Grower Summary

Application and Management of Biopesticides for Efficacy and Reliability (AMBER)

CP 158

Final report 2023

Project title:	Application and Management of Biopesticides for Efficacy and Reliability (AMBER)
Project number:	CP 158
Project leader:	Dr David Chandler University of Warwick Warwick Crop Centre, School of Life Sciences, University of Warwick, Wellesbourne, Warwick CV35 9EF UK
Report:	Annual report, January 2023
Previous report:	Annual report, January 2020
Key staff:	Jude Bennison Clare Butler Ellis John Clarkson Roma Gwynn Rob Jacobson Andy Lane Elysia Bartell Gill Prince David Talbot Erika Wedgewood
Location of project:	University of Warwick Warwick Crop Centre, School of Life Sciences, University of Warwick, Wellesbourne, Warwick CV35 9EF UK
Industry Representative:	Rob James, Thanet Earth Marketing Ltd, Barrow Man Road, Birchington, Kent, UK, CT7 0AX
Date project commenced:	1st January 2016
Date project completed	31st December 2020

DISCLAIMER

While the Agriculture and Horticulture Development Board seeks to ensure that the information contained within this document is accurate at the time of printing, no warranty is given in respect thereof and, to the maximum extent permitted by law the Agriculture and Horticulture Development Board accepts no liability for loss, damage or injury howsoever caused (including that caused by negligence) or suffered directly or indirectly in relation to information and opinions contained in or omitted from this document.

© Agriculture and Horticulture Development Board 2022. No part of this publication may be reproduced in any material form (including by photocopy or storage in any medium by electronic mean) or any copy or adaptation stored, published or distributed (by physical, electronic or other means) without prior permission in writing of the Agriculture and Horticulture Development Board, other than by reproduction in an unmodified form for the sole purpose of use as an information resource when the Agriculture and Horticulture Development Board or AHDB Horticulture is clearly acknowledged as the source, or in accordance with the provisions of the Copyright, Designs and Patents Act 1988. All rights reserved.

All other trademarks, logos and brand names contained in this publication are the trademarks of their respective holders. No rights are granted without the prior written permission of the relevant owners.

The results and conclusions in this report are based on an investigation conducted over a one-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.

Signature: Date:

Signature: Date:

GROWER SUMMARY

Headlines

- Spray application: Most biopesticides are applied at a constant dose. There can be a perception among growers that using a high water volume gives better coverage, but this is not true. Spray water volume affects the quantity of biopesticide deposited on the crop even at a nominal constant dose, which in turn affects efficacy. The best strategy is to use a water volume that results in the highest concentration of biopesticide product on the crop. As a general rule, lower water volumes are better. They are also faster to apply and are less wasteful.
- Biopesticides and environmental conditions: The performance of biopesticides is sensitive to environmental conditions such as temperature, humidity, UV light etc. In this report, we provide detailed summaries of the effect of environmental and management conditions on the efficacy for three different biofungicides (*Bacillus amyloliquefaciens*, *Gliocladium catenulatum* and *Ampelomyces quisqualis*) using data from the scientific literature.
- Biopesticide data recording: A new biopesticides management flow chart and data recording form have been written to help growers and agronomists. It allows you to record the information needed to help understand how environmental conditions and management practice affect biopesticide performance on individual crops.
- Biopesticides and temperature: Temperature is a key environmental variable determining the performance of microbial biopesticides. Selecting the best microbial strains to use under the environmental temperatures in the crop is a difficult task for biopesticide companies. Working with fungal pathogens of insects, we have shown that strain selection can be done by measuring spore germination rate in simple petri dish tests. This is far quicker and easier than measuring the effect of temperature on efficacy against target insect pests.
- Biopesticides application model: A computer 'box car' model has been developed that predicts how different application regimes (e.g. timing and frequency of application) might affect bioinsecticide efficacy. The model has been developed first with glasshouse whitefly and peach potato aphid.

Background

AMBER (Application and Management of Biopesticides for Efficacy and Reliability) is an AHDB project with the aim of identifying management practices that growers can use to improve the performance of biopesticide products within IPM. The project has three main parts:

1) to understand the reasons why some biopesticides are giving sub-optimal results in current commercial practice;
2) to research innovations in management practices that can improve biopesticide performance;
3) to exchange information and ideas between growers, biopesticide companies and others in order to provide improved best-practice guidelines for biopesticides.

Biopesticides include a wide range of active substances, including living microbial agents and non-living natural substances. As a rule, they are less 'forgiving' than synthetic chemical pesticides and require more attention to detail to get the best out of them. In AMBER we are developing tools and practices that can be applied to a wide range of biopesticides to improve their use. In this report we give the results from four different work areas:

(1) Studying how applied water volume for nominal fixed dose spray applications influences biopesticide efficacy, to identify the best water volume strategy for different types of crops;
(2) Analysing the scientific literature on microbial biofungicides to summarise the conditions that are best for performance. This was used to develop an improved data recording sheet for growers and agronomists;
(3) Using mathematical models to give new insights on the effects of temperature on microbial agents;
(4) Developing a 'box car' model of the population growth of insect pests that is used to inform biopesticide application strategy, taking into account the different features of the pest and control agent that determine their efficacy.

Making biopesticide spray application more efficient: studying the effect of water volume on biopesticide efficacy

AMBER research on biopesticide spray application has focused on optimising spray water volumes with a range of crop types. This is essential before other methods for improving spray application can be investigated, such as new equipment or application techniques.

Biopesticide sprays are applied in one of two ways of two ways:

1) A constant dose model, in which the total amount of biopesticide applied per ha is set at a fixed amount and the volume of water used for spraying the product is chosen by the spray operator (provided that it stays within a range that has been set by the manufacturer and given on the label). In the constant dose system, the concentration of the product reduces as the water volume increases.
2) A constant concentration model. Here, the concentration is fixed, and there is a minimum and maximum water volume specified on the label, and the spray operator chooses the water volume within these limits. In the constant concentration system, the total amount of product per ha will increase as water volume increases.

Most biopesticides are used at a constant dose, although a few products are now on the market that are applied at a constant concentration.

The label recommendations for biopesticides often specify a high water volume (up to 1500 L per ha) as the upper limit. This is possibly because the labels need to cover a wide range of crop sizes and structures. Unfortunately, data supporting the recommended volumes does not appear to be available, which makes it difficult for the grower to choose the optimum volume for their crop. We have found that there can be a perception among growers that high water volumes give better coverage and penetration into the crop canopy. However, it is known from work with arable crops that lower volumes result in higher quantities of active substance on the crop, when applied at nominal constant dose, and water volume has little effect on penetration. Low volumes are a more efficient method of transferring biopesticide to a crop and result in less waste. However, in the case of biopesticides, a minimum quantity of water may be needed to ensure it performs adequately (e.g. so that it does not dry out too quickly), but there is no information available relating to this. Work in this area is technically difficult and requires specialised facilities, which may explain why it has been given insufficient attention prior to AMBER.

So far in AMBER, we have undertaken studies in two areas:

- Firstly, research was done that measured the relationship between applied volume and the quantity of spray deposited on small pot-grown plants treated with a horizontal boom. Experiments with basil, sprayed with a three-nozzle horizontal boom, indicated that, where the biopesticide is applied at a constant dose, the maximum active substance will be applied using the lowest water volume providing that the maximum label concentration is not exceeded. Where biopesticide products are used at a constant concentration, the maximum volume that should be used is less than 1000 L/ha, and there are likely to be benefits for smaller plants of reducing this down to around 500 L/ha.

- Secondly, research was done on the relationship between applied volume and the quantity of spray deposited for large plants treated with a vertical boom. This was done using a vertical boom track sprayer within an experimental tomato crop. It showed that the quantity of active substance deposited on the plant appeared to be relatively insensitive to volume, although the data had a lot of variability which may be due to the structure of the canopy, which is more complex than short, pot grown plants. The data indicated that the maximum volume that should be used is 1000 - 1500 L/ha *applied to the crop* (rather than calculated per unit floor area). For biopesticide products applied at a constant dose to tall crops, water volume can be reduced from this maximum to suit other needs (such as using a lower water volume to reduce the time needed to spray the crop).

For the current part of AMBER, we investigated the effect of spray volume on biopesticide efficacy against a target pest. A fungal biopesticide (Botanigard) was sprayed onto small tomato plants with a horizontal boom, and then spider mites (*Tetranychus urticae*) were placed on tomato leaflets and their survival was monitored over time. The biopesticide was applied at a nominal constant dose in different water volumes from 250 L per ha to 1500 L per ha with the Silsoe Spray Applications Unit track sprayer. The main findings were as follows:

- The amount of fungus deposited by the spray (measured as numbers of fungal colony forming units, CFUs, from leaves and grown on agar) was much higher on the upper leaf surface than the leaf underside. In some cases, there was clustering of colonies at the edge of the upper side of the leaflets caused by draining of suspension across the leaf. CFUs on the underside of leaflets may have been deposited as a result of drainage of spore suspension to the leaflet edge and then running underneath. This is not unexpected because of the shielding effect of the upper leaf surface, but it does illustrate the challenges of applying an effective dose of a contact-acting biopesticide to the underside of leaves, and this is obviously going to be an issue for target pests and diseases that occupy the leaf underside.
- The numbers of CFU deposited on the upper leaf surface (CFU per cm^2 leaflet surface) varied with increasing water volume although there was no evidence of an effect of canopy position. The highest deposition occurred with 500 L / ha.
- After seven days all application volumes except the untreated control resulted in 70% mortality or higher. There was no difference in the median survival times of spider mites treated with the different volumes of Botanigard, with the exception of the 500 L / ha treatment, in which median survival time was significantly lower than for all other treatments. This is consistent with our finding that 500 L / ha produced a significantly higher concentration of CFUs on the tomato leaflets.

The results suggest that water volume can have affect the quantity of active substance deposited on the crop, with concomitant impacts on efficacy, even when applied at a nominal constant dose. This experiment was technically difficult and to our knowledge this is the first study of its kind with a biopesticide. Through AMBER, we now have the ability to relate efficacy to the quantity of biopesticide active substance deposited on the leaf surface as a result of different spray conditions, which is highly encouraging.

Improving knowledge for growers and agronomists on the conditions needed for getting the best performance from microbial biopesticides

The scientific literature was analysed for three microbial biofungicides on the UK market with recommendations for foliar application to horticultural crops: Serenade ASO, Prestop and AQ10. The information was then used to summarise the conditions in which the organism or the product has been shown to perform. A generic decision tree was developed for what to consider before, during and after using these products, alongside tables which specify the environmental parameters that need to be known. In the Science section of the report, we also provide an example recording sheet to indicate the type of records that would be advantageous to keep, so that when product efficacy is either good or poor they can be referred to and utilised for future applications. Finally, some examples of AHDB reports are given to show where conditions, or the pathogen severity, may have affected the level of control achieved from either of the three products.

For Serenade ASO, Prestop and AQ10:

- There is poor understanding of the physics of spray application, e.g., the pressures, nozzle types and droplet size required to achieve optimum coverage. Efficacy would be increased by improved application techniques. Application to leaf undersides is a challenge.
- The high water volumes which can be used for application, combined with wide plant spacing necessary for particular crops, can mean significant spray waste. Further investigation should look at optimising the level of coverage achieved using lower spray volumes and more efficient methods of delivery.

Bacillus amyloliquefaciens (= *Bacillus subtilis*) used in the biofungicide Serenade ASO

- The product is registered in the UK for the control of grey mould caused by *Botrytis cinerea* in protected strawberry and under permanent protection full enclosure on tomato, pepper and aubergine and lettuce. *B. subtilis* within Serenade ASO is reported also to have some efficacy against other bacteria and powdery mildew fungus when alternated with chemical control (note however that powdery mildew is not listed on the product label). More information is needed on the product's efficacy against other pathogens and its use within integrated crop management. There is a need for products that control bacteria and so work with Serenade ASO in this area would be particularly useful.

- For successful germination and colonisation of leaves *B. subtilis* requires humidity of around 76 – 98% RH and an optimal temperature around 25°C, but there is a good survival rate on foliage for at least two weeks in the absence of a host.

- The product has a maximum UK dose rate of 8 L / ha for foliar application, which is applied with 200 to 1500 L / ha of water. Information is lacking on the concentration of active substance on the leaf surface (i.e. spores per cm^2 of leaf) required for efficacy across the range of crops, crop situations and pathogens. Information published in scientific papers and articles rarely provides the final viable spore concentration applied.
- No information was found on specific exposure times to UV radiation and the loss in efficacy. If there is likely to be significant loss of viability over a sunny day this should be made known so that applications can where possible be done on cloudy days. Information is needed on whether crops under particular tunnel plastics or glass may benefit from greater efficacy due to UV filtration than outdoor crops. This could also be important when comparing efficacy against pathogens that tend to colonise leaf undersides rather than upper surfaces.
- *B. subtilis* can produce biofilms (where bacterial cells stick to each other and cover a surface using a sticky extracellular biochemical), but it is unclear whether biofilms are produced on foliage and then whether these may help to protect the *B. subtilis* from unfavourable environmental conditions. The relative importance of lipopeptides (which can digest pathogen cell walls) known to be produced by strain QST 713 in the product is unknown. Lipopeptide activity could be likely to be less affected by environment extremes.

<u>*Clonostachys rosea / Gliocladium catenulatum* used as the biofungicide Prestop</u>.

- *G. catenulatum* within Prestop can be efficacious against *Botrytis* spp. on foliage, but more information exists on its benefit as a substrate drench against root pathogens.
- Targets for spray application given on the label are restricted to Botrytis, Didymella and Mycosphaerella. A wide range of crop hosts of Botrytis are listed on UK Extensions of Application for Use and work should be carried out and published on these.
- For successful germination and colonisation of leaves *G. catenulatum* requires high humidity of around 60 – 80% RH and an optimal temperature around 25°C, but there is a good survival rate on foliage for at least two weeks in the absence of a host.

- The product is used at a constant concentration, at 0.5% for both foliar and drench applications. Research is needed to investigate the optimal water volume for the application of the product on different target crops. The number of CFU / ml necessary for the most efficacious use of Prestop remains to be elucidated.
- Although some information exists on the factors which influence both efficacy and persistence of Prestop on foliage, quantitative information on the nature of this persistence is minimal. More evidence is needed on the rate of *G. catenulatum* decline once applied to the foliage of individual crop species.
- Much of the literature on the delivery of Prestop refers to soil drenches rather than foliar sprays. There is thus a lack of knowledge on what aspects of product application are critical to improve performance for this biopesticide.
- Studies on the effects of UV radiation have been done on the related species *G. roseum*, but no information was available from the product labels or public literature on the effects of solar radiation or UV interception on the persistence of Prestop on foliar tissues and thus warrants further research.

Ampelomyces quisqualis used as AQ10

- *A. quisqualis* within AQ10 can be efficacious across multiple species of powdery mildew when the correct conditions are met, with no parasitism reported of other fungal groups.
- For successful germination and parasitism of powdery mildew, spores of *A. quisqualis* need high humidity or moisture; with efficacy decreasing rapidly below an RH of 90-95% at the site of parasitism, an optimal temperature around 25°C and the presence of a host.
- The maximum efficacious dose which should be applied to plants is no higher than $1x10^6$ CFU / ml perhaps due to *A. quisqualis*’ production of an unidentified self-inhibitor above this concentration.
- *A. quisqualis* has a long latent phase, and in the presence of powdery mildew takes between 5 and 10 days to invade powdery mildew colonies on foliar tissues and complete its life cycle within the fungal host.
- *A. quisqualis* is compatible with a large number of chemical fungicides able to control powdery mildew, making it suitable for use in programmes with alternating use.
- Though the UK Registration Report for AQ10 states that without its powdery mildew host, viability of *A. quisqualis* is rapidly lost e.g., within a few days, the number of days as well as the rate of decline is not defined for particular crop situations.
- Though the maximum effective dose is known, there is no consistent information on the minimum effective dose. No public data (e.g., Registration Reports) is available on the

minimum effective concentration of CFU / ml needed and this is important given the rapid decline in viable spore counts following application to foliage.

- The method of delivery of the product was given poor attention in the literature. In particular, there was limited detail available on parameters which can affect spray application of the product to foliage, such as nozzle type, droplet sizes, tank systems and operator pressure.
- There is conflicting evidence for any change in control with the addition of adjuvants. Further research is required using individual adjuvants to ascertain the nature of their activity: when, at what concentration and how they could be used with AQ10 to perhaps boost product efficacy of the product.
- Information is given on the AQ10 label of the different weight of product per hectare to be used for different height crops, but the instruction to apply it with sufficient water to ensure coverage of both leaf surfaces needs to be clarified, as there will be dilution of the product with increasing water volume. There was no AQ10 label guidance on water volumes, and further work is needed on individual crops across a series of growth stages to determine optimum water volumes for efficacious application of AQ10.

New insights into the effect of environmental factors on biopesticides

All microorganisms used in biopesticides are ectothermic, meaning their performance rate is determined by the temperature of their environment. It is important that biopesticide companies choose strains that are able to function well under the temperature conditions within the crop, while growers and agronomists need to be given reliable information about the thermal performance of the strains used in commercial products. If a biopesticide is developed from a strain that has been selected using unrealistic, room temperature conditions rather than the more demanding conditions that the agent is exposed to in the glasshouse or field, then the strain will not perform well in commercial practice.

We investigated the use of thermal equations to give new information on biopesticide biology. A thermal equation allows the performance of an ectothermic organism to be estimated for any temperature within the performance range using data generated in an experiment. We investigated 12 different equations applied to a data set of the effect of temperature on the colony growth, spore germination and infectivity levels of 14 different species / strains of entomopathogenic fungi (EPF) that were all pathogenic to caterpillar pests and which included strains used in commercial biopesticide products. The main findings were as follows:

- The model that we are recommending as the most suitable is the CTMI (Cardinal Temperature Model with Inflection): this gave consistently good fits for all variables studied and, in contrast to some other thermal models, all its parameters have simple biological significance. We used the model to provide estimates of the minimum, optimum and maximum temperatures for colony extension, spore germination, insect mortality and also insect development rate.

- There was a large variation between the EPF strains in the minimum temperature for activity, with the minimum germination temperature varying by up to 16 ºC. The thermal tolerance range for growth and germination also varied according to fungal strain.
- The level of virulence of fungal strains could be explained using data on spore germination rate (this explained 76% of the variance in the virulence rate of strains, in multiple linear regression analysis). This indicates that fungal pathogens of the target pest that germinate quickly are likely to be more virulent than fungal pathogens that germinate slowly.
- The results also showed that rates of germination and virulence respond to temperature in a proportionate way. This could prove highly valuable in screening programmes done by biopesticide companies. Screening of candidate strains could be done by measuring in vitro germination rate at a range of environmentally relevant temperatures, which is relatively quick and easy to do, as opposed to measuring virulence to the target pest, which is harder and takes considerably more resources. We think this is going to be particularly valuable for identifying fungal strains that work at low temperatures, as these are likely to be rare and so a large number of candidate strains will have to be screened to find them.

The data also provided new information on the thermal biology of EPF products, identifying the temperature conditions at which they are likely to work best. As stated, low outdoor temperatures are an issue, particularly if using EPF in autumn and spring, and more work is needed to devise targeted application strategies to make best use of strains during windows of favourable conditions as part of IPM.

The strains tested were all typical in that activity dropped off rapidly at temperatures that were slightly greater than optimum. This is important for glasshouse crops: in hot summers, when glasshouse daytime temperatures will be high, it would be worth spraying products in the evening when conditions are cooler so that spores are applied under the best environmental conditions for germination.

In this research, we followed the convention of estimating the minimum and maximum temperatures for activity as cardinal points. However, for best practice, we think that biopesticide companies may be better off using a different measure of thermal performance range to provide more agronomically useful information to growers. If the minimum and maximum temperatures are quoted as the thermal limits, people may mistakenly believe that the biopesticide is active at these temperatures. Instead, it could be helpful to identify an agronomically operative temperature range. For example, this could be the temperature range at which performance is no less than 50% of that at the optimum temperature.

A microbial biopesticide should not only work under the target environmental temperature range, but it should also have a thermal performance curve that matches, or overlaps, that of the target pest (which is also ectothermic). If the thermal performance curves are different, then there is likely to be set of temperatures at which the pest can feed, grow and reproduce but the biopesticide cannot control it. If the thermal performance curves match, however, then both pest and biopesticide will respond similarly to temperature changes. In theory, this means that successful levels of crop protection can still occur at suboptimal temperatures. For example, at low temperatures, while the speed of kill of the biopesticide will be reduced, provided the pest undergoes the same rate reduction in development, feeding and reproduction, then the total amount of pest control will be maintained, albeit at a slower rate. This is something that has not been explored in any detail and requires attention in the future.

A boxcar model to get new insights on biopesticide efficacy against peach-potato aphid

Understanding the optimal way to use biopesticides is crucial to maximising efficacy and minimising cost, compared with conventional pesticides. Unlike synthetic chemical pesticides, many biopesticides do not cause instantaneous death of their insect targets – instead they can take several days before death occurs. They can also have different levels of lethality to different pest life stage, for example eggs may be less vulnerable than the adult stage. As a result, the amount of pest control is affected by a range of features associated with pest biology; these include things like pest growth rate, reproduction, the relative susceptibilities of different instars to the biopesticide, and pest population size. There are also inherent features of the biopesticide that will determine its efficacy: speed of kill, lethal concentration, persistence on the leaf surface and so forth. Until now, these issues have not been considered in any detail when people are designing an IPM programme with biopesticides, but it is important that they are thought about.

It follows that the strategy for applying a biopesticide – i.e. the timing and frequency of spraying in relation to pest population size and growth rate – will have a profound effect on efficacy. Testing out the full range of possible application strategies in the glasshouse is prohibitively expensive. Instead, a mathematical model of pest population growth could be used to investigate different strategies and pick out those that are likely to be most effective. In this way, computer models could be used for rapidly testing many hypotheses to identify those that should be further investigated in practical experiments, thus saving time and money on laboratory and field trials. This is a novel approach and to our knowledge has not been investigated for biopesticides before now.

In this part of AMBER, a computer model was developed that predicts how biopesticide application strategy affects the level of pest control. Separate models have been developed for whiteflies and for peach potato aphid, *Myzus persicae*. Here we are reporting about the work on *Myzus*. The model was developed to predict *Myzus persicae* population increase over time using published data on aphid development rates and their susceptibility to neem-based bioprotectants. The model was then used to test and predict the efficacy of different numbers of spray applications of azadirachtin (the active ingredient in neem). An experiment was then done to test the computer model predictions. This was done using Azatin sprayed on to pansy as a model crop in a glasshouse, to compare with results from an experiment in AHDB project CP 124 which included a different azadirachtin product not yet approved in the UK. As Azatin is approved in the UK for control of thrips on protected ornamentals, the experiment aimed to provide growers with immediately applicable results.

The main findings were as follows:

- The model predicted that to eradicate an initial pest population of two adult aphids per plant with the first application after one week, it would be necessary to apply four sprays of a neem based biopesticide at weekly intervals. This prediction was then tested out in an experiment. There was a significant reduction in numbers of nymphs and winged adults where Azatin had been applied at least once, and also a reduction in the number of wingless adults where Azatin had been applied twice, indicating that application of Azatin can be used to reduce numbers of aphids as part of an IPM programme. However, the Aztin application regime did not eradicate the aphid population as predicted by the model. This is probably because the aphid development rate observed on pansy was faster than the rate used in the model, which used data published in the scientific literature for aphids on sweet pepper.
- The effect of host plant on pest population growth is probably underappreciated in IPM and it may explain why a biopesticide works against a pest species on one crop but does not give adequate control when applied against the same pest, with the same application regime, on another crop species.
- Percentage nymph mortality observed in this experiment was similar to the model parameter of 50% nymph mortality, but this level of mortality was not observed until 20 days from the first application. This suggests that Azatin acted more slowly on the nymph population than predicted by the model.

A speed of kill experiment was then set up to compare two treatments; an untreated control and Azatin applied once seven days at 1.4 L / ha in 1000 L / ha water. Azatin caused a reduction in the number of aphid nymphs and wingless adults one day after application, while winged aphids were produced nine days post infestation. The model prediction for aphid growth matched the observed numbers of aphids in the untreated control until day 27.

Accuracy of a biological model depends on the quality of information on which the parameters are based. In this case, the model overestimated efficacy of azadirachtin against *M. persicae* when compared with experimental results. Efficacy data from this trial could be used to reprogramme the model and create predictions for another research question, such as how many applications of Azatin would be necessary to control a starting population of two *M. persicae* per plant with the first application after one day rather than after one week, as in this experiment. The model could then be validated and improved and extended to other crops, with additional information.

Azadirachtin was less effective against *M. persicae* in this experiment compared with a similar trial conducted in CP 124 MOPS using a different azadirachtin product that is not yet approved in the UK. Further work is needed to determine whether observed differences in efficacy are due to formulation of azadirachtin products.

Financial benefits

Biopesticides are generally less forgiving of environmental conditions that synthetic pesticides so understanding the optimal way to use them is really important to maximising efficacy and minimising cost.

There is an assumption that using the highest water volume within the label guidance gives better coverage (and hence efficacy) on the plant. However, as a general rule this is unlikely to be the case. The best strategy is to use a water volume that results in the highest concentration of product on the crop, taking into account the potential need for water to activate the product. For nominal constant dose applications, lower water volumes are likely to be better. These reduce waste and are quicker to apply, which will save money.

Using fast track systems to screen biopesticides for response to temperature, as shown here in AMBER, will lead to more effective biopesticide products, with cost savings for growers in terms of better pest control.

The literature review of microbial biofungicides done in this report gives growers and agronomists a summary of the current ‘state of the art’ of knowledge about the conditions and management practices required for successful use of these products. The new recording template will enable growers to systematically collect the data needed to explain the performance levels obtained with biofungicides in commercial practice. This data is vital in situations where the biopesticide does not perform as expected, as it provides the evidence to help identify the problem and develop solutions to correct it.

The box car train model developed in AMBER is the first computer system in the world that predicts the effect of application strategy on bioinsecticide performance. The model still requires some additional work, as it has shown that plant species is likely to impact on biopesticide efficacy via effects on pest population growth rate, and hence data on pest growth rate is needed on different plant species. The big advantage of the model is that it allows rapid testing of different application scenarios to flag up the most promising options, which can then be tested in the laboratory or glasshouse. Attempting to investigate all components of a spray programme in a crop would be prohibitively expensive and time-consuming. At the moment, application strategies are often developed on a trial and error basis. The AMBER model has real potential to take the guess work out of spray programme development, leading to better performance of biopesticide products. Efficacy testing is also a significant fixed cost for biopesticide companies: if it can be reduced, this should result in making biopesticide products cheaper and more price competitive with other products.