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PRACTICAL SECTION FOR GROWERS

SCOPE AND OBJECTIVE

Onion thrips (*Thrips tabaci*) is the most important pest of leeks in the UK. It may attack other *Allium* crops, particularly salad onions. Despite the fact that several sprays of insecticide may be applied, growers in many areas obtain very poor levels of control. In addition, most of the insecticides that can be used are organophosphorus products, which are subject to the MAFF/PSD review of anticholinesterase compounds.

The purpose of this project is to evaluate previous research on the biology and control of thrips on leeks and other *Allium* crops and to make recommendations for future research and development work to improve thrips control in the UK. It will indicate whether there are techniques that could be developed for use by UK growers which would lead to a better use of resources and improved targeting of insecticide treatments.

SUMMARY

- *Thrips tabaci* is the main pest of leeks and onions in the UK. It has been studied most intensively on leeks in France, the Netherlands and Germany and on bulb onions in the USA. *Thrips tabaci* is also an important pest of cabbage. Several studies on this crop contain information relevant to *Allium* crops.

- Onion thrips overwinter on a range of host plants (cereals and *Allium* crops included) and in plant debris. In France they overwinter in both the adult and larval stages, whereas in the Netherlands they overwinter as adults only. Onion thrips are able to reproduce on their overwintering hosts in the spring, before migrating to new crops. Movement into new crops may be triggered by the senescence or harvesting of alternative hosts.

- In Europe, the timing of immigration into *Allium* crops has been studied most intensively on leeks in France, where there appear to be four periods of migration, the main period being in late July–August. The main period of migration appears to occur at the same time in most northern European countries. In France, researchers have used a day-degree model developed previously in the USA to predict periods of immigration. They consider that this provides a useful warning of the risk and timing of thrips invasions.

- Several research groups have developed onion thrips management systems based on crop sampling and the use of treatment thresholds. Large samples are required to estimate infestation levels accurately and destructive samples are far more accurate than visual assessments of thrips numbers or damage. However, such sampling is time-consuming and may be done too infrequently to detect the initial increase in thrips numbers. In France, researchers have developed an action threshold based on adult trapping to initiate a programme of insecticide sprays. They found that a threshold of 10 thrips/trap/day ensured that onion thrips infestations could be kept under control.

- There are several reasons for poor insecticidal control of thrips on leeks and onions. They include 1) a lack of effective insecticides, 2) inaccessibility of thrips adults and larvae to insecticides when they are hidden within the leaves of a plant, 3) inaccessibility of the egg and pre-pupal/pupal stages to insecticides and 4) poor timing of treatments, often due to the difficulties of seeing and identifying such small insects.

- Insecticidal control could be improved by the use of systemic insecticides. Two insecticides with systemic action (fipronil and imidacloprid) have been evaluated in trials in the Netherlands, France and the UK. The amounts applied to leek seed appeared to provide effective control for several weeks, although not in every trial. Fipronil seemed to be more effective than imidacloprid. The amounts of fipronil and imidacloprid permitted as film-coatings on salad onions may be too low to provide control.

- Even if fipronil and imidacloprid seed treatments are granted Specific Off-Label Approval for use on leeks, additional foliar spray treatments may be required to maintain levels of control. Thus it will be still be necessary to monitor the crop to determine when additional treatments are necessary.

- Of the insecticides evaluated as foliar sprays in the UK, chlorpyrifos appears to be the most effective. Pyrethroid insecticides can be effective also against thrips and alternatives to deltamethrin may be worth considering. Abamectin, an insecticide isolated by fermentation of *Streptomyces avermitilis*, is another possibility.

- Alternative cultural control methods for thrips include crop covers and reflective mulches. Crop covers have been shown to provide some thrips control and are recommended for protecting leeks during propagation in France. Reflective mulches have not been tested extensively.

- Undersowing leeks with clover may be a way of reducing onion thrips immigration into the crop. However, inter-specific plant competition reduces yield and the undersown crop would have to be managed to counteract this effect.

- Thrips are susceptible to rainfall and irrigation. Regular overhead irrigation is recommended for reducing thrips populations in France, in conjunction with foliar sprays of insecticide.

- Predators, parasitoids and disease can reduce natural thrips infestations. The most promising biological control agents would appear to be entomopathogenic fungi. Their use in field crops has not been investigated extensively. Fungal control of *T. tabaci* may have potential, but it is probably worth waiting for mycopesticides to be developed further on other crops, before attempting to transfer the technology to *Allium* crops.

- Host plant resistance has been assessed in both leeks and bulb onions. In onions it is associated with particular characteristics such as glossy leaves. Even partial resistance to onion thrips would be a useful component of an integrated control strategy.

- If further studies are to be undertaken, then careful monitoring of onion thrips populations should form part of the work. Experimental results on the performance of insecticides and other control methods could then be related to the size of the thrips infestation during the period when the treatments were applied. The data could be used also to validate the previously developed forecast of onion thrips immigration.

ACTION POINTS FOR GROWERS

There are several reasons for poor insecticidal control of thrips on leeks and onions. They include:

1) a lack of effective insecticides
2) inaccessibility of thrips adults and larvae to insecticides when they are hidden within the leaves of a plant
3) inaccessibility of the egg and pre-pupal/pupal stages to insecticides
4) poor timing of treatments, often due to the difficulties of seeing and identifying such small insects.

- Insecticidal control of adult and larval thrips could be improved by the use of systemic insecticides. Two insecticides with systemic action (fipronil and imidacloprid) have been evaluated as seed treatments in trials in the Netherlands, France and the UK. The amounts applied to leek seed appeared to provide effective control for several weeks, although not in every trial. Fipronil seemed to be more effective than imidacloprid. The amounts of these insecticides permitted as film-coatings on salad onions may be too low to provide effective control.

- Even if fipronil and imidacloprid seed treatments receive Specific Off-Label Approval for leeks, additional foliar spray treatments may be required to maintain levels of control. Thus it will still be necessary to monitor the crop to determine when additional treatments are necessary. Alternative insecticides to be considered as foliar sprays include pyrethroids other than deltamethrin, and abamectin.

- Accurate timing of treatments will continue to be a necessary part of thrips control. Its importance has been emphasised by studies in France. Practical methods for forecasting and monitoring thrips infestations should be developed to determine when foliar spray treatments should begin and when they should stop. It is also important to adhere to ICM principles and to apply treatments only when necessary, to reduce environmental damage and avoid the development of insecticide resistance in onion thrips and other pest insects.

- Of the cultural and biological control techniques tested, the use of overhead irrigation is the easiest to evaluate and implement in the short term. Regular irrigation is recommended for reducing thrips populations in France, in conjunction with foliar sprays of insecticide.

- If further studies are to be undertaken, then careful monitoring of onion thrips populations should form part of the work. Experimental results on the performance of insecticides and other control methods could then be related to the size of the thrips infestation during the period when the treatments were applied. The data could be used also to validate the previously developed forecast of onion thrips immigration.

BENEFITS

Thrips cannot be controlled effectively with the insecticides available currently and thrips damage invariably reduces crop quality. The UK crop of leeks and salad onions is worth about £50M annually. If the results of the project were to reduce crop losses by 1% then the cost benefit ratio would be £5,000/£2.5M or 1:500 over a period of five years.

- The project will increase leek and onion growers' knowledge of thrips biology and help them to plan a strategy for thrips control.
- It will indicate whether there are techniques that could be developed for use by UK growers which would lead to a better use of resources and improved targeting of insecticide treatments.
- This should in turn lead to a reduced number of supermarket rejections of produce damaged by thrips.
- Large numbers of insecticide sprays may be applied for thrips control. Pest management systems, which lead to targeted applications of lower numbers of sprays, would be favoured highly by consumers and would have considerable benefits for the environment.
- Information from this project will be used to develop proposals for field trials to develop techniques for improving thrips control in the UK.

SCIENCE SECTION

INTRODUCTION

Onion thrips (*Thrips tabaci*) is the most important pest of leeks in the UK. It may also attack other *Allium* crops, particularly salad onions. In 1995, approximately 54% of the area of *Allium* crops treated with insecticides was treated for thrips (Garthwaite *et al.*, 1997). Despite the fact that several sprays of insecticide may be applied, growers in many areas obtain very poor levels of control. In addition, most of the insecticides that can be used are organophosphorus products, which are subject to the MAFF/PSD review of anticholinesterase compounds.

Thrips tabaci is an important pest in other parts of the world and a considerable amount of research has been done on onion thrips biology and control. Apart from evaluating a range of insecticide treatments, researchers have attempted to forecast onion thrips attacks and to adopt systems of supervised control. In addition, experiments have shown that there may be scope for reducing thrips populations considerably using cultural control techniques such as undersowing. There may also be possibilities in the future for biological control.

At present there is some ongoing HDC-funded work on insecticidal control but other techniques are not being considered. Before proposals are made for further experimental work, there is a need to assess the results of past work, particularly from overseas, and relate it to environmental conditions and commercial practice in the UK.

The purpose of this project is to evaluate previous research on the biology and control of thrips on leeks and other *Allium* crops and to make recommendations for future research and development work to improve thrips control in the UK. It will indicate whether there are techniques that could be developed for use by UK growers, which would lead to a better use of resources and improved targeting of insecticide treatments. Detailed objectives are to review the results of research to:

1. Indicate possible methods of improving insecticidal control of thrips on *Allium* crops.
2. Propose improved methods of targeting treatments – forecasting, monitoring, treatment thresholds.
3. Determine the likely impact of techniques of cultural and biological control.

LITERATURE REVIEW

Biology and life-cycle

Thrips tabaci infests many crops in the UK including onions, leeks, leaf and root brassicas, spinach and sugar beet. It is thought to have originated in the eastern Mediterranean region from where its preferred host plant, onion, (*Allium cepa*) originated (Mound, 1997). However, it is now distributed almost worldwide, and is parthenogenetic over much of its range (Waterhouse & Norris, 1989). *Thrips tabaci* is an interstitial dweller and remains hidden in the host plant except before flight or in sunny weather (Lewis, 1973).

Waterhouse & Norris (1989) give a detailed description of the development stages of *T. tabaci*. It develops through two larval instars, a quiescent pre-pupal stage and a pupal stage. These stages are of similar general appearance to adults, but without functional wings. The egg is minute and kidney-shaped. On reaching a host plant, each female lays up to 100 eggs (see Waterhouse & Norris, 1989) in slits made by the ovipositor in the plants' soft tissues. The head end projects slightly to facilitate larval emergence. The larval period may last only 4-7 days in the UK (Edwards & Heath, 1964; Hill, 1985).

After the second moult, larvae develop the short wing sheaths of the pre-pupal stage. Thrips larvae conceal themselves, usually in debris or in the surface layers of the soil, before changing to pre-pupae, although they may sometimes remain on the host plant. In France, Thicoipe (1990) found only 5 pupae/pre-pupae out of the total of 12,839 *T. tabaci* that he sampled from leek plants, the remainder being adults or larvae. After about two days, pre-pupae change into pupae, which remain where the pre-pupa developed. These stages do not feed. Pre-pupae and pupae together require about 6 days for complete development, after which the adults emerge.

The number of generations varies greatly. In the UK, although each generation may be completed in less than three weeks, there are usually two generations only each year (Edwards & Heath, 1964).

Damage

Thrips tabaci adults and larvae puncture cells in the leaves and suck up the sap (Mound, 1971). The empty cells show a silvery mottling or blotching on the affected surfaces. These blotches later turn yellow in colour and affected tissues dry out or become mottled with fungal growth. Leaves may twist, crinkle and curl, or even die if heavily infested.

Sites *et al.* (1992) studied the distribution of *T. tabaci* on onion plants. No thrips were found in the bulbs. Adult *T. tabaci* were most numerous on the basal half of onion leaves. However, as the season progressed, the proportion found on the apical half of the leaves increased. Early in the season, immature thrips (not identified to species) were most numerous on the neck and basal half of each leaf, but later on, the proportion found on the apical half of each leaf increased.

Thrips damage may affect the yield of bulb onions. Studies in the USA on the effect of thrips on different onion growth stages showed that infestation with *T. tabaci* affected yield only during bulbing (Kendall & Capinera, 1987). The percentage yield reduction varied considerably between experiments.

On leek plants, onion thrips larvae are generally more numerous than adults and cause most plant damage (Theunissen & Schelling, 1996). Both stages feed within the shaft of tightly packed leaves, until the population becomes so large that larvae and adults are forced to feed on the exposed, green leaves (Theunissen & Legutowska, 1991b). Damage symptoms become visible on leeks only as the plant grows and hence should be related to the size of the thrips population at an earlier date (Theunissen & Legutowska, 1991a; Theunissen & Schelling, 1996).

Overwintering biology

During the autumn in the Netherlands, *T. tabaci* larvae disappear from plants and consequently the proportion of adults increases (Theunissen & Schelling, 1996). Although migration ceases, the numbers of adults decline gradually through the winter months (Theunissen & Schelling, 1996), presumably as a result of mortality (Waterhouse & Norris, 1989). Overwintering adult *T. tabaci* emerge in the early spring, having spent the winter in a quiescent condition (Straub & Emmett, 1992). There is no true diapause (Waterhouse & Norris, 1989).

Onion thrips' overwintering sites have been investigated extensively in the USA. During the winter months in Texas, *T. tabaci* adults were found in soil, as well as on alfalfa and winter wheat (Chambers & Sites, 1989). Some immature thrips were found also, but were not identified to species. In contrast, in New York State, soil did not appear to be an overwintering site. Here, adult *T. tabaci* overwintered on winter wheat, alfalfa and weedy vegetation (North & Shelton, 1986a). Larvae did not survive the winter.

In a later study in North Carolina, Cho *et al.*, (1995) sampled wild and cultivated plants, grass and wood litter, and soil. Few adult *T. tabaci* were collected from the plants and very few thrips were recovered in soil samples. The largest numbers of *T. tabaci* were recovered from grass and wood litter. The authors suggested that litter might provide greater protection from low temperatures and rainfall than standing plant hosts. Overwintering adults were mainly female.

In Europe, the overwintering biology of *T. tabaci* has not been investigated in such detail. However, Villeneuve *et al.* (1996; 1997) observed that both adult and larval thrips overwintered on various plant species in the Basse-Normandie region of France, whereas in the Netherlands, *T. tabaci* overwinters only in the adult stage (J. Theunissen, personal communication). Weather conditions determine the level of mortality each season (Villeneuve *et al.*, 1999). Overwintered leeks may be a primary overwintering site for this pest (Villeneuve *et al.*, 1997; J. Theunissen, personal communication).

Alternative hosts and infestation of new crops

In the spring, female *T. tabaci* were capable of ovipositing on the crops on which they had overwintered. In greenhouse tests, the highest rate of reproduction was on wheat, followed by alfalfa and oats. Oviposition on all other crops was relatively low (North & Shelton, 1986a). Shelton (1995) concluded that in New York State, winter wheat is probably the main crop harbouring *T. tabaci* prior to their movement into new crops.

In New York State, fluctuations in onion thrips abundance were attributed to changes in habitat structure, for example, senescence in wheat and oats, and cutting in alfalfa and clover (Shelton & North, 1986). North & Shelton (1986b) observed that there was a clear relationship between flights of *T. tabaci* from field crops and their oviposition on cabbage. As adult *T. tabaci* moved from each field crop, they colonised cabbage and started to reproduce.

In Austria, peak flight activity coincided with the rape harvest, but occurred well before the cereal harvest (barley, wheat & rye). Kahrer (1994) concluded that *T. tabaci* does not develop on cereals prior to the period of peak flight activity.

Thrips tabaci is a pest of cotton in Australia (Milne & Walter, 1998a). Reproductive *T. tabaci* were found on the flowers and leaves of wheat and several common weed species and it was assumed that *T. tabaci* migrated onto cotton from these hosts. Milne & Walter suggested that cotton seedlings are a minor host for *T. tabaci*, but that they are damaged because irrigated cotton crops are the only hosts available once other host plants have senesced. *T. tabaci* can feed on mite eggs on cotton (Milne & Walter, 1998b), which may supplement an inadequate plant diet.

Timing of infestation

Thrips fly weakly, but may be carried great distances on air currents. Greatest displacements of *T. tabaci* populations occur by mass flights, which are initiated when weather conditions are suitable (Waterhouse & Norris, 1989). Most temperate species of thrips can take off when temperatures reach 17-21°C (Lewis, 1997a), although Waterhouse & Norris (1989) indicated that *T. tabaci* required air temperatures of 26.5°C and above to initiate flight. This means that provided temperatures are high enough, adults that emerge from pupae the previous day, or overnight, are usually ready for take-off as soon as the threshold is reached the next day. Direct rain and heavy dew prevent take-off because the wing setae become clogged and small species cannot overcome the surface tension of water droplets (Lewis, 1997a).

The phenology of *T. tabaci* has not been recorded in detail in the UK. In a field trial in Cambridgeshire in the UK, the first adult thrips were detected in a leek crop on 23 June and using a range of treatment thresholds triggered by thrips' presence, Umpelby (1995) applied sprays from mid July until mid September.

It is likely that the pattern of infestation of *Allium* and other crops in the UK is most similar to that in other north European countries. In the Basse-Normandie region of France, data from sticky traps indicated that there was one large flight period, and that this occurred in late July – early August, the main risk period being 25 July – 10 August (Villeneuve *et al.*, 1996; 1997). Smaller numbers of *T. tabaci* were caught before and after this period, when there were still sufficient thrips to cause damage to certain leek crops. These smaller 'flights' occurred in May, at the end of June and in October (Villeneuve *et al.*, 1999). The first adults were observed during the same period in several other regions in France (Villeneuve, 1995). Within an area, a similar pattern of activity was recorded over the three years of the study. However, the numbers of thrips captured were highly variable. From their monitoring data Villeneuve *et al.* (1997) observed that there was an interval between adults arriving on the plants and an increase in larval numbers.

In France, large numbers of thrips were found on leek plants from the end of July until early August and this corresponded to the period of intensive flight activity. Following the initial immigration period, the original adults died and their larval progeny pupated. A second peak of adults and another peak of larvae followed. After that the population declined gradually (Villeneuve *et al.*, 1996).

In Belgium, flight activity of *T. tabaci* was monitored in 1998 and 1999, to obtain more information about periods of infestation in cabbage (F. van de Steene, personal communication). Peak flight activity occurred from 14-28 July 1998 and from 20 July-10 August 1999.

In Germany, *T. tabaci* numbers started to increase in leek plots during late June – early July. Peak numbers of infested plants were found usually in early August (Hommes, 1992). *Thrips tabaci* was active at a similar time of year in the Netherlands (Theunissen & Legutowska, 1991a), but immigration into cabbage crops occurred earlier in Austria (Kahrer, 1992; 1994). Here there were clear peaks of flight activity, which occurred on 29 June 1990, 13 July 1991, 4 July 1992 and 12 June 1993. The period of flight activity lasted for 10-20 days.

In New York State, Shelton *et al.* (1987) found that there was temporal and spatial variation in the invasion of onions from early season crops, so some fields were infested when plants were young and others when plants were older. Similar results were obtained for cabbage (North & Shelton, 1986c). Temporal differences in the abundance and species composition of thrips depended on the spatial relationship of cabbage fields to cereal and forage crops, and to when these crops senesced or were harvested.

Effect of temperature on development and forecasting periods of attack

Destructive infestations of *T. tabaci* are favoured when mean daily temperatures are > 14.4°C (Harding, 1961).

The duration of the pre-oviposition, egg and larva-adult stages of *T. tabaci* were determined under constant and fluctuating temperature conditions in the USA (Edelson & Magaro, 1988) and used to develop a day-degree model for predicting development in the field. The relationships they determined between the duration of each stage and temperature are shown in Figure 1. It was estimated that *T. tabaci* required 191 D° above a base temperature of 11.5°C to develop from an egg to an ovipositing adult female. Under fluctuating temperatures in the greenhouse, development took 228 D°, a difference of 37 D°.

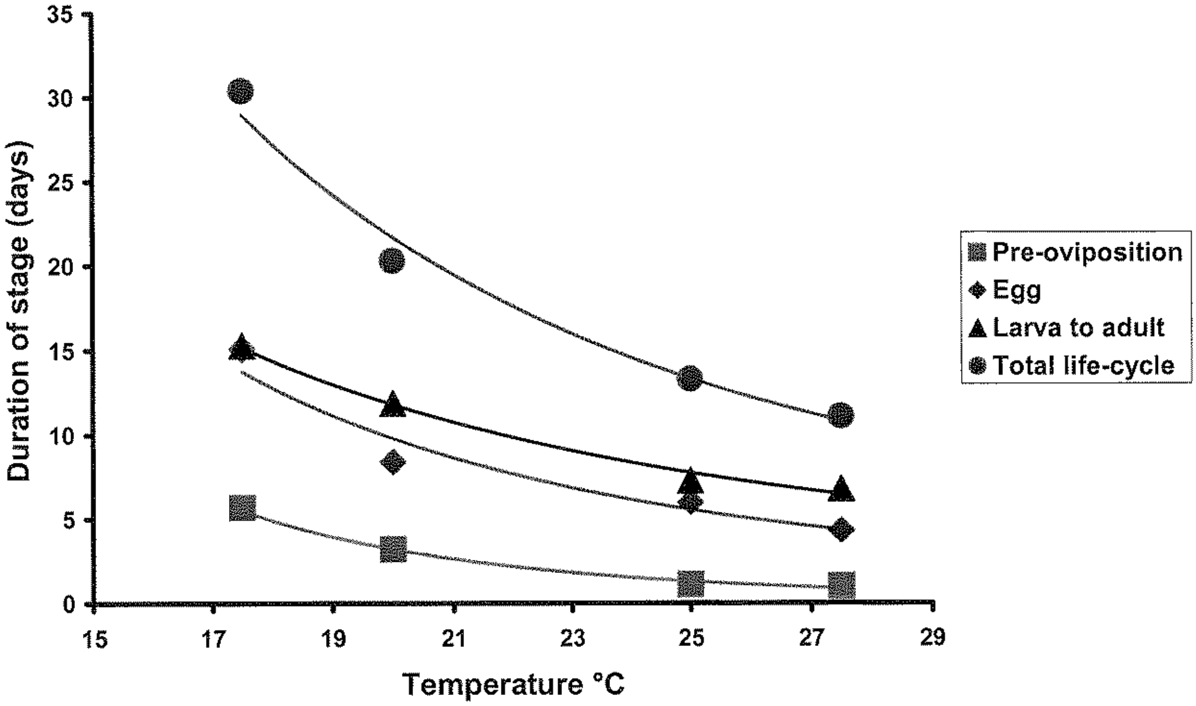
Edelson & Magaro (1988) compared their findings with the small amount of data published previously and found broad agreement. As yet, there is no evidence to suggest that the relationships between development rate and temperature vary between *T. tabaci* populations. *Thrips tabaci* does not appear to vary throughout its geographical range. This is in contrast to western flower thrips (*Frankliniella occidentalis*), which probably exists as more than one biotype (Mound, 1997). However, no specific studies have been made on development of *T. tabaci* in the UK.

Villeneuve *et al* (1996) made attempts to relate the data collected in leek fields in Basse-Normandie to accumulated day-degrees. They calculated accumulated day-degrees above a base temperature of 11.5°C from 1 January each year, to determine when population peaks could be expected, using the 228D°/generation and 133 D° for development from larva to adult, estimated by Edelson & Magaro (1988) for development under fluctuating temperatures. Both adult and larval onion thrips were included, as preliminary observations had shown that both stages overwinter on various plant species in this area. The model indicated that there would be two periods of adult emergence, the first at the end of June and the second between 20-25 July. In 1995, the timing of thrips captures on the traps agreed closely with that predicted by the forecast. Overwintering larvae became adults towards the end of June and gave rise to the first peak of adult emergence. A second generation that developed from the progeny of overwintering adults was expected towards the end of July and this was confirmed by sticky trap captures. Although agreement was good in 1995, subsequent studies showed that the discrepancy between observed and forecast activity could sometimes be as much as 10 days (Villeneuve *et al.*, 1999).

Using air temperatures recorded in the UK, and the day-degree sums calculated by Edelson & Magaro, it is possible to estimate the dates on which thrips activity would have been expected. For example, in 1997, the first peak of activity (after 133 D°) would have been expected on 8, 10 and 14 June at HRI Wellesbourne, Kirton and Stockbridge House respectively, whilst the second peak (after 228D°) would have been expected on 8, 9 and 16 July.

Sites and Chambers (1990) estimated that spring development of *T. tabaci* on the Texas South Plains required 88 D° (day-degrees) above a base temperature of 6.67°C.

Figure 1. The effect of temperature on the development of *Thrips tabaci*. Data from Edelson & Magaro, 1988.



Monitoring thrips numbers

Changes in onion thrips numbers can be monitored by capturing adults on traps or by recording the numbers of adult and larval thrips found on plants. Some of the advantages and disadvantages of the various sampling techniques have been summarised by Villeneuve *et al.* (1999).

Traps

Thrips may be captured using sticky traps, water traps or suction traps. Suction traps are expensive and require a power supply, so are impractical for routine crop monitoring. In general, they are used only for scientific studies.

Sticky and water traps can be used to monitor seasonal changes in thrips numbers. However, trap catches should be interpreted with caution when trying to relate them to infestation levels in surrounding crops (Umpelby, 1995; Villeneuve, 1995; Villeneuve *et al.*, 1999). In addition, it may be difficult to identify thrips to species when examining sticky trap samples. Although *T. tabaci* was the most numerous species on sticky traps in a leek crop in the UK, several other species were captured. For example, on one sampling date, 6% of the catch consisted of grain thrips (Umpelby, 1995).

Adult *T. tabaci* are attracted visually to coloured traps (e.g. sticky and water traps). Terry (1997) summarised the behavioural responses of *T. tabaci* and other thrips species to a range of colours. *Thrips tabaci* was attracted in highest numbers to yellow, blue and white (with a low UV content), whilst red and black were the least attractive colours. In France, light blue sticky traps were used to monitor adult thrips (Villeneuve *et al.*, 1996), because researchers found that this colour was more attractive to *T. tabaci* than the other colours tested (Villeneuve, 1995). Shelton & North (1986) and Kahrer (1992; 1994) used white sticky and water traps respectively.

Lewis (1997b) suggested that in the open field, cylindrical sticky traps might be more effective than flat ones because the airflow around them is less turbulent and because they catch insects blown from all directions. However, most of the sticky traps used in practice have been flat, although Wolfenbarger & Hibbs (1958) and Shelton & North (1986) used cylinders to monitor *T. tabaci* in onion and cabbage fields respectively.

In the UK, a range of sticky and water traps was evaluated in commercial leek crops (Umpelby, 1995). The traps were blue, white or yellow in colour. Net covers (two mesh sizes) were used with some traps in an attempt to exclude larger insects and make them more selective for thrips. Umpelby concluded that yellow sticky traps covered with a fine opaque mesh were the easiest to use in the field. The numbers of thrips caught on traps were higher generally than those found on plants, except at low infestations, when numbers were similar.

Several researchers have studied the response of thrips species to plant volatiles. The results of these studies have been summarised by Terry (1997). *T. tabaci* was attracted to varying degrees by ethyl nicotinate, anisaldehyde and benzaldehyde. Attempts have been made to improve trap captures of other thrips species by using attractive odours, but the results have been variable (Terry, 1997).

Sampling plants

Edelson (1985) compared two sampling methods for *T. tabaci* in onions. He related counts made in the field to records of absolute numbers obtained in the laboratory, using heat to drive the thrips out of leaf samples. He concluded that visual counts of thrips on onion leaves provided a feasible method of estimating absolute numbers. This is more difficult with leeks, since most thrips are hidden between the leaves in the upper part of the shaft. Although some thrips can be seen on plants *in situ* in the field, total numbers can be determined only by removing the leaves carefully (Theunissen & Legutowska, 1991a).

Theunissen & Legutowska (1991a) evaluated three methods of assessing thrips populations in leeks, 1) determining the percentage of plants showing fresh feeding damage, 2) counting thrips by dissecting a sample of plants and 3) recording the percentage of sampled plants found infested by thrips after dissection. They estimated that it would take 20-30 minutes to record accurately the numbers of thrips on an individual plant. In a later study, Theunissen & Schelling (1996) made visual inspections of plants *in situ* to estimate the percentage of plants infested. Destructive samples taken subsequently showed that a correct visual assessment was made on only 4% of the plants inspected.

In France, thrips were extracted from leek plants using Berlese funnels (Villeneuve *et al.*, 1996). Cut leeks were enclosed in a cylinder and a cloth soaked in turpentine was fixed beneath the top of the cylinder. The turpentine odour drove the thrips down through the samples and into a collection tube containing a 10% solution of alcohol. The thrips were then identified and counted. Villeneuve *et al.* (1999) found that thrips counts using this technique consistently underestimated the population present in leeks.

Sample size

Traps

The numbers of traps used to monitor adult thrips ranged from 2-5/field (North & Shelton, 1986c; Kahrer, 1992; Villeneuve *et al.*, 1996). No details are given about why particular numbers of traps were used.

Plants

The number of plants sampled to estimate the size of a thrips infestation should depend on the within-crop distribution of thrips and on the level of accuracy required. Several researchers have attempted to determine the distribution pattern of thrips within leek and onion fields (Suman *et al.*, 1980; Srinivasan *et al.*, 1981; Edelson *et al.*, 1986; Shelton *et al.*, 1987; Theunissen & Legutowska, 1991a; Fournier *et al.*, 1994). Most studies showed that thrips were aggregated when a single plant was considered as the standard sampling unit. According to Theunissen & Legutowska (1991a) the distribution of thrips larvae is more aggregated than that of adults.

On onions, Suman *et al.* (1980) found that the distribution of *T. tabaci* could be described adequately by a negative binomial distribution. However, Srinivasan *et al.*, (1981) found that the negative binomial distribution did not fit the data they collected and thought that this might be due to the higher density of thrips. Edelson *et al.* (1986) evaluated the dispersion characteristics of *T. tabaci* and found that populations became overdispersed as the density increased above one thrips/onion plant.

Shelton *et al.* (1987) examined the spatial distribution of *T. tabaci* in onions, by sampling 6 fields, each on one occasion. They concluded that although there were 'hot-spots' along field boundaries in some fields, the distribution throughout the field was essentially random. However, there is little evidence for this, other than visual assessment of the data and no formal statistical analysis was made of spatial pattern.

Theunissen & Legutowska (1991a) sampled a single field of leeks on several occasions. Sampling was non-destructive and assessments were made of fresh symptoms of onion thrips feeding damage, rather than thrips presence or numbers of thrips. They observed that the dispersion of feeding symptoms in the field showed a more or less random pattern in the beginning, but that immigrating onion thrips sometimes preferred a particular part of the field, causing an increasingly clustered dispersion of symptoms. This changed gradually to a uniform distribution of infested plants at high population densities. No data were presented to support these observations.

In addition, Theunissen & Legutowska determined the relationship between the mean number of thrips/plant, the percentage of infested plants and the percentage of infested leaves. Even at quite low thrips populations the percentage of infested plants increased rapidly (>50% plants infested at a mean level of 1-2 thrips/plant). No more than 40% of the leaves was infested regardless of the population level, indicating a preference for certain leaves.

Fournier *et al.* (1994) sampled 10 onion fields over a period of two years, with each field being sampled on 6-13 occasions. Each field was divided into five regions (four edges and the middle) and a random sample of 50 plants was taken across the whole field. A non-parametric statistical test was used to determine spatial effects. On some occasions, there appeared to be differences in infestation levels in different areas of the crop, but these were not consistent, either within or between fields.

Sampling plans
In India, Suman & Wahi (1981) developed a sequential sampling plan for *T. tabaci* in onions. This was based on the fitted negative binomial distribution (Suman *et al.*, 1980) and the numbers of thrips/plant were assessed. No validation data were presented in the paper.

Shelton *et al.*, (1987) developed a sequential sampling plan for *T. tabaci* in onions where decisions were based on a minimum sample size of 15 plants and a maximum sample size of 50 plants. Five plants were sampled at each of up to 10 sites along a V-shaped transect through the field, to fit in with simultaneous sampling for *Botrytis*. This type of sampling plan is adequate, provided the spatial distribution of thrips is truly random (A. Mead, personal communication). A threshold of 3 thrips/leaf was used, so that the number/plant varied with plant size, and hence different sampling charts were used for different stages of crop growth. Treatment decisions were reached in 88% of field inspections after looking at only 15 plants, and only 3% of inspections required a sample of 50 plants to reach a decision. Of 235 occasions where scouts reached a treatment decision based on both sequential sampling and a fixed-size sample of 50 or 100 plants, 95% of the decisions made were the same.

Hommes (1992) sampled five leek plants at each of 10 points distributed regularly over a plot. Each plant was inspected carefully for thrips. The proportion of plants infested with thrips was used in conjunction with tolerance levels to make spray decisions.

Fournier *et al.* (1994) considered two sequential sampling approaches, one based on counts of thrips/plant and the other based on binomial data (presence/absence), where presence was defined as more than 5 thrips/plant. Protocols were developed for two different economic thresholds – 0.9 thrips/leaf and 2.2 thrips/leaf. The maximum sample size in each case was calculated as a function of the thresholds, with no decision being made until at least 10 plants had been sampled. With neither approach was it obvious what should happen if the maximum sample size was reached before a decision could be made. The presence/absence approach required smaller samples and less time was spent inspecting each plant, since once five thrips had been found on a plant the inspection was complete. For the count-based approach, sequential decisions were compared with the results from a corresponding fixed-size sample of 100 plants, and for only 2% of samples was an incorrect sequential decision reached. The maximum sample size (40 - 60 plants) was reached for 8% and 14% of samples at the 0.9 and 2.2 thrips thresholds respectively. Maximum sample sizes for the binomial approach were much smaller than for the count-based approach, but at the lower threshold, the maximum sample size was reached more often. Incorrect decisions were reached less frequently than for the counts approach, except with the 10%, 2.2 thrips/plant protocol.

Treatment thresholds and supervised control

For bulb onions, where the main effect of thrips damage is on yield, Quartey (1982) estimated that onion plants of 5, 8, 10 and 12 leaves could tolerate 0.05, 5, 29 and 59 thrips/plant respectively without yield reduction. Shelton *et al.* (1987) used this information to establish 3 thrips/leaf as an action threshold for onion thrips in New York State, a threshold described as conservative. Since some fields are infested when plants are young and others when plants are older, Shelton *et al.* believed that the threshold used should be ‘dynamic’ to take account of plant age.

Fournier *et al.* (1995) estimated economic thresholds for onions grown in Quebec, Canada. These ranged from 0.9 to 2.2 thrips/leaf in the two years of study, the lower threshold being appropriate for drought conditions when onions are less tolerant to thrips damage.

An IPM programme for *T. tabaci* in onions, which included sampling plans and treatment thresholds, was developed for use in New York State (Hoffmann *et al.*, 1995). In the first year of evaluation (1986) 50 plants were sampled from each field and the recommended threshold was three thrips/leaf. In the second year (1993), a sequential sampling plan (Shelton *et al.*, 1987) was available, and growers were considered to comply with the IPM recommendations if thrips numbers were increasing and the infestation was greater than or equal to 1.5 thrips/leaf at treatment. This lower value was used because the fields were only sampled once a week and thrips populations could increase rapidly and greatly exceed the threshold by the following week.

In 1986, fields were considered to have been IPM compliant if sprays were applied only when the threshold had been exceeded and if no more than three additional sprays (for other pests) had been applied. In 1993, paired fields were used to make comparisons.

One field of the pair was monitored weekly using the recommended IPM system and treated accordingly by the grower. The grower managed the other field without guidance. Growers were considered to have complied if they had sprayed according to the IPM guidelines. Results showed that the use of the IPM programme reduced insecticide inputs significantly without affecting onion yield or quality adversely. However, this resulted in only small savings financially, once the cost of scouting had been subtracted.

Theunissen & Schelling (1997) determined the relationships between larval populations of *T. tabaci* on leeks, damage and crop marketability. This was because Theunissen & Legutowska (1991a) found that larvae were more numerous than adults and considered that they were the cause of the actual damage. Theunissen & Schelling estimated that the tolerance level was about 5-6 larvae/plant.

Similarly, Villeneuve (1994) proposed a spray threshold of five thrips/leek (adults + larvae). However, in 1996, Villeneuve *et al.* decided that this threshold was too high for use with the insecticides approved currently and that the appropriate threshold appeared to be closer to 0.5 or 1 thrips/leek. Villeneuve *et al.* (1996) found that the important period of thrips immigration into leek fields occurs usually during the first three weeks of August. Therefore if thrips populations could be controlled by the end of August there was no need for further treatments. Their results showed that effective crop protection could be achieved by applying insecticide treatments only when the crop was at risk.

After further studies Villeneuve *et al.* (1999) concluded that methods of assessing thrips on plants require a lot of work to obtain a good estimate and that they do not provide a sufficiently early warning of the start of infestation. They have therefore tried to determine an action threshold, based on adult trapping, to initiate a programme of insecticide sprays. They found that a threshold of 10 thrips/trap/day ensured that thrips infestations could be kept under control.

In Germany, Hommes (1992) used thresholds of 1%, 25% and 50% plants infested (presence or absence only – 50 plant sample), sampling at two-week intervals. The plots were sprayed with pyrethroids (deltamethrin or cypermethrin). He found that all of the threshold treatments produced 97-100% marketable leeks, compared with the 22-69% marketable in the untreated plots. The higher threshold treatments required fewer sprays.

The results of the German study were taken forward in a multi-site trial in Germany, Switzerland and Belgium (Hommes *et al.*, 1994). Thresholds used were 1% and 50% plants infested with *T. tabaci* (leek moth thresholds were included also). The insecticides approved in each country were applied in the trial (acephat, endosulfan or permethrin in Belgium, cypermethrin in Germany and deltamethrin and furathiocarb in Switzerland). Plots were sprayed routinely (every 2 weeks) in Belgium, but were sprayed according to the thresholds in Germany and Switzerland. For the treated plots the percentage marketable plants ranged from 12-58% (Belgium), 8-20% (Switzerland) and 91-99% (Germany). The leeks from untreated plots ranged from 2% (Germany) to 38% (Switzerland) marketable. It was concluded that the insecticides used in Belgium and

Switzerland were not sufficiently effective for a supervised control programme to succeed.

Umpelby (1995) attempted to establish a preliminary spray threshold for onion thrips control on leeks in the UK. Deltamethrin was used to control thrips using thresholds of from one thrips/10 plants to five thrips/plant. A random sample of 10 plants was sampled destructively from each treatment at approximately weekly intervals. However, it is unlikely that this was a sufficiently large sample to obtain a good estimate of the size of the infestation. The numbers of treatments applied ranged from 0-8 (including the untreated control and a routine programme of sprays). Damage levels were low and no differences were found in plant damage during the growing season, or at harvest.

Insecticidal control of thrips

Lewis (1997c) lists the main insecticides recommended specifically for thrips control throughout the world. These include organophosphorus, carbamate and pyrethroid insecticides; some of which are approved for thrips control or other uses in the UK. The list includes newer active ingredients such as imidacloprid and fipronil, and the entomopathogenic fungus *Verticillium lecanii*.

There are several reasons for poor insecticidal control of thrips on leeks and onions:

1. A lack of effective insecticides
2. Insecticides do not contact thrips adults and larvae that are hidden within the leaves of the plant
3. Eggs within the plant and pre-pupae/pupae in the soil are inaccessible to insecticides
4. Treatments are poorly timed, often due to the difficulties of seeing and identifying such small insects

In 1995, of the 4,400 ha where thrips were given as the reason for insecticide application, 80% of the area was treated with pyrethroids (mainly deltamethrin), 10% of the area (at most) was treated with malathion/fenitrothion and 9% was treated with dimethoate (Garthwaite *et al.*, 1997). Chlorpyrifos provides incidental thrips control on leeks and may be more effective than deltamethrin (C. Wallwork, personal communication).

Alternative insecticides

Many insecticides have been evaluated for control of *T. tabaci*, in several countries. Pyrethroids often give good control (Hommes, 1992; Bocak, 1993; Goncalves, 1996; Mayer *et al.*, 1987; F. Villeneuve, personal communication), although sprays of lambda-cyhalothrin appeared to be ineffective on leeks in France (Thicoipe, 1990). Ineffective insecticides were given as the reason why a supervised control system for *T. tabaci* failed in Switzerland and Belgium, when a similar system provided good thrips control in Germany (Hommes *et al.*, 1994).

Over the last ten years, the Horticultural Development Council has funded projects to evaluate new methods of chemical control for thrips and to find better ways of timing spray applications (Saynor, 1989; Umpelby 1995). Whilst applications of malathion, chlorpyrifos and deltamethrin were effective at a site in the Thames Valley in 1989, they were ineffective at another site in the Vale of Evesham (Saynor, 1989). The treatments (three/crop) were applied at different times at the two sites and there is no indication of how these timings related to thrips immigration and population development. Wetting agents mixed with deltamethrin did not appear to improve thrips control. However, it may be necessary to reduce water volumes to use wetting agents to greatest effect (J. Davies, personal communication).

In 1995, a number of insecticides were evaluated in a further trial in the Thames Valley (Umpelby, 1995). They consisted of one granule (disulfoton), one drench (imidacloprid) and 13 spray treatments. The granules were applied on 21 July, the drench on 23 July and the sprays on 5 occasions between 4 July and 1 September. At the time of the first assessment (8 August) there were no statistically significant differences between treatments in the numbers of thrips/plant. However, at the time of the second assessment (11 September), chlorpyrifos and an experimental product from Cyanamid provided better control (56% and 66% respectively) than treatment with water only. A range of spray adjuvants was evaluated also, in combination with chlorpyrifos, and in water volumes of either 500 or 1000 l/ha. None of the adjuvants improved the thrips control given by sprays of chlorpyrifos alone, which provided 70-75% control compared with sprays of water only.

A number of systemic insecticides, applied as film-coating on seed, were investigated in the Netherlands, the aim being to protect plants in the seedbed and possibly for some weeks after transplanting (Ester *et al.*, 1997). Fipronil and imidacloprid seed treatments were effective, but carbofuran, diflubenzuron, methiocarb, teflubenzuron and vamidothion were not. In 1993, the leeks were sown in mid-May and the effects of the imidacloprid (28 & 42 g a.i./250,000 seeds) and fipronil (20 & 50 g a.i./250,000 seeds) seed treatments on immature thrips persisted until August. There were no statistically significant differences between the two insecticide treatments. In 1994, immature thrips were again controlled effectively with fipronil (50 & 75 g a.i./250,000 seeds) and imidacloprid treatments (42 g & 56 g a.i./250,000 seeds), up to 19 weeks from sowing, but none of the treatments controlled adult thrips effectively. Finally, in 1995, almost no thrips were found on plants treated with fipronil (37.5 & 50 g.a.i./250,000 seeds), 11 weeks after sowing. Even 21 weeks after sowing, the plants were less damaged and contained fewer thrips than untreated plants. However, by this time, the damage index was higher than the economic threshold for marketable plants. Ester *et al.*, estimated that additional insecticide treatments might be required from approximately 13 weeks after sowing. It is likely that, as with brassicas, the apparent persistence of a seed treatment will depend on the size of the pest infestation (Collier *et al.*, 1999), since insecticide treatments kill a fixed proportion of the population. Preliminary field trials in France (Villeneuve *et al.,* 1999) confirmed that fipronil seed treatments were effective for thrips control on leeks.

In the laboratory in the Netherlands, germination was delayed when seeds were film-coated with imidacloprid or the highest rate of fipronil (Ester *et al.*, 1997). However, final germination counts were not statistically significantly different. Fipronil applied at either rate did not affect emergence in the field, but imidacloprid at 56g a.i./250,000 seeds delayed and reduced emergence compared with the untreated control.

In the UK, fipronil has been evaluated as a spray on leeks and salad onions in unreplicated field trials and was found to be effective (Saynor, 1997). However, it is unlikely that this treatment will ever be available to growers. In 1998, fipronil (50 g a.i./250,000 seeds) and imidacloprid (42 g a.i./250,000 seeds) seed treatments on leeks were assessed in a trial in the Thames Valley (Saynor, 1999). The seed was sown on 6 May. Imidacloprid seed treatment delayed germination, but did not reduce final yield. Fipronil appeared to be more effective than imidacloprid for thrips control. Compared with the untreated control, thrips numbers were reduced on both treatments, even 20 weeks after sowing.

Similarly, leeks grown from seed treated with imidacloprid were compared with those grown from fipronil-treated seed in a small trial at HRI Stockbridge House in 1998 (J. Davies, personal communication). Fipronil was more effective than imidacloprid. In a separate trial, imidacloprid seed treatment delayed emergence of module raised leek plants compared with the untreated control, and reduced emergence in one variety. In both of the trials, some plots were sprayed subsequently with a programme of insecticide sprays (deltamethrin, malathion). The results indicated that it would be necessary to apply insecticide sprays to some crops, once the seed treatment has become ineffective (J. Davies, personal communication).

In 1999, fipronil and imidacloprid seed treatments were evaluated again on leeks (M. Saynor, personal communication). Both naked and pelleted seeds were treated. The actual rates applied were 44-48 g a.i./250,000 seeds for fipronil and 52-55 g a.i./250,000 seeds for imidacloprid. The seed was sown on 8 April and damage assessments and thrips counts were made 15 and 18 weeks after sowing. The results were variable. Slightly less damage was recorded on the treated plants, but the effects are unlikely to be statistically significantly different.

Insecticide-treated salad onion seed was assessed in a separate trial. Actual rates of fipronil applied ranged from 1-16 g a.i./250,000 seeds and imidacloprid from 1-19 g/250,000 seeds. This was to coincide with the maximum amounts of a.i. allowed/ha, based on a seed rate of 1,250,000 seeds/ha. The highest rate of each insecticide used was twice the maximum permitted rate, to assess risks from phytotoxicity. None of the insecticide treatments affected germination adversely, but there was little difference between any of the treatments in thrips control. This may be because the amounts of insecticide applied/seed (0.06 – 0.07 mg a.i./seed) were too low to have any insecticidal effect. This is in comparison to 0.18-0.22 mg a.i./seed applied to leeks and the > 1mg a.i./seed applied to leafy brassicas (experimental rates) and lettuce (Specific Off-label Approval).

Once again, in 1999, fipronil and imidacloprid seed treatments were evaluated on leeks using both naked and pelleted seed, in a small trial at HRI Stockbridge House in 1999 (J. Davies, personal communication). The seed was drilled on two occasions (27 April and 24 May). There was some evidence that insecticide treatment delayed germination (particularly imidacloprid). The plots were assessed for thrips damage on 6 August, 11-15 weeks after the seed was drilled. Neither of the insecticide treatments appeared to have controlled thrips effectively.

If, as seems likely, seed treatments will not provide complete control throughout the life of a crop, then foliar sprays will still be required. Pyrethroids such as lambda-cyhalothrin, alpha-cypermethrin and tau-fluvalinate may be worth testing on leeks and salad onions. Of these three pyrethroids, lambda-cyhalothrin has been tested previously in the UK (Umpelby, 1995) and was less effective than chlorpyrifos. It was also considered to be ineffective against thrips in a study in France (Thicoipe, 1990). In contrast, Goncalves (1996) found that it was effective in a trial in Brazil. Alpha-cypermethrin has not been tested against thrips (B. Poyntz, Cyanamid, personal communication) and there does not appear to be any published information on its effectiveness. Tau-fluvalinate is known to be effective against thrips (Lewis, 1997c). It has contact and stomach action. In the UK it is approved for use against aphids and pollen beetles in cereals and oilseed rape. It has approval for aphid control on leeks in France (R. Jacobson, personal communication).

Alternatively, abamectin, isolated by fermentation of *Streptomyces avermitilis*, might be effective. It has contact and stomach action and exhibits translaminar movement. It is approved for use against leaf miners, mites and western flower thrips in ornamentals and protected salads. It is relatively expensive, but a low dose might be effective against *T. tabaci* (R. Jacobson, personal communication).

Insecticide resistance

Thrips may develop resistance to insecticides and some species (e.g. citrus thrips, western flower thrips) have become resistant to a range of active ingredients (Lewis, 1997c). Differential susceptibility of UK populations of *T. tabaci* to insecticides has not been tested. However, growers should be aware of the potential for resistance to develop as a result of repeated and/or exclusive use of particular active ingredients.

Insecticide application techniques

One of the reasons for poor thrips control in leeks is the inaccessibility of adults and larvae when they are hidden within the leaves of the plant. It is possible that certain spray application techniques might facilitate insecticide penetration, but this has not been investigated.

Alternatively, the intra plant distribution of thrips may vary during the day, so that they are more accessible to spray applications at certain times. Sites *et al.* (1992) investigated the diurnal periodicity of onion thrips distribution on onions. As presented, the results are difficult to interpret. However, they seemed to indicate that as temperatures increased, adult thrips moved upwards in preparation for flight.

Cultural control

Reflective mulches

Due to the repellent effect of UV on polyphagous and flower thrips, some thrips infestations have been reduced with mulches of UV-reflective sheets (Terry, 1997). Lu (1990) used silver reflective mulch against *T. tabaci* in China and reduced the numbers of thrips in a low density planting of onions. Blue plastic mulches have been tested in leek crops in Belgium (Benoit & Ceustermans, 1998).

Crop covers

In France, non-woven crop covers were used to exclude thrips in the seedbed and for the first three weeks after planting, where they reduced the thrips population by 75% during the first month (Thicoipe, 1990).

Non-woven fleece and woven mesh covers were used to exclude thrips from leeks in MAFF-funded trials at HRI Stockbridge House during 1991-93 (J. Davies, personal communication; Leatherland, 1995). All cover treatments reduced thrips damage, but did not prevent it completely, even when they remained in place until October or November. The fleece covers advanced maturity when used on an early-planted crop and quality had deteriorated by early November. Covers may increase shank length.

Novel techniques

Teerling *et al.* (1993) investigated the possibility of dislodging larvae of the thrips species *F. occidentalis* by exposing them to alarm pheromone. The response was weak, so was unlikely to improve the efficacy of control with 'Thripstick', a formulation of deltamethrin on a sticky base, which can be used on the floor of glasshouses to intercept larvae as they fall off the plant to pupate. However, Lewis (1997b) believed that there could be possibilities for enhancing the efficacy of an insecticide or fungal pathogen by formulating them with alarm pheromone, to increase thrips contact with the toxic agent.

Emulsions of the artificial rubber polymer polyisobutylene were sprayed onto onions and formed a non-phytotoxic film on the leaf surface which deterred feeding by *T. tabaci*, without causing them to stick (den Ouden *et al.*, 1987).

Irrigation

Warm dry weather is important for rapid thrips development. Population dispersal and damage decline in response to wet conditions (Harding, 1961; Straub & Emmett, 1992).

Heavy rain can wash thrips off plants and down to the soil surface causing sharp decreases in population density (Kirk, 1997). In contrast, dry weather, but not extreme drought, seems to favour the increase of some species including *T. tabaci*. In Australia, the effect of *T. tabaci* on reducing yield in onions was prevented by irrigation (Passlow, 1957). This may have been due to the direct effects of the water on *T. tabaci* survival and reproduction or to indirect effects, because water-stressed onions are less tolerant to thrips damage (Fournier *et al*, 1995). Wardle (1927) claimed that the effect of heavy rainfall in reducing thrips infestations was often more apparent than real for *T. tabaci* on cotton. The rain was sometimes not so much mechanically removing thrips as stimulating rapid leaf growth, which decreased thrips densities/leaf and decreased the proportion of damaged leaves. However, irrigation at the soil surface reduced the population more than rain, probably as a result of soil-caking killing thrips in the soil. Short intervals between watering and avoidance of furrow irrigation, which does not wet the tops of the ridges, were suggested as ways of preventing crumbly soil and thus increasing mortality.

Regular irrigation is recommended for reducing thrips infestations on leeks in France (Villeneuve *et al.*, 1999), in combination with insecticide applications. Water should be applied every day during the period of immigration. Application of 2-3 mm water/day with a sprinkler may be sufficient (F. Villeneuve, personal communication). Irrigation is likely to be most effective before the shaft is formed (J. Theunissen, personal communication).

Intercropping or undersowing

In Egypt, intercropping onion and garlic with tomatoes reduced infestations of *T. tabaci* by about 80%, but the yield from both crops declined (Afifi & Haydar, 1990). In the UK, infestation of *T. tabaci* on onions was halved when they were intercropped with carrots (Uvah & Coaker, 1984). The effect was greatest with closely alternating single rows of each species.

Undersowing leeks with clover reduced leek thrips infestations drastically and this was reflected in improved quality at harvest (Theunissen & Schelling, 1996). However, yield was reduced as a result of plant competition. Theunissen & Schelling believed that the effect of undersowing was to induce resistance in the leeks by changing either their attractiveness or quality, and thereby inhibiting or reducing insect reproduction. This may be the case in their field experiments, since the effect of inter-specific plant competition was to inhibit leek growth in the intercrop. This would have lead to a higher concentration of secondary plant compounds, which are likely to inhibit insect growth and development. Theunissen & Schelling (1997) found that a given number of thrips larvae/plant caused less injury to intercropped leek plants than monocropped leeks. However, they may well have confounded the effects of plant growth stage and pest numbers, since a particular level of infestation would occur at an earlier stage of growth in the monocrop than in the intercrop. They concluded that the total effect of intercropping in leeks is based on thrips population suppression and a reduced development of feeding symptoms.

Using a range of brassica pests, Finch & Kienegger (1997) demonstrated that the effects of undersowing persisted even when brassica plants of a similar size and growth stage were used in experiments. The visual and other effects of crop background on the host plant finding behaviour of the pests were sufficient to account for the reductions in pest numbers observed. The same mechanism is likely to occur with thrips in leek and onion crops.

Natural enemies and biological control

Predators

The main predators of thrips are mites, heteropteran bugs, lacewing larvae, ladybird larvae, hoverfly larvae, small spiders and other thrips (Waterhouse & Norris, 1989; Kirk, 1997). Although there are many records of predation in the field, a detailed analysis of the relative importance of predators, parasitoids, parasites and pathogens under natural conditions is virtually absent (Sabelis & Van Rijn, 1997). Theunissen & Schelling (1996) sampled leek plants for natural enemies of thrips and found very low numbers, which suggested to them that natural enemies do not play a role in controlling populations of thrips. In contrast, using Berlese funnels, Thicoipe (1990) extracted a number of beneficial insects from leek plants infested with *T. tabaci*, including anthocorid bugs, predatory thrips, mites and lacewing larvae.

Waterhouse & Norris (1989) discuss some of the possibilities for biological control of *T. tabaci* with predators such as anthocorid bugs and lacewings. The possibility of using ladybirds as predators of thrips on leeks has been investigated in laboratory experiments in Germany (Schade & Sengonca, 1998) and the use of predatory mites to control thrips on cabbage was investigated in the USA (Hoy & Glenister, 1991). Species of phytoseiid mite have been used to control *T. tabaci* in greenhouses (Ramakers, 1980; Bakker & Sabelis, 1986). First instar larvae of *T. tabaci* are more susceptible to these predatory mites than second instars, because the older insects defend themselves more effectively by jerking the abdomen and producing a drop of rectal fluid. The age distribution of thrips is a key factor in the maintenance and success of mite predators of this species.

Parasitoids

The main parasitoids of thrips are wasps (Kirk, 1997) and these all belong to the superfamily Chalcidoidea (Loomans *et al.*, 1997). Samples from onion fields in Japan showed that up to 88% of *T. tabaci* were parasitised by *Ceranisus menes* (see Kirk, 1997; Loomans *et al.*, 1997). There was a positive correlation between thrips density and percentage parasitism, so the wasp was having a positive density-dependent effect. In field collections of *T. tabaci* from other locations, parasitism ranged from 0 to 60% (see Loomans *et al.*, 1997). Classical biological control of *T. tabaci* with hymenopterous parasitoids has been attempted in the past with little success (Loomans *et al.*, 1997). Based on the limited information available, hymenopterous parasitoids are not considered to be promising biological control agents (Waterhouse & Norris, 1989; Loomans *et al.*, 1997). However, only a few species have been studied in any detail and there is plenty of scope for further investigations.

Parasites
Thrips may be parasitised also by nematodes (Loomans *et al.*, 1997). Very little is known about their impact under natural conditions and they have not been used in biological control studies.

Pathogens
There is relatively little information available on the pathogens of thrips (Butt & Brownbridge, 1997). There have been few co-ordinated searches for pathogens in thrips populations, but when these have been undertaken, the most commonly reported pathogens are invariably fungi. A range of fungi have been isolated from, or been shown to be pathogenic to, *T. tabaci* (Butt & Brownbridge, 1997). A species of *Entomophthora* infecting nymphs and adults of *T. tabaci* and related species was recorded in several countries in northern Europe (Carl, 1975). It was later identified as *Entomophthora parvispora (*MacLeod *et al.*, 1976). First infections were found in the field in Switzerland in early July or later and epizootics did not occur before September or October, when the host had already damaged the crop. Observations suggested that epizootics were largely dependent on host density (Carl, 1975). In the Netherlands, epizootics caused by *Entomophthora thripidum* have been observed in *T. tabaci* infestations on greenhouse crops (Ramakers, 1976; Samson *et al.*, 1979).

In laboratory studies, *T. tabaci* was susceptible to *V. lecanii*, *Beauveria bassiana*, *Metarhizium anisopliae* and *Paecilomyces fumosoroseus* (Gillespie, 1986; Fransen, 1990). Isolates of *V. lecanii* have been effective against *T. tabaci* in glasshouse trials (Gillespie, 1986). *Thrips tabaci* has soil-dwelling instars in its life-cycle, and these developmental stages are also susceptible to fungi ((Butt & Brownbridge, 1997).

While the effectiveness of some entomopathogenic fungi against thrips has been demonstrated, this has been in the greenhouse (Waterhouse & Norris, 1989), where environmental conditions can be manipulated and application methods ensure good coverage of the foliage. Activity in field crops has not been investigated extensively. The problems will be 1) can the fungi be effective at the temperatures and relative humidities which occur in the field and 2) can they be applied so that an effective dose reaches the thrips that are hidden in plant foliage? It is possible that these problems can be overcome by new formulations (some are being developed at the moment), application strategies and by using strains suited to more variable conditions. Thus, fungal control of *T. tabaci* may have potential, but it is probably worth waiting for mycopesticides to be developed further on other crops before attempting to transfer the technology to *Allium*s.

Host plant resistance
Morphological characteristics, including open plant architecture, have been associated with low thrips densities on onion cultivars (Coudriet *et al.*, 1979). Leaf structure may affect the numbers of thrips that onions can support (Waterhouse & Norris, 1989). Lack of protection from pesticides, natural enemies and adverse conditions have been suggested as mechanisms of this resistance (Fournier *et al.*, 1995).

Commercial onion cultivars have been evaluated for thrips resistance (See Straub & Emmett, 1992). White Spanish onions were the least susceptible of several cultivars tested in India (Lall & Singh, 1968; Verma, 1966). Breeding lines with glossy foliage were more resistant (Molenaar, 1984; Thicoipe, 1990). Studies are being undertaken to understand how to design breeding programmes to select for thrips resistance in onions (Hamilton *et al.*, 1999).

Twenty-eight leek cultivars were evaluated in the UK (Saynor, 1988). One variety suffered less damage, but was only partially resistant. Even partial resistance may be useful in an IPM programme for thrips control. Host plant resistance and insecticides were combined to manage thrips on cabbage in the USA (Shelton *et al.*, 1998).

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