possible to place greater emphasis on this predator as a component of the leaf miner control programme. Studies involving the release of purchased *M. caliginosus* began in 2007 (Jacobson & Morley, 2007) and were completed in 2008 (Section 6 of this report).

- o ***Diglyphus* release strategy –** One obvious method of speeding up *D. isaea* establishment is to release larger numbers at the correct time. The current release rates have been restrained by economics and there is an understandable reluctance by growers to spend more. However, it may be cheaper to do this than to suffer other consequences in the more susceptible cultivars. Furthermore, a new method was developed of collecting *D. isaea* from areas of surplus for release elsewhere (Jacobson & Morley, 2007). This enabled growers to recover their additional early season outlay on *D. isaea* products.
- o **An IPM programme** which utilised an increased number of *Diglyphus* and *Macrolophus* was evaluated in 10,000m^2 of vulnerable tomato crops in 2008. This approach greatly reduced foliar damage by leafminers and there were additional benefits in terms of reduced expenditure on spider mite control (Section 6 of this report).

Whitefly:

- A survey was completed to categorise the susceptibility of over 30 commonly grown cultivars of speciality tomatoes (Appendix 1 of this report). This has influenced *Encarsia formosa* release strategies in the more susceptible crops.

Russet mites:

- Russet mite infestations were controlled with Savona / Codacide while this project was being approved by HDC in 2005. No infestations have since been seen in the organic crops and no further studies have been deemed necessary.

Integrated control of mealybugs

Background

Mealybugs (*Pseudococcus viburni*) are the most difficult pest to control within the IPM programme for organic tomato crops. They have proved to be resilient to many products that were expected to kill them. Furthermore, they have a very high reproductive rate, which allows populations to rapidly recover from partially effective control measures.

HDC project, PC 161, which was completed in 2002, investigated the increase in incidence of *P. viburni* in UK tomato crops, studied relevant aspects of the biology of the pest and began to formulate a control strategy (Jacobson & Croft, 2002). Female *P. viburni* are wingless, soft-bodied insects with sucking mouthparts. They are covered in white waxy filaments, which provide protection from adverse conditions and insecticidal sprays. The males are small delicate winged insects that only live for a few days. Eggs are laid in batches of up to 500 in cotton-like pouches made of wax. There are four immature mealybug stages (first, second, third and fourth instar nymphs) (Malais & Ravensberg, 2003), which are similar in appearance to adult females.

The most effective and IPM compatible method of controlling mealybugs on tomato plants during the production season was shown to be the insect growth regulator, buprofezin (Applaud), but this could not be applied to organic crops. Project PC 161 also evaluated several biological control agents (*eg Hypoaspis* spp., *Chrysoperla* spp., *Beauveria bassiana*) but none proved to be very effective on tomato. However, preliminary investigations indicated that the parasitoids, *Leptomastix epona* and *Pseudaphycus maculipennis* had some potential (Jacobson & Croft, 2002).

The work continued in HDC Project PC 215. Studies focused on i) applications of soft chemicals to young plants to reduce the establishment of invading mealybugs, ii) use of parasitic wasps to suppress the mealybug population growth throughout the season, and iii) application of soft chemicals to stem bundles of mature plants in mid-season as a “second line of defence”.

The evaluation of “soft” chemicals to young plants at the beginning of the season showed that Savona and Eradicoat T had a similar effect, with repeated sprays providing over 90% control (Croft & Jacobson, 2007). The objective of these sprays was to reduce the numbers of mealybugs to a level that could be managed with a more sustainable control measure based on the parasitoids, *Leptomastix epona* and *Pseudaphycus maculipennis*. Both species were released weekly from week 10 with the intention of establishing intensive breeding areas (IBAs) in the crop from which the parasitoids would disperse as conditions became more suitable for searching over longer distances. Parasitised mealybugs were soon found in the IBAs but the wasps failed to suppress the rapid population growth of their mealybug host (Croft & Jacobson, 2007). By September, the plants in the IBA were seriously damaged and this resulted in two months lost production at the end of the season (Figure 1). These results indicated that *L. epona* and *P. maculipennis* were more likely to coexist with the pest than to control it in a commercial crop.

Figure 1. Plant damage in the area of commercial crop protected by the parasitoids, *Leptomastix epona* and *Pseudaphycus maculipennis* (HDC Project PC 215, September 2006).

The application of soft chemicals to stem bundles of mature plants in mid-season as a “second line of defence” to support the parasitic wasps was evaluated in several trials. Mealybug populations were reduced by both Savona and Eradicoat T but the overall effects in mature crops were disappointing due to the difficulty in contacting the pests among the horizontal stem bundles. An attempt to enhance the effect of Savona by applying it in sequence with the entomopathogenic fungi, *Verticillium lecanii*, did not significantly improve results. The level of survival, combined with the fecundity of the females, led to rapid recovery of the mealybug populations. It was necessary to apply the soft chemicals very frequently in order to suppress the pest population growth. However, this strategy was only partially effective and it proved to be prohibitively expensive.

The studies in the present project were initially complementary to those in HDC Project PC 215. For example, within the early stages of this project work began to evaluate the potential of entomopathogenic nematodes to replace the soft chemicals as the second line of defence. Treatments based on *Steinernema carpocapsae*, *S. feltiae* and *Heterorhabditis megidis* appeared promising in the laboratory but had little impact on the mealybug population in a commercial crop (Jacobson & Morley, 2006; & Jacobson & Morley, 2006a; Stewart, 2006).

The quest to find an effective mid-season remedial control measure continued in 2006 with in-crop trials evaluating steam and Pyrethrum 5EC (Jacobson & Morley, 2006a). It was proposed that steam would penetrate the stem bundles and provide better control than either soft chemicals or entomopathogenic nematodes. Where the steam contacted motile mealybugs, it stripped them of wax and knocked them from the stems. Similarly, steam severely damaged the surfaces of egg sacs. However, penetration of stem bundles was little better than high volume sprays and survivors were found in the usual places between overlapping stems. The immediate effect was 60% and 80% reduction in numbers of motile mealybugs on stems treated with steam and steam plus hot water respectively. Some mealybugs were collected from the floor and kept under observation in Petri dishes for 10 days. Many did not die but regenerated their waxy covering and started producing egg sacs within 48 hours. Observations within the crop revealed motile mealybugs back on the upper sides of stems after 16 hours. Some had probably moved from hiding places between the stems but others were seen climbing back from the soil. The reinvasion continued over the next few days. This aspect of survival and reinvasion of plants had not been specifically taken into account in previous evaluations of soft chemicals. It is therefore possible that some such trials, where numbers of survivors were assessed within 24 or 48 hours of treatment, may have over-estimated the level of control achieved. Although both treatments had a visual impact on the surface of egg sacs on stems, those collected and observed in the laboratory over the following week still produced healthy nymphs from deeper within the waxy mass. Overall, the effects of these treatments were considered inadequate and the study was terminated. However, the work was useful because it highlighted another aspect of mealybug survival which had to be taken into account when designing control programmes.

Pyrethrum 5EC was applied at three rates (up to 4ml per litre) to tomato stem bundles infested with mealybugs in September 2006. Each rate was tested with and without Eradicoat T or Savona, and all were compared to untreated controls. A flushing effect was noted immediately after the spray; *i.e.* some mealybugs emerged from hiding places and were actively moving around on the upper surfaces of stems. This effect was comparable to the use of aerosols based on natural pyrethrins to flush cockroaches out of hiding places in kitchens etc. This effect should be further investigated to determine whether it could be used to provide any advantage in the control programme. None of the individuals that received Pyrethrum 5EC at the highest rate would have contributed to any subsequent population growth. The lower rates were only partially effective suggesting that the 4ml per litre rate was at the lower end of the product's efficacy range against mealybugs. There was no evidence that the addition of either Eradicoat T or Savona to the spray mixture improved the efficacy of Pyrethrum 5EC. In fact, their addition to the spray appeared to reduce its effect, perhaps by locking up the active ingredients. While results with the higher rate of Pyrethrum 5EC were promising, it must be remembered that these specimens suffered a direct hit from the spray. Control in a commercial crop would be subject to the usual problems related to achieving contact with the pest.

Control of mealybugs between crops

As there had been so much difficulty in achieving acceptable remedial control of mealybug populations during the growing season, more emphasis was placed on minimising the numbers of invaders that successfully colonised plants in January. As a first step, we looked at means of reducing their survival between crops.

The use of flame produced from either tractor mounted burners or hand held lances was considered to have potential to reduce numbers of mealybugs in the surface layers of the soil, on dwarf walls, concrete post supports and low level steelwork. Both types of treatments were evaluated in November 2006.

The tractor mounted burner was used to scorch the surface layer of the soil both before and after final removal of crop debris. Some invertebrates were killed on the soil surface but this was not very effective even at the slowest possible tractor speed.

The hand held lance was used to flame the concrete dwarf walls / post supports and low level metal work / pipe rail stands where mealybug egg masses are frequently found. The technique was also used to flame the angle between the soil and the concrete roadway. Experience from 2005/06 had shown that many mealybugs collected here having been shaken from the old haulm as it was hauled out of the row. Inspection of concrete surfaces showed that motile stages of mealybugs were effectively killed by the treatment. Although the surface of the flamed egg masses were scorched and the outer eggs appeared brown and unhealthy, when they were teased apart under the microscope, the eggs in the middle of the mass appeared to be normal. Incubation of samples in the laboratory confirmed their viability. Control improved at slower speed but some survival must always be anticipated.

Crop invasion

Monitoring work in commercial crops showed that young mealybugs emerging from egg masses that had survived between crops began to colonise plants soon after the glasshouse heating was switched back on. It was not uncommon to find 200-300 nymphs on a single plant stem adjacent to a concrete dwarf wall or post support (*eg.* Figure 2).

The movement of mealybug nymphs hatching from egg sacs in the soil was more restricted because the soil surface was covered with polythene. The polythene most commonly used for this purpose prior to 2007 was white and translucent which allowed volunteer tomato seedlings to grow in the soil. These seedlings provided a "refueling station" for mealybug nymphs (Figure 3) and increased their chance of surviving until the plastic was split open for planting.

As a consequence, there were two flushes of invading nymphs; the first was 2-3 weeks after the plants were "stood out" and the second occurred when the plastic ground cover was opened up to allow planting in the soil.

Figure 2. Mealybug nymphs on a tomato stem close to a point of egg sac survival

Figure 3. Mealybug nymphs on a tomato seedling taken from under translucent white plastic sheeting in January 2006.

Monitoring the development of mealybugs which invaded the newly delivered tomato plants in 2006/07 showed when the first invaders produced egg sacs (Table 1). This is a critical time because the population suddenly increases by a huge factor and it becomes more difficult to achieve control. The estimates shown below proved to be reasonably accurate in the 2008 growing season and allowed us to predict both invasion and development times with confidence in 2009.

Table 1. Approximate mealybug development times predicted form observations in commercial tomato crops between 2006 and 2008.

Week number:			
Plants stood out	**First instar nymphs predicted to appear on plants 2-3 wks after heating switched on**	**Third instar nymphs predicted 4-5 wks after heating switched on**	**Adults / eggs predicted 9-10 wks after heating switched on**
50	52-1	2-3	7-8
51	1-2	3-4	8-9
52	2-3	4-5	9-10
1	3-4	5-6	10-11
2	4-5	6-7	11-12
3	5-6	7-8	12-13
4	6-7	8-9	13-14

A new strategy to prevent mealybug invasion

A new strategy was designed for the start of the 2007 growing season which was aimed at minimising the numbers of mealybugs that successfully reached the new plants. This was to be based on the use of physical barriers and carefully timed sprays of natural pyrethrins. The strategy was evaluated in 3ha of commercial crops which had been seriously damaged by mealybugs in the previous season (Figure 1).

The programme began with a thorough clean-up in the empty glasshouse. This involved removing all crop debris, soaking irrigation pegs / laces in nitric acid, power washing irrigation lines and flaming the glasshouse structure with a hand lance.

The soil was completely covered with black-backed plastic to prevent light penetration and growth of volunteer tomato seedlings. The overlaps between plastic sheets were offset so that they were to the side of the bed rather than directly under the plants and all joints were sealed with (60% polyisobutylene glue).

Thripstick 2 was diluted with water (two parts Thripstick 2 to one part water) and applied to the concrete dollies, metal posts to a height of about 2.1m, dwarf walls around the periphery of the crop and the edge of the central concrete roadway. After the floor plastic had been positioned and sealed at the joints, a 300mm wide band of similarly diluted Thripstick 2 was sprayed down the centre of each bed.

The plants were stood out on plastic saucers immediately above the polyisobutylene barrier in week 50 2006. At planting, which varied from four to six weeks later, the hole cut in the plastic to receive the plant pot was kept to the absolute minimum size so that the treated plastic was still touching it. No plastic clips were used to anchor the string as they had been shown to be a point of harbourage / protection for mealybugs in the previous season. Lower leaves were removed as soon as possible to reduce opportunities for mealybugs to find a green bridge across the sticky barrier. This was also important to aid monitoring and detection of the pest.

No mealybugs were detected on the plants within the first three weeks of being stood out. In the previous year, it had been common to find over 50 young mealybugs per tomato stem at row ends and near to concrete post supports in this glasshouse at this time. After planting into the soil, the crop was carefully monitored for several weeks but very few mealybugs were found before March; *i.e.* only one in crop week 5 and two in crop week 6. In each of these cases, the polyisobutylene barrier had been damaged by a water leak.

Crop week 8 was considered to be a critical time for the application of additional treatments should any mealybugs have gone undetected from the first flush of invaders because they would then begin to produce egg masses. In fact, no mealybugs were found on the plants at that stage and the planned applications of natural pyrethrins were not required.

Monitoring continued and a small colony of meaybugs that was detected on one plant in mid-May was physically controlled by hand. Similar sized colonies were detected periodically during the second half of the season and were dealt with in a similar manner. At first consideration, this may seen to be very labour intensive but the results proved to be cost-effective when compared to the application of partially effective routine sprays. This second physical approach became part of the standard recommendations from the start of the following growing season.

Some phytotoxic effects from Thripstick 2 were noted where young plants came into contact with treated surfaces (Jacobson & Morley, 2007). The symptoms initially comprised blackening of foliage and / or stems, which later became necrotic. However, such incidences were relatively uncommon and did not result in any loss of plants.

In contrast to the 2006 growing season, no sprays were applied specifically against mealybugs over these 3ha of crops and no plants were lost due to damage by this pest. This overall approach was considered to have been an overwhelming success.

Adoption of the new strategy on a wider scale in 2008

The strategies described in section 3.4 were adopted by crop managers in over 9ha of commercial organic tomato crops for the 2007/08 growing season. The growers were provided with clear instructions but were not given the intensive specialist support that had been available for the trial in 2007. This was seen as a true test of the robustness of the new techniques in a commercial environment.

For the main part, the barriers were effective (*eg*. Figure 4) and the initial invasion of mealybugs was greatly reduced in all crops compared to previous years. However, the mealybugs that breached the defences eventually gave rise to large populations which caused unacceptable damage in localised areas of crops by the end of the season. Overall, the strategy was not as successful as in the 2007 trial.

All localised infestations were investigated and the reasons for failure determined and documented so that we would learn from the experience. The reasons for failure fell into one of the following categories:

- Use of low grade white plastic which was easily damaged.
- An inadequate seal between plastic joints. Occasionally, there was only a very small overlap (<3cm) and the joint was directly below plants (Figure 5) so that mealybugs could reach the plants without encountering Thripstick 2.
- Inadequate coverage of Thripstick 2 in the protective band on the top of the bed due to either poor application technique or incorrect dilution of product.
- Poor seals around posts (Figure 6), irrigation pipes (Figure 7) or at dwarf walls (Figure 8).
- Failure to effectively treat irrigation pegs allowing nymphs a direct route onto the plant (Figure 9).
- Overly large holes cut in plastic for planting.

Figure 4. Effective physical barriers; note that the joint in the plastic is offset (red arrow), the seal between layers is good and leaves are clear of the floor. Although it doesn't show on this picture, the Thripstick 2 cover was complete and even.

Figure 5. Inadequate seal between plastic sheets and incorrect positioning of joint which allowed mealbug nymphs to reach leaves (red arrow) without encountering the sticky barrier.

Figure 6. Inadequate seals around post supports

Figure 7. Inadequate seals around pipework

Figure 8. Inadequate seal due to plastic creeping away from dwarf wall

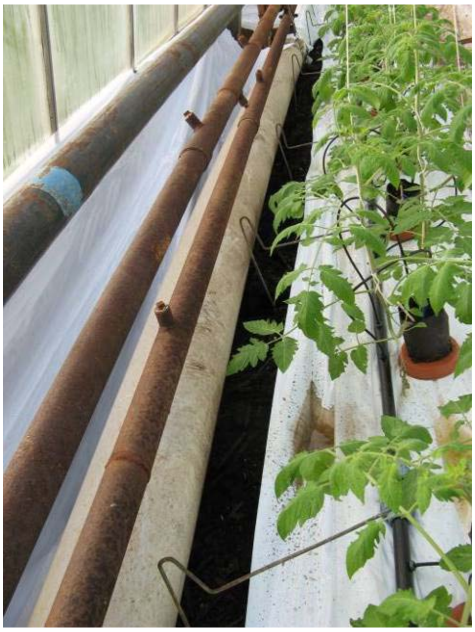


Figure 9. Mealybug egg sacs having survived treatment of irrigation pegs

In view of the disappointing results in 2008, the project was extended by three months so that the new control strategy could be refined and tested again at the start of the 2009 season.

Protocol for preparation of mealybug control measures 2009

The following protocol was prepared for growers to follow in 2009. This took into account all the reasons for failure in 2008. In addition, all crop workers were provided with formal training on mealybug control and all participating sites were visited at critical times to advise the crop mangers on the most effective means of implementing the measures detailed in the protocol.

Action between crops

- *When all debris from the previous crop has been removed, use a propane burner to clean up around pipe supports stanchions, dollies and perimeter walls.*
- *Remove lace /pegs from main irrigation line and dip in nitric acid (ph 2 or less).*
- *The main line should be hung on the "cow horns", washed with a pressure washer and then dropped back to the floor to be sprayed over with Thripstick 2.*

Preparation for new crop

- *Cover the soil with black-backed plastic to prevent growth of volunteer tomato seedlings.*
- *Ensure that the overlaps between plastic sheets are at least 200mm and not directly under the plants - they should be off-set to one side of the beds.*
- *Glue the joints in the plastic sheets by painting with Thripstick 2.*
- *Form plastic sheeting up and around dolly posts and dwarf walls. It will help to apply Thripstick 2 to the concrete surfaces beneath the plastic in these positions.*
- *Take special care to obtain a good fit where pipes pass through the plastic.*
- *Apply Thripstick 2 in a band (min 300mm) down the centre of the bed. Ideally, this band should extend over the joint in the plastic.*
- *In addition, apply Thripstick 2 over the plastic covering dwarf walls and dolly posts, to pipes, stanchions etc, and at the edge of the concrete roadways.*
- *Paint Thripstick 2 up the metal posts to a height of at least 1m and around points where other metalwork (eg cow horns) are attached as all these places provide harbourage for mealybug egg sacs.*

Use of Thripsick 2

- *Thripstick 2 is supplied as 60% polyisobutelene and 40% water. Each batch is made to order and may require up to 6 weeks delivery time.*
- *Where Thripstick 2 is to be applied by brush or sponge, it should be used as delivered without further dilution.*
- *Before spraying, dilute 2 parts Thripstick 2 with 1 part water, which should give a sprayable mixture. However, the consistency appears to differ slightly between batches. If it is too weak it will run into pools and not give complete coverage on the plastic. If it is too strong, it may block the sprayer. The temperature in the greenhouse may also affect the consistency of the mix. Each mixture should be tested and adjusted until correct.*
- *Agitate the spray mixture in the tank.*
- *The sprayed mixture should dry within 2 hours leaving a tacky deposit.*
- *Where water leaks occur, check and reapply Thripstick 2 as necessary to retain an effective barrier.*
- *WARNING – Thripstick 2 is phytotoxic and should not be sprayed directly onto plants.*

After the new plants are stood out

- *Inspect plants weekly for arrival of mealybugs. Squash any mealybugs that are seen.*
- *If possible try to avoid any contact between plants and surfaces treated with Thripstick 2. It is particularly important not to allow stems to droop / lie on treated plastic.*
- *Remove lower leaves as soon as possible so that stems can be thoroughly inspected.*
- *When the crop stem supports are put into position, paint the upright sections with Thripstick 2 to avoid mealybugs using them as a bridge to travel from beneath the plastic to the foliage.*
- *When the time comes to plant through the plastic, keep the holes as small as possible so that the treated plastic maintains contact with the pot.*
- *Cut off excess strings to avoid them trailing onto untreated plastic.*

Throughout cropping

- *Continue to inspect stems at weekly intervals for presence of mealybugs. Squash any mealybugs that are seen.*
- *Crop workers must be properly trained to recognise mealybug nymphs and must fully understand the importance of the task.*
- *The period leading up to the first mealybug eggs being produced (ie 9-10 weeks after the heating is put on) is particularly important.*

Implementation of refined strategies in commercial crops in 2009

The control measures described in the protocol (above) were implemented to a very high standard in all of the eleven participating organic crops (total 6.63ha). For example, a typical bed post-planting is shown in Figure 10 and seals around posts, pipes, dwarf walls and the edges of concrete roads are shown in Figure 11. An example of a typical planting hole is shown in Figure 12.

Figure 10. Typical plant bed 2009

Figures 11. Examples of seals at a) dwarf walls, b) edges of concrete roads, c) base of posts and d) around pipes.

11a.

11b.

11c.

11d.

Figure 12. Planting hole

Results of crop monitoring from plant arrival to late March 2009

The crop monitoring results from eleven organic crops and three conventional crops are summarised in Table 2. Separate records are provided for the periods from plant delivery to planting in the soil and from planting until week 13. For each period, the number of infestations recorded and the mean number of mealybugs per infestation are provided. The size of each glasshouse and the number of plants are also given to put the number of infestations into perspective.

Initial invasion from above ground level

The only mealybug nymphs that were seen or reported in any of the crops between the plants being delivered and being planted in the soil (usually a 3-4 week interval) were close to irrigation rigs and heating valves in houses 11 and 13 (Figure 13). Although all such equipment had been treated with Thripstick 2, some nymphs had found a direct path from within the casings to the adjacent plants. In the majority of such cases, the infestations consisted of a single nymph or a small group of up to three nymphs per leaf which was in stark contrast to the huge invasions recorded from similar refuges in previous years (*eg*. Figure 2). As a consequence of the initial sightings, all plants adjacent to these or other similar pieces of equipment were carefully inspected and any mealybugs were removed or squashed in situ.

Figure 13. Irrigation rig (a) and heating valve (b) within rows of young plants

13a.

13b.

Invasion after plastic was split for planting

No mealybug infestations were found in the conventional crops where the physical barriers remained intact nor were any found in five of the organic blocks. Three of the organic blocks had a very low incidence of infestations (*i.e.* approximately 1 per 6,000 plants). The other four blocks ranged from one per 300 plants to one per 750 plants. There were usually only 1 to 3 mealybugs present at each point of infestation (*eg.* Figure 14). This compared extremely well to previous years when there had been large infestations on plants adjacent to most posts, dwarf walls and row ends (*eg.* Figure 2). All mealybugs found were squashed in situ. No spraying was required during this period. Overall, the new control measures were considered to have been very successful.

Figure 14. Typical mealybug infestation in March 2009 (compare to Figure 2)

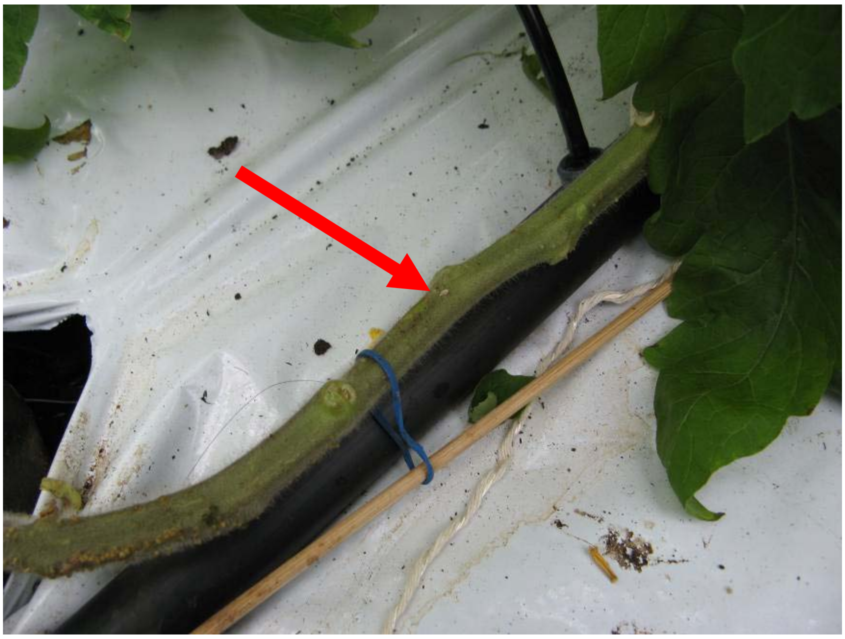


Table 2. Number of mealybug infestations recorded in three conventional and eleven organic crops up to week 13 2009.

Type of crop	Glasshouse reference number (plant delivery week)	Glasshouse size (m^2) and (number of plants)	Infestations recorded before plastic split for planting (mean number of mealybugs per infestation)	Infestations reported after planting and up to week 13 (mean number of mealybugs per infestation)
Conventional	19 – 20 (wk 1)	9,944 m^2 (23,866)	0	Conventional crops are not planted in the soil. There were no reported infestations up to week 13.
	21 – 22 (wk 1)	9,944 m^2 (19,888)	0	
	23 - 24 (wk 2)	9,944 m^2 (19,888)	0	
Organic	3 (wk 4)	2,446 m^2 (4,720)	0	0
	4 (wk 4)	2,446 m^2 (4,720)	0	0
	5 (wk 3)	2,446 m^2 (6,000)	0	0
	6 (wk 3)	2,446 m^2 (5,940)	0	1 (1)
	8 (wk 3)	2,775 m^2 (6,300)	0	20 (1)
	10 (wk 4)	2,775 m^2 (6,336)	0	1 (1)
	11 (wk 1)	10,572 m^2 (20,992)	24 infestations - all adjacent to 6 irrigation rigs and one heating valve (2)	28 (1)
	13 (wk 1)	10,572 m^2 (20,992)	Ditto (2)	53 (1-2)
	25 – 26 (wks 8 & 9)	9,944 m^2 (21,376)	0	0
	27 – 28 (wk 1)	10,740 m^2 (24,376)	0	0
	29 – 30 (wk 1)	9,944 m^2 (21,376)	0	40 (2-3)

Protecting young plants from woodlice

Background

Woodlice are isopods which live in the surface layers of the soil / compost below organic crops. The populations can become extremely large and they will climb plants to feed on stems and leaves. In the early weeks of the season this can seriously damage plant stems and deplete the foliage of young plants. Young tomato, cucumber, pepper and aubergine plants are all equally susceptible to attack.

Figure 15. *Armadillium nasatum* inside a tomato stem (cv Capri) creating an infection site for secondary disease organisms.

This project has evaluated several IPM compatible methods of controlling woodlice in small scale trials; *i.e.* the predatory beetles *Atheta coriaria*, three species of parasitic nematodes (*Steinernema feltiae*, *S. carpocapsae*, *Heterorhabditis megidis*), chitin compost additives, a silicon-based desiccant dust and natural populations of the predatory spiders *Dysdera* spp. (Jacobson & Morley, 2006; 2006a, 2007). However, none of these measures have provided adequate control in the glasshouse.

In 2007, we received unpublished information which indicated that ferric phosphate slug pellets may also be used to control woodlice (M. Jones, BCP Ltd, September 2007). Pelleted ferric phosphate (Ferramol) is approved for slug control in all crop types and has been widely adopted for use in conventional and organic cropping situations. The pellets also contain wheat flour as an attractant. Once eaten the ferric phosphate acts by destroying the slug’s mouth parts and gut lining. Feeding stops immediately and the effect is irreversible causing death within 3 to 6 days. The mode of action against woodlice is unknown but presumed to be similar.

This information prompted a preliminary laboratory-based study (Jacobson & Morley, 2007). The rates tested were all above 2.5g per plant and all provided useful levels of control of woodlice. Other observations suggested the pellets would begin to degrade after 4 days and become covered in mould growth after 8 days. It was clear that more substantive trials should be undertaken at the start of the 2008 growing season.

Before the commercial crop scale trials began, preliminary phytotoxicity trials were done in which growing plants (approx 30 days old) were exposed to rates of up to 5g of Ferramol pellets per plant. No plant damage was recorded over the following three weeks.

Natural populations of woodlice were quite small in the commercial tomato crops at the start of the 2008 season and so trials were established in equally susceptible cucumber and aubergine crops.

Objective:

To evaluate the protection against woodlice provided by three rates of Ferramol pellets

Materials and method:

Trial design:

Three rates of Ferramol pellets (*i.e.*.0.5g, 1g and 2.5g per plant) were tested in two separate trials on newly delivered and planted cucumber and aubergine plants.

All plants were delivered on 5 February 2008 and planted into the soil within 24 hours. They were watered in within the following 24 hours.

Cucumber plants were arranged in rows of 100 plants. There were six plots of 12 plants per row with 3 untreated plants between each plot. The intention was to carefully monitor untreated plants until they were attacked by woodlice and then provide protection to prevent plant loss. Each of the three treatments was replicated 4 times (see Figure 16). There were ten untreated plots of reduced size.

Figure 16. Trial layout in cucumbers

(A = 0.5g / plant, B = 1g/plant, C = 2.5g/plant, U = untreated)

path	A	U	B	U	C	U*	B	U	C	U	A
	B	U	C	U	A	U*	A	U	B	U	C
	Plants - 12	3	12	3	12	3	12	3	12	3	12

* These two plots were not used in statistical analysis 3 (see below).

Aubergine plants were arranged in rows of 60 plants. There were four plots of 12 plants per row with 3 untreated plants between each plot. As with the cucumbers, the intention was to carefully monitor untreated plants until they were attacked by woodlice and then provide protection to prevent plant loss. Each of the three treatments was replicated 4 times (see Figure 17). There were nine untreated plots of reduced size.

Figure 17. Trial layout in aubergines

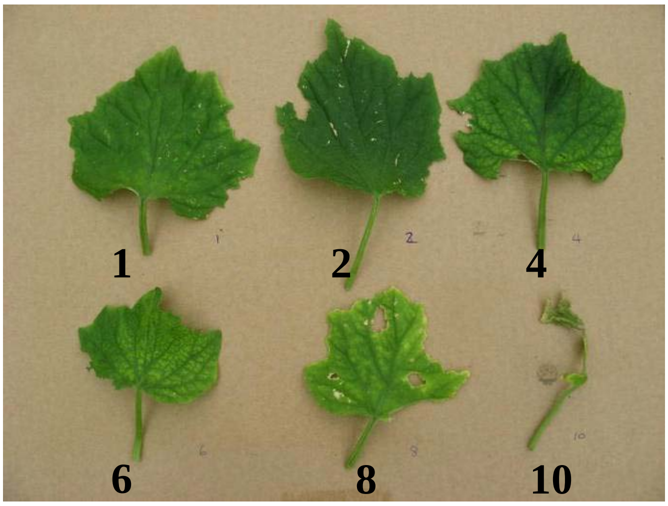
(A = 0.5g / plant, B = 1g/plant, C = 2.5g/plant, U = untreated)

path	A	U	B	U	C	U	A
	C	U	A	U	C	U	B
	B	U	A	U	B	U	C
	No. of plants - 12	3	12	3	12	3	12

Assessments:

Cucumber: Damage was noted on the lowest leaves soon after planting (6 February) and treatments were applied immediately. On 22 February (*ie* 16 days post-treatment), a preliminary assessment determined the range of damage symptoms on the lowest leaves. Samples were collected and used to establish a damage index with a scale of 0 to 10 (Figure 18). The lower leaves of all plants were then scored by matching to this reference material.

Figure 18. Cucumber damage index (scale 0-10)



Aubergine: Although some damage was noted on 22 February (Figure 19), this was restricted to very few plants and it did not trigger assessments. Monitoring continued for a further 21 weeks but no further damage to leaves was recorded. Throughout this period, there was no evidence of the severe stem damage that had been recorded on this site in previous seasons. The aubergine trial was eventually aborted.

Figure 19. Damage to leaves of untreated aubergine plants on 22 February 2008.

Statistical analysis:

Three separate analyses were conducted on the cucumber data:

1. An analysis of variance of the basic experimental design excluding untreated plants.
2. An analysis of covariance of the basic data using the combined scores of the adjacent untreated plots as a covariate.
3. An analysis of variance of the original data supplemented by the control data corresponding to the four experimental blocks.

In the first and second analyses only the Ferramol treatments are compared; for the second analysis some adjustment is made to the means depending on the level of damage to the surrounding 'control' plots. The third analysis compares the treatments and the control. Note that although there were 10 untreated plots, only eight of them are included in the last analysis as two of the untreated plots fall between blocks (see Figure 16).

Results and Discussion:

The mean damage scores to the lower leaves of the untreated cucumber plants and to the plants treated with three rates of Ferramol pellets are shown in Table 3.

Table 3. Mean damage scores to lower leaves of untreated plants and to plants treated with three rates of Ferramol pellets.

	Treatment rate (g / plant):			
	0	0.5	1.0	2.5
Mean damage index	4.08	1.12	0.52	0.25
Percentage of control	100	27	13	6

In the first analysis only the three Ferramol treatments are compared. The damage index means for the three treatments are 1.12, 0.52 and 0.25 for increasing dose levels with an sed of 0.277 (d.f. = 6). The difference between the treatments is just formally significant (p = 0.049), although the linear contrast (effectively the regression on order 1, 2 and 3) is significant at p = 0.020.

The analysis of covariance in the second analysis is not particularly helpful in that adjusting the treatments for the scores on the untreated plots has no overall effect on the analysis. The output shows that the 0.5g mean increases while the 1.0g mean decreases, but the sed increases so nothing is gained.

In the third analysis the treatment means are the same and the mean for the control is 4.08. The sed for comparing the treatments to the control is 0.873 (d.f. = 13) confirming the highly significant difference (p < 0.001) between the control and the mean of the treatments. However, the sed for treatments is 1.008, nearly four times that in the original analysis, so that the distinction between the treatment means can no longer be sustained. The reason for this change is the much greater variability in the controls than in the treated plots. Transforming the scores to log (scores) overcomes this by compensating for the higher variability on the controls, so that the linear trend across Ferramol treatments is now significant (p = 0.002).

In conclusion, analysis of variance shows that there is a marginal difference between the damage scores on cucumbers when treated with different levels of Ferramol pellets but that all the Ferramol treatments had a marked effect relative to the untreated control.

On 22 February (*i.e*. 16 days post-treatment), the pellets were breaking down and were covered in mould growth (Figure 20).

Figure 20. Condition of pellets on 22 February

Added value from *Phytoseiulus persimilis*

Background

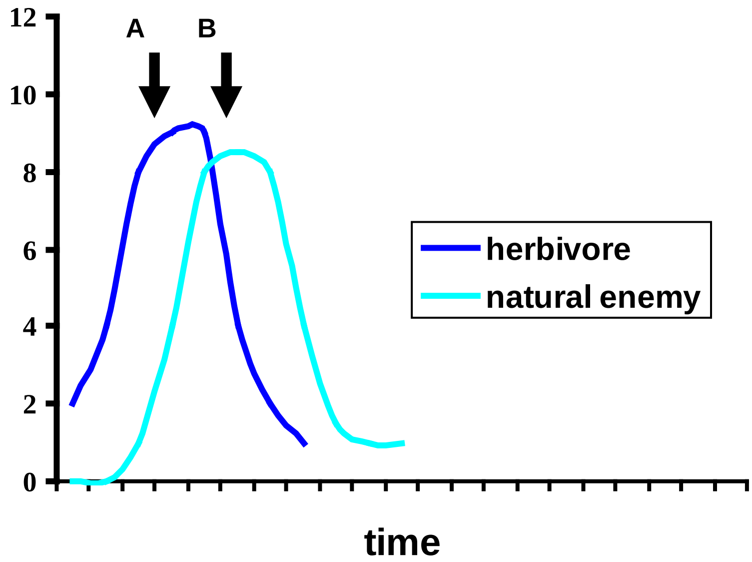
Phytoseiulus persimilis products

Standard bean-reared *Phytoseiulus persimilis* are notoriously slow to establish on tomato plants. This is due at least in part to the presence of glandular trichomes on the surface of the plant which release exudates that are toxic to many invertebrate species. Drukker *et al.* (1997) demonstrated that *P. persimilis* could adapt their behaviour and eventually become acclimatised to this hostile environment. Croft *et al.* (1999) subsequently showed that the population growth of *P. persimilis* reared on tomato plants for more than five generations was greater than that of standard bean-reared predators. However, it was considerably more expensive to rear *P. persimilis* on tomatoes than on beans and this was reflected in the unit price of the products. As a compromise, some biocontrol producers began to supply “tomato-conditioned” *P. persimilis*. Such predators may have been held as stock cultures on tomato plants and numbers boosted on bean plants before dispatch to the customer. Alternatively, they may have been held as stock cultures on beans and then passed through a single generation on tomato plants before sale. The cost-effectiveness of the use of tomato-conditioned *P. persimilis* was evaluated in this project.

Harvesting Phytoseiulus persimilis from commercial crops

The use of inundative biological control in single season crops, such as glasshouse-grown tomato, inevitably leads to distinct peaks in pest and natural enemy population development. Figure 21 shows a hypothetical but typical scenario. The pest arrives in the crop and numbers rapidly increase in the absence of any natural constraint. There is usually a short delay before natural enemies are released and begin to feed on the pests. The natural enemies then start to produce offspring but there is a further delay before the population growth of the pest becomes constrained (*i.e.* Point A in Figure 21). The pest numbers then crash leaving a substantial population of natural enemies without any prey. The latter remain in the crop for a short time before dying of starvation or dispersing in search of prey elsewhere (*i.e.* Point B in Figure 21).

Figure 21. Hypothetical representation of herbivore and natural enemy population trends in a single season crop (nb: vertical scale indicates population size in arbitrary units)



In an earlier phase of this project, it was shown that *P. persimilis* could be successfully collected from a commercial crop when the predator population was equivalent to point B in Figure 21 (Jacobson & Morley, 2007). The following two factors were critical to the success of the technique:

1. Spider mites, and therefore *P. persimilis*, are attracted to young side shoots in the upper parts of the plants.
2. When in dispersal mode, *P. persimilis* climb to the highest available point.

The side shoots, which are routinely removed during crop work, were collected separately from other crop debris and stored in crates in the glasshouse. Small conical cups were then placed on the top of vertical canes within the plant debris (Figure 22). The predators climbed the canes and were collected in the cups

Figure 22: Collection of *Phytoseiulus persimilis* from side shoots routinely removed from tomato plants

Implications of harvesting natural enemies from commercial crops

Harvesting large numbers of natural enemies from commercial crops offers an obvious short term financial benefit to growers. However, it is important to remember that these individuals are properly tomato-reared and could therefore have considerable added value compared to both the standard bean-reared and tomato-conditioned *P. persimilis* products.

In 2008, Ms Jade Taylor (Imperial College, London) completed a comparison of standard bean-reared *P. persimilis*, tomato-conditioned *P. persimilis* and harvested *P. persimilis* under the guidance of Dr Jacobson as a "spin off" from this project. Ms Taylor's report was submitted in partial fulfillment of the requirements for the degree of Master of Science of Imperial College London (Taylor, 2008). A summary of her work is provided below.

Objective:

The overall aim of the study was to estimate the population growth of *P. persimilis* produced from three different types of cultures when each was released on tomato plants to control established populations of spider mites. The study compared two commercially available *P. persimilis* products (*i.e.* standard bean-reared and tomato-conditioned) with *P. persimilis* harvested from commercial tomato crops.

Approach:

The study was based on a series of laboratory bioassays which recorded the following key factors in *P. persimilis* population growth over a five day period:

- Fecundity (via oviposition rate).
- Adult survival.
- Offspring survival.

The bioassys were done on *P. persimilis* harvested from a commercial tomato crop (referred to as tomato-recycled), tomato-conditioned *P. persimilis* as delivered from the supplier and standard bean-reared *P. persimilis* as delivered from the supplier. In addition, the standard bean-reared *P. persimilis* were allowed to breed on tomato plants and the same bioassays were done on their first and second generation offspring. Each bioassay on each type of predator was replicated 20 times giving a total of 100 replicates. Data were statistically analysed using R.2.4.1 (R Development Team, 2007) under the guidance of Dr Alan Jones, Imperial College, London.

A simple mathematical model, based on an original developed by Dr John Fenlon (see Croft *et al.,*1999), was then used to predict the potential increase in *P. persimilis* numbers over one generation. The model ($500n_1p_1p_2$) took into account the number of eggs laid per day (n_1), the proportion of adults assumed to survive over five days (p_1) and the proportion of eggs assumed to survive to maturity (p_2).

The bioassays

Tomato leaves infested with *Tetranychus urticae* were cut from the host plant and placed dorsal side down on damp filter paper (12cm diameter) within 15cm Petri-dishes. An individual adult female *P. persimilis* was placed on each leaf. This was replicated 20 times for each of the five *P. persimilis* rearing methods. The experimental dishes were kept at 22^{o}C +/- 1.5 ^{o}C and 70% RH +/- 5% for 5 days. Extra *T. urticae* were added to the dishes throughout the experiment to ensure that the predators were not deprived of prey.

In the first series of bioassays, the numbers of eggs laid were recorded every 24 hours. Data from *P. persimilis* which did not survive the experiment were excluded from the analysis as adult mortality was taken into account in a later bioassay.

In the second series of bioassays, the status (*i.e.* live or dead) of the adult *P. persimilis* was recorded at 24 hour intervals for 5 days. There were 20 replicates of each type of *P. persimilis*.

In the third series of bioassays, experimental dishes were set up as described above and the number of *P. persimilis* eggs that hatched was recorded at 24 hour intervals. After 5 days, the adult *P. persimilis* was removed and the remaining eggs were left to hatch over a further 3 days. The numbers of unhatched eggs, surviving nymphs and dead nymphs were recorded at the end of the experiment. There were 20 replicates of each type of *P. persimilis*.

Results:

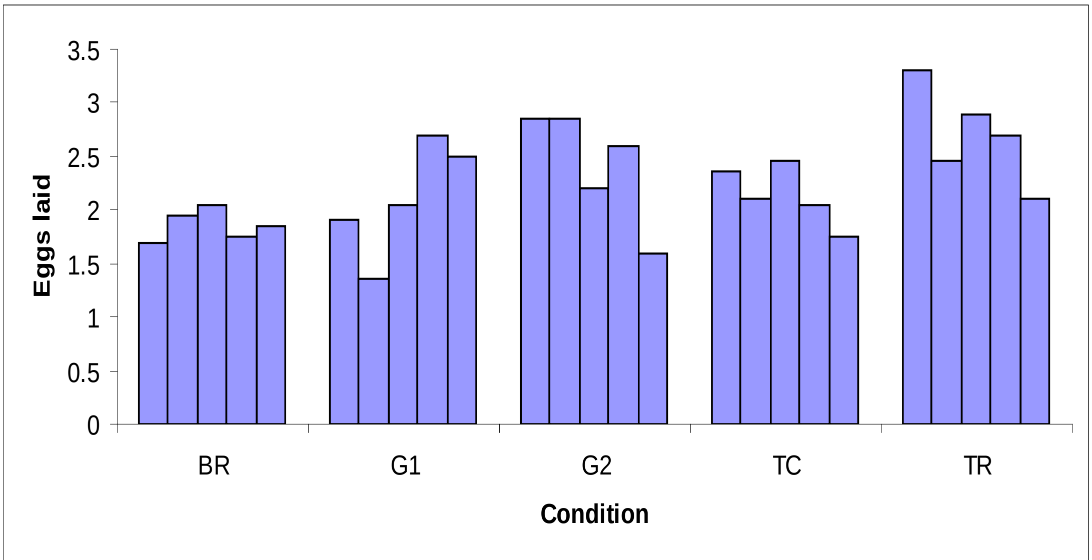
Phytoseiulus persimilis fecundity

The average number of eggs laid per female *P. persimilis* during the experiment (Figure 23) gradually increased from bean-reared (BR) (9.3 eggs / female), through first generation bean-reared (G1) (10.5 eggs / female) to second generation bean-reared (G2) (12.1 eggs / female). Tomato-conditioned (TC) *P. persimilis* had a similar mean (10.7 eggs / female) to the first generation bean-reared data. Tomato-recycled (TR) individuals produced the greatest number of eggs (13.45 / female).

Analysis using a generalised linear model with poisson errors showed that second generation and tomato-recycled *P. persimilis* fecundity was significantly higher than bean-reared individuals. First generation bean-reared and tomato conditioned fecundity was not significantly different from bean-reared individuals. Further analysis by ANOVA showed that the five rearing conditions had a highly significant effect on the fecundity of *P. persimilis* ($f = 4.53$, $df = 95$, $p = 0.0012$).

The time from release of the *P. persimilis* had no overall influence on the daily fecundity of the predators (Figure 24) ($f = 2.18$, $df = 494$, $p = 0.1393$). However, when interacting with rearing condition, time did have a significant influence ($f = 3.80$, $df = 490$, $0 = 0.0043$) with tomato-recycled *P. persimilis* (TR) producing most eggs immediately after release.

Figure 24. Average number of *Phytoseiulus persimilis* eggs per day for each rearing condition (NB - Each bar represents one day starting with the first 24 hour period after release of the predators to the left and the fifth 24 hour period to the right)



Adult survival

Bean-reared adult females had the lowest survival when transferred to tomato plants (75%), whilst their first generation and second generation offspring both had a survival rate of 90%. Tomato-conditioned adult females had a survival rate of 85% and tomato-crop recycled adult females had the highest survival rate of 95%. However, analysis using ANOVA / generalised linear model showed that these apparent trends were not significantly different ($f = 0.982$, $df = 4$, $p = 0.4158$).

Offspring mortality

Analysis using a generalised linear model showed that second generation and tomato-recycled individuals' offspring had a significantly higher survival rate (99.62% and 98.76% respectively) than bean-reared individuals' offspring (94.07%). First generation and tomato-conditioned individuals' offspring survival were intermediate and not significantly different from the bean-reared sample. Further analysis by ANOVA showed that the five rearing conditions had a highly significant effect on the offspring survival of *P. persimilis* ($f= 4.0243$, $df = 95$, $p = 0.0029$).

Population growth model

The population growth model predicted that 100 females of each of the five types of *P. persimilis* would produce the following numbers of offspring over five days. The figures in curved brackets show each result as a multiple of the starting population. The figures in square brackets show all results as multiples of the standard bean-reared predators.

Standard bean-reared	656	(6.6x)	[1.0x]
Tomato-conditioned	884	(8.8x)	[1.3x]
Standard bean-reared – first generation	922	(9.2x)	[1.4x]
Standard bean-reared – second generation	1076	(10.8x)	[1.6x]
Tomato-recycled	1273	(12.7x)	[1.9x]

Conclusions

Based on the above data, it can be seen that the rate of population growth of standard bean-reared *P. persimilis* increases over the first two generations on tomato leaves from 6.6x to 9.2x for the first generation and to 10.8x for the second generation. This trend was broadly consistent with the results of previous studies (Drukker *et al.,* 1997; Croft *et al.,* 1999) given that the experiments had been done on different tomato cultivars and under different conditions.

The population growth of tomato-conditioned *P. persimilis* (8.8x) was similar to the standard bean-reared predators after the latter had completed one generation on tomato leaves (9.2x). As they were not fully conditioned to the host plant, it is reasonable to assume that their performance would have continued to improve.

If we consider the rate of population growth of standard bean-reared *P. persimilis* to be the norm, then numbers of tomato-conditioned predators should increase about 33% more rapidly. However, the retail cost of tomato-conditioned *P. persimilis* is approximately 50% greater than the standard bean-reared product, so we could buy 1,500 standard bean-reared *P. persimilis* for the same cost as 1,000 tomato-conditioned predators. The question is "which option offers the best value for money?"

Let us first consider standard bean-reared *P. persimilis*; 1.5k purchased females should increase by 6.6 fold to produce 9.9k first generation offspring and then by 9.2 fold to produce 91.1k second generation offspring. By comparison, 1.0k purchased tomato-conditioned *P. persimilis* should increase by 8.8 fold to produce 8.8k first generation offspring. It is reasonable to assume that the population growth of these individuals would be equivalent to the second generation bean-reared predators and so their numbers should increase 10.8 fold to give 95k second generation offspring. While it is acknowledged that these calculations are based on a number of assumptions, the results do seem to suggest that the tomato-conditioned predators provide marginally better value for money.

The situation is very different when we consider the performance of the predators harvested from commercial tomato crops. These individuals have been reared on tomato plants for several generations and numbers could increase 12.7 fold over each subsequent generation. Therefore, 1.0k released females should produce 161.3k second generation offspring.

The method of collecting *P. persimilis* from a commercial tomato crop involves very little additional labour; hence the predators are virtually free to the grower. In addition, the above study shows that they are considerably more productive than the purchased products.

Our whole approach to IPM of spider mites could change to accommodate these findings. For example, the first seasonal releases of natural enemies in each season could have two functions:

1. To control those specific pest infestations
2. To establish biocontrol cultures that can be harvested at a later date.

On this basis, growers could greatly increase the numbers of *P. persimilis* released at the start of the season in the knowledge that the investment could yield considerable financial savings at a later date.

Control of leafminer by the combined use of *Diglyphus Isaea* and *Macrolophus Caliginosus*

Background:

Diglyphus isaea has been the principal biocontrol used against leafminer in recent years. However, the final flush of leafminer activity before control is achieved has consistently caused an unacceptable amount of foliar damage in the more vulnerable cultivars (*eg* cv Piccolo). One possible means of reducing the impact of this final flush of leafminer is to release more *D. isaea* when the threshold is reached. To date, there has been an understandable reluctance by growers to do this because the product is relatively expensive. However, the newly developed techniques for collecting *D. isaea* from areas of surplus for release elsewhere (Jacobson & Morley, 2007) now mean that growers can recover their early season financial outlay.

Another possible means of reducing the impact of this pest is to supplement the activity of *D. isaea* with another natural enemy. All mobile stages of *Macrolophus caliginosus*, from the first instar to the adult, are voracious predators and will feed on many pest species, including leafminers, spider mites and whiteflies. Previous studies in this project and PC 251/251a have shown that when *M. caliginosus* are present in sufficient numbers they can make a substantial contribution to the control of all these pests. A trial in 2007 monitored establishment in cv Piccolo from releases made in week 8 (Jacobson & Morley, 2007). The population remained very low for about 12 weeks, which is estimated to be the time required for the predator to complete two generations at this time of year. The predators were then numerous for the remainder of the season. With hindsight, we believe that the predators should have been released earlier in the season.

The present trial investigated the independent and combined benefits of new / modified *D. isaea* and *M. caliginosus* strategies.

Objective:

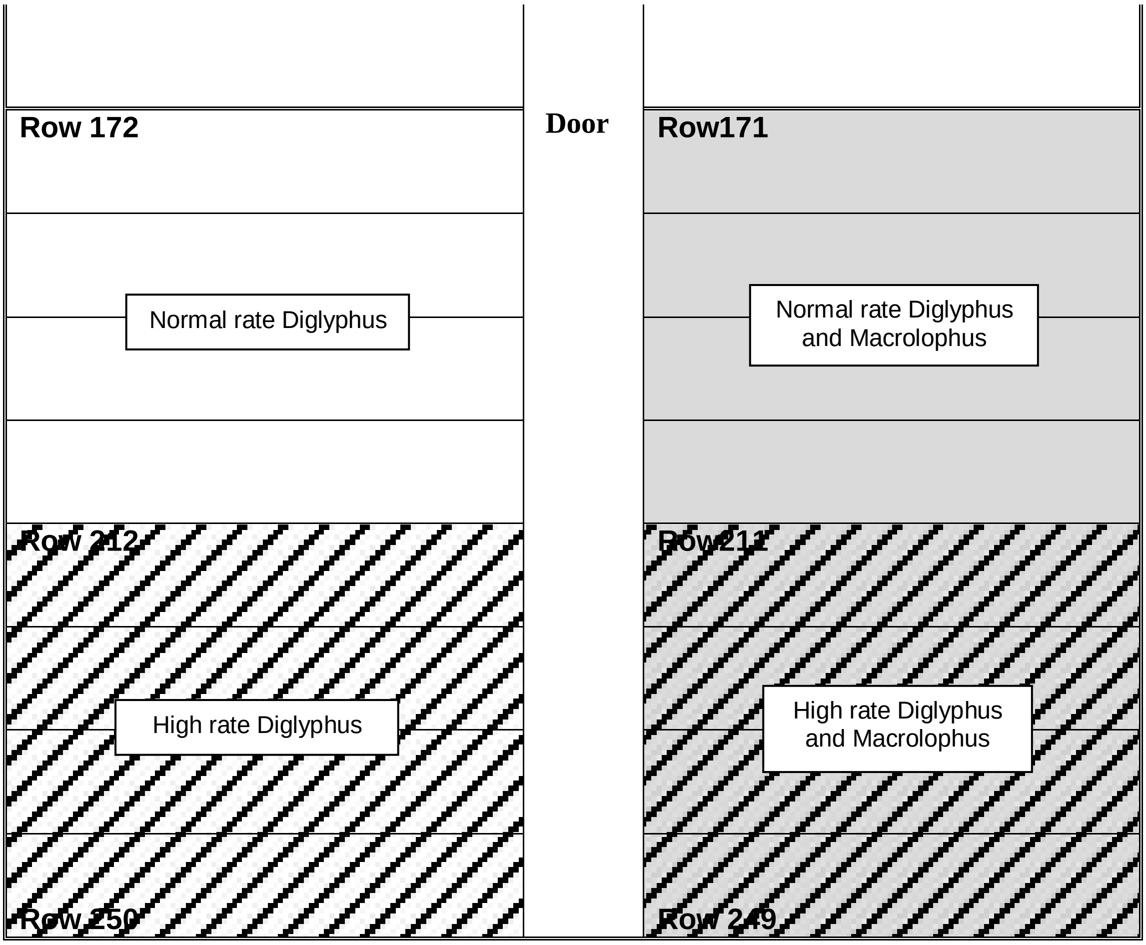
The overall objective was to evaluate the control of leafminer in cv Piccolo using a combination of higher than normal releases of *Diglyphus isaea* and early season releases of *Macrolophus caliginosus.*

Materials and method:

Layout of trial

The trial was done in a crop of organic tomato (cv Piccolo). The young plants were stood out in week 50 2007 and were planted into the soil in week 2 2008. The crop was approximately 10,000m^2 and consisted of 72 (double) rows, orientated north east to south west and bisected by a longitudinal concrete road (Figure 25). Due to the mobility of the pest / biocontrol agents, the crop was divided into four large plots and assessments were concentrated in the central area of each.

Figure 25. Layout of plots in glasshouse



Biological control agents:

Five thousand *M. caliginosus* were released to the south west side of the central road (ie odd numbered rows from 171 to 249) in week 52 (crop week 2) providing a density of one *M. caliginosus* per m^2 in that area.

Small numbers of *D. isaea* were released locally between week 52 and week 4 but the first main release was made when the leafminer population reached the pre-determined threshold of one active mine per 1-2 plants (Jacobson & Morley, 2006) in week 6. They were released at the approximate rate of 2 *D. isaea* / m^2 in half of the crop (rows 212 to 250) and at the normal rate of 1 *D. isaea* / m^2 elsewhere.

Assessments:

The normal weekly leafminer monitoring was done by crop staff to determine when the pest reached the *D. isaea* release threshold. The initial interpretation of the monitoring data was done by Mr Brian Moralee (WSG) and Mr Mark Jones (Biological Crop Protection).

Macrolophus caliginosus monitoring stations were established at four points in each of seven rows in the release area (*i.e.* 28 in total) and the same (as a mirror image) in the untreated area of the house. Numbers of *M. caliginosus* were initially recorded at three week intervals using the now standard sampling method developed earlier in this project (Jacobson & Morley, 2006). The sampling frequency was reduced to two week intervals as the season progressed and the speed of *M. caliginosus* population growth increased.

Diglyphus isaea establishment was monitored from week 7 by collecting 50 leaflets containing partially developed mines from each of the four plots. These were examined under the microscope and the following were recorded: number of mines, number of active leafminer larvae, number of leafminer pupae, number of leafminer larvae killed by either *M. caliginosus* or *D. isaea*, and number of immature *D. isaea.*

Although *D. isaea* were well established by week 15, adult leafminers continued to feed in the heads of the plants for several weeks and this lead to a resurgence of larval activity in some areas of crops. This continued until week 25 but then declined and the tops of all plants were completely free of leafminer damage by week 28. Three additional leafminer assessments were done to quantify this continued leafminer activity:

1. Week 18 - Numbers of leafminer larvae completing their development to the pupal stage (thus escaping *D. isaea*).
2. Week 21 – Numbers of adult leafminers active in the tops of plants and the number of

feeding punctures on leaves.

3. Week 25 – Mean number of partially developed mines on the leaves initially sampled in week 21.

The presence of *M. caliginosus* in the crop had secondary benefits in terms of spider mite control. To quantify this effect we drew on the nursery's own spider mite recording data, which used a severity index of 0-10. For each week in which spider mite monitoring was done, we calculated the sum of the severity index recorded in all patches. This continued until week 24.

Results and Discussion:

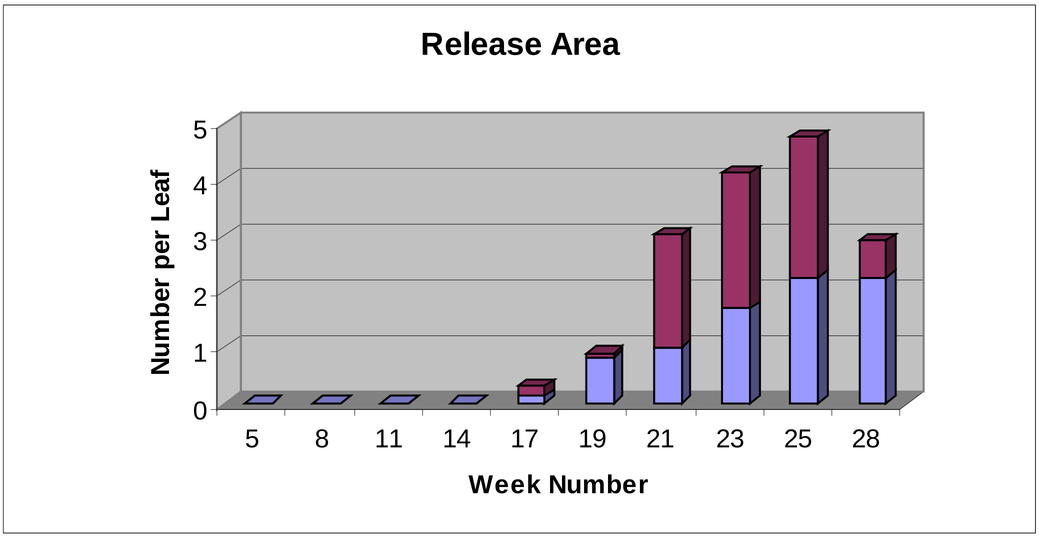
Macrolophus population growth:

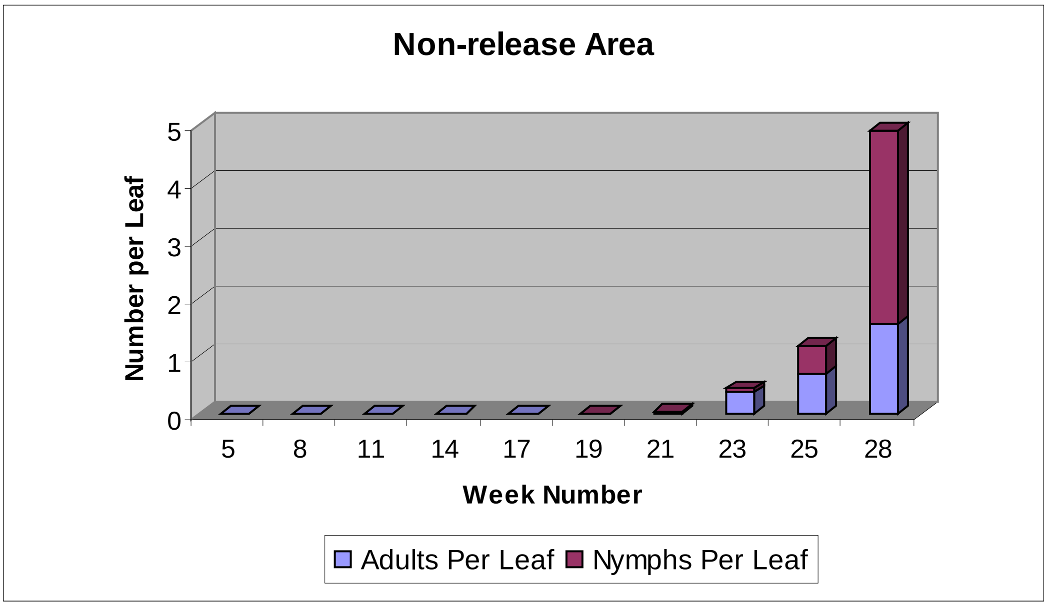
Some *M. caliginosus* will have survived from the previous season. The impact that their numbers had on the overall population growth may be gauged from the untreated "non-release" area (*i.e.* even numbered rows from 172 to 210).

The growth of the *M. caliginosus* populations during 2008, in the areas where it was and was not released, are shown in Figure 26. Where they were released, numbers remained very low until week 17, *i.e.* approximately 18 weeks from the time of release. The delay until the predator could be easily found was six weeks longer than it had been in 2007. The initial release had been made in week 8 in 2007 and it would therefore appear that releasing the predators nine weeks earlier in 2008 had only provided a measurable benefit of three weeks in the crop. After week 17, the population grew rapidly until week 27 when truss damage was noted and the population had to be culled with natural pyrethrins.

In contrast, numbers remained very low in the non-release area until week 23 when they started to migrate across the glasshouse from the release area. This movement was obvious from the pattern of establishment. Thereafter, the population increased rapidly in that area.

Figure 26. ***Macrolophus*** **population growth during 2008 in the areas where it was released and was not released.**





Leafminer development:

The numbers of new mines, active leafminer larvae and leafminer pupae are shown for the four treatment areas in Figure 27. The numbers of leafminer larvae killed by *D. isaea* and *M. caliginosus* are shown for the four treatment areas in Figure 28, as are the numbers of live immature *D. isaea* within the mines.

Figure 27. Mean numbers of new mines, active leafminer larvae and leafminer pupae per leaflet in the four treatment areas.

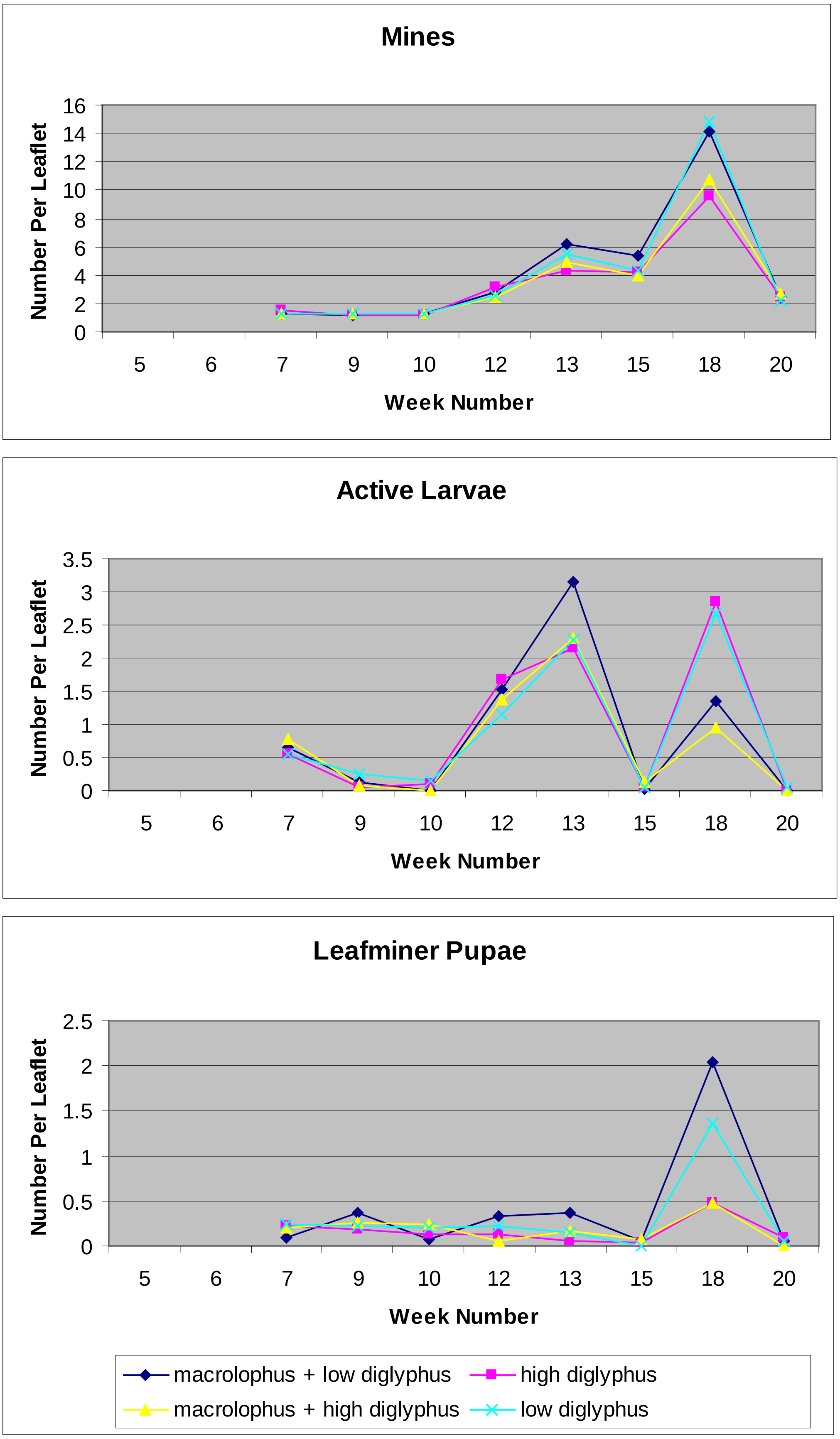
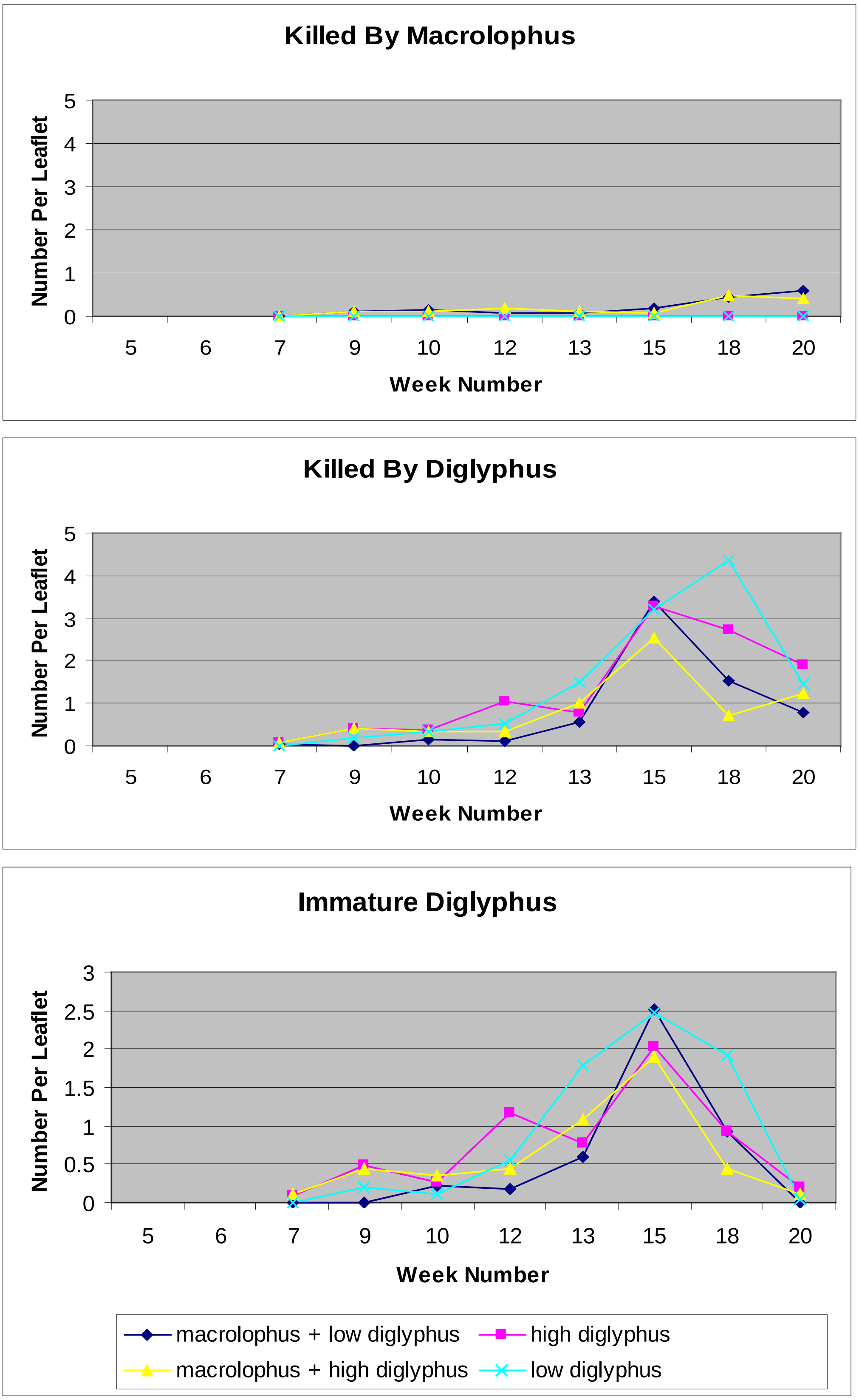


Figure 28. Mean numbers of leafminer larvae killed by *Diglyphus isaea* and *Macrolophus caliginosus*, and numbers of live immature *Diglyphus* within mines per leaflet in the four treatment areas.



The leafminer population peaked between weeks 13 and 18. The *D. isaea* population peaked slightly later and then crashed between weeks 18 and 20. It would appear that *M. caliginosus* had little impact on the leafminer population up to this point and there was little difference between the four treatments.

A more detailed illustrated history throughout the critical period, including the degree of plant damage, is provided below.

Illustrated notes to support monitoring data and results of assessments:

<u>Week number 13</u>

The situation was similar in all treatment areas in week 13. The general condition of the crop is illustrated in Figure 29. A lot of leaf had been left on the plants to retain immature *D. isaea* at this critical time. Normal deleafing resumed in week 14.

The typical amount of foliar damage on leaves in the position shown in Figure 29 is inset. This was the most serious damage seen in the crop so far this season but it was still acceptable. Note that the leaves were large and each was carrying about 60-80 mines.

Figure 29 – Condition of crop in week 13 and typical damage at sample point.

This was considered to be a critical time for *D. isaea* establishment and additional assessments were done to provide crop managers with extra information between weeks 13 and 15. The numbers of live leafminer larve, leafminer pupae and immature *D. isaea* per leaf are shown for the four treatment areas in Table 4. In addition, the ratios of leafminer larvae to leafminer pupae and *D. isaea* are shown in the same table.

Table 4. Mean numbers of live leafminers and *Diglyphus isaea* per leaf in each of the four treatment areas.

Treatment	Mean numbers per leaf:			Ratio of: Im larvae : Im pupae : Diglyphus
	Live leafminer larve	Leafminer pupae	Live immature Diglyphus	
Macro + low Dig	8.5	1	33	1 : 0.1 : 3.9
Macro plus high Dig	4	0	20	1 : 0.0 : 5.0
Low Dig	3.5	2	15	1 : 0.6 : 4.3
High Dig	5	1	26	1 : 0.2 : 5.1
Overall mean	5.2	1	23.3	1 : 0.2 : 4.5

Over 90% of mines contained dead leafminer larvae and there were very few leafminer pupae in the crop. There was no obvious treatment effect at this point. The ratios of pests to parasites (*i.e.* 1 : 4.5 overall) would normally have indicated that the pest was now under control. However, we had learned to be cautious in interpreting the success of *D. isaea* in cv Piccolo and monitoring continued.

There was some evidence of *M. caliginosus* feeding on leafminer larvae but no individuals were seen during this assessment. The timely release of *D. isaea* appears to have been the most important factor up to this point in time.

<u>Week number 15</u>

The monitoring results in week 15 showed excellent *D. isaea* establishment and very few live leafminer larvae or pupae. However, there was a flush of leafminer adults at the top of the plants and numerous feeding punctures (Figure 30). Nonetheless, adult *D. isaea* were easily found on leaves and this was assumed to be the final flush of leafminer activity.

Figure 30. Feeding punctures at top of the crop in week 15

Week number 18

Assessments in week 18 surprisingly showed that some leafminers had completed their development despite the presence of large numbers of *D. isaea* and increasing numbers of *M. caliginosus*. The feeding punctures shown in Figure 30 had given rise to more mines than anticipated; a typical leaf, now one third of the way down the plant, is shown in Figure 31. Closer inspection of a leaflet revealed that many mines had started to develop but most were stopped at an early stage.

Nonetheless, some leafminers had completed their development and this was quantified by counting pupae on 50 leaflets in each of the four treatments. The results of this assessment, which are shown in Figure 32, indicated that *M. caliginosus* was beginning to have an impact on the leafminer population and the tops of the plants in the *M. caliginosus* release areas were finally beginning to improve (Figure 33).

Figure 31. Leafminer development between weeks 15 and 18 on the leaves previously illustrated in Figure 30 (NB. Now positioned approximately 0.9m from the top of the crop). The lower image shows that many of the leafminer larvae had been killed by adult *Diglyphus isaea.*

Figure 32. Mean numbers of leafminer pupae / leaflet in each Treatment in wk 18.

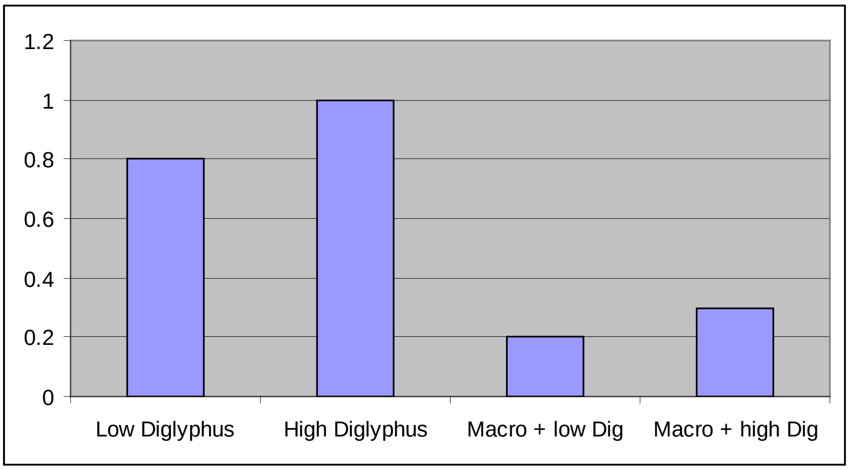


Figure 33. Typical leaf from the top of a plant in the *Macrolophus caliginosus* release area in week 18.

<u>Week number 21</u>

Adult leafminers were still active in the tops of the plants in week 21. Although they were producing feeding punctures, few mines were developing from them. Adult *D. isaea* were also numerous but there were now few immature parasites due to the lack of prey.

There was now a large difference in the numbers of *M. caliginosus* in the release and non-release areas (Figure 26) but it was not clear whether the predator population had built up in time to have an impact on leafminer population. A one-off assessment was therefore done to record the numbers of adult leafminers and feeding punctures throughout the glasshouse. Within each of the four treatment areas, 100 fully expanded leaves, positioned approximately 200mm from the top of the plants, were chosen at random and the numbers of adult leafminers were recorded. The mean numbers are shown in Figures 34. In addition, 100 leaflets were chosen at random from the same crop stratum and the numbers of feeding punctures were recorded on each (Figure 35). These data indicate that *M. caliginosus* did have an impact on the leafminer population growth between weeks 15 and 21.

Figure 34. Mean numbers of adult leafminers in each Treatment in week 21.

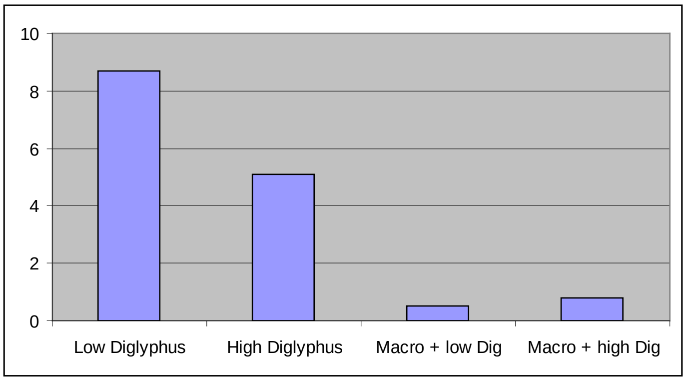
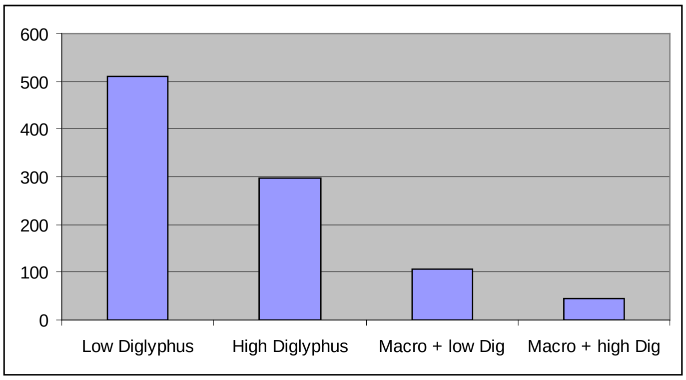


Figure 35. Mean numbers of adult leafminer feeding punctures in each Treatment in week 21.



<u>Week number 25</u>

Leafminers were still present in the crop in week 25. It was immediately obvious that very few mines had developed from the feeding punctures previously reported in week 21 in the *M. caliginosus* release area while a considerable number of mines had developed in the non-release area. An additional assessment was devised to quantify this. The stratum of the crop now containing the leaves which had been assessed in week 21 (Figures 34 and 35) was identified and fifty terminal leaflets were collected at random from each Treatment area. The mean numbers of whole or partially developed mines were recorded on each and these data are shown in Figure 36. There was a very clear difference in the *M. caliginosus* release and non-release areas. This is further illustrated in Figure 37.

No adult leafminers were now present in the tops of the plants in the *M. caliginosus* release areas but it was intriguing to still see them in the non-release areas. Generally, the plants in the non-release area were now weaker than those in the release area, which was presumed to be due to the prolonged leafminer attack.

Figure 36. Mean numbers of whole and partially developed mines recorded on terminal leaflets (n=50) in all Treatment areas in week 25.

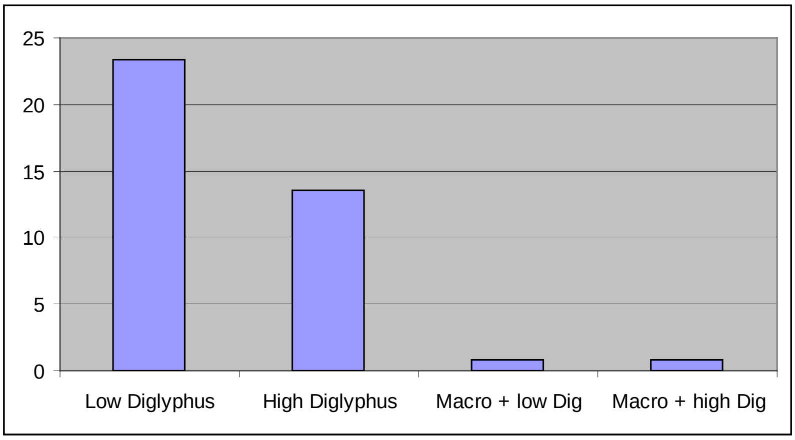


Figure 37. Examples of condition of leaves in the mid-stratum of the crop in the *Macrolophus caliginosus* release (upper image) and non-release (lower image) areas in wk 25.

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Week number 28

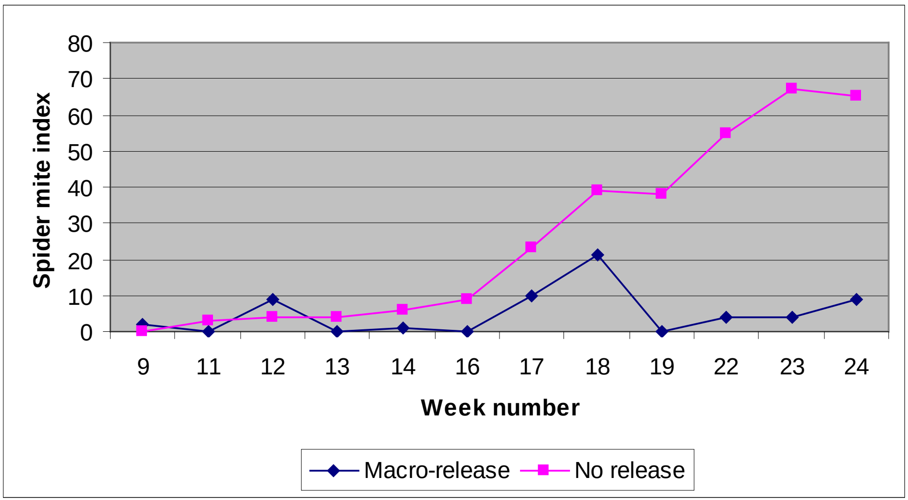
By week 28, *M. caliginosus* had spread throughout the non-release areas and the leafminer populations were finally under control. There was now no evidence of any leafminer activity in the tops of the plants anywhere in the glasshouse.

Summary of effect of Macrolophus release on spider mites:

We first became aware of an apparent effect of the released *M. caliginosus* on the spider mite population growth in week 21. To quantify this effect we drew on the nursery's own spider mite recording data, which used a severity index of 0-10. For each week in which spider mite monitoring was done, we calculated the sum of the severity index recorded in all patches. Figure 38 shows the results of these assessments between weeks 9 and 24. Thereafter, it became difficult to make a sensible interpretation of the monitoring results because localised areas were being treated with Eradicoat T.

The scores from the spider mite severity index were comparable in both areas until week 18. Thereafter, *M. caliginosus* numbers rapidly increased in the areas where it had been released (Figure 26) and there was a corresponding crash in the spider mite population. In contrast, the spider mite population continued to increase in the areas where no *M. caliginosus* had been released until week 23 when localised applications of Eradicoat T began.

Figure 38. Spider mite severity index in the areas that *Macrolophus caliginosus* was released and not released between weeks 9 and 24 2008.



Overall summary and conclusion:

- There was no apparent Treatment effect to week 13 and control of leafminer population development to this point was considered to be primarily due to the timely release of *D. isaea* parasites.
- *Macrolophus caliginosus* numbers did not increase significantly until after week 17. It has been assumed that the predator had little impact on leafminer population growth to that point.
- Despite there being large numbers of *D. isaea* in the crop from week 15, adult leafminers continued to cause feeding damage in the tops of the plants and a significant number of larvae survived to cause foliar damage as the plants grew.
- By week 18, *M. caliginosus* had begun to have an impact on this persistent leafminer infestation and the pest was coming under control in the “release area”. However, leafminer damage continued in the “non-release area” until after week 25 and it was week 28 before it was finally brought under control.
- *Macrolophus caliginosus* had a secondary effect on spider mite population growth in the “release area” and this provided considerable benefits from week 18 onwards.

In conclusion, the trial demonstrated that the combined use of *D. isaea* and *M. caliginosus* provided improved control of leafminers in cv Piccolo and additional benefits in improved control of spider mites.

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APPENDIX 1

Comparative susceptibility of 30 cultivars of speciality tomatoes to four important pest species.

Category	Cultivar	Seed House	Susceptibility ranked on 1-5 scale with grade 3 being the standard:			
			Leafminers	Whiteflies	Spider mites*	Macrolophus
Cherry	Claree	EZ	3-4	4**	4*	5
	Conchita	DRS	3-4	4**	4*	5
	Jenita	DRS	3-4	4**	4*	5
	Nectar	DRS	3-4	4**	4*	5
Baby cherry	Piccolo	Gautiers	5	4**	4	5
Santa (Baby plum)	Santa	SAK	2	4**	4	2
	Santolina	Westerns	2	4**	4	2
	Dasher	DRS	2	4**	4	2
	WSS1704	EZ	2	4**	4	2
Baby plum; yellow	Yellow Santa	T	2	4**	4	2
Baby plum	Petite Cherie	T	4	4**	4	4
Midi-plum	Romalina	Westerns	3	4	3	3
	Daydream	EZ	3	3	3	3
Midi-plum; yellow	Amber Jewel	Br	3	3	3	3
Midi-plum; vine	Sunstream	Br	2	3	3	3
Classic	WSR16.04	EZ	2	3	3	3
	Honey	EZ	2	3	3	3
	Dometica	RZ	2	3	3*	3
	Delicimo	RZ	2	3	3	3
Classic vine	Admiral	RZ	2	3	3	3
	Cheem	Br	2	3	3	3
	Elegance	DRS	2	3	3*	3
	Temptation	EZ	2	3	3*	3
	WST 1604	RZ	2	3	3*	3
Cocktail loose	Capri	SG	5-5	4	4	4
Cocktail vine large	Campari	EZ	4	4	4	4
Cocktail vine	Caran	EZ	4	4	4	4
	Aranca	EZ	4	4	4	4
Beef	Jack Hawkins	SS	2-3	3	3	3
Novelty	Tiger Soul	Br	3	3	3	3

* considered to be particularly susceptible to hyper-necrosis
** due to deleafing strategy