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**IMPACT OF CHANGES IN
ARABLE AGRICULTURE ON
THE BIOLOGY AND CONTROL
OF WHEAT BULB FLY**

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IMPACT OF CHANGES IN ARABLE AGRICULTURE ON THE BIOLOGY AND CONTROL OF WHEAT BULB FLY

by

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1. SUMMARY

Wheat bulb fly is one of the most serious insect pests of winter wheat in Britain. The pest is currently restricted to the eastern counties of England and Scotland. Eggs are laid in July and August in bare or partially covered soil. The eggs hatch in January, February and March. Winter wheat is often attacked when sown after crops such as potatoes, sugar beet and vining peas. Wheat after fallow and fallowed set-aside is also at high risk of attack. Each larva enters a host plant below the soil surface at the basal node to bore upwards and feed within a leaf shoot. Larvae migrate between shoots and plants while completing three larval instars (stages). Infested shoots turn yellow, wither and die to produce deadhearts. Pupation occurs in the soil between mid-April and mid-May and adult flies emerge in June. The severity of attack varies considerably between years and is mainly dependent on the number of eggs laid in the summer and the interaction of larval attack with crop growth and development during the winter.

A number of factors influence yield loss by wheat bulb fly. Generally, crops sown before the end of October tiller well and tolerate pest attack better than those drilled in November or December. However, damage tends to be worse in cold winters, owing to slower crop development and a reduction in the capacity of the crop to compensate for loss of plants or tillers during the winter. Previous cropping, the availability of exposed soil and weather conditions during the egg-laying period also influence the risk of attack. Highest egg numbers occur in fallow or in the large areas of soil exposed in open-canopy or low-standing crops such as potatoes or sugar beet. A rough and freshly cultivated soil surface appears to be preferred for egg laying. Hot, dry conditions during the egg-laying period of July and August reduce the number of eggs laid.

Egg numbers and the associated risk of attack vary considerably between fields and between districts. The potential risk of wheat bulb fly attack can be estimated reliably at field level only by taking soil samples in the autumn to extract and count the number of eggs. Water and soil traps have also been used to provide an early warning of potential egg numbers. As an alternative to sampling or trapping, a regional forecast of attack has been developed using a multiple regression model to predict egg numbers.

There are now fewer insecticides available for control of wheat bulb fly than at any time over the last decade and all are broad-spectrum organophosphorus products. Concerns over the general environmental safety and toxicity of organophosphorus insecticides may, in future, threaten the continued approval and use of these chemicals. The current range of insecticides should be safeguarded by fostering a rational and precise approach for their use.

Seed treatments (fonofos and chlorfenvinphos) are widely used as a low-cost preventive measure when crops are sown after mid-October. Efficacy is reduced by earlier sowing. Insecticide sprays may be applied at egg hatch to kill larvae before they enter plants (egg hatch spray) or after larval invasion when the symptoms of attack become visible (deadheart spray). Individual insecticide applications provide only partial control of the pest. When damaging attacks are expected, various control strategies, combining several types of insecticide, have been shown to be cost-effective, although none is fully effective in completely eliminating damage. Research and development of integrated control strategies, utilising cultural and biological techniques in addition to insecticides, may improve the relatively poor standard of control often obtained solely from chemical control.

There are various natural enemies of all life stages of the pest, many of which may be exploited in future as biological control agents. Adult wheat bulb flies are infected by a fungal parasite (*Entomopthora* spp.) and may also be preyed upon by certain flies, spiders and birds. Eggs and pupae are destroyed by several species of predatory beetle. Pupae are also attacked by parasitic staphylinid beetles (*Aleochara* spp.). Levels of natural mortality can be high. Many larvae die between hatching and plant invasion. A greater understanding of the factors affecting larval survival could, therefore, contribute to new or improved methods of control.

Cultural control of wheat bulb fly is often overlooked but there are a number of options. Sowing date, depth of drilling, seed rates, cultivations, trap fallows and crop rotation can all be used to reduce egg numbers or the crop's ability to tolerate larval attack.

Various other methods of control have also been studied. Attempts have been made to control populations over a large area, using either insecticides or cropping restrictions. Control of adult flies with insecticides at their emergence sites before they lay eggs is another strategy but is environmentally undesirable. Further research of environmentally benign insecticides or biocontrol agents could prove useful for this purpose. Research into larval host location may enable the disruption of this process to prevent plant invasion. There are also a number of beneficial invertebrate species which could be investigated as candidate biocontrol agents. There is potential to develop an integrated pest management (IPM) system for wheat bulb fly by unifying existing knowledge of cultural, biological and chemical control measures.

In the current economic conditions, it is prudent to examine the cost-effectiveness of wheat bulb fly control. An analysis of insecticide experiments has shown that chemical control is cost-effective above a treatment threshold of 2.5 million eggs/ha. There is scope to increase the efficiency of egg hatch sprays and deadheart sprays by improving the accuracy of spray decision making and timing of application. Research into enhancing the efficacy of dimethoate, the only remaining deadheart spray, may limit the number of applications needed to achieve acceptable levels of control.

The resurgence of summer fallowing in the management of set-aside has caused widespread concern about the risk of wheat bulb fly attack and the potential for an overall increase in the frequency of the pest. Results of monitoring suggest to date that set-aside fallows may cause localised increases in wheat bulb fly populations in districts currently considered to be at marginal risk. Experiments are also underway to investigate cultural control measures against the pest in set-aside fallow. The possible increase in wheat bulb fly populations resulting from set-aside fallowing will heighten the need for further research into cost-effective and environmentally acceptable forms of control.

An improved understanding of crop growth and development in relation to the severity of wheat bulb fly attack could reduce expenditure on insecticides. Plant growth models are likely to become increasingly important in determining the ways in which pests affect

plant growth, development and yield. Precision farming provides the opportunity to adjust inputs according to the spatial distribution of factors within a field and so potentially reduce pesticide use. Decision support systems and geographic information systems should also contribute in the development of precision farming. A prototype expert system for the management of wheat bulb fly control has been developed with HGCA funding. This system could be refined by inclusion of GIS technology and predictive models to estimate the distribution and severity of the pest.

There is considerable concern over misuse of pesticides. In particular, the potential for residues in food, effects on non-target organisms and the development of insecticide resistance have stimulated a move towards a rational approach to pesticide use. Pressure for the adoption of environmentally friendly integrated control strategies will increase and their development should be a major research priority.

There is a dual need to reduce reliance on insecticides and improve the cost-effectiveness of wheat bulb fly control. Suggested priority areas for further research include alternative control strategies such as biological control, control of adult flies, population control incorporating trap fallowing, varietal tolerance and interference with host location. Decision support systems and predictive models also have a future role in forecasting damage and technology transfer to the farmer. Most importantly, improvements gained in individual methods of chemical, cultural or biological control require unification in a practical and fully researched integrated pest control strategy which may be readily adopted by the agricultural industry.

2. INTRODUCTION

Wheat bulb fly (*Delia coarctata* (Fallén), Diptera: Anthomyiidae) ranks amongst the most serious insect pests of winter wheat in Britain (Anon., 1992). Damage is caused by the larvae feeding within the shoots. The intensity of attack varies from year to year and is influenced by a variety of factors, including the number of eggs laid in the summer and the growth stage of the crops during attack in the winter. The pest is particularly prevalent in the eastern half of Britain (Fig. 1). Damage can occur as far south as Kent and as far north as the Tayside region of Scotland. The traditionally endemic districts are in eastern England, particularly on the organic soils of the Cambridgeshire and Lincolnshire fens, and in Humberside.

Winter wheat is the most important host but other winter cereals, including barley, rye and triticale are also attacked. However, oats are virtually immune. Spring wheat and barley can also be seriously damaged if sown before egg hatch of the pest is complete, which is usually in late March (Young, 1987).

Wheat bulb fly completes one generation per year (Fig 2). Eggs are laid mainly in late July and early August. Oviposition (egg laying) occurs on the exposed soil surfaces of fallows, freshly cultivated or harvested fields, or beneath the canopy of root or tuber crops. Eggs hatch in January or February, and the young larvae die unless the field has been sown with a host crop. Each larva enters a host plant below the soil surface at the basal node, to bore upwards and feed within a shoot. Up to five shoots may be damaged by a larva before its development is complete. Wheat, rye and barley crops are susceptible to attack when they are sown after fallow, potatoes, sugar beet, peas or early-harvested crops such as oilseed rape which allow soil cultivation during the egg-laying period. Fallowed land, which may form part of set-aside management, poses a great potential threat when preceding wheat.

Figure 1. The distribution of economic wheat bulb fly damage
in England
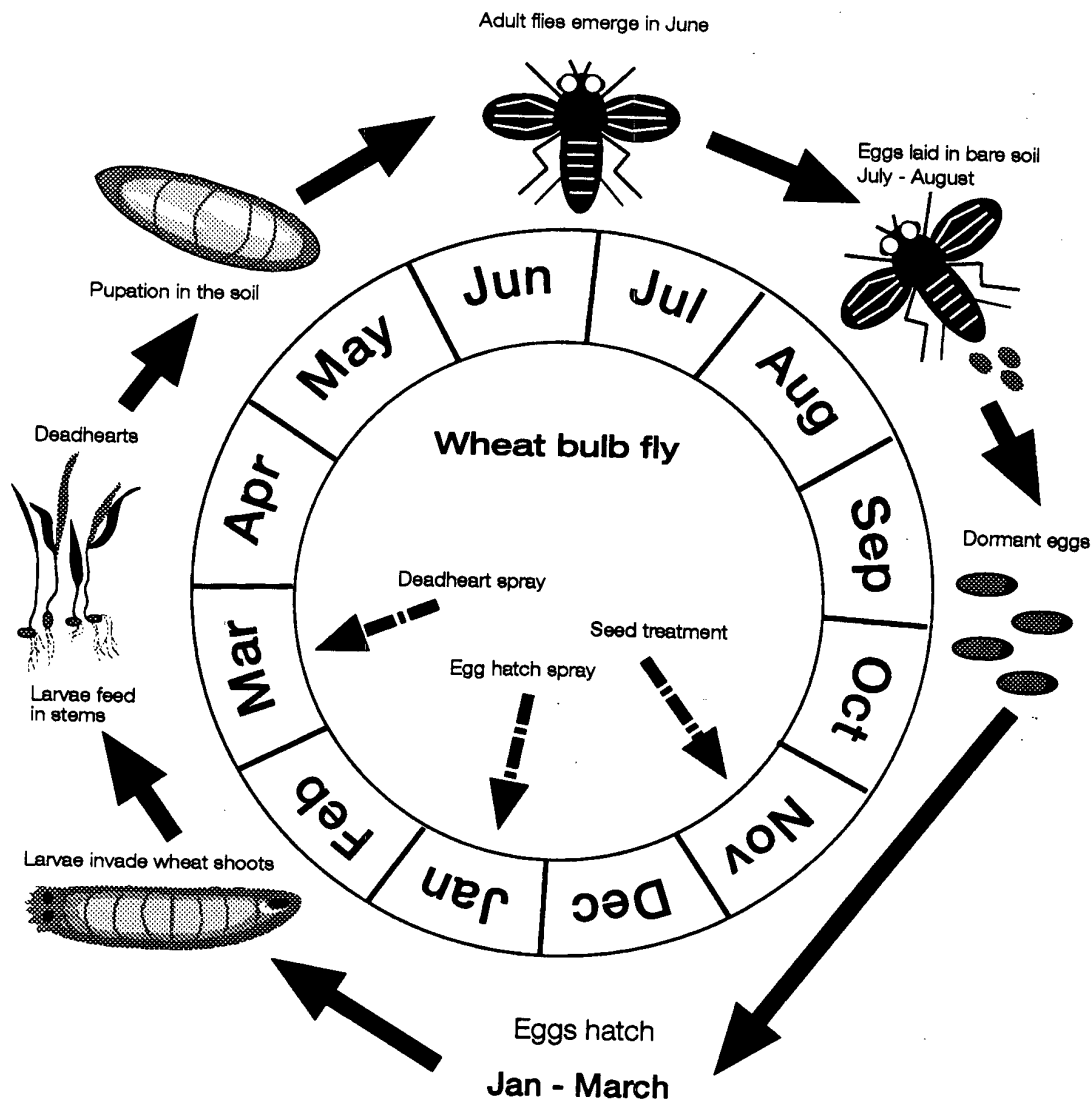
Figure 2. Life history of wheat bulb fly

In the eastern counties of England where wheat bulb fly is established, it is estimated that approximately one third of the annual area of wheat (MAFF Census data) is potentially at risk of attack by the pest (Fig. 3). Annual records of wheat bulb fly egg numbers from field survey samples collected by ADAS allow estimation of the area of wheat exposed to possible economic damage by the pest (Fig. 3). ADAS records for the past 40 years indicate that the proportion of fields with economically damaging numbers of eggs may vary annually between approximately 5 and 50% (Young & Cochrane 1993).
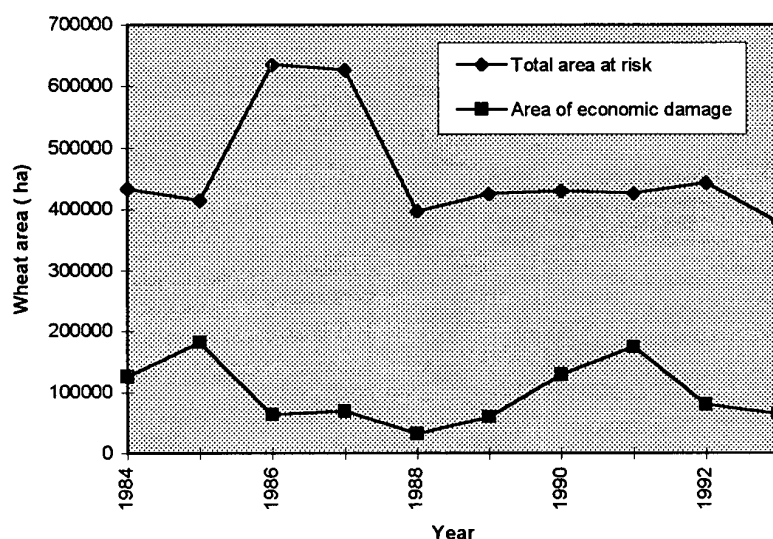
Figure 3. Estimated annual areas of wheat at risk of wheat bulb fly attack in England, 1984 - 1993.

At present, the control of wheat bulb fly is mainly dependent on insecticides. The most recent MAFF survey of pesticide use (Davis *et al.*, 1992) indicated that approximately 89,000 ha of wheat were treated against wheat bulb fly in the 1991/92 season (including seed treatments). Taking the average cost of treatment as £19/ha (including application), the national cost of treating this area of wheat was estimated as £1.7 million. However, this national estimate is probably less than average as the level of attack experienced in the year of the pesticide use survey (1991/92) was reduced by the favourable effect of mild winter weather on crop growth.

Estimations of annual yield losses caused by wheat bulb fly in England (Fig. 4) were based on the annual area of wheat subjected to possible economic damage by the pest (Fig. 3) and the average yield loss per hectare. The average yield response to the intensive ("Full") insecticide regime applied at eight high-risk (Category C) experimental sites with egg populations of between 2.5 and 5.0 million eggs/ha (Young, 1992) was used to represent the theoretical yield loss. Average grain yield was taken as 7.2 t/ha and the sale price of grain as £120/tonne. The net financial benefits of three chemical control strategies (Fig. 4) commonly applied to high-risk fields were calculated from the same set of experimental data as used for calculation of the average yield loss (see above), using current insecticide prices (Table 1) and a spray application cost of £6.35/ha.
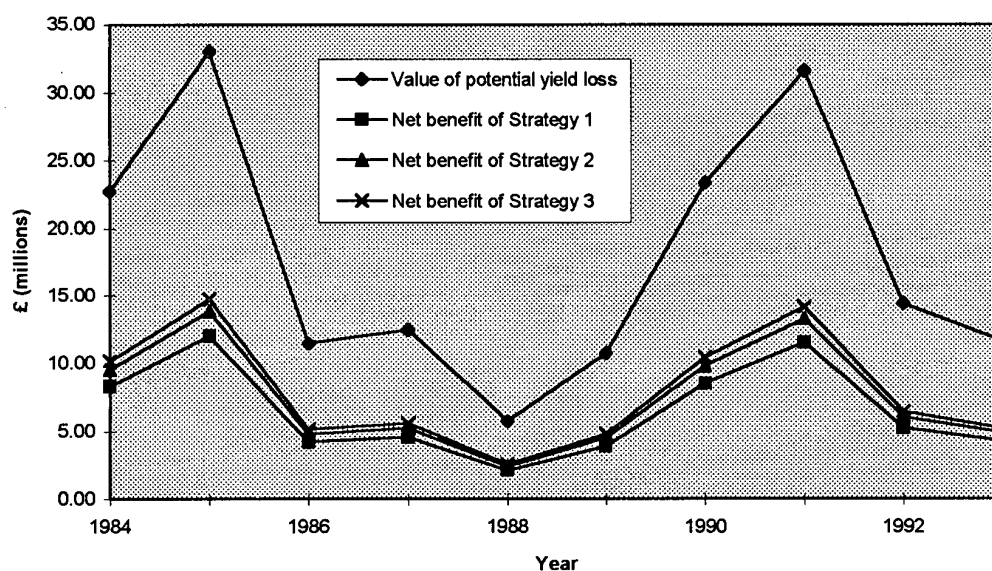
Figure 4. Estimated national wheat bulb fly annual losses and net benefits of three insecticidal control options in England, 1984 - 1993. Strategy 1 = seed treatment; Strategy 2 = seed treatment plus egg hatch spray; Strategy 3 = seed treatment plus deadheart spray.

The estimated financial value of yield losses caused by wheat bulb fly in England (1984-1993) ranged from £5.8 million to £33.0 million (Fig. 4). In contrast, the

estimated net benefit gained from the various insecticide strategies ranged from £2.1 million to £14.8 million in the same period. These figures emphasize the annual fluctuations in the severity of wheat bulb fly attack. Furthermore, the financial deficit between the three chemical control strategies and the potential yield loss serve to illustrate that although the currently applied control measures are cost-effective, they are relatively inefficient in terms of recovering the total estimated losses in yield and income. There is scope to reduce yield losses and increase the financial benefit of treatment by further development and improvement of control strategies against wheat bulb fly.

In recent years, there have been a number of developments which may influence the level of wheat bulb fly attack and also the re-evaluation of control strategies against the pest:

1. The introduction of rotational set-aside has created ideal egg-laying sites for wheat bulb fly. There is concern over the effect of set-aside summer fallowing on the severity and distribution of wheat bulb fly damage.

2. The range of insecticides available for control of wheat bulb fly has been reduced as agrochemical companies have allowed approvals to lapse. Reliance on fewer products may have implications for the development of insecticide resistance and enhanced degradation of soil applied products.

3. Environmental concerns arising from pesticide use, such as residues in food, effects on non-target organisms and the development of resistant pest species, have resulted in a need to develop a rational approach to agrochemical use. There is scope to reduce reliance on insecticides for wheat bulb fly control through the development of alternative, non-chemical, methods.

4. Integrated pest management (IPM) strategies in protected crops have been particularly successful in horticulture and have greatly reduced reliance on pesticides. There are now moves to apply these techniques to arable crops combining both chemical and non-chemical means of control.

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5. Developments in crop physiology may form an important component of an integrated pest management strategy for wheat bulb fly. The ability of a crop to tolerate wheat bulb fly attack is dependent on its ability to tiller (Raw, 1967). HGCA-funded work is currently underway to investigate the influence of cultivar, temperature and sowing date (Projects 0037/1/91, 004/1/91, and 0023/1/93) on tillering. This work may in turn impinge on aspects of wheat bulb fly control.

6. In the last decade, declining farm incomes, the reform on the Common Agricultural Policy (CAP), the influence of the General Agreement on Tariffs and Trade (GATT) and the threat of reduced grain prices have increased the need to reduce cost per unit of output to maintain profitability. This in turn has tested the robustness of current thresholds for pest attack and/or loss of yield. All crop protection inputs increasingly need to be justified in economic terms.

7. The relevance of new developments in precision farming techniques should assist or improve the standard of wheat bulb fly control. For example, decision support systems and geographical information systems may be of value in a future control strategy.

It is, therefore, timely to review the biology and control of wheat bulb fly, including the effects of set-aside, reduced pesticide availability and the current economics of wheat production. The options for an integrated control strategy against wheat bulb fly will also be considered with the aim of reducing pesticide inputs. Such a system could incorporate the use of less-environmentally damaging pesticide formulations, such as seed treatments, non-chemical control measures and new developments in crop physiology. This will provide alternative options for control of the pest and will highlight areas where further research is required.

3. LIFE HISTORY

3.1 Early studies

Investigations into the life history of wheat bulb fly began over 100 years ago when Miss E Ormerod recorded details of wheat bulb fly attacks in her annual reports, issued in the period 1882 to 1892, of observations on injurious insects (Raw, 1967; Gratwick, 1992). Miss Ormerod concluded that there was only one wheat bulb fly generation a year and that the larvae infesting wheat shoots in the spring came from eggs laid in the soil the previous summer. Further details of the life history were determined by Gemmill (1927), largely confirmed by Gough (1946, 1947, 1949) and summarised by Raw (1967).

3.2 Adult flies

The adult fly (family Anthomyiidae) appears similar to a house fly (family Muscidae) but is slightly smaller. Taxonomic identification of the adult wheat bulb fly and other anthomyiids has been described by Seguy (1923). The males are dark brown and the females yellowish grey.

The flies emerge from pupae in June and there is a maturation period of about three weeks before mating occurs. During this period flies feed on fungal spores, particularly of *Septomyxa affinis* (Jones, 1970 and 1971) yeast and aphid honeydew, all of which are present in cereal fields (Bardner *et al.*, 1977). The fungus *S. affinis* is found on the dead leaves of cereals and grasses, so senescing cereal crops provide a valuable source of protein for the fly.

Most females stay at the emergence site until egg laying starts, approximately one month later. They then disperse, and it is suggested that the stimulus to fly to an oviposition site may be connected with increased internal pressure in the abdomen (Jones *et al.*,

1972). Flight occurs chiefly in the late afternoon and evening (Bardner *et al.*, 1977). Bardner *et al.* (1968) used water traps to show that most flies were caught downwind of emergence sites and that few were caught more than 0.4–0.8 km away.

The amount of time spent at the egg-laying site is unknown but it may be brief, as there is no obvious food source on the soil. Many flies are known to return to shelter in cereals and grassland after laying some eggs (Bardner *et al.*, 1977). Egg laying usually begins in mid to late July and continues through August into early September. The eggs are not laid on or near a host plant but on bare or partially covered soil. Egg-laying therefore takes place on bare soil found in fallows or in early-harvested fields of potatoes, vining peas or oilseed rape. Eggs may also be laid on the bare soil beneath the canopy of root crops (e.g. sugar beet and potatoes), or other low and open-canopy crops (e.g. peas, onions and celery). Both the condition of the soil and the type of ground cover at the egg-laying site influence the overall number of eggs laid (see Section 4.3).

Long (1958a) observed that the temperature threshold for flight appeared to be 12 to 13°C. Flight was unaffected by wind speeds up to 13 kph (8 mph) but was markedly reduced at 24 kph (15 mph).

The number of eggs laid by each female depends on the number of batches produced, which is in turn dependent on her life span (Jones *et al.*, 1972). Up to three batches of eggs can be laid at about four, eight and twelve weeks after adult flies emerge. In laboratory studies (Long, 1957), the rate at which eggs were laid rarely exceeded 2–3 eggs/fly/day. Gough (1946) considered that each mature female laid, on average, up to 32 eggs, but Long (1958b) estimated the number to be nearer 50. Raw (1967) suggested 40 eggs per female as an estimate of the average fecundity.

3.3 Eggs

Wheat bulb fly eggs are whitish-cream in colour, 1.3 mm long and 0.4 mm wide. Following oviposition, the eggs enter diapause (physiological dormancy). Diapause ends most rapidly at about 3°C (Way, 1959a). In most years, the eggs begin to hatch by the end of January when soil temperatures are above 0°C. Therefore, in natural conditions, the weekly average soil temperatures after mid-October are within ± 4°C of the optimum constant temperature (3°C) for the completion of diapause (Way, 1959a).

Eggs buried deeply in the soil by ploughing are not subjected to temperatures as low as those at the surface, consequently prolonging diapause and delaying hatch. Once diapause is complete, eggs hatch when the temperature is above freezing. In the field, hatch is usually detected in January and, in mild winters, may be completed before the end of February (Young, 1987). However, it is usually delayed by prolonged frosts and in exceptionally cold winters may not be completed until late March.

McKinlay (1980) demonstrated that the termination of diapause and the initiation of hatching of wheat bulb fly eggs in Scotland appeared to be associated with diurnal fluctuations of more than 5°C between minimum and maximum soil temperatures. He proposed that fluctuating temperature may alternately expand and contract the thin film of air held by the water repellent, innermost layer of the egg-shell (Hinton, 1962). This in turn could rupture the thin, waxy membrane which is closely attached to the innermost layer of the shell. Alternatively, this membrane could be ruptured by enzymes activated by the fluctuating soil temperatures. A ruptured membrane would allow water to flow into the wheat bulb fly egg and this could terminate diapause and initiate hatching.

The German workers Roloff and Wetzel (1989a) largely confirmed the influence of soil temperature on the emergence of larvae. They found that the emergence period tended to start later and last longer under continental climatic conditions than under those experienced in England or Scotland.

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3.4 Larvae

In January and February, when soil temperatures permit, the larva emerges from the egg by rasping a small hole just below the micropyle (Gough, 1946). Upon hatching, it moves towards the soil surface in search of a host plant. Gough (1946) showed that plants can be infested by a larva emerging from eggs buried up to 45 cm beneath the surface of a light soil.

The neonate larva (newly emerged from egg) locates a host plant by responding to a plant exudate (Stokes, 1956 & 1957), thought to be a polyphenolic compound, possibly a glycoside (Greenway *et al.*, 1976), which functions as an arrestant rather than an attractant (Bardner *et al.*, 1972). Larvae are extremely vulnerable during this period of host location and mortality may be high (Kowalski and Benson, 1978).

Once the larva locates a host plant it enters at the basal node (bulb). It then proceeds to feed by boring spirally upwards for 1–2 cm before descending into the central leaf cylinder of the shoot. Uninfested plants tend to be attacked, as infested plants are seldom found to contain more than one larva (Long, 1960). Plant symptoms become visible within 1–2 weeks of larval invasion; the centre shoot withers, turns yellow and dies. This condition is commonly known as "deadheart".

The larva has been described in detail by Puri (1925). It is white and maggot like, pointed at the front and blunt at rear. There are three larval instars, with average lengths of 1.8, 3.1 and 7 mm, respectively. During the first few weeks the larva feeds slowly in its first shoot and subsequently migrates to an adjoining shoot or plant, normally following the second moult. Intensive feeding by a the third instar may kill the plant and force the larva to make a further migration. Third-instar larvae are known to move up to 45 cm through the soil and can survive for up to 15 days in the absence of a host plant. Therefore, damage is spread between shoots and between plants, each larva requiring a total of up to five shoots to complete development (Ryan, 1973a).

Although winter wheat can be regarded as the chief host plant, other winter cereals (e.g. barley, rye and triticale) can be attacked. However, oats are virtually immune (Gough, 1946). Wheat bulb fly is also known to breed successfully in several *Triticum* species and in many grasses including couch (*Agropyron repens*), creeping bent (*Agrostis stolonifera*), common bent (*Agrostis tenuis*), meadow fescue (*Festuca pratensis*), wall barley (*Hordeum murinum*), smooth meadow grass (*Poa pratensis*), rough meadow grass (*Poa trivialis*), and possibly perennial rye grass (*Lolium perenne*) (Stokes, 1955). However, although both laboratory and field tests have shown that these species can be hosts for wheat bulb fly there is little if any data indicating the extent to which they provide a natural reservoir of the pest. Raw and Stokes (1958) recovered a small number of larvae from graminaceous weeds but, in general, survival on these hosts was very poor.

3.5 Pupae

In most years, larval development is completed by late April, the larval stages having lasted 2-3 months. The fully grown larva, approximately 10 mm long, finally enters the soil and develops the yellowish colour of the pre-pupal stage. Pupation occurs between mid-April and mid-May, the pupa resting beneath the surface within a short distance of the plant. The puparium is barrel shaped, has an average size of 6 × 2 mm and is initially a light yellowish-brown colour which darkens with age.

3.6 Predators and parasites

3.6.1 Natural enemies of adult flies

The first recorded fungal parasite attacking adult wheat bulb fly was *Empusa* (=*Entomophthora*) *muscae* in Denmark (Rostrup, 1916). A detailed study of Entomophthora infecting adult wheat bulb fly was made at Rothamsted Experimental Station, 1967-71 (Wilding & Lauckner, 1974). The most common fungi found were

those of the Entomophthora including *Entomophthora muscae*, *E. dipterigena* and *E. hylemiae*. Another fungus attacking adult wheat bulb fly, *Strongwellsea castrans*, was also described (Wilding, 1969). *E. muscae* was observed to form white annuli (rings) around the abdomen, each annulus consisting of many conidiophores (spore-bearing fungal hyphae) protruding from each intersegmental membrane.

Wilding and Lauckner (1974) found that the mean proportion of flies infected with *Entomopthora* spp. increased with the number of flies that emerged each year. They also found no clear relationship between infection and the hours of sunshine or rainfall during the life of the flies. Levels of infection were highest in warm dry years, contrary to the commonly held belief that outbreaks of *Entomophthora* occurred mainly in wet years. In a study field in 1970, two thirds of the females emerging were killed by entomophthorus fungi before they had laid any eggs, suggesting that these parasitic species can be very important in the regulation of wheat bulb fly populations.

There are few reports of predators of adult wheat bulb fly, although the predatory fly (*Empis livida*) and dung flies (*Scathophaga* spp.) have been observed feeding on them (Bardner & Kenton, 1957). Other general predators may include spiders and birds.

3.6.2 Natural enemies of eggs

Wheat bulb fly eggs may not be greatly affected by predation. Ryan (1973b) showed that few eggs disappeared between the time of laying in July and August and hatching in February. Of 3,000 eggs from soil samples, none was parasitised, 1% were diseased and 2–14% were sterile. In this study, excluding predatory carabid beetles from the plots did not affect egg mortality. However, in laboratory experiments the carabid species *Agonum dorsale*, *Trechus quadristriatus* and *Clivinia fossor* fed on wheat bulb fly eggs. Furthermore, Jones (1975) reported that 50% and 67% of eggs disappeared in experiments in 1971 and 1973 respectively, where known numbers were placed in soil and the controls were protected from predation. Most of the eggs disappeared before the end of October, when *Trechus quadristriatus* was abundant. Therefore, the evidence suggests that carabid beetles do feed on wheat bulb fly eggs but their impact on pest populations requires clarification.

There have also been reports of diseases of wheat bulb fly eggs (Cockbain & Wilding, 1968). A fungus, *Phialophora* sp. was isolated from discoloured eggs. In the field, flies may feed on *Phialophora* spores, so infecting eggs before they are laid (Cockbain & Wilding, 1969).

3.6.3 Natural enemies of larvae

According to Ryan (1973a), parasitism, overcrowding, disease and predation had little effect on the mortality of larvae. Jones (1975) also concluded that predation had little influence on larval survival. However, there is some evidence that a gram-negative bacterium infects the larvae, causing black spots and segmental banding (Hamid, 1966).

3.6.4 Natural enemies of pupae

Natural enemies have a significantly greater effect on wheat bulb fly pupae than on their eggs or larvae. In two populations of pupae studied by Ryan (1975), 34 and 27 per cent were destroyed by predators, possibly carabid beetles. In feeding tests, *Agonum dorsale* and *Pterostichus melanarius* ate pupae. A further 0.5–5.8 per cent of pupae were killed by parasitic hymenoptera which included *Phygadeuon trichops* and *Trichopria* spp. Parasitism by staphylinid beetles (*Aleochara bipustulata* and *A. bilineata*) of pupae collected from Cambridgeshire ranged from 2.0 to 12.5 per cent. Roloff and Wetzel (1989b) also noted the importance of staphylinid parasites and recorded up to 48.5% parasitism of pupae by *Aleochara* spp. in 1985.

3.7 Natural mortality (other than predators and parasites)

Ryan (1973b) found that 2–14% of eggs laid in fallow fields were sterile. Raw (1967) also noted that 20% of eggs laid were non-viable. Many larvae die between hatching and plant invasion. Gough (1946) estimated losses of 56–81%. Raw (1954) showed that mortality of newly hatched larvae was affected by the number of shoots available on which to feed. More larvae died in plots sown at a low seed rate than in those sown at a higher seed rate (Raw 1960). Raw (1967) went on to show that the number of larvae

invading a crop was significantly correlated with the number of shoots. Ryan (1973a) concluded that the mortality of both newly hatched and older larvae was related to the number of host shoots available per larva at the time of hatching. There is no evidence to suggest that the pupae are affected to any great extent by mortality factors other than predators and parasites.

Ryan (1975) proposed that fluctuations in wheat bulb fly egg populations at Rothamsted Experimental Station were caused by the weather (see Section 4.4) and stabilised by density-dependent larval mortality due to food shortage. For example, a cold winter reduces tillering of wheat plants and a similar effect might occur if sowing was delayed by a wet autumn. Ryan concluded that the weather has a pervasive effect on wheat bulb fly populations, by affecting fluctuations in egg numbers and the food source that governs the survival of larvae. Kowalski and Benson (1978) went on to investigate comprehensively the population dynamics of wheat bulb fly in their work, also based at Rothamsted. They did not fully agree with Ryan's findings. Although they considered that larval survival was dependent upon egg density and shoot density, they also showed that the key factor causing population change was variation in the number of eggs laid; they therefore proposed that adult emigration and immigration played a governing role in regulating and stabilising the population.

Kowalski and Benson also discussed other factors affecting larval survival, which may vary between years and sites, including January and February soil temperatures (Kempton et al., 1974; Young & Cochrane, 1993), soil type and pH (Long, 1960, Young 1992), depth of ploughing (Petherbridge et al., 1945), changes in egg viability or fungal infection (Ryan, 1973b) and changes in predator activity (Jones, 1975).

Most recently, Young (1992) found that mortality of eggs or neonate larvae before plant invasion was often in excess of 90%. The soil type at the sites where high mortalities were experienced was a peaty loam with a high (10–20%) organic matter content. Long (1960) also found the highest mortality (98%) of newly hatched larvae in a peaty loam compared with a sandy loam soil (73%). The reasons for this were not clearly

established but may be linked with the physical characteristics of the soil, which may impede larval migration to the soil surface prior to plant invasion.

Petherbridge *et al.* (1945) suggested that where land with or without a cover crop of mustard was deeply ploughed invasion was reduced. However, further experimentation (J E B Young, unpublished) has been unable to support this finding.

3.8 Key point summary

- Adult wheat bulb flies emerge in June and later disperse to find egg-laying sites up to about 0.8 km (0.5 mile) away.

- Eggs are laid in bare soil in the absence of a host plant. Wheat is at risk of attack when sown after fallow (e.g. set-aside), potatoes, sugar beet, vining peas and other early-harvested or low-canopy crops.

- Eggs remain dormant during the autumn and hatch from early January until late March. Each larva requires up to five individual tillers to complete development.

- There are many natural enemies which could be of future use as biocontrol agents. Adult flies are attacked by fungal infection. Eggs are eaten by predatory beetles. The pupae are attacked by parasitic staphylinid beetles.

- Many larvae die through natural causes between hatching and plant invasion. It may be possible to exploit the factors responsible for larval death as cultural control measures.

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4. PREDICTING THE RISK OF ATTACK

4.1 Factors affecting crop damage

Young (1987) reviewed the factors which influence yield loss following wheat bulb fly attack and much of the information in this section is taken from that source. A complex interaction of many factors determines the final level of crop damage. Yield losses arise as a result of larvae killing plants or shoots and reducing the number of ear-bearing shoots. This effect varies widely between fields and depends on the number of larvae invading the crop, plant density, growth stage and growth rate at the time of attack. The outcome of this pest-crop interaction is ultimately determined by environmental factors, primarily the effect of the weather on crop growth. Losses can range from around 0.1 t/ha up to levels of damage which warrant re-drilling. Recent studies (J E B Young, unpublished) have indicated that yield losses in excess of 4 t/ha are possible in untreated crops sown from November to February.

In theory, grain quality may also be affected, mainly because of the compensatory growth of an attacked crop. Surviving primary tillers tend to have heavier ears which contain larger grains. Late-developing secondary tillers produce slow ripening, smaller grains. The resulting grain sample may therefore vary in bulk density, moisture content, protein content and Hagberg Falling Number. Recently, HGCA-funded studies on the chemical control of wheat bulb fly (Young, 1992) failed to reveal any effect of attack on grain quality. However, recent work (J E B Young, unpublished) has shown that heavy attacks of wheat bulb fly can substantially decrease the specific weight of harvested grain in untreated late-autumn sowings.

4.2 Sowing date

The date of sowing has an important effect on potential yield loss due to wheat bulb fly attack (Bardner, 1968; Bardner *et al.*, 1970; Young, 1992). Crops sown before the end of October can withstand heavy infestations, as the plants have normally produced two or more tillers by the time of attack. In contrast, crops drilled in November or December are extremely vulnerable as the plants often remain at the single shoot growth stage at the time of attack. These young plants are often killed following the invasion of larvae. Late-sowing is common on the Cambridgeshire and Lincolnshire fens, when wheat follows potatoes or sugar beet. Attacks are often aggravated by deep sowing, which delays crop emergence, slows tillering and reduces the efficacy of insecticidal seed treatments (Griffiths, 1986). A more recent trend is the sowing of spring wheat and spring barley from January to March. In this case, germination coincides with the period of wheat bulb fly egg hatch and these crops often suffer pre-emergence, underground damage and may fail to emerge (Young and Talbot, 1987).

4.3 Soil and previous cropping

Differences in the scale of attack can often be linked with the effects of the previous crop, and soil condition, on oviposition. Gough (1957) drew a distinction between attacks on heavy and light (peat, sand and silt) soils in eastern England. This distinction no longer applies, largely because true fallow does not form a major part of the rotation on heavy land. However, attacks following root crops still tend to be worse on light soils and the introduction of rotational set-aside in 1992/93 has created a resurgence in the use of summer fallowing (Section 6.2).

Kempton *et al.* (1974) stated that the most obvious factor affecting egg density per hectare was the availability of egg-laying sites. They argued that if egg-laying sites were in short supply then egg density per hectare would increase without necessarily changing the number of eggs laid. Furthermore, Raw (1967) showed that egg densities in heavy land were inversely related to the annual change in fallow area. However, Young and

Cochrane (1993) considered that this theory did not apply to the results of analysis of egg numbers in East Anglia between 1953 and 1990. During this period, egg numbers declined and it was suggested that this was largely due to a decrease in the area of fallow preceding cereal crops, together with an increase in the use of insecticides. It is likely that flies were unable to locate fallows and so laid eggs in other areas which, although less preferable, were more readily available. This included rowed arable crops such as potatoes and sugar beet. This would have the overall effect of reducing oviposition density, as eggs were spread over a larger area.

In Denmark, Rostrup (1924) observed that the physical condition of the soil after cultivation appeared to affect oviposition. Experiments by Raw (1955) showed that a coarse seedbed favoured oviposition more than a fine seedbed, possibly because a greater surface area was exposed and there were more cracks and crevices into which flies could penetrate to lay their eggs. Cultivation during the oviposition period also increased the number of wheat bulb fly eggs laid. More recently, these observations were partly confirmed by Young et al. (1994) in a study of the effect on oviposition of soil cultivation and ground cover of set-aside land. Fewer eggs were laid on fallow soil cultivated to produce a smooth tilth before the July-August oviposition period than on soil that remained in a rough, ploughed condition. Secondary cultivations during July and August also increased the number of eggs laid at some sites, particularly on organic soil (Section 6.2.2).

Petherbridge et al. (1945) found weak evidence to suggest that deep ploughing (25 cm) appeared to reduce the level of attack following a catch cover crop of mustard. Recent studies (J E B Young et al., unpublished) have yielded new evidence that deep ploughing may reduce plant attack by approximately one third compared with non-inversion tillage. Presumably, fewer larvae survive the migration phase between hatching and invading a host plant when eggs are buried at greater depth by ploughing.

The highest egg numbers are usually found after the bare soil of a fallow or the large areas of soil exposed in open canopy vegetable crops such as onions. Large numbers of eggs can also occur in low standing crops such as potatoes, peas or sugar beet. In

contrast, oviposition rarely occurs in tall standing crops such as beans and cereals. In an analysis of egg counts made in East Anglia between 1953 and 1990 (Young & Cochrane, 1993) the greatest risk of attack from wheat bulb fly occurred (in descending order of risk) after fallow, potatoes, peas (mainly vining peas) sugar beet and oilseed rape. Young commented that the proportion of fields with potentially damaging numbers of eggs had remained very similar throughout the 37 year data period. However, post-1973 it was noted that the proportion of fallows with potentially damaging numbers of eggs had declined and that the risk of attack following oilseed rape, a recently introduced crop, was low.

The differences in egg numbers found in the various preceding crops have been explained in terms of oviposition behaviour. It is suggested that the wheat bulb fly does not descend more than 45 cm into an open crop to seek a suitable surface for oviposition. The effect of the previous crop has thus been interpreted in terms of the opportunity for the adult flies to come into contact with the soil (Long, 1960). Soil odour is not believed to be involved. It has been established (Bardner *et al.*, 1969) that female flies cannot detect soil odour and that the soil is identified only on contact, following a random flight.

4.4 The effect of weather

The effect of the weather has already been discussed, in connection with the response of the crop to attack by wheat bulb fly. In addition, weather may affect the number of eggs laid. Petherbridge (1921) suggested that serious infestations occur after a hot summer, but Rostrup (1924) could find no connection between August weather and attack. Bardner *et al.* (1973) suggested that fewer eggs are laid when the weather is wet in July and August. This, however, is in contrast to the work of Young and Cochrane (1993) who showed that egg numbers were negatively correlated with departure from average July temperatures and positively correlated with August rainfall. It is suggested that a wet August may increase the supply of fungal spores (particularly *Septomyxa affinis*) available as a food source; conversely, a warm July accelerates development of the

wheat crop so that it is harvested early and flies are deprived of their preferred habitat and food. Data from wheat bulb fly egg numbers in autumn 1995 support this theory. Both July and August were extremely hot and dry and egg numbers'are the lowest recorded since 1992 (ADAS, unpublished data).

Kempton *et al.* (1974) and Young and Cochrane (1993) also recognised January air or soil temperatures and rainfall in the previous October/November as important in influencing wheat bulb fly egg numbers. Warm temperatures in January cause eggs to hatch early so increasing the amount of larval mortality resulting from competition for tillers during the initial stages of plant invasion or later stages of larval development (Young and Cochrane, 1993). The survival of newly hatched larvae depends on the number of tillers present (Raw, 1967). A wet October/November of the preceding year would delay drilling of winter wheat crops which might in turn result in low tiller populations at egg hatch (Section 5.2.1).

Evans and Hughes (1996) and Evans *et al.* (1996) used a geographical information system model and a climatic model (CLIMEX) to study the distribution of wheat bulb fly in Scotland and England and the effect of climate change on distribution of the pest. A climatic matching function within CLIMEX allowed the definition of areas with climates currently suitable for wheat bulb fly survival. In Scotland, these areas were restricted to the eastern side of the country where most arable crops are grown. These findings agreed generally with those of Thomas (1948), who suggested that areas where annual rainfall exceeded 840 mm were not suitable for wheat bulb fly (Section 4.5). Furthermore, using a projected scenario for climate change, it was considered unlikely that wheat bulb fly would extend its current range of distribution by the year 2050. However, it was noted that changes in land use, such as the introduction of set-aside, may lead to an increase in the pest's range due to the greater availability of egg-laying sites (Section 6.2).

4.5 Geographical location

The geographical location of the crop also has a bearing on the likelihood and severity of attack. Although wheat bulb fly is a widespread problem in eastern England, the distribution tends to be characterised by widely scattered and localised "hot-spot" areas, which harbour large populations of the pest. Adult flies do not migrate more than 0.8 km to find suitable egg-laying sites (Section 3.2), so populations tend to remain localised.

In England, the distribution of wheat bulb fly as a pest is roughly bounded by the 840 mm rainfall isohyet (Thomas, 1948), i.e. the pest occurs mainly in the eastern area of the country where annual rainfall is less than 840 mm per annum. This area also coincides with the main wheat-growing area (Gough, 1957). The eastern side of England is thus apparently favourable for wheat bulb fly, owing to a combination of factors. These include the warmer, drier, continental type climate and, more importantly, the concentration of wheat in rotation with crops such as potatoes, sugar beet and peas, all of which serve as suitable oviposition sites. However, wheat bulb fly outbreaks can occur also in the wetter areas of England where rainfall exceeds 840 mm per annum. For example, problems have been noted periodically in the Culcheth district of Lancashire, and in the Vales of Evesham and White Horse (J N Oakley, pers. comm.).

Concerns have been voiced over the possible effects of the recently introduced rotational set-aside scheme on the distribution of wheat bulb fly. This issue is further discussed in Section 6.2. The adoption of summer fallowing under rotational set-aside could create a favourable crop rotation which would allow the pest to become more commonly established in the wetter, western areas of England.

In Germany, Wetzel and Lutze (1977) found that July and August rainfall, in combination with the proportion of root and tuber crops grown locally, defined those areas of eastern Germany worst affected by wheat bulb fly. Most recently, Evans *et al.* (1996) and Evans and Hughes (1996) have adopted a geographical information system and a climatic program (CLIMEX) to predict areas at risk from wheat bulb fly in

Scotland and England and to study the effect of climate change on the distribution of the pest (Sections 4.4 and 6.6).

4.6   Forecasting and monitoring

4.6.1 Forecasting egg numbers

There has been much debate on the value of egg counts to provide a regional forecast of the risk of wheat bulb fly attack. Gough (1947) suggested that the number of larvae is less important than how the crop is affected by soil type or the weather. He concluded that it seemed unlikely that egg counts would be of much value in forecasting pest outbreaks. Long (1959) also questioned the reliability of egg counts as a forecasting method. He considered that the large variation of the local distribution of eggs between fields, together with variation in egg and larval mortality, rendered forecasts of damage too unreliable for practical purposes. At the individual field level, this problem remains. Young (1992) reported an inconsistent relationship between egg and larval numbers. At some sites the estimated mortality of eggs or young larvae prior to plant invasion exceeded 90% (Section 3.7).

At present, the only practicable method of estimating attack at individual field level is to sample soil to obtain an egg count in the autumn. The prohibitive cost to the client and the labour intensive nature of soil sampling and the process of egg extraction means that only relatively small numbers of fields are sampled in this way each year. Historically, it was customary for ADAS Entomologists to issue a generalised regional forecast of wheat bulb fly incidence and severity, based on the overall numbers of eggs found in individual fields throughout the region in the autumn, compared with previous years. A large database of egg counts, dating back to the 1950s, was available to assist in interpretation of the findings. This forecast was used by farmers and crop consultants, in the absence of individual field egg counts, as part of their assessment of the annual risk of wheat bulb fly damage and the need to apply insecticides. Other factors, such as previous cropping and local experience of the pest, also contributed to the assessment of

risk. Additionally, the agrochemical industry used regional forecasts in their strategic assessment of the likely market demand for wheat bulb fly insecticides.

More recently, Young and Cochrane (1993) recognised the continuing demand for a regional forecast of wheat bulb fly egg numbers. Records of wheat bulb fly egg populations in East Anglia for the period 1953 to 1990 were studied in relation to previous cropping and climate. A multiple regression model was developed to predict egg numbers from meteorological data (Section 4.6.1) and archive records of egg numbers. Young considered that the model should be tested and modified as necessary according to experience, changing climate or agricultural factors. Furthermore, advice from annual forecasts (Fig. 5) would need to take account of the effects that other important factors, such as sowing date, crop structure and winter weather, have on the severity of wheat bulb fly damage. It was expected that the model would be incorporated into decision support systems in order to refine advice on integrated control measures for the pest.
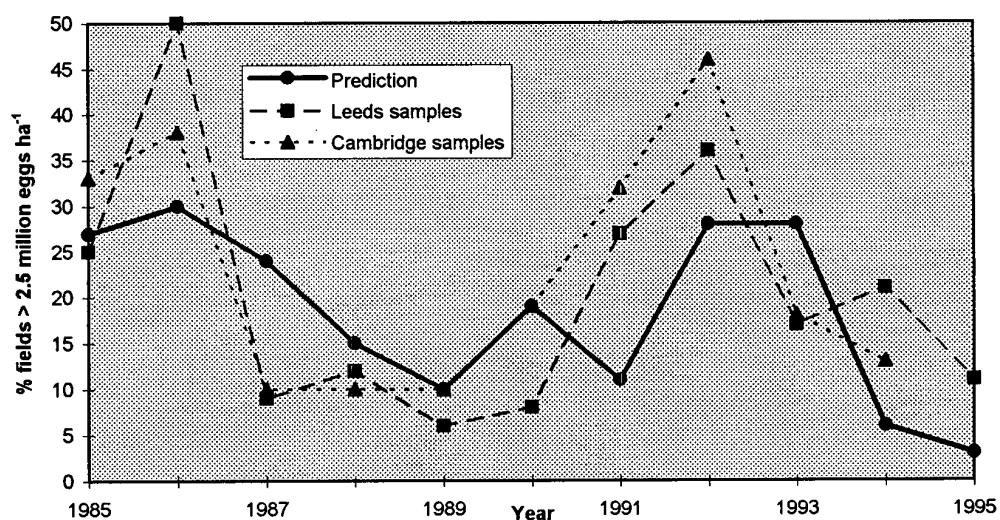
Figure 5. Predicted and observed fields with wheat bulb fly egg numbers above threshold.

4.6.2 Egg and adult trapping methods

Various trapping methods for the capture of adult wheat bulb flies have been investigated, including oviposition trays (Oakley & Uncles, 1977), light traps (Bowden & Jones, 1979) and water traps (Cooper, 1981). In each case, the number of eggs or female flies trapped was correlated with the egg population in the soil at each trapping site. Water and light trapping have the advantage of providing an early warning of egg numbers in July and August, well before that provided by soil sampling. Cooper (1981) considered that such early-season estimates of egg numbers were of use in giving advice on the need for seed treatments against wheat bulb fly, which often need to be ordered before an estimate of risk based on soil sampling was available.

4.6.3 Monitoring egg hatch

The start and progress of egg hatch is monitored by ADAS by soil sampling at representative sites at approximately weekly intervals throughout the winter. Hatched eggs are identified by the appearance of a small, ragged, emergence hole below the operculum. Predated, physically damaged or non-viable eggs are discarded. Egg-hatch monitoring information is used by ADAS consultants and their clients to enable the correct timing of egg hatch sprays (Section 5.1.3).

4.6.4 Monitoring plant invasion

The invasion of crops by wheat bulb fly larvae is assessed at the same sites used for egg hatch monitoring. Plant samples are taken at approximately weekly intervals during the winter. These are dissected in the laboratory to determine the proportion plants and tillers attacked and the developmental stage of the larvae. This information is useful in determining the optimum timing of deadheart sprays (Section 5.1.4). This is towards the end of egg hatch when the majority of larvae have invaded the crop and are in their first instar but before they move to other plants or shoots and cause secondary damage (Griffiths & Scott, 1969). For individual fields, samples examined during the critical period of plant invasion also provide a threshold-based decision on whether a deadheart spray is required (Section 5.4.2).

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4.7   Key point summary

- Wheat bulb fly is mainly restricted to the eastern half of Britain.   Distribution is affected by climate and crop rotation.

- Yield losses are variable but may exceed 4 t/ha in untreated crops sown from November to February.

- Early-sown crops drilled before the end of October usually tiller well and can withstand heavy pest infestations.

- Egg numbers are influenced by the availability of egg-laying sites and the weather during egg laying.   Hot, dry, weather during the egg-laying period reduces the number of eggs laid.

- Rough and freshly cultivated soil surfaces favour wheat bulb fly oviposition.

- The greatest risk of attack (in descending order of risk) occurs in wheat sown after fallows, potatoes, vining peas, sugar beet and oilseed rape.

- Weather conditions influence the severity of attack through their effect on larval survival and crop growth.   Severely cold winters result in greater crop damage as growth is checked and tillering delayed.

- Regional forecasts of attack are based on autumn sampling to determine egg numbers or a model using climatic data.

- Soil sampling for egg numbers and monitoring egg hatch and plant invasion help predict the need for and timing of insecticide treatment.

5. CONTROL MEASURES

5.1 Chemical control

British farmers rely primarily on chemical control to reduce losses from wheat bulb fly. The early experiments of over 40 years ago (Gough & Cohen, 1954) indicated that spraying against the adult flies in crops where they were laying eggs (e.g. potatoes, sugar beet and peas) was unsatisfactory. Seed treatment appeared to be the simplest and most promising approach.

Until 1967, organochlorine seed treatments were the mainstay of wheat bulb fly control. However, as their adverse environmental effects became known, restrictions were placed on their use. Much concern surrounded the accumulation of insecticide residues in certain birds and mammals, and these effects have been well documented (Stickel, 1973). As a result, the development of wheat bulb fly chemical control over the past 30 years has focused mainly on organophosphorus and, to a lesser extent, synthetic pyrethroid insecticides, the residues of which do not persist or accumulate in animals. Promising compounds currently in development include a soil-active synthetic pyrethroid, tefluthrin (Frost *et al.*, 1994).

The chemical control measures currently employed in Great Britain are a result of many field experiments carried out over the past 40 years, the work of Maskell and Gair (1986a, 1986b) and Young (1992) being particularly comprehensive. Insecticides can be applied as seed treatments, seedbed treatments with sprays applied at sowing, and sprays at egg hatch or at the first signs of plant damage. A range of insecticides is currently available (Table 1). No single insecticide treatment will give complete control of the pest (Young, 1992) so combinations of two or more are normally applied where there is a high risk of attack.

5.1.1 Seed treatments.

Seed treatments are widely used, particularly in the fenland areas of East Anglia where much winter wheat is sown late following sugar beet or main-crop potatoes. In most situations, seed treatments are not the sole means of chemical control and tend to be used in conjunction with supplementary egg hatch or deadheart sprays.

The early tests of candidate insecticides demonstrated that organochlorine seed treatments containing aldrin, dieldrin or gamma-HCH effectively reduced attack and increased yield (Gough and Woods, 1954; Gough et al., 1961). Aldrin, dieldrin and, to a lesser extent, gamma-HCH, were found to have a penetrant mode of action, killing the larvae within the plant in addition to a protective contact action (Way, 1959b). Griffiths (1986) ranked the following seed treatments in descending order of ability to kill larvae within the plant: dieldrin > chlorfenvinphos > ethion > carbophenothion > gamma-HCH > permethrin. The two currently available wheat bulb fly seed treatments, chlorfenvinphos and fonofos, are believed to have a dual mode of action. Larvae are killed on contact before they enter the plant and there is also some penetrant activity, killing larvae within attacked shoots.

As early as 1954 (Gough & Woods, 1954), it was recognised that seed treatments were most effective on later sowings and this finding was confirmed by Maskell (1970) and Griffiths et al. (1976). Their use is normally confined to crops sown later than mid-October. Currently, shallow sowing, no deeper than 3 cm, is always recommended in conjunction with seed treatment as it is known to enhance efficacy and encourage rapid establishment of the crop. The effect of sowing depth on the efficacy of wheat bulb fly seed treatments was first demonstrated by Way (1959b) and confirmed by Griffiths et al. (1975) and Scott (1981).

Deep sowing (e.g. 7.6 cm) results in increased pest damage compared with shallow sowing (e.g. 1.3 cm). Deep-sown seed has a lower concentration of insecticide seed treatment around the 'bulb' (basal node area) of the seedling, particularly in the case of compounds that are less mobile within the plant and which rely on contact activity against the larvae. The larvae, which tend to migrate to the surface layer of soil before

invading plants, tend to enter the plant within about 2.5 cm of the soil surface (Way, 1959b). Therefore, less contact is made with the seed treatment which is usually concentrated around the seed located at a greater depth. Furthermore, deep sowing also results in 'backward' plants because the time taken for the shoot to reach the surface is increased and tillering is delayed. This may have severe implications for late-sown (November onwards) crops as single-shoot plants, prior to the formation of lateral buds, are killed by larval invasion. However, slightly older plants with small lateral shoots are able to continue growing (Griffiths, 1986).

Phytotoxic effects have been observed in conjunction with many seed treatments. Maskell and Gair (1986a) demonstrated that chlorfenvinphos seed treatments delayed germination but that the effect was transient and subsequent plant densities and growth compared favourably with untreated control plots. Crop yield was also unaffected. Such effects have also been noted by other workers (Maskell, 1967 and 1970; Dixon, 1967; Heath, 1967; Mathias and Roberts, 1969; Griffiths *et al.*, 1975 and Scott, 1981). The phytotoxic effects of chlorfenvinphos were also shown to be worse in organic than in mineral soils (Maskell, 1967 and 1970; Heath, 1967 and Maskell and Gair 1986a). However, reductions in plant population and yield resulting from chlorfenvinphos seed treatment were noted by Oakley (1977 & 1980).

McKinlay (1982) demonstrated that virtually all seed treatments investigated in Scotland were phytotoxic with the exception of micro-encapsulated fonofos. Maskell and Gair (1986a) also showed that micro-encapsulated fonofos had no adverse effect on germination or subsequent plant growth and these findings were in agreement with the studies of Catling (1967) and Catling and Cook (1967). Micro-encapsulated seed treatment formulations reduce the risk of phytotoxicity (Scott, 1981) and in future it is likely that more insecticidal seed treatments will be formulated in this way.

Although seed treatments have the merit of exposing the environment to minimal, well-targeted, amounts of insecticide, there remains the risk that they may affect grain-eating birds (Bunyan *et al.*, 1971; Jennings *et al.*, 1975). Deaths of wild geese in east Scotland in 1971-72 and 1974-75 have been attributed to the ingestion of wheat

seed treated with carbophenothion, and to a lesser extent dieldrin (McKinlay, 1977). As a result of these incidents, carbophenothion was withdrawn from use in Scotland. The risk to birds is minimised by adhering to the conditions of approval for use and the associated precautions on the product label. Most importantly, sown seed should always be well covered by soil. Treated seed should not be left exposed on the soil surface. Seed spillages must also be cleaned up and safely re-used or buried.

5.1.2 Seedbed treatments

Experiments showed that a seedbed spray of chlorfenvinphos was generally effective at controlling wheat bulb fly in both mineral and organic soils (Maskell and Gair, 1986b). Young (1992) applied fonofos spray to the seedbed immediately after sowing at four high-risk sites and found a cost-effective yield increase (+29%) at one site. However, fonofos spray was withdrawn from sale in 1992. Sprays of chlorfenvinphos and chlorpyrifos are currently approved for application at, or soon after, sowing. In practice this option is rarely used because of its relatively high cost, which is currently about £40/ha and £68/ha for chlorfenvinphos and chlorpyrifos, respectively.

5.1.3 Egg hatch sprays

Oakley (1977) found that protective sprays applied immediately before or during the early stages of egg hatch compared favourably with seed treatment. Chlorfenvinphos, chlorpyrifos and pirimiphos-methyl are now recommended for use as egg hatch sprays. Chlorfenvinphos and chlorpyrifos are generally considered to be the more persistent of these insecticides and they are applied at the start of egg hatch (normally in January). Maskell and Gair (1986b) showed that chlorfenvinphos was more effective in mineral than in organic soil. The rate of application in organic soil is therefore double that in mineral soil, to counteract the potential adsorption of active ingredient by the organic fraction of the soil. Seedbed and egg hatch treatments act mainly by killing newly hatched wheat bulb fly larvae in the soil, thus preventing them from invading the crop. Egg hatch treatments can be difficult to apply when the soil is wet (McKinlay, 1981) although the development of low pressure ground spraying equipment reduced this problem (Maskell and Gair, 1986b). In Humberside, egg hatch sprays are the most frequently used treatment against wheat bulb fly.

Table 1. Insecticides approved in the UK for wheat bulb fly control in winter wheat

Type of treatment	Active ingredient	Product	Formulation	Rate (l/ha)	Approx. 1995 cost (£/ha)
Seed treatments	Chlorfenvinphos	Birlane LST	32% liquid	3 ml/kg seed	11
	Fonofos	Fonofos	43% liquid	2.5 ml/kg seed	12
Seedbed sprays applied at or soon after drilling	Chlorfenvinphos	Birlane 24	24% EC	{5.6 pre-drilling	53
		Sapecron 240 EC	24% EC	{4.2 post-drilling	40
	Chlorpyrifos	Spannit	48% EC	4.0 pre-emergence	68
Egg hatch sprays, applied at the start of egg hatch	Chlorfenvinphos	Birlane 24	24% EC	{2.8 mineral soil	27
		Sapecron 240 EC	24% EC	{5.6 organic soil	53
	Chlorpyrifos	eg Dursban 4	48% EC	1.5	26
		Spannit	48% EC	'	
	Pirimiphos-methyl	Blex	49% EC	1.8	34
Deadheart sprays, applied at the onset of plant damage	Dimethoate	Various approved products*	37% EC	1.7	5-10

EC = emulsifiable concentrate.   LST = liquid seed treatment.

Products marked * have approval for aerial application.

5.1.4 Deadheart sprays

The deadheart sprays are so called because they are applied at the first signs of plant damage (deadheart) when most of the larvae have invaded the plants and are in their first or second instar, but before they move to other shoots and cause secondary damage (Griffiths and Scott, 1969). The only insecticide available within this category is the systemic organophosphorus insecticide dimethoate.

In late-sown, high-risk, fields subjected to heavy attack, dimethoate is often applied in support of earlier treatments such as seed treatments or egg hatch sprays (Sections 5.1.2 & 5.1.3). Follow-up treatment with a deadheart spray may be vital in those years when seed treatments and egg hatch sprays lack the persistence to control attacks delayed by cold weather.

The organic fenland soil (peat) of East Anglia is highly adsorptive and reduces the efficacy of many soil-active insecticides. This effect can be partially overcome by the use of higher rates of active ingredient but, in general, egg hatch and seedbed treatments do not perform well on peat soils. As a result, seed treatment followed by up to two deadheart sprays is the most widely used means of controlling wheat bulb fly on peat soils.

Field experience suggests that between 30 and 60% of larvae are killed from a single application of dimethoate (J E B Young, unpublished). Young and Talbot (1988) demonstrated that dimethoate significantly reduced larval numbers in comparison with untreated control plots. Yield responses to dimethoate are often variable. Severely attacked crops at pre-tillering or early tillering growth stages are normally the most likely to benefit from treatment. Maskell and Gair (1986b) were unable to show any yield increase following dimethoate treatment. However, yield increases of up to 0.9 t/ha have been observed with a single application of dimethoate (J E B Young, unpublished). Maskell and Davis (1974) demonstrated the importance of spray timing with a previously available deadheart spray, omethoate. Omethoate was generally regarded to be more effective than dimethoate. The correct timing of dimethoate is,

therefore, vital to maintain acceptable standards of control now that dimethoate is the only remaining deadheart spray.

5.1.5   Tank mixtures

Soil conditions can often delay the application of egg hatch sprays and, as previously discussed, in some seasons when egg hatch is prolonged by cold weather, plant damage can occur well before the completion of egg hatch. In such difficult situations it has become common practice to apply an egg hatch spray, such as chlorfenvinphos, in combination with dimethoate. This technique is viewed as a compromise because neither ingredient of the mixture is being applied at the optimum time. However, the tank mix option has been shown to be effective in some circumstances. In previous HGCA-funded studies, Young (1992) found that a chlorpyrifos plus dimethoate mixture applied during the mid-phase of egg hatch when plant invasion was underway gave significant yield increases, averaging 10% of the untreated yield, at five out of eight high risk sites.

5.2 Cultural control

The advantages offered by adopting cultural control techniques against wheat bulb fly are often overlooked. Other agronomic considerations usually have an overriding influence in determining which control measures are implemented against wheat bulb fly. Although the use of insecticides against wheat bulb fly is often relatively cheap and convenient, cultural methods offer the advantage of being less hazardous to the operator, wildlife and the environment.

5.2.1 Sowing date and depth

The most widely adopted and practical means of cultural control is early sowing in the autumn. Early-sown crops are more tolerant of wheat bulb fly attack and are able to compensate for damage (Section 4.2). In most years, wheat sown before the end of October has produced at least two tillers per plant (Growth Stage 22, after Tottman and Broad, 1987) by the time of larval invasion in January. Subsequent damage is,

therefore, minimised owing to compensatory plant growth. However, early-sown crops bearing more tillers can assist the survival of larvae and consequently maintain or increase the pest population which could add to the risk of damage in the following year (Raw & Lofty, 1959; Raw, 1967). Although early-sown crops are at increased risk from diseases, particularly barley yellow dwarf virus (BYDV), the majority of winter wheat is sown before the end of October in Great Britain. This has been made possible by advances in plant breeding and crop protection which allow the higher yield potential of early-sown crops to be realised.

In the case of spring-sown cereals, crops sown during the egg hatching period (early January to late March) may suffer severe pre-emergence damage (Section 4.2). Delaying sowing spring cereals until the egg hatch is finished (late March or early April) is an effective way of avoiding attack. However, such a delay is normally unacceptable, owing to the higher yield potential of earlier sowing.

Drilling depth influences the severity of wheat bulb fly attack. Sowing seed no deeper than 3 cm enables the crop to establish and tiller more rapidly than if it was sown deeper. This is particularly important in late-sown crops (November onwards), as the effect of attack is less severe where tillering is underway by the time larvae invade the crop during January, February and March.

5.2.2 Cultivation and soil conditions

The number of eggs laid is influenced by previous cropping, the condition of the soil tilth and date of cultivation in relation to the egg–laying period (Sections 3.2 & 4.3). Delaying cultivations after crops such as vining peas or oilseed rape until mid-August may reduce the number of eggs laid and lower the risk of attack in a following crop of wheat. However, delaying seedbed preparation for a first wheat may be both inconvenient and impractical.

Where land is fallowed as part of rotational set-aside during the summer, in readiness for autumn-sown wheat, certain cultural procedures can minimise the number of eggs laid (Sections 4.3 and 6.2.2). Cultivations which disturb the soil should be avoided during

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the egg laying period of July and August. Freshly cultivated fields, or plots within fields, attract greater egg-laying than undisturbed soil (Raw, 1955 & 1960; Oakley & Uncles, 1977). Creating a fine tilth with a flat seedbed surface before egg laying starts will also reduce the number of eggs laid (Young *et al.*, 1994).

Petherbridge *et al.* (1945) found that where land with or without a cover crop of mustard was deep ploughed (25 cm) after the end of egg laying but before egg hatch started the subsequent level of attack was reduced. Recent experimental evidence gives some support to this observation (J E B Young, unpublished).

5.2.3 Trap fallows and cover crops

Trap fallows sited near infested fields and subsequently planted with a non-host crop have long been suggested (Rostrup, 1924; Oakley, 1980) as a means of safely diverting the egg laying of local populations of wheat bulb fly. Young (1987) commented that trap fallows stood little chance of adoption in the intensive system of agriculture found in eastern England unless set-aside was introduced. Rotational set-aside started in 1992/93, presenting a new opportunity to utilise trap fallowing to reduce wheat bulb fly populations (Section 6.2.2). Sowing a non-host crop such as oilseed rape after set-aside fallow renders the pest harmless, as larvae die in the absence of a host crop. If trap fallows were strategically deployed in areas where wheat bulb fly is established they may prevent any further increase in pest populations. However, this strategy requires further investigation.

Alternatively, smaller areas within fields (e.g. headland strips) could be cultivated repeatedly during the egg-laying period, to induce the laying of larger numbers of eggs within the cultivated area than the surrounding undisturbed ground (Section 6.2.2). Such areas would then be treated as pest "killing grounds" by sowing a non-host crop such as oilseed rape, or by the selective application of insecticides in a following crop of wheat.

Cover crops offer a way of preventing or severely restricting egg laying in bare soil. For example, Young *et al.* (1994) demonstrated that white mustard sown in May as a cover

for land coming out of rotational set-aside (prior to winter wheat) greatly reduced the number of eggs laid compared with the fallow treatments. To prevent egg-laying, cover crops need to be established and to have produced sufficient ground cover before egg laying commences in July. Cover crops such as mustard may also require topping with a high-set mower during flowering to prevent seed return to the soil. Destruction of a cover crop in preparation for the following crop should be delayed until late August when the risk of egg laying is receding. However, such a delay may, in some years, pose problems in the preparation of a favourable seedbed for the early-autumn sowing of wheat or oilseed rape.

5.2.4 Crop rotation

Changing rotations to avoid growing first wheats after crops that attract wheat bulb fly egg laying (e.g. potatoes, vining peas, sugar beet, set-aside fallow) is often impractical. However, one possibility is to use oilseed rape instead of winter wheat immediately after rotational set-aside where fields are fallowed in the summer.

The concept of eliminating host cereals from the rotation over a wide area has been considered as a means of reducing wheat bulb fly populations. This work is discussed further in Section 5.3.2.

5.2.5 Varietal resistance

The development of wheat cultivars with resistance to wheat bulb fly attack has not been investigated. Raw (1967) found that wheat cultivars did not vary in the proportion of shoots infested but there were differences in their tillering capacity. Although cultivars with the most tillers tolerated and survived attack better than those with few tillers, they also favoured a high survival of the pest. Lupton and Bingham (1967) concluded that differences between cultivars in their ability to recover from attack were unreliable, ineffective in cases of severe infestation and too small to be usefully exploited in a breeding programme. However, it was suggested that advanced cultivar selections of wheat should be screened for their ability to recover from wheat bulb fly attack.

In an HGCA-funded research project, Young (1992) concluded that there were no important differences in the inherent susceptibility of contemporary wheat cultivars to wheat bulb fly. However, high yielding soft-endosperm feed wheats (cvs Apollo, Beaver and Riband) yielded relatively well in the presence of substantial attacks by wheat bulb fly. In contrast, the hard endosperm, bread-making quality cultivars (cvs Hereward, Mercia and Tonic), were relatively lower yielding, irrespective of the level of attack, as would be expected from their agronomic characteristics. Although other factors such as sowing date and the weather have a greater effect on the level of attack than the choice of variety, Young (1992) suggested that if grain yield is of prime importance, the stronger tillering feed wheats were best suited for use in fields where the risk of damage was high. Gene transfer technology may now offer a means of developing new cultivars of wheat resistant to wheat bulb fly.

5.2.6 Seed rates

Raw (1960) found that with an early autumn (October) sown crop, the main effect of a high seed rate was to favour the survival of the pest by supporting greater numbers of larvae. However, the highest seed rate used (3 bushels/acre = approx. 205 kg/ha, assuming average bulk density of 76 kg/hl) consistently outyielded the lower seed rates (less than 100 kg/ha) by an average of 0.34 and 0.41 t/ha at two sites respectively. Raw concluded that to reduce wheat bulb fly attack, early sowing should be combined with the lowest seed rate consistent with high yield in order to minimise survival of the pest.

In recent MAFF-funded studies (J E B Young, unpublished), larval numbers tended to be greatest in the highest seed rates of early-sown (October) crops, agreeing with the earlier work by Raw. Young concluded that increasing the seed rate was justified to compensate for loss of plants to wheat bulb fly larvae. The highest seed rate used was 550 seeds/m^2, which is equivalent to about 248 kg/ha at an average thousand grain weight (TGW) of 45 g. This remained profitable in later sowings (late November onwards) but did not eliminate the need for insecticidal treatment. In contrast, increasing the seed rate of earlier sowings (mid-October to mid-November) remained profitable up to 450 seeds/m^2 (203 kg/ha @ 45 g TGW), as did insecticide use. At high

levels of attack, increases in seed rate could not entirely replace the cost-effective use of insecticides in October or November sown crops.

Young concluded that further work was required to investigate if increases in seed rate could eliminate the need for insecticides in crops subjected to lower levels of attack (< 500 eggs/m^2) than those studied. An integrated control strategy was proposed, combining higher seed rates with a reduced level of insecticide use. The tendency of dense crops to support high populations of wheat bulb fly larvae could result in an increase in pest levels. Another component of the integrated strategy would therefore be needed to counteract this possibility.

5.3 Alternative methods of control

5.3.1 Population control

Raw (1967) proposed that more attention should be given to controlling wheat bulb fly populations over a wide area than to controlling crop damage. The concept of integrating population control with chemical control measures was considered further by Oakley (1980). He demonstrated that wheat bulb fly populations could be reduced by various insecticidal control strategies which varied according to sowing date and the amount of tillering by the crop at the time of attack. Once the pest had been reduced to levels generally considered to have negligible effect on yield (100 eggs/m^2 or 50 larvae/m^2), he proposed that insecticides should be applied selectively to contain the population below this threshold. He concluded that maintaining larval numbers below 50/m^2 would prevent potential yield loss in the following season by reducing the emergence of egg-laying flies. In addition, populations could be reduced further by inducing egg laying in 'killing grounds' prepared by creating small areas of trap fallow in the summer before the start of egg laying. The resulting concentrations of eggs would then best be dealt with by sowing a non-host crop. Alternatively, an intensive insecticide regime could be used in a following crop of wheat.

During the early 1980's, Oakley and High (in Luers, 1986) tested the theory of wheat bulb fly population control in a farm-scale project based at Nocton, Lincolnshire ("The Nocton Project"). The objective was to reduce the adult wheat bulb fly population on a large (2,740 ha) farm estate and to minimise the scale of attack and associated cost of treatment in subsequent years. Dimethoate or omethoate (deadheart sprays) were applied to all fields with larval populations exceeding 35 larvae/m². In fields with large egg populations, normally in excess of 250 eggs/m², residual insecticides such as fonofos were applied conventionally at sowing or at the start of egg hatch.

Over a four-year period (1981-1984) egg numbers laid in the experimental area were reduced by 40%, compared with a reduction of 13% on adjoining land. The average cost of wheat bulb fly treatment on the farm was reduced from £22,500 in 1981-2 to £2,300 in 1984-85. Financial savings were made by minimising the use of relatively expensive residual insecticides applied at sowing or at egg hatch. However, high egg counts, believed to have resulted from immigrant flies, continued to be found in a small number of fields in the experimental area. It was suspected that one source of re-infestation was from areas of uncultivated land alongside a railway track. The Nocton Project showed that wheat bulb fly population control was a viable concept but required the long-term co-operation of farmers over a large area of land, together with intensive monitoring and supervision by entomologists.

5.3.2 Cropping restrictions

Alterations in the sequence of crop rotation to avoid sowing winter wheat after crops suitable as egg-laying sites are usually impractical. Legowski *et al.* (1968) showed that cropping restrictions over a large area can successfully reduce the wheat bulb fly population and the risk of serious damage in following years. Winter wheat and winter rye were excluded from an 800 ha area during 1966/7. Spring wheat was not sown until after mid-March, after egg hatch. In the centre of the experimental area the average egg count was reduced from 1.9 million/ha in 1966 to 0.2 million in 1967. No such reduction was observed in fields adjoining the experimental area. Legowski commented that it would be necessary to avoid growing wheat only on those fields suitable for egg-laying. On many farms this would permit a large proportion of the winter wheat

area to be retained. Because of the difficulties involved in controlling crop rotations over large areas, changes in rotational policy may be more appropriate to farming co-operatives or large farm estates in areas prone to serious damage by the pest. The fact that winter wheat remains one of the most profitable and convenient arable crops to grow continues to pose a major obstacle to the cropping restriction approach.

5.3.3 Control of adult flies

The concept of applying control measures against the adults in early July, at their emergence sites and before their eggs matured, was proposed by Jones *et al.* (1972). Control of adult flies had already been attempted unsuccessfully by Gough and Cohen (1954). However, their treatments of persistent insecticides were applied against flies at their oviposition sites. Bardner *et al.* (1977) observed that adult flies remained concentrated at their emergence sites (i.e. wheat crops previously infested by larvae) for several weeks before the start of egg laying. It was also suggested that control measures applied against adult flies whilst they remained at their emergence sites could potentially be very effective in reducing crop damage the following year by decreasing the number of eggs laid. Such a technique could also form a useful component of an integrated population control strategy (Section 5.3.1). However, Kowalski and Benson (1978) cautioned against the control of adult flies, as they considered that increased immigration from other sources would occur. They stated that, to be effective, adult control would need to be extended to all identifiable sites of infestation (presumably over a wide area) rather than focused on emergence sites with a known high density of the pest. They concluded that wide-area insecticide use against adults would be an undesirable practice on environmental grounds.

The control of adult flies has not been fully investigated, although J N Oakley (pers. comm.) attempted a farm-scale observation in 1979 at Holderness, South Humberside. Chlorpyrifos was applied to two fields of wheat (after vining peas) when adult flies were emerging in early July. Post-treatment monitoring of adult fly activity in treated and untreated fields indicated that numbers were initially depressed by the sprays. However, by early August immigration of flies from outside the treated area eliminated these differences. Oakley concluded that flies redistribute between

emergence and feeding sites once they start to seek suitable oviposition sites. Provided that the treatment area was isolated (at least 0.8 km) from other sources of flies to minimise immigration, this observation supported the theory that it might be possible to control wheat bulb fly populations by killing adults at their emergence sites before oviposition.

The prospect of applying insecticides against adult flies in large areas of wheat during peak summer would be environmentally undesirable. However, this technique would be more acceptable if adults could be controlled with biological agents such as the fungal pathogen *Entomopthora muscae*.

Other possible techniques targeted against adult flies include mass trapping or poison baiting with food or pheromone-baited lures, mating disruption techniques (including semiochemical-based methods) and the release of sterile males. However, the large scale and expense of techniques such as mass trapping and the sterile-male technique make them unlikely candidates for future development.

5.3.4 Host location

Immediately after hatching from the egg, the neonate larvae locate a suitable host plant by responding to an arrestant plant exudate (Section 3.4). This is a chemical which causes insects to aggregate in contact with it (Greenway *et al.*, 1974). Greenway *et al.* (1976) investigated the nature of the chemicals produced by wheat and oats that influence the host-locating behaviour of wheat bulb fly larvae. Their results suggested that the wheat 'arrestant' was a polyphenolic compound, possibly a glycoside. The oat 'anti-arrestant' was thought to be a polyhydroxylated aliphatic compound.

Bardner *et al.* (1972) stated that the insect repellents DEET and MGK11 decrease the larval arrestancy of wheat extracts. Attempts were made at utilising insect repellent compounds to deter the larvae from entering the plants (Griffiths *et al.*, 1974). However, experimental seed treatments containing the insect repellents DEET and MGK11 failed to protect winter wheat against attack by wheat bulb fly in the field.

Scott and Greenway (1984) attempted to disrupt the host location process as a practical method of crop protection. In laboratory tests, they found a decrease in larval attack in wheat plants grown in soil treated with activated charcoal. The activated charcoal was believed to have adsorbed the arrestant compound(s) exuded from the plants. However, in field experiments comparing activated charcoal with conventional insecticides, the control exhibited by the charcoal was disappointingly low. This was thought to be due to the lowering of larval sensitivity thresholds under natural conditions in which no alternative food sources were readily available. Young (1992) and Long (1960) noted higher levels of larval mortality in organic (peaty) soil than mineral soil. It is possible that the high organic carbon content of peat soils may adsorb the arrestant compounds exuded by the host plant and lower the success rate of larval invasion.

Oats are not attacked to any great extent by wheat bulb fly (Gough, 1946) and are virtually immune. Greenway *et al.* (1974) found that the arrestant effect of wheat extract was decreased on combination with an oat extract. This suggested that oats contain material which repels the larvae, or inhibits their ability to sense or respond to wheat arrestant, or affects it chemically. Advances in plant breeding technology using genetic engineering techniques may now offer a means of neutralising or eliminating the arrestant material(s) in wheat or of utilising the factor in oats which make them unsuitable as a wheat bulb fly host.

5.3.5 Biological control

The use of biological control agents against wheat bulb fly has not been fully investigated and none has been used commercially. There are a number of candidate beneficial species and these are discussed in Section 3.6. The only attempt at biological control in the literature was the use of an experimental seed treatment based on commercial formulations of spores of *Bacillus thuringiensis* (Cockbain, 1968). Heat-stable *B. thuringiensis* exotoxins were also tested in this work. Seedlings were dipped in an aqueous solution of the exotoxins and larvae then allowed to feed on them. The spore-based seed treatments were not very effective in reducing the number of shoots attacked at the rates applied. It was noted that the dose rate would need to be increased by up to ten times (maximum dose applied was 1.0% viable spores/weight of seed) to

halve the number of attacked shoots. The exotoxin tests also showed only partial activity against wheat bulb fly larvae at the dose rates tested. In the future, genetically engineered strains of *B. thuringiensis* with improved activity against wheat bulb fly could possibly be developed.

5.3.6 Flame throwers

There was interest during the 1960s in destroying wheat bulb fly eggs on, or just below, the soil surface by the use of a flame thrower. A tractor pulled, propane powered, flame thrower was used at three experimental sites in 1965/66 (Legowski, 1968). The flame thrower failed to control subsequent attacks by wheat bulb fly larvae. It is likely that sufficient eggs, possibly just under the soil surface, remained unharmed and gave rise to a significant pest infestation. Equipment capable of thoroughly heating the entire surface layer of soil to a lethal temperature would be required to kill the eggs.

5.4 Current control recommendations and thresholds

5.4.1 Chemical control strategies

The risk of wheat bulb attack in individual fields may be defined according to an egg count, derived from soil sampling in the autumn (Table 2). Alternatively, information on the local prevalence of wheat bulb fly, combined with details of previous cropping and a region-wide forecast of egg numbers may assist in defining the risk of attack. However, there may be considerable variability associated with predicting the final level of attack from egg numbers alone (Section 4.6.1). The chemical control strategies currently recommended vary according to category of risk and sowing date (Table 2).

5.4.2 Action thresholds

The action thresholds based on egg numbers/ha are largely empirical. The origin of the action threshold of 2.5 million eggs/ha can be traced back as far as the work of Gough *et al.* (1961) and F E Maskell (unpublished). Gough stated that larval numbers below 1.25 million/ha were unlikely to influence yield, whilst numbers above this level would exert an increasingly greater effect. The current threshold was subsequently derived from this

figure, based on the assumption that 50% of eggs would produce surviving larvae. The resulting 2.5 million eggs/ha threshold has been in use for many years in England and Scotland and has proved to be generally reliable. However, it is not applicable to crops sown after November, where germination may coincide with egg hatching. Such crops are particularly vulnerable to wheat bulb fly and may merit insecticide treatment at egg numbers less than 1 million/ha. The differing susceptibility of crops according to sowing date is, therefore, taken account of in current recommendations (Table 2).

In Germany, an action threshold of 0.6–0.8 million eggs/ha has been used as a threshold for the application of wheat bulb fly seed treatments (Roloff & Wetzel, 1989c). Furthermore, a threshold of 40 to 60 damaged shoots/m² was used to trigger cultural control measures such as the early application of nitrogen to aid crop recovery. However, owing to changes in wheat growing practices, the authors considered that these thresholds were too low for practical conditions.

The decision to apply a systemic deadheart spray (dimethoate) in February or March may also be threshold driven. The deadheart spray thresholds, based on empirical experience, were implemented by ADAS (Young, unpublished) in support of a plant dissection service. Wheat plants are dissected under low-power microscopes in the laboratory to determine the proportion of tillers attacked and the developmental stage of the larvae. The following action thresholds are used for plant populations of no fewer than 200 plants/m²:

Growth Stage (Tottman & Broad, 1987)	% tillers attacked
GS 20	10%
GS 21	15%
GS 22 +	20%

These thresholds have been in use for over five years and have been found to be generally reliable. Applying deadheart sprays in response to the findings of plant dissection may allow greater precision in the timing of treatment, before the full extent of damage becomes visible in the field.

5.4.3 Future options for control and IPM

The principles of chemical control of wheat bulb fly and the various strategies of insecticide use are now generally well established. In future, advancements could be made by improving the integration of cultural and biological control techniques with the existing chemical methods. Much fundamental knowledge about cultural and biological control already exists (Sections 5.2 & 5.3.5). It should be possible to apply this knowledge to develop integrated pest management (IPM) strategies against wheat bulb fly.

Various forms of non-chemical control are currently under-exploited and could be better utilised in future to reduce dependence on insecticides. The concepts of trap fallowing and control of adult flies or pest populations over large areas could be adopted more widely. The subject of biological control also merits further consideration. There may be scope to enhance the activity of beneficial predators and parasites and to manipulate other factors which govern the natural mortality of the pest.

Farm-level decision making could also be improved by the development of decision support systems which could incorporate the latest advances in forecasting and predicting attack. The research required to achieve this is discussed in Section 6. The following subjects could form components of an IPM strategy targeted against wheat bulb fly, some of which require further research (Section 8):

Chemical control:	Insecticides targeted at larvae and adults using cost-effective action thresholds.
Cultural control:	Sowing date, seed rates, cultivations, trap fallowing, cover crops, varietal resistance/tolerance, crop rotations.
Biological control:	Exploitation of predators, parasites, pathogens and other mortality factors.
Alternative methods:	Population control (including control of adult flies), disruption of host location, mating disruption.
Decision support system:	Cost-effective treatment decisions, management, information and help, predictive models for forecasting distribution and severity, pest monitoring.

Table 2: Currently recommended chemical control strategies against wheat bulb fly in winter wheat (Young 1992).

Risk category	Typical previous crop	Sowing date		
		Sept. - Oct.	Nov. - Dec.	Jan. - March
Low Less than 1.0 million eggs/ha	Oiseed rape Dry peas	Economic damage is unlikely. No treatment	No treatment	A
Moderate 1.0 to 2.5 million eggs/ha	Sugar beet Maincrop potatoes	No Treatment	A Optional D	A Optional D
High 2.5 to 5.0 million eggs/ha	Early/Second early potatoes, Vining peas	Optional D	A Optional C or D	A B Optional D
Very High More than 5.0 million eggs/ha	Fallow Onions	C Optional D	A C	A B Optional D

Key:

A = Seed treatment - fonofos or chlorfenvinphos
B = Seed-bed treatment - chlorfenvinphos or chlorpyrifos sprays
C = Egg-hatch spray - chlorfenvinphos or chlorpyrifos
D = Deadheart spray - dimethoate

5.5   Key point summary

- Control of wheat bulb fly in Britain is primarily reliant on insecticides and treatments are defined according to risk of attack and sowing date.

- Seed treatments are widely used in the late-sown crops but insecticides can also be applied at drilling, at egg hatch and at the first signs of plant damage.

- Cultural control methods, although often overlooked, have the advantage of being less hazardous to the environment.

- Early sowing is most practical and these crops usually produce at least two tillers by the time of larval invasion.

- Cultivations, trap fallows and cover crops can be used to influence the number of eggs laid and reduce severity of attack.

- There is little evidence of varietal resistance but high yielding feed wheats are generally best suited in high risk situations.

- Alternative methods of pest control including trap fallowing, adult control, biological control and disruption of host location are also worthy of investigation.

- Developing integrated control strategies, unifying cultural, biological and chemical control measures offers the means to minimise pesticide use and maintain profitability.

6.   IMPACT OF CHANGING AGRICULTURE

6.1   Economics of wheat production

Throughout the 1980s net farm income in real terms declined considerably and by 1989 was approximately 88% lower than in 1980 (Nix, 1995). Many small/medium farms were becoming only marginally financially viable and the general outlook was poor. In recent years, however, the situation has altered greatly.

6.1.1   The current economic climate

The introduction of area payments in 1991 to compensate for expected low grain prices, allied to payment for land in set-aside, increased farm profitability. In addition, withdrawal from the exchange rate mechanism (ERM), in October 1992, increased the payment rates after conversion from ECUs to sterling and proved a significant bonus to farm incomes. This has also coincided with a general increase in demand for cereals particularly from south east Asia and low production due to droughts in certain exporting nations such as America and Australia over the last couple of years. Wheat prices for 1994/95 rose to over £120/tonne and are forecast by some to remain at similar levels for the next year or two. The futures market for September 1996 is currently quoting a price of £110-112/tonne. Therefore, the combination of high grain prices, area payments withdrawal from the ERM and a falling pound, in comparison with other European currencies, has engineered a return to profitable farming.

Despite a return to profitable farming for the majority, many budgets suggest that 70-80% (or more) of this results from area aid payments. Therefore if this was to be reduced, limited or even withdrawn farm incomes would suffer considerably. Consequently under the current healthy financial situation it is prudent to consider the possibility for reducing inputs for pest control. This would have an immediate benefit of improving the cost-effectiveness of production, at a time when grain prices are high, and also help to maintain profitability should the economic climate worsen. The environmental benefits of this approach are also considerable (Section 6.3).

6.1.2 *Cost-effectiveness of insecticides*

A cost can be calculated for each insecticide and insecticide programme based on the cost of the product plus that of its application. This in turn can be expressed as yield response necessary to cover the cost of treatment both in t/ha and as a percentage of the average yield for both feed and milling wheat (Table 3).

In general, results in Tables 3 and 4 suggest that the yield response to cover the cost of insecticide treatment is similar for feed and milling varieties. The lower yield of milling wheat is compensated by its higher value and, conversely, the lower value of feed wheat by higher yield.

The percentage yield response required to cover insecticide treatment has been used to compare the cost-effectiveness of insecticide treatment for wheat bulb fly control (Tables 5 and 6). Published experimental data (post-1970) and unpublished ADAS data (post-1970) have been consulted to provide yield responses for insecticide treatment at a range of wheat bulb fly egg populations in early-sown or late-sown crops in mineral or organic soil types.

Over the last 40 years a large number of products have been screened against wheat bulb fly at a range of application rates. However, many of these are no longer available, were never approved for use, or were studied at different dose rates to those currently recommended. Most work also involved the use of seed treatments with a much smaller proportion of experiments concentrating on sprays applied at sowing, egg hatch or deadheart timings. In addition, experiments tended to be sited on land known to have a large number of eggs of the pest present. Consequently there is little data, with the exception of Young (1992), which covers a range of egg numbers both above and below the current 2.5 million/ha threshold. The data sets which are summarised in Tables 5 and 6 are therefore small but do give some indication of where chemical control against wheat bulb fly was cost-effective.

Table 3. Cost of insecticide treatments for wheat bulb fly control and yield response required to cover cost of treatment.

Type of treatment	Active ingredient	Rate l/ha	Cost £/ha[1]	Yield response to cover cost			
				Feed wheat[2]		Milling wheat[3]	
				t/ha	%	t/ha	%
Seed treatments	Chlorfenvinphos	-	11.00	0.11	1.5	0.10	1.5
	Fonofos	-	12.00	0.12	1.6	0.10	1.5
Seedbed sprays applied at or soon after drilling	Chlorfenvinphos	5.6 pre-drilling 4.2 post-drilling	58.79 45.68	0.59 0.46	7.9 6.1	0.51 0.40	7.6 5.9
	Chlorpyrifos	4.0 pre-emergence	74.45	0.74	9.9	0.65	9.6
Egg hatch sprays, applied at the start of egg hatch	Chlorfenvinphos	2.8 mineral soil 5.6 organic soil	32.57 58.79	0.33 0.59	4.4 7.9	0.28 0.51	4.1 7.6
	Chlorpyrifos	1.5	31.85	0.32	4.3	0.28	4.1
Peak egg hatch sprays	Pirimiphos-methyl	1.8	40.05	0.40	5.3	0.35	5.2
Deadheart sprays, applied at the onset of plant damage	Dimethoate	1.7	12.30	0.12	1.6	0.11	1.6

1   Application cost £6.35/ha (excluding seed treatments).
2   Feed wheat @ £100/tonne, 7.5 t/ha.
3   Milling wheat @ £115/tonne, 6.75 t/ha.
(Nix, 1995)

Table 4. Combinations of insecticide treatments used against wheat bulb fly and the yield response required to cover cost of treatment.

| | | Yield response to cover cost | | | |
| | Cost | Feed wheat | | Milling wheat | |
Combination of treatments	£/ha	t/ha	%	t/ha	%
Seed treatment plus one or two deadheart sprays					
Chlorfenvinphos + 1 × dimethoate	23.30	0.23	3.1	0.20	3.0
Chlorfenvinphos + 2 × dimethoate	35.60	0.36	4.8	0.31	4.6
Fonofos + 1 × dimethoate	24.30	0.24	3.2	0.21	3.1
Fonofos + 2 × dimethoate	36.60	0.37	4.9	0.32	4.7
Egg hatch spray plus deadheart spray tank mix					
Chlorfenvinphos + dimethoate	38.52	0.39	5.2	0.34	5.0
Egg hatch spray plus follow up deadheart spray					
Chlorfenvinphos + dimethoate	44.87	0.45	6.0	0.39	5.7
Chlorpyrifos + dimethoate	44.15	0.44	5.9	0.39	5.7

Table 5. Historic data for yield responses in winter wheat to insecticide treatments against wheat bulb fly on mineral soil.

Treatment	Active ingredient	WBF risk[1]	Range of % yield responses				Mean % yield response		% cost-effective treatments		Source of data
			Early sown[2]		Late sown[3]		Early sown	Late sown	Early sown	Late sown	
			No. of expts.	Response range	No. of expts.	Response range					
Seed treatment	fonofos	Low	4	-1-2	4	-9-11	0	0	25	25	Young, 1992
		Medium	4	3-16	3	-4-69	9	24	100	67	
		High	4	0-40	4	-5-23	11	7	25	75	
		Very high	2	6-30	2	5-59	18	32	100	100	
	chlorfenvinphos	Medium	1	-	1	-	7	-	100	-	Maskell, 1970
		High	3	16-98	2	250-333	48	291	100	100	Maskell & Gair, 1986a; Oakley 1980
		Very high	5	7-240	-	-	105	-	100	-	Mathias & Roberts, 1973; Maskell & Gair, 1986a, Oakley, 1980
Seedbed sprays at sowing	chlorfenvinphos	High	1	-	1	-	15	-	100	-	Maskell & Gair, 1986b
		Very high	1	-	1	-	88	16	100	100	Oakley, 1980
Egg hatch spray	chlorfenvinphos	Medium	1	-	-	-	0	-	0	-	Ellis, unpublished
		High	2	28-34	-	-	31	-	100	-	Maskell & Gair, 1986b
		Very high	2	38-92	1	-	65	24	100	100	Maskell & Gair, 1986b; Oakley, 1980
	chlorpyrifos	Medium	1	-	-	-	-1	-	0	-	Ellis, unpublished
		High	2	14-23	-	-	19	-	100	-	Maskell & Gair, 1986b
		Very high	2	14-20	1	-	17	1	100	0	Oakley, 1977; Young, unpub.
Deadheart spray	dimethoate	Medium	1	-	-	-	-2	-	0	-	Ellis, unpublished
		Very high	2	12-15	1	-	14	-1	100	0	Maskell & Gair, 1986b; Young, unpublished

1,2,3 See footnotes, Table 6

Table 6. Historic data for yield responses of winter wheat to insecticide treatment against wheat bulb fly on organic soil.

Treatment	Product	WBF risk[1]	Range of % yield responses				Mean % yield response		% cost effective treatments		Source of data
			Early sown[2]		Late sown[3]						
			No. of expts.	Response range	No. of expts.	Response range	Early sown	Late sown	Early sown	Late sown	
Seed treatment	fonofos	Very high	2	-3 to -1	2	0-2	-2	1	0	50	Young, 1992
	chlorfenvinphos	Medium	0	-	2	-2-94	-	46	-	50	Maskell and Gair, 1986a
		High	0	-	2	9-40	-	25	-	100	
		Very high	1	-	3	6-109	7	57	100	100	
Seedbed spray at sowing	chlorfenvinphos	Very high	-	-	1	-	-	16	-	100	Maskell and Gair, 1986b
Egg hatch spray	chlorpyrifos	Very high	-	-	1	-	-	-8	-	0	Young, unpublished
Deadheart spray	dimethoate	High	1	-	2	0-7	1	4	0	50	Young, unpublished
		Very high	-	-	1	-	1	-4	-	0	

1   Low   < 1.0   million eggs/ha
    Medium   1.0 - 2.4
    High   2.5 - 5.0
    Very high > 5.0

2   Before November

3   After November

The influences of a range of factors, egg numbers, soil type and early or late-sown crops on cost-effectiveness of treatment are summarised (Figs 6–11). In general there was a trend for increasing cost effectiveness as egg numbers increased (Fig. 6). This was particularly evident in mineral as compared with organic soil types (Fig. 7). The wheat bulb fly action threshold of 2.5 million eggs/ha defines the start of the high risk category and 32 out of 38 experiments (84%) in mineral soil with egg numbers in excess of this resulted in cost-effective control. Approximately 60% of medium risk category sites in organic and mineral soil types benefited from insecticide application, particularly seed treatments. These relatively inexpensive treatments also accounted for the cost-effective yield responses in the low risk category. The proportion of experiments giving a cost-effective yield response within each category, for both early and late-sown crops, was similar for low, medium and high risk categories (Fig. 8). However, in late-sown crops in the very high risk category, insecticide treatment was markedly less cost effective than in those crops drilled earlier. Analysis of data independent of egg category further emphasised the trends evident in Figures 6–8. A cost-effective yield response was most likely in mineral compared with organic soil (Fig. 9) in early-sown crops but there was little difference between soil types in crops that were sown late (Fig. 10). Overall there was little difference in the proportion of cost-effective sprays applied to early-sown and late-sown crops (Fig. 11). This is surprising in view of increased susceptibility of late-sown, poorly tillered wheat to wheat bulb fly attack. However, the data analysed take no account of the magnitude of the yield response which was on average higher (34%) for late-sown than early-sown (28%) crops.

Chlorfenvinphos was generally more effective than fonofos as a seed treatment in both mineral and organic soils and early or late-sown crops. In 18 out of 19 experiments (95%) chlorfenvinphos produced a cost-effective yield response compared with 17 out of 31 experiments (55%) with fonofos. The scale of the yield responses was very variable for both products ranging from 7–33% for chlorfenvinphos and 2–69% for fonofos. Generally, the yield response was greater in mineral than organic soils.

Chlorfenvinphos applied to the seed bed gave a cost-effective yield response in four out of four experiments and in five out of six experiments as an egg hatch spray in mineral

soil. Yield responses were again variable and ranged from 15 to 92%. Chlorpyrifos at egg hatch was cost effective in four out of six experiments in mineral soil but failed to improve yield in one experiment undertaken in organic soil. Yield responses varied from 14 to 23%. Dimethoate as a deadheart spray was generally the least effective product against wheat bulb fly. A cost-effective yield response was recorded in two of four experiments in mineral soil and one out of four in organic soil. The scale of yield response was lower than with other products and ranged from 7 to 15%.

Results of yield responses to seed treatments dominate the data set used to undertake the analyses discussed above. Results should therefore be interpreted with care. However, it is possible to suggest some generalised conclusions. Overall, the data demonstrate that insecticidal control of wheat bulb fly when egg numbers exceed the current ADAS threshold is cost effective, particularly in mineral soil types. Seed treatments, seedbed applications and egg hatch sprays were generally more cost effective than a deadheart spray of dimethoate. In addition, although experiments tended to be sited where egg numbers were high, an average yield response to wheat bulb fly control of 31% suggests that chemical prices would need to increase significantly before their use becomes uneconomic. The potential for reducing inputs is mainly within medium risk, and to a lesser extent, high risk category sites. A greater understanding for the factors influencing yield loss would help to forecast those medium and high risk sites where savings on insecticide treatment could be made.
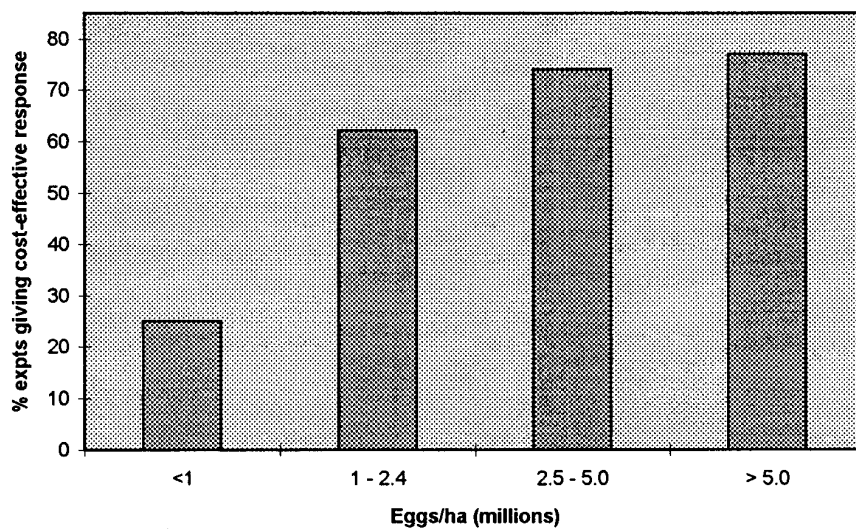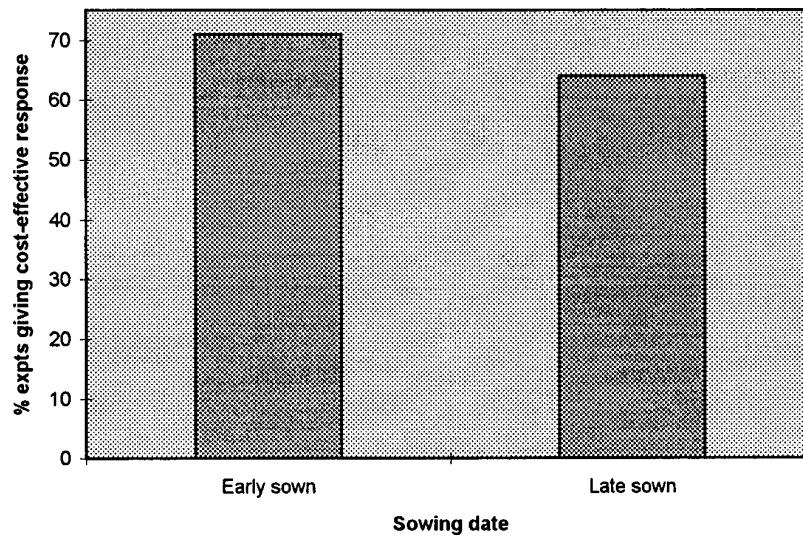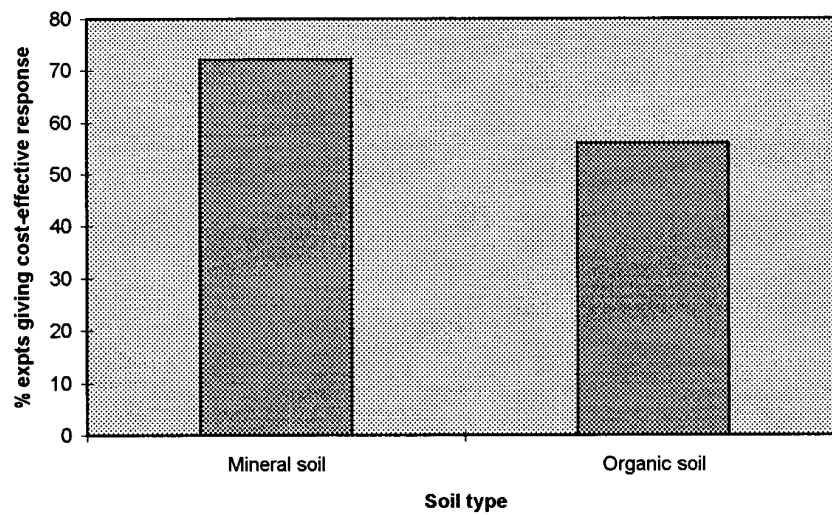
Figure 6. The effect of wheat bulb fly egg numbers on the proportion
of experiments giving a cost-effective yield response to insecticide treatment
against wheat bulb fly.
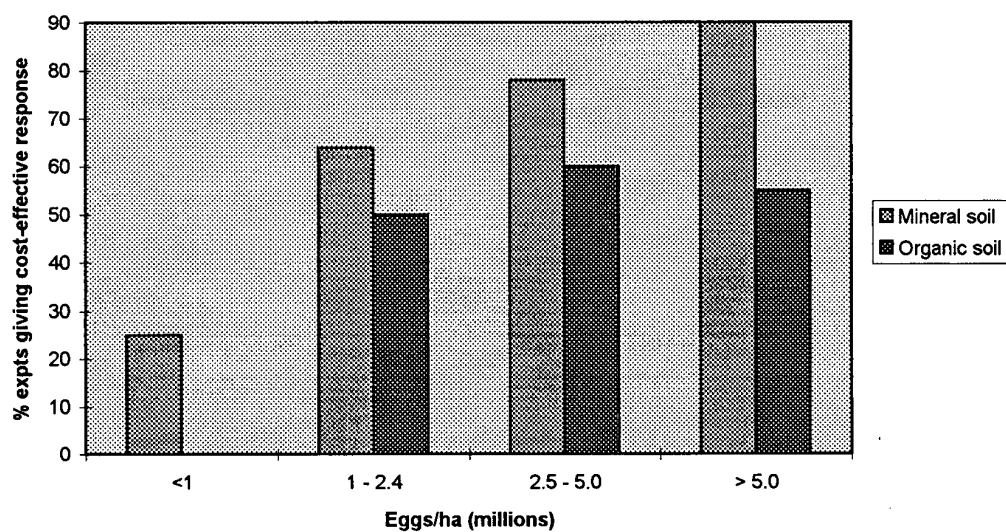
Figure 7. The effect of soil type and wheat bulb fly egg numbers on the proportion of experiments
giving a cost-effective yield response to insecticide treatment against wheat bulb fly.

Figure 8. The effect of sowing date on the proportion of experiments giving a cost-effective yield response to insecticide treatment against wheat bulb fly.

Figure 9. The effect of soil type on the proportion of experiments giving a cost-effective yield response to insecticide treatment against wheat bulb fly.
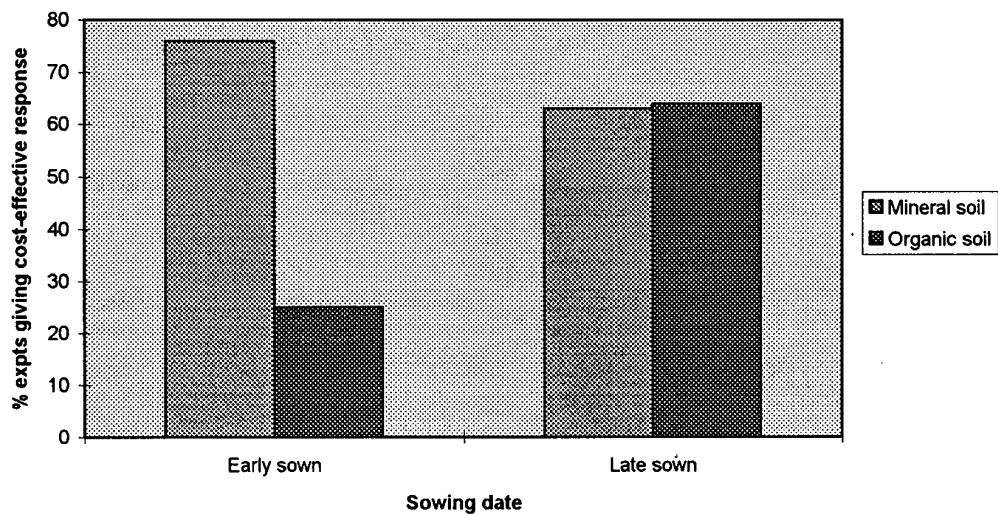
Figure 10. The effect of soil type and sowing date on the proportion of experiments giving a cost-effective yield response to insecticide treatment against wheat bulb fly.
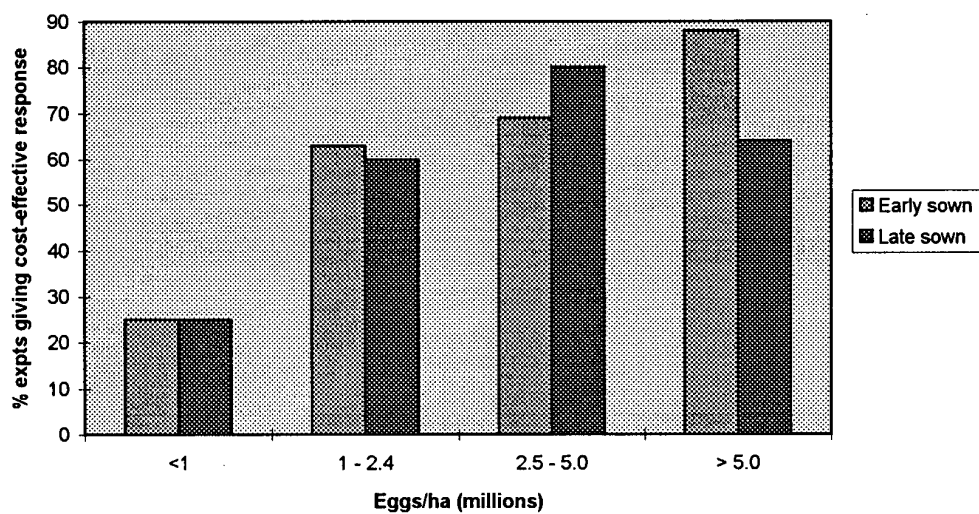

Figure 11. The effect of sowing date and wheat bulb fly egg numbers on the proportion of experiments giving a cost-effective yield response to insecticide treatment against wheat bulb fly.

Oakley (1994) assessed the impact on pest control strategies of possible reductions in cereal prices following revisions to the Common Agricultural Policy (CAP). No changes to the existing thresholds were indicated. It was noted that reduced crop value tended to favour using low-cost prophylactic control measures for frequent pests and tolerating damage caused by infrequent pests. Smaller financial returns from insecticide use could make the cost of evaluating treatment needs (by sampling or crop monitoring) uneconomic.

For October-sown crops and at a reduced cereal price of £80/t, Oakley (1994) found the use of a prophylactic seed treatment was the best financial option across a wide range of wheat bulb fly population levels or risk categories. Additionally, the use of soil samples to decide on the need for additional treatments in the form of egg hatch or deadheart sprays could only be justified on farms with an above average risk of damage. For crops sown later than October, additional treatments could be more profitable and sampling these crops to establish the need for treatment was cost-effective over a greater range of potential risk.

6.2 The impact of set-aside

In 1992/93, changes in the European Community (EC) Common Agricultural Policy saw the introduction of a the rotational set-aside scheme in the UK. Land is taken out of production for at least seven months, effectively one cropping year. Growers must set-aside an annually adjusted proportion (10% in 1994/95) of their arable cropping area to qualify for EC arable area aid payments. These payments are intended to compensate growers for reductions in the EC support price for cereal, oilseed and protein crops. Under the rules of management of rotational set-aside (Anon., 1995), cultivation to create bare fallow is permitted from May onwards prior to a new crop being sown in the late summer or autumn. Summer fallowing of rotational set-aside has been a frequent choice because of the benefits for weed control and because it provides an early entry for an autumn-sown crop. Winter wheat has been a popular choice of crop to grow after set-aside despite it being traditionally at high-risk of attack by wheat bulb fly when

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sown after a fallow. The non-host crop oilseed rape also ranks as one of the most frequently grown crops after set-aside fallow.

6.2.1 Monitoring the effect of set-aside

The resurgence of summer fallowing in the management of rotational set-aside has caused widespread concern about the risk of wheat bulb fly attack in following crops of wheat. Additionally, there have been fears that the increase in fallowing might cause an overall increase in frequency of the pest in districts presently considered to be at little risk of economic damage.

A MAFF-funded study started in 1993 to monitor and assess the impact of set-aside fallowing on wheat bulb fly egg populations and the subsequent level of attack in winter wheat (Young & Corless, 1994). Seventy sites were sampled annually to assess egg numbers in the autumn and the severity of plant attack in the winter. The monitoring sites were selected to represent farms of contrasting risk to the pest and were categorised as either low risk or high risk. Low risk sites were defined as farms where wheat bulb fly was rated only as a sporadic problem, rarely warranting treatment. However, at the high risk sites, wheat bulb fly was considered to be an annual threat, often requiring treatment and causing appreciable yield losses.

In autumn 1995, the third year of monitoring, the overall proportion of set-aside fallow fields above threshold (2.5 million eggs/ha) was the lowest recorded since the study started (Fig. 12). This finding agreed with the forecast of a low background level of wheat bulb fly egg numbers in the unfavourable hot, dry conditions of summer 1995 (Fig. 5). However, there was an increase in the number of fields above threshold in certain low-risk sites, particularly in Cambridgeshire and Suffolk. Furthermore, 50% of all fields above threshold in autumn 1995 were located within 0.8 km (0.5 miles) of a set-aside fallow field monitored in the previous year (1994). The fields monitored in the previous year were, therefore, subsequently growing winter wheat in summer 1995 and served as emergence sites and sources of adult wheat bulb flies. The evidence gathered so far is suggesting that set-aside fallows may cause localised increases in wheat bulb fly populations in districts hitherto considered to be at marginal risk from the pest.
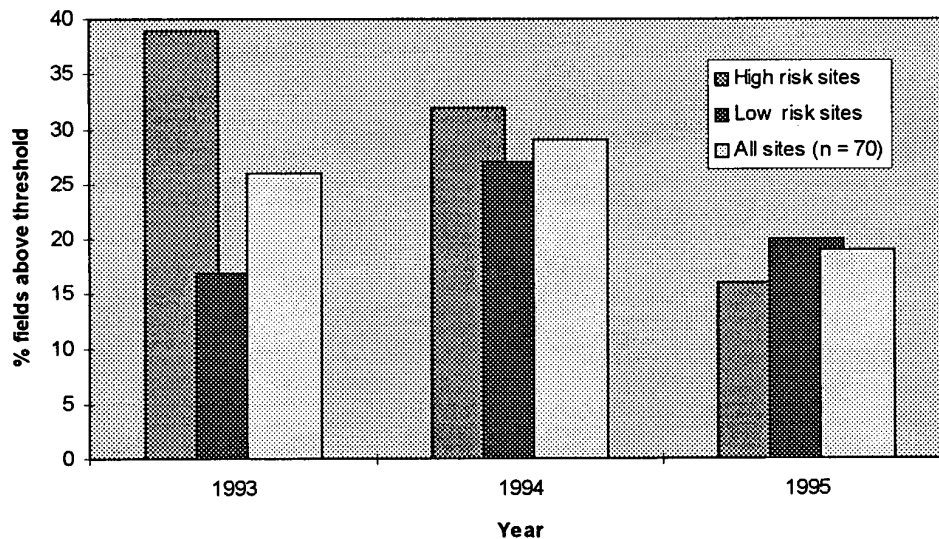
Figure 12. The effect of set-aside fallowing on wheat bulb fly egg populations in the eastern counties, 1993, 1994 and 1995.

The majority of wheat crops after set-aside fallow were sown in early autumn (before November) and were well tillered (average GS 22) by the time of attack (Young *et al.*, 1994). The vigorous and forward condition of most crops has enabled them to withstand and compensate for attack. Despite the overall low to moderate levels of wheat bulb fly larval attack, 42% of fields monitored in 1993/94 (n = 70) were treated with insecticide. In 1994/5, a low-risk of wheat bulb fly attack was forecast, this, together with the robust state of wheat crops sown after set-aside, may have convinced many farmers that insecticide treatment was not required. The proportion of monitored fields treated with insecticide subsequently fell to 18% in 1994/95 (Young, unpublished). To date, the average impact of wheat bulb fly attack on the yield of wheat crops grown after set-aside is estimated to be minimal. There would also appear to be scope to improve gross margins and safeguard the environment by reducing the unnecessary usage of insecticides applied against wheat bulb fly in wheat after set-aside.

6.2.2 Cultural control in set-aside fallow

MAFF-funded work is (Young *et al.*, 1994) investigating and defining the best cultural control strategies to limit or eliminate the risk of wheat bulb fly attack in winter wheat sown after rotational set-aside. This is being achieved by various cultural control regimes which are intended to limit or eliminate the number of wheat bulb fly eggs laid on set-aside land. By reducing the risk of attack, cultural control measures should also serve to reduce insecticide use.

The early findings of this study confirm previous work (Raw, 1955 & 1960) that showed that wheat bulb fly prefers to lay eggs in a rough, rather than a smooth tilth (Sections 3.3; 5.2.2). The reasons for this are not fully understood. A rough tilth probably presents a greater surface area with more cracks in which eggs may be laid. Eggs laid in a rough tilth may also be better protected from predators such as carabid beetles, (Section 3.6.2). To date, the effect of cultivation of bare soil during the egg laying period on the numbers of eggs laid has been inconsistent. However, the cultivation of an organic (peat) soil during the 1995 egg-laying period caused a seven-fold increase in egg numbers in comparison with an uncultivated treatment.

The initial results suggested several options for the cultural control of wheat bulb fly in the management of set-aside fields. If a summer fallow is to be created, working the field to a smooth tilth before July and leaving the soil undisturbed during July and August will present the least favourable surface for egg laying. The establishment of a cover crop well before the start of oviposition, or the maintenance of naturally regenerated cereal stubble throughout the egg laying period, were also shown to virtually eliminate the risk of wheat bulb fly attack.

6.2.3 Set-aside trap fallowing

Rotational set-aside presents a new opportunity to exploit set-aside fallows as trap fallows (Section 5.2.3). Trap fallows are sited as close as possible to potential emergence sites of adult wheat bulb fly (eg wheat after set-aside fallow) where they serve as an ideal egg laying site. Large numbers of eggs can be laid. The trap fallow is subsequently planted with a non-host crop such as oilseed rape. The larvae hatching

from eggs in the following winter die in the absence of a host crop. The trap fallow functions by diverting egg laying away from areas which are sown with wheat. The level of attack in the surrounding area is reduced and the carry-over population in the following year is also minimised.

The technique of trap fallowing has not been utilised in any large scale co-ordinated effort to control wheat bulb fly. This method may be useful to counteract any increase in wheat bulb fly populations which could result from growing wheat after set-aside fallow. For the best chance of success, trap fallowing would need to deployed over a wide area to minimise the effect of immigration of adult flies (Section 5.3.1). The minimum size of such a controlled area may need to be as much as 1,000 ha (Luers, 1986). Trap fallowing should not be considered in isolation but as one component of an IPM control strategy against wheat bulb fly, utilising a range of diverse cultural, chemical and biological control techniques (Section 5.4.3).

6.3 Environmental concerns

There are considerable environmental concerns over the misuse of pesticides. Pressure has been brought to bear by the European Union, the government and consumers for farmers to become more concerned about environmental protection and food quality. Pesticide residues in food have recently been discussed in the agricultural, horticultural and national press. Blythman (1995) commented on the high levels of organophosphorus residues in carrots and suggested that it was for the consumer to create the impetus for change.

The effects of pesticides on non-target organisms has been the subject of a large number of studies including the Boxworth project (Greig-Smith et al., 1992) and SCARAB (Çilgi and Frampton, 1994; Tarrant et al., 1994). Jepson (1989) summarised experimentation on the side effects of pesticides on non-target, terrestrial macroinvertebrates. As a requirement of pesticide registration manufacturers must now complete an ecotoxicological package to demonstrate that their products are not unduly

harmful to non-target invertebrates. These species may be important as parasites and predators of pests, as pollinators and for their contribution to the decomposer cycle and maintenance of soil fertility. Birds and mammals can also be killed as a result of pesticide use (Section 5.1.1).

Continued use of pesticides exerts selection pressure on the target pest, disease or weed population which can ultimately lead to the development of resistance. Insecticide resistance in many pest species has been well documented. It is generally associated with insects of a relatively short life cycle where there are several generations per year. Resistance has not been reported with wheat bulb fly but other related anthomyid flies such as onion fly (*Delia antiqua*) (Gostick *et al.*, 1971) and cabbage root fly (*Delia radicum*) (Finch & Thompson, 1992) are known to be resistant to organochlorine insecticides. Although there is a only a relatively low risk of risk of resistance developing in wheat bulb fly, the potential exists in all insect populations and will be greater where insecticides are applied unnecessarily.

Concern over residues in food, effects on non-target organisms and resistance problems allied to considerations of the cost-effectiveness of treatment have therefore stimulated a move towards a rational approach to pesticide use. To date this has largely been a voluntary initiative on the part of the crop protection industry. In general, there has been less pressure on British farmers to reduce agrochemical inputs than in some European countries where particular problems associated with intensive pesticide use have had to be addressed (Ogilvy *et al.*, 1995). However, pressure for adopting pest control strategies which have less reliance on pesticides are likely to strengthen and it is therefore both prudent and timely to investigate alternative more environmentally benign control strategies for wheat bulb fly. A 50% reduction in pesticide usage is required in Holland by halving the quantity of active ingredient used and in Sweden and Denmark by halving the number of applications. If consumer pressure or legislation makes similar demands in Britain it is vital that proven alternative control strategies for the pest are already available, in order to maintain the cost-effectiveness of cereal production.

It is most likely that any reduction in pesticide used against wheat bulb fly will come from the adoption of an IPM strategy for the pest (Section 5.4.3). This is likely to involve improved methods of monitoring and forecasting to increase the accuracy with which the risk of attack can be predicted, cultural, biological and novel control methods (Sections 5.2 & 5.3) and the potential for linking pesticide inputs with risk forecasts (Section 4.6).

6.4 Insecticide availability

There are now fewer insecticides available for control of wheat bulb fly than at any time over the last decade. In general, this can be attributed to greater awareness of the potential impact of pesticides on the environment. This in turn has resulted in more stringent requirements for pesticide registration, as laid down by the Pesticides Safety Directorate, particularly as regards ecotoxicology and to a lesser degree efficacy and residue data. The cost of generating the complete data package for product registration has therefore increased considerably and so when products come up for review or re-registration, the agrochemical company must decide whether their market is sufficient to justify the additional expenditure necessary to maintain approval.

In the cases of Dyfonate 10G (10% w/w fonofos, Farm Protection) which could be applied to the soil immediately before or at drilling, Dyfonate MS (550g/litre fonofos, Farm Protection) which could be applied at or soon after drilling and at egg hatch and Folimat (575g/litre omethoate, Bayer UK Ltd) a deadheart insecticide, the decision was made not to support the products and their approvals subsequently lapsed. At present, five active ingredients are approved for wheat bulb fly control in Great Britain; chlorfenvinphos, chlorpyrifos, dimethoate, fonofos and pirimiphos-methyl. However, not all of these are represented at each treatment timing, so effectively farmers must choose between two seed treatments, two soil applied sprays at drilling, three egg hatch insecticides and have no alternative to dimethoate as a deadheart spray. Additionally, in practice, the cost of pirimiphos-methyl means that egg hatch treatments are usually chosen from the relatively less expensive chlorpyrifos and chlorfenvinphos.

This limited choice of insecticides could have serious implications for pest control. The risk of the development of pest resistance will be greater where there is little scope to vary product choice. With wheat bulb fly the case is exacerbated by the fact that all available insecticides belong to the organophosphorus group and consequently have a similar mode of action. Taylor (1986) suggested that the best strategy to limit the evolution of resistance would be to use a high dose of rapidly degraded insecticide. However, wheat bulb fly egg hatch can continue over two months and a persistent product is therefore necessary to prevent larvae invading plants.

Enhanced degradation is another phenomenon which could limit pesticide efficacy (Suett, 1990). It has been recorded with chlorfenvinphos but not with chlorpyrifos. Frequent, repeat doses of a pesticide stimulate the development of an antagonistic soil microflora. These microbes rapidly degrade the product so that its persistence is greatly reduced, resulting in poor control of the target pest. However, chlorfenvinphos is most likely to be applied against wheat bulb fly in January or February, as an egg hatch treatment, when soil temperatures are low. Under these conditions there will be limited soil microbial activity and so enhanced degradation is unlikely to affect the efficacy of wheat bulb fly control, (D L Suett, pers. comm.). Seedbed treatments such as chlorfenvinphos may be applied in the autumn when soil temperatures are higher. However, this practice is uncommon owing to the high cost of treatment and, in any case, would not be applied to the same ground in two or more consecutive years. The potential for the development of enhanced degradation of chlorfenvinphos in association with wheat bulb fly control is, therefore, one of low risk.

The reliance of wheat bulb fly control on broad-spectrum organophosphorus insecticides could be a problem should these compounds come under review. Recently there have been reports in the national media of the alleged effects on human health of organophosphorus products used in sheep dips. Although the likelihood of exposure is significantly greater for farmers dipping sheep than for those spraying crops, public awareness of the potentially damaging aspects of organophosphorus insecticides has increased. The literature also provides examples for the damaging effects of

chlorpyrifos and dimethoate on non-target invertebrates. Dimethoate has been shown to cause significant reductions in about 10% of arthropod species in cereal fields (Cole *et al.*, 1986). Numbers of carabid and staphylinid beetles and spiders in plots of winter wheat were all reduced by dimethoate (Powell *et al.*, 1985). Chlorpyrifos reduced numbers of adult carabid beetles in grassland for more than 18 months after application (Luff *et al.*, 1990). Similar harmful effects have also been observed in the SCARAB (Seeking Confirmation About Results After Boxworth) experiment (Çilgi & Frampton 1994). In contrast, Mowat and Coaker (1967) suggested that chlorfenvinphos was not toxic to carabid beetles.

In summary, as wheat bulb fly control is currently almost totally reliant on insecticides, the limited range of alternative products could increase the risk of resistance and enhanced degradation. The safety risks associated with organophosphorus products could result in pressure to have them withdrawn from use. Therefore it is important to try and ensure that the current choice of insecticides is not further diminished, that research is undertaken to investigate means of improving control with currently available products and that alternative non-chemical means of combating wheat bulb fly are studied.

Maintenance of the current product range is largely dependent upon commercial decisions made by agrochemical companies and the policy decisions of legislative bodies. However, it may be possible to influence the latter by ensuring that insecticides are used in a rational manner. Assessing the risk of attack by egg sampling or improved predictive methods (Section 4.6) will mean that insecticides are applied only in response to egg numbers in excess of the threshold. This in turn will prevent the need for insurance treatments, reduce the risk of development of insecticide resistance and reassure environmental pressure groups and the public that a decision to spray is taken only after consideration of potential crop loss and impact on the environment.

Only dimethoate is now available as a deadheart insecticide and Young and Talbot (1988) showed that it was generally inferior to the previously available alternative, omethoate. However, addition of a surfactant, L1700, significantly improved control of

wheat bulb fly larvae with dimethoate although there was no associated increase in yield. The role of adjuvants in combination with dimethoate therefore deserves further investigation. The efficacy of a systemic insecticide is also improved if it is applied when the plant is actively growing and able to take it up. It may be possible, therefore, to define the optimum conditions under which deadheart sprays should be applied to achieve maximum uptake.

Alternative non-chemical means of controlling the pest will help to prolong the life of current insecticides. The integration of chemical and non-chemical methods of control is discussed in Section 5.4.3. New insecticides with alternative modes of action would greatly improve the options for wheat bulb fly control. At present, tefluthrin, a soil applied pyrethroid shows promise as a seed treatment (Frost *et al.*, 1994). Wheat bulb fly control should be considered as a valuable addition to the target portfolio of any new insecticide.

6.5 Developments in crop physiology

The presence of insect pests which cause extensive and visible damage to crop plants can often easily be associated and correlated with crop yield loss. However, it is frequently more difficult to determine a causal relationship between insect infestation, damage and yield loss (Dent, 1991). In many cases this is because effort is concentrated on plant yield and the behavioural and physiological adaptations of the insect and too little emphasis placed on plant growth and development.

The ability of a wheat crop to tolerate wheat bulb fly attack is governed by its capacity to tiller in the autumn (Raw, 1967). Pre-tillering crops are at greater risk from wheat bulb fly than those at a more advanced growth stage, and it may be that through an understanding of tillering capacity, and tiller development, an improved assessment of a crop's tolerance to wheat bulb fly could be possible. A number of factors can affect tiller populations at the start of wheat bulb fly egg hatch. Set-aside, in which the cover is removed early, provides a high nitrogen supply and an opportunity for early drilling of winter wheat. Choice of cultivar is also important, with slow developing cultivars being shy tillering, even though they eventually yield as well as those that develop more

rapidly. High nitrogen supply, such as occurs after summer fallow (e.g. set-aside) or break crops such as oilseed rape or peas, tends to stimulate tillering although the effect is moderated while root systems are small in the autumn. The way in which tillering and crop development are affected by cultivar, temperature and sowing date are currently the subjects of other HGCA funded projects (0037/1/91, 0044/1/91 and 0023/1/93).

An understanding of tiller development may provide an alternative, environmentally friendly strategy of pest control which could reduce or eliminate the need for costly, broad-spectrum egg hatch insecticides. It will also help to highlight cultivars ideally suited to specific cropping situations in relation to the perceived risk of wheat bulb fly attack. Ultimately, it may be possible to predict and rank the tolerance of chosen varieties to attack by wheat bulb fly and to forecast which crops will fail to compensate for damage.

Lupton and Bingham (1967) considered that varieties with the greatest tillering capacity are best able to tolerate and recover from wheat bulb fly attack (Section 5.2.5). Knowledge of the relative tillering capacity of individual varieties in a range of typical growing conditions is a useful measure of varietal susceptibility to wheat bulb fly. Young (1992), suggested that high yielding field wheats were suitable for use in high risk situations. Nine varieties of winter wheat were assessed for their susceptibility to wheat bulb fly. When assessed towards the end of attack in March or April, feed varieties tended to produce 0.5 tillers/plant more than bread-making varieties and crops sown in October produced an average 0.4 tillers/plant more than those sown in November. However, this observation is too general to apply to all varieties. For example, the bread-making variety Spark is known to have a higher tillering capacity than certain feed varieties (J H Spink, pers. comm.).

Further information is required on the physiological mechanism of crop tolerance and the role played by the pest. Studies on the Yorkshire Wolds (S A Ellis, unpublished data) showed that a crop at pre-tillering growth stage at the time of wheat bulb fly egg hatch was able to tolerate attack from egg numbers of 1.1 million/ha. However, where insecticides were applied the crops ability to compensate was reduced such that yields

were significantly lower than in untreated controls, which had a higher level of larval invasion. It is possible in this instance that the presence of a live larva helped to initiate crop compensation, possibly by suppressing apical dominance at a critical time. Phytotoxicity of the insecticide used is another possibility that was not quantified. Irrespective of the explanation of this particular observation, it is important to ensure that insecticides are only applied when the value of loss of crop yield exceeds the cost of application.

In general, little information is available on the relationship between actual or potential tiller populations and the effects of wheat bulb fly attack, although this is likely to be fundamental to forecasting the risk of damage. There should be scope to moderate the egg threshold in relation to assessments of tillering, and there are likely to be interactions between cultivar, sowing date, seed rate and the action thresholds for wheat bulb fly control. Further study of these interactions may improve strategies for control of the pest and enable pesticide input and perceived risk of wheat bulb fly attack to be rationalised.

Plant physiologists use the technique of plant growth analysis to study the effect of the environment on plant growth. Dent (1991) provided a summary of how this technique may be applied to determine the influence of insect pests on crop development. One approach is to follow the changes in growth of plant parts. During growth, photosynthetic materials are distributed to particular organs according to the developmental stage of the plant. For example, during the early stages of growth materials are directed towards the production of roots and leaf area but later are re-directed towards development of stem and reproductive structures of the plant. The sequence in which this redistribution occurs has important implications for an understanding of the relationship between the timing and intensity of pest attack and crop yield. The effect of pest attack on yield may depend on both the type and timing of damage relative to the redistribution of new assimilates. A defoliating insect may therefore cause greater yield loss if attack occurs before redistribution of new assimilates to reproductive structures of the plant. In the case of wheat bulb fly, an understanding

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of the timing of plant invasion in relation to the dynamics of tiller production is likely to be of major importance in the prediction of potential yield loss.

The use of plant growth models is also likely to become increasingly important as a means of understanding the way in which pests affect plant physiology and how this ultimately determines yield. It has been suggested (Hughes, 1988) that if a model of canopy development is combined with one that deals with the relationship between crop growth and yield and the spatial arrangement of plants and resource capture (e.g. Benjamin and Hardwick, 1986, Sutherland and Benjamin, 1987), it would also describe the spatial pattern of crop damage by insects. Such a model would be applicable to wheat bulb fly which causes plant or tiller death and thereby influences inter-plant competition.

In summary, an improved understanding of the relationship between wheat bulb fly attack and yield loss will only be achieved by taking into account the response of the crop to pest invasion. This requires a greater understanding of plant physiology and current HGCA studies in this field will help to define further areas of research.

6.6 Precision farming

Precision farming, or site-specific farming, is farm management based upon the variable conditions that occur within most fields (Peterson et al., 1995). In conventional management, the variable conditions within each field are managed uniformly. In precision farming, inputs are adjusted according to the spatial distribution of particular factors within a field. Inputs such as fertilisers, pesticides, and crop cultivar may be precisely matched with land and climate attributes. Economic and environmental benefits can be realised through precision farming by the reduction of excessive or unecessary applications of, for example, nitrogen fertiliser.

Peterson *et al.* (1995) considered that new opportunities were available to extend the use of precision farming with the following techniques:

a) Microcomputer capabilities.

b) Soil information sources.

c) Enhanced imagery for soil mapping.

d) Climatic databases.

e) Geographic information systems (GIS) and GIS-based models.

f) Decision support systems.

g) Variable rate fertiliser and pesticide applicators.

h) Global positioning systems (GPS).

In relation to wheat bulb fly, a role for decision support systems and geographical information systems has already been identified (Section 6.6.1). Quantifying and mapping the within-field distribution of wheat bulb fly to guide the application of control measures would require labour-intensive grid sampling which is unlikely to be cost-effective. Such techniques may be more applicable to pests such as cyst nematodes which remain relatively static within the same field year after year, although the sampling required is also likely to be expensive. However, advances in image recognition technology may in future enable remote sensing of pest infested plants at a sufficiently early stage of attack to allow variable application of insecticides. Where areas within the same field have been managed differently and as a result contain differing numbers of wheat bulb fly eggs, global positioning systems could be used to guide the sowing of non-host crops or in the application of insecticides to the high risk parts of the field. For example, blocks of trap fallows could be created as patchwork pattern within a single field to attract large numbers of wheat bulb fly eggs. A global positioning system could be used to accurately record the siting of the trap fallows and then to position a non-host crop such as oilseed rape in their place after egg laying. Alternatively, a GPS could be used to direct the selective application of cultural or chemical control measures to winter wheat sown in the areas of field corresponding to the trap fallows.

6.6.1 Decision support systems and GIS

Over the past decade computerised decision support systems have been evolving to improve many aspects of decision making and management in agriculture. The main advantage offered by decision support systems is their ability to store vast amounts of data which may be rapidly analysed and interpreted to provide users with information relating to a specified problem. Such systems are capable of being readily and cheaply accessible to a wide range of users and are an efficient means of transferring technology to the practitioner. Decision support systems have numerous levels of possible use in the agricultural industry, including the farmer, crop consultant, agrochemical distributor and student.

Decision support systems can be made up of either a single component such as database, geographic information system, expert system or simulation model or a combination of these (Knight & Mumford, 1994). The development of a decision support system is reliant upon the development of its component parts. Knight and Mumford (1994) considered that before any attempt is made to produce a decision support tool it is vital that the problem has been rigorously defined and the requirements of the decision-maker are fully understood. Whatever the purpose of a decision support system, they are all designed to solve a particular problem. A model will predict the development of a pest and the response to treatment; a database will provide information on the incidence, distribution or risk of attack from a particular pest.

The HGCA has funded the development of a prototype expert system for wheat bulb fly control in wheat (Jones *et al.*, 1990). This computer-based expert system (BULBFLY) incorporated the facts and rules necessary for the estimation of egg numbers, crop susceptibility and control recommendations. Encyclopaedic information was also included on topics such as the biology of the pest, cultural control practices and the safe use of insecticides. BULBFLY offered practical and specific recommendations on wheat bulb fly control, and was aimed at the non-specialist user. Experience in the use of BULBFLY was also intended to be of educational value in illustrating the benefits of assessing wheat bulb fly risk and of taking the appropriate action. In this way BULBFLY was considered to be of benefit in improving the efficiency and cost-

effectiveness of control treatments and reducing the unnecessary use of insecticides. Although BULBFLY demonstrated the practical value of decision support systems, it was not developed beyond the prototype phase owing to the high cost of preparing such a system for commercial use.

The development of decision support systems serves to highlight gaps in existing knowledge which require further research. In the case of the BULBFLY expert system, the need to estimate more accurately the annual region-wide risk of attack was identified. Consequently, Young and Cochrane (1993) developed a regression model to forecast the annual incidence of wheat bulb fly egg laying in eastern England. The model utilised long-term records of wheat bulb fly egg numbers dating back to 1953 in combination with readily available climatic data (Section 4.6.1).

Recently, Evans *et al.* (1996) studied the distribution of wheat bulb fly in Scotland and England with the aid of a geographical information system model and a climatic model called CLIMEX (see also Sections 4.4 and 4.5). Evans noted that a more accurate prediction of risk of wheat bulb attack at individual farm or area level may be possible by coupling climatic data such as on-farm temperature and rainfall measurements with the CLIMEX/GIS models. This approach could complement the regression model to forecast egg numbers and would also be suitable for incorporation in a future decision support system for wheat bulb fly control.

6.7 Key point summary

- Recommendations for chemical control are currently cost effective when used in conjunction with treatment thresholds.

- Set-aside fallows may cause localised increases in wheat bulb fly populations in districts considered to be at marginal risk from the pest.

- Cultural measures can reduce egg laying in set-aside fallow. Using set-aside for trap fallowing could be of value in population control.

- The number of insecticides available for wheat bulb fly control has diminished and may continue to do so. Development of alternative and integrated control strategies will lessen reliance on insecticides.

- A better understanding of the factors influencing crop growth and development in relation to attack may help to identify susceptible varieties and improve the accuracy of insecticide use.

- Precision farming technology including geographic information systems and decision support systems provide an opportunity to adjust inputs according to risk forecasts and to facilitate information transfer.

7. DISCUSSION

This review has served to highlight the vast amount of wheat bulb fly research and the great depth of knowledge so generated over the past 50 years. The seminal works of Dr Harold Gough heralded the start of a ground-breaking era of wheat bulb fly research in the 1950s and 1960s. The development of agriculture since 1945 and the emergence of the crop protection industry is reflected in the history of wheat bulb fly research and control.

Wheat bulb fly control is currently dependent mainly upon insecticides. Chemical control recommendations are based on an egg threshold of 2.5 million eggs/ha and vary according to sowing date. Analysis of experimental data suggests that the threshold is robust and that control measures applied on the basis of an egg count in excess of 2.5 million/ha are cost effective. However, individual or multiple insecticide applications against wheat bulb fly usually provide only partial control. Development of alternative, non-chemical, methods of control and their incorporation in an integrated strategy, combining chemical, cultural and biological methods, may improve the standard of control and financial benefit obtained from using insecticides alone.

At present, in comparison with the previous decade, arable farming has shown a return to profitability. This has generally resulted from high grain prices, area payments, withdrawal from the ERM and a pound which is falling in value in comparison with other European currencies. Consequently, the pressure to reduce inputs has been less than if the profitability of wheat production had been more marginal.

However, a review of the literature suggests that despite this apparently optimistic outlook, there are a number of factors that could have a major influence on current strategies for wheat bulb fly control. The current profitability of arable farming is largely determined by arable area payments. If these are reduced or withdrawn then farm incomes would decline considerably. Although at present economic pressures to reduce insecticide inputs are low, the influence of environmental issues on government policy is likely to strengthen.

Wheat bulb fly control is achieved with a relatively narrow range of insecticides, all of which are organophosphorus products. Numerous studies have reported a deleterious effect of certain insecticides on some non-target organisms. In addition, awareness of the potential environmental impact of insecticides has increased. Therefore, the long-term future of some wheat bulb fly insecticides may be jeopardised. Reliance on a reduced range of products with similar modes of action also increases the risk of the development of resistance. A rational approach to pesticide use, using integrated control measures, is essential to minimise these risks and to demonstrate a commitment to environmental protection.

The introduction of rotational set-aside has created ideal egg-laying sites for wheat bulb fly. Results from work on the effects of set-aside on wheat bulb fly population suggest that it is now becoming more prevalent in areas which, in the past, were considered to be at low risk. This threat is likely to strengthen the need to investigate alternative control measures and to contain the potential population build-up of the pest.

In summary, there are a number of factors which could undermine the long-term efficiency of wheat bulb fly control. Current strategies must evolve to take into account environmental concerns and address potential problems resulting from reduced insecticide availability and the influence of set-aside. Decision support systems and predictive models are likely to become increasingly important as an additional aid to rationalising pesticide use. In general, it is likely that in the future, control of the pest will be less reliant on pesticides and move towards an integrated management strategy incorporating chemical and non-chemical methods. This approach requires a detailed understanding of the biology of wheat bulb fly. This review has summarised our current knowledge and has highlighted those areas where further study may benefit the cereal farmer (Section 8). A pro-active response to potential changes in agriculture will ensure that the profitability of wheat production in the UK is maintained.

8. FUTURE RESEARCH AND DEVELOPMENT

As a result of this review the following priority areas of research on wheat bulb fly are suggested as future research topics (A to H).

A) *Integrated Control System*

- Investigate opportunities for integrating cultural, biological and chemical control measures.

- Aim to unify individual components of control into a single, practical and cost-effective strategy (Section 5.4.3).

- Demonstrate economic and environmental benefits of integrated control strategy in comparison with current commercial practice.

- Favourable probability of developing a viable system by applying current knowledge.

- High priority rating as applied specific research conforming to MAFF and HGCA policies on minimisation of pesticide use and maintenance of farm profitability.

B) *Biological control*

- Investigate candidate biocontrol agents of wheat bulb fly.

- Include study of staphylinid beetle (*Aleochara* spp.) parasites of wheat bulb fly pupae.

- Pathogens of larvae and adult flies, including *Entomopthora* spp. and *Bacillus thuringiensis* (BT) merit investigation.

- Aim to enhance the natural activity of biocontrol agents. (Section 3.6).

- Investigate biological and physical factors governing larval survival (Section 3.7).

- Exploit methods to increase natural mortality of larvae.

- High research priority rating to minimise pesticide use by developing alternative methods of control.

- Biological control is of future importance as a component of an integrated control system (Topic A).

C) *Exploiting new knowledge of crop physiology*

- Develop crop tillering models to predict crop response to wheat bulb fly damage.

- Predict varietal tillering responses to attack based on sowing date and temperature.

- Aim to modify treatment thresholds and insecticide inputs according to predicted crop growth and yield potential.

- High priority for future use in an integrated control system (Topic A) and in improving precision of insecticide use.

D) *Investigation of the efficacy of dimethoate and new compounds*

- Investigate ways of improving control with dimethoate, the only remaining deadheart spray.

- Evaluate spray adjuvants, growth stage of larvae, physical condition of the crop and environmental conditions in relation to the efficacy of dimethoate.

- Evaluation of promising new compounds (e.g. tefluthrin, a soil-acting synthetic pyrethroid).

- Also of priority for collaborative action by the corporate sector.

E)   *Decision support systems*

- Improve and develop the wheat bulb fly decision support system.

- Ensure compatibility with other decision support systems e.g., DESSAC (Section 5.6.1).

- Incorporate and extend existing predictive models for use in a decision support system.

- Include development of geographical information systems and climatic models to improve risk prediction at farm level.

- Future value in implementation of an integrated control system and in technology transfer to the agricultural industry.

F)   *Adult fly control*

- Investigate as a stand-alone technique and as part of integrated control strategy (Topic A).

- Examine use in population control over large areas of land (Topic E).

- Investigate environmentally friendly methods of adult control.

- Assess low-dose selective insecticides and biocontrol agents such as fungal (*Entomophthora* spp.), bacterial (BT) or viral pathogens (Sections 3.6.1 & 5.3.3).

- High research priority rating to underpin strategic and scientific understanding of integrated control.

G) *Population control*

- Study applicability over large areas where wheat bulb fly is a persistent and expensive problem.

- Evaluate adult control, larval control and trap fallowing as part of a population control strategy.

- Investigate value of trap fallowing (Section 5.2.3) as method to counteract population growth resulting from early-sown wheat crops sown after set-aside fallows.

- Population control offers long-term, sustainable control requiring large-scale collaboration at farm level.

H) Host location and varietal resistance

- Investigate and define the larval host-location mechanism (Section 5.3.4).

- Aim to exploit disruption of host-location as an alternative control method.

- Identify biochemical and genetic basis of oat resistance to wheat bulb fly.

- Investigate oat-based resistance for use in wheat (Section 5.2.5).

- Requires fundamental research which could offer a durable and environmentally safe method of control.

9. ACKNOWLEDGEMENTS

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