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A review of invertebrate pest thresholds

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Contents

Abstract

Current best practice on the need for pest control relies on the use of thresholds. For these to be of value to farmers/agronomists they must be based on sound scientific research and evolve with developments in crop production and physiology. Although some thresholds are based on experimental evidence others are based on much less robust information. Also many thresholds were developed at least 20 years ago and so may not be relevant to current varieties and agronomic practices. The aim of this project was to: 1) assess and score the robustness of existing thresholds; 2) identify how recent advances in the understanding of yield formation can be used to develop new thresholds; and 3) to highlight knowledge gaps for future research.

Of 22 pest species that attack oilseed rape and cereals, thresholds have been developed for 16 and the origin of eight of these is unknown. Of the eight thresholds of known origin two are more than thirty years old. Most farmers are aware of thresholds and consider them an important component of pest control. However, pesticide usage survey data suggests a lot of insecticides are applied unnecessarily. In oilseed rape there is an excessive level of insecticide use compared with the proportion of crops in which pests exceed the thresholds, and in most years all of the British rape area is sprayed at least once for unspecified reasons. Lack of confidence in existing thresholds, time consuming and complex pest assessment methods and inexpensive insecticides are all potential reasons why farmers/agronomists may not use thresholds to assess pest risk.

The physiological mechanisms of yield formation are reviewed for wheat, barley and oilseed rape. Improved physiological understanding of how yield develops has determined some of the minimum crop parameters required to achieve potential yield. Using a physiological approach, along with an understanding of pest biology, will help to develop more quantitative/mechanistic thresholds. It is clear that crops have a very wide range of tolerance to pest damage which depends on variation in crop growth caused by weather and crop management. The tolerance of autumn sown crops may have been increased by warmer temperatures increasing over-winter growth, although the trend towards lower seed rates for wheat may make this crop less tolerant of shoot loss.

It is recommended that an assessment of crop tolerance to pest damage should be carried out before assessing pest numbers because it is likely that some crops will have such a high tolerance that the likelihood of experiencing sufficient pest numbers to reduce yield is negligible. To fully account for the degree of crop tolerance to pests several pieces of information are required including; the minimum crop parameter value to achieve potential yield, a method of easily assessing the crop, and knowledge of how much damage each pest causes. It is feasible that quantitative schemes for estimating crop tolerance can be developed for several pests which cause damage including pollen beetle, flea beetle, slugs (post-emergence), stem-boring insects, wireworms and leather jackets. Developing quantitative prediction schemes for other pests such as virus vectors and pests that reduce the amount of assimilate available for seed growth (e.g. aphids) will be more difficult because the damage is less easy to quantify. A qualitative scheme for estimating crop tolerance may be required for these pests.

In order to develop more quantitative thresholds that account for the wide variation in crop tolerance, several areas of future work have been identified. These include quantifying the minimum plant number required to achieve yield potential in barley and oilseed rape and how this is affected by sowing date and variety in order to improve thresholds against slugs, flea beetles, leatherjackets and wireworms. Understanding how many plants are destroyed by slugs, flea beetles and leatherjackets and how many shoots are destroyed by wheat bulb fly will improve thresholds for these pests. Methods for rapidly assessing shoot numbers and plant numbers in cereals are also required as well as improved methods of monitoring some pest species.

The review concludes with a discussion of how pest thresholds might be revised in relation to an improved understanding of crop physiology; potential areas for future research are proposed.

Introduction

Current best practice for decisions on the need for pest control relies on the use of thresholds which define a particular infestation level, at a particular crop growth stage at which the cost of potential economic loss outweighs the cost of treatment. The aim of thresholds is to make the most economic use of inputs but also to avoid prophylactic use of pesticides thus limiting their environmental impact and minimising the risk of development of resistance. For thresholds to be effective, farmers and advisers need to be confident that they accurately reflect the risk of economic loss in relation to current varieties, agronomic practices and input and output prices. Lack of confidence can lead to the use of insurance sprays which may be environmentally damaging, increase the risk of development of resistance and decrease gross margins. The low cost of some frequently used insecticides (e.g. pyrethroids) has also tended to favour insurance treatments. However, in future the range of available active ingredients is likely to decline which in turn will increase the risk of development of insecticide resistance. It will become increasingly important to safeguard existing products and ensure that they are used only when absolutely necessary. This will require our confidence in, and understanding of, pest thresholds to evolve.

For thresholds to be of value to farmers/agronomists they must be based on sound scientific research and to evolve with developments in crop production and our understanding of the yield forming process. Although some thresholds are based on experimental evidence others are much more subjective with little scientific basis. As this knowledge is not available to the industry there is no way of knowing how much reliance should be put on any given threshold. For example, cereal crops are said to be at risk from yellow cereal fly at less than 200 plants/m^2, however, this fails to take account of numbers of tillers per plant. A spray is justified against grain aphid if 66% of ears are infested from GS 61, but this assumes plants which have few aphids or many aphids to be equally infested. Current thresholds for pollen beetle in oilseed rape in winter crops are 14/plant, 5/plant for backward crops and 2/plant for varietal associations but there is little if any experimental evidence to support this. Seed weevil is sprayed at 0.5 weevils per plant in northern Britain and 1 per plant elsewhere but this seems to be based on limited research. Wheat bulb fly and wireworms reduce yield by killing tillers and/or plants but thresholds for these pests take no account of the tiller populations and potential crop yield.

Thresholds are available for the majority of invertebrate crop pests of oilseed rape and cereals. However, many of these were developed at least 20 years ago and so may not be relevant to existing varieties or for modern agronomic practices and will not take into account recent advances in the understanding of yield formation. Since the 1970s and 1980s the understanding of various crop characteristics that are required to achieve potential yield, e.g. the optimum number of plants, shoots and pods, has improved. This understanding will help to predict whether a crop is likely to be able to compensate for various types of crop damage that specific pests cause.

HGCA project RD-2005-3242, Re-evaluating thresholds for pollen beetle in oilseed rape, aims to update thresholds that were developed in the 1970s which provide no way of accounting for differences in tolerance to pest damage between crop types (Tatchell, 1983; Williams and Free, 1979). Farmers and agronomists have little confidence in current thresholds in relation to modern crops, particularly restored hybrids, which are perceived to be more susceptible to damage. If the levels of incidence of pollen beetle in the UK rarely cause economic damage and this is accepted by the industry, then the potential for resistance to pyrethroid insecticides will be significantly reduced and the use of these products reserved for the rare occasions on which they are needed. This review proposes the development of new thresholds by quantifying the inherent tolerance of rape to pest attack. In particular, it is important to recognise that variation in growth caused by weather or husbandry will lead to a large variation in tolerance to pest damage. Understanding how to estimate the degree of tolerance that a crop has based on the measurement of key crop characters (such as the number of plants, shoots or leaf area) is vital.

Dipterous stem borers are another example of pests where thresholds developed at least 30 years ago are in need of re-evaluation. Stem boring insects reduce the yield of wheat by killing shoots and reducing final ear number. The potential yield loss therefore depends on the plant population and number of shoots per plant, the pest population and whether the pest destroys single or multiple shoots/plants. A single pest threshold is therefore unlikely to be appropriate for all situations as it could lead to either treating unnecessarily or not treating and suffering significant yield penalties. Crops with a high maximum shoot number (>1000 shoots/m^2) have a high tolerance of wheat bulb fly and should therefore have a higher egg threshold for spraying, whereas crops with fewer shoots must have a lower threshold. Relationships developed for wheat bulb fly would also be applicable to other dipterous stem borers such as yellow cereal fly (*Opomyza florum*) and gout fly (*Chlorops pumilionis)* once allowance has been made for the number of shoots/plants they destroy.

In addition to pollen beetle and dipterous stem borers, there are thresholds for many other pests of cereals and oilseed rape that have not been reviewed for many years or may have been based on little or no experimental evidence when originally set. These include slugs in both oilseed rape and cereals, seed weevil (*Ceutoryhnchus assimilis*), pod midge (*Dasineura brassicae*), peach potato aphid (*Myzus persicae*) and cabbage aphid (*Brevicoryne brassicae*) in oilseed rape, and summer aphids (*Sitobion avenae*, *Metopolophium dirhodum*), orange wheat blossom midge (*Sitodiplosis mosselana*), wireworms (*Agriotes* spp) and leatherjackets (*Tipula paludosa*) in cereals.

This review aims to assess and score the robustness and reliability of current thresholds for pests of cereals and oilseed rape. Farmers and advisers have also been canvassed to determine whether they are aware of existing thresholds, their value, if they are being used and if not, why not. Particular attention has been paid to how our improved understanding of pest/crop interactions will impact on the need for control. Suggestions are made as to which thresholds need to be updated in the light of improved understanding of crop yield formation and how that might be achieved. This is used to highlight knowledge gaps and areas for future research.

Therefore the overall aim of the project is to review current thresholds for pests of cereals and oilseed rape in relation to changes in agronomy, varieties and climate, and advise how they can be improved by using recent advances in understanding yield formation.

This has been achieved by addressing the following specific objectives:

1. Assess and score the robustness of existing thresholds incorporating farmer and adviser opinion in light of changes to agronomy and climate

2. Identify how recent advances in understanding yield formation can be used to develop new thresholds with greater accuracy

3. Highlight knowledge gaps and areas for future research.

Thresholds in crop protection

Thresholds for invertebrate crop pests were introduced with the aim of minimising pesticide use, consistent with efficient crop production. This benefits the environment by limiting the impact on non-target species such as parasites and predators, reduces the potential for the development of insecticide resistance and improves the cost effectiveness of production. Thresholds are available for a wide range of pest species across a wide range of crops and can be defined as below.

1. Action threshold – The pest density that warrants initiation of the control strategy.
2. Economic damage – The amount of damage that justifies the cost of artificial control.
3. Economic injury levels (EIL) – The lowest population density that will cause economic damage.
4. Economic threshold (ET) – The level at which control measures should be implemented to prevent pest populations reaching the EIL.

In the UK, decision making in crop protection relies mainly on ET's. In the future it is likely that thresholds will assume even greater importance than at present. The number of available and effective active ingredients for pest control is likely to decline due to EU legislation and the development of resistance, so the cost of remaining products is likely to increase. Consequently, risk management is going to become increasingly important as a means of ensuring cost effective crop production. Therefore this project provides the ideal opportunity to review existing thresholds to take account of our improving and evolving understanding of the factors that influence yield production.

Current thresholds

The current thresholds for pests of cereals and oilseed rape are listed in Table 1. The origin of individual thresholds is also included, this being either the research work which led to their development or their appearance in literature available to the agricultural industry. Out of 22 pest species known to attack cereals and oilseed rape, thresholds have been developed for 16, of which the origin is unknown for eight. Of the eight thresholds of known origin two are more than thirty years old. Little is known about the origin of the thresholds for gout fly, wireworms, leatherjackets and numbers of soil-borne stages of orange wheat blossom in cereals and for pollen beetle, seed weevil, cabbage stem weevil and leaf feeding by cabbage stem flea beetle in oilseed rape. The age of some existing thresholds, coupled with their uncertain experimental provenance, is one of the main reasons for this review. Varieties and crop husbandry have changed significantly since the 1970’s and 1980’s and therefore it is debatable whether some of the existing thresholds are still relevant to modern crop production.

As well as knowing how many of any pest can potentially affect yield, it is also important to know when to assess pest numbers in the field. Table 2 provides details of when the main cereal and oilseed rape pests occur during the growing season. Some pests, such as aphids and slugs, can potentially be active throughout the year, whereas others, such as yellow cereal fly and brassica pod midge, have a relatively short time during which they can damage the crop.

Whether or not the pest is active during the stage when the crop is susceptible to attack is also crucial for determining the need for control. In some instances the susceptible stage is included as part of the threshold and is quoted in Table 1, but for completeness all are given in Table 3. Once a crop is beyond the susceptible stage for a particular pest then there is no longer any need to control it.

Table 1. Current thresholds for invertebrate pests of cereals and oilseed rape and their origins

Crop	Pest	Threshold	Origin
Cereals	Autumn aphids, transmission of BYDV Grain aphid (*Sitobion avenae)* Bird cherry aphid (*Rhopalosiphum padi)*	None – spray if aphids present	
	Grey field slug (*Deroceras reticulatum*)	Four or more slugs per refuge trap	Glen, 2005, Glen *et al* 2006
	Wireworms (*Agriotes* spp.)	Use seed treatment if >750,000/ha. Damage likely even with seed treatment if numbers >1.25 million/ha	Unknown
	Yellow cereal fly (*Opomyza florum*)	>300 eggs/m2 (drilled before mid-October)	Unknown
	Gout fly (*Chlorops pumilionis*)	Eggs present on half of plants at GS12 for winter crops. No threshold for spring crops	Unknown
	Wheat bulb fly (*Delia coarctata*)	>5 million eggs/ha – damage inevitable 2.5-5 million eggs/ha – damage likely <1.25 million eggs/ha – late sown (Nov-Mar) crops may suffer damage	Gough *et al.*, 1961
		10% tillers attached at GS20 15% tillers attached at GS21 20% tillers attached at GS23	Young, unpublished
	Leatherjackets (*Tipula paludosa, Tipula oleracea*)	>50 leatherjackets/m^2 for spring cereals 5 leatherjackets/m row for spring cereals	Unknown
	Summer aphids, direct feeding damage Grain aphid (*S. avenae*) Rose-grain aphid (*M. dirhodum)*	50% tillers infested before GS 61 66% tillers infested from GS61 to two weeks before end of grain filling	George & Gair, 1979; Oakley & Walters, 1994

Table 1. (cont.) Current thresholds for invertebrate pests of cereals and oilseed rape and their origins

	Orange wheat blossom midge (*Sitodiplosis mosellana*)	>120 male midges/trap/day in pheromone traps	Ellis *et al*., 2009
		Feed crops – 1 midge/3 ears Milling and seed crops – 1 midge/6 ears	Kurppa & Hursburg, 1989; Larsson, 1992; Pivnik & Labbe, 1993; Oakley, 2003
		Low risk <10 larvae and cocoons/kg soil Moderate risk 11-40 larvae and cocoons/kg soil High risk >41 larvae and cocoons/kg soil	Unknown, quoted in ADAS Plant Diagnostic Unit literature. Anon, 1994
Oilseed rape	Grey field slug (*D reticulatum*)	One or more slugs per refuge trap	Glen, 2005b; Glen *et al*, 2006.
	Peach potato aphid (*Myzus persicae*) transmits turnip yellows virus	None. Treat if aphids present	
	Cabbage stem flea beetle (*Psylloides chrysocephala*)	>25% leaf area eaten at 1-2 true leaf stage.	Unknown
		>50% leaf area eaten at 3-4 true leaf stage.	Green, 2007
		>35 beetles/water trap	Walters *et al*., 2001
		2 larvae/plant	
		50% leaves scarred	
	Wessex flea beetle (*Psylliodes luteola*) Turnip flea beetle (*Phyllotreta* spp.) Large striped flea beetle (*Phyllotreta nemorum*)	None	
	Pollen beetle (*Meligethes aeneus*)	Winter rape >15 beetles/plant at green/yellow bud >5 beetles/plant at green/yellow bud for backward crops >2 beetles/plant at green/yellow bud for varietal association	Unknown
		Spring rape >3 beetles/plant at green/yellow bud (1 beetle/plant in Scotland)	

Table 1. (cont.) Current thresholds for invertebrate pests of cereals and oilseed rape and their origins

Cabbage aphid (*Brevicoryne brassicae*)	Winter rape - >13% plants infested before petal fall. Spring rape - >4% plants infested before petal fall	Ellis *et al.*, 1999
Cabbage seed weevil (*Ceutorhynchus assimilis*)	>0.5 weevils/plant in northern Britain 1 weevil/plant elsewhere	Unknown
Cabbage stem weevil (*Ceutorhynchus pallidactylus*)	Treat if 2 weevils/plant of any species exceeded	Unknown
Brassica pod midge (*Dasineura brassicae*)	None	

Table 2. Seasonal occurrence of cereal and oilseed rape pests (Continuous lines indicate the main period of activity, dotted lines indicate when the pest can also be present)

	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
Cereals												
Aphids (BYDV)	___	___	___	___……	……	……	……	……	……			
Slugs	___	___	___	___	___	……	……	___	___			
Gout fly	___	___	……	___	___	___	___	……		……	___	___
Wheat bulb fly			……	……	……	……	___	___	___			
Yellow cereal fly							……	___	___			
Leatherjackets					……	……	___	___	___	……		
Wireworms			___	___	___	……	……	___	___	___	……	
Aphids (direct feeding)									……	___	___	___
Orange wheat blossom midge										___	___	……
Oilseed rape												
Slugs	___	___	……									
Cabbage stem flea beetle	___	___	……	___	___							
Peach potato aphid (Turnip yellows)	……	___	___	___	……							
Rape winter stem weevil		……___	___	___	……							
Pollen beetle								……	___	___	……	
Cabbage seed weevil										……___	___	……
Brassica pod midge										……	……___	___……
Cabbage aphid									……	……___	___	……

Table 3. Growth stages at which cereals and oilseed rape are susceptible to attack from invertebrate pests

Crop	Pest	Susceptible stage	Comments
Cereals	Aphids (BYDV)	Up to GS31	Plants can still be infected after GS31, but there is little impact on yield
	Slugs	Up to 4 leaves	
	Gout fly	Early sown winter crops most susceptible (before mid-September). Early sown spring crops least susceptible	Control measures directly against gout fly are rarely required.
	Wheat bulb fly	Single shoot crops at time of egg hatch most susceptible	Well tillered crops can tolerate damage.
	Yellow cereal fly	Young seedlings most susceptible	Rarely a problem, appears to feed mainly in secondary tillers
	Leatherjackets	Young seedlings most susceptible. Spring crops most at risk	-
	Wireworms	Young seedlings most susceptible	-
	Aphids (direct feeding)	GS61 to two weeks before end of grain filling	Treatment may be necessary if 50% or more of tillers are infested before GS61
	Orange wheat blossom midge	GS53-59	Once the majority of the crop is in flower the risk has passed.
Oilseed rape	Slugs	Up to four true leaf stage	-
	Cabbage stem flea beetle	Young seedlings most susceptible, particularly at cotyledon stage	Large plants can tolerate significant levels of infestation
	Peach potato aphid	Early sown winter crops and late sown spring crops most at risk	-
	Rape winter stem weevil	Plants attacked early autumn may be killed	-
	Pollen beetle	Green/yellow bud stage	Once crops are in flower beetles will preferentially seek out the flowers
	Cabbage seed weevil	Requires pods in which to lay eggs	Feeding and egg laying punctures provide sites for egg laying by brassica pod midge

Brassica pod midge	Dependent upon seed weevil for egg laying sites	-
Cabbage aphid	Greatest damage from early infestations	-

Do farmers use thresholds?

Pest survey and pesticide usage data

Data from the Fera oilseed rape survey (K. Walters, pers. comm.), and the pesticide usage surveys for arable crops (e.g. Garthwaite *et al*., 2006), provide a good indication of whether farmers/agronomists use thresholds to control invertebrate pests. Data from these two sources for oilseed rape are presented in Figures 1-5.

The most revealing data is that relating to applications of insecticides to oilseed rape for unspecified reasons (Figures 1 and 2). Since 1988, the total area treated for unspecified reasons has been greater than for specified reasons in all years except 1988 and 1990 (Figure 1). This has become particularly marked since 1998, and during the period 1998-2006 the area treated for unspecified reasons has been four to six times greater than for specified reasons. Comparison of the percentage area of crop treated for specified compared with unspecified reasons (Figure 2) shows that the latter is significantly greater than the former for all survey years. In all years except 1988, at least 100% of the area of oilseed rape received an insecticide for which the target pest was unspecified. In seven out of the last 10 survey years, at least 140% of the crop was sprayed for unspecified reasons, and in 2006, 2004 and 1996 this figure was as high as 160%. Clearly this level of insecticide usage is not sustainable and has significant implications for the environment and for insecticide resistance. It is also clear that such unspecified insecticide use is making little if any use of thresholds to predict the risk of pest damage.

Data on pesticide use where farmers/agronomists specify which pest is being controlled by a particular treatment are shown for cabbage stem flea beetle, pollen beetle and seed weevil in Figure 3-5.

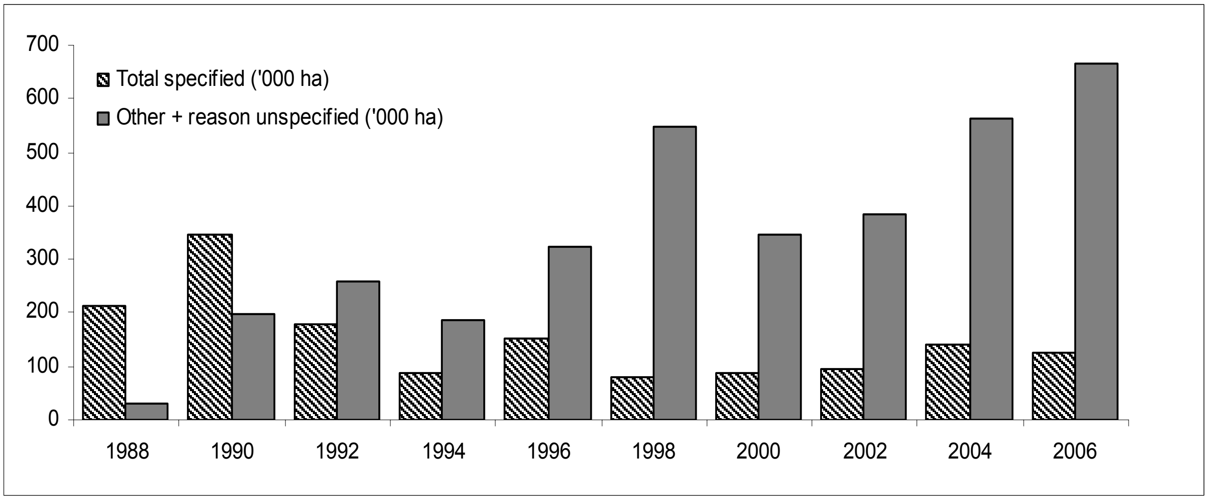

Figure 1. Comparison of area of oilseed rape treated with insecticide against specified pests or for other or unspecified reasons

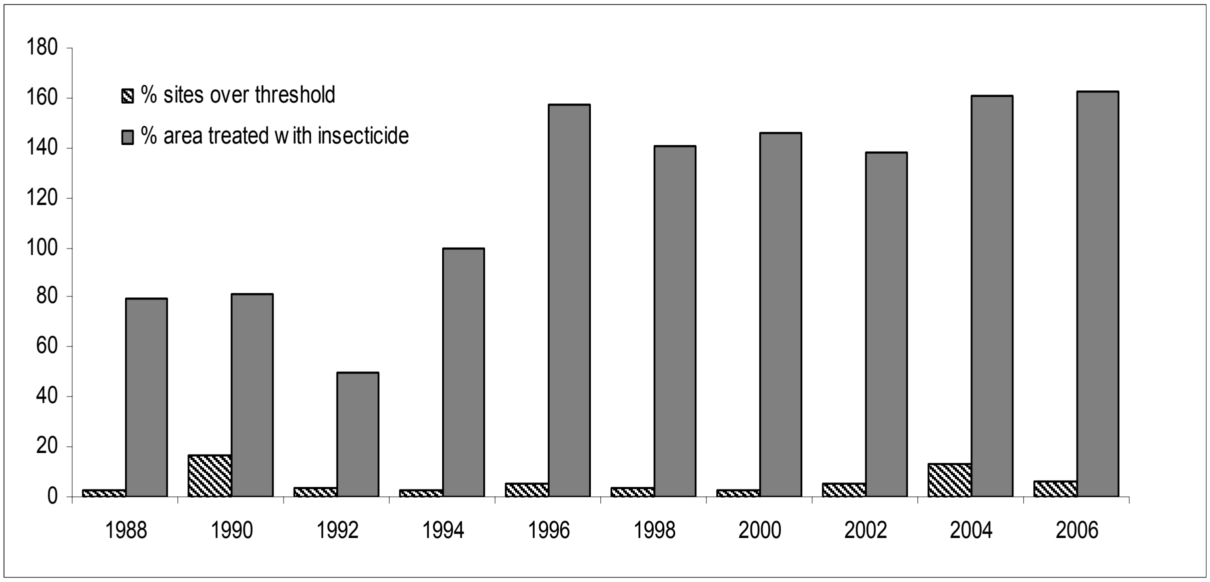

Figure 2. Percentage of oilseed rape crop treated with insecticide compared with the percentage of crop over threshold for insect pests

For cabbage stem flea beetle (Figure 3) more fields were treated than was necessary in all years except 1998. However, in six of the nine survey years only 5% or less of the total crop area was treated which does not represent significant over-use, if it is assumed that none of the unspecified insecticide applications were applied for cabbage stem flea beetle. The highest area of crop treated was 16% in 1990 but this was in response to 12% of surveyed fields being over threshold. In 1992 9% of crop was treated when only 2% of surveyed crops were over threshold, so it seems likely that some treatments were applied in response to the high levels of the pest in 1990. This might also account for the overuse of insecticides in 1996 but it is interesting that in 1994 there was much closer correlation between the area over threshold and the area treated.

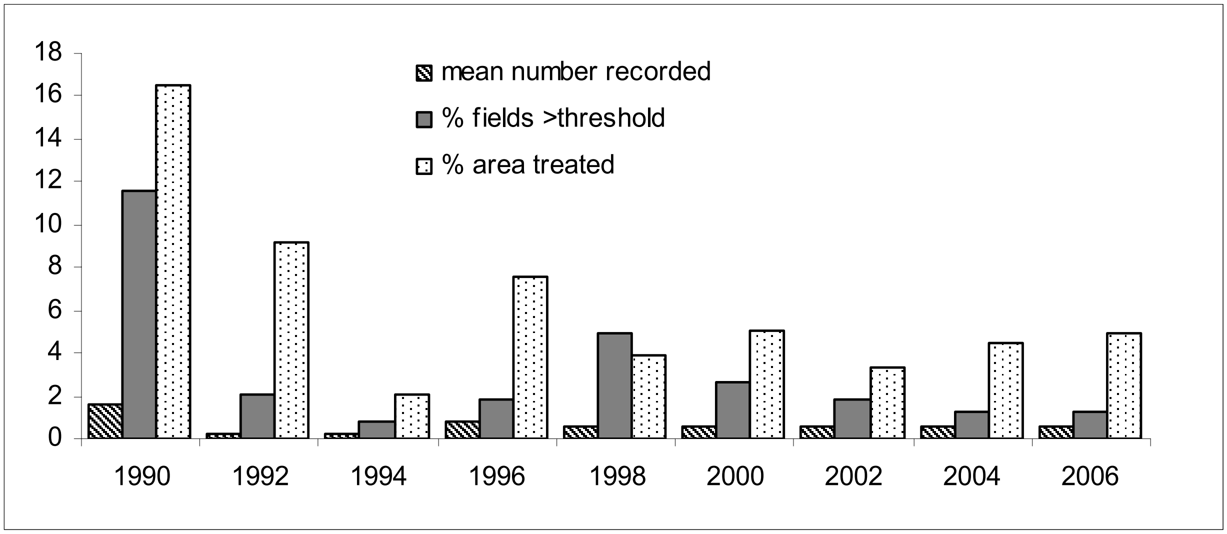

Figure 3. Percentage of fields over threshold for cabbage stem flea beetle, percentage fields treated and mean number of larvae/plant

In nine out of ten years when pollen beetle was surveyed, the percentage area treated against the pest was greater than the percentage of fields over threshold (Figure 4). This was most marked in the years 1988 to 2000. In 1990 almost 20% of the crop area was treated despite no fields being recorded as being over threshold. In the survey years 1988, 1992, 1994 and 1996 the percentage area treated against pollen beetle was between five and eight times greater than the percentage of sites over threshold. Between 2002 and 2006 there has been much closer correlation between the percentage of fields treated and the percentage of fields over threshold suggesting that thresholds were playing a greater role in decision making.

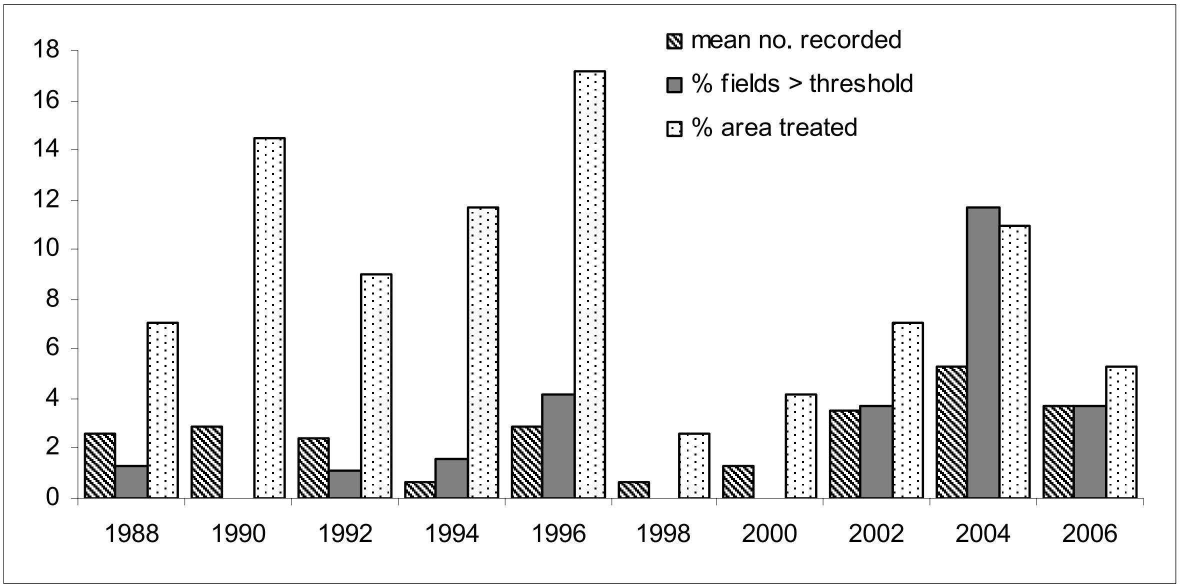

Figure 4. Percentage of fields over threshold for pollen beetle, percentage of fields treated and mean numbers of adults/plant

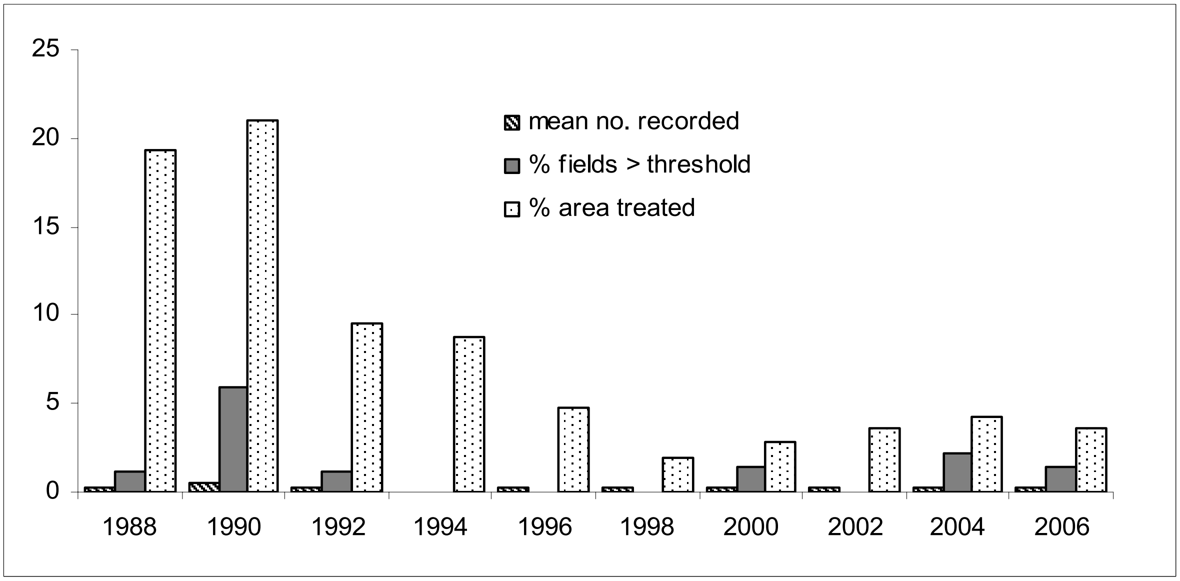

Figure 5. Percentage of fields over threshold for cabbage seed weevil, percentage of fields treated and mean number of adults/plant

Data for seed weevil (Figure 5) are similar to those for pollen beetle in that the percentage area treated is greater than the percentage of fields over threshold in each surveyed year. Between 1988 and 1992 the percentage area treated was between four and twenty times the percentage area over threshold, and from 1994 to 1998 between 2% and 8% of the crop was treated, despite no fields being recorded as being over threshold. In 2000, 2004 and 2006, there is closer correlation between the percentage area treated and the percentage of fields over threshold. This again suggests that thresholds are becoming part of the decision making process as was the case with pollen beetle.

In summary, data relating to the use of insecticides against specific pests shows that the percentage area treated is usually greater than the percentage of fields over threshold. However, there is limited evidence to suggest that thresholds are taken into consideration when deciding whether or not to spray. There is some correlation between the percentage fields over threshold and the percentage area treated for cabbage stem flea beetle. This is less obvious for pollen beetle and seed weevil where in general the percentage area treated is greater than the percentage fields over threshold, particularly up to 2000 for pollen beetle and 1998 for seed weevil. However, for both these pests more recent surveys suggest that a more rational approach to decision making is developing.

However, to suggest that data for insecticide use against a specified pest provides limited evidence of the use of thresholds, is to completely ignore data regarding pesticide use for which there is no specified target. The area of unspecified usage of insecticides completely dwarfs the area of crop treated in a responsible manner, and suggests little regard for the use of thresholds. It is likely that some of the unspecified use is targeted against cabbage stem flea beetle, pollen beetle and seed weevil, but that treatment timing is compromised as farmers prefer to tank-mix insecticides with herbicides/fungicides to limit unnecessary travelling through the crop. While this may prevent some mechanical damage, it is debatable whether the compromised timing of insecticide treatments is ultimately worthwhile. It is also possible that insecticides such as pyrethroids are tank-mixed and applied as a matter of course with no regard for the target pest because they are relatively inexpensive. Whatever the reason for this significant amount of unspecified insecticide use, it is clearly not sustainable as part of a rational approach to insect pest control.

Cereal pests are monitored less intensively than oilseed rape pests. There is no comparable information on the percentage of crop area sprayed against pests in comparison with the percentage of crops over threshold. However, some general data on pesticide use (Garthwaite *et al*., 2006) gives an indication of the level of insecticide use in cereals (Table 4).

Approximately 109% of the British wheat area is treated with an insecticide, with most treatments targeted against the aphid vectors of BYDV in the autumn and orange wheat blossom midge in the summer. Between 1996 and 2006 the use of pyrethroids against aphids in the autumn has increased from 85% to 96% of the treated area. The area treated with chlorpyrifos for orange wheat blossom midge has virtually doubled between 2004 and 2006. These increases in insecticide use have occurred despite no apparent increase in the risk from either pest.

Insecticides are applied to 83% of the area of winter barley grown in Great Britain. This is primarily to control the aphid vectors of BYDV. BYDV can have a significant effect on the yield of barley, and the crop is generally at greater risk of infection than winter wheat due to its earlier sowing date. The absence of any means of determining whether aphids are carrying virus, combined with the relatively low cost of pyrethroids, means that most crops will be treated as a precaution against BYDV infection.

Table 4. Percentage area of cereal crops treated with insecticides and the primary target pest

Crop	% area treated with insecticide	Primary target
Winter wheat	109	Autumn – Aphid vectors of BYDV Summer – Orange wheat blossom midge
Winter barley	83	Aphids vectors of BYDV
Spring barley	11	Aphids and leatherjackets
Oats	54	Aphids
Rye	92	Not specified. (Possibly aphids)

Relatively little insecticide is applied to the spring barley crop, with only 11% of the total area treated. This is targeted mainly against aphids and leatherjackets.

Approximately 54% of the oat area is sprayed with an insecticide for control of aphids. In rye 92% of the crop area is treated but the target pest is not specified.

In general, the overall use of insecticides in cereals does not imply that thresholds play an important role in decision making. This is probably primarily due to the main target being the aphid vectors of BYDV. Currently there is no reliable means of predicting the risk of BYDV infection so inexpensive insurance treatments are relatively common. The increased usage of chlorpyrifos in wheat for control of orange wheat blossom midge is a concern as in recent years the level of infestation of wheat ears by orange wheat blossom midge larvae has been relatively low. This has probably resulted due to the incoincidence of the timing of midge migration and the susceptible stage of the crop. Further work to improve the precision with which the risk of orange wheat blossom midge attack can be predicted would help to minimise insecticide use against this pest, particularly as farmers/agronomists are generally averse to applying chlorpyrifos.

HGCA Oilseed Rape Disease and Pest Management Workshops (November/December 2008)

The HGCA Oilseed Rape Disease and Pest Management Workshops (November/ December 2008) were used to provide feedback on farmer opinions of the value of thresholds for the range of oilseed rape pests. There were five workshops in total at Wellesbourne, Warwickshire; Newmarket, Suffolk; Winchester, Hampshire; York, North Yorkshire and Grantham, Lincolnshire. At each workshop a breakout session entitled “Pest thresholds – useful or useless” enabled farmers to complete short questionnaires on the value of thresholds for pest control in oilseed rape (Appendix 1).

Two particular questions were asked regarding the use of pest thresholds. These were:

1. Do you use thresholds when deciding whether to treat against pests? Answer yes, no or sometimes.
2. What percentage of your decisions to control pests are based on thresholds?

There were 57 respondents to question 1 and 64 respondents to question 2.

In response to question 1 (Table 5), approximately 31% of respondents said that they used thresholds when deciding whether to apply insecticides. A further 61% said that they sometimes made use of thresholds. About 8% of respondents did not use thresholds at all and it is unclear how they made decisions on pest control.

Table 5. Farmer/agonomist response to question 1. Do you use thresholds when deciding whether to treat against pests? Answer yes, no or sometimes.

	Workshop						
	Wellesbourne	Newmarket	Winchester	York	Grantham	Total	%
Yes	4	2	4	6	4	20	31.3
No	1	2	0	0	2	5	7.8
Sometimes	4	3	6	15	11	39	60.9

Question 2 (Table 6) followed on from question 1 by enquiring what percentage of decisions were based on thresholds. Responses were allocated to one of four percentage ranges, 0-25, 26-50, 51-75 and 76-100. In general, the greatest percentage of respondents (57.9) considered that up to 50% of their decisions were based on thresholds. A total of 43.1% of respondents thought that 50% or above of their pest control decisions were based on thresholds. In total 73% of respondents based 25% or more of their decisions on thresholds which is in agreement with data summarised in Table 5 where at least 92% of respondents admitted to using thresholds sometimes to make decisions on pest control. About a quarter of respondents to question 2 considered that only 25% or less of their treatment decisions were based on thresholds.

Table 6. Farmer/agonomist responses to question 2. What percentage of your decisions to control pests are based on thresholds?

	Workshop						
Percentage range	Wellesbourne	Newmarket	Winchester	York	Grantham	Total	%
0-25	2	4	0	6	3	15	26.3
26-50	1	2	4	3	8	18	31.6
51-75	0	0	3	7	1	11	19.3
76-100	3	1	2	5	2	13	22.8

Thresholds as components of decision support systems

In a Defra-funded study (K Walters, pers. comm.) a consultation exercise was undertaken to help determine those factors that were considered by farmers/growers as important components of a decision support system. This included information on economic thresholds. The consultation involved Focus Group Workshops for farmers/ agronomists and postal questionnaires.

Results from the Focus group workshops indicated that despite the apparent poor uptake/use of thresholds by the farming industry, all agronomists/farmers specifically highlighted their use as potentially being central to their decisions on whether to take action against a pest. In addition to indicating a general recognition of the usefulness of thresholds, the results suggested that in isolation they were not considered adequate for modern needs, and that other factors should be taken into account. It was also made clear that labour intensive/expensive pest sampling/assessment techniques can easily make the use of thresholds uneconomic when the low cost of many insecticides was taken into account, thus providing an economic argument against threshold use. The latter issue was also confirmed by an earlier study of assessment methods for cabbage stem flea beetles infesting oilseed rape (Walters *et al*., 2001).

Results from the postal questionnaires indicated that the third highest ranked factor identified as important for making decisions on pest control was economic thresholds. This reinforces the conclusion that despite the apparent poor uptake/use of thresholds they have the potential to play a central role when deciding whether to take action against a pest.

Factors that influence the use of thresholds

a. Farmer/agronomist awareness of, and confidence in, thresholds

Farmer/agronomist awareness of the range of thresholds available for different pests is fundamental to their adoption. The HGCA publication ‘Pest management in cereals and oilseed rape – a guide’ (Oakley, 2003) provided information on the thresholds for invertebrate pests of cereals and oilseed rape but it is difficult to determine whether it encouraged their use. Data from Pesticide Usage surveys (see previous section) suggests that this was not necessarily the case as insecticide use in oilseed rape shows a poor correlation with pest levels with many sprays being applied unnecessarily.

Mathias (1990) reviewed the use of treatment thresholds in entomology for ADAS entomologists. The review recognised that revision of thresholds was desirable but also commented that in practice such changes had not been implemented regularly. Confidence in thresholds was scored from A to E ranging from robust, to good, to moderate, to poor, to arbitrary. The results are summarised in Table 7.

Only two thresholds, those for wheat bulb fly eggs in soil, were considered to be robust. Overall confidence in 12 out of 21 thresholds scored was considered to be only moderate or below.

Table 7. A review of confidence in treatment thresholds in entomology for cereal and oilseed rape pests after Mathias (1990) – A = robust; B = good; C = moderate; D = poor; E = arbitrary

Pest	Threshold		Score (A-E)
Cereals			
Aphids as BYDV vectors	Aphid presence justifies spray		C
Direct feeding damage	>30-50% infested tillers G		C
	>66% ears infested GS 61-73		B
Wheat bulb fly	2.5 million eggs/ha (sowing Sept-mid Nov)		A
	1.25 million eggs/ha (sowing Nov-Mar)		A
	10% tillers infested GS20		B
	15% tillers infested GS21		B
	20% tillers infested GS22+		B
Leatherjackets	>50/m^2		D
	>15/30 cm row length		C
Yellow cereal fly	>300 eggs/m^2 (drilled before mid-Oct)		D
Wheat blossom midge	Feed wheat, 1 midge/3 ears		C
	Seed or milling wheat, 1 midge/6 ears		C
Wireworms	>1.25 million/ha		C
Slugs	4-5/baited trap		E
Oilseed rape			
Pollen beetle	Winter rape 15/plant	At green/yellow bud	C
	Backward crop 5/plant		C
	Spring rape 3/plant		B
Seed weevil	1 weevil/plant (in north)		B
	0.5 weevils/plant (elsewhere)		B
Cabbage stem flea beetle	5 larvae/plant Oct-Dec		B
Cabbage aphid	10-15% infested plants		E

The HGCA Oilseed Rape Disease and Pest Management Workshops provided useful information on farmer/agronomist confidence with thresholds. The questionnaire asked respondents to indicate how confident they were with each threshold for each pest by considering the statement “The threshold is a valuable tool when deciding whether or not to apply an insecticide against the pest”. Their confidence level was scored as 1 – strongly agree, 2 - agree, 3 - disagree and 4 - strongly disagree. In total there were 47 respondents on winter oilseed rape and 35 respondents on spring oilseed rape. The average response was calculated for each pest for each workshop so the lower the score the greater the farmer confidence in the specific threshold (Table 8). Farmers/agronomists were not 100% confident with any threshold. There was least confidence in thresholds for cabbage stem flea beetle and seed weevil for winter oilseed rape and for seed weevil in spring rape. Greatest confidence was in the threshold for pollen beetle for winter rape and for pollen beetle and pod midge in spring rape. The apparent confidence in the pollen beetle threshold for both winter and spring rape is surprising in view of the level of insecticide usage against this pest.

Garthwaite *et al.* (2006) showed 20% of winter rape crops were treated with insecticides against pollen beetle despite average pest numbers not exceeding 4/plant, well below the 15/plant threshold (K Walters, pers. comm.). This suggests that confidence in the threshold is not the only factor that contributes to unnecessary insecticide applications. There was little difference in the general level of confidence in thresholds for winter or spring crops and also between workshops with the exception of Newmarket as already discussed.

Table 8. Farmer/agronomist response to statement “The threshold is a valuable tool when deciding whether or not to apply an insecticide against the pest (4 = strongly agree, 3 = agree, 2 = disagree, 1 = strongly disagree)

	Wellesbourne	Newmarket*	Winchester	York	Grantham	Mean
Winter oilseed rape						
Slugs	2.4	4.0	2.1	2.6	3.0	2.8
Autumn aphids	2.8	4.0	2.6	3.3	2.4	3.0
Cabbage stem flea beetle	2.8	1.0	3.0	2.9	2.7	2.5
Pollen beetle	3.4	4.0	3.2	3.4	2.9	3.4
Summer aphids	2.3	4.0	2.4	2.5	2.8	2.8
Seed weevil	3.0	1.0	2.8	2.8	2.8	2.5
Pod midge	3.0	4.0	2.3	2.9	3.7	3.2
Turnip sawfly	3.0	4.0	2.6	2.3	3.0	3.0
Spring oilseed rape						
Pollen beetle	3.2	4.0	3.4	3.1	2.3	3.2
Summer aphids	2.2	4.0	3.0	2.5	4.0	3.1
Seed weevil	3.0	1.0	2.8	2.6	2.8	2.4
Pod midge	3.0	4.0	2.3	2.9	3.7	3.2
Turnip sawfly	3.0	4.0	2.6	2.3	3.0	3.0

*only one respondent at Newmarket

b. Assessing pest numbers

A threshold expressed as numbers of pests per plant unit (e.g. tiller, ear, raceme) or unit area, is an extremely valuable tool when assessing the risk of crop damage. However, a reliable and cost effective means of assessing pest numbers is also vital if farmers/agronomists are to use thresholds to decide on the need for pest control. A complex or time consuming method of pest assessment is counter productive and may increase the likelihood of insurance sprays, particularly if the product to be applied is relatively inexpensive. This point was stressed in the Defra funded study of Walters (K Walters, pers. comm.).

A summary of the methods available to assess cereal and oilseed rape pests is given in Table 9, together with comments on their simplicity, cost effectiveness and time to assess a single 4ha field. In general, it does not take a significant amount of time to assess pest numbers in an individual field but where agronomists are advising over a number of farms the process will become more time consuming. This emphasises the need for simple but accurate assessment techniques.

Assessment methods for wheat bulb fly and wireworms are particularly time consuming and involve collecting large volumes of soil. Very few soil samples are now received by ADAS Pest Evaluation Services or the Fera Plant Clinic for these pests. Water trapping has been investigated for wheat bulb fly with limited success, although the technique has been applied in France. Bait traps are also available for wireworms and are likely to be more user friendly than soil sampling. Both these techniques warrant further investigation.

Monitoring crops for the presence of viruliferous aphids, for example vectors of BYDV and turnip yellows, has always been difficult. Current advice is to spray if aphids are present in the crop. This assumes that the aphids are carrying the virus, which is not always the case. Attempts have been made to estimate an infectivity index which is a function of aphid numbers and the proportion carrying virus (Plumb, 1976), but generally this was not successful. Farmers and agronomists are most likely to resort to insurance sprays for control of virus vectors as there is currently no reliable method of assessing the risk of virus transmission.

In recent years the ability to predict the risk of damage due to orange wheat blossom midge has advanced significantly (Oakley *et al*., 2005, Ellis *et al*., 2009, Bruce *et al*., 2007). Pheromone traps are very effective at indicating the start of midge activity and trigger the need to assess numbers of females in crops. These assessments involve parting the crop but unfortunately are best done from mid-evening and are very weather dependent. This creates problems for farmers/agronomists who have only a short time in the evening in which to assess all their crops. Also, midges will not fly at temperatures below 15ºC or in high winds. Therefore it can be difficult to gain a precise count of numbers of female midges. Thresholds are quoted at one midge per three ears for feed wheat and one midge per six ears for milling or seed crops. It is virtually impossible to relate the numbers of midges seen to the number of ears, so in practice sprays are applied if a cloud of midges is seen. Yellow sticky traps are an option to replace visual examination of the crop for midges, but require further work to determine how best they should be used and to validate thresholds.

Assessment of pollen beetle and seed weevil in oilseed rape requires beating of plants over a tray and counting the number of pests that are dislodged. While this is relatively straightforward, it is very weather dependent as insects are less likely to be present at the top of the crop in dull, cool weather. Also, even when assessing in optimum conditions (hot and dry), the insects tend to be very active and may fly off before they can be counted. When combined with the difficulties of walking through an oilseed rape crop, it is not surprising that pyrethroid insecticides are often applied as insurance sprays. However, this is clearly not a sustainable option, particularly in view of the potential for the development of insecticide resistant pollen beetles.

Certain assessment methods are not practical for farmers/agronomists as they involve the use of pieces of bulky technical equipment, e.g. Salt and Hollick extraction of wheat bulb fly eggs and wireworms (Salt and Hollick, 1944), Blasdale extraction of leatherjackets (Blasdale, 1974)). These apparatus are effective at estimating pest numbers and are used as part of surveys to give an estimate of national and regional risk of pest attack through projects sponsored by HGCA and Dow AgroSciences. HGCA project RD-2004-3153 (www.hgca.com), Autumn survey of wheat bulb fly incidence, monitors egg laying by wheat bulb fly to give an indication of the need to use seed treatments for late sown (November onwards) crops. The Dow Pest Watch web site (www.dowagro.com/uk) provides details on a survey of leatherjacket populations in December to help predict the potential risk of damage to cereals in the spring. Data on the progress of orange wheat blossom midge development and wheat bulb fly egg hatch are also provided. These initiatives are very useful for farmers/agronomists to give a general indication of the potential for pest attack and may be exploited further in the future, particularly as part of product stewardship schemes. However, there may still be a need to assess risk on an individual field basis.

In summary, there are a wide range of methods available for assessing pest numbers in the crops or in the soil. Such assessments are vital to determine whether threshold levels have been reached. Therefore it is crucial that any assessment is made as user friendly as possible so that it can be undertaken quickly and cost effectively. Whilst some current assessment methods meet these criteria, others are more complex and less cost effective when compared against a treating prophylactically with relatively inexpensive chemical treatment.

Table 9. Assessment methods for invertebrate pests of cereals and oilseed rape and time to assess a field of 4ha

Crop	Pest	Assessment method	Time (hours)	Comments
Cereals	Aphids and BYDV	Visually examine at least 50 randomly chosen plants for aphids during September to November	1.0	Aphids are very difficult to spot without kneeling in the crop. Even when aphids are found it is not possible to easily test whether or not they are viruliferous.
	Grey field slug	Nine refuge traps or 13 for fields larger than 20 ha in a "W" pattern. Bait with chicken layers mash	0.5 to set traps, 0.5 to examine	Indicates when slugs active on soil surface. Effectiveness of pellets also very dependent on wet weather.
	Wireworms	Assess numbers in soil by taking 20, 10 cm diameter x 15 cm deep soil cores/4 ha	1.5 to sample, 1.5 to extract (depends on soil type	As per wheat bulb fly.
		Set grain traps to attract wireworms	1.0 to set traps 1.0 to examine	Traps not readily available
	Yellow cereal fly	No recognised assessment method. Can assess tiller infestation as above	0.5 to sample, 1.0 to dissect	Can dissect tillers
	Gout fly	Examine plants for gout fly eggs	0.5	Requires ability to identify gout fly eggs.
	Wheat bulb fly	Assess egg laying by taking 20, 10 cm diameter x 15 cm deep soil cores/4ha	1.5 to sample, 1.5 to extract (depends on soil type)	Very time consuming. Will involve collecting approximately 20 kg soil. Samples must be processed by an accredited laboratory.
		Assess tiller infestation by dissecting 50 randomly chosen plants.	0.5 to sample, 1.0 to dissect	Time consuming. Plants should ideally be dissected by an accredited laboratory. Need to be able to distinguish different dipterous stem borer larvae which requires a microscope.
	Frit fly	Can assess tiller infestation	0.5 to sample, 1.0 to dissect	Can dissect tillers

	Leatherjackets	Extraction in brine solution. Drive 10cm diameter drainpipe into soil and part fill with brine. Leatherjackets float to surface (Stewart and Kozicki, 1987)	1.5	Rarely if ever used. Brine drains too quickly in some soils
		Extraction using Blasdale apparatus (Blasdale, 1974)	0.5 to sample, 1.0 to extract	Requires bulky extraction equipment only available via an accredited laboratory
	Summer aphids (Direct feeding)	Visually examine 100 randomly chosen tillers for presence of aphids	1.0	Relatively straightforward assessment. No distinction drawn between a single or many aphids on a tiller.
	Orange wheat blossom midge	Assess soil for presence of cocoons/larvae. Take 60 cores with 2.5 cm cheese corer in “W” pattern from area not exceeding 15 ha	1.5 to sample,	Rarely used. Risk of damage most dependent on timing of midge emergence and susceptible stage of crop.
		Pheromone traps	0.5 to set, 0.5 to examine	Good indicator of midge activity but only traps males.
		Field monitoring by parting crops and counting midges disturbed.	0.5	Best indicator of females in crop but time consuming. Also weather dependent. Impossible to count numbers of midges per ear as suggested by threshold.
		Yellow sticky traps	0.5 to set, 0.5 to examine	Will catch female midges but threshold not validated. Worthy of further investigation.
Oilseed rape	Grey field slug	Nine refuge traps or 13 for fields larger than 20 ha in a “W” pattern. Bait with chicken layers mash	0.5 to set traps, 0.5 to examine	Indicates when slugs active on soil surface. Effectiveness of pellets also very dependent on wet weather.
	Peach potato aphid	Visually examine at least 50 randomly chosen plants for aphids in autumn	1.0	Aphids very difficult to spot. Even when aphids are found it is not possible to easily test whether or not they are viruliferous.

Cabbage stem flea beetle	Assess plants for presence of shot holes	0.5	
	Yellow water traps (two in headland, two in field)	0.5 to set, 0.5 to examine	Relatively recent recommendation, unlikely to have widespread use.
	Dissect up to 50 randomly chosen plants for larvae	0.5 to sample, 1.5 to extract	Usually done by an accredited lab. Very few samples received. Probably too time consuming when compared with inexpensive treatment option. Can be combined with assessment of plants for aphids if plants are returned to the lab.
Other flea beetles	Assess plants for presence of shot holes	0.5	
Pollen beetle	Beat 25 randomly chosen plants over a white tray	0.5	Very weather dependent. Insect numbers are low in cool conditions. Difficult to decide what constitutes a plant.
Cabbage aphid	Visually examine at least 50 randomly chosen plants for aphids in spring/early summer	0.5	Difficulty with accessing crop and also determining what constitutes a plant. Assessment rarely done.
Seed weevil	As above for pollen beetle	As above	As above.

c. Pesticide costs

Pesticide costs are another potential barrier to the adoption of thresholds. Some pyrethroids which are used for a range of crop pests (aphids, caterpillars and beetles) are particularly cheap at about 98p/ha. At such a low price it is not surprising that insurance sprays are sometimes applied rather than assessing pest numbers and deciding on the need to treat.

It is difficult to argue against insurance sprays of inexpensive insecticides in terms of cost effectiveness, but other arguments may become more persuasive in future. The risk of development of insecticide resistant insects could create significant problems. This is currently the case in Poland and Germany where pyrethroids are no longer effective against pollen beetle. In Germany alone 30,000 ha of winter rape was destroyed and 200,000 ha seriously damaged in 2008.

It is also often the case that insurance treatments are tank-mixed to coincide with the application of fungicides and/or herbicides. In some instances this is a cost-effective approach and limits the number of field operations. However, it can also mean that the insecticide is applied at a compromise timing at which it is too early or too late to affect the pest.

Insurance sprays, no matter how inexpensive, are clearly not a sustainable option. Non-target invertebrate species will suffer, some of which are predators and parasites of pest species. Some pesticides also affect birds and mammals. Consumers are becoming increasingly aware of environmental issues regarding the use of pesticides, for example residues in food, and will continue to exert pressure on the agricultural industry. This is already becoming apparent through the imposition of assurance schemes by supermarkets which restrict the use of certain pesticides. It is important that the industry is seen to respond to these consumer concerns. It is also possible that changing legislation relating to pesticide use may affect which insecticides are available. Although the latest estimates indicate that the revision of 91/414/EEC is only likely to result in the loss of two insecticides, there are a number of active substances that are still being assessed. The implementation of the Water Framework Directive is also likely to impact on a number of active substances that are available for use (Clarke *et al.*, 2009).

In summary, whilst there is currently an economic argument for use of insurance sprays, this is likely to become less strong in future. Reduced insecticide availability, the potential for insecticide resistance and environmental concerns will increase the requirement for a rational threshold based approach to pest control. In anticipation of this, it is vital that robust thresholds, combined with user friendly assessment methods, are in place to allow farmers/agronomists to assess with much greater precision the risk of pest damage and the need for insecticide treatment.

Review of advances in crop physiology

While varieties and crop husbandry have changed significantly since the 1970's and 1980's there has been little if any revision of pest thresholds and so it is debatable whether they are still relevant to modern crop production. Our understanding of yield formation and the crops ability to tolerate the effect of pests and diseases has also advanced; this section reviews this work and discusses how it might relate to control of invertebrate pests.

Physiological mechanisms of yield formation

It has been found that the yield of barley and oilseed rape are generally limited by insufficient seeds/m^2 and are referred to as being sink limited (Berry and Spink, 2006; Mendham *et al*., 1981; Bingham *et al*., 2007a,b), whereas the yield of UK wheat has been shown to be either limited by insufficient resources to fill the grains (source limited) or is co-limited by insufficient source and sink (Shearman *et al*., 2005). Whether or not a crop is source or sink limited will determine how tolerant it will be to pest damage at different growth stages. A crop which is sink limited will be particularly vulnerable to damage during the period when the number of grains/m^2 is determined, e.g. barley would be expected to have a low tolerance to pests which reduce tiller numbers because this would reduce seeds/m^2 and sink size. A crop which is source limited will have a low tolerance to pests which reduce the supply of assimilate to the growing grains, e.g. wheat would have a low tolerance to pests which reduce green area during seed filling as this will reduce photosynthesis and the supply of photo-assimilate for filling the grains (Figure 6). This section summarises the current physiological understanding of how yield is determined in wheat, barley and oilseed rape and how tolerant these crops will be to pest damage during different phases of growth.

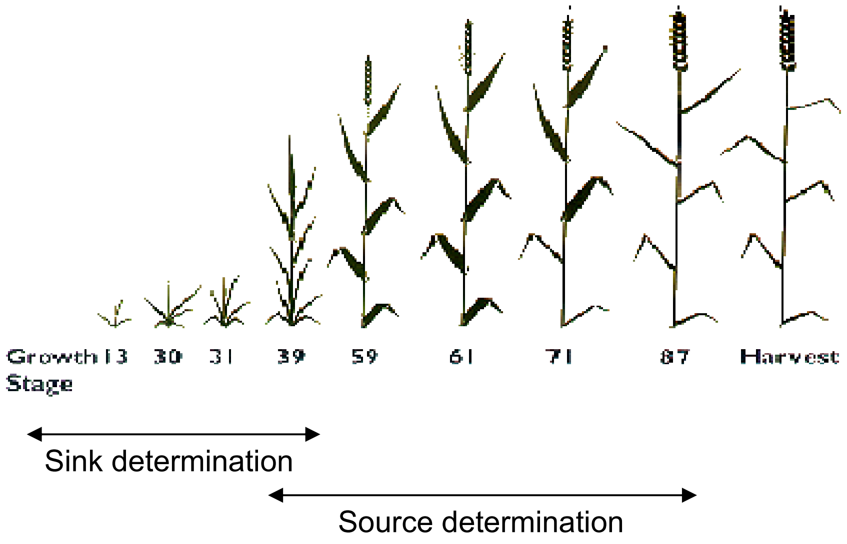

Figure 6. Phases of growth when sink size (seeds/m^2) and source size (supply of assimilates for filling the seeds) are determined.

Wheat

The number of grains/m^2 is determined by the number of ears/m^2 and the number of grains per ear. It has been shown that, for crops with a yield potential of about 10 t/ha, a minimum of 400 ears/m^2 is required for a crop to achieve its yield potential (Spink *et al*., 2000). The timing of shoot production depends on sowing date, the number of plants established and the temperature. After early sowing the main tillering phase occurs in autumn. If many plants are established (more than 250 plants/m^2) then tillering is usually completed before winter. If few plants are established (<100 plants/m^2) then tillering can continue into the spring (Figure 7). With late sowing (November) tillering is usually delayed until spring unless late autumn and winter temperatures are unusually warm. Tillering seldom occurs after stem extension has begun because assimilates are required for stem growth. The maximum shoot number therefore usually occurs at GS30-31 or just before. Early sown crops or crops with many plants/m^2 tend to have a greater maximum shoot number. Varieties that reach stem extension early, such as Soissons, tend to have a lower maximum shoot number. In general, wheat crops produce more shoots than are required to achieve yield potential and a proportion of tillers die between the beginning of stem extension and flowering. The last formed tillers tend to die first. In general, a greater proportion of tillers die in crops which produce a high maximum shoot number. Shoot survival also varies significantly between varieties from 40% to more than 70% (Berry *et al.*, 2002). Producing shoots that are destined to die is also wasteful for the plant and this should be minimised. It is therefore apparent that many wheat crops produce more tillers than the minimum required to achieve potential yield and therefore many crops should be able to tolerate the loss of some tillers to slugs or stem boring insects.

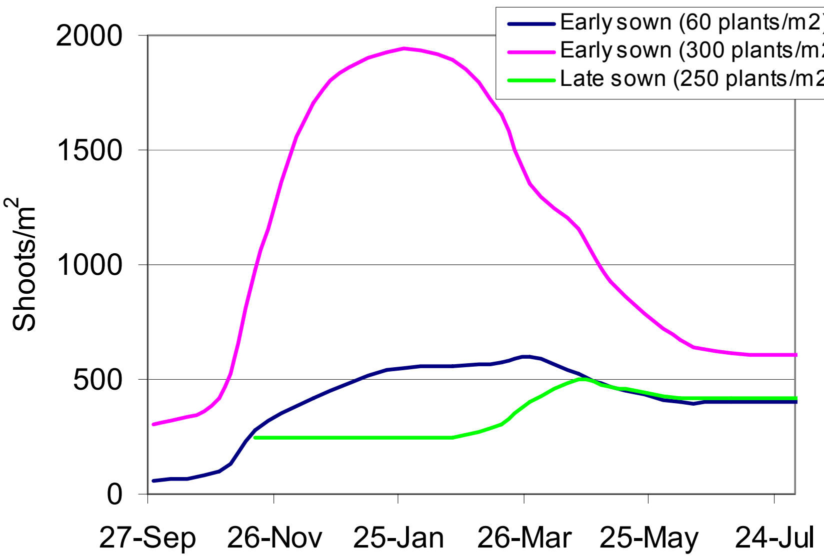

Figure 7. Patterns of wheat tillering from the Wheat Growth Guide 2nd edition 2008.

Between 16 and 23 spikelets develop in each wheat ear (Brooking and Kirby, 1981; Kirby *et al*., 1989). The Rht2 dwarfing gene introduced in the late 1970s and 1980s reduced spikelet number by one per ear (Brooking and Kirby, 1981). Between seven and 11 florets are initiated in each spikelet between terminal spikelet and GS39. Modern varieties have been shown to initiate more florets per spikelet (Siddique *et al*., 1989). Floret death occurs during a short period of about 100^{o}Cd (day degrees) beginning at flag leaf fully emerged (Siddique *et al*., 1989) or at the ear peep stage (Kirby, 1988). The proportion of florets which survive to become fertile depends upon the supply of assimilate during this critical period. Typically about one third of the florets remain fertile. The number of florets which remain fertile is increased by greater radiation and lower temperature during the 20-30 day period before anthesis (Fischer, 1985; Bindraban *et al*., 1998; Beed *et al*., 2007). Crops with fewer shoots per m^2 set a greater proportion of fertile florets (and grains per ear) because they generally produce more assimilate per shoot as a result of less mutual shading (Whaley *et al.,* 2000). This is a key way in which crops with few shoots/m^2 (perhaps as a result of earlier pest damage) can compensate and achieve potential yield. The Rht2 dwarfing gene has also been shown to increase grain number per spikelet by 0.7 or by nine grains per ear (Brooking and Kirby, 1981). At anthesis, each floret retains the potential to be fertilised for three to five days and under stress free conditions 75% to 100% of fertile florets set grains after anthesis. High temperatures of 30^oC and above reduce grain set (Hoshikawa, 1959). The potential grain size is determined during flowering and early grain development when the endosperm cell number is set (Brocklehurst, 1977; Calderini *et al*., 1999). Potential grain size has been shown to be reduced by high temperatures between ear emergence and flowering (Calderini *et al*., 1999) and dull light during early grain development (Singh and Jenner, 1984).

Assimilate for grain growth comes from current photosynthesis and the relocation of stem reserves accumulated before flowering. The size of canopy required to intercept 95% of the radiation varies between a green area index (GAI) of 5 and 7 depending on the extinction coefficient (angle of leaves). The economic optimum canopy size depends on several factors including the price of nitrogen fertiliser and the price of grain (Sylvester-Bradley *et al*., 1997) and usually lies between a GAI of 5 and 7. The percentage of the total green area made up by different parts of the plant have been measured as follows; 7% by the ears, 20% by the flag leaf, 21% by leaf 2, 18% by leaf 3, 14% by leaf 4, 1% by leaf 5 and 19% by the stems (Sylvester-Bradley *et al*., 2009). It has been estimated that the amount of light intercepted by different parts of the plant is approximately 20% by the ears, 40% by the flag leaves and 20% by leaf 2 (Sylvester-Bradley *et al*., 2009). It is clear that any damage to leaves 1 and 2 and the ear by pests, such as aphids, will constrain the plant's ability to photosynthesise and fill the grains. Wheat also accumulates between 2 and 4 t/ha of water soluble carbohydrate, mainly in the stem, by flowering (Foulkes *et al*., 1998a). The proportion of the stem reserves accumulated by flowering that are relocated to the grain have been shown to vary with estimates of 0.42 (Austin *et al*., 1977), 0.72 (Gebbing *et al*., 1999), 0.50 to 0.92 (Yang *et al*., 2001) and 0.5 to 0.6 (Bidinger *et al*., 1977). Radio-active labelling experiments have shown that drought stressed crops relocate proportionately more of the maximum amount of stem reserves to the grain (Bidinger *et al*., 1977; Yang *et al*., 2001). It is possible that that this response is invoked when the sink capacity is not met by current photo-assimilate. If this is the case then a reduction in green area and photosynthesis during grain filling caused by pest damage may trigger a similar compensatory mechanism. However, the work of Foulkes *et al.* (1998) shows that varieties with high yield potential tend to be dependent on carbohydrate reserves even in an unstressed state. The potential contribution that water soluble stem carbohydrates contribute to yield has been estimated at 20 to 50% (Sylvester-Bradley *et al*., 2009). This is a maximum potential contribution because it ignores possible losses in respiration and transfer below ground.

Barley

Barley in the UK has been shown to be predominantly sink limited (Bingham *et al.,* 2007a). Grains/m^2 are increased by factors which increase the production and survival of tillers, spikelets per ear and fertile florets per spikelet, e.g. grains per spike were increased when the amount of radiation intercepted per shoot increased (Arisnabarreta and Miralles, 2008). Each ear has adjacent nodes, each with three spikelets, and each spikelet contains a single floret. In 2-row barley only the median spikelet is fertile, and all three spikelets are fertile in 6-row barley (Kirby and Appleyard, 1984). In comparison each spikelet of wheat may produce up to nine grains. Barley therefore has less potential to produce large numbers of grains per ear than wheat and therefore has a lower capacity to compensate for low tiller numbers. Similar to wheat, the potential size of the grain is determined between ear emergence and early grain development (Cochrane and Duffus, 1983; Bingham *et al*., 2007b). Greater radiation and lower temperatures between ear emergence and the start of grain filling were positively related to final grain weight which indicates these factors increased potential grain size (Bingham *et al*., 2007b).

As with wheat, the assimilate for grain growth comes from current photosynthesis and the relocation of stem reserves accumulated before flowering. Barley requires a GAI of between 5 and 7 to intercept 95% of light. In barley, each successive emerging leaf has a smaller green area. The percentage of the total green area made up by different parts of the plant have been measured as follows; 11% by the ears, 4% by the flag leaf, 7% by leaf 2, 11% by leaf 3, 15% by leaf 4, 16% by leaf 5 and 36% by the stems (Spink *et al.,* 2006). It is therefore clear that pest damage to upper leaves will cause a smaller reduction in canopy photosynthesis in barley than in wheat, but pest damage to lower leaves will cause a greater reduction in photosynthesis in barley. Barley accumulates between 1 and 3 t/ha of water soluble carbohydrate by flowering

(Bingham *et al*., 2007a). The potential contribution of water soluble carbohydrates to grain yield has been estimated at between 11% and 45%.

Oilseed rape

The number of seeds/m^2 is determined during a critical phase for pod and seed abortion lasting about 300^{o}Cd after mid-flowering (Mendham *et al*., 1981; Leterme, 1988). In most field situations this equates to about 19-25 days. Pod and seed survival have been shown to be related to the amount of radiation intercepted by photosynthetic tissue per flower and per pod respectively during this critical period (Leterme 1988; Mendham *et al*., 1981). Radiation intercepted by each unit of green area is reduced when the canopy size is too small (i.e. less than a GAI of 3). Large canopies of more than a GAI of 4 also reduce the radiation intercepted by unit of green tissue because the layer of flowers absorb and reflect radiation. Canopies with a GAI of more than 4 have a thicker flower layer which reduces the amount of radiation reaching the green tissues. The flowers of a crop with a flower cover of 62% at mid-flowering were measured to absorb and reflect 58% of photosynthetically active variation (Yates and Stevens, 1987). An optimum GAI of between 3 and 4 during flowering has therefore been found to be ideal for maximising radiation intercepted by photosynthetic tissue (Lunn *et al*., 2001).

A significant proportion of flowers do not form pods in typical oilseed rape crops, e.g. Mendham *et al*. (1981) observed that thick crops produce approximately 20,000 flowers/m^2, but only 10,000 fertile pods/m^2 are required to produce optimum yield. Current HGCA project RD-2005-3242 ‘Re-evaluating thresholds for pollen beetle in oilseed rape’ has shown that thinner crops that result from either lower plant population or poor growth have fewer excess flowers. The components of seed number/m^2, pod number/m^2 and seed number per pod, are negatively related (Figure 8). This relationship results in an optimum fertile pod number of between 6000 and 8000 pods/m^2 (Figure 7). It is likely that the canopy size of crops with fewer than 6000 pods/m^2 is too small to trap all incident radiation, which results in fewer set seeds/m^2. For crops with more than 8000 pods/m^2 it is likely that the thickness of the flowering layer reduces the amount of radiation reaching the photosynthetic tissues, which reduces the number of seeds/m^2 and per pod. During flowering, crops with an optimum number of pods have a GAI of between 3 and 4 units (Lunn *et al*., 2001). It has been shown that crops with a GAI at flowering of less than 3 units produce fewer pods than the optimum and have a lower yield potential (Lunn *et al*., 2001). Therefore pests, such as slugs, flea beetle or pollen beetle, which reduce the canopy size to below a GAI of 3 or reduce the number of pods to below about 6000/m^2 are expected to reduce the final seeds/m^2 (sink size) and reduce yield potential.

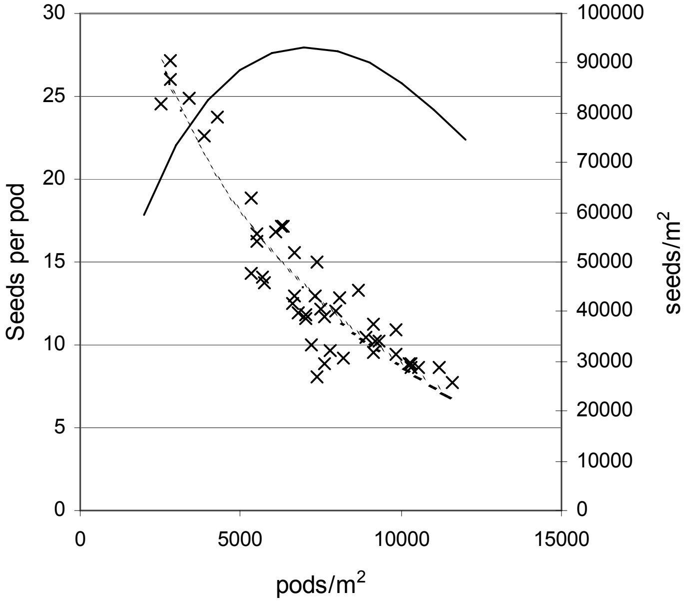

Figure 8. Seeds per pod plotted against pods per metre squared (crosses) for sowing date, seed rate and N fertiliser treatments at two UK sites in 1996, 1997 and 1998 (Lunn *et al*., 2001). Best fit line (dashed); y=13.2 Ln(x) +130.2, R^2=0.87 (P<0.001). Relationship between seeds per metre squared and pods per metre squared (solid line) calculated from relationship between seeds per pod and pods per metre squared.

The period of seed filling has been shown to last for a set period of thermal time (Mendham *et al*., 1981). Therefore warmer temperatures will curtail the period during which the seeds can fill. During grain filling a GAI of between three and four units is required to intercept the majority of the light. During this period the pods intercept most of the incoming light and carry out most photosynthesis. Stems and leaves intercept less light, but still make significant contributions to assimilate production. The photosynthetic capacity of stems and pods has been estimated at 37% and 67% respectively compared with the leaves (Gammelvind *et al*., 1996; Major, 1975). Therefore, maximising the proportion of leaves within the canopy will increase overall photosynthesis. Pests such as pod midge or cabbage aphid which reduce the GAI of the canopy during seed filling to below 3 will reduce the crop’s ability to fill seeds.

Water soluble carbohydrate accumulated before flowering, and predominantly stored in the stem, has been estimated to contribute variable amounts to final yield including 0% (Stafford, 1996), 10% (Mendham and Salisbury, 1995) and 12% (Habekotte, 1993). These contributions are significantly less than the contribution made to yield by stored water soluble carbohydrate reserves in wheat and barley. This indicates that oilseed rape will have less ability to compensate for damage to the canopy during seed filling by pests such as pod midge or cabbage aphid.

Phases of growth with the greatest influence on yield

In general, the yield of crops which are sink limited is influenced most by factors which impact before flowering (when the sink size is determined) and source limited crops are influenced most by factors which impact after flowering (when the source size is determined). The yield of crops which are co-limited by sink and source is affected by factors impacting on both pre- and post-flowering phases of growth. Therefore for sink limited crops such as barley and oilseed rape, it is expected that factors which restrict the determination of seeds/m^2 will be of great importance, e.g. insufficient shoot production in barley, and failure to achieve the optimum canopy size and optimum pod number in oilseed rape. Factors which affect seed filling in these crops, such as reducing canopy size after flowering, are expected to have a smaller effect on yield. For wheat, it is expected that factors which affect the determination of seeds/m^2 and seed filling will be important. However, it must be recognised that there will be exceptions to these general principles. Firstly, environmental conditions or crop management may change a crop from being sink to source limited, or vice-versa. For example, a barley crop which produces an unusual number of tillers, and as a result many seeds/m^2, may become more source limited than sink limited. Secondly, the severity of the impacting factor is important, e.g. a severe reduction in canopy size during seed filling will reduce the yield of a sink limited crop. Nonetheless the nature of the sink/source limitation of a crop will generally be a useful indicator about which phases of crop growth that pests damage will have the greatest effect on yield.

Estimating the degree of tolerance to pest damage

It is clear from the above sections that crops can tolerate pest damage that occurs early in the crop’s life-cycle due to its ability to compensate, e.g. crops with few tillers usually produce more grains per ear. The crop has less tolerance to damage that occurs later because there is less time for compensatory growth. However, even damage that occurs during seed filling may be compensated for by remobilising more water soluble carbohydrate reserves accumulated in the stem before flowering, although potential for this is limited in oilseed rape. It should also be recognised that crops which are sink limited are less vulnerable to yield losses from pest damage during seed filling because these types of crop generally have an excess of source to fill a limited number of seeds.

Improved physiological understanding of the determination of yield has enabled the amount of tolerance to pest damage before yield is reduced to be estimated. An assessment of the scope for tolerating damage is described in Table 10. This illustrates that most crops have some ability to tolerate pest damage, but that there is a very large range in tolerance caused by differences in crop growth resulting from variation in weather and husbandry.

Table 10. Tolerance of cereals and oilseed rape to pest damage

Crop parameter	Minimum to achieve potential yield	Range in practice	Degree of tolerance to loss in a typical crop
Winter wheat			
Plants/m2	<100 early sown 200 late sown	50 to 600	High
Ears/m2	400	400 to >2000 shoots/m^2	High
GAI at flowering	5 to 7	5 to 10	Moderate
Post-flowering photo-assimilate	Unknown	Unknown	Low
Winter barley			
Plants/m2	unknown	Up to 600	Moderate
Ears/m2	unknown	400 to >2000 shoots/m^2	Low
GAI at flowering	5 to 7	4 to 9	Low
Post-flowering photo-assimilate	Unknown	Unknown	Moderate
Spring barley			
Plants/m2	unknown	Up to 600	Low
Ears/m2	unknown	unknown	Low
GAI at flowering	unknown	unknown	Low
Post-flowering photo-assimilate	unknown	unknown	Moderate
Winter oilseed rape			
Plants/m^2	Unknown	20 to 120	Moderate
Pods/m^2	7000-8000	5000 - 12000	Moderate
GAI at flowering	3 to 4	3 to 6	Moderate

Crop parameter	Minimum to achieve potential yield	Range in practice	Degree of tolerance to loss in a typical crop
Post-flowering photo-assimilate	Unknown	Unknown	Moderate
Spring oilseed rape			
Plants/m^2	Unknown	20 to 120	Low
Pods/m^2	7000-8000	Unknown	Low
GAI at flowering	3 to 4	Unknown	Low
Post-flowering photo-assimilate	Unknown	Unknown	Moderate

Effects of changes in varieties and crop management on crop growth

Since 1970, the yield of wheat has approximately doubled from 4 t/ha to almost 8 t/ha, the yield of spring and winter barley combined has increased from about 3.5 t/ha to 6 t/ha, and the yield of oilseed rape has remained static at about 3 t/ha (Figure 9).

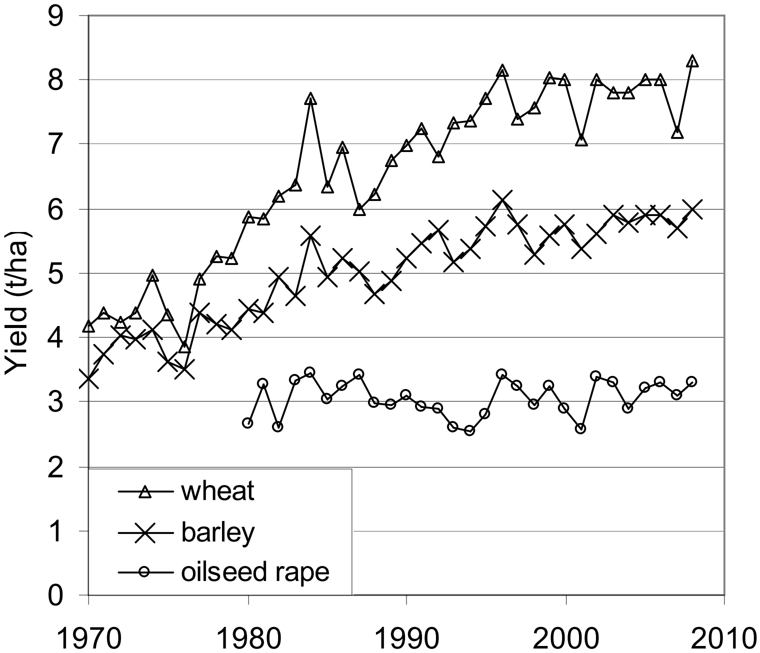

Figure 9. UK average farm yields. Defra statistics.

Until the late 1980s half of the improvement in wheat yields was attributed to plant breeding and half to improved crop husbandry (Austin *et al.*, 1989). In more recent years there has been evidence to demonstrate that a greater proportion of the yield increase has resulted from breeding (Philpott *et al.*, 2008). The improvement in genetic potential has been associated with the development of new wheat varieties during the 1970s and 1980s that were shorter, with more assimilate partitioned to the grain and a lower lodging risk, more shoots resulting from greater shoot survival, smaller flag leaves and more latterly a greater overall crop biomass and greater water soluble carbohydrate reserves (Shearman *et al*., 2005). There was no difference in the date of the start of stem extension or flowering. This study concluded that increased pre-anthesis growth had increased the number of grains/m^2 (sink size), and an increase in water soluble carbohydrates meant there was sufficient source to fill the grains. This was supported by the observation that individual grain weight had not changed over time. It was concluded that improvements to both sink size and source size had occurred, and that wheat yield remained co-limited by sink and source.

There is much less evidence available for how plant breeding has affected the yield of oilseed rape. Since 1980, farm yields have remained the same at 3 t/ha. In contrast, mean yields within the HGCA Recommended List (R.L.) variety trials have increased by about 0.5 t/ha per decade since 1980. Analysis of the R.L. scores for various plant traits (Spink and Berry, 2004) indicates that flowering occurs earlier whilst the date of ripening has not changed. Resistance to downy mildew, light leaf spot and stem canker has improved, but have only exceeded the rate of breakdown in disease resistance for downy mildew. Height and lodging resistance do not appear to have changed significantly. It is likely that breeding has altered oilseed rape in other ways that have not yet been detected. Little information has been gathered about how plant breeders have altered barley other than a reduction in crop height.

Several changes in the way in which wheat, barley and oilseed rape are grown have occurred since the 1970s, not all of which have increased yield. The most important changes in crop management have been considered for wheat by Sylvester-Bradley *et al*. (2004) and include; the introduction of effective fungicides in the late ’60s and their more widespread use through the ’70s, together with the introduction of semi-dwarf varieties and heavier use of nitrogen fertilisers during the 1970s, combined to bring a fast period of yield increase, interrupted by the 1976 drought, but culminating with the exceptionally high yields of the 1984 harvest (7.7 t/ha; 2.9 t/ha above the linear trend). Since the early 1980s there has been little change in the rate of nitrogen fertiliser usage on cereal crops, and applications to oilseed rape declined from about 270 kg N/ha in the early 1980s to about 190 kg N/ha in the early 1990s from when they have remained constant (British Survey of Fertiliser Practice). More recent advances in husbandry were more concerned with improving efficiency: reducing labour by further mechanisation, reducing nutrient leaching by improved fertiliser timing, introducing agrochemicals with better efficacy, adjusting to the ban on burning straw, adoption of minimal cultivation techniques and reducing costs of inputs such as seeds. Similar changes have also occurred in barley and oilseed rape, although the adoption of minimal cultivation techniques has been stronger in oilseed rape and the interval between oilseed rape crops has shortened.

Changes in crop management which have the potential to impact on tolerance to pests are increased fertilisation, reduced seed rates in wheat and the use of improved fungicides in all species. Greater use of nitrogen fertiliser increases the sink size by increasing shoot number and source size by prolonging the life of the green tissue. The stimulus for using lower seed rates in wheat came from pressure to reduce costs and evidence that seed rates could be reduced significantly in many situations (Spink *et al*.,2000; Whaley *et al*., 2000; Spink *et al*., 2004). Anecdotally it does appear that lower seed rates are often used in wheat, and to a lesser extent in oilseed rape, but no surveys have been carried out to provide conclusive evidence. Establishing fewer plants/m^2 will reduce the sink size by reducing the potential number of shoots/m^2. There is no evidence that fewer plants affect the size of the source. Therefore establishing fewer plants will generally make wheat more sink limited. Although more effective fungicides have been developed for cereals and oilseed rape, the trend towards more susceptible varieties, earlier drilling and greater nitrogen fertiliser has probably resulted in little change in the level of disease control. Therefore it is not possible to conclude that for example the development of more effective fungicides has resulted in longer grain filling and greater source size.

Effects of changes in climate on crop growth

In the main cereal and oilseed rape growing regions of the UK between 1961 and 2004, the increase in average temperature has been estimated at 1.36°C (Perry, 2006). The greatest rise in temperature was estimated to occur in winter (1.82°C) and the smallest in autumn (0.79°C) with spring and summer approximately 1.4°C. The most significant rise in temperature occurred from 1987 onwards. Between 1961 and 2004, the autumn and winter rainfall has been estimated to increase by 19% and 27% respectively, although these trends were not statistically significant. Between 1929 and 2004, the amount of sunshine over England increased by about 17% in winter and by about 9% in autumn. The majority of this increase occurred from the late 1960s and may have been associated with the clean air acts introduced from

1956 onwards. There were no trends in winter and autumn sunshine in Scotland or SW England, nor in any region during summer or spring. The concentration of CO_2 in the atmosphere has increased from approximately 320 ppm in 1970 to 380 ppm currently. Doubling CO_2 increases the biomass production of C3 plants by 30% and increases water use efficiency (Rozenweig and Colls, 2004), but these may be negated by increasing tropospheric ozone (Long *et al*., 2005).

Warmer conditions shorten phases of crop development. The degree to which each phase of development is shortened depends on other factors that also control development. For example temperature has a limited effect on the duration from crop emergence to the start of stem extension in winter cereals and winter oilseed rape because these crops must experience a vernalisation period (period of low temperatures) and a particular length of day before reproductive development begins. Temperature is a stronger determinant of the duration from stem extension to ear emergence, and the period from flowering to maturity has been shown to last for a given period of thermal time. Spring sown crops have little or no requirement for vernalisation and therefore the duration of all developmental stages are shortened by warmer temperatures. In winter cereals and oilseed rape, warmer conditions are expected to increase the number of leaves produced between crop emergence and the start of stem extension. In cereals, each leaf is associated with a tiller bud, therefore a greater number of leaves will result in a greater potential shoot number. It is possible that greater radiation levels during autumn and winter will further increase leaf and tiller growth over winter. Warmer temperatures are expected to reduce the number of leaves and tillers produced for spring sown crops. Warmer temperatures will shorten the period between the start of stem extension to maturity for winter and spring sown crops which will reduce growth during this period, e.g. Monteith (1981) showed that warmer temperatures during grain filling reduced grain yield. However, it seems likely that this will be compensated for by the greater level of $CO_{2,}$ and for wheat, the possibility of warmer conditions bringing the seed filling period forward into brighter conditions.

Effects of changes in climate, varieties and crop management on tolerance to pest damage

This section assesses whether changes in climate, varieties and crop management since the 1970s are likely to have affected crop tolerance to pest damage (Table 11). In order for a factor to affect ability to tolerate pest damage it must have a different effect on the size of the sink and source. If both source and sink are altered by the same amount then there will be no change in vulnerability to pest damage. It should also be recognised that if sink size is increased, then the size of the source will automatically become closer to the limit at which the yield will be limited and therefore the crop will tolerate less damage to the source. It seems likely that the warming climate will have made autumn sown crops more tolerant of damage between plant emergence and the start of stem extension (e.g. to loss of plants or shoots). However, this advantage will be countered if the seed rate has been reduced, although the uncertainty regarding whether seed rate has been reduced, and if so by how much, should be recognised. It is likely that greater nitrogen fertiliser during the 1970s and new wheat varieties have increased both source and sink size and therefore have not altered the crop's tolerance to pest damage.

Table 11. Effects of changes in climate, varieties and management on tolerance to pest damage.

	Sink size	Source size	Change to more sink or source limited?	Tolerance to pests reducing sink size	Tolerance to pests reducing source size
Winter wheat					
Climate change	↑	=	source	↑	↓
Varieties	↑	↑	=	=	=
†Greater N fertiliser	↑	↑	=	=	=
Reduced seed rate	↓	=	sink	↓	↑
Winter barley					
Climate change	↑	=	source	↑	↓
†Greater N fertiliser	↑	↑	=	=	=
Spring barley					
Climate change	=	=	=	=	=
†Greater N fertiliser	↑	↑	=	=	=
Winter oilseed rape					
Climate change	↑	=	source	↑	↓
†Greater N fertiliser	↑	↑	=	=	=
Reduced seed rate	↓	=	sink	↓	↑
Spring oilseed rape					
Climate change	=	=	=	=	=
†Greater N fertiliser	↑	↑	=	=	=

† Fertiliser applications increased during the 1970s.

Effects of pests on the size of the source or sink components of yield formation

Different pests affect the crop’s sink or source size depending on the crop growth stage when they cause damage, and the type of damage they cause. In general, pests which affect the crop early in its lifecycle reduce its sink size, e.g. slugs, stem-boring insects, wireworms, leatherjackets, flea beetles and pollen beetles (Table 12). Viruses reduce crop growth throughout its lifecycle and therefore reduce both the sink size and the source. Seed weevil and pod midge tend to reduce the number of seeds by direct feeding and therefore reduce the sink size, whereas aphids reduce the supply of assimilates to the seed and thereby reduce the source size. Orange blossom midge feeds directly on the grain and reduces grain weight and quality, but seldom destroys seeds completely, so this pest also reduces source size.

The tolerance that crops have to pests will be influenced by whether the crop species is sink or source limited and whether the pest affects the source or the sink. For example, sink limited crops will be relatively tolerant to pests that reduce the source (e.g. cabbage aphid on oilseed rape), whereas sink limited crops will be less tolerant to pests which reduce the sink (e.g. slugs on barley). It should therefore be recognised that different crop species may have different tolerances to similar pests depending on whether they are source or sink limited (e.g. barley will be less tolerant to slugs than wheat).

Table 12. Effects of pests on the size of the source or sink components of yield formation

Crop	Pest	Pest affects source or sink
Cereals		
	Grey field slug	Sink
	Grain aphid	Source and sink
	Bird cherry aphid (transmit BYDV)	
	Gout fly	Sink
	Wheat bulb fly	Sink
	Yellow cereal fly	Sink
	Wireworms	Sink
	Leatherjackets	Sink
	Orange wheat blossom midge	Source & grain quality
	Direct feeding damage	
	Grain aphid	Source
	Rose-grain aphid	
Oilseed rape		
	Grey field slug	Sink

Peach-potato aphid (transmits turnip yellows virus)	Source and sink
Cabbage stem flea beetle	Sink
Wessex flea beetle	
Turnip flea beetle	
Large striped flea beetle	
Pollen beetle	Sink
Cabbage stem weevil	Source
Cabbage seed weevil	Sink
Brassica pod midge	Sink
Direct feeding damage	
Cabbage aphid	Source

Effects of economics on thresholds

Economic thresholds depend upon the nature of the relationship between the level of pest and yield loss, the value of the yield lost, and the cost of the control method. It is likely that a given level of pest damage will generally reduce yield by a proportion of the crop's potential. For example, there is no evidence that the relationship between plant population and yield varies significantly for crops with a different yield potential (Spink *et al*., 2004). If for example, the optimum plant population for wheat is 100 plants/m^2, and pest damage reduces plant number to 80/m^2, it has been estimated that yield will be reduced by approximately 10%. The increase in wheat and barley yields since the 1970s mean that reducing yield by 10% will result in a greater absolute yield loss in modern wheat crops. This will reduce the threshold at which it is economic to control the pest if the value of grain and the cost of pest control are unchanged. Further work is therefore required to quantify the yield losses caused by different pests in current high yielding crops, and to develop a method for linking this with variation in the value of the crop and cost of pest control to assess whether it has a significant effect on thresholds.

Conclusions from the review of crop physiology

- Improved physiological understanding of how yield is determined has quantified some of the minimum crop parameter values required to achieve potential yield. This will help to develop more quantitative/mechanistic thresholds.
- Typical crops have a significant amount of tolerance to pest damage. However, it is clear that there is a very large range in a crop's tolerance to pest damage depending on variation in crop growth caused by weather and crop management. New thresholds must take this into account and methods must be developed for growers to quickly assess the state of the crop.
- Different crop species have different tolerances to similar pests because of differences in how yield is formed, e.g. barley is less tolerant to pests which reduce shoot number compared with wheat.
- Climate change may have increased the tolerance of autumn sown crops to leaf/shoot loss. A possible trend towards using lower seed rates in wheat may have made this crop less tolerant to shoot loss.
- Pests should be classified in terms of whether they affect the crop's source or sink to help link their effects with crop physiology.

Pest threshold revisions

There is no doubt that risk assessment will become increasingly important in crop protection. The range of available actives is likely to decline as a result of legislation such as the review of 91/414/EEC and the Water Framework Directive (Clarke *et al*, 2009). In addition, the industry must respond to consumer concerns over the use of pesticides, their effects on the environment, and their potential to create residues in food. The need to minimise the potential risk of insecticide resistance is another factor that will limit pesticide use. Risk assessment is fundamental to the use of thresholds so it is crucial that there is confidence in, and widespread adoption of, this concept. The final part of this review will highlight how this might be achieved by further research and KT activities.

Taking account of crop tolerance

Out of 22 pest species that are known to attack cereals and oilseed rape, thresholds have been developed for 16. However, for eight of these thresholds, their origin is unknown, and for the eight thresholds of known origin, two are more than 30 years old. Results of farmer/agronomist surveys generally indicate that they value thresholds and use them in decision making. However, this is not supported by pesticide usage figures that show that a number of sprays are applied unnecessarily, and in oilseed rape, often against an unspecified target. It is difficult to state precisely why this is the case, but it is likely that it is due to a combination of factors including a lack of awareness of the thresholds, limited confidence in thresholds, time consuming methods of pest assessment and, in some cases, relatively inexpensive insecticide treatments. A review of crop yield physiology has revealed that crops have a very wide range of tolerance to pest damage as a result of differences in the way that yield is formed between crop species, and due to differences in crop growth arising from variation in weather and crop management. It is also predicted that changes to the climate and crop husbandry since the 1970s and 1980s has affected the tolerance of crops to certain pests and this will affect the validity of some of the thresholds.

In order to take account of the variation in tolerance that crops have for pest damage it is important that thresholds account for the capacity of the crop to tolerate damage.

It is recommended that this should be done before assessing pest numbers because it is likely that some crops will have such a high tolerance that the likelihood of experiencing sufficient pest numbers to reduce yield is negligible, thus making an assessment of pest number unnecessary. For example an oilseed rape crop with 20,000 flowers/m^2 could tolerate 36 beetles per plant, assuming 40 plants/m^2 and that each beetle destroys nine flowers/pods. This level of beetles is very unlikely. It is feasible that quantitative schemes for estimating crop tolerance can be developed for several pests which cause damage including pollen beetle, flea beetle, slugs, stem-boring insects, wireworms and leather jackets. Developing quantitative prediction schemes for other pests, such as virus vectors and pests that reduce the amount of assimilate available for seed growth (e.g. aphids), will be more difficult because the damage is less easy to quantify. A qualitative scheme for estimating crop tolerance may be required for these pests. A sequence of decisions for assessing whether a pest must be controlled is therefore recommended (Figure 10).

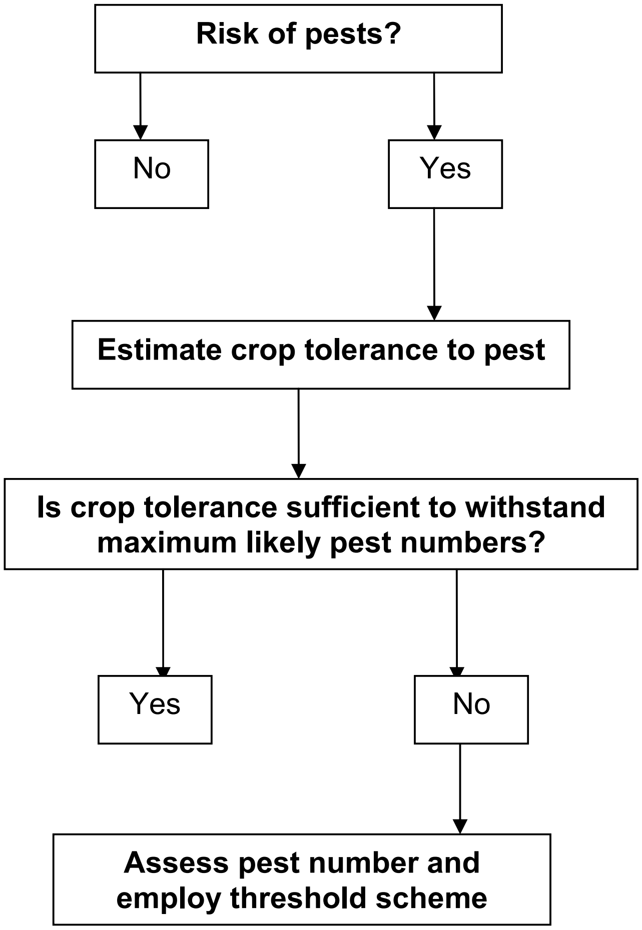

Figure 10. Proposed decision flow chart for assessing the requirement to control pests.

To fully account for the degree of crop tolerance to pests several pieces of information are required including: the minimum crop parameter value to achieve potential yield; a method of easily assessing the crop; and a knowledge of how much damage each pest causes. The existence of this information is summarised in Table 13. This indicates that it should be possible to develop quantitative schemes for estimating the tolerance of wheat crops to slugs (post emergence), wireworms, leatherjackets and stem-boring pests if information about how many plants or shoots are destroyed by a single pest can be developed. More developmental work would be required for barley and oilseed rape because it is not known what the minimum plant number and shoots/m^2 (barley) is in these crops. It is also clear that a method for rapidly assessing the number of shoots/m^2 of cereal crops would be of great benefit. It may be possible to develop a method that estimates shoot numbers from a digital photo similar to the web tool for estimating the GAI of oilseed rape found at www.totaloilseedcare.co.uk. It may also be possible to adapt this system to rapidly assess plant number. Quantitative prediction schemes are also feasible for seed weevil and pod midge because these pests reduce the number of seeds/m^2 by direct feeding and destroying individual seeds or entire pods.

A qualitative prediction of crop tolerance is more feasible for virus vectors, pests which reduce the amount of assimilate available for seed growth (e.g. aphids which cause feeding damage) and for stem weevil in oilseed rape. It is likely that these must rely on empirical relationships between pest numbers and yield loss, but with modifying factors that take account of any variation in crop tolerance to damage.

Table 13. Information required to estimate crop tolerance to pest damage

Crop	Pest	Crop character affected	Method of rapidly assessing crop character	Minimum crop character for potential yield	Is pest damage quantifiable?	Amount of crop damage caused by single pest	Type of scheme to estimate tolerance
Wheat							
	Grey field slug	Plants/m^2	Yes	Known	Yes	Unknown	Quantitative
	Grain aphid Bird cherry aphid (transmit BYDV)	General growth	No	Unknown	Difficult	Unknown	Qualitative
	Gout fly	Shoots/m^2	No	Known	Yes	Known (1 shoot)	Quantitative
	Wheat bulb fly	Shoots/m^2	No	Known	Yes	Unknown	Quantitative
	Yellow cereal fly	Shoots/m^2	No	Known	Yes	Known (1 shoot)	Quantitative
	Wireworms	Plants/m^2	Yes	Known	Yes	Unknown	Quantitative
	Leatherjackets	Plants/m^2	Yes	Known	Yes	Unknown	Quantitative
	Orange wheat blossom midge	Seed filling	No	Unknown	Difficult	Unknown	Qualitative
	Grain aphid Rose-grain aphid (direct feeding)	Seed filling	No	Unknown	Difficult	Unknown	Qualitative
Barley							
	Grey field slug	Plants/m^2	Yes	Known	No	Unknown	Quantitative
	Grain aphid Bird cherry aphid (transmit BYDV)	General growth	No	Unknown	Difficult	Unknown	Qualitative
	Gout fly	Shoots/m^2	No	Known	Yes	Known (1 shoot)	Quantitative
	Wheat bulb fly	Shoots/m^2	No	Known	Yes	Unknown	Quantitative
	Yellow cereal fly	Shoots/m^2	No	Known	Yes	Known (1 shoot)	Quantitative
	Wireworms	Plants/m^2	Yes	Known	Yes	Unknown	Quantitative
	Leatherjackets	Plants/m^2	Yes	Known	Yes	Unknown	Quantitative

	Grain aphid Rose-grain aphid (direct feeding)	Seed filling	No	Unknown	Difficult	Unknown	Qualitative
Oilseed rape							
	Grey field slug	Plants/m^2	Yes	Unknown	Yes	Unknown	Quantitative
	Peach potato aphid (transmits turnip yellows virus)	General growth	No	Unknown	Difficult	Unknown	Qualitative
	Cabbage stem flea beetle	Plants/m^2	Yes	Unknown	Yes	Unknown	Quantitative
	Wessex flea beetle	Plants/m^2	Yes	Unknown	Yes	Unknown	Quantitative
	Turnip flea beetle	Plants/m^2	Yes	Unknown	Yes	Unknown	Quantitative
	Large striped flea beetle	Plants/m^2	Yes	Unknown	Yes	Unknown	Quantitative
	Pollen beetle	Pods/m^2	Being tested	Known	Yes	Being tested	Quantitative
	Cabbage stem weevil	General growth	No	Unknown	Difficult	Unknown	Qualitative
	Cabbage seed weevil	Seeds/m^2	N/A	Known	Yes	Known	Quantitative
	Brassica pod midge	Seeds/m^2	N/A	Known	Yes	Known	Quantitative
	Cabbage aphid	Seed filling	No	Unknown	Difficult	Unknown	Qualitative

Priorities for future work

The aim of thresholds is to minimise unnecessary pesticide use by fostering a rational approach to pest control. Therefore the greatest benefits will come from concentrating on pest species which are already the subject of significant pesticide inputs. This information is summarised in Table 14. In addition, where products are under threat from 91/414/EEC or the water Framework Directive there is an urgent need to review pest control strategies.

Table 14. Area of cereals and oilseed rape treated against specific invertebrate pests

Crop	Active ingredient	Area treated (ha)	% of crop area treated	Primary target
Winter wheat	Pyrethroids eg cypermethrin	1,673,333	96	Autumn aphids & BYDV
	Organophosphates eg chlorpyrifos	224, 283	15	Orange wheat blossom midge & wheat bulb fly
	Molluscicides eg metaldehyde	399,758	20	Slugs
Winter barley	Pyrethroids eg cypermethrin	282,411	83	Autumn aphids & BYDV
	Molluscicides	15,808	4	Slugs
Spring barley	Pyrethroids eg cypermethrin	42,438	9	Aphids
	Organophosphates eg chlorpyrifos	9,712	2	Leatherjackets
Oilseed rape	Pyrethroids eg cypermethrin	819,791	168	Cabbage stem flea beetle (37%), aphids (24%), pollen beetle (20%), seed weevil (9%)
	Molluscicides eg metaldehyde	290,818	59	Slugs

Pyrethroids are the most frequently used insecticides in cereals and oilseed rape. Cypermethrin is by far the most widely used product, accounting for 52% of all pyrethroid applications, no doubt because it is an inexpensive option costing approximately 98p/ha. Targets include aphid vectors of BYDV and turnip yellows virus, and cabbage stem flea beetle, pollen beetle and seed weevil in oilseed rape. Limiting the use of pyrethroids in both cereals and oilseed rape would have a significant impact on pesticide usage in these crops.

Metaldehyde is the most frequently used molluscicide, accounting for about 610,266 treated hectares or 86% of the treated area. This product is under threat from the water framework directive so any means of increasing the precision with which it, or any other molluscicide, is applied, would be a major benefit.

Chlorpyrifos is the main organophosphate insecticide. It is only used in cereals, with about 10% of the area of winter wheat, winter barley and spring barley treated. The primary targets are orange wheat blossom midge and wheat bulb fly in wheat, and leatherjackets in barley.

Further research to improve thresholds of specific pests

The ultimate aim of pest thresholds is to encourage a rational approach to invertebrate control that takes into account the potential of the crop to tolerate damage, the cost effectiveness of pesticide application, the potential for the development of pest resistance, and the environmental impact of treatment. As a result of this review, a number of potential topics for future research can be suggested which will help to achieve these aims; these are summarised in Table 15. The priority for research has been scored from 1-5 in terms of the potential to decrease insecticide usage and improve margins, whether current actives are under threat from legislation and the potential to improve on current thresholds. The higher the score, the higher the priority for the research.

Table 15. Potential to improve thresholds for specific pests or groups of pests (highest score = greatest potential for improvement and future research)

Pest	Potential to decrease insecticide usage/increase margins	Actives under threat from legislation	Potential to improve on current thresholds	Total (Max 15)
Slugs	3	5	4	12
Wheat bulb fly and other stem borers	3	4	4	11
Cabbage stem flea beetle and other flea beetle species	3	1	4	8
Orange wheat blossom midge	4	3	4	11
Seed weevil and pod midge	3	1	3	7
Leatherjackets and wireworms	2	2	4	8
Cabbage stem weevil and rape winter stem weevil	4	1	5	10
Aphid virus vectors	4	1	2	7
Aphids causing feeding damage	2	1	3	6

Slugs

It should be possible to develop a quantitative threshold for slug control post-plant emergence in cereals and oilseed rape. Cereal plants are at risk up to GS14/2.1 and oilseed rape plants are at risk until GS14. Requirements include the minimum plant number for potential yield and the number of plants that a single slug has the potential to destroy. In wheat, the number of plants required to achieve yield potential, and how sowing date affects this number, is known. Further work would be required to quantify the minimum plant number for barley and oilseed rape and how this is influenced by sowing date and variety (for oilseed rape). Further work must also quantify the potential number of plants that individual slugs may destroy at different growth stages. Whilst plant numbers are relatively straightforward to assess, it would be useful to develop faster automated methods of assessing plant numbers in cereal crops.

Wheat bulb fly and other stem-borers

Current thresholds for wheat bulb fly suggest that there is a risk of yield loss if egg numbers exceed 2.5 million/ha. However, this threshold was established in 1961 by Gough *et al.* and does not account for the wide range of tolerance that the crop has for loss of shoots. Wheat bulb fly attack is dependent upon the growth stage of the crop at the time of egg hatch, and plants with a single shoot are most at risk. Knowledge already exists about the minimum number of shoots that wheat crops require to achieve potential yield. However further research is required to quantify how many shoots a single pest can destroy, and for rapidly assessing the number of shoots in the crop. It will then be possible to predict more precisely those crops likely to be at risk, and which crops may benefit from a soil sample to determine egg numbers. This scheme would also be applicable to other stem-borer pests in wheat such as gout fly and yellow cereal fly, both of which only damage a single tiller.

Cabbage stem flea beetle and other flea beetle species

It should be possible to develop a quantified threshold scheme for flea beetle damage in oilseed rape, using knowledge of the minimum plant number for potential yield and the potential number of plants that a single flea beetle may destroy. Further research will be required to quantify these two parameters to develop this threshold scheme. Further work must also assess the practicality of being able to assess plant/seedling numbers in time to make a decision about control.

Orange wheat blossom midge risk

Despite the sporadic nature of significant attack by orange wheat blossom midge (owbm), pesticide usage figures indicate that about 12% of British wheat crops are treated against the pest. This suggests that the perceived risk of attack is often greater than occurs in practice, which has important environmental implications, not least because the favoured product is chlorpyrifos, a broad spectrum insecticide. Therefore, monitoring (see Oakley *et al,* 2005 and Ellis *et al*, 2009) and forecasting are essential tools in the effective control of owbm, while at the same time minimising the environmental impact of insecticide applications.

It is the sporadic nature of owbm outbreaks that creates uncertainty among farmers and agronomists over the need to spray against the pest. This has hindered attempts to develop a rational control strategy and led to some insurance insecticide sprays. The recent HGCA/LINK project (Ellis *et al*, 2009) refined the procedures for use of pheromone traps and suggested treatment thresholds at a field level. However, the availability of regional forecasts presented using a GIS map based format would complement these more time consuming monitoring techniques.

The sporadic nature of owbm outbreaks is at least in part a function of the synchronicity between insect development and crop phenology, both of which are controlled by environmental variables. Unless resistant varieties are grown, crops are at most risk if peak adult emergence of owbm coincides with GS53-59 in the crop. The environmental variables that determine owbm development, primarily soil temperature and soil moisture content, and crop phenology (primarily temperature and photoperiod), are now well understood. Therefore it should be possible to combine these two aspects to develop a predictive model, based on regional meteorological data, to determine the risk of an owbm outbreak and hence the need for crop monitoring such as deploying pheromone traps.

Current thresholds for assessing adult owbm infestations in crops by parting the crop and counting the numbers of the pest that are disturbed are impractical. It is impossible to determine the number of midges per ear and so differentiate between the thresholds for feed and milling and seed crops. Yellow sticky traps are effective at trapping owbm and should be evaluated to produce a more practical approach to assessing risk which does not involve numerous evening visits to crops.

Seed weevil and pod midge

Oilseed rape is sink limited and therefore is not very tolerant to losing seeds during this late phase of development because there is limited scope for compensatory growth of other seeds. Limited information already exists about how much damage is caused by these pests, i.e. seed weevil may destroy 25% of the seeds within a pod, and the impact of feeding by pod midge could lead to the splitting of the pod and loss of all the seeds. However, further work is required to validate these figures. It should then be possible to calculate the threshold based on the value of yield lost (using information for a typical crop with 8000 pods/m^2 and 90,000 seeds/m^2) and the cost of control measures.

Leatherjackets and wireworms

Leatherjackets are a problem in spring cereals, in particular spring barley. A quantitative threshold can be developed using information about the minimum number of plants for potential yield and the number of plants destroyed by a single leatherjacket. A similar scheme could be developed for wireworms.

Cabbage stem weevil and rape winter stem weevil in oilseed rape

Rape winter stem weevil (*Ceutorhynchus picitarsis*) is a potentially serious pest of winter oilseed rape in northern European countries including Germany, France and Britain. Recent reports have indicated a possible re-emergence of this pest causing severe damage to winter oilseed rape crops, particularly in Cambridgeshire and Northumberland. The current assumption is that observed damage is indeed being caused by rape winter stem weevil, however, confirmation is required to exclude other similar species including the non-native rape stem weevil (*C. napi*) or the native cabbage stem weevil (*C. pallidactylus*).

The level of insecticide use against unspecified targets in oilseed rape is significant, with at least 100% of the crop receiving a single treatment most years. This is clearly not sustainable and greater effort must be made to target insecticide treatments more precisely. Further information on the geographical distribution and timing of migration of both rape winter stem weevil and stem weevil is required to allow more precise targeting of control measures against these pests. In addition, thresholds need to be developed for both pests to indicate at what level they are potentially damaging. This would require further information on the impact of both species on growth and yield of the crop. Rape winter stem weevil attack occurs in the autumn and results in stunting of the crop and the proliferation on secondary racemes. Stem weevils migrate into the crop in the spring and are likely to have less effect on the potential yield.

Aphid vectors

Currently there are no thresholds for the aphid vectors of BYDV or turnip yellows virus. An insecticide treatment is applied if aphids are present simply because there is no effective way of determining whether the pests are carrying the virus. Ultimately this results in a significant level of insurance sprays, as pyrethroid insecticides are relatively inexpensive. An improved method of risk prediction could have a significant impact on insecticide usage in oilseed rape. The potential for an early warning system based on the proportion of aphids carrying virus in geographically separate locations (eg, north east, south and west) may be worth investigating. However, this would also need to take into account autumn temperatures and how these might affect the spread of viruliferous aphids within the crop. Re-investigation of the relationship between aphid numbers, virus infection and yield may also be worthwhile to try and establish what level of BYDV/turnip yellows virus could be tolerated.

Aphids causing feeding damage

Further work on the relationship between cabbage aphid levels and potential yield loss in rape would be worthwhile to check the validity of existing thresholds. Also, current thresholds for cereal aphids rely on the assessment of the percentage of ears infested. This was derived as it less time consuming to assess infested ears than to attempt to count the number of aphids per ear. However, the threshold takes no account of the level of infestation, and it seems unlikely that 100 aphids/ear will have the same impact as 1 aphid/ear.

More research is required to investigate whether crops with a large GAI during seed filling are more tolerant to damage by aphids. If they are, future thresholds must take this into account and methods for rapidly assessing the size of the canopy will be required.

Assessing pest numbers

Straightforward methods for assessing pest numbers can only help to facilitate the adoption of a rational approach to pest management. In particular, improved methods of assessing levels of beetle pests in oilseed rape are needed to supersede current techniques involving beating plants over trays. It is very difficult to relate pest numbers to plant numbers and the technique is very weather dependent. Water/sticky traps seem to offer the best alternative.

Sampling soil for eggs of wheat bulb fly is very time consuming and involves collecting large quantities of soil. The potential for trapping adult flies should be re-investigated in view of the success of this technique in France. This would also require investigating the relationship between numbers of flies and eggs of the pest.

The potential to use yellow sticky traps to assess numbers of orange wheat blossom midge is also worth investigating and has already been discussed.

Knowledge Transfer activities

In view of the excessive use of insecticides on oilseed rape, a factsheet could be produced to increase general awareness of rape pests. This would supplement “Pest management in cereals and oilseed rape – a guide" and would be used to stress more precise targeting of insecticides. This would include a calendar of pest species detailing the timing of pest migration, comments on the likely need for control, and the optimum timing of control measures, should they be required. The key principles based on crop physiology should be included to provide greater reassurance to farmers and agronomists about the risks they are seeing.

Summary of recommendations for future research

- Taking account of crop tolerance is fundamental to improving pest risk assessment. A knowledge of the minimum plant number required for potential yield in barley and oilseed rape, and how these are affected by sowing date and variety, are required to improve thresholds against slugs, flea beetles, leatherjackets and wireworms.
- Understanding how many plants are destroyed by slugs, flea beetles and leatherjackets, and how many shoots are destroyed by wheat bulb fly, are required to improve the thresholds against these pests.
- Methods for rapidly assessing shoot numbers and plant numbers in cereals are required.
- Thresholds for a number of cereal/rape pests require revision but priority should be given to slugs, wheat bulb fly and other dipterous stem borers, orange wheat blossom midge, rape winter stem weevil and cabbage stem flea beetle.
- There is potential to improve methods for assessing wheat bulb fly, summer pests of oilseed rape and orange wheat blossom midge.
- Knowledge transfer activities should be considered to improve awareness of when to target rape pests, and to try to minimise the significant overuse of insecticides in the crop.

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