SESSION 8D

ALIEN PEST AND DISEASE PROBLEMS AND APPROACHES TO THEIR CONTROL

Session Organiser Dr K F A Walters
Central Science Laboratory, York

Papers 8D-1 to 8D-9

ERADICATING ALIEN PESTS OF WESTERN AUSTRALIAN HORTICULTURE

W WOODS
Agriculture Western Australia, 36 Railway Parade, Midland, Western Australia 6056

ABSTRACT

Western Australia is in an unique position in that a number of key horticultural pests have not established despite their presence in other states of Australia. The non establishment of these pests is due to isolation, quarantine barriers, and an active policy of pest eradication. Eradication of incipient outbreaks of alien pests prevents increased pesticide usage on horticultural crops, whilst eradication of the long established exotic pest Mediterranean Fruit Fly (*Ceratitis capitata*) will result in significant reduction in insecticide use.

INTRODUCTION

Western Australia has an expanding horticultural industry supplying both domestic and export markets. A range of horticultural produce is available from subtropical areas in the north of the state, and Mediterranean regions in the south.

Western Australia is effectively isolated from the rest of Australia by desert (Figure 1) which provides a barrier to the natural spread of exotic pests. Quarantine barriers on the few major roads into the state, at airports and seaports moderate spread through commerce and travel.

By chance, many fruit crops were established in Western Australia without the presence of major pests. Examples of pests never established in Western Australia include European red mite (*Panonychus ulmi*) and grape phylloxera (*Daktulasphaira vitifolii*). On other crops pests were found and eradicated before wide establishment. For example, codling moth (*Cydia pomonella*) has been eradicated eighteen times from the state giving apple growers an important competitive and marketing advantage. Other pests previously eradicated include oriental fruit moth (*Cydia molesta*) and Queensland fruit fly (*Bactocera tryoni*).

There are many pests that pose threats to Western Australian horticulture. However because of the proximity and trade between different states of Australia, the greatest threat is from pests established in the eastern states. For these pests quarantine barriers are being strengthened, early warning systems put in place and eradication plans developed for key species. A generic plan is being developed to handle incursions of pests from outside Australia. Preparation for pest outbreaks is being given highest priority and with a core of trained and experienced staff, complemented with adequate funding, the eradication capability of Agriculture Western Australia has been strengthened.

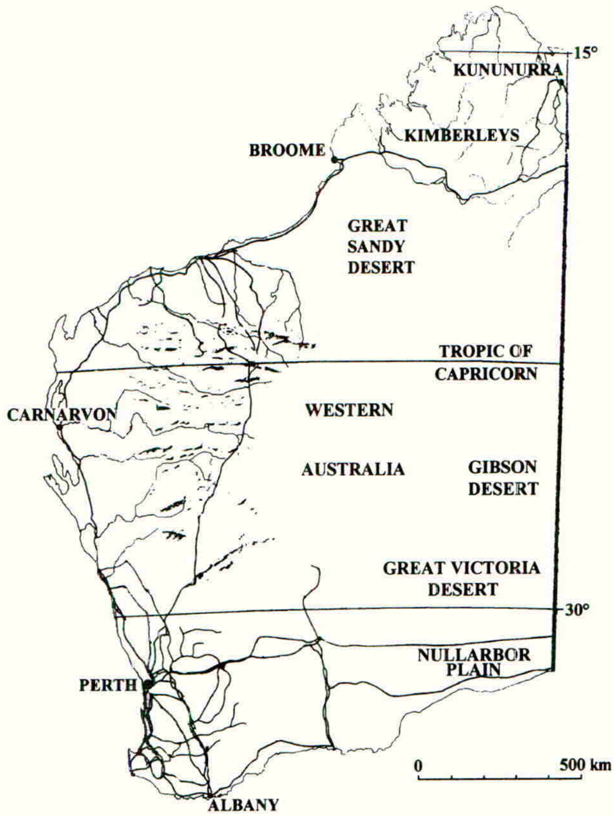

Figure 1 Map of Western Australia

However, one exotic pest has become widely established in Western Australia and is the bane of fruit producers. Mediterranean fruit fly or Medfly (*Ceratitis capitata*) is found from Albany in the south to Broome in the north (Figure 1). Medfly was first found in Western Australia at the turn of the century and is now an entrenched pest. Most towns support Medfly populations in home gardens and backyard orchards. Conditions are especially favourable in Perth , which has a Mediterranean climate, a continuity of hosts and favourable microclimates in irrigated backyards.

Although Medfly is only established in Western Australia outbreaks are regularly eradicated from the adjacent state of South Australia. It is of economic significance to all mainland Australian states as Japan does not recognise area freedom within Australia. Thus Queensland exporters must disinfest produce to a standard required to kill Medfly even though Medfly is not present in that state and Australian fruit growers must fund Medfly disinfestation research in Western Australia.

Medfly is the only economically significant fruit fly pest in Western Australia and growers use more insecticide against it, than against any other horticultural pest. It can be very abundant in the major horticultural areas, especially those close to centres of population, where the fly breeds in backyard orchards. Despite the regular application of insecticide cover sprays (dimethoate, fenthion) and protein hydrolysate / maldison baits for its control severe damage occurs on susceptible crops such as stonefruit, in bad fruit fly years.

Eradication of this pest would provide a significant reduction in pesticide usage across a range of horticultural crops and expedite entry of horticultural produce from Australia into many export markets, where presence of Medfly is a barrier to entry.

Medfly is not only a pest of commercial orchards : it makes the production of quality backyard fruit in Perth a difficult and sometimes impossible task. Even the regular application of insecticide cannot guarantee maggot free fruit. Householders are becoming increasingly sensitive to the use pesticides in the urban environment and the possibility of growing fruit without insecticide use is a tantalising one. The absence of other major pests and the acceptance of cosmetic flaws in backyard fruit makes this a reality once Medfly has been removed.

The possibility of eradicating Medfly has always been an ultimate aim of horticultural entomologists in Western Australia. In 1977 Mr A. Sproul of the Western Australian Department of Agriculture instigated an eradication program in the isolated community of Carnarvon using the sterile insect technique (SIT). This exercise was successful (Fisher *et al.,* 1986) but lack of quarantine barriers allowed re-entry from the south of the state.

In 1994 a cost benefit analysis on eradication of Medfly from Western Australia was carried out, but the estimated total cost of $200 million was enough to stall the project at that time (Fisher, *pers comm*). However recent successes in pest eradication have refocussed attention on the possibility of eradicating Medfly from Western Australia.

MATERIALS AND METHODS

There have been several successful eradication campaigns against major pests in Western Australia which may illustrate approachs to tackling the Medfly problem. From 1989 - 1991 an outbreak of Queensland fruit fly was eradicated from Western Australia at a cost of A$8 million. The outbreak of Queensland fruit fly extended over 300 square kilometres of metropolitan Perth, Western Australia's capital city (population 1 million). The eradication program utilised backpack bait spraying with protein autolysate / maldison to reduce fly numbers. Male fly numbers were also reduced with cannite lure blocks impregnated with Cuelure and maldison. Final eradication was achieved using sterile male flies , 40 million of which were released per week at the height of the program (Fisher, 1994,1996).

In 1995 a smaller outbreak in Perth was detected by some of the 2000 early warning traps put in place after the earlier Queensland fruit fly outbreak. As the outbreak was intercepted early it was eradicated using protein / maldison bait spraying at a cost of only A$200,000.

In late 1995 Medflies were trapped at Kununurra in the Ord irrigation area in the far north of the state. This blossoming horticultural area had previously been free of the pest and area freedom permitted export of produce, such as mango, to southern states without any disinfestation requirements. An eradication program was immediately commenced. Once again protein / maldison baiting was used, complimented with fruit stripping or cover spraying with fenthion as previous experience from South Australia (Perepelecia, *pers comm*) was that baiting alone was not sufficient.

At Kununurra difficulties were experienced with female wet traps not working in the tropical environment and male traps requiring accurate placement in fruiting trees for best effect. However once again eradication proved successful at a cost of A$300,000.

In 1996, after a 3 year program, an outbreak of codling moth was eradicated from Bridgetown in the southwest of Western Australia at a cost of A$3 million (Woods and Thwaite, 1994). Eradication was achieved using fruit removal and deep burial, destruction of older trees and cover spraying orchards with azinphos methyl every two weeks from petal fall to harvest. Quarantine checkpoints were put in place to prevent movement of infested fruit from the area. In total 30,000 trees were grubbed out and burnt, 50.000 trees were stripped of fruit and 200,000 apples were closely inspected for presence of codling moth (Woods *et al.,* 1996).

These successful programs provided staff with expertise in eradication, and made many people aware of the possibilities and advantages of eradicating key pests. Successful Medfly eradication campaigns in California (Minyard, *pers comm*) and Chile (Robertson, *pers comm*) also added weight to the possibility of eradicating Medfly from all of Western Australia.

DISCUSSION

Medfly is more difficult to eradicate than many other species of fruit fly (Morse *et al,* 1994). Eradication from Western Australia will therefore be a long and expensive task. For eradication to progress a number of preconditions resulting in a positive benefit / cost ratio are required.

Firstly the benefits of eradicating Medfly must increase. This will happen as Western Australia's horticultural industry expands and becomes more export orientated. The inevitable loss of inexpensive and effective insecticides for Medfly control and disinfestation will increase the desireability of eradication.

Secondly the cost of eradication must decrease. The use of the cost effective and more efficient genetic sexing strains of Medfly for sterile release is one way this can be achieved. The temperature sensitive lethal strain (TSL) costs less to rear and is several times more efficient than the standard Medfly strain (Fisher, *pers comm.*).

The development of more efficient attractants and traps is also crucial for any large scale Medfly eradication such as would be attempted in Western Australia. Current traps do not inspire confidence in this critical area. Medfly females do not respond well to traps and male attractants are much less efficient when compared to attractants for other fruit flies. Much work is being carried out world wide in this area and promising new traps are appearing (Heath et al 1995).

The Ord Irrigation area on the far north of Western Australia is now free of Medfly. We hope to extend the area freedom to the Kimberley region which extends from Broome north to Kununurra, an area of approximately 50,000 square kilometres. In this area Medfly is probably surviving in far from optimum conditions, with the high temperatures and humidity of the wet season acting to reduce fly numbers.

Medfly was first found in Broome in 1980 and numbers drop to low levels at the beginning of the dry season. This would be a perfect time to attack with the sterile insect technique. Such an eradication program based on the use of SIT, and insecticide baiting, if required, will give a us good experience which we can use in the planning of a larger operation for all of WA.

Eradication from northern areas down to Perth appears readily achievable. Horticulture is restricted to a few centres, and towns are widely seperated. The environment outside these oases is hostile to fly survival.

The situation in the southwest is more difficult with a mixture of towns, hobby farms, commercial orchards and feral fruit all supporting Medfly populations. Hot dry summers and cold winters mean that Medfly numbers at times drop to low levels and are susceptible to attack with SIT.

The Perth metropolitan area and associated urban sprawl will be the greatest challenge. Medfly numbers will need to be reduced by protein/ insecticide baiting before SIT can be used. The use of aerially applied bait would simplify this problem but environmental considerations negate this as an option and we would need to rely on ground application. This technique although expensive has proved effective in the past and has been readily accepted by the public. The problem in Perth is not one of technique, but of scale, and of preventing reinfestation of clean areas.

It has been shown that pests can be eradicated from Western Australia provided sufficient resources are made available. The technology now exists to eradicate Medfly, and it is a question of when the benefit / cost ratio will reach a level where it is economically feasible to do so.

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COMPUTER MODELS IN PLANT HEALTH CAMPAIGN MANAGEMENT: THEIR USE IN *BEMISIA TABACI* ERADICATION

J HEAD, D MORGAN
Central Science Laboratory, MAFF, Sand Hutton, York, YO4 1LZ, UK

ABSTRACT

Plant Health campaigns aim to eradicate/contain outbreaks of non-indigenous pests in the UK. Eradication can be difficult to achieve as pests are often not susceptible to the available chemical treatments in at least some of the instars. To optimise the impact of pesticides, applications need to coincide with periods when pest populations are at susceptible developmental stages. Predicting the phenology of pest populations by computer models is a valuable tool in designing pest control programs and there is scope for the use of such models in campaign management strategies.

The tobacco whitefly, *Bemisia tabaci*, is a major threat to UK horticulture and agriculture, particularly as a vector of viruses and was chosen as a 'model' pest to investigate the role of computer models in Plant Health Campaigns. Computer models describing the population dynamics of *B. tabaci* and subsequent spread of tomato yellow leaf curl virus have been developed, and their use in the design and implementation of campaign management strategies is discussed.

INTRODUCTION

Introductions of non-indigenous plant pests are often associated with the international trade in plant material and plant products. International plant health (quarantine) legislation requires that measures be taken to prevent the introduction and establishment of damaging organisms to new areas. Controls on the movement of plant material within the EC are enforced under EC plant health legislation. Measures which can be taken range from the prohibition of imports of certain commodities from countries outside the EC (third countries), to the designation of 'Protected Zone' status to certain areas within the EC where particular pests are not established. Extra measures may be applied to movement of certain commodities into these zones (Bartlett, 1994). Despite the measures taken a small number of harmful species have been introduced, and in such instances statutory controls are necessary to achieve eradication or containment.

Eradication is often not easily achieved. Alien pests are frequently not susceptible to the available chemical treatments in at least some instars, for example they may exist in stages tolerant to insecticides, or concealed within a host or soil for large proportions of their development time. Therefore the timing of treatments is critical to optimise efficacy, and prolong the effective life of available treatments in eradication campaigns. Computer simulation models can be used to predict points in the population dynamics of an outbreak where the maximum number of susceptible individuals are present, thus the application of chemicals can be targetted more effectively. Such models have been used extensively in indigenous pest control (Morgan & Solomon, 1993) and there is scope for the development of similar models for use in Plant Health Campaigns.

The tobacco whitefly, *Bemisia tabaci,* is considered to be a potentially serious pest in the UK, mainly because it is an effective vector of over 60 viruses from several groups, particularly geminiviruses. Many of these have been reported to cause economic damage to crops worldwide (De Barro, 1995). *B. tabaci* is increasing its worldwide distribution, thus enabling some of these viruses to infect previously unaffected plant species (Markham *et al.*, 1994). The UK has Protected Zone status within the European Community to prevent the introduction of *B. tabaci* (Anon., 1993). It is the damaging 'B-type' or poinsettia strain of *B. tabaci* which is of major concern as in addition to its ability to transmit a greater number of plant pathogenic viruses than the 'A-type' strain, it is also more polyphagous, develops faster and is more fecund. The 'B-type' was first intercepted in the UK in 1987 and since then outbreaks have occurred annually, predominantly on poinsettia. All outbreaks must be eradicated in order to prevent pest establishment and safeguard the UK protected vegetable industry (Bartlett, 1994). To date, *B. tabaci* has not been found on a UK vegetable crop.

The principal risk posed to the UK agriculture and horticulture industries is from the introduction of *B. tabaci* on ornamentals, such as poinsettia, and the subsequent transferral to protected vegetable crops, in particular tomatoes. The primary UK concern is that adult whitefly can infect tomatoes with Tomato Yellow Leaf Curl virus (TYLCV), a virus not currently present in the country. This paper discusses the use in Plant Health campaigns, of computer models which were developed to predict the population dynamics of *B. tabaci* on poinsettia and tomato and the subsequent spread of TYLCV in tomato crops.

METHODS

Population dynamics models of *B. tabaci* on poinsettia

A computer model was initially developed to simulate the population dynamics of *B. tabaci* on poinsettia. The model contained algorithms describing the temperature-dependent development of each life stage of *B. tabaci* and fecundity of the adult female. Data from Enkegaard (1993) were used to derive these relationships. To maximise the biological realism of the model, non-linear equations were used to describe the relationships between temperature and development and reproduction. Output from the model is given as hourly and daily predictions of numbers of eggs, larvae and adult females.

Population dynamics models of *B. tabaci* on tomato

Experiments were carried out to determine the effect of host transfer (from poinsettia to tomato) and temperature on development and fecundity of *B. tabaci*. The biological data obtained was then used to re-parameterise the model to predict the population dynamics of *B. tabaci* on tomatoes.

Model predictions for *B. tabaci* on poinsettia and tomato were compared to evaluate the potential threat of the pest to more than one crop. Simulations were run using both models, with identical input variables, to determine the relative differences in pest abundance on both crops.

Epidemiology model of TYLCV

A simulation model was developed to predict the spread of TYLCV. The model distinguishes between inoculations and infections; inoculation is used to refer to a successful insertion of virus into a host plant, and if the plant is susceptible it will become infected. The model assumes that inoculations are made randomly within the crop, with no distinction between healthy and infected plants. The model also assumes that in any one time period a plant may fall into one of three categories; it may be healthy (contains no virus), latent (virus titre is too low for a healthy potential vector to acquire the virus), or infectious (after the latent period it enters this category). All variables and relationships used in the model were formulated using published data. The probability of a successful inoculation (per vector) has been estimated to be 0.05 (Mehta *et al.*, 1994) and the virus latent period to be 8 days (Kegler, 1994).

RESULTS

Population dynamics models of *Bemisia tabaci* on poinsettia and tomato

The simulations for the population development of *B. tabaci* on poinsettia and tomato are summarised in Figure 1 and Figure 2, respectively. The time needed for *B. tabaci* to develop from egg to adult is shorter on tomatoes than poinsettia (Head, unpublished data) and this was reflected by the model; the appearance of second generation adults occurred after 14 days on tomatoes, while on poinsettia adults emerged after 17 days. This resulted in the earlier appearance of eggs laid by this generation of adults on tomatoes. Laboratory results showed that adults on tomatoes laid more eggs than those kept on poinsettia and this was also reflected by the model which predicted greater egg densities on the vegetable crop.

Sensitivity Analysis

The tomato-based model was used to carry out a sensitivity analysis to investigate the relative importance of several processes on the dynamics of *B. tabaci* populations. Increasing temperatures by 5°C increased the numbers of individuals of all life stages by between 124 and 185%, while lowering temperature by a similar amount reduced the number of adult females by 20%. Small changes in survival rates greatly affected abundance of the pest; increasing mortality by 5% reduced the numbers in all life-stages by between 21 and 52%, while reducing mortality by 5% at least doubled pest abundance.

Figure 1. The results of the simulation of the population development of *B. tabaci* on poinsettia at 25°C.

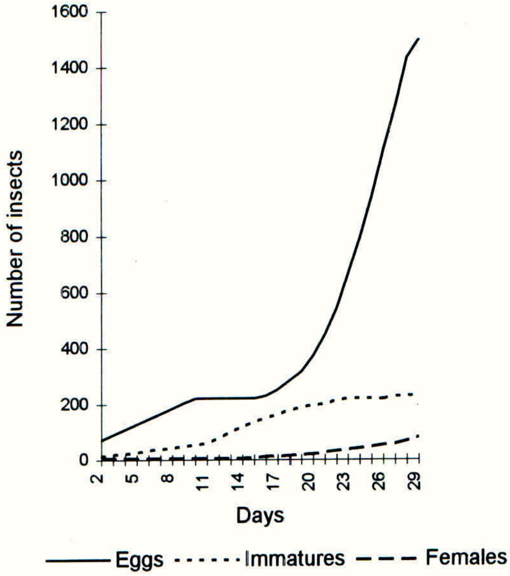
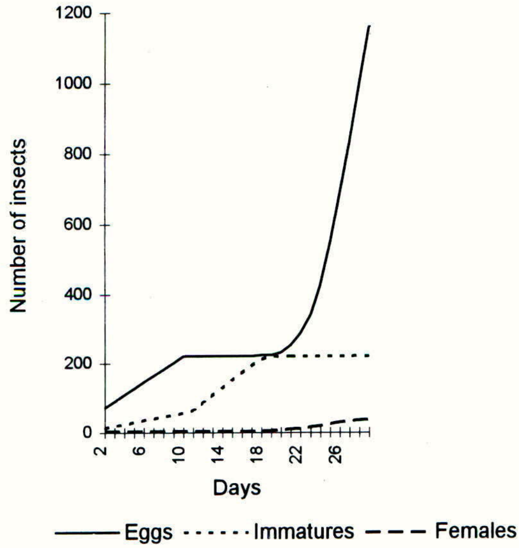


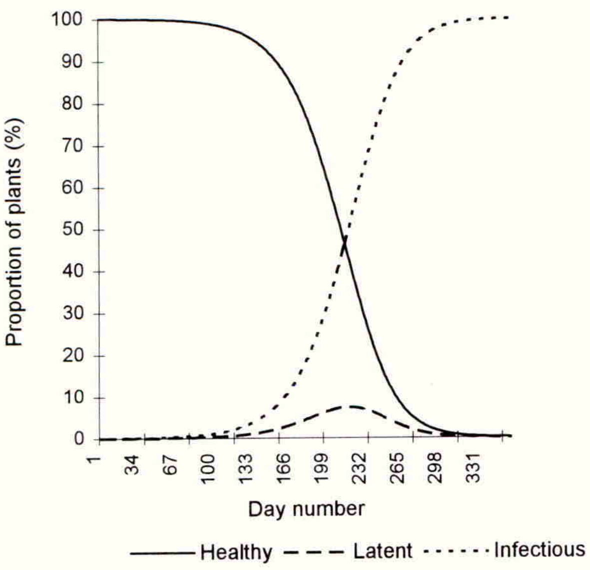
Figure 2. The results of the simulation of population development of *B. tabaci* on tomato at 25°C.



Epidemiology model of TYLCV

The proportion of plants in all three categories of virus infection (healthy, latent and infectious) changed with increasing time after the initial infection (Figure 3). Early in the simulation, the majority of plants are healthy and few sources of infection are available for vectors to acquire and spread virus. However the numbers of source plants quickly increase and by day 219 of the simulation run, 50% of all plants have become infectious. Virus spread continues and eventually all plants in the crop are infected.

Figure 3. Predicted disease progress of TYLCV on tomatoes at 25°C.



DISCUSSION

Models have been developed to simulate the population dynamics of *B. tabaci* on poinsettia and tomato and the subsequent spread of TYLCV on tomato. The pest models predict the presence of all developmental stages and can be used in eradication campaigns to identify points in time when the maximum number of individuals exist in each developmental stage. Treatment schedules can then be devised to ensure that applications of each type of treatment, for example insect growth regulators, are made at the optimal time, targetting the most susceptible growth stages.

Additionally, the virus model has shown that considerable and rapid spread of TYLCV is likely after a low level introduction. Under this scenario eradication of the whitefly vector is necessary if virus outbreaks in the UK are to be prevented. If individual *B. tabaci* in a pest population are viruliferous, the model indicates that eradicatory measures would need to be taken quickly to prevent further and rapid virus transfer from occurring.

These models have been developed initially for use in the eradication of *B. tabaci* and have proven useful in providing further insight into the population dynamics of the pest and the epidemiology of TYLCV. The modular structure of the models will ensure cost-effective and efficient conversions for other insect pests of quarantine concern. Therefore they can potentially be applied to simulate the dynamics of a wide range of alien pest and disease outbreaks.

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IMMUNOCHEMICAL STUDIES FOR THE DEVELOPMENT OF A RAPID ASSAY AGAINST *THRIPS PALMI*

J N BANKS, D W COLLINS, R H RIZVI, B J NORTHWAY
Central Science Laboratory, MAFF, Sand Hutton, York, YO4 1LZ, UK

ABSTRACT

Thrips palmi is a polyphagous, EU-listed pest which has greatly expanded its geographic range in the last 18 years. For use in a rapid detection system to facilitate measures to prevent its establishment in the UK, monoclonal antibodies (MAb) were raised against *T. palmi*. These were characterised through cross-reactivity studies with other insects including the two species of thrips most commonly found under glass in the UK, *Frankliniella occidentalis* and *T. tabaci*. Several promising cell lines secreting MAb that showed specificity to *T. palmi* were produced. Alongside this work, antigen characterisation studies through protein profiles produced by SDS PAGE were carried out. Profiles were analysed by scanning laser densitometer and clear differences between the band patterns of the different species were apparent. The implications of this work and the practical considerations inherent in producing a modern diagnostic assay for quarantine work are discussed.

INTRODUCTION

Hitherto an obscure Asian species, *Thrips palmi*, was first noted by the Japanese as a pest in 1978 (Nakazawa, 1981). Since then, the species has not only become a polyphagous pest of considerable importance but has rapidly spread across the world. Infestations on curcubits and solanaceous plants (e.g., Kawai, 1990) result in economic loss caused by an accumulation of feeding damage. It has also been shown to be a vector of tospoviruses (Honda *et al*., 1989; Yeh *et al*., 1992).

T. palmi is a listed species in the European Union Plant Health Directive (77/93/EEC). In any statutory campaign to prevent its establishment under glass in the UK, the ability to rapidly detect and identify the species at all life stages is critical. The identification of thrips is currently restricted to morphological examination of the adult under a high-power microscope.

If *T. palmi* is ever found in the UK, the initial survey, and subsequent monitoring, of nurseries that would be carried out would generate the need for large numbers of thrips identifications. The use of an Enzyme-Linked Immunosorbent Assay (ELISA) offers the greatest potential for maximising the diagnostic throughput. This paper describes work to produce monoclonal antibodies (MAb) showing specificity to *T. palmi*. The screening programme was designed to exclude the two most common thrips species found under glass in the UK, *Frankliniella occidentalis* and *T. tabaci*, as they are likely to make up the vast majority of samples sent for laboratory identification. The ability to rapidly separate *T. palmi* from these species would allow the resources of the plant health quarantine service to be effectively targeted which is vital if an eradication campaign is to succeed.

MATERIALS AND METHODS

Insects

T. palmi were collected from two sources: field grown *Solanum melongena* in Florida, USA, and *S. melongena* grown under glass in Okayama, Japan. In each case, the leaves and associated thrips were frozen and sent by air-courier packed in dry ice. On arrival they were immediately stored in the deep freeze at -80^{0}C.

Five other insects species were used for cross-reactivity testing; *T. tabaci*, *Frankliniella occidentalis*, the aphid *Myzus persicae*, and the leaf mining flies *Liriomyza bryoniae* and *L. strigata*. Mixtures of all life stages were used in each case except for *L. bryoniae* (pupae only) and *L. strigata* (adults only). All these insects were obtained from cultures maintained at the Central Science Laboratory and stored at -80^{0}C until use.

Insects were homogenised in a phosphate-buffered saline, pH 7.4, using a plastic homogeniser (Biomedix, Pinner, Middlesex). Insoluble material was removed by centrifugation at 14,000 rev/min for 2 minutes. Prior to use, total protein estimations were performed on each preparation (Banks *et al.*, 1992). Soluble protein extracts were prepared for all 5 insects and used for immunization, coating of plates in the ELISA and to determine the protein profiles by electrophoresis.

Immunization and six- week sera cross-reactivity testing

Immunizations were carried out using techniques described previously (Banks *et al.*, 1994, 1996), except that the final protein concentration of the antigen (*T. palmi* extract) was 100 µg ml^{-1}. To assist in the selection of the spleen most likely to yield specific MAb to *T. palmi*, cross-reactivity testing of polyclonal antibodies (PAb) obtained from sera taken 6 weeks after the start of immunizations was performed against *T. palmi* and the other insect species.

Indirect / antibody capture Enzyme Linked Immunosorbent Assay (ELISA)

An indirect ELISA was used to screen the antisera for PAb to the insect extracts and later to identify positive hybridomas. This was essentially the same as the indirect ELISA previously described (Banks *et al.*, 1994) except that the ELISA plates were coated with soluble insect extracts at a protein concentration of 2 µg ml^{-1}.

MAb production

Standard MAb production techniques as described previously (Banks *et al.*, 1994, 1996) were used. The cell lines that secreted antibodies that reacted mainly to the homologous antigen (*T. palmi*) rather than the heterologous antigens (other insects) were identified (by ELISA) and selected for at the fusion and cloning stages. Cultures of each clone were allowed to overgrow and the supernatant collected for antibody. This MAb was then used in the indirect

ELISA at a dilution of 1 : 2 for final cross-reactivity testing before the cell lines were stored in liquid nitrogen.

Electrophoresis

Electrophoresis was carried out using standard methodology with 8-18% gradient SDS-PAGE gels, and silver staining (Laemmeli, 1970). Soluble extracts, as prepared above, were loaded on to flat bed electrophoresis equipment (Pharmacia) at protein concentrations of 4 and 8 μg in 40 μl^{-1}. The resultant protein profiles were analysed by scanning laser densitometer.

RESULTS

MAb cross-reactivity

Four fusions were carried out on mice immunized with soluble extracts of *T. palmi*. The most promising fusion resulted in 14 cell lines being cloned twice and the resulting MAb tested for cross-reactivity (Table 1).

Two cell lines (5B10 E7 H10 and H7) had very high absorbances with *T. palmi* and very low absorbances for the other insects, except for *L. strigata* and *L. bryoniae* which were about half that of *T. palmi*. The MAb from 5B4 B6 D5 had a reasonably high absorbance for *T. palmi* with low absorbances for the other insects except for *L. strigata* and 5B4 B6 D8 had a much higher absorbance for *T. palmi* than the other insect extracts. The MAb derived from 5B4 B6 B9 cross-reacted with all of the insects albeit slightly more strongly with *T. palmi*.

Table 1. ELISA absorbance values of selected tissue culture supernatants from the most successful fusion at 1/2 dilution. Tp = *Thrips palmi*; Tt = *Thrips tabaci*; Fo = *Frankliniella occidentalis*; Mp = *Myzus persicae*; Ls = *Liriomyza strigata*; Lb = *Liriomyza bryoniae*

Cell Line	Tp	Tt	Fo	Mp	Ls	Lb
5B10 E7 H10	2.163	0.611	0.413	0.175	1.011	1.296
5B10 E7 H7	2.004	0.589	0.369	0.592	0.953	1.080
5B4 B6 D5	0.781	0.273	0.109	0.169	0.498	0.131
5B4 B6 B8	0.756	0.521	0.439	0.552	0.798	0.301
5B4 B6 D8	1.003	0.409	0.163	0.442	0.346	0.262
5B4 B6 B9	0.686	0.429	0.454	0.301	0.640	0.304
5B4 B6 C9	0.844	0.485	0.387	0.434	0.886	0.508
3H6 E8 A6	1.411	0.150	0.369	0.160	0.326	0.164
3H6 E8 E6	1.521	0.433	0.199	0.198	0.268	0.141
3H6 E8 D11	0.809	0.365	0.210	0.227	0.194	0.160
3H6 D10 D8	1.348	0.118	0.316	-	-	-
3H6 D10 A11	0.610	0.300	0.304	-	-	-
3H6 D10 C12	1.783	0.432	0.510	-	-	-
3H6 D10 D12	0.837	0.283	0.459	-	-	-

The MAb from cell lines 3H6 E8 A6 and E6, and 3H6 D10 D8 and C12 had very high absorbances for *T. palmi* with little or no cross-reaction with the other insects tested.

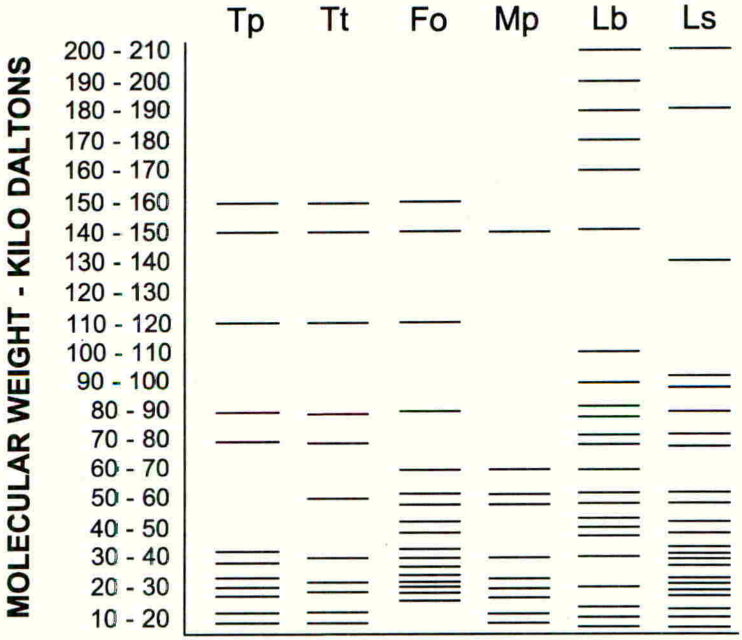
Electrophoresis

The occurrence of all and the major (most densely stained) protein bands were recorded and a diagrammatic representation of the major bands is shown in Figure 1. For *T. palmi*, all the bands were detected in the molecular weight (MW) range of 10 to 320 Kilodaltons (Kd). There were specific bands that were not apparent in the other extracts at 290-300, 270-280 and 240-250 Kd. A band at 230-240 Kd also only occurred with *L. bryoniae* and at 310-320 and 100-110 Kd also with only *L. bryoniae* and *L. strigata*. The major bands occurred between 10-160 Kd. Bands at 110-120 and 150-160 Kd occurred with only *T. tabaci* and *F. occidentalis*. At 30-40 Kd, there were 2 bands one of which may have occurred in all the other extracts and 1 or 2 with *F. occidentalis* and *L. strigata*.

DISCUSSION

When raising MAb to organisms containing a diverse range of antigens, resulting antibodies can often have unwanted cross-reactions. Four fusions were carried out and hundreds of cell lines screened in this study with the primary objective of obtaining a MAb that could distinguish *T. palmi* from *T. tabaci* and *F. occidentalis* at the juvenile and adult stages and as a secondary consideration from other unrelated insects. Many of the resulting MAb from these fusions, had undesirable cross-reactions but for the purpose of this paper, the results of the most promising fusion are presented.

Figure 1. Diagrammatic representation of the protein profiles (major bands only) produced by electrophoresis of the insect homogenates. (For explanation of abbreviations see Table 1.)



From this fusion, 14 stable cell lines secreting MAb were produced (Table 1). Most of the MAb showed a greater reaction (higher absorbance value) with *T. palmi* than with *T. tabaci* and *F. occidentalis*. The strongest MAb were derived from the cell lines 5B10 E7 H10 and H7 as these had absorbances of > 2.0 with the homologous antigen *T. palmi* and low absorbances for *T. tabaci* and *F. occidentalis*, which could probably be reduced further by dilution of the MAb or different assay conditions. These two MAb however, had high absorbances (about 1.0) for *L. bryoniae* and *L. strigata*. There were a number of MAb that were relatively weak (5B4 B6 D5 and B8, 5B4 B6 B9 and C9) but the remaining MAb showed a much greater specificity for *T. palmi* than any of the other insects. In particular, MAb derived from the cell lines 3H6 E8 A6 and E6, and 3H6 D10 C12 had very high absorbances (1.4 to 1.8) with *T. palmi* and were very low (0.1 to 0.5) for all the other insect extracts tested.

Monoclonal antibodies with strong specificity for *T. palmi* have therefore been produced and could be used to develop a diagnostic assay although further cross-reactivity testing (e.g. against other thrips, plant sap, etc.) needs to be carried out as does further assay development. It would also be important to ensure that the candidate MAb show the required specificity in the different life stages.

The difficult part in setting up an immunoassay for insects is the initial establishment of cell lines producing MAb with the desired specificity. The traditional approach, as was used here, is to use a well designed MAb screening programme to obtain the desired degree of specificity and then to 'work backwards' to characterise the specific antigen. If specific antigens can be identified and isolated at the outset the process of immunization would be more targeted and the chances of rapid success increased. Preliminary work in this area was started by the use of electrophoresis to produce protein profiles. Too much data was produced to present here, but will be reported more fully in another paper. However, bands at specific MWs (290-300, 270-280 and 240-250 and possibly a major band at 30-40 Kd) were identified for *T. palmi* that were not apparent in, most importantly, *T. tabaci* and *F. occidentalis* but also *M. persicae*, *L. bryoniae* and *L. strigata*. If the protein or glycoprotein(s) in these band(s) could be eluted or fractionated by chromatographic methods, they may provide unique antigens for the production of specific MAb to *T. palmi*.

It was interesting to note that slight differences were also apparent in the profiles of the different populations of *T. palmi* from Florida and Japan (unpublished data). However, further work needs to be carried out to confirm these possible differences.

Unique and common protein MWs were also found in the profiles produced for other insects (e.g., *L. strigata* at 130-140 Kd). It may be possible to utilise these in a similar way to produce either a general MAb for use in trapping the antigen in an assay and further species or genus specific MAb for identification purposes either singularly or in a panel of antibodies.

Such an approach is likely to be utilised in the future when developing immunoassays for use in statutory quarantine work for a wide variety of pests. Further work, however, is necessary in the isolation of specific antigens, possible production of further specific MAb and additional testing of existing MAb against different insects at different life stages and from different populations. Additional development and refinement of existing prototype immunoassays also needs to be carried out.

Profiles produced by electrophoresis or chromatography may also be of use for taxonomic purposes to distinguish very similar species from each other in a similar way to that in which they are used for bacteria (Stead *et al.*, in press).

In order to obtain sufficient antigen for this work very large numbers of *T. palmi* had to be imported in a frozen state (because of quarantine restrictions). Ideally the target organism of such a diagnostic assay would be obtained from a laboratory culture kept under strict quarantine conditions. To be fully effective, such an assay should be developed before the organism of note begins to be imported into the country.

ACKNOWLEDGEMENTS

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FIELD EVALUATION OF THE AGGREGATION PHEROMONE OF THE RED PALM WEEVIL, *RHYNCHOPORUS FERRUGINEUS*, IN EGYPT

M E EL GARHY
Plant Protection Research Institute, Agriculture Research Centre, Ministry of Agriculture, Dokki, Egypt

ABSTRACT

The Asian red palm weevil, *Rhynchophorus ferrugineus* was first discovered in north-eastern Egypt in 1992 and has now become established as a primary pest of date palm in Egypt. Sizeable cavities are created in stem tissue by larval tunnelling, in which multiple generations may be completed. Even in advanced stages of infestation visible signs of stress are few and infestations are usually located by detection of exit holes.

Experiments examined the use of pheromone/food traps to determine seasonal variation of the abundance of adult *R. ferrugineus* and the effectiveness of traps for monitoring populations. Pheromone/food traps were strapped to date palms 3 metres above ground to prevent vandalism and to be above off-shoots. Many more adult weevils were captured during the warmer summer months than during the cooler winter months. The threshold for *R. ferrugineus* was found to be in the range 12-14°C with very low numbers of weevils being captured in December and January the only months in which the average daily temperature fell below 14°C.

Captures rates were highest in the months of April, May and June, which corresponds to the onset of warmer weather in Egypt. The higher capture rates during this period are probably due to the emergence of broods whose development was slowed by the cooler winter months. Twice as many female as male weevils were caught.

INTRODUCTION

The Asian red palm weevil, *Rhynchophorus ferrugineus*, is sympatric throughout South and South East Asia (Wattanaponsiri, 1966; Sadakatherlla, 1991). During the last decade multiple introductions of the weevil to the Middle East have occurred and it has now become a serious pest of date palm in the Arab Gulf States and the Arabian peninsula (Anonymous, 1995). *R. ferrugineus* was first discovered in north-eastern Egypt in 1992 and has now become established as a primary pest of date palm in Egypt (Anonymous, 1995). Although adult weevils live for 2-3 months females lay 75-355 eggs over a period of only six weeks (Butani, 1975). Eggs are laid in soft stem tissue which has been exposed by mechanical wounds, or wind damaged portions of frond axil bases. Larvae live and feed destructively in stem tissue or frond axil bases. Sizeable cavities are created in stem tissue by larval tunnelling, and multiple generations may be completed in the cavities. Even in advanced stages of infestation, visible signs of stress are few and infestations are often located by detection of exit holes from which sap usually slowly flows.

Current Egyptian strategies for management of *R. ferrugineus* infestations involve monthly surveys of all palms in the infested regions. Infested palms are removed and infected parts are sectioned and buried. As a preventative measure all palms in infested areas are sprayed to run off with a variety of insecticides. Because of the environmental pollution and economic costs of continuous insecticide spraying, more environmentally and economically acceptable alternatives are being sought to aid in the management of this pest.

The discovery of a potent male-produced aggregration pheromone [ferrugineol, 4-methyl-5-nonanol] for *R. ferrugineus* (Hallett *et al*.,1993b) makes monitoring and mass trapping of this weevil possible. Monitoring is a prerequisite for improving timing and placement of insecticide.

This paper reports the results of experiments designed to investigate, under the climatic conditions in north-eastern Egypt, seasonal variation in the abundance of adult *R. ferrugineus* in date palm, and the correlation between capture rates and temperature, relative humidity and wind velocity. In addition, the effectiveness and persistence of ferrugineol for monitoring populations and possible mass trapping of the weevil, were considered.

MATERIALS AND METHODS

Trials were conducted in the Om Shaker of Esmailia Governorate in north-eastern Egypt from September 1994 to October 1995. Date palms in this areas are planted in a disperse pattern around fields in which low row crops are planted. The area covered by the experiment was approximately 27 ha. Normal weevil management practices of monthly survey, burial of infested palms and spraying were carried out during the entire term of the experiment.

Traps consisted of inverted 9 litre flower-pots covered in jute. Weevil entry was via 12 holes (25 mm diameter) drilled within 3 cm of the trap top. Pheromone lures that released pheromone through a plastic membrane at a rate of 3 mg/day under laboratory conditions, (Hallett *et al*., 1993a) were hung from the underside of the trap tops. Traps additionally contained approximately 0.5 kg of freshly chopped date palm tissue (Hallet *et al*., 1993a) or 15-20 cm quartered sections of sugarcane stalk. The latter has been found to be a superior food additive to traps baited with the aggregation pheromone of *Rhynchophorus palmarum* (Oehlschlager *et al*., 1993). Food additives were immersed for approximately 2 min in an aqueous solution of either Lannate sp. (methomyl 90% a.i.) 15 g/litre of water or cypermethrin (EC 200 a.i.) 10 ml/litre of water, to retain captured insects.

Pheromone/food traps were strapped to date palms 3 metres above ground to prevent vandalism and to be above off-shoots. Traps were located in the centre of the experimental plot approximately 25 metres apart. Lures were replaced at different sampling dates to detect loss of efficiency.

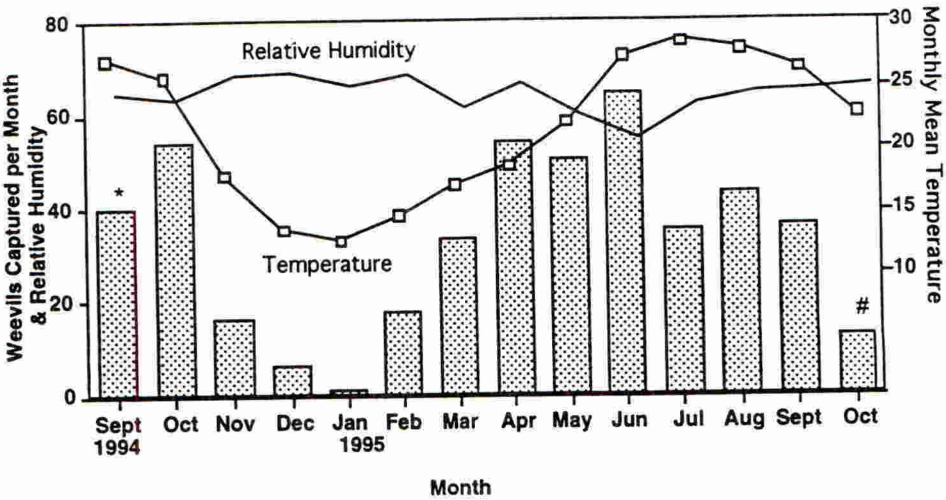

Figure 1. Monthly totals (░) of *R. ferrugineus* caught in 3 pheromone/food traps in c.27 ha stands of date palm in the Om Shaker area of Esmailia Governate of Egypt, mean daily temperature (□) and relative humidity (-), (September 1994 to October 1995). * = 21 days trapping only; # = 18 days trapping only.

RESULTS

Catches varied significantly with season (Fig 1) and many more adult weevils were caught during the warmer summer months than during the cooler winter months. Within each month capture rates were extremely variable. For example, during the first 12 days of March capture rates were 4 times those of the next 14 days, although the mean daily temperature during the entire period varied by less than 2°C. Relative humidity during the same period varied by less than 2%. Such variable catches are consistent with the emergence of broods from nearby palms. A similar variability in capture rates has been observed for *R. palmarum* at low population densities (Chinchilla *et al.*, 1993). The possibility that the periodic removal of infested palms from the experimental plot may give rise to the periodic changes in the observed capture rates was tested. No correlation was found between the timing of palm removal and the detection of higher numbers of weevils by pheromone/food traps. Given that the normal geographical range of this insect is much closer to the equator and much more humid, it was not surprising to find a distinct seasonal variation in adult flight activity in Egypt.

The threshold for flight of *R. ferrugineus* appears to be in the range of 12-14°C since very low numbers of weevils were caught in December and January, the only months in which the daily average temperature was below 14°C. Weissling *et al.*, (1994) also found a dramatic increase in flight initiation by *Rhynchophorus cruentatus* at temperatures above 15°C.

Comparison of the ratio of total monthly catches of *R. ferrugineus* to monthly means of daily temperature (Fig 2) indicated that weevils were caught at the highest rates relative to mean

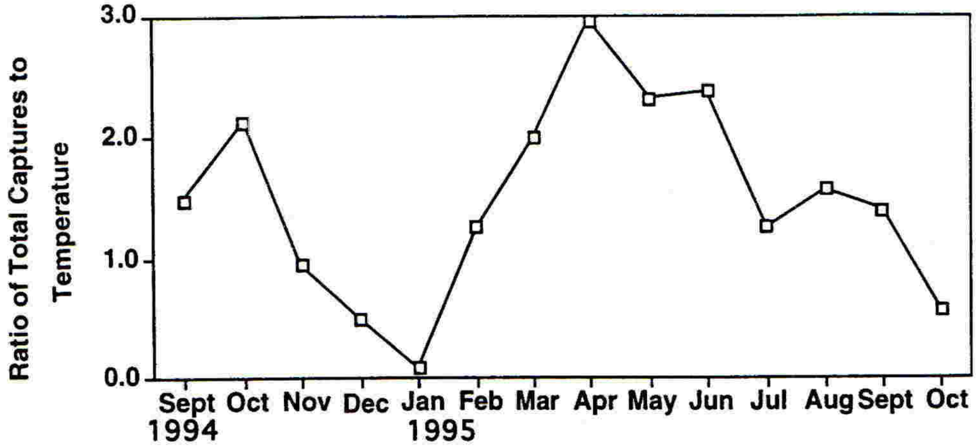

Figure 2. Ratio of total captures of *R. ferrugineus* to mean daily temperature in Esmailia Govenate of Egypt, September 1994 to October 1995.

temperature in the months of April, May and June. This corresponds to the onset of warmer weather in Egypt. The higher capture rates during this period are probably due to the emergence of broods whose development had been slowed by the cooler winter months. A related study (Weissling *et al.*, 1994) found that there was a high seasonal variation in the flight of *R. cruentatus* which corresponded to the onset of spring in Florida, the original location of this weevil.

Capture data was transformed by $(Y + 0.5)^{0.5}$ and subjected to an analysis for simple and multiple correlation coefficients (Dewey and Lu, 1959; Sokal and Rohlf, 1969; Snedecor and Cochran, 1980). The analysis (Tables 1 and 2) showed that there was a significant correlation of trap catches with temperature and relative humidity but that wind velocity did not significantly influence capture rates. There was an appreciable residual term which could be accounted for by the many other factors which influence capture rates such as trap design, type and persistence of toxic bait, weevil population and the behaviour and number of traps per area.

The relationship between capture rates and temperature, relative humidity, wind velocity and other factors could be represented by:

$$y=b_1x_1 + b_2x_2 + b_3 x_3-a$$
$$y=0.84x_1 - 0.045x_2 + 0.412x_3 - 2.649$$

where y = the predicted number of weevils, a = constant, b_1, b_2, and b_3 = partial regression coefficients and x_1, x_2 and x_3 = mean temperature, relative humidity and wind velocity, respectively. The minimum and maximum mean temperatures, relative humidity and wind velocity during the trial were 12.09-29.9°C, 51.4-73 and 1.2-3.6 kilometre/h respectively.

Lures were examined for pheromone content at each sampling period (67 sampling periods

Table 1 Simple and multiple correlation coefficients between number of weevils/trap (y) and the average temperature (x_1), relative humidity (x_2) and wind velocity (x_3); and the path coefficient (p).

Relationship	Correlation Coefficient	Path Coefficient
yx_1	0.478***	0.4423***
yx_2	-0.391**	7.5756**
yx_3	0.179	1.8454

Table 2. Components of variability of number of weevils captured

Factor	Effect (%)
Temperature	22.87
Relative Humidity	15.25
Wind Velocity	3.21
Residual	55.67
Total	100.0

over 14 months). Lures which contained liquid pheromone were replaced periodically by fresh lures. No differences in capture rates were noticed as long as lures contained pheromone. Fresh lures and lures which have been in the field appeared to be equally attractive as long as there was pheromone present.

Of the 472 weevils captured during this study twice as many female as male weevils were captured. It can be hypothesised that females have the strongest impetus to disperse from infested palms which may represent a limited food resource for her progeny. The ability to preferentially capture females in pheromone/food traps makes trapping a potentially powerful tool for management of this pest.

DISCUSSION

This study showed that, under the conditions prevailing in north-eastern Egypt, adult *R. ferrugineus* have higher flight activity in the summer months than in the winter. This may be due primarily to the higher summer temperatures, and to a lesser extent to humidity. Wind velocity is not an important determinant of capture rates. These results agree with those obtained for catches of potato tuber worm moth in pheromone traps in Saudi Arabia (El Garhy, 1980) and *R. cruentatus* in Florida (Weissling *et al.*, 1994).

If insecticide spraying is to be used as a preventative measure to protect palms then spraying would be most effective during those months in which more weevils are dispersing to new hosts and in those areas in which capture rates in pheromone/food traps are highest.

Current membrane release pheromone lures, which allow visualisation of pheromone in the lure, remain attractive as long as pheromone can be seen to be present which is usually for several months. Such lures will be suitable for population monitoring and mass trapping (Chinchilla *et al.*, 1993; Oehlschlager *et al.*, 1995).

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THE EFFECTS OF BUPROFEZIN AGAINST THE CITRUS MEALYBUG, *PLANOCOCCUS CITRI*

I D BEDFORD, A KELLY, P G MARKHAM
Department of Virus Research (Trials Section), John Innes Centre for Plant Science Research, Colney Lane, Norwich, Norfolk, NR4 7UH, UK

R P TUCKER
Zeneca Crop Protection, Fernhurst, Haslemere, Surrey, UK

ABSTRACT

Buprofezin, an insect growth regulator, was evaluated at three different application rates, 37.5, 75.0 & 150ppm, for control of the mealybug species *(Planococcus citri)*, on celery plants. Adult female *P. citri* were added to young celery plants within insect proof perspex containers and allowed to establish over a four week period. The infested plants were then divided into four groups for treatment, each of three groups receiving one of the buprofezin concentrations and the fourth, a plain tap water application as a control. All plants were individually sprayed to "just before run-off" point. No visible reduction in infestation levels were observed within any of the treatments until twenty six days after treatment, when large numbers of dead early instar larvae were observed on buprofezin treated plants. A destructive analysis of all plants revealed that mealybug infestation had been significantly reduced on plants receiving the buprofezin treatments when compared to the water treated controls. There was an indication that effects on mealybugs were greater, the higher the rate of buprofezin applied. However, low numbers of surviving mealybugs, within even the 150ppm treatment, indicated that a repeat application may be required for complete or continued control. No phytotoxic damage or response was observed on any of the celery plants within any of the treatments.

INTRODUCTION

Buprofezin based treatments, that control certain sap-sucking insects by disrupting chitin production, have been available as part of the Integrated Pest Management of whiteflies within Europe since the late 1980 s, offering a high level of selectivity. Buprofezin has been shown to control *Nilaparvata lugens*, the rice brown planthopper (Asai *et al.*, 1983 and Uchida *et al.*, 1985), *Hautidia marocanna*, the tomato leafhopper (Jacobson & Chambers, 1996) and effects have also been noted on Comstock mealybug, *Pseudococcus comstocki* (Nihon Nohyaku Technical Information summary, 1982).

Mealybugs are sap sucking, soft-bodied insects belonging to the order Hemiptera and the sub-family Homoptera. They belong to the superfamily of scale insects and yet in contrast to other members of this family, the adult stage can move.

The citrus mealybug, *(Planococcus citri*, Risso), is probably the most important species within the genus *Planococcus*. It is found worldwide and on many different plant species (Malais & Ravensberg, 1992). In the tropical and sub-tropical regions it is a pest on outdoor fruit crops, but in the more temperate regions it is a pest within glasshouses on a wide range of ornamental plants. Female *P. citri*, as with other mealybug species, produce their eggs within an increasing matrix of waxy threads which often pushes the female away from the plant surface. It has been shown that sudden temperature changes and injury appear to stimulate the females into producing more eggs and at a greater rate (Bedford & Kelly, unpublished data). Around 300 eggs are produced at 25^{0}C. Male mealybugs are considerably smaller than females and can fly. They do not have mouthparts, so, unlike the females, cannot feed and are relatively short-lived. Unfertilised females however, are capable of surviving for up to eight months and continue to feed on host plants for this time.

Development time from egg to egg varies greatly at different temperatures. At 18^{0}C it can take 81 days, yet at 30^{0}C it can be 29 days. Population development is optimal at 26^{0}C and 60%RH (Malais & Ravensberg, 1992).

This study was undertaken to evaluate the efficacy of three different application rates of the insect growth regulator 'Applaud'(Zeneca Crop Protection), an SC formulation containing 250g/l of buprofezin, for controlling an established infestation of *P. citri* on celery plants. The results were compared to those obtained from a tap water treated control.

MATERIALS AND METHODS

Test plants and replicates

The evaluation involved four treatments. Each treatment consisted of three replicate arenas and each replicate contained ten mature celery plants.

Celery seed, *Apium graveolens*, var. White Pascal, were sown in Levington M2 compost within seed trays. Once germinated, 120 seedlings were individually transplanted into 9cm^2 plastic pots containing 500mls of Levington M2 compost. These were kept within a heated, sodium lit, glasshouse until they reached a suitable size to infest with mealybugs (approximately 12 weeks).

Origin, identification and maintenance of insects

Approximately 1,000 females of the mealybug, *P. citri*, were obtained from Koppert Biological Systems one week before the start of the trial. They arrived as an established colony on etiolated potato shoots where they had been bred for use in developing biological control agents. These were kept in an insect-proof growthroom within a perspex cage, on moist tissue paper at 25^{0}C with a 16h florescent daylength.

Infestation of test plants

Groups of ten celery plants were randomly selected from the 120 plants growing individually in 9cm^2 pots and placed into vented, insect proof perspex cages. Sections of etiolated potato shoots, infested with approximately 80 adult female mealybugs were placed amongst the celery plants within each cage which was then sealed at the front with a layer of spun-bonded polypropylene fleece. These cages remained within the containment glasshouse (no supplementary lighting), until mealybugs had become established on the celery plants.

Application of treatments

Four weeks after application of mealybugs, three perspex cages, each containing ten mealybug infested celery plants, were randomly selected as replicate arenas for the control and each of three buprofezin treatments. Celery plants from the three cages assigned to each treatment were removed and after being checked to confirm mealybug infestation, were individually sprayed with tap water for the control, and a solution of either 37.5, 75.0 or 150ppm buprofezin for the treatment test. These foliar applications were made with a fine mist hand sprayer, to "just before run off" point and a freshly prepared solution of buprofezin was used for the plants within each of the three arenas for each treatment. Plants were then allowed to air dry for approximately 2 hours, before being individually sealed in a "cryovac" perforated bag and moved to a heated yet unlit containment glasshouse. Each pot was watered with approximately 50 mls of tap water three times each week through a hole in the "cryovac" bag.

Mealybug Infestation Assay Procedure

At approximately 5 day intervals, all plants were observed to visually assess the level of mealybug infestation. When a clear difference was observed between infestation levels on control plants and those treated with buprofezin, a destructive analysis of the plants was undertaken. The number of live *P. citri* on each plant and the number of egg clusters that had been produced were recorded.

RESULTS

Mealybug Infestation Levels

Visual assessments, five and an eleven days after treating the celery plants, indicated no effect on the mealybug infestations within any of the buprofezin treatments when compared to the controls. Both adult *P. citri* and the egg clusters that were being produced appeared normal.

Fifteen days after treating the celery plants however, it was noted that a number of dead mid-instar mealybugs were present on plants within the 150ppm buprofezin treatment. However, egg clusters laid on plants receiving this treatment were still producing live mealybug larvae, and no apparent treatment effect could be seen within the 37.5ppm and 75.0ppm applications.

Twenty six days after treating the celery plants, there was a clear visual difference between the mealybug infestation levels on the control plants and those within the buprofezin treatments. A reduction in the number of mealybugs on all buprofezin treated plants was apparent as well as a lack of egg clusters. Egg clusters within all the treated plants were surrounded by dead mealybug larvae and unhatched eggs appeared discoloured and in many cases showed signs of collapse. Very large adult females which were not producing eggs, were also observed within all the buprofezin treatments. The tap water treated control plants contained many mealybug larvae, adults and healthy looking egg clusters. A destructive analysis of all plants within all treatments, undertaken after 26 days, confirmed the differences between the numbers of surviving mealybugs and healthy egg clusters (Tables 1 & 2).

A scanning electron microscopy study of the dead mealybug larvae failed to elucidate any morphological changes associated with the buprofezin treatments, as had previously been shown to occur with the tobacco whitefly, *Bemisia tabaci*, (Bedford *et.al.*, 1995).

Table 1. The total number of live mealybugs recorded 26 days after treatment within each replicate arena of ten celery plants per treatment, and the mean number per arena.

Arena	Water Control	150ppm buprofezin	75.0ppm buprofezin	37.5ppm buprofezin
1	1116	45	88	134
2	416	26	17	139
3	1016	13	27	182
Mean	849.30	28.00	44.00	151.70

Table 2. The total number of visually healthy egg clusters recorded 26 days after treatment, within each replicate arena of ten celery plants per treatment and the mean number per arena.

Arena	Water Control	150ppm buprofezin	75ppm buprofezin	37.5ppm buprofezin
1	52	2	4	6
2	16	4	0	13
3	37	2	4	10
Mean	35.00	2.67	2.67	9.60

DISCUSSION

By applying a foliar treatment at three different rates to celery plants, var. White Pascal, infested with *P. citri*, it has been shown that, after 26 days from application, a dramatic reduction in mealybug numbers occurred on all plants treated with 37.5, 75.0 & 150ppm buprofezin, when compared to tap water treated control plants. Buprofezin was most effective at the 150ppm rate, where a control of almost 97% was achieved with only one application, although a 95% and 82% control was achieved with a single application of 75.0ppm and 37.5ppm buprofezin respectively. The unexpectedly long period between buprofezin application and visual effect on the mealybug infestation, may have been a reflection of environmental conditions during this trial. Temperature was shown to have averaged around 18^{0}C, which has already been shown to result in an 81 day life cycle, compared to 29 days at 30^{0}C (Malais & Ravensberg, 1992).

During the destructive assay, it was noticed that many of the live mealybugs within the buprofezin treatments were large females that had not produced egg batches. If these were fertilised females, then this inhibition of egg lay was possibly another result of treatment with buprofezin. This effect has already been seen with the brown plant hopper, *Nilaparvata lugens* in previous studies (Asai *et al.*, 1985; Uchida *et al.*, 1987).

A small number of healthy-looking egg batches (yellow and firm in appearance, compared to dark orange/grey and slightly collapsed for the unhealthy) were, however, found within all the buprofezin treatments. Whether mealybugs would have hatched and developed normally was not investigated, but this does indicate that a second application of buprofezin might be necessary for continued control.

The final assessment, revealed that one of the control arenas had a much reduced mealybug number when compared with the other two. The reasons for this are unclear but could have been due to the loss of egg-laying adults during the foliar application of tap water. It could also have been due to the position of these control plants within the trial glasshouse, where buprofezin vapour from treated arenas may have had an effect on the developing mealybugs.

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STRATEGIC INCORPORATION OF BIOCONTROL AGENTS FOR MANAGING ALIEN INSECT PESTS

E C WILLIAMS, K F A WALTERS
Central Science Laboratory, MAFF, Sand Hutton, York, YO4 1LZ, UK

ABSTRACT

A strategic approach which enables the inclusion of biocontrol agents in schedules for the containment and eradication of alien insect pests has been developed for leaf miners. This study investigated whether this approach can be applied to another group of insects, noctuid moths. At moderate humidities (80% r.h.) the application of *Steinernema feltiae* resulted in significant mortality of fifth instar larvae of *Spodoptera littoralis* and *Helicoverpa armigera* but not *Laconobia oleracea*. At high humidity (>90% r.h.), fourth instar *L. oleracea* and *S. littoralis* suffered high mortality with similar numbers of nematodes infecting the hosts. At 80% r.h., however, significantly fewer nematodes infected *L. oleracea* compared to *S. littoralis*. The strategic incorporation of these agents for the management of alien noctuids is discussed.

INTRODUCTION

Recent research has shown that biological control techniques can be incorporated into schedules for the containment or eradication of alien pests (Williams and Walters, 1994; Williams and Macdonald, 1995). Management campaigns for alien pests often have to be implemented rapidly and at short notice, severely limiting the development time for biocontrol strategies. Accordingly an approach has been developed which enables basic research to be completed prior to any introduction of alien species. Groups of insects with similar life history strategies are defined, and model (representative) pest species chosen and used to determine the baselines and strategies required for the successful application of one or more selected biological control agents. The extent to which these strategies can be extrapolated to other members of the group is determined. Protocols are developed in which only the critical data on factors governing the successful application of the technique are researched and thus can be obtained rapidly. Newly intercepted alien pests are allotted to the appropriate group, the protocols are implemented and management strategies, based on the data obtained, drawn up. The method has been successfully applied to dipteran leaf miners (Williams & Macdonald, 1995), and this study investigates the use of the approach to another group of insects, noctuid moths.

Spodoptera littoralis (Boisduval) is a major pest in many regions of the world. In the UK, it was first intercepted in 1963 following the importation of *Dendranthema* (chrysanthemum) cuttings for all year round cut flower production. This pest is highly polyphagus and can attack numerous economically important crops throughout the year. Although a number of outbreaks have been reported in the UK (Bartlett & Macdonald, 1993), *S. littoralis* has been successfully contained and eradicated. With increasing reports of resistance and cross resistance to organophosphates, synthetic pyrethroids (CABI/EPPO, 1992) and bio insecticides such as *Bacillus thuringiensis* (Salama & Foda, 1982) alternative strategies for the control of this pest need to be investigated.

Helicoverpa armigera Hübner is a serious outdoor pest in Mediterranean countries and a risk to glasshouse crops in northern Europe. In the UK, it is regularly intercepted on cut flowers and vegetables such as mangetout, but has hitherto been eradicated successfully Although there have been no reported outbreaks since 1986, it is considered a potential threat to protected crops such as tomatoes, where it could prove difficult to find suitable control measures that are compatible with the biological control programmes at these nurseries.

Laconobia oleracea (L.) is an indigenous species, with young larvae that feed on leaves of tomato plants and can totally defoliate them. Older larvae may attack stems and burrow into fruits. In the UK this moth is mostly a pest on protected crops such as tomatoes but can also cause damage to cultivated chrysanthemums (Becker, 1974). With the increasing reduction in the use of conventional pesticides and changes in cultivation methods, some authors believe that there could be an increase in tomato moth outbreaks in greenhouse tomatoes (Corbitt *et al.*, 1996).

This paper compares the susceptibility of *S. littoralis*, *H. armigera* and *L. oleracea* to a foliar application of entomopathogenic nematodes. The application of the model species method to develop the strategic use of biological control agents for the management of alien moths is discussed.

MATERIALS AND METHODS

Nematode products and insect cultures

Commercial formulations of *S. feltiae*, (Nemasys) were used in all experiments. Nematodes were stored at 5°C in water for up to one month, and after each experiment stocks were subjected to an infectivity bioassay with *Galleria mellonella* as described by Fan & Hominick (1991). Only results from experiments using nematode populations with infectivity levels greater than 15% were analysed.

Larvae of *S. littoralis* were cultured on an artificial diet in propagating trays lined with sterilised coarse sand and vermiculite, and sealed with vented propagating lids (Williams, 1996). Cultures were maintained at 25 ± 3°C with a 12:12 h light:dark regime and an artificial dawn and dusk. All experiments were conducted under the same light:dark regime. Similar techniques were used to culture *H. armigera* but to avoid cannibalism, 2nd instar and older larvae were reared individually. The *L. oleracea* were reared from eggs to pupae under conditions described in Corbitt *et al.* (1996).

Infestation of plants and treatments

Treatments included suspensions of *S. feltiae* made up to 1000 nematodes/ml with 0.02% of a liquid non-ionic wetting agent, Agral (a.i. alkyl phenol ethylene oxide), and a control without nematodes. These treatments were applied to run off at a rate of 900-1200 l/ha (9-12 nematodes/cm^2 leaf surface) using a Hozelock® hand sprayer, to two week old broad bean plants (cv. The Sutton) grown in 9 cm diameter pots. After application, the soil was covered with 9 cm filter paper (Whatman No 1) to minimise the exposure of the larvae to the soil. Five larvae were placed on the leaves of each plant and then covered either by a plastic container to maintain a high humidity of >90% r.h., or a mesh net to prevent the larvae from escaping. Each plastic container had two 1.5 cm diameter mesh covered holes, one at the top and one on the side to assist ventilation. These containers and nets were sealed to the pots with either masking tape or an elastic band respectively. They were then maintained at 20°C and either 80% ± 10% r.h. or >90% r.h. with a 12:12 h light:dark regime in which the first 12 h were in darkness. The efficacy of the nematode treatments was assessed by counting the number of surviving larvae after 48 h.

Susceptibility of *S. littoralis*, *H. armigera* and *L. oleracea* larvae

A suspension of *S. feltiae* was applied to run off to three out of six plants. The remaining plants were sprayed as a control without nematodes. Five first instar *S. littoralis* were placed on the leaves of each plant which were then covered in mesh netting and sealed. The plants were maintained at 20°C and 80% ± 10% r.h. with a 12:12 h light dark regime with the first 12 h in darkness. After 48 h larval mortality was assessed. This experiment was repeated with fourth and fifth instar *S. littoralis* and first fourth and fifth instar larvae of *H. armigera* and *L. oleracea*.

Comparison of *S. littoralis* and *L. oleracea* at 80% r.h. and >90% r.h.

A suspension of *S. feltiae* was applied to run off to 10 out of 15 plants. The remaining five were sprayed, as a control, without nematodes. Five fourth instar *S. littoralis* were placed on the leaves of each plant. Five of the plants sprayed with *S. feltiae* were covered with a mesh net, the rest were covered with plastic containers which retained a humidity of >90% r.h. This was repeated for *L. oleracea*. All the plants were maintained at 20°C and 80 ± 10% r.h. Larval mortality was assessed after 48 h. The cadavers were then kept for a further 48 h after which time they were dissected and the numbers of nematodes present recorded.

RESULTS

Susceptibility of *S. littoralis*, *H. armigera* and *L. oleracea* larvae

A three way analysis of variance indicated that the application of *S. feltiae* to all three species caused a significant mortality of the noctuid larvae compared to the control (F=59.07, d.f. 1,72 p<0.001; Table 1). This effect was dependent on the instar to which the nematodes were applied (F=9.41, d.f. 2,72 p<0.001) with fifth instar larvae of *S. littoralis* and *H. armigera* being more susceptible than the other instars tested. There was also a significant difference in the susceptibility between species (F=8.82, d.f. 2,72 p<0.001). Overall *L. oleracea* was less susceptible to *S. feltiae* at low humidities than either *S. littoralis* or *H. armigera*, the latter two being similar in susceptibility (F=1.81, d.f. 1,45 p>0.1).

Comparison of *S. littoralis* and *L. oleracea* at 80% r.h. and >90 r.h.

Humidity had a significant effect on the mortality of both species of caterpillar (F=14.89, d.f 1,16p=0.001) with greater mortality occurring at humidities >90% r.h. (Table 2.). When the

Table 1. Mean susceptibility of *S. littoralis*, *H. armigera* and *L. oleracea* to a foliar application of the nematode *S. feltiae* at 20°C and 80% ± 10% r.h.

	Mean number of surviving larvae ± standard error								
	Instar of *S. littoralis*			Instar of *H. armigera*			Instar of *L. oleracea*		
Treatment	first	fourth	fifth	first	fourth	fifth	first	fourth	fifth
water	3.4 ± 0.67	5.0 ± 0.0	5.0 ± 0.0	4.6 ± 0.4	4.8 ± 0.2	5.0 ± 0.0	4.8 ± 0.2	5.0 ± 0.0	5.0 ± 0.0
S. feltiae	3.0 ± 0.71	4.2 ± 0.37	2.4 ± 0.51	4.4 ± 0.25	3.4 ± 0.6	1.0 ± 0.32	4.2 ± 0.37	4.0 ± 0.32	4.2 ± 0.58

Table 2. Mortality of *S. littoralis* and *L. oleracea* after a foliar application of *S. feltiae* at 20°C and 80 ± 10% r.h. and >90% r.h.

	S. littoralis		*L. oleracea*	
Treatment	Mean % mortality/ treatment	Mean no. of *S. feltiae*/insect/ plant ± SE	Mean % mortality/ treatment	Mean no. of *S. feltiae*/insect/ plant ± SE
S. feltiae at 80 ± 10% r.h.	52	1 ± 0 2 ± 0 22.4 ± 9.8 30.7 ± 29.7 0 ± 0	20	0.33 ± 0.33 1 ± 0 0 ± 0 0 ± 0 0 ± 0
S. feltiae at >90% r.h.	88	125.8 ± 42.4 63.8 ± 11 54.4 ± 25.7 261 ± 91.8 95.2 ± 49.1	84	137.6 ± 55.6 105.6 ± 33.9 49.6 ± 23.1 181.5 ± 158.7 46 ± 35.4

numbers of nematodes inside the cadavers were counted, it was found that overall, significantly more nematodes invaded *S. littoralis* than *L. oleracea* ($F=6.12$, d.f. 1,56 $p<0.05$). This difference relied upon the results of experiments conducted at 80% r.h., in which a mean of 18.9 ± 8.9 nematodes was recovered per *S. littoralis* larva compared to 0.6 ± 0.3 for *L. oleracea*.

DISCUSSION

The larvae of *S. littoralis*, *H. armigera* and *L. oleracea* were all susceptible to a foliar application of the nematode *S. feltiae*. However, the degree of susceptibility of these insects depended on the instar to which the nematodes were applied and the humidity. At lower humidities first instar larvae of all three species were less susceptible to *S. feltiae*, whereas the fifth instars of *S. littoralis* and *H. armigera* exhibited a high level of susceptibility. A number of laboratory investigations have been carried out on the larval instar and the susceptibility of *Spodoptera* spp. and *Helicoverpa* spp. to entomopathogenic nematodes (Kaya, 1985, Kondo & Ishibashi, 1985, Fuxa *et al.*, 1988 and Glazer, 1992). Contradictory results have been obtained with Fuxa *et al.* (1988) finding that older larvae were less susceptible than younger ones, whereas Kaya (1985) demonstrated that younger larvae (0-1day old larvae) were less susceptible than older (3-8) day old larvae. These differences have been attributed to the bioassay techniques employed by individual researchers. In this study the application to whole plants aimed to simulate the likely susceptibility in the field more accurately by allowing the natural behaviour of the different larval instars to be incorporated into the design.

Glazer *et al.*, 1992 investigated the efficacy of *S. carpocapsae* against *S. littoralis*, *H. armigera* and *Earias insulana* (Boisduval) on whole plants. These researchers reported a differential susceptibility between third instar larvae of these species, with *H. armigera* requiring the application of a higher concentration of nematodes to achieve comparable levels of control compared to *S. littoralis* and *E. insulana*. The results of the current study indicate that differences in susceptibility occur between species with *S. littoralis* and *H. armigera* being more susceptible than *L. oleracea* at 80% r.h. This difference may be explained by the numbers of nematodes that invaded each host. At this humidity, the number of nematodes entering *L. oleracea* larvae was significantly lower than those entering *S. littoralis*. This could be the result of qualitative or quantitative differences in the cues produced by *L. oleracea* which cause a differential attractiveness to the nematodes (Kondo and Ishibashi, 1986). Alternatively the behaviour of *L. oleracea* on the plant could reduce the ability of the nematode to enter this insect species.

This study indicates that it is possible to apply the model species approach for the rapid determination of biocontrol methods for alien pests, to noctuid moths. Strategic protocols, on which management strategies for the control of alien noctuids can be based, can be developed from such studies and further research has confirmed their validity (Williams, 1996). Baseline research reported in this paper has shown that entomopathogenic nematodes can be applied successfully for the control of noctuid larvae. However, the efficacy of these nematodes is dependent on the instar to which they are applied. The temperatures and humidities required for the effective control of noctuid larvae are similar to those for the foliar application of *S. feltiae* to leaf miners (Williams & Macdonald,1995). Thus, protocols for the rapid development of biocontrol strategies for the control of newly introduced noctuids should concentrate on tests of the susceptibility of different moth larval instars to *S. feltiae*. The management strategy for noctuids should include foliar applications at intervals determined by the larval susceptibility and development rate of the moth species at humidities and temperatures defined in Williams and Macdonald (1995).

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ASSESSING THE ECONOMIC THREAT OF *BEMISIA TABACI* AND TOMATO YELLOW LEAF CURL VIRUS TO THE TOMATO INDUSTRY IN ENGLAND & WALES

D MORGAN, A MACLEOD
Central Science Laboratory, MAFF, Sand Hutton, York, YO4 1LZ, UK

ABSTRACT

The tobacco whitefly, *Bemisia tabaci*, is an important plant pest world-wide. It is regarded as a quarantine pest in the UK and small numbers are introduced into the country annually. It poses a serious threat to the viability of the UK horticulture industry, in particular to the tomato industry, since it is an efficient vector of tomato yellow leaf curl virus (TYLCV). To determine the extent of this threat to one sector of the UK horticulture industry, heated tomato production, an economic analyses of the eradication of *B. tabaci* and control of TYLCV were made. Pest population dynamics, virus epidemiology and financial models were integrated with crop production and pest control costs, and predictions of likely pest and virus outbreak scenarios and associated financial consequences were made. The models predicted that the introduction of *B. tabaci* and TYLCV would have severe consequences for both the individual grower and the national tomato industry alike.

INTRODUCTION

The tobacco whitefly, *Bemisia tabaci*, is serious pest throughout the world with a host range of over 500 plant species (Greathead, 1986). It damages plants by direct feeding, depositing honeydew on which sooty moulds develop and by causing phytotoxic reactions in plants. However, the most serious threat to growers of horticultural crops in the UK is from its ability to transmit plant viruses.

B. tabaci can transmit many different plant viruses, including around 60 geminiviruses (Markham *et al.*, 1994). One of the most important viruses transmitted is tomato yellow leaf curl virus (TYLCV). Infected plants show severe stunting, and small or misshapen and severely chlorotic leaflets. Flower abscission and fruit set may also be inhibited or prevented (Smith *et al.*, 1988). Wide variation in yield response by tomatoes infected with TYLCV has been reported and the growth stage of the tomato plant at the time of inoculation with virus has been shown to be important (Kegler, 1994). Losses of around 80% of the crop have been reported when young tomatoes were inoculated with TYLCV (Ioannou, 1985).

Control of the virus has traditionally been based upon the use of insecticides targeted at the whitefly vectors. However, the pest has developed resistance to several of the commonly used insecticides in many countries throughout the world (De Barro, 1995) and management strategies must be carefully designed if effective eradication campaigns are to be mounted in the UK.

This paper reports an economic assessment of the financial consequences of the introduction and development of a population of *B. tabaci* and subsequent spread of TYLCV, and assesses the potential costs that both pest and virus may inflict on individual tomato growers and the tomato growing industry in England & Wales.

MATERIALS AND METHODS

Introduction of *B. tabaci* into tomato-growing glasshouse and outbreak scenarios

To calculate the possible costs of *B. tabaci* and TYLCV to tomato growers it was necessary to consider different outbreak profiles of the pest and virus. Four scenarios of pest introduction were defined and models describing the population dynamics of *B. tabaci* and spread of TYLCV (Head & Morgan, 1996) were used to determine the consequence of these outbreaks.

Interception statistics show that low levels of *B. tabaci* are intercepted annually on poinsettia cuttings supplied to the UK for Christmas pot-plant production (Cheek, 1995). Thus in this research it was assumed for each of the scenarios that *B. tabaci* was imported into the UK on poinsettia and that in December a number of adult whitefly were introduced onto a newly transplanted tomato crop, a small proportion of which were carrying TYLCV.

The effects of TYLCV infection on fruit yield and quality were derived using the data of Polizzi & Asero (1994) and pest control costs were taken from ADAS gross margin budgets (Anon, 1994). Each of the four scenarios described the development of an outbreak on the holding of a single producer: Nil - No introduction of *B. tabaci* or TYLCV; Low - 5 *B. tabaci* were introduced into a glasshouse. *B. tabaci* numbers increase and TYLCV spread occurs causing a loss in fruit yield and a 50% loss in quality of infected fruit. Annual cost of pest control is increased 2 fold; Medium - 20 *B. tabaci* were introduced into a glasshouse. Pest numbers increase causing yield and quality losses. Annual cost of pest control is increased 2.5 times; and High - 100 *B. tabaci* were introduced into a glasshouse. Damage occurs and the annual cost of pest control is increased 3 fold.

Tomato production costs

The management budget for a December planting of heated tomatoes was taken from the ADAS gross margin budgets, which provided the model with costs of producing tomatoes per 0.1ha of heated glass in the UK (Anon.,1994).

The management budgets were modified for each *B. tabaci*/TYLCV outbreak scenario, whereby vector and virus establishment were assumed to cause yield and quality losses to the tomato crop resulting in lower financial margins. Although there are many data describing the direct impact of *B. tabaci* infestations on yield, few data are available relating the indirect effects of virus infection to yield loss. To derive this relationship, the results of Polizzi & Asero (1994), who formulated a relationship between tomato yield and the time before plants expressed TYLCV symptoms, and Kegler (1994), who reported that disease symptoms first appear 15 days after inoculation, were used.

Control measures

Since *B. tabaci* is a quarantine pest, statutory measures are taken (including destroying the crop) to ensure eradication of any pest outbreaks. Traditionally growers have relied upon chemical control of whitefly, using active ingredients such as buprofezin, nicotine and fatty acid detergents, although much interest has been shown in using biological control agents, such as *Encarsia formosa* and *Delphastus pusillus*. An integrated approach using both chemical and biological control is also possible, although careful consideration of appropriate chemical regimes must be made to avoid upsetting any integrated/biological management of other tomato pests already in place. Costs of appropriate control measures were taken from the ADAS gross margin budget (Anon.,1994).

A financial model

ADAS gross margin budgets (Anon.,1994) were used as the basis of the financial model to determine the effect of each pest and virus outbreak scenario on a single producer growing a winter planting of tomatoes in south east England. This grower profile was used as over 76% of heated tomato production in England and Wales is planted in winter, 45% of which occurs in south east England (Anon., 1995). Ministry of Agriculture, Fisheries and Food (MAFF) consensus data (Anon., 1995) were used to determine the effect of each pest and virus outbreak scenario for the national tomato industry. Correction factors were used when scaling-up from the single producer (0.1ha) financial model to the national scale so that the figures closely matched the national MAFF consensus statistics for national heated tomato production.

All calculations were based on monthly variables of tomato production which could be altered for each month from February to October. A common procedure was used for each of the four pest outbreak scenarios; the dynamics of *B. tabaci* populations and subsequent spread of TYLCV were derived from the models described by Head & Morgan (1996) and entered into the financial model together with appropriate pest control costs. Losses in crop yield and quality were calculated, dependent upon the age of the plants, and were altered monthly in the financial model.

The model calculated the monthly and cumulative yields, variable production costs and sales for the year. The gross margin at the end of the year was determined as a result of yield, quality and control measure costs.

RESULTS

Single producer scale

The gross margin changes for a single tomato producer for each *B. tabaci* outbreak scenario is summarised in Table 1. Under the nil scenario (no *B. tabaci* outbreak) a tomato crop grown under 0.1ha of heated glasshouse resulted in sales of over £30,000, while the gross margin (considering crop production and marketing costs) was over £13,700, which is the equivalent to around 45.5% of the sales value. This percentage decreased with increased pest and virus pressure, reaching 33.1% for high pest outbreak scenario (Table 1).

Table 1. Changes to Gross Margins in tomato production: revenue and costs under four pest and virus outbreak scenarios in 0.1ha heated glasshouse

	Nil loss in yield or quality (Standard Gross Margin) £	Low numbers of *B. tabaci* £	Medium numbers of *B. tabaci* £	High numbers of *B. tabaci* £
Sales	30,280	26,533	26,818	24,574
Production costs	11,138	11,452	11,609	11,766
Marketing costs	5,379	5,160	4,950	4,688
Gross Margin	13,763	11,921	10,258	8,131
% of standard Gross Margin	100	86.6	74.5	59.1
Gross Margin as % of Sales	45.5	44.9	38.3	33.1

Sales of the tomato crop decreased with increased pest/virus pressure; sales under high pest outbreaks (scenario 4) were only around 80% of the sales under the nil scenario (Table 1). Sales were reduced because of the reduction in tomato yield and the loss in fruit quality, while marketing costs were reduced because of the reduction in fruit yield and, hence, lower transport costs needed to ship less produce. However, production costs were increased with larger pest outbreaks, as greater expenditure was incurred in controlling the increased pest populations.

National production scale

The changes in gross margins for tomato growing on a national scale for each of the scenarios are summarised in Table 2. Assuming no *B. tabaci* nor TYLCV outbreaks (scenario 1) then the expected national sales of tomato was calculated to be nearly £63M, as derived from the MAFF consensus statistics (Anon.,1995), while the gross margin was approximately £27.5M. The effects of increasing pest/virus pressure on national crop profitability were similar to those effects for the single producer; sales and marketing costs were reduced, while production costs were increased resulting in decreased percentages of standard gross margin. The financial model predicted that if severe *B. tabaci* outbreaks occurred (scenario 4) then the gross margins would be nearly half of those if pest outbreaks did not occur (Table 2).

Table 2. National-scale changes to gross margins in tomato production: revenue and costs for four *B. tabaci* and TYLCV damage scenarios to tomatoes in heated glasshouses in England & Wales

	Nil loss in yield or quality (Standard gross margin) £ '000	Low numbers of *B. tabaci* £ '000	Medium numbers of *B. tabaci* £ '000	High numbers of *B. tabaci* £ '000
Sales	62,785	59,162	55,605	50,952
Production costs	23,662	24,329	24,663	24,996
Marketing costs	11,643	11,169	10,715	10,148
Gross Margin	27,480	23,664	20,227	15,808
% of standard Gross Margin	100	86.1	73.6	57.5
Gross Margin as % of Sales	43.8	40	36.4	31

CONCLUSIONS

In regions of the world where *B. tabaci* occurs, severe outbreaks of TYLCV can cause serious reductions to crop yield and quality and, hence, economic damage. If plants become infected sufficiently early, within a few weeks of being transplanted, crop yields can be reduced by 80% (Ioannou, 1985). Interceptions of *B. tabaci* suggest that there is a distinct risk of the pest and TYLCV becoming established in northern European glasshouses and affecting tomato production.

The analysis presented in this paper shows that the consequences of outbreaks of this pest and virus to the production of tomatoes in heated glasshouses would be severe for the single tomato producer and national industry alike; the single producer might expect to reduce margins by around £5,500 per 0.1ha, while the national industry might suffer losses of around £11.5M. Therefore, continued careful consideration of appropriate outbreak management strategies should be made if the UK tomato industry is to avoid suffering significant financial losses resulting from *B. tabaci* and TYLCV and great care is needed to maintain and build upon the effective monitoring and control programmes already in place for this pest.

The financial model used for the single producer scale is an example of partial budgeting, an economic technique capable of determining the profits of an individual business using details of costs and returns, and is one of three quantitative techniques recommended for use when assessing the potential economic impact of alien pests or diseases during pest risk assessment (EPPO, 1995). Although the partial budgeting framework presented in this paper is based on many assumptions relating to pest outbreaks, it has proven useful in preparing informed pest risk assessments for *B. tabaci*. In addition the simple and flexible structure ensures that it has the potential for application in the risk assessment of alien pests other than whitefly.

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ALIEN TERRESTRIAL PLANARIANS IN ENGLAND & WALES, AND IMPLICATIONS FOR HORTICULTURAL TRADE

D V ALFORD
ADAS Boxworth, Boxworth, Cambridge, CB3 8NN, UK

M J LOLE
ADAS Plant Clinic, Woodthorne, Wergs Road, Wolverhampton, WV6 8TQ, UK

B J EMMETT
ADAS Horticulture, 27 Long Meadows, Bramhope, Leeds, LS16 9DU, UK

ABSTRACT

Two alien species of terrestrial planarian (the New Zealand flatworm, *Artioposthia triangulata* (Dendy) and the so-called Australian flatworm, *Australoplana sanguinea* var. *alba* (Moseley)) are causing concern in England, and elsewhere in Europe, as they are predators of earthworms. The former species, although most abundant and widespread in Northern Ireland and Scotland, is of particular significance and is now established in parts of northern England; the latter species occurs mainly in South West England and in Merseyside. South of the Scottish border, most flatworms occur in private gardens, many probably having been introduced accidentally in association with containerized hardy ornamental plants; to date, relatively few flatworms have occurred in commercial nurseries or garden centres. To protect both national and international trade, steps within the horticultural industry should be taken to minimize the risk of flatworms occurring or persisting in commercial sites and to prevent nurserymen accidentally distributing flatworms or flatworm egg capsules to customers. Chemical control is not seen currently as a viable answer to flatworm problems; however, in commercial nurseries, it might eventually form part of an overall flatworm management strategy.

INTRODUCTION

There are several indigenous species of terrestrial planarian (flatworm) in England & Wales but none poses any threat to either agriculture or the natural environment. In recent years, however, some alien species, notably the New Zealand flatworm (*Artioposthia triangulata* (Dendy)) and the so-called Australian flatworm (*Australoplana sanguinea* var. *alba* (Moseley)), have been discovered in the UK (e.g. Willis & Edwards, 1977; Jones, 1981). These two large flatworms (the former is sometimes capable of extending to 300 mm or more in length) are predators of earthworms and both, but especially *Artioposthia triangulata*, are considered undesirable inhabitants. Other accidentally introduced alien species, however, such as *Rhynchodemus sylvaticus* Leidy (which is reported from England, Ireland and Wales), are relatively small in size and, along with our native species, are not considered in any way harmful.

By the early 1990s, *Artioposthia triangulata* had become widely distributed and common in both Northern Ireland and Scotland (e.g. Stewart & Blackshaw, 1993; Boag *et al.*, 1994b). However, although known to occur in England since the mid-1960s (Willis & Edwards, 1977), confirmed records south of the Scottish border were very few (Boag, *et al.*, 1994a). *Australoplana sanguinea* has been recorded mainly in the extreme south west of England (including the Isles of Scilly) and around Merseyside (Jones, 1988).

Since 1994, largely following concern over the rapid spread of *Artioposthia triangulata* in Scotland, ADAS has been studying the distribution of alien terrestrial flatworms in England & Wales. ADAS was also commissioned to assess the potential impact of *Artioposthia triangulata* on agriculture and the environment (Alford *et al.*, 1995). In this paper, up-to-date information on the distribution of *Artioposthia triangulata* and *Australoplana sanguinea* is presented and the threat these organisms pose to national and international horticultural trade discussed. Possible options for the management or control of flatworms in nurseries and garden centres, to reduce the risk of introducing or spreading these undesirable organisms, are also considered.

METHODS

Widespread national publicity about alien flatworms was initiated in January 1994, following a press conference at the Royal Horticultural Society, Wisley. This requested horticulturists and members of the public to report suspected specimens of flatworms and, where appropriate, to submit samples for examination. Reports and material from England & Wales, Northern Ireland and Scotland were handled by ADAS, DANI (Belfast) and SCRI (Dundee), respectively. Only data for England & Wales are reported here.

RESULTS

During the ADAS survey, most reported 'specimens' of alien flatworms proved to be leeches. Occasionally, other 'organisms', including earthworms, slow-worms and, in one instance, a caterpillar of the large elephant hawk-moth (*Deilephila elpenor* L.) were mistaken for flatworms; a small number of native flatworms were also received: *Microplana scharfii* (von Graff) (5), *M. terrestris* (Müller) (3) and *Rhynchodemus sylvaticus* (Leidy) (4) (see Table 1).

Data for *Artioposthia triangulata*

Before the commencement of the survey, south of the Scottish border *Artioposthia triangulata* had been found in only four 10 × 10 km National Grid squares: NY35, SD70, SE35 & TQ18. By spring 1995, records for a further 14 squares were confirmed and by summer 1996 for an additional 25 (Figure 1). Most records from any one location in England were of one or two individuals, often thought to have been introduced accidentally along with containerized hardy ornamental plants. In a few locations, specimens were more numerous and the flatworms appeared to have become established. Apart from the original record from near Carlisle in 1965 (see Willis & Edwards, 1977) and some infestations found

Figure 1. Confirmed distribution of *Artioposthia triangulata* in England & Wales (to summer 1996).

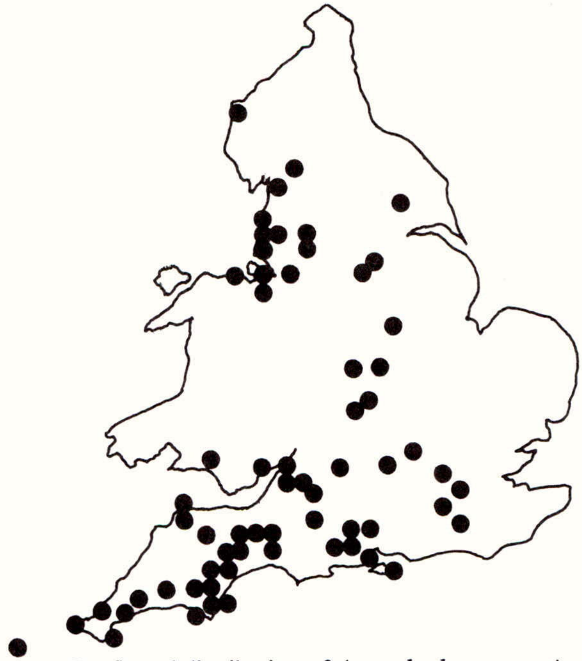

Figure 2. Confirmed distribution of *Australoplana sanguinea* in England & Wales (to summer 1996).

recently in northern England, most if not all specimens in England have been located in allotments or private gardens; in some places, notably around Harrogate, Yorkshire, several private gardens in the same area have become infested. To date, *Artioposthia triangulata* has not been found in Wales.

Table 1. Samples from England & Wales suspected of being alien flatworms.

Confirmed identification	1994	1995	1996
Artioposthia triangulata	5	20	5
Australoplana sanguinea	0	66	17
Native flatworms (see text)	0	12	0
Leeches	106	252	117
Other organisms/artifacts*	15	82	16

*Includes earthworms, slugs, leatherjackets, millepedes, beetle larvae, hover fly larvae, water planarians, thunderworms, slow-worms, a slime mould, controlled-release fertiliser granules (thought to be egg capsules), a piece of animal gut, a decaying leaf and a piece of a plastic comb.

Data for *Australoplana sanguinea*

As with *Artioposthia triangulata*, this species is also most often found in private gardens. During the course of the survey, the first record from Wales was confirmed (in 1995), in a private garden near Rhyl, Clwyd. Other new records (received mainly in 1995/96) showed this species to be now widely distributed in Devon and Cornwall and also present in several sites further to the east; additional records for Merseyside were also obtained. The distribution of this species in England & Wales (to summer 1996) is shown in Figure 2.

DISCUSSION

Alien flatworms such as *Artioposthia triangulata* have the potential to alter the balance of terrestrial ecosystems by preying upon lumbricid earthworms, with varied and largely unknown consequences (Alford *et al*., 1995). The perceived significance of the indirect threat posed to British wildlife through the reduction in numbers or elimination of earthworms, particularly to earthworm-feeding birds (e.g. blackbirds, *Turdus merula*), mammals (e.g. badgers, *Meles meles*, and moles, *Talpa europaea*) and other creatures (e.g. testacellid slugs, *Testacella* spp.), is such that *Artioposthia triangulata* is currently included in schedule 9 of the 1981 Wildlife and Countryside Act. Accordingly, it is an offence to release or allow the flatworm to escape into the wild. There is no statutory requirement for any authority or body to eliminate outbreaks of *Artioposthia triangulata* within the UK.

However, the pest is now so widely distributed and well-established that its eradication from the wild would appear to be quite impractical; the eradication of *Australoplana sanguinea* from the UK may now be equally impractical.

Flatworms do not damage plants. However, *Artioposthia triangulata* has been found in commercial hardy ornamental nurseries in Northern Ireland and Scotland, sheltering beneath containers, matting and plastic sheeting in contact with the ground, where the damp, relatively undisturbed conditions are clearly favourable for their survival; similarly, the flatworms will readily enter containers through drainage holes, to shelter between the wall and the root ball (Blackshaw & Stewart, 1992). Egg capsules are also deposited in all these situations. Records of both *Artioposthia triangulata* and *Australoplana sanguinea* in commercial nurseries in England exist, but they are currently few and far between.

Although, locally, terrestrial flatworms are capable of moving independently from site to site (Stewart & Blackshaw, 1993; Mather & Christensen, 1995), most of the spread to 'new' areas is probably as a result of accidental passive transfer of the flatworms or their egg capsules, especially in association with containerised hardy ornamentals. Other passive means are also possible (see, for example, Christensen & Mather, 1995). Actual and circumstantial evidence was available to indicate that several 'new' English records of *Artioposthia triangulata* obtained in the current ADAS study originated from 'infested' material bought-in from Scotland.

Frequently cultivated and cropped arable or horticultural sites are less favourable for flatworm survival than, for example, undisturbed permanent grassland. Also, the risk of spreading flatworms from any infested sites on harvested bulbs, potatoes or other root crops is considered negligible, owing to the significant disturbance caused to consignments prior to packaging and the statutory requirements limiting the quantities of soil which may be present. These are important considerations in defence of international trade in such products. Although the risks are slight, importing countries in Europe have more justified fears of introducing alien flatworms in consignments of hardy ornamental plant material. Although the introduction of plant quarantine measures is not considered appropriate, Sweden now requires evidence that UK exporters are checking such plant material for flatworms prior to sale and are monitoring around the borders of plant-production sites (using trapping techniques), to reduce the risk of flatworm invasion and establishment. To minimize if not prevent the development of flatworm problems in commercial nurseries and garden centres in England & Wales, the Plant Health Division of MAFF has recently published a Code of Practice, within which such measures are explained (Anon., 1996).

Although tolerant of a wide range of soil pH conditions, e.g. 4.7 to 8.0 (Willis & Edwards, 1977), *Artioposthia triangulata* is known to be susceptible to slight increases in salinity and to increased acid levels. Some MAFF-funded work on chemical control is in progress, but there are currently no viable recommendations available for controlling terrestrial flatworms within nurseries, garden centres or elsewhere. Were chemical treatments to become available, they would probably not kill juveniles within egg capsules and so may be of limited value; persistent soil treatments, for example (even if available), are unlikely to be acceptable on environmental and other safety grounds. Thus, chemical control measures (if used) would need to form part of an overall flatworm management strategy. The latter should also include the adoption of suitable on-site hygiene measures, and routine inspections of sites and plant material, to minimize the risk of introducing and spreading flatworms. On commercial sites where flatworms become established, targeted trapping and destruction of specimens (including egg capsules) might also be appropriate. Adoption of such measures would address fears expressed by customers within the UK and, particularly, by importers from wider afield.

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CONTROL OPTIONS FOR THE NEW ZEALAND FLATWORM

R P BLACKSHAW
Seale-Hayne Faculty of Agriculture, Food and Land Use, University of Plymouth, Newton Abbot, Devon, TQ12 6NQ, UK

ABSTRACT

The New Zealand flatworm *Artioposthia triangulata* has successfully colonised several geographically distinct areas of the British Isles. Its potential to affect earthworm numbers may cause problems in three areas - agriculture, environment and trade. A number of control strategies can be postulated and different scenarios need different responses. These are outlined and strategic recommendations made.

INTRODUCTION

Artioposthia triangulata is a terrestrial planarian from New Zealand that has successfully colonised some areas of north-west Europe, principally the British Isles. It feeds on earthworms and Hancock (1988) suggested that it might have a significant impact on their numbers but it was not until Blackshaw (1989) associated the presence of the flatworm with the disappearance of earthworms from an experimental site in Belfast that this potential received widespread recognition.

Long-term studies in Northern Ireland have shown that earthworms can be eliminated from areas by flatworm predation and that there is a significant reduction in average earthworm population size (Blackshaw, 1990). Christensen & Mather (1995) have reported similar observations from the Faro Islands. Some species, notably *Lumbricus terrestris* (L.), are eliminated early in the colonisation process and do not reappear, as other species do, when flatworm numbers have declined (Blackshaw, 1995).

The significance of earthworms for soil fertility has been emphasised in recent years by changes in the management of agro-ecosystems towards sustainable farming systems, and organic farmers in particular rely heavily on the positive impacts of earthworms. The concept of earthworms as a valuable biological resource will become increasingly important as trends towards more environmentally friendly agricultural practices continue. *A. triangulata* is considered a significant threat to earthworms in the UK and elsewhere.

DISTRIBUTION AND SPREAD

Accidental introduction of *A. triangulata* to Europe probably occurred through an importation of plant material from New Zealand. From the first reports in Belfast (Anon., 1964), the number of records increased to 30 (Willis & Edwards, 1977), then 47 (Anderson,1986). By 1995 there were over 800 records for Northern Ireland.

A similar pattern of spread has occurred in Scotland with an initial report from Edinburgh in 1965 followed by later discoveries in Invernessshire in 1973 and Edinburgh (new location) and Lanarkshire in 1976 (Willis & Edwards,1977). Another 417 records have since been added and the flatworm's distribution extended to include some Hebridean islands and the Orkneys; the majority of records are from gardens, reflecting, in part, the distribution of observers (Boag *et al.*, 1994a). The flatworm is now established across Scotland, as far north as the Shetland Islands (Jones & Boag,1996).

In England, *A. triangulata* was reported from Carlisle in 1965 but there were no further records until sightings were confirmed from north Manchester in 1992 and Yorkshire and East Anglia in 1993 (Boag *et al.*, 1994b). A recent nationwide survey (Jones & Boag, 1996) indicates a notable increase in records from Yorkshire, Lancashire and Cheshire, with records from Staffordshire and Shropshire representing significant new localities some distance away from previously known infested areas.

It is likely that *A. triangulata* will be limited in its eventual European distribution by environmental conditions since it is sensitive to moisture. It is also known to be susceptible to temperatures of 20 °C or greater in the laboratory (Blackshaw & Stewart, 1992). Attempts to use climate-matching software to predict eventual distribution have been made and these have suggested that most of the British Isles and large areas of north-west Europe may be vulnerable (Boag *et al.*, 1995). This projection, however, underestimates the potential distribution since records exist (McGiffen & O'Shea, 1993) for that part of Ireland excluded from the vulnerable area; this discrepancy largely arose from choosing Edinburgh as the climate reference site.

The majority of records for the New Zealand flatworm are from gardens but it is also present in nurseries and, in Northern Ireland at least, has also been found in pasture, cereal and potato fields (R P Blackshaw & J P Moore, unpublished data). Distribution records for Scotland suggest a pattern of dispersal from botanic gardens and nurseries, to domestic gardens and eventually farms, with a period of about 15 years from first sightings to infestation of agricultural land (Boag *et al.*, 1994a). *A. triangulata* is frequently seen resting between the root-ball of a containerised plant and the inside of the liner or pot. As no correlation between genetic and geographic distances for isolated flatworm populations in Northern Ireland has been found, trade in ornamental plants appears to be an important mechanism for spread (Stewart & Blackshaw,1993).

ECONOMIC IMPACT OF THE NEW ZEALAND FLATWORM

Placing a value on the contribution that earthworms make to agricultural output is problematic because of geographic and cropping system variability. The biggest impact is likely to be in grassland. This is in part geographic, in that cooler, wetter areas will favour the flatworm but also because husbandry practices favour the development of large earthworm populations. Four-fold yield increases attributed to earthworms in grassland (Stockdill, 1982) are unlikely to be reflected as yield reductions if earthworm numbers are significantly reduced by flatworm predation but each 1% loss of herbage output equates to about £50 m per annum in animal outputs in the UK.

Of more immediate concern are moves in Europe and elsewhere to restrict UK exports of ornamental plants and, possibly, other crops such as seed potatoes unless certified free of flatworms. In February 1995, Iceland became the first country to enact plant health legislation to prevent the importation of *A. triangulata*. Other countries are currently considering similar action and it is likely that any exported plants or plant material will have to be sourced from a certified flatworm-free grower. This will present a non-tariff barrier to trade and severely handicap growers selling into highly competetive markets.

In addition, earthworms provide a valuable source of food for many birds and mammals in the UK (Alford *et al.*,1995). *A. triangulata* will function as a competitor and depletion of earthworm resources may have serious consequences for some species.

POTENTIAL CONTROL STRATEGIES

The main thrusts of research into *A. triangulata* to date have been concerned with biology, distribution and spread and little attention has been paid to control other than physical destruction using mechanical force, salt or hot water. Nevertheless, enough is known about *A. triangulata* and other flatworms to postulate control options:

Cutural control

Flatworms are prone to mechanical damage and it is likely that cultivations would kill many that are at or near the soil surface. However, susceptibility to heat suggests that warm water treatment may be able to kill those in plant pots.

Artioposthia. triangulata will shelter under surface debris and this behaviour can be used to catch them (Blackshaw, 1990) suggesting that removal trapping may be possible. Initial studies, however, indicate that this will be ineffective unless high intensity trapping is undertaken (R P Blackshaw *et al.*,1996).

Chemical control

Artioposthia triangulata is known to be susceptible to some pesticides, e.g. gamma HCH (C McGee, personal communication) so that potential use on farmland can be considered. Tests on a range of 14 pesticides showed that at 1000 ppm a.i. flatworms survived over a three week period when earthworms died (J P Moore & R P Blackshaw, unpublished data).

Earthworms are generally not present in pot plants and so chemicals can be considered for use. *A. triangulata* survived exposure to a slow release formulation of chlorpyrifos in soil over a period of 30 days with no apparent ill-effects (R P Blackshaw & J P Moore, unpublished data).

Biological control

Carabid and Staphylinid beetles will attack *A. triangulata* but there is no substantive evidence that they exert control. Nothing is known of the natural enemies of *A. triangulata* in its native New Zealand but as an invasive organism colonising virgin territory, classical biological control to recreate part of its natural enemy complex is an option. A mycetophylid fly whose larvae are parasitic on closely related flatworms has been described from Tasmania (Hickman, 1964) and such parasitoids are likely to provide the best control. The use of pathogens as biopesticides can also be considered but there is, as yet, no knowledge of suitable organisms.

DISCUSSION

Control of *A. triangulata* will require a combination of measures that are suited to different economic aims and the spatial dimension of the problem (Table 1). For example, the introduction of restrictive plant health legislation necessitates a control strategy that can provide immediate, full control. Biopesticides tend to be less reliable than conventional insecticides and the release of biological control agents will take time to exert control and also requires a residual target population; biological methods are therefore unlikely to deliver solutions for problems associated with non-tariff barriers to trade. Chemicals may provide an answer, but only if they can be safely used.

Table 1. Possible control options for *A. triangulata* and their relevence to different problem areas.

	CONTROL OPTIONS		
	CULTURAL	CHEMICAL	BIOLOGICAL
	Removal trapping	Farmland	Biopesticides
	Cultivation	Pot plants	Introductions
IMPACT AREA	Hot water treatment		
TRADE	+	+	-
ENVIRONMENT	-	-	+
AGRICULTURE	?	?	+

+ = potential application - = unsuitable ? = problematic

The use of agrochemicals to protect earthworms in natural and semi-natural habitats, such as woodland, will not find favour because of ecotoxicological considerations, let alone difficulties of application. Such an approach might, however, find favour on agricultural land, especially if the selected pesticides were already approved for the crop so that environmental hazards were minimised. The few existing data, however, suggest that it may be difficult to find a suitable pesticide for flatworm control.

Other problems of pesticide application to control *A. triangulata* in farmland are apparent. Firstly, control in any one field is only going to provide temporary alleviation because reinvasion from surrounding areas will occur. Timing of control will also be difficult since discovery of individual flatworms do not relate to a spray threshold. Finally, individuals shelter under debris on the surface or are in the soil (Blackshaw & Stewart, 1992) so spray contact may be difficult.

Artioposthia triangulata can be considered a local problem for plant producers seeking to export into protected markets. An appropriate strategy for these conditions should comprise two phases. Detection of flatworms on the holding should be undertaken by regular routine trapping, to be followed by 'clean-up' treatments of plant consignments. This could be either through the use of a drench or, preferably, some form of cultural control such as a wet or dry heat treatment. That such control measures do not yet exist argues strongly for their development within the industry.

In agricultural and other environments flatworm control needs to be addressed on a regional or national basis. The only realistic option under these circumstances is for biological control using an introduced natural enemy since control at the field scale is unlikely to have significant impacts on population levels. Only Government can provide the necessary resources for research on this spatial scale.

This approach will undoubtedly encounter resistance from groups seeking to protect the countryside who may oppose the release of any alien species into the UK. It is appropriate at this stage, therefore, to evaluate public preferences for different control strategies (including doing nothing) so that research resources can be directed towards those strategies that are most likely to be widely acceptable. Socio-economic methodologies, such as contingent valuation (Hanemann, 1994), can be used to achieve this aim.

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SESSION 9A

PRECISION FARMING – I. FEASIBILITY AND SCOPE FOR VARYING INPUTS

Chairman & Session Organiser	Professor W Day *Silsoe Research Institute, Bedford*
Papers	9A-1 to 9A-4

ISSUES AND OPPORTUNITIES FOR PRECISION APPROACHES TO CROP MANAGEMENT

R T PLUMB
IACR-Rothamsted, Harpenden, Herts, AL5 2JQ, UK

ABSTRACT

The technology to enable spatially selective treatment of crops is developing rapidly and often faster than the biological knowledge on which its effective use depends. The need to minimise costs and environmental pressures will encourage targeted approaches to crop management and precision treatments will increase. This paper considers some of the influences on the use of precision approaches and some areas where they may be used in the short, medium or longer term.

INTRODUCTION

Developments in engineering and the increasing availability of precise location technology, including global positioning satellite (GPS) systems have led to the development of the concept of Precision Agriculture. This is based on a number of developments, the principal of which are:-

- the ability to generate yield maps, principally of cereals, but more recently of root crops
- the control and selective delivery of materials to crops
- Image acquisition analysis methods
- The ability to control equipment applying materials selectively in response to information from real time sensors or maps.
- An increasingly detailed knowledge of the underlying processes and components of crop growth, protection and management.

Like many newly-coined terms, it can mean different things to different people and some may consider it a term to describe something that is already being done. There are also different types of precision, spatial or temporal, and levels, based upon the unit area that can be selectively treated. Farmers and growers have always been selective at a field scale. Few fields are treated identically, although the post-war expansion of field sizes has certainly increased the unit area of uniform application. Thus, what follows is not intended to be a definition of what Precision Agriculture is or is not, but rather a view of the current position and future opportunities based on emerging technologies and developments both biological and non-biological.

THE ISSUES

Why be precise?

The current debate on biodiversity, and the underlying assumption that it is a desirable

feature may suggest that the world, and perhaps especially agriculture, is heading rapidly for uniformity. Some of the discussion neglects the driving forces behind this desired uniformity, such as marketing and consumer pressures, but also tends to ignore the need to manage the diversity that does exist.
To the casual, or untrained, observer one field of wheat looks much like another, and it is only obvious variability, such as strips of poppies where the sprayer blocked or undulating crops on light land of varying texture during drought that points up variability. At a frivolous level, if variability did not exist then there would be little demand for statisticians and appropriate experimental design; agricultural science assumes variability. On the other hand, crop husbandry often seems to assume uniformity. Fertilizers are applied to whole fields; herbicides, fungicides and insecticides are applied to fields, often on the basis of relatively casual observation, sampling, 'gut reaction' or tradition.

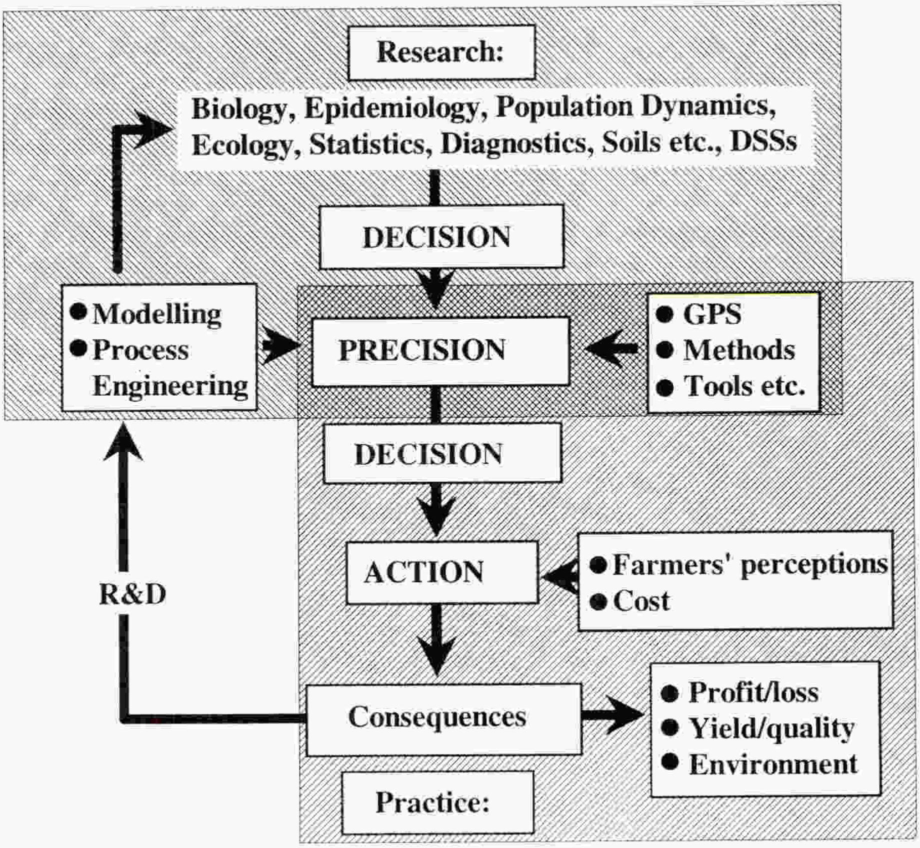
For most purposes it is yield and quality that are the measures of the actions that have, or have not been taken. These two measurements integrate the interactions between potential productivity, that determined by the genetic composition of the host as modified by Nature, and man's actions to overcome those limitations. For protected crops some of the variables are controllable e.g. the growing medium, nutrient and water supply, and to some extent temperature, light and gaseous environment. The protected environment also requires a wider range of approaches to crop protection than is usually possible in crops grown out of doors. For example the balance between chemical and biological methods of crop protection favours biological approaches more in protected than outdoor crops. The discipline of the market place and the need for a blemish-free uniform crop has also, for a long time, influenced decisions often in favour of more treatments, in horticulture where the production process is geared to producing a predictable uniform crop at a particular time. Many supermarkets already have in-house production systems; blueprints for producing crops to known standards by known methods. This will extend to a wider range of products, especially when, as seems probable, it is linked to an audit trail or traceability requirements. Environmental pressures to decrease wasteful pesticide use continue, and ethical considerations and concerns surround the introduction of transgenic crops and materials. Adhering to such requirements are likely to be increasingly required as a 'ticket to the market place'. Like it or not the market for production for its own sake has gone. Few growers produce just potatoes. They grow salad potatoes, bakers, potatoes for processing in an increasing variety of ways, or for sale washed in prepacks. The only potatoes that now come with soil on them are those grown for the early market, or are imported from abroad.

A consequence of all these pressures is that the whole production process needs to be more precise.

What is precision?

It is a general human assumption that accuracy is a desirable character, and accuracy is at the heart of precision. However, the ability to be accurate is often dictated by the tools that are available. Technology exists, although much of it is military, to target areas as small as a few cm^2. For many agricultural purposes such precision is unnecessary and the spatial scale relevant to the particular problem is important, as increased precision is likely to mean increased costs to set against benefits. Similarly for *time*, for which our ability to be precise about its measurement continually improves. Thus, precision is more relative than absolute and should be described in terms of the function that is to be measured. What is the most sensible unit of precision for agriculture? This will clearly differ and be influenced by how risk averse the user is. Photographers are encouraged to bracket their exposure to ensure that at least one is correct. Farmers do not have that freedom they often have only one opportunity and thus to get it 'right' they are naturally inclined to err on the generous side as a precaution or insurance. To minimise this tendency very precise information is required. Thus the ability to be precise is only part of the problem. It is the decision that is made that is critical. Temporal precision in the application of fertilizers, crop protection agents cultivations and crop drilling and establishment is important and the subject of other presentations at this conference. In consequence, in considering opportunities, it is developments in spatial precision that will be principally considered.

Fig. 1. Factors influencing decision making in agriculture



Decisions are made in real time; shall I spray today? The research community provides the farmer/grower with options and tries to describe the outcome of those options. Will the herbicide spray (i) work, (ii) be cost effective, (iii) what will happen if no herbicide is applied? What, I believe the farmer wants is help in making decisions and predicting outcomes. Precision is the contribution that the research community can make to these decisions. Thus in Fig.1 Precision is the point of overlap between research and practice. Research can deliver the tools to allow precise decisions to be made, the farmer uses these tools, and his own perceptions of risk based on his business to take any action. The consequences of this action are direct and measured in financial or quality terms, which includes environmental effects/benefits and indirect through feedback into the research and development loop to refine decisions and their precision.

THE OPPORTUNITIES

The knowledge on which to base precision can be of different types. Initially it is knowledge of where you are in a crop and the ability to apply treatments to selected parts of that crop. Underlying this is knowledge and understanding of the biological, physical and chemical processes within crops, and between crops and the organism(s) at which treatments are to be targeted.

Soils. Even over short distances soil type and structure can differ. Topography will be an influence but even on flat land a uniform field is rare. Variability will increase with size, especially if fields have been amalgamated by ploughing out grass or hedgerow boundaries. Headlands, gateways, and shaded areas all have characteristics that differ from those of the rest of the field. While these differences may be readily visible from the ground, other more subtle differences such as ancient earthworks, buildings, drainage patterns, may only be evident in extreme conditions of drought or flood. All of these differences will affect crops and thus yield.

Yield mapping of cereals is now well established (Stafford *et al*, 1996) and yield integrates the effects of all factors influencing the crop of which soil type, water availability, pH and nutrition are important components, but interpretation of yield maps is complex (Lark, 1996), and yield patterns need to be carefully interpreted before action resulting from them can be used to benefit the grower. Retrospective interpretation could be useful in identifying areas of crop that require more, or less, of a nutrient, or applications to correct acidic pH, which itself affects nutrient availability, or areas of soil structure (e.g. impeded drainage) that could be ameliorated by farmer action. Some of these actions, pH adjustment, soil structure changes, would need to be done before the next crop is sown, others, such as selective nutrient application would be applied to the growing crop and could be supported by real time measurements of the need of each crop for nutrients. Such measurements are available for the major nutrients but the optional time for addition of nutrients needs further definition.

Such selectivity should also offer the opportunity of more accurately applying fertilizer applications to achieve a target yield. Production for its own sake is a declining approach to crop husbandry. Spatially selective fertilizer applications can contribute greatly to achieving a target yield and anticipated quality output for the minimum of costs. The farmer can also choose how to address apparent deficiencies in soil nutrition or structure and may choose to withhold fertilizer from some areas as a more cost effective approach than removing, say a structural constraint on yield. At one extreme it may be possible, if the location is suitable, to take such areas out of cropping altogether. The options available to the farmer will increase and it is quite likely that at a farm and field scale variability and diversity may increase.

Crop Protection

Weeds. In arable crops weeds are patchily distributed (Marshall, 1988; Rew, Cussans, Mugglestone & Miller, 1996) and the patches are relatively stable (Wilson & Brain, 1991). Currently, fields are usually treated as if they were uniformly infested. Rew and Cussans (1995) considered weed patch ecology and dynamics at the 1995 Brighton Conference. As a consequence of the comparative stability of patches, mapping weed distribution (Rew *et al*., 1996) has the potential to be used retrospectively as the basis for spatially variable treatment. Only the mapped patches, plus a buffer zone as a margin for error and safety, need be treated and savings on herbicide use of 27 - 95% have been calculated (Rew, *et al*., 1996). However, it is interesting that the current patchy distribution has resulted from many years of uniform treatment and the consequence of any future use of selective treatments are unknown.

However, the ability to map weeds differs with species, which in turn will influence the products used, and is very inefficient for isolated plants that may form the nuclei of future patches. Currently, identification depends upon a trained observer and, inevitably errors, both of identification, positioning, and data entry occur. Future developments may permit aerial or satellite identification of patches through managing system, although such methods are unlikely to be able to identify species (Thompson, Stafford & Miller, 1991) and ground identification would be necessary, at least initially, and to calibrate the imaging systems for density of weeds which would influence both the need and the rate of herbicide that should be used. However, recent work on transplanted crops at Silsoe Research Institute suggests that is an area in which some progress is possible. The opportunities for spatially variable treatment of weeds are greatest for grass and perennial weeds, for which patchiness is a more common feature than broad leaved annual weeds. Thus opportunities for decreased herbicide use and thus input costs will depend upon the species present. As far as savings are concerned it is, therefore, encouraging to know that grass herbicides are usually the most expensive.

Pests. Pests arrive in crops either by moving in from the edge by walking or short flights, or fly into them from longer distances. The control that pests have over their movement and hence their selection of landing sites is largely determined by wind speed. Only in relatively still air can pests such as aphids control their flights. More often, once airborne, they are carried and deposited on wind currents. This often means that they are deposited downwind of barriers, such as hedgerows, at a distance related to the height and density of the barrier (Lewis, 1968). Thus both movement from the edge and deposition into the crop tend to place insects around the margins of fields. Thus selective treatments around headlands can target more pests than areas in the centre of fields. However, the anticipated yields, and yield benefits, from headland sprays are less than in the rest of the field and would also adversely affect beneficial species that can contribute to natural control. Recent moves to establish conservation headlands (Sotherton, 1990) as reservoirs of beneficial species also mitigates against this selective approach. However, a strong element of spatial diversity is seen to be of potential benefit as a mosaic of small fields, both of variable size and crops is believed to encourage the natural enemy complex (Altieri, 1990). Nevertheless, a knowledge of the specialization of parasitoids for particular species is needed before such diversity can be exploited in practical crop protection. It is also true that the nutritional state of the crop affects population development. For example cereal plants deficient in nitrogen usually bear few aphids than those with an adequate nitrogen supply (Dixon, 1987), thus, areas on which nutrients have been witheld for other reasons are also less likely to repay treatment to control aphids. Such interactions between crop, pest and beneficial populations are complex and knowledge is only slowly accumulating that might allow more precise applications of either chemical or biological control agents.

While individual pests can cause direct damage on their own, for many the damage done is related to the numbers present or to the transmission of a disease agent, especially viruses. The pattern generated by these activities differs with the pest, the crop, the season and the presence of any disease agent. The presence of yellow patches in sugar beet caused by virus transmitted by the aphid *Myzus persicae* is characteristic, and if local sources are present can be directly related to them. However, as it can take 3-4 weeks for symptoms to appear after infection, when patches are visible the damage has been done, and, indeed, none of the vector aphids may be present. Earlier detection by satellite imaging of incipient infected patches at an early stage of development may be possible and permit treatment of the focus rather than the whole field. However, in this as in many other areas of precision the relative costs will be vital. Insecticides are cheap, in relation to the losses that their use can prevent, even when whole fields are treated. Indeed, for sugar beet an increasing proportion of seed is now treated with insecticide. (Dewar, 1996).

An alternative precise approach which incorporates spatial selectivity of treatment is the use of novel methods and materials. The stimulo-deterrent diversionary strategy, or push/pull strategy, (Pickett, Wadhams & Woodcock, 1995) employs a knowledge of pest biology and exploits it through the use of semiochemicals, to deter pest attack on the majority of the crop while simultaneously attracting the pest to a small part of the crop where it can be controlled by pesticides or biocontrol agents. For insects this seems to be a more likely way forward than precise spatial targeting of pests with conventional agrochemicals. However, the areas required for each component may differ for crops and pests and have yet to be determined. It is also uncertain whether the most efficient methods will be separate blocks of crop strips or a mosaic, all of which would require increasingly complex levels of spatially variable treatment.

Diseases. Diseases are by their nature patchy in occurrence. Few diseases, powdery mildew (*Erysiphe graminis*) on cereals may be one, are common enough, and widely and regularly dispersed enough to cause widespread primary infection. Some diseases e.g. eyespot (*Pseudocercosporella herpotrichoides*) have only one generation a year and thus often cause relatively random primary infection, especially as the source of infection is largely debris from the previous crop. However, when the sexual stage, *Tapesia yallundae* is the source of wind-dispersed spores, the laws of aerodynamics determine where spores are deposited and thus where infection may start and from which epidemics may develop. In terms of spatially precise treatment little can be done with eyespot, although knowledge of conditions, sources and epidemic development can ensure that treatments are correctly timed. Other pathogens e.g. yellow (stripe) rust (*Puccinia striiformis*) spread from primary foci within the crop, to form distinct patches and for diseases such as *Septoria* spp, *Puccinia* spp, *Pyrenopeziza brassicae*,in which secondary spread is important, both between plants and between parts of plants, the method of dispersal by wind or rain, or a combination of both (Gregory, 1973) determines the pattern of spread, the distance over which it can occur and, in consequence, the area of crop that might be selectively treated, if the primary, or early stages of secondary infection, could be identified. Monitoring inoculum by traps (Hirst, 1952) are well established; there is also the prospect of increasing sensitivity through immunological methods (Schmechel & McCartney, 1995). While such methods can improve timing they contribute little to spatial precision. Real-time detection of the early stages of disease epidemics are still some way away, and at present only seem likely through imaging systems that can detect the stresses imposed by disease, and that can separate those images from other stresses imposed by drought, waterlogging and nutrition.

The release by plants of volatile materials during the infection process is now well established, especially for oilseed rape (Blight *et al.,* 1995) and such materials could help locate plants during the early stages of infection. However, diffusion and dispersal of such materials would make it difficult to identify precisely points of infection, although monitoring gradients could help to identify sources.

Where the same crop, or crops susceptible to the same pathogen, are grown consecutively, there is potential for using maps of disease incidence in one crop to identify risks in the next. Take-all, a damaging root disease of wheat and barley is a classic example of a patchy disease (Bateman & Hornby, 1995). However, severe patches in one year, because of microbiological interactions within severely infected areas, are rarely the most damaged in the following year, even if chemicals were available that gave economically acceptable control, and patchiness is also influenced by other treatments, especially fertilizer and previous cropping. The carry-over of infected debris is rarely well enough identified to permit mapping. For broad-leaved crops, mapping of root pathogens such as *Sclerotinia* spp. would indicate areas of risk but infection conditions in the subsequent crop will dictate whether infection occurs.

CONCLUSIONS

- Opportunities for more precise crop management will increase The stiletto approach v the blunderbuss or scatter gun.
- The value of such precision may be as much in witholding treatments as in applying them.
- On a field or farm scale it is possible that diversity will increase.
- Nutrient use will become more directed to end product quality and target yield.
- Weed control is likely to be the first commercially viable target of spatially selective treatment based on retrospective mapping.
- The further development of spatially selective treatments may be constrained more by the cost/benefit analysis than technology.
- Real-time decision making for spatially variable treatments in arable crops will not be seen before 2001.
- There is a need to ensure that precision is driven by practical use and value rather than by technology for its own sake.

- As knowledge of the biological, physical and chemical components of crop management increase opportunities for more precise action will increase.

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PRECISION FARMING - A HANDS-ON PERSPECTIVE

J P FENTON
Yokefleet Farms Ltd, Hall Farm, Yokefleet, Goole, East Yorkshire, DN14 7XY, UK

ABSTRACT

The concept of precision farming may be in its infancy, but the information gained from yield mapping is proving to be an invaluable management aid in determining future input strategies adopted within the farming system.

INTRODUCTION

While the concept of Precision Farming, or Computer Aided Farming Systems (CAFS), may seem a new phenomenon to arable farmers, the same cannot be said about other sectors of the industry. For years those in the dairy sector have fed animals in direct relation to output. Those in the sheep sector have fed ewes in relation to scanned lamb numbers. Why then should the concept of treating every square metre of a field seem so difficult to accept?

It may be easy for today's generation to lose sight of it, but our forefathers employed a form of Precision Farming in their production systems. Think of a man with a hoe. He sees a weedy area, wacks it a few times and then moves on to the next weedy area; quick, neat and efficient with little time lost. Unfortunately this is no longer practical in today's farming environment. The quest for increasing output and greater economies of scale since the war has resulted in the removal of hedgerows, drainage dykes and other natural field boundaries, many of which existed for good agronomic reasons - often demarcating different land types and indicating the degree of difficulty involved in cultivating the land. It may be that with the aid of CAFS, these previous field boundaries will take on a new significance in the quest for lower unit costs of production.

With any CAFS, there are two key questions which need to be asked: Why do we need them? and will or do they work practically?

WHY DO WE NEED CAFS ?

Economic pressures

Commodity returns will decline from their current levels under the CAP reform. It is essential therefore that we look beyond the current reform phase and it is my belief that all those in the EU will be farming at world market prices in the very near future and that if, as an industry, we are to survive, the sooner this transition is made the better. Subsidies merely propagate inefficiency, and we need more efficient utilisation of input resources.

In order to maintain our incomes, our response to these pressures can be twofold; a reduction in the fixed costs associated with the production of any commodity; and/or a better targeting of the variable costs of production. This does not necessarily mean a reduction in the total variable costs, rather a more accurate distribution of the input resources involved in any production system. In doing so, the aim must be to optimise the unit cost of production - the days of output maximisation at any cost are gone.

Environmental Pressures

Whether these are actual - nitrates or phosphates in water, residual herbicides in water - or perceived by the public, it is essential that the issue is addressed by the industry. Failure to do so will result in more stringent controls being imposed on production systems than are necessary. The ability to tailor chemical applications to actual need is a victory for the environment. Spatially variable applications reduce the potential for nitrate leaching and also influence pesticide leaching and run off.

The environmental advantages of CAFS may well turn out to be more valuable than the economic advantages. In an age of ever increasing scrutiny and government regulation, such systems may well help to ensure the right to continue farming. Here, I would cite the introduction of Nitrogen Vulnerable Zones.

Population Pressures

Though it may not apply directly to us in Europe, world population figures are increasing at an alarming rate and with this will come the need for greater output from an ever declining resource - land.

WILL CAFS WORK?

My involvement with CAFS has primarily been through the use of Yield Mapping Systems (YMS) over the past seven years and I consider myself extremely privileged to have been involved in the development and evaluation of the Massey Ferguson system, through my involvement with Dronningborg almost from its conception. In that time I have developed enormous confidence in the concept.

The concept of YMS is based on the detection of yield variations within fields. Once you know where you are, the quest for solutions can begin. My experience has lead me to believe that the system does work, and that it provides an invaluable management aid. As with the introduction of any new technology, there is a learning process. New technology often generates more questions than answers, and there is still a great deal we have to understand before we are able to realise the full potential offered by YMS. At the very least, YMS provide an accurate picture of what you already know - or think you know - about in-field yield variations.

If YMS are to have any credibility they are reliant on two critical factors: an accurate and reliable yield measuring device; and an accurate field positioning system. On Massey Ferguson combines, yield measurement is carried out using a radio active source. In my experience the accumulated yield figures have consistently been within 0.5% of weighbridge figures. There is a single calibration for all crop types and no in-field alteration for hectolitre weights or moisture. Differential GPS is the most practical method of in-field positioning because of its accuracy, which is sometimes down to 50 cm, but well within the 6m combining table width over which information is being collected. It requires no setting up other than the initial installation of a base station and this too will disappear as the use of multiple base stations becomes more widely available.

If any system is to achieve widespread adoption by the industry then it must be 'user friendly'. Harvest is a busy and often frustrating operation at the best of times. Those systems which offer the least amount of operator input in the data collection process will be the ones most widely adopted by the industry. Transfer of data from the combine to a PC must be quick and easy, thereby minimising the possibility of data loss.

ON-FARM USE OF CAFS

Initially the system has to be used as an information gathering tool, and this is a continuous process. In the initial years the task consisted of collecting yield and soil sample data to establish if there was any correlation between yield and the major soil properties such as phosphate, potash and manganese content, and pH. If this did nothing else, it highlighted the variations which exist in any given field and the inadequacy of the reliance on a single soil sample analysis or yield figure for any given field. The soils at Yokefleet are classified as Blacktoft Marine Alluvial, being artificial silts overlying clay, and were considered to be extremely uniform. Yield and soil mapping were to show otherwise.

In the initial years, soil sampling was carried out on a very close grid system which entailed enormous cost. Since then it has been found that five samples per hectare are sufficient to provide meaningful indications of nutrient levels and to establish if there is a correlation with yield. While this may be expensive, the cost spread over a five year sampling interval is more bearable. In the intervening years, or as an alternative to sampling whole fields, comparisons can be made between very high and low yielding areas to ascertain if there is a correlation between yield and inherent soil fertility. The more widespread adoption of CAFS will depend on the development of more automated soil sampling systems which can provide instant results, avoiding the delay associated with laboratory analysis. The procedure for taking soil samples also needs to be refined so as to produce consistent results.

While I accept that many farmers may think they know where the high and low yielding areas of a field may be, they have no idea as to the magnitude of these variations, or how to treat them accordingly. YMS, as a management tool, now offers the means by which these variations can be identified and more importantly quantified. This information can then be used to influence future management decisions, so as to optimise the unit cost of production for future crops grown in a particular field.

In the early years, we were told that our soils would be too uniform to find any meaningful variation in yield within fields. To the naked eye this may have seemed true, but yield mapping showed that yield variations of 10 t/ha were not uncommon. This would understandably stimulate any enquiring mind to ask why. Yield maps can be converted into net or gross margin maps, through the introduction of growing costs, reinforcing the financial implications of such yield variations.

Clearly there are a considerable number of factors causing yield variations within any field. We need to establish if there is any consistency in these variations from year to year, within the same crop and between different crops in the rotation. Reliance on a single year's yield data would be foolhardy. A minimum of three years' and ideally five years' harvest data are required before it is possible to establish an agronomic blueprint for a given field. Advances in software now mean that it is possible to make comparisons between different crop types through the use of normalised yield maps. In this way the relative variations in high and low yielding areas within fields can be established over a rotation. Seasonal variations in weather patterns, different crop types, cultivation systems and nutrient applications can be evened out so establishing a more reliable yield pattern. As this data bank grows, we are able to place more emphasis on it as a management tool.

While it may be a number of years before the system can be used to establish an agronomic blueprint for a field, the information gained after harvest can be of immediate use, either directly or indirectly.

DIRECT BENEFIT INFORMATION

A farmer's own field trials cannot be undertaken with the same statistical rigour that is available to experiments in research organisations. However yield maps allow simple and realistic trials to be readily undertaken and used to establish a picture of the consistency of performance of crops and treatments, with replication built in by studying the effects over a number of years. Some information can be used immediately after harvest and be of immediate benefit to the following crop or the farming system as a whole.

Cultivations

With a substantial fall in oilseed rape prices on the UK market in 1988, it was necessary to find ways of reducing the growing costs involved in establishing the crop so as to maintain margins. By their nature, variable costs are in reality now fixed - any reduction in inputs results in a direct reduction in output where a blanket treatment approach is employed.

Over a four year period, five different cultivations systems were evaluated with the aim of achieving the lowest cultivation cost per tonne. With the aid of yield mapping and with the confidence provided by the results, it was possible to reduce the cultivation costs from £105 to £33 per hectare. This equates to a saving of some £3,500 p.a. on the establishment costs for oilseed rape in our rotation.

This comparison has been carried out for all crops within a given field rotation. In this way it has been possible to see what influence a specific cultivation system may have on the yield of the following crop, or on the yield of another crop within the rotation.

Chemical applications

This is of particular importance in assessing new products or product mixes for on farm use. Not only does it enable us to see how yield is influenced, but more importantly the effect can be quantified. Trials of this nature hold far more credibility than taking a single yield figure for a trial block and using that to determine future input strategy. The overall yield figure can be assessed in conjunction with the yield map to determine if it was indeed the inputs which influenced yield, or if the variation was merely the result of inherent soil fertility differences.

Previous yield maps have been used to great effect, in conjunction with a direct injection sprayer, to target specific areas of high blackgrass populations. This has allowed rates of chemical (IPU), to be varied between one and five l/ha, resulting in considerable financial savings as well as a significant environmental benefit.

Yield maps have also been used to highlight those parts of fields which have been more prone to slug damage in the past. This has enabled bait traps to be placed more precisely to determine slug activity, or alternatively previously damaged areas have been treated as a matter of course prior to drilling. The result of this has been a very noticeable reduction in the amount of molluscicide used over the past four years.

Plant populations

The ability to vary seed rates within fields brings with it the ability to influence crop microclimates. This in turn requires a different approach to fungicide policy. The task is not straight forward, but the benefits can be a direct saving in terms of seed costs where plant populations are reduced from 300 to 150 plants per square metre with no reduction in yield. Reduction in plant populations does not necessarily signify a more manageable crop, as tillering ability between different varieties can have an enormous impact.

The down side of lower seed rates is that they require a higher management input in terms of time. The direct benefit is that they have resulted in a saving of some £4,500 p.a at Yokefleet, a figure which could be even greater were variable application rate techniques employed.

With potatoes, end tuber size is of particular importance as 40 % of the crop is grown specifically for the baker market. This requires a different seed spacing and if possible the best soil in the field to achieve high quality skin finish. The ability to spatially vary seed spacing within a field is now a reality. Prior to yield mapping it was not possible to make decisions of this nature and indeed the question was never raised.

Nitrogen applications

Nitrogen is applied to all crops in a single pass, as a liquid containing the nitrogen inhibitor Didin. Since the introduction of Didin in 1986, nitrogen rates have been reduced substantially from a high of 220 kg/ha to an average of 150 kg/ha and in some cases as low as 100 kg/ha. Trial work, backed up by yield maps, established that, where Didin was used, nitrogen leaching was likely to have been reduced by 60% against the traditional solid nitrogen three-way split application technique. Yield mapping, in conjunction with soil mineral nitrogen sampling in the spring, has enabled the optimum rates of application for specific fields to be determined far more scientifically, albeit on a blanket treatment basis.

The use of direct injection systems has also enabled the rate of Didin application to be varied across fields in relation to variations in soil mineral clay contents. In this way the release of nitrogen can be more accurately timed to coincide with rises in spring soil temperature, thereby promoting more even growth.

Interpretation of in-field variability

Yield maps not only provide information on the harvested crop, but can also pin-point problems which have been caused by the preceding crop. This information is of immense benefit in determining which parts of fields may require subsoiling or, in a difficult year, which fields should take priority if time is a limiting factor.

Yield mapping has helped to quantify financially the problems of increased compaction on headlands, resulting in a different approach to field working. A policy of moving the turning area every year, more widespread use of flotation tyres and the unloading of all combines on the headlands has helped to reduce these effects very noticeably. Yield mapping has also highlighted problems with in-field drainage systems before they have become apparent to the naked eye. Early rectification of such problems will have resulted in damage to future crops being minimised.

It is possible to evaluate the potential long term damage caused by growing root crops on certain land types and therefore whether they should be in the rotation at all. Alternatively I can assess the suitability of a particular field for a specific crop, in my case sugar beet and potatoes.

Planning for setaside

The information gained from yield maps has been used to assess areas for setaside under the current rules. The order of fields going into setaside has been established, as not all land will be setaside under the six year rule and it makes sense to setaside the worst land first. Evaluation of a move to permanent setaside has also been possible. In making this assessment the availability of several years yield maps has been invaluable. Reliance on a single year's data would have been foolhardy.

INDIRECT BENEFIT INFORMATION

The indirect benefit information is that which is of use when interpreted over a period of three to five years, and is more likely to be incorporated in the development of the agronomic blueprint for a field. Already technology is available to spatially vary treatments across fields, but we are not in a position at present to be able to generate agronomic blueprints, because we do not know enough about the interrelationships between various inputs and how they are affecting yield, or how they should be applied in response to variations in inherent soil fertility.

Do we apply more or less to the lower yielding areas to achieve the same return, or are we not applying sufficient to the high yielding areas to enable them to achieve their potential? We know that if we reduce nitrogen application rates below the optimum, then yield will fall. We know also that if we exceed the optimum, then crops will require greater management inputs in terms of growth regulators and fungicides - but how do we deal with variations in inherent soil fertility?

We can adjust inputs and record the results of these changes very accurately - yield mapping for the first time enables us to quantify these variations and use the information to influence future management decisions relating to the input strategy for a particular field. In this way we will be able to reduce the unit cost of production in a far more scientific manner.

P & K replacement

Directly after harvest it is possible to replace phosphate and potash removed by a crop. Indeed if we are to retain the same level of fertility in a field then this should be done. P & K removal from the soil is directly related to the amount of crop removed from the field, therefore it is possible to establish how well applications have been in balance with targeted yields. If the target yield has not been achieved across the whole field, a uniform treatment would be inappropriate. This would merely result in too much being applied to the low yielding areas and insufficient to high yielding areas.

P & K applications are therefore the first area in which indirect benefit can result. Though this is the first step in spatially variable applications and may seem small, it is a vitally important one and one from which financial benefits will flow immediately. Reliance on a single soil sample to determine compound applications is misleading as yield maps indicate. In my experience , while the indices for P & K may not vary across a field, variations in yield of 10 t/ha are not uncommon.

Liming

Closely allied to this is the application of lime at variable rates. The soil pH can vary enormously over a field and if a 100% take up of N, P & K is to take place, then this must be as close to pH 7 as possible. A move to pH 6 results in a reduction of nitrogen availability by 11% and 48% for phosphorus. The financial implications are enormous.

CONCLUSIONS

It would be impossible to estimate exactly the financial benefits resulting from the implementation of policies as a result of the direct benefits generated by yield mapping over the past seven years. They have clearly been enormous and will have resulted in a payback many times greater than the actual cost of installing the system.

In time I believe that direct injection systems will be used to great effect to achieve spatially variable treatments, resulting in enormous financial savings and environmental benefits to the industry. Variations in seed rates and therefore plant counts create very different microclimates within the crop and we will need to adjust our inputs accordingly.

At present we do not know enough about how the various factors relating to soil nutrients, moisture retention, compaction and differing microclimates influence yield. Nor, more importantly do we know enough about how they interact with each other in different situations to give final yield. Given time these relationships will be established and will, I am sure, be very farm specific.

While it is still early days, the information gained as a result of yield mapping at Yokefleet has substantially influenced the management policies and philosophies adopted, resulting in substantial savings in both fixed and variable costs - and, though not covered extensively in this paper, substantial environmental benefits too. CAFS will never be a substitute for management, but they are certainly an extremely beneficial aid to the decision-making process in management and one we can ill afford to ignore.

CAFS are no longer a myth, but reality. Yield mapping in particular enables a far more in depth understanding of yield variations within fields, enabling us to quantify them, and adjust future inputs so as to optimise the unit cost of production. Even if the indirect benefits of yield mapping were never capitalised on, the direct benefits have resulted in a radically different approach to farming, one in which I have seen the in-field variation in yield of wheat being reduced from ten to four t/ha. It is a system in which I have total confidence and no intention of going back.

The technology is currently driven by economics, but it could be driven by politics. If you were allocated a certain financial quantity of fertiliser, through say a nitrogen tax, you would need to apply it carefully and accurately. The technology now exists to enable you to do that and you get the secondary benefit of having records to prove it. Once you have had first hand experience of the benefits of yield mapping, you will never farm in the same way again.

A US VIEW ON THE PRECISION FARMING REVOLUTION

S W SEARCY
Agricultural Engineering Department, Texas A&M University, College Station, TX 77843, USA

ABSTRACT

Precision agriculture is the use of knowledge about important crop parameters to optimize production system management on an appropriate scale. As a concept it is gaining attention within American agriculture. Early adopters of precision agriculture products and services are finding not only economic advantages, but also that more detailed information leads to unanswered questions. Although technologies are available for site-specific managemant of most agronomic inputs, we still need research to set the appropriate scale for that management. More site-specific agronomic relationships, improved sensors and better decision support tools are needed for analysis of the extensive data that result from precision agriculture.

INTRODUCTION

Precision agriculture is an information intensive approach to agronomic management. The basis for this so-called "revolution" in agriculture is the ability to generate, analyze and use detailed data describing soil and crop conditions at the level of a few square meters. While engineering principles have provided the technology for precision agriculture, the fundamental agronomic principles must be properly applied if this management strategy is to be economically viable. As this document examines the status of precision agriculture in the United States, it will also consider the state of development in both engineering and agronomic sciences as applied to precision agriculture.

PRECISION AGRICULTURE: WHAT IS IT?

Many terms have been used for the concept of managing production areas as a collection of unique units rather than a single homogeneous unit. While the terms have changed as the technologies have evolved, the basic idea has remained the same. Today, terms such as site-specific management, precision farming or precision agriculture are most often used. While arguments continue about the breadth and overlap of these "synonyms," most observers recognize the similarity of the terms and use them interchangeably. Here, I will use the term precision agriculture, because I view it to be broader in scope that some alternatives.

To eliminate possible confusion, I will use the following working definition of precision agriculture. This definition expresses my view of precision agriculture and is open to argument:

> *Precision Agriculture: The use of knowledge about important crop parameters to optimize production system management on an appropriate scale.*

I will build on several key aspects of this definition during the discussion of American precision agriculture. Knowledge implies accurate information and an understanding about how it can be used. Optimization should include economic, environmental and human concerns. The knowledge must be systematically incorporated into management decisions. The appropriateness of the scale at which the knowledge is applied will vary with the situation.

HISTORY OF PRECISION AGRICULTURE

In the early 1980 s, soil scientists and agricultural engineers began to consider the possibility of varying agronomic inputs according to parameters that varied within the field. This was not an entirely new concept. Linsley and Bauer (1929) described the variable rate application of lime in an Illinois field based on rate maps developed from specific soil sampling techniques. The advances of microprocessors, and their use in relatively inexpensive control systems, allowed on-the-go adjustment of application rates. What was needed was an accurate and repeatable system for determining geographic position and methods for generating and handling geo-referenced data.

The SoilTeq firm of Waconia, Minnesota, was the leader in the mid 80 s in the development of equipment for variable rate chemical application. A patent (Ortlip, 1986) for a fertilizer spreading mechanism and control system assigned to the firm is the first patent directly related to precision agriculture. The concept was for fertilizers to be applied in a variable manner on the basis of soil types. An early term for the concept of varying agronomic inputs was soil-specific management.

In the period between 1988 and 1993, interest in precision agriculture grew and the tools available began to mature. Positioning systems moved from dead reckoning, Loran and local triangulation systems to the Global Positioning System (GPS) as the satellite constellation was expanded and became fully functional. The ability to obtain reasonably accurate position information at any time, night or day, expanded the possibilities of precision agriculture. Unfortunately, the GPS accuracy was not suitable for agricultural use. A system of differential corrections generated by fixed receivers was necessary to achieve sufficient accuracy. The use of this additional signal became known as Differential GPS or DGPS. These correction signals could be provided locally, or through a wide area system. Local DGPS base stations were often not available in many areas and the wide area systems were expensive.

During this period, the early adopters began to practice variable rate fertilization with phosphorus, potassium and some micro-nutrients. The rates of application were determined by measuring the soil's residual nutrients obtained by grid sampling. Consequently, the topics of sampling technique and grid resolution became active subjects of research by agronomists and soil scientists. During this period, many researchers recognized that nutrient variations within soil type could be as variable as those between soil types. As a result, research programs began to emphasis site-specific rather than soil-specific management. Research studies were undertaken to determine the yield and profit advantage of variable fertilization (Wollenhaupt and Buchholz, 1993; Hammond, 1993).

While many questions remained unanswered about the economics of variable rate fertilization, commercial adoption of the practice was underway, and increasing gradually. Prior to 1993, producers did not have access to yield mapping systems, which could quantify any yield responses to variable rate fertilization. This did not stop the early adopters from using variable rate management. When asked why, most would give an answer to the effect, "I know my fields are variable, and it seems like the logical thing to do." Figure 1 shows the rate of growth in the area grid sampled for variable rate fertilization for a single cooperative in the state of Illinois. Illini Farm

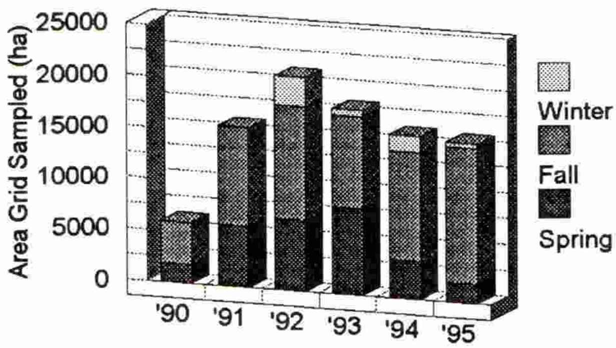

Figure 1. Area grid sampled by Illini Farm Services. Not all areas may have had variable fertilization. Data provided courtesy of Illini Farm Services Web site.

Services was one of the earliest providers of variable rate fertilization, and they are located in the center of the Midwestern Corn Belt. The Midwest region has been the area where much of the development and adoption of precision agriculture techniques have taken place. Through grid sampling and variable fertilization, producers typically reported net returns of 12-37 $US per hectare. Most frequently this return resulted from reductions in the amount of fertilizer applied. The resultant application maps were used for a three to five-year period, without resampling. Sampling grid resolution was typically 0.8-2.0 hectares. The sampling density and resampling period decisions were driven more by economics than by agronomic principles.

Variable rate application of nitrogen was used to a limited extent commercially on high value crops such as sugar beets and potatoes. In these situations, the profit potentials were quite significant. In the Red River Valley of Minnesota, typical returns of 125 $US per hectare can be attributed to greater recoverable sugar levels (Hilde, 1994). Closely managed nitrogen levels proved to be important in increasing the sugar content of the beets. Although not widely adopted commercially, variable nitrogen management for grain crops was studied by many researchers. Investigations were initiated across the United States by university and USDA researchers to evaluate the potential for variable rate nitrogen applications to reduce leaching and runoff pollution.

Since 1993, interest in precision agriculture has continued to increase. A major factor driving this interest is the availability of reliable yield mapping systems. Although a few yield monitors were available earlier, and research had been underway for several years (Bae et al., 1987; Howard et al., 1993), the combination of the yield monitors and reliable positioning with differentially corrected GPS sparked a more intense interest. As producers become more convinced of the value of yield maps, more vendors were seeing an opportunity. By 1996 there were more than ten manufacturers of yield mapping systems in the United States. Figure 2 shows the estimated growth in sales of the yield monitors. It is estimated that only half of these monitors are combined with a positioning system to enable mapping capabilities (Anon., 1996). Although the continental United States is covered by wide area differentially corrected GPS signals, many producers have viewed this service

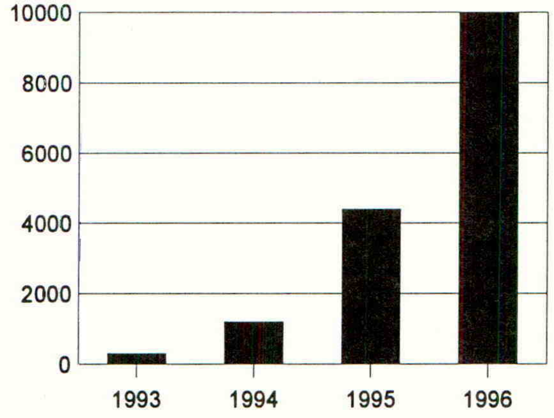

Figure 2. Estimated number of yield monitors operating in the USA (Anon., 1996).

as too expensive. Local base station signals for differential correction are often unavailable. This situation may change in the future, as the large agricultural machinery manufacturers are now offering site-specific management systems based on the wide area DGPS.

CURRENT STATUS OF PRECISION AGRICULTURE COMMERCIAL PRACTICE

American farmers have access to a wide range of products and services for precision agriculture. In addition to yield mapping and variable rate fertilization, controllers are available for variable rate pesticide applications, variable seeding rates and on-the-go variety changes. Systems have been designed and field-tested for variable rate irrigation through center-pivot and lateral-move irrigation

Table 1. Type of Soil Sampling Services Offered by Ag-Service Dealerships (Akridge and Whipker, 1996)

Sampling Service	Percent Offering*
Conventional sampling only	71
Grid sampling (< 1.0 ha)	5
Grid sampling (1.2-1.8 ha)	4
Grid sampling (2.0-4.0 ha)	9
Grid sampling (> 4.0 ha)	12

* Does not total to 100 percent due to rounding.

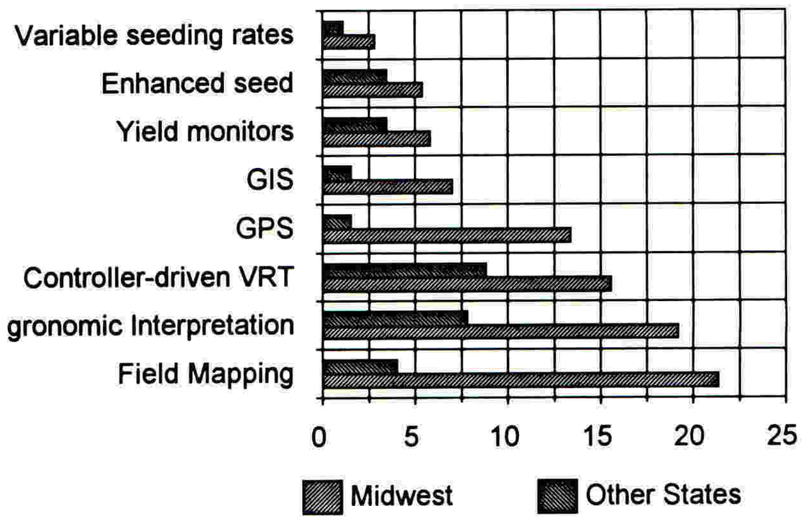

Figure 3. Percentage of dealerships offering precision agriculture services and technologies (Akridge and Whipker, 1996).

systems (Camp and Sadler, 1994; King et al., 1995). GPS receiver manufacturers have determined that agriculture is a potentially lucrative market, and have been targeting it with receivers that can be linked to controllers from various manufacturers, integrated with geographic information systems (GIS)/mapping software and will provide guidance information for wide swath and night operations.

While farmers may purchase some of the precision agriculture technologies (particularly yield mapping and planter controllers), much of the detailed sampling, data analysis, map generation, interpretation and variable rate application is done as a contract service. The Center for Agricultural Business of Purdue University and *Farm Chemicals* magazine recently conducted a survey of Ag-Services dealerships across the United States (Akridge and Whipker, 1996). Respondents to the survey were from 40 states, with the majority (64 percent) from twelve Midwestern states. The respondents represented a broad cross-section of cooperatives and independent dealerships, small (single outlet) and large (>25 outlets) dealerships. The dealerships typically offered a wide range of services, including custom application of materials (93%), soil sampling (88%), agronomic consulting (72%) and record keeping (53%). Currently only a minority of these dealerships is involved in precision agriculture activities, but they are expecting their service offerings in this area to increase dramatically over the next three years.

Grid soil sampling is one of the first precision agriculture services offered by many dealerships because it is an extension of services already offered. Table 1 shows that 29 percent of the dealerships provided grid soil sampling services of some sort. The resolution of the sample grid varies considerably. Obviously, taking geo-referenced soil samples leads to the need for other services, such as mapping, agronomic consulting and variable rate application. Figure 3 gives the various services offered at the time of the survey in Spring, 1996. There are obvious differences between the services of the Midwestern dealers and those from other states. The greater emphasis on field mapping, agronomic interpretation and GPS in the Midwest results from the more extensive use of variable rate fertilization. The costs charged for these services varied widely with controller-driven VRT services ranging from 2.50 - 30 $US per hectare. Field mapping charges ranged from no cost (included under other services) to 37.50 $US per hectare.

Ag-service dealerships expect their precision agriculture services to grow over the coming two year period, with field mapping and yield monitoring leading the way. Twenty five percent of the dealerships expect that, in three years time, more than 30 percent of their customers will be using field mapping and yield monitoring. However, while they expect use of these technologies and services to increase, they are concerned about the cost. More than 60 percent of respondents listed cost as a barrier to implementing precision agriculture.

The economics of precision agricultural techniques is receiving a great deal of scrutiny, both from academics and practitioners. While most site-specific management studies will determine the economic impacts (Wollenhaupt and Wolkowski, 1994), relatively few long term, system level analyses have been done. Lowenberg-DeBoer and Swinton (1995) conducted a thorough review of the impacts of site-specific management (SSM), and concluded that "the profitability of any given SSM technology is site-specific, and should be evaluated on a farm by farm basis."

CHALLENGES FOR THE FUTURE

Most American farmers are skeptical about the long term economic advantage of precision agriculture practices. While adoption of these practices continues to increase, it is still only a small portion (generally fewer than 10-20 percent) of the producers. Site-specific management is not yet proven to be profitable on a wide basis. Many questions exist regarding which parameters are most important, how the various parameters should be used in variable rate management and what kind of tools will be needed to handle and analyze the extensive data sets that are generated. More data about the soils and crops have created more questions than answers. Correlations between yield and available nutrients are often low, indicating that other factors may be more important in determining yields. Much research and development remain to be done in order for precision agriculture to mature as a management strategy. Although closely intertwined, this research can be classed into two categories; agronomic and engineering.

Agronomic research needs are centered about the need to understand the interactions of various soil, pest, water and weather factors on a site-specific basis. Past agronomic work has focused on the development of relationships that worked for a range of conditions. This was appropriate because that is the way farming has been done. Under the new approach, where nutrients, seed, chemicals and irrigation can all be optimized at any point in the field, knowing what that optimum rate actually should be is a new and non-trivial task. These interactive relationships are needed to determine application rates and to better model the actual production of the plants in the field. With greater information about the crop's development, the temporal variability can be managed in addition to spatial variability. Temporal variability is directly related to weather conditions and pest populations. Much of a farmer's risk is associated with these variables. An accurate predictive capability has been shown to be of value in managing plant diseases and insect outbreaks. The combination of improved sensing techniques with predictive modeling may provide earlier detection of problems and a greater ability to target susceptible areas.

Engineering research needs are concentrated in two areas; sensing and decision support systems. Sensing of important agronomic factors is a requirement for long term utilization of precision agriculture. Timeliness and cost of that data are important issues that must be addressed. Remote imaging of crops has the potential to provide information on in-season crop status quickly and at a reasonable cost, if the images can be delivered in a format that is easily integrated into a precision database. Those images must also be calibrated to provide more that just relative intensity values. Sensors are needed to provide real time measurement and control during agricultural operations. Weed detection sensors have proven capable of drastically reducing herbicide applications. However, these only work in situations where any green material can be considered weed. Imaging systems that can discriminate noxious plants from the crop have been under investigation for several years and recent advances hold promise for commercial systems. Sensors that can eliminate or reduce the amount of soil sampling necessary are needed. On-the-go assessment of soil physical parameters may be as important as the soil's nutrient status when factors such as water holding capacity or depth to claypan are limiting factors. Sensing techniques such as electromagnetic induction and soil mechanical impedance are current under investigation. Yield mapping systems for non-grain crops such as cotton and vegetables are needed for regions where crop rotations are important. Weather is an important contributor to yield variability, and sensing systems such as weather station networks and Doppler radar can also play an important role in precision agriculture.

Decision support tools will be critical to the effective use of site-specific data. While the GIS and mapping software used today are evolving, greater integration of the data gathering, data interpretation/analysis and agronomic relationships is needed. Standardization of data interchange, linkage to crop models and incorporation of decision functions are all part of the developments that are required.

Numerous research and development activities are underway in the United States to support the precision management approach to crop production, both in industry and public institutions. While these efforts will help precision agriculture to mature as a technique, they are also likely to contribute to other changes in agriculture. In America, precision agriculture has been criticized as favoring large producers at the expense of the smaller farmers. Since much of the precision agriculture technology has been provided by dealerships on a fee basis, this criticism does not hold true. What is true however, is that the technology is most likely to be used by the producers with more sophisticated management abilities. If variable rate fertilization or planting don't prove to have long term profits, those techniques will be abandoned. However, the ability to obtain and use detailed information about their fields is likely to be retained by the farmers of the future.

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PRECISION FARMING: FARMER AND COMMERCIAL OPPORTUNITIES ACROSS EUROPE

A M HOUGHTON
Produce Studies Group, Northcroft House, West Street, Newbury, Berks, RG13 1HD, UK

B E A KNIGHT
Innovation Management, Station Yard, Wilbraham Road, Fulbourn, Cambridge CB1 5ET, UK

ABSTRACT

The advent of precision farming offers EU farmers the opportunity to be more careful in their placement and dose rate variations of inputs of seed, fertiliser and agrochemicals. Around 39% of farmers in Europe are aware of the technology. Increasing this awareness and conveying more detail as to how the techniques can be used will be essential for early and rapid adoption. Most farmers perceive that the technology will reduce the use of inputs, the cost of which represents a significant proportion of gross margins. From two surveys of farmer opinion, there seem to be good prospects for precision farming to reduce input use. Some farmers see the automation of recording of inputs as a benefit in itself, facilitating better management of increasingly complex crop husbandry. Smaller farms and farms with smaller fields perceive less benefit from the placement precision: the larger the farms, the greater chance that lack of precision represents a dis-economy of scale.

INTRODUCTION

Much of the work on precision farming is examining the integration of different parts of the technology into a viable system. There has been little examination of the practical interest at the farm level and the potential impact on production systems. Europe has a wide divergence of farm structures and production methods. The suitability of precision farming and the benefits vary.

Widespread adoption could represent a significant investment. Such an investment is a sales opportunity for the technology suppliers: if 5% of Europe's arable farms adopted precision farming then capital investment could be 1-2 M ecu. As with all new technology, significant adoption rates could lower unit costs. It is important therefore to assess awareness of precision farming and the potential benefits. This paper examines potential farmer adoption by considering crop economics, attitudes to input use, awareness of precision farming as a technique and perceived impact on input use.

RESEARCH METHOD

The results are based on two surveys. The first is work in five countries of Europe (Germany, France, Spain, Italy, UK) during February 1996. This was qualitative, using group discussions amongst a small number of farmers (74 attended 7 meetings). The work formed part of a review of fertiliser practice and business opportunities under the multi-client project SPECTRUM run by the Produce Studies Group (Houghton, 1996). The second source is part of a major survey carried out by Kemira Agro with interviews amongst 2,500 farmers during June 1996. The study was executed in Belgium, Denmark, Germany, France, Ireland, Netherlands, Finland and UK.

CROP ECONOMICS

The opportunity for better precision in the application of inputs depends on the economics of each crop. In Table 1 the key variable costs are compared for a number of EU crops and shown in relation to gross margin. The analysis is based on average results for Denmark, Germany, Spain, France and UK weighted by the area of each crop in that country.

Table 1. Estimated variable costs (ecu ha^{-1}) for key arable crops in the EU.
(Source: Produce Studies farm economics database)

	Winter wheat	Maize	Oilseed rape	Sunflower	Potatoes	Sugar beet
Seed	63	126	50	72	796	154
Fertiliser	111	106	143	61	129	267
Agrochemicals	130	31	124	47	230	287
Total Variable Costs	303	262	317	181	1156	708
Gross Margin	903	1210	796	583	3524	1955

Comparing individual input costs to the gross margin, seed costs range form 6% of gross margin for oilseed rape to 23% for potatoes. Fertiliser costs range from 4% for potatoes to 18% for oilseed rape. Agrochemicals amount to 3% of gross margin for maize but 16% for oilseed rape. It can be seen that variable costs can represent a significant component of the gross margin. Achieving greater precision in the use of these inputs promises a useful return.

ATTITUDES TOWARDS GREATER PRECISION

After a number of years of decline, fertiliser prices are increasing. It seemed relevant therefore to discuss with farmers their inherent interest in fertiliser as an input. During the group discussions in the five countries in February, the following alternatives were put:

In the future, fertiliser application will need to become more precise and more sophisticated to optimise return: it will become an increasingly expensive input.

In the future, the need to cut labour and save time means simplifying fertiliser application and management: it is a commodity whose cost does not justify greater sophistication of use.

Figure 1 Farmer attitudes towards fertiliser use

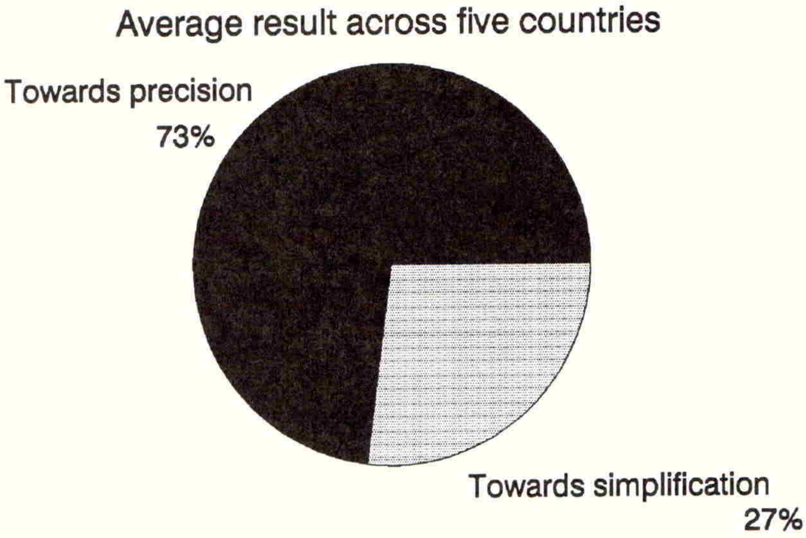


Figure 1 shows that the majority of farmers consider, even for a commodity product such as fertiliser, that they would expect to move towards more precision in use in the future. Interest appeared lower in Germany and France than Spain, Italy and the UK.

AWARENESS OF PRECISION FARMING

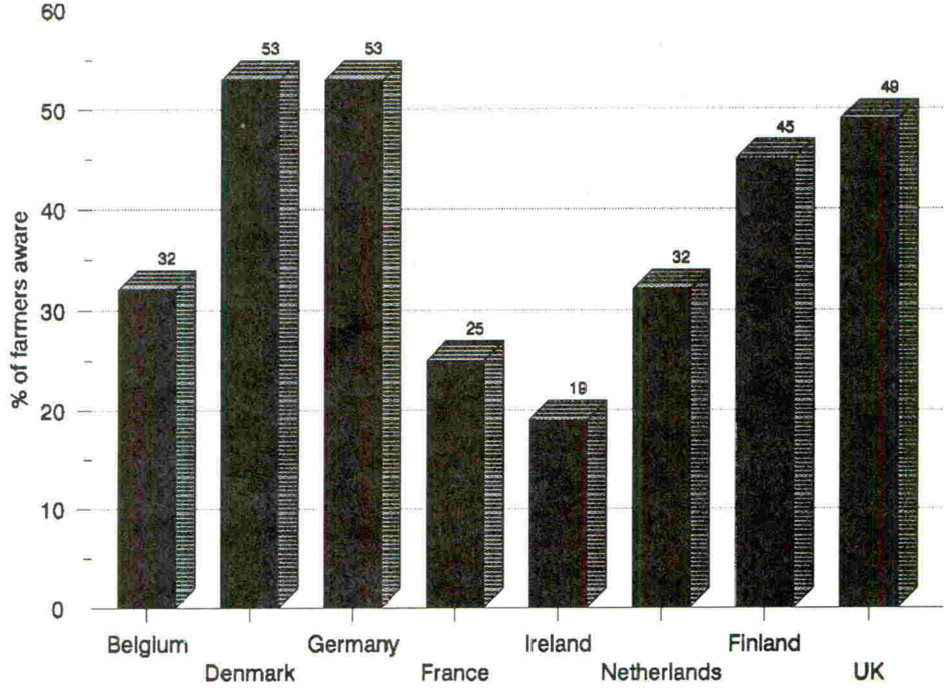
In the Kemira Agro survey, 2,500 farmers were asked whether they had heard of Geographical Positioning Systems (GPS) in the context of fertiliser applications (Figure 2). On average 39% of farmers had heard of GPS for fertiliser. In countries such as Germany, Denmark and UK, awareness was highest. Awareness in France was relatively low. Farmers with less than 50 hectares were less aware of GPS (18%) compared to farmers with 50+ hectares (24%).

IMPACT OF ADOPTION OF PRECISION FARMING

The Kemira Agro farm survey asked farmers who had heard of precision farming whether they expected such systems to increase or decrease the use of fertiliser. The majority of farmers believed that, by adopting precision farming, use would decline (Figure 3). The overall average was that 28% of farmers thought use would decline, 1% that it would increase and 71% were not sure.

A similar question was asked in relation to agrochemical use and the impact of precision farming. The proportions expecting a decrease in use and expecting an increase (Figure 4) were similar to those for fertiliser. The overall average was that 30% of farmers thought use would decline, 1% that it would increase and 69% were not sure.

Figure 2 Farmer awareness of GPS for fertiliser



In the start up meeting for the current precision farming project (Houghton & Knight, 1996) with French farmers, they seemed less keen on the technology than their British counterparts. They felt that large British farmers were trying to recapture some of the benefits of being small by means of technology. With smaller farms and smaller fields in this part of France, the variability of yield within each field is expected to be less extreme. The farmers consider that their management is already more precise than that of large East Anglian farmers. Smaller farms also mean less possibility of spreading the fixed cost of yield measurement and GPS over large areas. Thus, they anticipate higher costs and lower benefits from precision, per unit land area, though group sharing of machinery is becoming increasingly common.

On the other hand, French farmers are enthusiastic about giving greater emphasis to individual field management. Six out of 10 farmers attending the meeting were recording on computer the treatments and performance of crops, field by field. "We are probably not using this information to its full capacity" said one farmer, "if precision farming can automate our record keeping, we can spend more time fine tuning our management". French farmers have a larger range of crops than an equivalent UK farm. This poses a greater challenge to achieving maximum performance through judicious use of inputs.

Thus it seems that application to French farming could have a different philosophy: more orientated towards optimising complex multi-cropping farm management. The attractiveness here centres more on the automatic recording aspect of precision farming than the placement of inputs.

Figure 3 Farmer expectation on impact of precision farming on fertiliser use

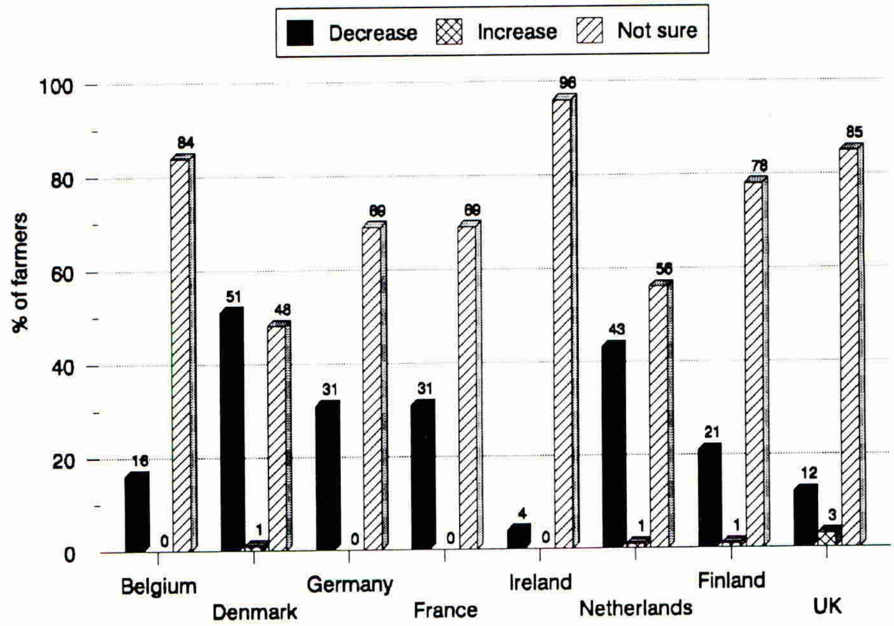
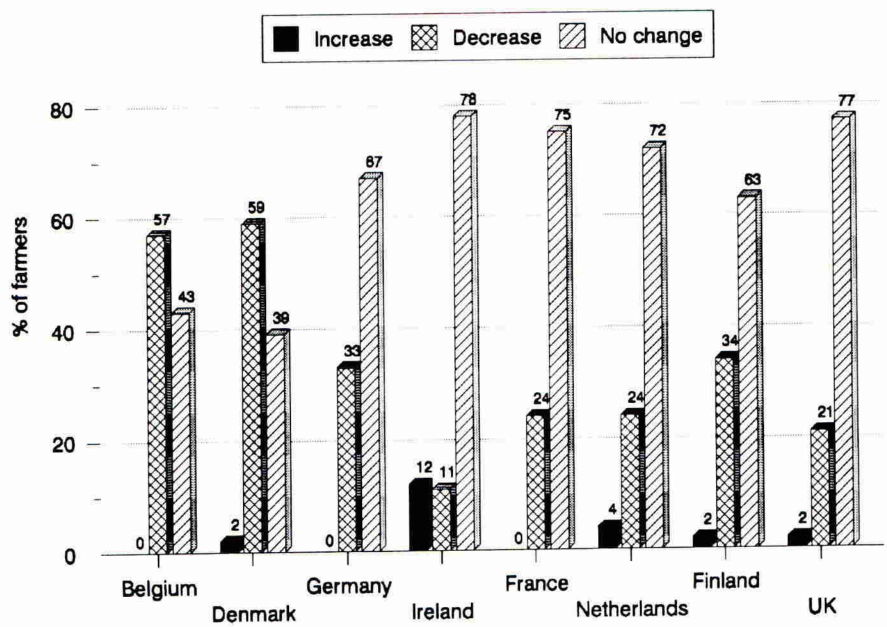


Figure 4 Farmer expectation on impact of precision farming on agrochemical use



RELATIVE INTEREST IN PRECISION FARMING AND OTHER SERVICES

From the SPECTRUM analysis, the relative interest in precision farming for fertiliser can be compared to other possible improvements or services. This suggests that farmers are more interested in leaf analysis for nitrogen (67% of farmers said they were interested in doing more) and spreader calibration (50% of farmers) than in precision farming (41% of farmers). Of course it would seem logical to address deficiencies in precision in these domains prior to investing in the technology of precision farming. Farmers were also interested in advice on conformity with environmental legislation (53% of farmers).

CONCLUSIONS

Farmer awareness about precision farming is variable between countries. Fertiliser and agrochemicals are expensive inputs and maximising efficient use represents an important element of good gross margins. Most farmers appear interested in moving towards greater precision of use of fertiliser. Those who are aware of precision farming are unsure whether adoption of the technology will reduce levels of use of inputs or not. Amongst those who had a view, the expectation was much more that use would decline rather than increase. At this point in time farmers appear more interested in other methods of gaining precision in application, but no doubt this is born out of unfamiliarity and uncertainty of what precision farming is offering.

It is interesting that the results in France identified other benefits from precision farming than just application precision, most notably automatic recording. Automated records of fertiliser and agrochemical use as well as yield recording may have considerable and widespread advantages. The legislation may well move towards more and more recording of input use and automation of this task will prove attractive to farmers. Information management may well represent an opportunity for those firms in distribution of inputs to farmers.

As with all new technologies several spin off benefits may well arise. The farmer survey work needs to be continued to enable further testing of the practical considerations. It will also be necessary to get good marketing and communication to achieve successful adoption.

ACKNOWLEDGEMENTS

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SESSION 9B

STRATEGIES FOR MANAGING ALIEN PESTS AND DISEASES

Chairman & Session Organiser	Dr D L Ebbels *Central Science Laboratory, York*
Papers	9B-1 to 9B-4

MIGRATION AND DISPLACEMENT; RECOMBINANTS AND RELICTS: 20 YEARS IN THE LIFE OF POTATO LATE-BLIGHT *(PHYTOPHTHORA INFESTANS)*

R C SHATTOCK, J P DAY
School of Biological Sciences, University of Wales, Bangor, Gwynedd, LL57 2UW, UK

ABSTRACT

A recent (mid 1970s) migration of novel, varied genotypes of *P. infestans*, of mating types A1 and A2, has largely displaced the previous, uniform 'old' A1 genotype. This displacement may have been related to the concomitant introduction of phenylamides: resistance to these is more common amongst the 'new' isolates. Evidence has also been found that 'new' isolates are more aggressive than 'old' isolates, when sporulation and infection frequency were measured on detached leaves of different potato cultivars. 'New' A1 and A2 isolates are able to combine sexually to produce oospores, which may provide both a novel and alternative source of inoculum, with increased gene flow resulting in 'hot spots' of genetic diversity. Nuclear DNA fingerprinting and mitochondrial DNA typing have been used to locate such sites. Recombination may also have taken place between 'new' A2 isolates and 'old' A1 isolates.

INTRODUCTION

Techniques to detect and assess variation in populations of plant pathogens have improved rapidly over the past decade, with the development of biochemical and molecular genetical markers. Structural changes in populations during and between seasons can be followed, and the various evolutionary processes such as mutation, selection, recombination, genetic drift and migration can be investigated (Caten, 1996). In the case of *Phytophthora infestans*, responsible for late-blight of potato and tomato, various phenotypic and genotypic analyses have provided sufficient data to identify several major migrations out of Mexico, beginning approximately 150 years ago (Goodwin, 1996).

MIGRATION

The first migration, resulting in the appearance of late-blight in Europe in the 1840s, resulted in a founder effect since the disease was invading previously unoccupied territory (Goodwin, 1996). Goodwin *et al.* (1994a) suggest that the introduction involved only the A1 mating type. Subsequently, the same single genetic lineage was transported to the rest of the world, this long distance migration occurring in blighted tubers. Rare variants of this founding genotype, described as US-1 (Goodwin *et al.*, 1994b), appear to have arisen by mutation and /or mitotic recombination. These same mechanisms are probably responsible for the diversity exhibited by *P. infestans* for host-specific pathogenicity (= virulence) in the United Kingdom (Shattock *et al.*, 1977). Various cereal rusts lacking a sexual cycle also exhibit diversity in virulence superimposed upon an otherwise narrow genetic base (Caten, 1996). In both cases these virulence variants have compromised the efforts of plant breeders, producing the familiar 'boom and bust' scenario associated with monogenic race-specific resistant cultivars.

The clonal lineage (US-1) dominated North American late-blight populations until a further migration brought the new genotype US-6 into the western United States in the early 1980s. In the 1990s, two further genotypes, US-7 and US-8, arrived in the United States and Canada (Fry & Goodwin, 1995). The discovery of A2 mating type isolates in Switzerland (Hohl & Iselin, 1984) and elsewhere in Europe (listed in Drenth *et al.*, 1993) in the early 1980s was the first phenotypic evidence of significant genetic change in European late-blight populations. Migration rather than mutation was confirmed as the cause of this development when various genotypic analyses were carried out using isozymes and DNA fingerprinting (Spielman *et al.*, 1991, Drenth *et al.*, 1993, 1994, R. Folkertsma, R. C. Shattock and D. S. Shaw, (unpublished data). The source of these novel isolates (both A1 and A2 mating type) was first described by Niederhauser (1991), who pinpointed a shipment of 25 000 tonnes of Mexican tubers to western Europe in 1976.

DISPLACEMENT

Co-incident with this importation into Europe was the announcement of a new, powerful class of systemic fungicides, the phenylamides, for control of oomycete pathogens. Unfortunately, soon after their commercial release, insensitivity to phenylamides was reported in 1980 in isolates of both potato late-blight and vine downy mildew *(Plasmopara viticola)* from phenylamide-treated crops (Staub, 1994). Various surveys have since shown that insensitive isolates are common and widespread (Shattock *et al.*, 1990, Bradshaw & Vaughan, 1996), even though sampling methods and assay procedures may sometimes inflate the actual frequency (Table 1). Insensitivity to the phenylamides may have its origins in the novel 'new' immigrant genotypes of the mid-1970s migration. Alternatively, mutation may have occurred. Probably both played a role, since phenotypes both fully- and intermediately-insensitive to phenylamides occur amongst 'old' European isolates of *P. infestans* (Table 1, Goodwin *et al.*, 1996). 'Old' isolates refer specifically to those characteristic of the US-1 lineage with minor variations (described earlier). These always carry the glucosephosphate isomerase allele *86* and the peptidase allele *92*, and have the mitochondrial DNA haplotype Ib (Carter *et al.*, 1990), a subset of the haplotype A described by Drenth *et al.* (1993).

Using the mitochondrial DNA (mtDNA) marker, we have screened 290 isolates of *P infestans* collected in 10 of the past 18 years in England and Wales. (Table 1, Day & Shattock, 1996). In 1978 the 'old' type Ib was detected in 100% of a small sample (4 isolates), compared with 67% in a larger sample (33 isolates) in 1982. Thereafter, apart from single isolates recorded in 1986 and 1995, type Ib has been displaced by 'new' isolates characterised by type Ia and type IIa mtDNA haplotype (Table 1). Whilst type Ib isolates were all A1 mating type, both A1 and A2 mating types were identified among the 'new' type Ia and IIa mtDNA haplotypes. This (almost) complete displacement of 'old' isolates by 'new' immigrant types with isozyme and DNA markers akin to those of indigenous Mexican strains (Goodwin, 1996) may be a result of the lower aggressiveness (= non-host-specific pathogenicity) exhibited by the 'old' isolates, and of their general lack of full insensitivity to phenylamides (Day & Shattock, 1996). Among the 'new' isolates, mtDNA haplotype Ia isolates are much more numerous than IIa isolates, and the former were found to be more aggressive than IIa isolates when compared for two components of aggressiveness on detached leaflets of different potato cultivars (Table 2a). Analysis of

Table 1 Mating type, response to metalaxyl and mitochondrial DNA (mtDNA) type for isolates of *P.infestans* collected in England and Wales between 1978 and 1995.

Year	Mating type			Response to metalaxyl			mtDNA type		
	A1	SF[3]	A2	Sensitive	Intermediate	Insensitive	Ib	Ia	IIa
1978	4(100)[1]	0(0)	0(0)	3(75)	1(25)	0(0)	4(100)	0(0)	0(0)
1981	3(75)	0(0)	1(25)	4(100)	0(0)	0(0)	1(25)	3(75)	0(0)
1982[2]	27(79)	0(0)	7(21)	29(85)	5(15)	0(0)	22(67)	9(27)	2(6)
1983	2(100)	0(0)	0(0)	2(100)	0(0)	0(0)	0(0)	2(100)	0(0)
1985	21(81)	1(4)	4(15)	12(46)	11(42)	3(12)	0(0)	22(85)	4(15)
1986	11(61)	0(0)	7(39)	10(56)	1(6)	7(39)	1(5)	14(74)	4(21)
1987	7(50)	0(0)	7(50)	11(79)	0(0)	3(21)	0(0)	10(71)	4(29)
1993	201(97)	0(0)	6(3)	164(79)	19(9)	24(12)	0(0)	70(92)	6(8)
1994	138(95)	4(3)	3(2)	63(43)	20(14)	62(43)	0(0)	75(93)	6(7)
1995	162(99)	0(0)	2(1)	56(34)	66(40)	42(26)	1(3)	29(94)	1(3)

[1]Figures in parentheses are percentages. [2]Samples from 1982 were collected exclusively from Anglesey, North Wales. [3]Self-fertile phenotypes producing oospores in the absence of A1 or A2 testers.

Table 2 Chi-square contingency tables for aggressiveness of (a) 'old' (mtDNA type Ib) and 'new' (mtDNA type Ia and IIa) isolates, and (b) metalaxyl-sensitive, intermediate and insensitive isolates of *P.infestans* collected from England and Wales between 1978 and 1995, on detached leaves of potato cv. Cara.

(a)

mtDNA type	non-aggressive	Aggressiveness[1] low	intermediate	high	Totals
Ib	1(5)[2]	17(85)	1(5)	1(5)	20(100)
Ia	10(6)	49(31)	52(33)	49(31)	160(100)
IIa	1(4)	17(68)	16(24)	1(4)	25(100)
Totals	12(6)	83(40)	59(29)	51(25)	205(100)

$\chi^2 = 33.1$, df = 6, $P < 0.001$

(b)

Metalaxyl phenotype	non-aggressive	Aggressiveness[1] low	intermediate	high	Totals
Sensitive	4(3)[2]	38(32)	43(37)	32(27)	117(100)
Intermediate	2(5)	17(39)	9(20)	16(36)	44(100)
Insensitive	5(8)	34(58)	11(19)	9(15)	59(100)
Totals	11(5)	89(40)	63(29)	57(26)	220(100)

$\chi^2 = 18.5$, df = 6, $P < 0.01$

[1]Aggressiveness categories were determined using a detached leaf assay (Day & Shattock, 1996), summarised here. Five leaflets on each of three compound leaves were inoculated with 20µl sporangial suspension (2-3 x 10^4 sporangia per ml) of the isolate taken from previously inoculated leaves of cv. Home Guard (a highly susceptible cultivar). Inoculated leaves were incubated at 18°C for 6 days, then infection was scored using infection frequency (proportion of inoculated leaflets bearing lesions) and number of spores per lesion (measured using a Coulter Counter). The product of these two measurements was used to categorise isolates, on the basis of comparison with the scores obtained from three 'standard' isolates of consistently low, intermediate or high aggressiveness, which were included in each experiment.

[2]Figures in parentheses are percentages.

grouped data from similar detached leaflet experiments revealed that phenylamide sensitive isolates were more aggressive than insensitive isolates (Table 2b). Pre-packaged phenylamide + dithiocarbamate compounds have remained popular with potato growers, resulting in a selection pressure against phenylamide-sensitive isolates, which were predominant among 'old' isolates, but are a minority among 'new' isolates. These data also support the various findings that when phenylamide-based fungicides are withdrawn there is a concomitant decrease in the frequency of insensitive phenotypes (Staub, 1994). The predominant genotype in the eastern USA in 1994 was the immigrant US-8. It too is insensitive to phenylamides, and it proved to be especially pathogenic towards potato, causing severe losses ($100 m) and additional costs in crop protection measures ($100 m) (Fry & Goodwin, 1995).

RECOMBINANTS

Sexual reproduction between A1 and A2 mating type isolates of *P. infestans* was first identified in Mexico, the centre of diversity of the pathogen, but may also be occurring elsewhere. Whether or not novel combinations of genes will be produced by recombination and segregation depends upon the frequency of sexual reproduction, the viability of the resulting oospores, and the infectivity and pathogenicity of sexual progeny. Already there are reports of apparently recombinant genotypes isolated from blighted plants in locations where both mating types have been identified, e.g. in British Columbia (Goodwin *et al.*, 1995) and The Netherlands (Drenth *et al.*, 1995), and putative recombinants have also been isolated at a non-commercial site in North Wales (K. Hanson, unpublished data). Such recombination may be quite rare if either of the two mating types occurs at a low frequency. For example, in England and Wales only 11 out of 516 isolates characterised between 1993 and 1995 were A2 mating type (Table 1), and similar low frequencies of A2 have been reported elsewhere in Europe. Despite this, the finding of 'self fertile' isolates (likely to be mixtures of A1 and A2 isolates), which produce oospores in culture without the presence of 'tester' strains, suggests that local populations of *P. infestans* may be capable of producing oospores in the field (Shattock *et al.*, 1990).

Where detailed genotypic surveys have been conducted, genotypes common in one season were not observed either previously or subsequently (Drenth *et al.*, 1993, Fry & Goodwin, 1995). Drenth *et al.* (1994) point out that these annual differences are typical of a sexually reproducing population with overlapping generations. Equally, it may be a consequence of the 'metapopulation' structure typified by *P. infestans* in temperate countries, where expanding epiphytotic summer populations are drastically reduced each year to only a few overwintering remnants. The following season, the new epidemics which arise from these founder isolates may differ significantly from the previous population.

Before the 1970s migration into Europe, living mycelium in tubers was considered the main source of each new season's inoculum. More recently, the possibility of sexual recombination means that long-lived oospores, surviving either in the soil or perhaps in potato tubers, may provide a new source of early inoculum. The significance of oospores and their fate in the soil is currently being examined (Pittis & Shattock, 1994, Drenth *et al.*, 1995). K. Hanson (unpublished data) demonstrated that oospores, produced in leaf disks inoculated with A1 and A2 isolates of UK origin and introduced into soil, subsequently produced stem lesions on potatoes. Isolates from these blighted plants were confirmed as recombinants by nuclear DNA fingerprinting. In the case of late-blight, allotments and private gardens may provide ideal refuge

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GYPSY MOTH OUTBREAKS IN CENTRAL EUROPE: DAMAGE, CONTROL AND POSSIBLE CAUSES

A WULF
Federal Biological Research Centre for Agriculture and Forestry,
Institute for Plant Protection in Forests, 38104 Braunschweig, Germany

ABSTRACT

In the early 1990s, Germany and some neighbouring countries suffered the first pandemic outbreak of gypsy moth *(Lymantria dispar)* observed in central Europe. The extent of the outbreak is reported and information on the area of damage and control measures is given. The climatic circumstances and the introduction of Asian strains of gypsy moth are discussed as possible causes for the outbreaks. From current research results, there is no indication that foreign strains of the pest had an important influence on the recently observed population dynamics.

INTRODUCTION

From 1991 to 1995, the most severe epidemic of gypsy moth (*Lymantria dispar*) ever observed in central Europe took place. The centre of infestation was south-west Germany, but some surrounding countries were affected as well. In this part of Europe, the native insect caused hitherto unknown defoliation of forests and the destruction of plants, and the caterpillar invasion even extended into urban areas. Therefore, control measures became necessary. The extent of the recent outbreaks, the amount of damage they caused, the methods used for control and the possible causes of this unusual epidemic are the subject of the following contribution.

BIOLOGY OF THE GYPSY MOTH

The distribution area of *Lymantria dispar* extends from England in the west to Japan in the east. In Europe, the species is found from a latitude of 60° N in the middle of Scandinavia to 35° N on the Mediterranean coast. *Lymantria dispar* thus occurs from the vegetation zones of temperate deciduous forests to the Mediterranean scrub land. Since its accidental introduction to the east coast of North America in 1869 (Forbush & Fernald, 1896), the gypsy moth has become established there and is currently still spreading westwards, having nearly reached the middle of the continent.

In line with its huge distribution area, *L. dispar* is one of the most polyphagous insects, possessing an extremely wide range of host plants. Although it prefers oak (*Quercus*) species, followed in preference by hornbeam (*Carpinus*), beech (*Fagus*) and chestnut (*Castanea*), it also feeds on several other deciduous trees (*Betula, Populus, Salix, Acer, Tilia, Ulmus, Alnus*), even accepting larch (*Larix*) if no other plants are available.

In Europe the damage caused by gypsy moth generally increases from west to east and from north to south. The area that suffers most is the Balkan Peninsula, where severe outbreaks and defoliation of forest trees occur over thousands of hectares every 7 - 8 years, lasting about 4 years per outbreak. In the western parts of Europe, the intervals between outbreaks and their duration are longer. On the Iberian Peninsula, in contrast, both the period between outbreaks and their duration is usually more than 10 years. The concentration of the mass development in south-east and southern Europe is caused primarily by the climate and by the affinity of the insect to warmth and drought (Schwenke, 1978). In central Europe, only a few local outbreaks were reported up to 1993.

OUTBREAKS IN CENTRAL EUROPE

In 1995 a conference of the European and Mediterranean Plant Protection Organization (EPPO) reflecting the gypsy moth situation was held in Poznan (Roy *et al.,* 1995). Next to Germany, **France** has suffered most from the current outbreaks. In Alsace alone, 23,500 ha were defoliated in 1994 (Landmann & Barthod, 1996). Since the outbreak lasted longer in France than in other middle European countries, control measures using *Bacillus thuringiensis* were carried out in 1995 on 2,500 ha. In **Switzerland,** 2,000 ha composed mainly of chestnut trees south of the Alps were defoliated in 1992. After the breakdown of the insect population in 1993, the trees appear to have recovered without any treatment (Anon., 1995). **Austria** registered infestation on 1,500 ha in 1993, with severe defoliation affecting 400 ha of oak stands, but neither insecticide treatment nor important losses were reported (Krehan, 1994). **Slovakia** and the **Czech Republic** had outbreaks in 1993/94 in oak forests in regions with a wine-growing climate, and treatments with *B. thuringiensis* or diflubenzuron insecticides were necessary. **Poland** was also affected during the recent outbreak period, but so far gypsy moth has not been a serious pest there. In Scandinavia, *L. dispar* specimens were collected in **Sweden** and perhaps in **Finland**, but never in **Norway**. The species is not considered to be a pest in the Nordic countries. In the **UK**, gypsy moth has been found several times recently, but is not regarded as a native species. An outbreak was discovered in a suburban district of London in 1995 and was treated with permethrin and *B. thuringiensis*. Eradication efforts continue in 1996.

In **Germany**, the southern and south-western areas which have a warm climate suitable for wine growing were at the centre of the recent gypsy moth outbreaks. Bavaria, Baden-Württemberg, Hessen and Rheinland Pfalz suffered most from the outbreaks (figure 1), while a second, eastern, focus became established in Sachsen and Brandenburg. First indications of an increasing gypsy moth population were observed in 1991, and one year later almost 2,000 ha were affected. In 1993, the first epidemic year, infestation covered 47,000 ha, and in 1994, before the natural population breakdown, the pest was present on about 80,000 ha.

DAMAGE AND CONTROL

Since there was no previous experience with *L. dispar* as a pandemic pest in central Europe, the forest authorities had problems deciding whether protection measures were necessary, their extent, and means. The number of egg masses per tree in addition to age and vitality of the forest stands were considered as indicators for determining the necessity for control measures. In accordance with the present German situation on pesticide registration, *Bacillus thuringiensis* and diflubenzuron insecticides were chosen for treating forest stands. In 1993, c. 11,000 ha and in 1994 c. 34,000 ha were treated by helicopter (figure 2). The treated area increased from 24% of the total infested area in 1993 to 43% in 1994, one quarter being treated with *B. thuringiensis* and the rest with diflubenzuron. Due mainly to adverse weather conditions, some of the area treated in 1993 using *B. thuringiensis* failed to provide sufficient protection, but otherwise the control measures were largely successful. The experimental application of a virus pesticide showed satisfying results (Langenbruch *et al.*, 1996).

The planning and carrying out of protection measures were accompanied by many heated debates concerning environmental problems and side effects of pesticides. In order to provide a basis for objective discussions, two conferences on the subject were organised by the Federal Biological Research Centre for Agriculture and Forestry. The first was held in advance of the expected climax of the outbreak and was aimed at preparing the co-ordinated management of the outbreak (Wulf & Berendes, 1993). The second conference dealt with the epidemic retrospectively, in order to learn from past experience and try to find solutions for similar problems in the future (Wulf & Berendes, 1996).

One of the most intensely discussed problems dealt with the possible side effects of pesticide treatments to beneficial organisms and antagonists of gypsy moth. Fear was expressed that protection measures could interfere with the natural breakdown of gypsy moth populations and thus prolong the epidemic. The subsequent collapse of the pest population showed that there was no basis for this assumption. In Germany, in 1994 the breakdown of *L. dispar* populations occurred simultaneously over the whole infestated area, in treated forests as well as in non-treated ones, mostly caused by a virus disease of the caterpillars. No serious prolongation of the outbreak due to control measures has been observed or reported.

A second point of discussion was the necessity for protection measures in general. Based on experience from the Balkan region, where forests are adapted to surviving gypsy moth outbreaks, it was doubted that repeated defoliation could really mean severe damage to deciduous trees in Germany. However, results show that treatment was mostly justified, since individual trees and even large areas of forest can be killed. Severe losses and damage especially to some oak forests have been reported (Lobinger & Skatulla, 1996, Wezel 1996). One of the most impressive examples was demonstrated by Delb (1996) for the Bienwald region in Rheinland Pfalz, where circumstances led to the extensive, sudden decline of oak trees on more than 500 ha following defoliation by caterpillars in 1994, while treated forests in the vicinity were able to survive without loss. In some cases valuable forest stands where control measures were rejected for environmental reasons were destroyed or much altered in their structure and species composition. Much research has been done on the side effects of forest protection products on non-target species, but in spite of the many interesting results yielded by these efforts there can be no doubt that the decline or even death of a forest is a much more lasting ecological loss for a given site than any limited influence of control measures on the invertebrate fauna.

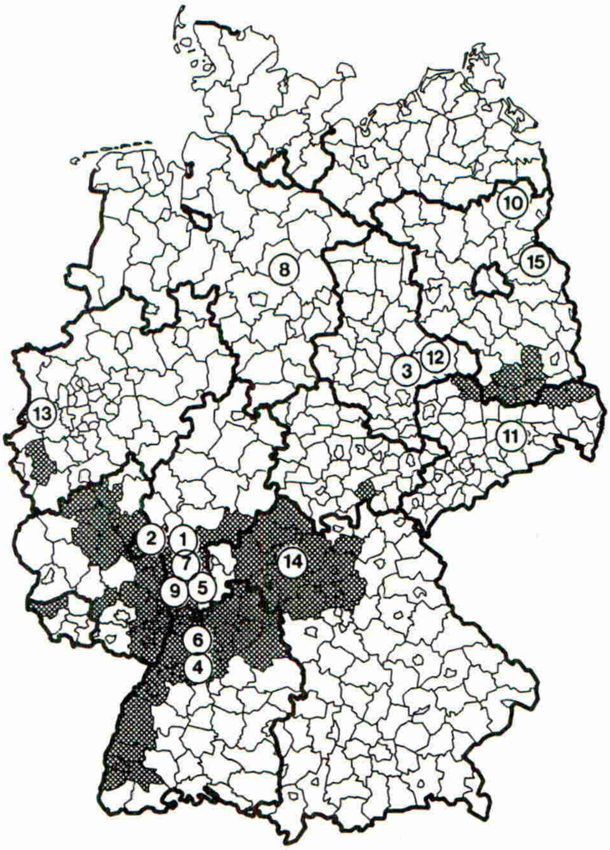
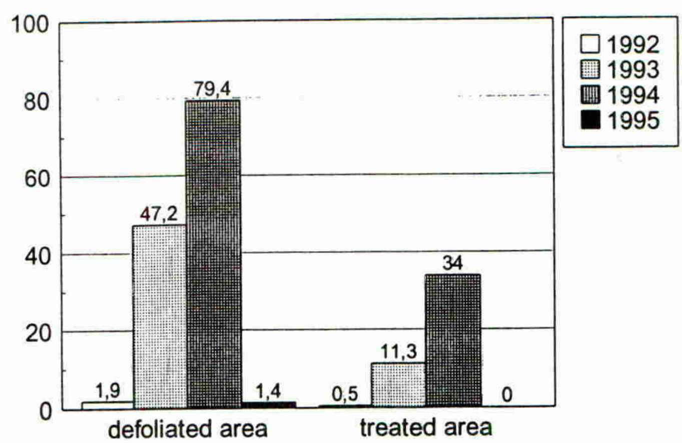


Figure 1: Area affected in Germany by gypsy moth in 1993. Counties with more than 10 ha of defoliation. Numbers denote sampling localities for cluster analysis of RAPD-PCR data (see figure 3).

Figure 2:

Relation between total outbreak area and area treated by control measures against gypsy moth in Germany in thousand ha.



ASIAN GYPSY MOTH

One hypothesis for the recent unusual outbreaks is the introduction or migration of Asian gypsy moths to central Europe, because Asian strains are considered to be more aggressive. More support for this hypothesis was supplied by the observation of flying females in the outbreak area. In contrast to gypsy moths of European origin, the females of Asian strains are reported to be good flyers. The importance of knowing if central Europe was dealing with Asian gypsy moths increased dramatically when, in 1993, egg masses were discovered on military equipment being brought back to the USA from the German outbreak areas. As a result, quarantine measures for all transatlantic transports from contaminated regions were taken into consideration.

The lack of morphological characteristics for differentiation of *L. dispar* strains necessitated research based on molecular biology (Bogdanowicz *et al.,* 1993). Preliminary trials comparing specimens collected in Germany with Asian material from Kazakhstan using the RAPD PCR (Random Amplified Polymorphic DNA-Polymerase Chain Reaction) technique showed certain differences (Graser *et al.,* 1995) but had to be extended by testing a larger number of Asian specimens. In addition, eight reference specimens from different localities in Russia, eastern China, south-eastern China and Japan were obtained. For those and for several specimens collected from the German outbreak area (see figure 1), patterns of amplified DNA fragments were prepared in order to determine the genetic relationships between populations by means of cluster analysis.

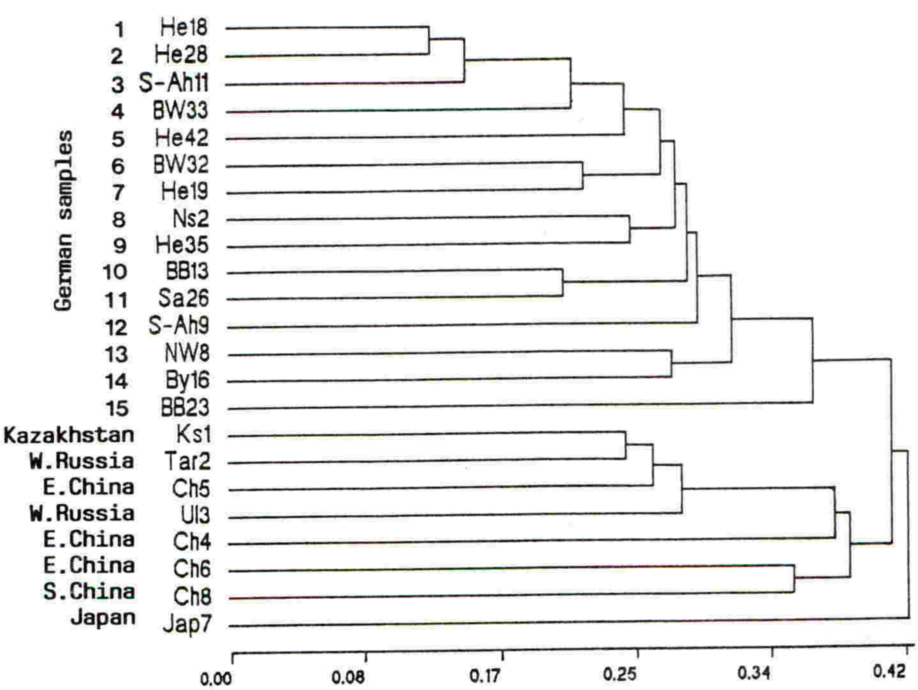


Figure 3: Dendrogram of RAPD-PCR cluster analysis for Asian and European strains of gypsy moth (for sampling localities, see figure 1).

Cluster analysis with RAPD patterns follow the same rules as any other taxonomic method: conclusions can be reinforced by increasing the number of characters. Therefore, the final results were corroborated by using data sets with an increasing number of characters for cluster analysis. Evaluations of 12-16 characters obtained with a single primer resulted in predominantly separate clustering of Asian and European populations, with only the occasional appearance of one to three Asian populations in the European branch of the dendrogram. The use of 97 characters obtained with seven primers resulted in the clear differentiation of Asian and European provenances. Moreover, with one exception, the geographical origin was reflected in the form of the dendrogram: Asian populations were clustered according to western and eastern provenances (figure 3).

Although results of further analyses show the occasional appearance of Asian specimens in the European branch of dendrograms (Graser, 1996) and preliminary indications of the presence of certain Asian genes (Reineke *et al.*, 1996), there is no support for the idea of a major introduction of Asian *L. dispar* genotypes which could have influenced the severity of the recent gypsy moth outbreaks in Central Europe (Wulf & Graser, 1996). As for the question of the females` flight capability for differentiating Asian and European strains, it seems very probable from recent observations that in European populations females have always possessed a certain degree of flight capability which can become more obvious during periods of high population density.

CLIMATIC INFLUENCE

As a second hypothesis, climatic conditions could be an explanation for the recent extraordinary population development of gypsy moth in central Europe. Temperature and precipitation data during the growing season in south-west Germany shows the climate has substantially changed to favour *L. dispar* (figure 4). Warmth and drought have stressed trees for several years while favouring gypsy moth. (The copious fruiting of oak and beech in consecutive years is indicative of such stress.) Such conditions are known to improve food quality, caterpillar and pupae development, copulating possibility and egg production (Schwenke 1978). The fact that several different forest lepidoptera (e.g. *Lymantria monacha, Dendrolimus pini*) also developed outbreaks during the early 1990`s, necessitating control measures comparable to gypsy moth treatments, supports the idea that climatic factors were important. The conspicuous abundance of pests (e.g. *Phaenops cyanea*) and plant diseases (e.g. *Sphaeropsis sapinea*) adapted to warm and arid conditions was noticeable during the period.

CONCLUSIONS

Climatic conditions provide a plausible explanation for the processes involved in the population dynamics of gypsy moth during the recent outbreaks. Although there may be a certain gradation of Asian genes from east to west, there is no indication of the recent introduction of an Asian form as a pest to Europe which could account for the outbreaks. The complete breakdown of the epidemic, as expected, and the realisation that females possessing flight capability tend to occur during periods of high population density support this point of view. In accordance with these conclusions, EPPO decided to reject quarantine regulatory action for the time being (Roy *et al.*, 1995).

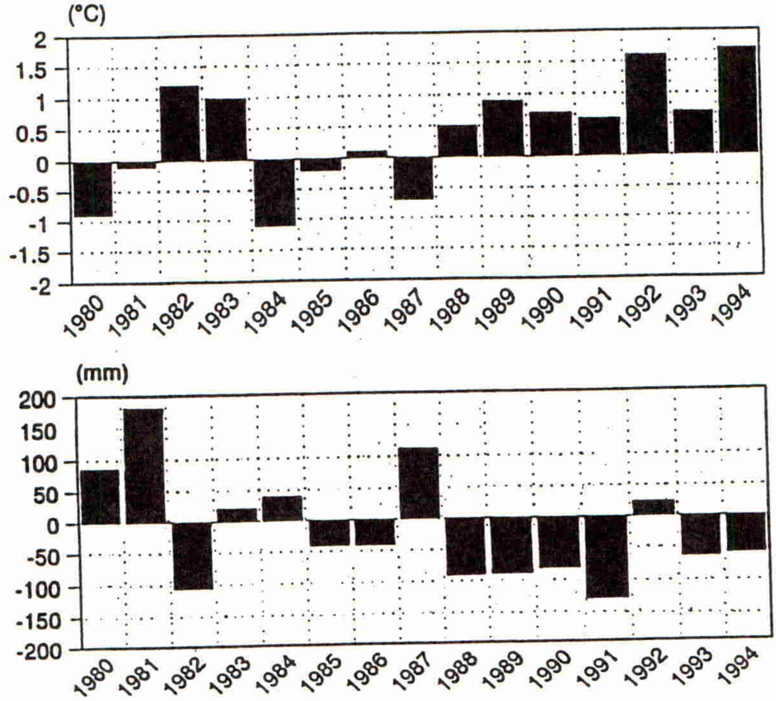


Figure 4: Climatic data during the growth period (May to September) for Frankfurt, Germany. Deviation from the mean value of the years 1949-1994 for temperature (above) and precipitation (below). (Source:German Weather Service, Frankfurt)

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POTATO BROWN ROT IN EUROPE

D E STEAD, J G ELPHINSTONE, A W PEMBERTON
Central Science Laboratory, MAFF, Sand Hutton, York, YO4 1LZ

ABSTRACT

Potato brown rot disease, caused by the bacterium *Pseudomonas solanacearum* (Smith) Smith biovar 2A, has occurred in Southern Europe (1940-1970) and in Sweden (1972). More recently, an isolated outbreak recorded in England (1992) was followed by reports of other sporadic outbreaks in northern Europe. In the Netherlands, more widespread outbreaks were reported in 1995 and infected seed potatoes were implicated as sources of infection. Evidence from several countries suggests that infected *Solanum dulcamara* growing in watercourses is an important secondary host in which the pathogen can successfully overwinter and from which it can spread to potato crops when associated water is used for irrigation. Current control measures, governed by national and European Union plant health legislation, rely on (i) accurate detection and reporting of brown rot outbreaks and distribution of the pathogen, (ii) prevention of importation of potatoes from known infected areas and (iii) restrictions on use of infested land and irrigation water for potato production.

INTRODUCTION

Potato brown rot is caused by *Pseudomonas solanacearum* (Smith) Smith (1914). Other currently valid names are *Burkholderia solanacearum* (Smith) Yabuuchi *et al*. (1992) and the newly accepted *Ralstonia solanacearum* (Smith) Yabuuchi *et al*. (1995). Because much plant health legislation refers to *Pseudomonas solanacearum*, this name is still widely used and will be until changed in the legislation.

P. solanacearum is a heterogeneous species. Many strains are pathogenic to plants but there is no record of pathogenicity to animals or humans. The species has been classified into five races (Buddenhagen, 1986) and five biovars (Hayward *et al*., 1990). Strains pathogenic to potatoes from race 1 (including strains of biovars 1, 3 and 4) tend to have wide host ranges and require high temperatures and are thus restricted to the tropics and sub-tropics and occasionally to warm temperate regions. Race 3 strains have almost exclusively occurred on potato in cool upland areas in tropical, sub-tropical and warm temperate regions. World-wide, the commonest strain of race 3 is a variant of biovar 2 known as biovar 2A (French *et al*., 1993). Despite the fact that this strain has a lower temperature optimum than other strains, the risk to plant health in Europe has been regarded as fairly low due to the perceived restriction of its geographical distribution.

It is likely that *P. solanacearum* biovar 2A has been transported round the world in seed tubers exported initially from South America (Hayward, 1991). It is also possible that the pathogen was introduced to Europe several centuries ago (French *et al*., 1993) where it could have survived as latent infection, being spread in turn to other parts of the world within seed exports. There has been little, if any, recent import of seed potatoes into Europe from areas where potato brown rot was known to occur, whereas there has been much import, out of the growing season, of ware potatoes from these areas.

HISTORY OF POTATO BROWN ROT IN EUROPE

Potato brown rot has been known for some time in southern Europe. There are records between 1940-1970 from Cyprus, Greece, Italy and Portugal. In addition there have been large-scale imports to Europe of ware potatoes from Egypt and Turkey where the disease has long been known.

The following countries report that the pathogen was found but has been eradicated (Smith *et al.*, 1992): Israel, Poland, Portugal, Spain and Sweden. Since then, eradication has also been recorded from southern Cyprus (Anon., 1996a). Romania reports a single possible case from 1957 and now considers itself to be free. Outbreaks in Bulgaria were recorded in 1944 and 1951 on tomato and sunflower respectively and Bulgaria now considers itself also to have eradicated the pathogen. There were reports of the pathogen in Poland prior to 1945 but the EPPO Reporting Service (Anon., 1996a) claims that these were possibly misidentifications. There is also reference to the presence of the pathogen in Yugoslavia. As far as is known, all potato strains from Europe and the Mediterranean basin belong to Race 3 (biovar 2A).

In the early 1970's, Sweden reported two outbreaks of potato brown rot at 56° latitude north; these were unexpected being some 11° north of what was anticipated to be the geographical limit (Olsson, 1976a). These outbreaks are well documented (Olsson, 1976a) and set an important precedent for the series of outbreaks that have been detected in Europe since 1989.

The Swedish outbreaks

The first outbreak was at Hököpinge in southern Sweden in 1972, when several thousand tubers showed symptoms at inspection (Olsson, 1976a). A further single infected tuber was found on a nearby field in 1973. The second outbreak was from Ostra Ljungby, again in southern Sweden, in 1973 in cv. Bintje on several fields with up to 5% tuber infection.

The source of the Ostra Ljungby outbreak appeared to be the local Pinn River because there was a clear link to irrigation. On the affected farm only fields that had been irrigated were infected. Crops from sister seed stocks on other farms showed no infection. Subsequent sampling of water and aquatic weeds showed that *Solanum dulcamara* plants in the Pinn river were infected. The Pinn River received water from a potato processing factory but there was no conclusive evidence that potato waste was the source, despite the fact that more than one brown rot-infected imported consignment was disposed of by processing. Olsson (1976a) reports that although potato waste was steam-treated at 145 °C, the water used to wash the infected potatoes was released untreated into a local stream. Olsson (1976a) initially suggested that the earlier Hököpinge outbreak may have been connected with a massive Colorado beetle swarm from Poland where brown rot was then reported to occur. By 1978, the pathogen was also detected in water from a stream linked to the second outbreak, although it seems that no infected *S. dulcamara* was found in this case (Persson, personal communication).

Olsson's epidemiological studies clearly demonstrated the ability of the pathogen to infect and multiply naturally in *S. dulcamara* and artificially in several other weed hosts including *Eupatorium cannabinum*. She showed the link to irrigation and suggested that the *S. dulcamara* plants could have been infected several years prior to the outbreaks. Due to the severe winters at 56° north, groundkeepers in the infested fields were not considered a major means of survival. The pathogen could not be detected in infested soil after the winter. Prohibition of growing potato crops in infested fields and of using known contaminated irrigation water were the key elements of an eradication campaign which was immediately successful in potatoes. *S. dulcamara* plants were also cut back in the two affected rivers and regular testing in the late 1970s and early 1980s showed no further infection of plants (Olsson, 1985).

Recent history in Europe

The Swedish outbreaks were considered by many to be freak occurrences, although they indicated that the risks of the potato brown rot bacterium becoming established in northern Europe were higher than previously thought (Lelliott, personal communication). Generally in Europe, a nil tolerance was enforced for all ware imports from infested countries, based on visual symptoms. Sweden reported interceptions on ware from Israel in 1970 (Olsson, 1976a). The UK has intercepted brown rot in ware potatoes from Cyprus (1959-63) and on many occasions from Egypt since 1961. Also, there are isolates of *P. solanacearum* biovar 2A in the UK National Collection of Plant Pathogenic Bacteria (NCPPB) from Portugal (1960), Greece (1965) and from potatoes imported from the Netherlands in 1982.

In late 1992, ware potatoes of several different cultivars from two fields on a farm in Oxfordshire, England, were rejected for marketing, having more than 2% vascular rot which was later diagnosed as brown rot. This was thus the third reported case in northern Europe, some 20 years after the first two. Seed infection was soon ruled out and irrigation water seemed a more likely source. Infected *S. dulcamara* plants were eventually found in a stream adjacent to the farm and later in a small stream linking a reservoir on the farm to the river Thames. The pathogen has not been detected in soil in the affected fields since January 1993 or in groundkeepers in the affected fields since the autumn of 1993. However, the pathogen has persisted in *S. dulcamara* and more widespread infection of this species has been detected in the Thames and its tributaries, the Rivers Lea and Ray. A national survey of *S. dulcamara* plants in over 100 rivers in England, Wales and Scotland resulted in one further finding. Two infected plants in the River Witham in Lincolnshire were found and destroyed; intensive inspections revealed no further infected plants.

Intensive surveys of UK potato crops for both visual and latent infection resulted in only one further finding (in Berkshire in 1996). This was linked to irrigation from the Thames river system via the Colne and Wraysbury tributaries. In each case infection furthest upstream appears to coincide with outfalls of sewage works.

After the first UK outbreak was reported there came reports of outbreaks in Belgium in 1989, 1993 and 1994 and in the Netherlands in 1992 and 1995 (Anon., 1996a). The Belgian cases were all in a small area close to the Dutch border. Again they were linked to infected *S. dulcamara* plants in the watercourses used to irrigate potato crops. The 1992 Dutch report was of a crop grown from uncertified seed and has not been linked to irrigation. In 1995, Italy and Portugal reported cases of brown rot and both suggested links to seed potatoes imported from the Netherlands. In the same year France reported four foci of infection, two in glasshouse tomato crops, one in outdoor tomatoes and one in potato trial plots (Anon., 1996b). The latter was shown to be linked to irrigation from a stream now known to harbour infected *S. dulcamara*. In autumn 1995, 38 infested farms were found in the Netherlands and further surveys showed that more than 90 farms, including many seed potato crops, were infested.

POSSIBLE SOURCES OF INFECTION AND MEANS OF SPREAD IN EUROPE

World-wide spread of biovar 2 of *P. solanacearum* has long been associated with its dissemination in symptomless infected seed potato tubers (Hayward, 1991). It is likely that this was a major pathway by which the pathogen spread undetected within the Netherlands, eventually causing the widespread disease outbreaks reported in 1995. Outbreaks in Italy and Portugal in the same year were associated with the planting of possibly infected seed tubers. In contrast, potato brown rot outbreaks in Sweden, the UK, Belgium, France and in certain instances in the Netherlands have been associated with probable dissemination of the pathogen in surface waters used for irrigation of potato crops (Olsson, 1976a; Stead, 1996).

The finding of *P. solanacearum* in *S. dulcamara* in watercourses indicates a source other than seed potatoes. In Belgium, France and the UK infected *S. dulcamara* plants can be traced growing in watercourses up to points at which sewage effluent is introduced, but no further upstream (D Caffier, J Van Vaerenbergh, personal communications). There is thus strong circumstantial evidence that the pathogen has at least occasionally survived or bypassed sewage treatment. A likely source is infected ware potatoes. The European Union imports large quantities of ware potatoes from several countries where brown rot is known to occur. This source remains speculative, but the risks of pathogen spread from infected ware, e.g. during industrial washing and processing or domestic use, require careful assessment.

In the UK, surface water collected from rivers in which infected *S. dulcamara* was detected was shown to contain viable and virulent populations of *P. solanacearum* (J G Elphinstone, unpublished). Waterborne pathogen populations were not detected in rivers in which only healthy *S. dulcamara* was found. Regular sampling at single sites on different UK rivers has shown that populations fluctuate seasonally and with day of sampling. Maximum populations of 6×10^5 viable cells per litre of *P. solanacearum* biovar 2A were detected in late summer when temperatures favoured pathogen multiplication and *S. dulcamara* was actively growing. However, populations were rapidly diluted below detectable levels following heavy summer rain and during winter and spring months when water levels rose, temperatures dropped and *S. dulcamara* died back. In Belgium and the Netherlands similar results have been observed but the pathogen was detected earlier in the year (from May onwards) in water sampled from irrigation canals (J D Janse, J Van Vaerenbergh, personal communications). Under quarantine glasshouse conditions, potatoes irrigated with single doses of water containing 6 x 10 viable cells per litre become latently infected and in some cases have developed symptoms of bacterial wilt and brown rot disease in progeny tubers (J G Elphinstone, unpublished).

Preliminary work (J G Elphinstone, unpublished) has shown that successful infection of *S. dulcamara* requires relatively high temperature (> 15 °C) and inoculum density (> 10^4 viable cells per ml). It is difficult to hypothesise how *S. dulcamara* plants in watercourses were originally infected since there must be a low probability of these conditions arising. Dilution effects must be large and most consignments are imported during cold winter months. It is tempting therefore to believe that such events are rare, perhaps only occurring when sewage treatment is ineffective or when effluents have been discharged untreated. Original infection of *S. dulcamara* in a water course could have occurred some time ago, the pathogen surviving winters and being released from infected plants during the summer months when temperatures favour infection of other plants downstream. *S. dulcamara* plants can be long-lived and rarely show symptoms due to *P. solanacearum*. Thus, in time, the river system downstream of the introduction could become infested. Four northern European countries have independently found damaging outbreaks of potato brown rot since 1989, all of which are linked to irrigation from infested rivers. In only one of these countries have seed potatoes been infected, but the findings in the Netherlands have demonstrated only too clearly the risks involved once the pathogen enters seed multiplication schemes.

POTENTIAL FOR PATHOGEN SURVIVAL IN COOL ENVIRONMENTS

P. solanacearum survives best as a seed borne vascular infection in potato tubers. Under tropical conditions it has also often been considered a soil borne organism. However, the survival of biovar 2 of *P. solanacearum* in soil is strongly influenced by a number of interacting physical, chemical and biological factors. It is known that the organism persists longest, when protected from desiccation and antagonism by other micro-organisms, in environments such as alternative crop and weed hosts, self-sown volunteer potatoes (or groundkeepers), host debris or in the deeper soil layers down to at least 75 cm (Graham & Lloyd, 1979). Soil type is an important factor affecting survival (Moffet *et al.*, 1983; Prior *et al.*, 1993) and different soils may be conducive or suppressive to pathogen survival and/or subsequent disease development (Nesmith & Jenkins, 1985). Soil moisture also affects pathogen persistence (Moffet *et al.*, 1983) which tends to be longest in moist well-drained soil, but is inhibited by desiccation or flooding (Hayward, 1991). Extremes of soil temperature can inhibit survival of the pathogen, but persistence for well over 1 year was observed at 4 °C in naturally infested soil stored in plastic bags (Granada & Sequeira, 1983). In addition, *P. solanacearum* is also susceptible to antagonism by a number of common soil bacteria (Nesmith & Jenkins, 1985), the population dynamics of which are affected by all of the factors already mentioned.

Under temperate conditions in Australia, Kenya, Sweden and the UK, the bacterium could be detected in field soil for no longer than 2 years after harvest of potato crops affected by brown rot (Shamsuddin *et al.*, 1979; Harris, 1976; Olsson, 1976a; J G Elphinstone, unpublished). In the UK, this occurred despite high populations of *Solanum nigrum* weeds and potato groundkeepers in the outbreak fields during subsequent seasons. A low frequency of infection in groundkeepers was detected in the season following harvest of one UK infected potato crop but not in subsequent seasons despite extensive testing, whereas in Sweden infection was not detected in groundkeepers at all. Furthermore, planting of healthy potatoes in experimental plots within known infested fields in the UK did not result in infection in subsequent seasons. From this limited evidence, long term persistence in soil is unlikely to be a major factor in the establishment of the pathogen in cool climates. Further study over a wide range of soil types and climatic conditions will be required to substantiate this.

In cool conditions, infection of perennial weed hosts appears to be an important protected environment for pathogen overwintering and long term persistence. Infection of aquatic plants of *S. dulcamara* in watercourses was detected several years consecutively in Sweden (Olsson, 1976a) and the UK (Stead, 1996). Similar infections in this host have also been detected in watercourses used for irrigation at some outbreak sites in Belgium, France and the Netherlands (J Van Vaerenberg, D Caffier and J D Janse, personal communications). It is possible that these plants had been infected for several years.

In the cool temperate regions of Australia, another perennial solanaceous host not found in Europe (*Solanum cinereum*) was implicated in the overwintering of biovar 2 of *P. solanacearum*. However, several other weed species have been identified as potential European hosts following artificial inoculations under controlled conditions; although there is no evidence that they are infected naturally. These represent several families and include *Solanum nigrum, Eupatorium cannabinum, Tussilago farfara, Portulaca oleracea, Cerastium glomeratum* and *Ranunculus scleratus* (Olsson, 1976a and 1976b; Hayward, 1991; J G Elphinstone and P. M. Pradhanang, unpublished). Of these, *E. cannabinum*, *T. farfara* and *R. scleratus* commonly inhabit river banks. Other weed hosts may contribute to survival, but *S. dulcamara* in aquatic environments is likely to be the most significant in northern Europe.

EUROPEAN UNION LEGISLATION AND CONTROL MEASURES

European Union (EU) plant health legislation (Anon., 1995) lists *Pseudomonas solanacearum* (Smith) Smith as a harmful organism of quarantine concern to all Member States. Its presence or suspected presence must be notified to the responsible Plant Protection Organisation of the Member State concerned and confirmed infections must be notified to all Member States and measures applied to combat the infection. Potatoes marketed within the EU must be declared free from the organism and seed potatoes must originate either from an area free of the disease or from a place of production declared free. Potatoes imported into the EU must be certified free from the disease and must originate in an area where the organism is not known to occur.

Potato brown rot has been regularly intercepted in ware potatoes imported into the EU from certain Mediterranean countries and the various outbreaks of the disease have occurred despite these regulations. It has therefore been agreed that EU control measures relating to the disease must be strengthened. Measures under discussion relating to potato production include the following:

- routine surveys of seed and ware potato crops for symptomatic and latent infections.
- routine surveys of at risk water courses used for the irrigation of potato crops.

- derivation of seed potatoes from *P. solanacearum* tested lines.
- notification and immediate investigation of suspected infections combined with restrictions on the movement of suspect lots pending investigation.
- destruction of infected lots and restrictions on at risk lots.
- prohibition on the growing of potatoes on affected fields.
- restrictions on the growing of potatoes on other fields of an affected farm and decontamination of machinery.
- restriction on the irrigation of potato crops from contaminated watercourses.

Many of these measures were used by the Netherlands authorities as the basis for their containment and eradication programme following the findings in 1995. Because of the extent of the infections, the Netherlands also intensively tested all seed potatoes marketed in the country and also monitored ware potatoes. More than 50,000 tests for latent infection were made. Despite extensive monitoring of imported Dutch seed potatoes by other EU Member States in the 1995-96 import season, only two infections were confirmed.

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TEPHRITID FRUIT FLIES - A QUANDARY FOR INTERNATIONAL PLANT QUARANTINE

P W BARTLETT
Central Science Laboratory, MAFF, Sand Hutton, York, YO4 1LZ, UK

ABSTRACT

The World Trade Organization Agreement on the Application of Sanitary and Phytosanitary Measures obliges those concerned with plant quarantine to reconsider some of the assumptions made when imposing trade restrictive legislation. Present concerns about regulations intended to prevent the introduction of Tephritid fruit flies but which also have a cost to grower, trader, importer and the environment are discussed. These include eradication, treatment of fruit and the security standards demanded by importing countries. Regulation is justified, but perhaps not for all fruit flies, not on the present global scale and not always to the strict standards demanded for medfly (*Ceratitis capitata*).

INTRODUCTION

Hedley (1994) described how the signing of the Uruguay Round of the General Agreement on Tariffs and Trade had implications for international plant quarantine. This is via the World Trade Organization Agreement on the Application of Sanitary and Phytosanitary Measures, which requires that quarantine restrictions are applied only to the extent necessary to protect plant life or health, are based on scientific principles and are not maintained against scientific evidence. Bartlett (1994) described the concurrent developments in establishing a single market plant health regime for the European Union (EU). Earlier preparations for this revolution are described in Ebbels (1993).

In the past two years there has been progress and international dialogue on plant quarantine topics, especially through the Regional Plant Protection Organisations and the Food and Agriculture Organization (FAO) Committee of Experts on Phytosanitary Measures. Part of the framework for the future development of international plant quarantine regulations is now agreed and published by FAO as International Standards for Phytosanitary Measures. However, this dialogue has revealed misunderstandings between nations in the aims and implementation of plant quarantine, for example in how much protection is warranted, how this should be justified and the significance of trade interests in quarantine discussions.

THE FRUIT FLY PROBLEM

A wide range of organisms or trade pathways could be used to illustrate these issues, but this paper considers the control of Tephritidae fruit flies as a good example of the dilemmas confronting national and international plant quarantine legislators. Although fruit flies are not important pests in north-west Europe, their effects on fruit production and trade affect all consumers of fruit products.

A number of extensive reviews and conference proceedings illustrate why these pests are a problem. These include Robinson & Hooper (1989) and Aluja & Liedo (1993). The excellent and comprehensive work by White & Elson-Harris (1992) clarifies the classification, distribution and hosts whilst also describing adults and larvae. The family Tephritidae contains about 4,000 species arranged in 500 genera and the larvae of most species develop in the seed-bearing organs of plants. About 35% of species attack soft fruit and a further 40% develop in the flowers of Asteraceae. Most of the remainder are associated either with flowers or are miners in leaves, stems or roots. These authors list the problems caused by fruit flies as follows:

- They damage commercially produced fruit;
- Some species have become pests in regions far removed from their native ranges;
- Quarantine restrictions have to be imposed to limit further spread;
- Quarantine regulations can either deny a producing country a potential export market or force the producer to carry out expensive treatment.

This is a revealing assessment showing how in this case dissemination to new areas necessitates quarantine restrictions which impinge on the economy of crop production. This is the quandary for international plant quarantine, because quarantine should be part of the solution and not a problem. In such circumstances, the question of whether the potential damage by fruit flies justifies the quarantine restrictions imposed deserves consideration.

ECONOMIC DAMAGE IN NATIVE RANGES AND COLONISED AREAS

Some fruit flies are economically damaging because the larvae live within fresh fruit which are then unsaleable. There may be several generations per year and a number of larvae can inhabit a single fruit. However, the reviews quoted (Aluja & Liedo, 1993; Paull & Armstrong, 1994; Robinson & Hooper, 1989) rarely analyse the trade pathways or give sufficient details to provide suitable assessments of economic damage. O A Fernandes *et al.* (pp. 151-153 in Aluja & Liedo, 1993) estimated 1.5 million boxes of citrus were lost annually in Sao Paulo state, Brazil and S Vijaysegaran (pp. 455-463 in Aluja & Liedo, 1993) emphasises the value of fruit exports to some Asian countries (US$1 billion for Thailand in 1983), explaining that control of fruit flies is of primary importance, but no costs are provided.

However, direct costs of control may be small. In experiments in guava and mango orchards in Pakistan, Z A Qureshi & T Hussain (pp. 375-380 in Aluja & Liedo, 1993) compared mass trapping using six modified Steiner traps in five acres with two sprays of malathion per year. Both methods reduced the populations of *Bactrocera dorsalis* and *B. zonatus* to tolerable levels. Neither treatment appears excessive in comparison with those used for many other common pests and both are far less than is required for most quarantine control protocols. But control strategies have additional and sometimes hidden costs which include impact on beneficial organisms, enhanced pesticide resistance of target and non-target pests and other more generalised environmental effects. The latter have been recognised by the public in some areas, such as California, which has resulted in political resistance to control campaigns. Less noticeable but also important are the consequential restrictions on choice of cultivars, because plant resistance and fruit tolerance to treatments may have higher priority than yield, disease resistance, shelf-life or flavour.

Globally, the main economic impact is from semi-tropical fruit flies. The importance of the temperate species is more difficult to estimate. For example, the recent establishment of the North American species *Rhagoletis completa* and *R. indifferens* in Switzerland and northern Italy shows how easily introduced fruit flies can go undetected with little reported damage. In this case neighbouring countries have taken little official notice of the new situation in southern Europe. Baker (1991) modelled the risk of *R. cerasi* (which is well established in south and central European cherry orchards) establishing in south-east UK. He concluded that in three of the years between 1984 and 1990 the month of June was favourable for production of an indigenous generation but that there were some years which were much less favourable. Establishment was expected to be short-lived, as the climate in some years was sufficiently detrimental to eradicate the pest naturally. Although large numbers of larvae have been found in some imported consignments, adults have never been trapped in the UK.

ERADICATION

Introduction to new areas frequently necessitates extensive containment and eradication campaigns. A battery of control strategies are available for eradication, including detection, trapping, including selective trapping of males (R T Cunningham, pp. 345-351 in Robinson & Hooper, 1989), fruit sampling, chemical control with baits and sprays, and mechanical control by destroying unharvested fruit. Most sophisticated and probably the most expensive of all is the sterile insect technique, which requires culturing and controlled release of millions of sterile flies (J E Gilmore, pp. 353-363 in Robinson & Hooper, 1989).

Eradication campaigns in California, Hawaii, Japan, and Suriname against *Bactrocera cucurbitae, B. dorsalis, B. latifrons* and *Ceratitis capitata* are described in Robinson & Hooper, (1989) and Aluja & Liedo (1993). F Hentze *et al.* (pp. 449-454 in Aluja & Liedo, 1993) describes control of the complex comprising *Anastrepha* spp., *Taxotrypana curvicauda* and *C. capitata* in central America. According to Nilakhe *et al.* (pp. 395-399 in Aluja & Liedo, 1993) US$200 million have been spent in the USA during the past 60 years on eradication with US$10 million per year being spent on detection programmes. They estimate that if *C. capitata* were to become established, the annual cost would be between US$578 million to US$1,002 million in California alone.

THE MEDFLY PROBLEM

These estimates help to explain why *C. capitata* (medfly), alone of all of the Tephritidae, has a special place in the pest literature and as a quarantine problem. It is considered to be the most important pest of the fruit industry, attacking c. 200 species of fruit. Apparently originating from West Africa, it is established on all continents (except Antarctica) due to its adaptability and high reproductive rate (A J Schwarz *et al.*, pp. 375-386 in Robinson & Hooper, 1989). Entire symposia have been devoted to medfly. L E LaChance (pp. 389-394 in Aluja & Liedo, 1993) discusses the FAO/IAEA project in north Africa where in 1990 it was estimated that combined annual losses in Algeria, Libya, Morocco and Tunisia were US$28 million.

There are many papers on eradication and on methods of ensuring freedom from medfly in exports (Rossler & Chen, 1994). The programmes described are exceptional by any standards. In California the 1989-90 programme cost US$52 million (R Penrose, pp. 401-406 in Aluja & Liedo, 1993). Programme activities for the year included detection trapping with 45,000 traps over 3,336 square miles, dispersal of 228,000 gallons of malathion bait dispersed over 655 square miles and release of 6.6 billion sterile flies over 515 square miles. Fruit cutting, stripping and other quarantine arrangements were also required. Since its introduction in 1975, Guatemala and Mexico have operated medfly containment, barrier and eradication programmes (F Linares & R Valenzuela, pp. 425-438 in Aluja & Liedo, 1993). These are also very large programmes with 13,797 traps in Guatemala and 4,414 in Mexico requiring examination at least fortnightly. Since 1979 a sterile insect production factory has produced and released 500 million pupae per week, whilst another in Guatemala has produced 250 million weekly since 1986. Woods (this volume, Session 8D) discusses *C. capitata* containment and eradication in Australia, emphasising that although restricted to Western Australia its economic importance is increased because Japan does not recognise area freedom within Australia, thus affecting the economy of the whole continent. He confirms that medfly is more difficult to control than many other fruit flies.

Fear of introducing *C. capitata* (which is a high risk for Mediterranean and warmer climates, as illustrated above) has stimulated the adoption of stringent quarantine precautions. However, such quarantine measures, which are operated for many, if not all, other Tephritidae, cannot be justified by the evidence available. This action is comparable to prohibiting every species in the Chrysomelidae because *Leptinotarsa decemlineata* has proved destructive when introduced to new areas or, to use the more recent example of *Frankliniella occidentalis*, to suggest that all Thysanoptera should have high quarantine status. Experience has shown that neither action would be justified, although experience of these pests correctly signals the need for careful pest risk assessment of these groups.

THE PRESENT QUARANTINE SITUATION

Many countries impose severe restrictions on the import of fruit and some vegetables to prevent introduction of fruit flies. This approach is common, but Australia, Japan and the USA can be used as examples. Import of these commodities is prohibited so that an import permit is needed in addition to the phytosanitary certificate (PC) and control of the potential import is thus gained.

National quarantine requirements normally impose conditions on the exporter and these must be met before a PC can be officially issued. There are many variants of these requirements according to the quarantine risk: e.g. production in an area known to be free of quarantine pests, appropriate treatments, indexing, and/or visual freedom on inspection. On arrival in the importing country it is usual to carry out documentary checks and it is sometimes also considered necessary to inspect visually a sample of the consignment.

Import permits for fruit flies usually go further. During the growing season there can be requirements to show how area or orchard freedom is being verified, specification of the appropriate treatment which must be used and the efficacy that must be achieved, and details of how pre-export inspection is to be undertaken. During transportation, the packing, means of transport, and loading and unloading arrangements may all be stipulated. In-transit environmental controls may be required in addition to those needed for the safe delivery of wholesome food. The place of landing may be stipulated and there may be additional post-entry quarantines and indexing.

For many well established trades these requirements are so familiar that they go largely unremarked. The variety of disinfestation and in-transit treatments that have been developed is a tribute to scientific and technological ingenuity. Treatments in use include fumigation with methyl bromide (and other fumigants), insecticide or hot water immersion, high temperature forced air, vapour heat, cool or cold periods, quick freezing, controlled atmosphere, fumigation followed by refrigeration (or vice versa) and γ-irradiation. The possibility of using any one of these varies with the species of fruit fly and the genus, species and (in some cases) cultivar of the fruit (Armstrong, 1994; Meheriuk & Gaunce, 1994). The variety of treatments and outcome coupled with the withdrawal of the USA registration of ethylene dibromide in 1984 (an example which was followed by many other countries), together with the fact that continued use of methyl bromide cannot be guaranteed, means that considerable effort is currently being put into testing new treatment/host combinations. Many such experiments are reported every year, but few analyse the costs of industrial scale implementation and only a few suggest that savings would be likely compared with present systems.

It is notable that none of the reviews cited dwell on the costs of quarantine strategies which are borne by growers or by industry. In Aluja & Liedo (1993) the industrialists D E Buchinger (representing California fruit) and R Kinney (representing Florida citrus), mention costs only in passing. C Riherd (pp. 407-413 in Aluja & Liedo, 1993), when discussing the interception by Japan of *Anastrepha suspensa* on Florida grapefruits in 1974, values the lost trade at U$20 million per year (8 million cartons), but does not give costs of establishing and undertaking the quarantine treatments already required in some other southern states, nor of the long and complex work required to establish a fruit fly area freedom protocol which slowly permitted the trade with Japan to recommence.

Within Europe, costs of pre-export treatments have been estimated to be US$10 per tonne, but universal justification of such treatments in this trade seems doubtful. This estimate also excludes costs of growing crop treatments and inspection, which can be high for the official service, the trader, or both. In the UK at present, costs of moving containers for inspection are borne by the trade and plant health inspection costs are borne by the nation. The total cost of this activity varies considerably but for citrus it is more than US$10 per tonne. A hidden cost in this process is the breaking and re-establishment of the controlled atmosphere which is sometimes demanded by the trade end-user during shipment.

PROBIT 9, IMPORT SECURITY AND PATHWAY ANALYSIS

"Probit 9 treatments" are those established by test to give a mortality set at probit 9 security: a kill of 99.99683% (not more than 32 organisms surviving per 100,000 treated). This standard, set originally by the USDA during the 1930s (Baker, 1939), by default has become internationally recognised. It is now realised that this is an arbitrary level that does not take into account the degree of pest infestation in consignments, consignment size, or other factors affecting survival and establishment (e.g. likelihood of mating). Landolt *et al.* (1984) estimated that if a "probit 9 treatment" was applied to consignments comprising 36,000 grapefruit infested with one fly larva per 10 fruit, this would result in only one potential mating pair of adult flies per 312.5 consignments. Pathway risk analysis has been used more generally for some years in plant quarantine although (with only a few exceptions) there has been a tendency for it to be subjective. Probit 9 and its role within pathway analysis is being challenged and there are now attempts to introduce quantitative methods of estimating pest establishment (Whyte *et al.,* 1995; Yamamura & Sugimoto, 1995). In December 1995 statisticians and biologists met to discuss these inter-related problems and the resulting monograph will be published by the Horticultural Research and Development Corporation of Australia (HRDC).

It is difficult to judge the success of these quarantine efforts and to predict what might happen if they did not exist. Recently, the EU Plant Health Inspectorate has required notification of all pest interceptions. Interceptions by the trade occur, but they are rare. All the fruit commonly grown in the EU is subject to quality control standards including freedom from pests and diseases, and this extends to all imports. Although this is only a visual standard, it should eliminate any badly infested consignments. However, the introduction of fruit in international passenger baggage is not controlled. As this may come from either home gardens or the local market, it may be of poor quality in comparison with internationally traded produce. There is ample evidence that many fruit flies are introduced in this way. To counter this, countries such as Australia, Japan, New Zealand and the USA have very strict quarantine restrictions for fruit introduced in the baggage of international passengers.

REGIONAL SOLIDARITY

Political and not environmental boundaries have been used in plant quarantine to demarcate both export production areas which are believed to present a risk and to delineate areas justifying protection. For both statutory and control reasons this is justifiable and has only recently been questioned, most noticeably by the EU Commission when seeking justification for EU Protected Zones (ZP) (Bartlett, 1994). Consideration of ZPs shows that there may be a problem which is exacerbated when Regional Economic Integration Organisations (REIO) give priority to internal trading arrangements. These politically defined customs unions can be very large and biologically diverse. For example, both the USA and the EU extend from sub-Arctic to sub-tropical or Mediterranean zones. If all imports are to be free to move throughout these REIOs they must meet the standards required to safeguard the agricultural production of all parts of the region. It is questionable whether this arrangement should have priority over a trading arrangement which recognises ecological and therefore production differences. Similarly, it is questionable whether certain exports should be prohibited or subject to excessive control because only one part of a REIO is at risk. Double standards sometimes seem to be applied when the authorities of an importing country refuse to recognise that such ecological differences occur in an export area but, when it comes to their own exports, the same authorities demand recognition of their internal pest free areas.

The presence or absence of crops at a susceptible stage in the importing country at different times should also be taken into account. If they are not present throughout the year (which is frequently the case) then consideration should be given to relaxing or even removing safeguard measures during the part of the year when no crops are at risk. In the EU this is done for fruits of *Prunus*, which must be imported free from *Monilinia fructicola* only between 15 February and 30 September. However, no similar derogation is made for Tephritidae because of the long period during which fruit is produced.

A European solution

The European and Mediterranean Plant Protection Organisation (EPPO) has recently responded to the problems caused by the listing of all Tephritidae in some quarantine legislation and to the safeguards required for large areas of Europe where the risk is low. An EPPO Specific Quarantine Requirement is expected to advise limiting legislative controls to a few of the higher risk species. It will also recommend that controls are only imposed on the main hosts of each of these and that countries which are at low risk from semi-tropical Tephritidae may choose not to require a PC for fruit. As plants for planting are recognised as being a higher risk than fruit, the measures advised for them are more stringent and always include a requirement for a PC.

CONCLUDING REMARKS

In both international quarantine and in pest control more generally, fruit flies have a high profile. They are subject to a high degree of regulation at an economic, environmental and political cost which may have a disproportionate effect on developing countries, sometimes preventing them from participating in world trade. The highest quarantine risks are in moving either the organisms themselves (e.g. for scientific research) or together with their host plants. Science and trade demand movement of both these commodities and in these cases rigorous quarantine controls can often be justified.

Fruit is frequently transported long distances, often between continents. Life would be poorer if exotic fruits were not available and for the temperate zone this includes all *Citrus*. There is certainly a risk to the tropical and sub-tropical regions from exotic fruit flies and, to a lesser extent, there is also a risk to temperate regions from temperate fruit flies. But there seems to be little justification for the expensive and damaging arrangements which many temperate areas use to protect themselves from most fruit flies. There is also minimal evidence that the Draconian measures required to meet a probit 9 standard are justified for trade flows even into areas at risk. Quality standards backed up by simpler PC requirements should be sufficient. Further requirements may be justified for a few high risk genera including the "pulpy" fruits *Mangifera* and *Annona* and for some trade flows to high risk import areas within an exporting country.

The blunt instruments of prohibition and bilateral permit arrangements mentioned above to combat Tephritidae will be increasingly difficult to justify within the SPS Agreement by the 21st Century. Perhaps it is time to decrease the effort given to perfecting disinfestation techniques and instead to expand studies aimed at increasing knowledge of pest biology so that all can agree on which pests can be classified as high risk and what minimum safeguards are necessary to prevent their further dispersal. However, it is unlikely that there will be early international agreement on how to resolve these fundamental differences. Fruit flies will remain a problem which will be solved only slowly by increased co-operation between plant health authorities.

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