The impact of herbicides on weed abundance and biodiversity

PN0940

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We also thank colleagues in our own institutions for their input, without whom this document would not have been as wide-ranging as it is. This report has been achieved in just over four months. While there is undoubtedly scope for further work and there are a number of gaps within the report, it provides a timely review of the impact of herbicides in the arable ecosystem.

EXECTIVE SUMMARY AND CONCLUSIONS

In considering non-target plants within arable fields, the majority of plant species that are found are of only minor concern to farmers, unless present at high population density. Under horticultural conditions, it can be argued that all weeds are targets, providing some difficulty for formal risk assessment. In arable, there are a number of key weed species that are typically controlled irrespective of density. In contrast, rare arable weeds may require specific conservation protection; these species may be non-targets under almost all conditions. The majority of species usually present can be both targets and non-targets and are most likely to be of greatest significance for biological diversity within fields, as they occur frequently and with moderate abundance.

Data on farmland birds and invertebrates indicate that there have been significant reductions in populations and ranges over the past thirty years. In the case of the grey partridge, there is good evidence that herbicides have played a significant role in their decline. Whilst *habitat loss* and fragmentation may play a role in bird declines, the evidence indicates that *habitat degradation* is of greater importance. Changes in farming practice in general are the cause of most population declines of farmland birds. Whilst the exact causal links are not known for most species, herbicides are implicated.

This review has shown that there have been changes in weed assemblages over the past century, with some species becoming less common, other increasing in frequency and others remaining static. Studies of weed seed banks indicate little change in weed seed abundance or a slight trend for reduced densities. Where weed control has been relaxed, either as set-aside or where herbicide use has been halved, weed seed banks can increase rapidly. However, the commonest and most competitive weed species tend to become the most abundant, under these conditions. Rare species may not recover.

Analysing changes in cropping and herbicide use, the move from spring to winter cropping since the 1970s has been a dramatic change in cropping practice. Co-incident with the change to winter cropping, there have been major changes in the pattern of herbicide use. In the 1970s, herbicides were used primarily for broad-leaved weed control and on only about 50% of fields. Today, herbicides are used on most fields and are targeted on grass weeds as well as dicotyledonous species. An examination of the weed spectra controlled by the herbicides in use over the past 25 years indicates that on average today's herbicides control more weeds. Broader spectrum products were introduced in the early 1980s. Factors other than herbicides may play an important role in changing weed assemblages, particularly fertilisers and cropping pattern.

Data collected from the literature and from the Phytophagous Insect Database demonstrate close links between invertebrates and a range of representative weed species. Different weed species support differing numbers of insect herbivores, with some species hosting numbers of rare species, as well as pest species. The data indicate that a number of weed species that are particularly important for insect biodiversity in the arable habitat can be selected.

Data on the use of weed species by birds has also been examined. Whilst, as with the invertebrate data, there is some lack of quantitative information on preferences, it is clear that bird species of conservation importance utilise particular genera of weeds. Thus it is possible to identify genera that are of greater importance for farmland birds.

The data indicate that herbicides, by controlling weeds and modifying abundance and species assemblages, have impacted on wildlife in arable land. These non-target effects need to be considered for regulatory reasons, particularly with the requirements under EU Regulation 91/414. With such dramatic changes in biodiversity, there are also calls for more sustainable production methods. The challenge will be to grow crops and maintain an appropriate population of weed species to support farmland wildlife. Under horticultural conditions, this may be difficult, in terms of crop quality protection. Nevertheless, under arable and horticultural production, there may be opportunities to develop sacrifice areas, such as conservation headlands, or to develop much greater selectivity of herbicide action, either through selective chemistry or application or a combination of these.

In terms of regulatory needs, the approach of selecting representative weeds and assessing their importance for biodiversity has been successful. A shortlist of species has been identified. The approach can now be applied to other weed species, to check the most important species have been identified. Regulatory approaches reviewed in PN0923 can be applied as non-target protocols, with adjustment of acceptable risk to achieve control where required.

There are a number of areas where knowledge is lacking. These are briefly reviewed and a priority list for research and development is given below:

1. classification of the competitive ability of a wider range of weed species under different cropping conditions
2. confirmation of the trends shown from data derived from the Phytophagous Insect Database linking plants to insect herbivores by ecological field study
3. assessment of the biodiversity importance of common weeds not included in this study
4. surveys of the status of weed and invertebrate populations
5. quantification of the importance of particular weeds for invertebrates and birds, including preferences and resource values
6. investigation of the interactions between weeds, invertebrate fauna and birds, including those that are insectivorous at the chick stage
7. modelling the functioning of the agricultural ecosystem to identify clearer causal links between population change and agronomic practice
8. investigation of the nature and effect of selection pressures within agroecosystems at genetic, individual, population and community levels
9. development of weed management systems that allow biodiversity to be maintained in the crop
10. tests of spatial methods of herbicide risk avoidance at appropriate spatial scales

1. INTRODUCTION

1.1. Policy Rationale

Herbicides are used to limit reduction in crop yield and quality due to weed competition, yield contamination and interference with harvesting. Herbicide use has undoubtedly contributed to crop yield increases and the efficiency of production. However, their widespread use may have detrimental and unexpected effects on wildlife both within crops and in associated semi-natural habitats in farmland. DEFRA's Pesticides Safety Directorate has a duty to assess risks to non-target organisms as part of its responsibilities for regulating pesticide use. Aspects of non-target effects of pesticides on terrestrial wildlife were reviewed in the desk study PN0923, which was completed in 1999. Developments in assessing risk to non-target organisms since that time have concentrated on non-target areas, particularly field boundaries, where pesticide drift is likely to occur. However, significant changes in both population size and population ranges have been recorded for common bird species of farmland (sustainability indicators) over the past 30 years. There are concerns that significant ecological changes have occurred or are occurring within arable and horticultural crops associated with herbicide use. Within the crop, non-crop plants naturally occur. Some of these might be regarded as non-targets. There is a need to understand the potential direct and indirect effects of herbicides, which may be mediated by the removal of plant biomass or particular plant species with which higher trophic taxa are associated, or by affecting processes within soils. What evidence is there that weed flora have changed with herbicide use? What information is available for interrogation? How might risks to non-target species be assessed and how might non-target effects be mitigated?

The study addresses the available information on weed changes, herbicide use patterns and trophic interactions and non-target effects with invertebrates and birds. In addition, the conflict between production imperatives and environmental (biodiversity) concerns are explored, as an attempt to identify approaches to risk assessment within crops and approaches to practical management of weed flora.

1.2. Scope of the Desk Study

This project examines non-target effects of herbicides on higher plant species within arable and horticultural crops. It is not concerned with off-target effects, such as drift to semi-natural habitats, but is particularly concerned with the biodiversity implications of herbicide use within crops.

1.3. Objectives

The overall objectives of this desk study are to update the review of known effects of herbicides on weed populations and communities within arable crops and to review the subsequent indirect effects on fauna, to identify gaps in knowledge, to prioritise research needs and to examine potential approaches to a) risk assessment for non-target plants in fields and b) practical means of maintaining appropriate weed cover in crops.

Specific objectives are to:

1. Define non-target plants in crop situations
2. Review indirect effects of herbicides and other weed management techniques in the terrestrial environment, building on the review PN0923
3. Examine and evaluate data on the changes in weed communities over the past 50 years
4. Review the relationships between flora and fauna in crop situations
5. Establish nature of current weed control practices and impacts of weeds on arable crops
6. Define approaches to risk assessment schemes for non-target plants within fields
7. Identify possible and potential approaches to practical weed management that will satisfy agronomic and wildlife requirements with regard to weed community structure and abundance
8. Identify gaps in knowledge and prioritise research needs

1.4. Target and Non-target Plant (Weed) Species

Within a crop field, there may be a number of unsown plant species present forming a weed assemblage. As many of these species compete with the sown crop and reduce yield, or interfere with harvesting, or contaminate grain samples, farmers and growers regard them all as weeds worthy of removal, usually by using herbicides. Nevertheless, amongst these non-crop species, there may be both target and non-target species for weed control. A number of rare weed species are subject to conservation effort including within Biodiversity Action Plans (BAPs). These may be regarded as non-target species. Of greater significance, as they are commoner and often have significant biomass, there is a suite of species that might be targets at higher density, but non-targets at low population levels. Finally, there are a number of species that are almost invariably targets for control, because of their competitive ability and/or their ability to reproduce rapidly.

The weed species that are always targets in arable crops are typically annual grasses, as well as cleavers (*Galium aparine*) (Table 1.1). These are particularly associated with autumn-sown crops, reflecting the predominance of these crops in cultivation.

Table 1.1. Weed species that are almost always targets for weed control if found within crops.

Species	Germination (A = autumn; S = spring)
Winter wild-oat (*Avena fatua*)	A/S
Spring wild-oat (*Avena* ssp. *ludoviciana*)	S
Blackgrass (*Alopecurus myosuroides*)	A
Barren brome (*Anisantha sterilis*)	A
Couch grass (*Elytrigia repens*)	
Common cleavers (*Galium aparine*)	A/S

As well as these species, many other species are recorded in arable crops (Jauzein, 1995; Rodwell, 1995). These may be regarded as both targets and non-targets for weed control, depending on a variety of factors. The most important factors affecting the perception of weeds from the viewpoint of farmers and growers are the relative competitive effect of particular species and their density. The product of competitive effect and weed density has been used to estimate crop yield loss (Marshall, 1987; Wilson et al., 1995). Other factors that will impact on the status of weeds include their effect on harvesting, the purity of grain samples and their threat to following crops from seed return. Whilst these views are paramount to farmers, little concern has been paid to the importance of weeds in general or species in particular for other aspects of the ecological functioning of agroecosystems. With significant declines reported for a number of plants and animals associated with farmland, herbicides and weed control may be having rather greater impacts than hitherto understood. This review addresses both the practical management requirements for weeds and their role for biological diversity.

At this point, an important caveat to what follows, is required. The review has concentrated on arable production systems, as these are the largest land uses in the UK. Nevertheless, horticultural systems are important in certain areas. In these systems, harvested crop quality is paramount. Therefore, growers would argue that there are no circumstances under which weed species can be left within the crop as non-targets. There are "*high demands on crop quality and contamination in the horticultural markets, e.g. one* Solanum nigrum *(black nightshade) berry found amongst your vining peas and your crop risks being discarded*" (pers comm.. A Grundy, HRI).

In order to evaluate the present state of knowledge in relation to non-target effects of herbicides and the impact of weed species on agroecosystem function and biodiversity, a representative list of common weed species has been drawn up. The review has identified 32 common weed species that may or may not be targets for control (Table 1.2). These species have been selected to represent the spectrum of the following criteria:

1. Frequency: common to less common
2. Competitive ability: economically important to uncompetitive with the crop
3. Environmental value: important to unimportant (so far as known)
4. Taxonomy: representative of main families

The species range from highly competitive to uncompetitive with the crop, with a range of importance for associated invertebrates and as food for farmland birds. For those plant species that are often regarded as targets for weed control, many will not need control if populations are low. For those that are regularly targeted for control, some may be of particular value for biological diversity. Therefore, the list of plant species given in Table 1.2 includes both target and potentially non-target species. These species are further examined in terms of their competitive ability, problems for growers, ecology, prevalence, and their importance for associated animals and birds and ecosystem function.

Table 1.2. A representative list of common weed species that may be both targets and non-targets for weed control using herbicides.

Common name	*Latin name*	Weeds & birds	Weeds & inverts	Specialist insects	WMSS status	Competitive index	No. for 5% yield loss	%fields infested	Birds (CSL review)
Grass weeds									
Annual Meadow-grass	*Poa annua*	*		*****	priority	0.10	50	79	"
Barren Brome	*Bromus sterilis*		* (mice?)	*****	key			13	
Black-grass	*Alopecurus myosuroides*		* (mice?+D8)	*****	key	0.40	2-10	38	
Wild-oat	*Avena fatua*			*****	key	1.00		42	
Broad-leaved weeds									
Black Nightshade	*Solanum nigrum*			*****					
Black-bindweed	*Fallopia convolvulus*	*	* (birds)	**nd**		0.30			"
Broad-leaved Dock	*Rumex obtusifolius*			*****					"
Charlock	*Sinapis arvensis*		* (birds)	*****		0.40		36	"
Cleavers	*Galium aparine*		* (mice?) (insects)	*****	key	3.00	<1	58	
Common Chickweed	*Stellaria media*	*	* (birds, mice)	*****	other	0.20	25	94	"
Common Field-speedwell	*Veronica persica*	*		*****	other	0.08		72	
Common Fumitory	*Fumaria officinalis*		* (birds)	*****		0.08		17	"
Common Hemp-nettle	*Galeopsis tetrahit*	*		*****					"
Common Mouse-ear	*Cerastium fontanum*			*****					
Common Poppy	*Papaver rhoeas*	*	(insects)	*****	priority	0.40		18	
Corn Marigold	*Chrysanthemum segetum*			**nd**					
Corn Spurrey	*Spergula arvensis*			*****					
Cornflower	*Centaurea cyanus*			**nd**					
Creeping Thistle	*Cirsium arvense*		* (birds) (insects)	*****		0.30			"
Cut-leaved Crane's-bill	*Geranium dissectum*			*****		0.08		11	
Fat-hen	*Chenopodium album*	*	* (birds) (insects)	*****	priority	0.20	25	13	"
Field Forget-me-not	*Myosotis arvensis*	*		*****	other	0.20	25		
Field Pansy	*Viola arvensis*	*		*****	other	0.02	250	45	
Fool's Parsley	*Aethusa cynapium*			*****					
Groundsel	*Senecio vulgaris*	*		*****		0.06			"

Common name	*Latin name*	Weeds & birds	Weeds & inverts	Specialist insects	WMSS status	Competitive index	No. for 5% yield loss	%fields infested	Birds (CSL review)
Knotgrass	*Polygonum aviculare*	*	* (birds) (insects)	*	other	0.10	50		"
Red Dead-nettle	*Lamium purpureum*			*	other	0.08		47	
Redshank	*Persicaria maculosa*			*					"
Scarlet Pimpernel	*Anagallis arvensis*			*		0.05			
Scented Mayweed	*Matricaria recutita*		* (birds) (insects)	*	priority	0.40		67	
Scentless Mayweed	*Tripleurospermum inodorum*		* (birds) (insects)	*	priority	0.40		67	
Shepherd's-purse	*Capsella bursa-pastoris*	*		*				23	
Smooth Sow-thistle	*Sonchus oleraceus*			*					"
Sun Spurge	*Euphorbia helioscopia*			*					

nd = no data

Some species will always be regarded as targets, typically highly competitive weeds. Some species will always be regarded as non-target species, typically the rare or endangered cornfield flowers. A list of such rare weeds, mostly receiving conservation attention from the Arable Plants Group (Plantlife) and English Nature, and some the subject of UK Biodiversity Action Plans, are listed in Table 1.3. Whilst it may be argued that even less common weed species, such as *Scandix pecten-veneris*, may require control under some circumstances, most of the species listed in Table 3 should be considered as non-target plants. These species are not considered further in any detail in this review.

Table 1.3. Rare arable flowers on UK Biodiversity Action Plan (BAP) Lists, or noted under the Cereal Field Margin Habitat Biodiversity Action Plan, or surveyed under the Botanical Society of the British Isles Scarce Plant Project. * = species on BAP middle list; # = BAP long list; A = autumn-germinating; S = spring-germinating. G = dormancy known in the genus.

Species	Germination (A = autumn; S = spring)	Seedbank longevity (m=months; y=years)	Soil type	Seed Dormancy
pheasant's eye (*Adonis annua*) #	S/A	Transient	chalk/brash	G
ground pine (*Ajuga chamaepitys*)#	A			
small alison (*Alyssum alyssoides*)#				G
dense silky-bent (*Apera interrupta*)	A?			G
loose silky-bent (*Apera spica-venti*)	A	1-5 y	Sand	Yes
cornflower (*Centaurea cyanus*)*	A/S	Persistent		Yes
broad-leaved spurge (*Euphorbia platyphyllos*)#	A/S		chalk/clay	G
red-tipped cudweed (*Filago lutescens*)*		?Transient		
broad-leaved cudweed (*Filago pyramidata*)*			chalk/sand	
Western ramping-fumitory (*Fumaria occidentalis*)			sand/loam	G
purple ramping-fumitory (*Fumaria purpurea*)*				G
tall ramping-fumitory (*Fumaria bastardii*)	A/S			G
dense-flowered fumitory (*Fumaria densiflora*)	A/S		Chalk	G
few-flowered fumitory (*Fumaria vaillantii*)	A/S		Chalk	G
red hemp-nettle (*Galeopsis angustifolia*)*	S			G
false cleavers (*Galium spurium*)				G
corn cleavers (*Galium tricornutum*)*				G
field gromwell (*Lithospermum arvense*)#	S	?Transient	chalk/clay	
field cow-wheat (*Melampyrum arvense*)#	A/S	Short-term		
prickly poppy (*Papaver argemone*)	A/S	>20 y		Yes
rough poppy (*Papaver hybridum*)	A/S	> 20 y	Chalk	G
corn parsley (*Petroselinum segetum*)#	Summer		chalk/clay	G
purple-stem cat's-tail (*Phleum phleoides*)#		Transient		G
cornfield knotgrass (*Polygonum rurivagum*)	S			G
corn buttercup (*Ranunculus arvensis*)#	A/S	Short-term	Clay	G
shepherd's-needle (*Scandix pecten-veneris*)*	A/S	3-12 m	Clay	
small-flowered catchfly (*Silene gallica*)*	S	Short-term	sand/gravel	
night-flowering catchfly (*Silene noctiflora*)	S	5-20 y	all soils	Yes
spreading hedge-parsley (*Torilis arvensis*)#	A		clay/loam	G
narrow-fruited cornsalad (*Valerianella dentata*)#	A/S			
broad-fruited cornsalad (*Valerianella rimosa*)*		Transient	clay/chalk	
Breckland speedwell (*Veronica praecox*)	Winter	Transient		G
fingered speedwell (*Veronica triphyllos*)#				G
slender tare (*Vicia parviflora*)			clay/brash	G

2. ECOLOGY OF REPRESENTATIVE WEED SPECIES

Data on the taxonomy, habitat preferences, life forms, phenology, size, breeding mechanisms, seed germination and dormancy of the selected species are scattered through the literature. The Sheffield dataset (Grime et al., 1988), the EcoFlora database (released on the WWWeb at: http://www.york.ac.uk/res/ecoflora/cfm/ecofl/index.cfm Fitter & Peat, 1994), Seedbanks of Northern Europe (Thompson et al., 1997) and recent floras, notably Stace (1997) provide the data summarised below. Collected data on the habitats of the selected weeds are given in Table 2.1.

Table 2.1. Taxonomy of selected weed species and their habitats. Nomenclature is according to (Stace, 1997) with common names from (Dony et al., 1986) . Habitat use is taken from (Grime et al., 1988) with the following key: ++ = very common and characteristic; + = common within habitat; . = widespread; - = infrequent; -- = largely absent

Species	English name (from Dony *et al*. 1986)	Family	Wetland	Skeletal	Arable	Pasture	Spoil	Waste	Wood-land	Terminal Habitat
Grass weeds										
Poa annua	Annual Meadow-grass	Poaceae	-	.	++	.	+	.	--	Path
Bromus sterilis	Barren Brome	Poaceae	--	+	+	.	.	.	.	Hedgerow
Alopecurus myosuroides	Black-grass	Poaceae								
Avena fatua	Wild-oat	Poaceae								
Broad-leaved weeds										
Solanum nigrum	Black Nightshade	Solanaceae								
Polygonum convolvulus	Black-bindweed	Polygonaceae	--	--	++	--	.	--	--	Arable
Rumex obtusifolius	Broad-leaved Dock	Polygonaceae	.	-	++	-	+	.	--	Soil
Sinapis arvensis	Charlock	Cruciferae	--	--	++	--	.	-	--	Arable
Galium aparine	Cleavers	Rubiaceae	-	--	+	-	-	.	.	Hedgerow
Stellaria media	Common Chickweed	Carophyllaceae	--	-	++	-	.	.	-	Arable
Veronica persica	Common Field-speedwell	Scrophulariaceae	--	--	++	--	.	--	--	Arable
Fumaria officinalis	Common Fumitory	Fumariaceae								
Galeopsis tetrahit	Common Hemp-nettle	Labiatae	--	-	++	--	-	.	.	Arable
Cerastium fontanum	Common Mouse-ear	Carophyllaceae	--	.	.	+	.	.	--	Meadows
Papaver rhoeas	Common Poppy	Papaveraceae	--	--	++	-	.	.	--	Arable
Spergula arvensis	Corn Spurrey	Carophyllaceae	--	--	++	--	.	--	--	Arable
Cirsium arvense	Creeping Thistle	Asteraceae	--	-	+	.	+	.	--	Coal-mine spoil
Geranium dissectum	Cut-leaved Crane's-bill	Geraniaceae								
Chenopodium album	Fat-hen	Chenopodiaceae	--	--	++	-	+	--	--	Arable
Myosotis arvensis	Field Forget-me-not	Boraginaceae	--	--	++	.	-	--	--	Arable
Viola arvensis	Field Pansy	Violaceae	--	--	++	-	.	.	--	Arable
Aethsa cynapium	Fool's Parsley	Umbelliferae								
Senecio vulgaris	Groundsel	Asteraceae	--	-	++	--	+	-	--	Brick
Polygonum aviculare	Knotgrass	Polygonaceae	--	--	++	-	.	.	--	Arable
Lamium purpureum	Red Dead-nettle	Labiatae	--	--	++	--	+	--	--	Arable
Persicaria maculosa	Redshank	Polygonaceae	--	--	++	--	.	--	--	Arable
Anagallis arvensis	Scarlet Pimpernel	Primulaceae	--	-	++	--	.	--	--	Arable

Matricaria recutita	Scented Mayweed	Asteraceae	--						--	
Tripleurospermum inodorum	Scentless Mayweed	Asteraceae	--	--	++	--	+	-	--	Arable
Capsella bursa-pastoris	Shepherd's-purse	Cruciferae	--	--	++	--	.	.	--	Arable
Sonchus oleraceus	Smooth Sow-thistle	Asteraceae	--	.	+	--	+	.	--	Brick
Euphorbia helioscopia	Sun Spurge	Euphorbiaceae								

Details of the life forms, flowering and seed biology of the key plant species are summarised in Tables 2.2, 2.3 and 2.4.

Table 2.2. Life forms and flowering times of key plant species of farmland.

Key: Life history - As = summer annual, Aw = winter annual, B = biennial, M = monocarpic perennial, P = polycarpic perennial.
Life form (UCPE) - Ch = chamaephyte, G = geophyte, H = helophyte, Ph = phanerophyte, Th = therophyte.
Established strategy (UCPE) - C = competitor, S = stress-tolerator, R = ruderal.
Reproduction - S = seasonal regeneration by seed, Sv = seasonal regeneration by vegetative means (offsets soon independent of parent), V = lateral regenerative spread, (offsets remaining attached to the parent for a long period, usually for more than one growing period), (V) = instances where the period of attachment is intermediate between those of V and Sv, W = regeneration involving numerous widely-dispersed seeds or spores, Bs = a persistent bank of buried seeds or spores, ? = strategies of regeneration by seed uncertain.

Species	**Life history**	**Life form UCPE**	**Established Strategy**	**Reproduction**	**Flowering 1st month**	**Flowering period (m)**
Grass weeds						
Annual Meadow-grass	A/P	Th/H	R	V, S, Bs	1	12
Barren Brome	Aws	Th	R/CR	S	5	3
Black-grass		Th		S	5	5
Wild-oat		Th			7	3
Broad-leaved weeds						
Black Nightshade		Th			7	3
Black-bindweed	As	Th	R	Bs	7	4
Broad-leaved Dock	P	H	CR	Bs	6	5
Charlock	Asw	Th	R	Bs	5	3
Cleavers	Aws	Th	CR	S	6	3
Common Chickweed	Aws	Th	R	Bs, (V)	1	12
Common Field-speedwell	Aws	Th	R	Bs, V	1	12
Common Fumitory		Th			5	6
Common Hemp-nettle	As	Th	R/CR	Bs	7	3
Common Mouse-ear	P/A	Ch/Th	R/CSR	(V),Bs	4	6
Common Poppy	Asw	Th	R	Bs	6	6
Corn Spurrey	As	Th	R	Bs	6	4
Creeping Thistle	P	G	C	V,W, Bs	7	3

Cut-leaved Crane's-bill		Th			5	4
Fat-hen	As	Th	R/CR	Bs	7	4
Field Forget-me-not	Aw	Th	R/SR	S, Bs	4	6
Field Pansy	As	Th	R	?Bs	4	7
Fool's Parsley		Th			7	2
Groundsel	Asw	Th	R	W, Bs	1	12
Knotgrass	As	Th	R	Bs	7	4
Red Dead-nettle	Aws	Th	R	Bs	3	8
Redshank	As	Th	R	Bs	5	6
Scarlet Pimpernel	Asw	Th/Ch	R/SR	Bs	6	3
Scented Mayweed	Asw	Th	R	Bs	6	3
Scentless Mayweed	Aws	Th	R	S, Bs	7	3
Shepherd's-purse	Asw	Th	R	Bs	1	12
Smooth Sow-thistle	Aws	Th	R/CR	W, Bs	1	12
Sun Spurge		Th			5	6

Table 2.3. Plant size, structure and pollination

Species	**Foliage height (mm)**	**Flower height (mm)**	**Plant height/ length (Stace)**	**Fertilzation**	**Pollen vector**
Grass weeds					
Annual Meadow-grass	150	300		Usually inbreeding	Wind
Barren Brome	<400	1000		Inbreeding, some outcrossing	Wind
Black-grass	700	700		Obligate outcross	Wind
Wild-oat	1000			Normally self	Wind
Broad-leaved weeds					
Black Nightshade	600			Normally self	Insect
Black-bindweed	1200		1000(1500)	Normally self	Selfed
Broad-leaved Dock	<300	1200	1000(1200)	Normally cross	Wind; selfing
Charlock	500	800	1000(1500)		Insects or selfing
Cleavers	1200			Cross or automatic self	
Common Chickweed	400	400	500	Cross or automatic self	Selfing or insects
Common Field-speedwell	400	400		Cross + self	Insect; selfing
Common Fumitory	1000			Cross + self	Insect
Common Hemp-nettle	1000	1000		Inbreeding	Selfed
Common Mouse-ear	450		500	Cross or automatic self	Insect
Common Poppy	600		600(800)	Obligatory cross	Insect
Corn Spurrey	600		400(600)	Normally self	Insect
Creeping Thistle	900			Cross or automatic self	Insect
Cut-leaved Crane's-bill	600			Normally self	Selfed
Fat-hen	1000		1500	Cross + self	Wind
Field Forget-me-not	600			Normally self	Insect
Field Pansy	450		400	Normally self	Insect
Fool's Parsley	1200			Cross + self	Insect
Groundsel	450	450		Normally self	Selfed
Knotgrass			2000	Normally self	
Red Dead-nettle	450	450		Cross or automatic self	Insect
Redshank	750	750	800	Cross + self	Insects
Scarlet Pimpernel	300	<200		Normally self	Selfed
Scented Mayweed	600				Insect
Scentless Mayweed	600	600		Outcrossing; self-incompatible	Insects
Shepherd's-purse	<100	400	500	Cross or automatic self	Insect
Smooth Sow-thistle	1500	1500		Normally self	Insect
Sun Spurge	500			Normally cross	Insect

Data on seed banks is available in Thompson et al. (1997), as well as the EcoFlora database.

Table 2.4. Seed biology characteristics of key plant species of farmland

Key: Seed bank type – 1 = transient, 2 = short-term persistent, 3 = longer-term persistent.
Germination requirements - Chill = chilling, Dry =- dry storage at room temperature, Scar = scarification, Warm = warm moist incubation, Wash = water-washing to remove inhibitor in seed coat. - = immediate germination, / = different seeds have different requirements, , = several alternative mechanisms are effective, Unclassified = lack capacity for immediate germination, but mechanism has not yet been identified, ? = mechanism requires confirmation
Germination periodicity – A = Autumn; S = Spring
Time of germination - Sp = spring, Su = summer, Au = autumn, Wi = winter.
Normal method of propagation - Seed or vegetative or seed & vegetative (S&V).
Seed bank longevity – m = months; y = years
Seed bank type - A score from 0-1 where 0 = all records transient, and 1 = all records persistent.
Confidence - Species where there are less than 10 records are marked *.

Species	UCPE Seed bank type	Germination requirements	Germination periodicity (from literature)	EcoFlora Time of germination	EcoFlora Normal propagation	EcoFlora Seed viability	EcoFlora Seed bank longevity	Thompson Seed bank type	Confidence
Grass weeds									
Annual Meadow-grass	3		All year	All year	S & V	high			
Barren Brome	1		A	Su/Au	seed	high	3-12m		
Black-grass			A (+s)	Au/Sp	seed	Some nonviable	1-5y		
Wild-oat			A/S	Sp	seed		Persistent		
Broad-leaved weeds									
Black Nightshade			S	Sp/Su	seed		>20y		
Black-bindweed	4	Chill	S	Au/Sp	seed				
Broad-leaved Dock	4		A/S	Au/Sp	seed	high	>20y		
Charlock	4	Dry	S	Au/Sp	seed		>20y		
Cleavers	1	Chill	A/S	Sp/Au/Wi	seed	high	1-5y	0.31	
Common Chickweed	4	Dry	A/S	Au/Sp	seed	high	Persistent		
Common Field-speedwell	?4	Dry	A/S	All year	seed		Persistent		
Common Fumitory			S (+a)	Sp	seed		Persistent		
Common Hemp-nettle	?4	Chill	S	Sp	seed		Persistent		
Common Mouse-ear	3		A	Au/Sp/Su	S & V	high	>20y		
Common Poppy	3	Chill	A (+s)	Au/Sp	seed	high	>20y	0.867	
Corn Spurrey	4	Dry	A/S	Au/Sp	seed		>20y		
Creeping Thistle	3	- / Unclassified	A	Au/Sp	S&V	some non-viable	5-20y	0.521	
Cut-leaved Crane's-bill			A/S	Sp/Su	seed		Persistent		
Fat-hen	3	- / Chill,Dry	S	Sp/Su	seed		>20y	0.931	
Field Forget-me-not	3	Dry	A (+s)	Au/Sp	seed		Persistent		
Field Pansy	?4	Unclassified	A/S	Au/Sp	seed		Persistent		
Fool's Parsley			S	Au/Sp	seed		Persistent		
Groundsel	3	Dry	All year	All year	seed	high	1-5y		
Knotgrass	3	Chill	S	Sp	seed		Persistent	0.813	

Red Dead-nettle	4	Dry	A/S	All year	seed		Persistent		
Redshank	4	Chill, Dry	S	Sp/Su	seed		>20y		
Scarlet Pimpernel	4	Chill	All year	Sp	seed		Persistent		
Scented Mayweed	2		A/S	Sp/Su/Au	seed		Persistent	0.778	*
Scentless Mayweed	3	Dry	A/S	Au/Sp	seed		5-20y		
Shepherd's-purse	4	Chill, Scar	All year	All year	seed	high	>20y		
Smooth Sow-thistle	3		S	Au/Sp	seed	high	Persistent		
Sun Spurge			S	Su	seed		Persistent		

Species show several adaptations to survival and reproduction, with seed production and a persistent seed bank the most common attributes. Some species also have vegetative propagation and some depend mostly on this form of reproduction.

3. UPDATING PN0923 - NON-TARGET EFFECTS OF HERBICIDES

3.1. Is Biodiversity Important?

Increasingly, it is argued that biological diversity within ecosystems, including agroecosystems, provides a range of biological functions, such as nutrient recycling and pest control (Altieri, 1999) . Thus biodiversity has a functional component. For example, there are some indications that more diverse agricultural systems may enhance natural control of crop pests (Estevez et al., 2000). Nevertheless, most ecological research on biodiversity is made outside the arable habitat. Thus there is a need for basic research in arable systems to understand any links between biodiversity, ecosystem function and sustainability.

Studies from other habitats indicate a variety of factors operate at different temporal and spatial scales, to affect the survival of populations, species and communities.
A comparison of low diversity and high diversity seed mixtures sown on ex-arable land, has indicated that higher plant diversity gave higher productivity and better weed suppression (Leps et al., 2001; Van der Putten et al., 2000). This was dependent on individual species within the grass and herb mixtures. There is also experimental evidence that more diverse grassland is less susceptible to invasion, thought this effect is often obscured by extrinsic factors (Naeem et al., 2000). The proposed unimodal relationship between productivity and species richness (highest species diversity is typically found at intermediate levels of productivity (fertility) (Marrs, 1993)) may not hold in some habitats and may be scale-dependent (Waide et al., 1999).

3.2. Change in Weed Communities (See also Sections 4 and 5)

The Sussex Study by the Game Conservancy investigated the changes in fauna, flora, gamebirds and farm management in an area of 62 km^2 from 1970 in southern England. (Aebischer, 1991) reported on the first 20 years of the study, noting that there were no obvious major effects on weed occurrence, using a simple weed score for all grass weeds and all broad-leaved weeds. There were increases in the numbers of fields containing particular weed species, notably *Bromus sterilis* and *Galium aparine*. Whilst the weed data indicated little overall change, there were highly significant effects on a range of invertebrate taxa. Examination of data to 1995 (Ewald & Aebischer, 1999), indicated that the broad categories of broad-leaved weeds were reduced in abundance by dicotyledon-specific herbicide use. Grass weeds were reduced in abundance by broad-spectrum herbicide use. Contact and contact + residual herbicides reduced the abundance of both groups. Nevertheless, there were no significant temporal trends overall. Herbicide use in spring and summer, rather than autumn, was associated with declines in occurrence of *Fallopia convolvulus, Sinapis arvensis, Viola arvensis, Chenopodium* spp., mayweeds and *Capsella bursa-pastoris* (Ewald & Aebischer, 1999).

Reviewing changes in biodiversity in arable land, (Robinson & Sutherland, In prep.) note that there is evidence of declining seed banks in arable land in Britain (Fig. 4.1.). A similar trend has been reported in Denmark (Jensen & Kjellsson, 1995). Viable seed density declined by 50% in Danish arable fields between 1964 and 1989.

Studies of weed communities of organic arable fields in Sweden indicated that a number of rare species might be supported by such systems (Rydberg & Milberg, 2000). There was also a tendency for conventional fields to support more nitrophilous weed species. A comparison of organic versus an integrated arable system in Germany indicated that the abundance and diversity of weed flora increased on the organic system (Gruber et al., 2000), though no rare species were recorded. No-plough tillage increased weed abundance, notably grass species. A significantly more diverse flora was found in organic compared with conventional fields in Denmark by (Hald, 1999b) and in Sweden (Rydberg & Milberg, 2000). However, organic production will not automatically preserve and encourage a diverse field weed flora under current economic pressures (van Elsen, 2000).

3.3. Impacts of Farming

Detailed examination of the changes in farming practice in the UK and its relation to changes in farmland bird species indicates a plausible link between intensification of production and bird population declines (Chamberlain et al., 2000). There is an apparent time lag between bird declines and intensification of production. However, as many components of intensification are interdependent, it is not possible to easily identify specific factors at work. Moreover, it may be a suite of factors affecting bird populations and ranges.

Studies of the usage of pesticides in an area of West Sussex from 1970 to 1995 indicate an increased intensity of use over the 26 years (Ewald & Aebischer, 2000). The spectrum of activity of herbicides on weed taxa increased from an average of 22 in 1970 to 38 taxa in 1995. A comparison of use on two farms in the area, one the most traditional and the other the most modern, indicated similar use of herbicides but significantly less insecticide and fungicide on the traditional farm. The difference mirrored differences in wildlife abundance (Ewald & Aebischer, 2000).

Changes in crop rotation and herbicide use can result in changes in weed seed banks in arable soils (Squire et al., 2000). Numbers of species can increase if herbicide use is reduced. However, the commonest species present tended to show largest increases and rarer species were less favoured. Spring-germinating species were relatively more abundant with more spring cultivation in the crop rotation. Targeting particular weeds with herbicides can lead to their relatively low abundance in the seed bank (Squire et al., 2000).

The difference between spring and winter cereal weed flora identified by (Chancellor, 1985) has been examined in unsprayed fields in Denmark more recently (Hald, 1999a). Whilst individual plant species may have different germination periodicities and thus react differently to timing of cultivation, there is a highly significant overall effect. A change to winter cereals from spring cereals is likely to result in a 25% reduction in weed density and species diversity (Hald, 1999a). In addition, plants that are important food resources for arthropod herbivores occurred at greater densities in spring rather than winter cereals.

A long-term study of crop rotation and weed control in the USA has shown the relative importance of these factors in maize, soybean and barley (Doucet et al., 1999). Overall, weed management explained 37.9% of total variation, while rotation only accounted for 5.5%. Nevertheless, crop rotation is an important component of integrated weed management. Similarly, studies on conventional versus no-tillage soil management in

Canada, confirm the selective effects on weed communities of herbicides and soil preparation (Swanton et al., 1999).

3.4. Interactions between Weed Diversity and Biodiversity

A comparison of herbicide-treated and untreated plots in the headlands of winter cereal fields in southern England (Moreby & Southway, 1999) clearly demonstrated that untreated plots had greater weed density and diversity and significantly higher numbers of many invertebrate taxa, notably those that are important in the diet of farmland birds. The Heteroptera, Auchenorrhynca and Coleoptera were particularly reduced on herbicide-treated plots.

Studies of the insects associated with soybean in Iowa, USA, indicate that weedier fields have generally higher insect densities. Weed management in herbicide-resistant soybean generally gave fewer insects (Buckelew et al., 2000). The effects were not direct impacts of herbicide, but rather indirect effects, mediated through the weed flora. Again in soybean, greater numbers of spiders were associated with weedier plots (Balfour & Rypstra, 1998). Similarly, a study of the carabid beetle fauna in fields undergoing conversion to organic production in Europe, demonstrated that increased activity-density could occur (Andersen & Eltun, 2000). The rise in carabids could in part be explained by the increase in the number of weed species present. Staphylinid beetles tended to show the opposite effect, suggested to be a response to competition from Carabidae.

There is good data to indicate that there is a relationship in alfalfa fields in Canada between insect diversity and the amount of woody field boundary surrounding the field (Holland & Fahrig, 2000). There was no relationship with insect density. This and other work indicates that mobile insects will respond not only to the botanical structure, management and size of fields, but also to the structure of the landscape.

3.5. Non-target Effects within the Crop

Surprising little data is published on non-target effects within fields or on plant susceptibilities to herbicides.

Laboratory studies indicate that there can be direct effects of herbicides on invertebrates. For example, (Ahn et al., 2001) demonstrate effects of glufosinate-ammonium at concentrations used in orchards on different life history stages of several predatory arthropods.

Whilst not necessarily a non-target effect, several herbicides applied as desiccants in the late stages of crop growth can affect weed seed viability and inhibit germination (Bennett & Shaw, 2000).

3.6. Non-target Effects beyond the Crop

Studies on the flora of field boundaries in The Netherlands, where plant species diversity has declined markedly, indicate that fertiliser use in the adjacent field is a key influence on species richness. There were no relationships between the boundary flora and herbicide use in the boundary or boundary management (Kleijn & Verbeek, 2000) in the dataset. Data on within-crop herbicide use were not examined, though the implication is that fertiliser is the major influence on boundary flora (Kleijn, 1997; Kleijn & Verbeek, 2000).

In Canada, the species composition of boundary habitats differed between farming systems, with a weedier often introduced flora in intensively managed areas (Boutin & Jobin, 1998). The effects of different tillage, herbicide and fertiliser regimes could not be ascribed, but overall effects were obvious.

3.7. Genetically Modified Herbicide Tolerant (GMHT) Crops

The introduction and testing of GMHT crops, whilst widely accepted in North America, has been opposed by many interest groups in Europe. Current work on the field-scale evaluation of the biodiversity impacts of these crops in the UK is examining the likely impact of modified herbicide use within the crop. The first generation of GMHT crops are engineered for tolerance to broad-spectrum herbicides, such as glyphosate and glufosinate. These *may* allow greater flexibility in weed management, but there may be effects on biodiversity as a result.

Watkinson et al. (2000) simulated the effects of the introduction of genetically modified herbicide-tolerant (GMHT) crops on weed populations and the consequences for seed-eating birds, using fat-hen as the model weed. They predicted that weed populations might be reduced to low levels or practically eradicated, depending on the exact form of management. Consequent effects on the local use of fields by birds might be severe, because such reductions represent a major loss of food resources. The regional impacts of GMHT crops are shown to depend on whether the adoption of GMHT crops by farmers co-varies with current weed levels.

Buckelew et al. (2000) have shown that herbicide-resistant soybean crops tend to have lower insect population densities. The effect is mediated through the impact of weed management, rather than direct effects of herbicide.

Preliminary studies of aphid populations on beet plants (Dewar et al., 2000) that were resistant to the herbicide glyphosate, indicate that early-sprayed plots had higher pest aphid populations than weedy or late-sprayed plots. The weedier plots supported large numbers of a different aphid species, accompanied by predators and parasites that eventually caused substantial aphid mortality.

Whilst it may be argued that GMHT crops offer the opportunity to delay weed control, some crops, most notably maize, are particularly susceptible to early weed competition, e.g. Bradley et al. (2000). Such crops are likely to be treated with herbicide around the time of crop emergence to eliminate weeds early in the life of the crop.

3.8. Spatial Distribution, Remote Sensing and Mapping of Weeds

As weeds are not uniformly distributed within fields, several research initiatives aim to combine accurate maps of distribution with precision weed control techniques. There are opportunities to reduce herbicide use with such approaches, though the technology is not presently available commercially. Remote-sensing of weeds may provide rapid data acquisition for ground-based technology (Lamb & Brown, 2001). A combination of image-processing and computer decision-making may prove useful for more precise herbicide use in the future (Yang et al., 2000a; Yang et al., 2000b).

The reasons for spatial variability of weeds have been investigated in Iowa, USA, using multivariate analyses of spatially-referenced weed occurrence and soil environment data (Dieleman et al., 2000). The approach is applicable to UK conditions and is an important area to develop to enhance current work on weed patchiness.

3.9. Farming Systems

An appreciation of the impact of intensive production on environmental, nature and landscape values in The Netherlands (ten Berge et al., 2000) is leading to the consideration of modified production systems. Conceptual modelling, involving the combination of technology, stakeholders and empirical testing, is one current approach (ten Berge et al., 2000).

Whilst the trend of the past century has been the simplification of production systems, there is a contrary debate that more diverse systems are more sustainable in terms of resource conservation. There may be opportunities to exploit complimentarity in resource capture by species in more diverse systems (Vandermeer et al., 1998).

4. CHANGES IN ABOVE-GROUND WEED ABUNDANCE

A basic question to answer is whether weed populations have actually changed in the UK. If so, then we should ask if this is of significance for biodiversity and is it the cause of other recorded changes in the food chain in agroecosystems.

Classic studies by Brenchley were reported in the early twentieth century (Brenchley, 1911, 1912, 1913), which attempted to identify the associations of weeds in arable land with soil types and crops. The strict association of weeds with soil types was limited, with many species of weeds being of general occurrence. Some species are nevertheless most often found on some soils (see on). This data gives a picture of the arable weed flora 90 years ago. There have not been any large-scale surveys of weeds in the UK for some years. The last such survey was conducted by technical staff of Schering Agriculture (now AgrEvo) in 1988 (Whitehead & Wright, 1989). Weeds in fields of winter wheat and winter barley were recorded, representing a 4% sample of UK fields. The commonest broad leaved and grass weeds are given in Table 4.1. below (Whitehead & Wright, 1989).

Table 4.1. The main broad-leaved and grass weeds in winter cereals (% fields infested out of a total of 4000 fields assessed) in Great Britain (total) and from three main regions. From (Whitehead & Wright, 1989).

	Percentage of fields with species present				
Species	**Total**	***Rank***	**Anglia**	**Southern**	**Western**
Chickweed (*Stellaria media*)	94	*1*	92	90	96
Common speedwell (*Veronica persica*)	72	*3*	76	69	59
Mayweeds (*Matricaria* spp.)	67	*4*	68	63	63
Cleavers (*Galium aparine*)	58	*5*	60	55	58
Red deadnettle (*Lamium purpureum*)	47	*6*	36	47	39
Field pansy (*Viola arvensis*)	45	*7*	45	49	54
Charlock (*Sinapis arvensis*)	36	*10*	41	38	42
Ivy-leaved speedwell (*Veronica hederifolia*)	30	*11*	33	33	26
Shepherd's *purse (Capsella bursa-pastoris*)	23	*12=*	21	20	24
Volunteer rape	23	*12=*	22	10	16
Common poppy (*Papaver rhoeas*)	18	*15*	27	20	11
Fumitory (*Fumaria officinalis*)	17	*16*	7	17	20
Fathen (*Chenopodium album*)	13	*18=*	11	10	13
Parsley piert (*Aphanes arvensis*)	12	*20*	13	17	14
Cranesbills (*Geranium* spp.)	11	*21*	11	11	14
<u>Grass weeds</u>					
Annual meadow grass (*Poaannua*)	79	*2*	66	78	88
Wild-oats (*Avena* spp.)	42	*8*	51	45	40
Blackgrass (*Alopecurus myosuroides*)	38	*9*	70	35	26
Couch grass (*Elymus repens*)	21	*14*	21	19	20
Ryegrass (*Lolium* spp.)	14	*17*	7	15	19
Sterile brome (*Bromus sterilis*)	13	*18=*	12	12	10
Rough-stalk meadow grass (*Poa trivialis*)	7	*22=*	3	12	2
Volunteer cereals	7	*22=*	7	9	5

Certain species are more prevalent in the East, notably blackgrass, while others, notably fumitory, are commoner in the West. An earlier survey examined weed incidence in central southern England [Chancellor, 1984 #213; Froud-Williams, 1982 #214].

Table 4.2. Occurrence of weeds in 900 cereal fields, mostly winter wheat, in central-southern England in 1982 after herbicide applications (Chancellor & Froud-Williams, 1984).

Grass weeds	No. fields / 900	Dicotyledonous weeds	No. fields / 900
Couchgrass	327 (36%)	Field pansy	102 (11%)
Winter wild-oat	273 (30%)	Cleavers	89 (10%)
Spring wild-oat	56 (6%)	Common chickweed	57 (6%)
Black-grass	261 (29%)	Field forget-me-not	56 (6%)
Rough stalk meadowgrass	227 (25%)	Field bindweed	56 (6%)
Barren brome	135 (15%)	Knotgrass	53 (6%)
Annual meadow-grass	124 (14%)	Black bindweed	33 (4%)
Black bent	90 (10%)	Red deadnettle	33 (4%)
Timothy	71 (8%)	Broad-leaved dock	33 (4%)
Italian ryegrass	70 (8%)	Creeping thistle	29 (3%)
False oat-grass	36 (4%)	Common poppy	23 (3%)
		Field speedwell	23 (3%)
		Hogweed	21 (2%)
		Mayweed	21 (2%)
		Fools parsley	20 (2%)

The major agrochemical companies have been approached to ascertain what data might be available for interrogation. Surveys were made by Fisons in 1968 and 1973 and one by Rhone-Poulenc is referred to by (Whitehead & Wright, 1989) (pers com M Read, Aventis). Monsanto utilise a database of incidence and severity of major arable weeds, based on farmer perception (Pers comm.. CR Merritt). This database is produced by the National Farm Research Unit of consultants Precision Prospecting and goes back to 1993. Likewise, Produce Studies Limited may also have farmer survey information.   These surveys are unlikely to cover full weed assemblages or to be based on abundances, but may provide useful insights into changes over time. Access to this commercial data would require further funding.

Another potential data source are the records of weed seed contaminants of grain samples assessed by the National Institute of Agricultural Botany (NIAB). This data is quantitative in terms of seed numbers and species represented and can be compared year-to-year, though this will not be a full representation of weeds present.

Apart from these sources, there are a number of current potential data sources that may allow comparison with earlier weed surveys. These are the Countryside Survey 2000, 1990 and earlier datasets and the current field-scale assessment of biodiversity impacts of GMHT crops. The latter project is funded by DETR and compares conventionally-managed crop cultivars with herbicide-tolerant cultivars on a split-field basis at many sites across Great Britain. Assessments of weed populations at different times and standing crop before harvest are made. There is a bias towards spring–sown crops in the project, as only winter and spring rape, sugarbeet and maize are examined and none of the major cereals is included. The Countryside Survey data include within-field quadrats (Barr et al., 1993) [Haines-Young, 2000 #218]. There are 162 field plots recorded in 1978, 1990 and 1998, which could be used to compare weed flora over a 20-year period. For the 1990-1998 comparison, there are 368 cultivated land quadrats. An additional habitat area was assessed in the 1998 Countryside Survey, comprising the cultivated field edge in quadrats 1m by 100m in size (pers com. C Barr, S Smart). A total of 501 such plots were recorded, together with 588 field plots.

In addition, the Sussex Study by the Game Conservancy records weed species occurrence in about 100 arable fields from 1970 (Aebischer, 1991; Ewald & Aebischer, 1999; Ewald & Aebischer, 2000). These data indicate no major temporal changes in crude weed abundance, divided into grasses and dicotyledonous species. However, it is noted that by 1970 herbicides had been used routinely for many years. So the weed flora may have changed before recording began. Certainly, a study of the arable flora of central southern England by (Sutcliffe & Kay, 2000) reveals changes since the 1960's. Some species have become commoner, others have remained stable, while others have become rarer. Species that were less common in the 1960s have tended to become rarer. A suite of species has become commoner, including *Alopecurus myosuroides, Anisantha sterilis, Galium aparine* and *Sisymbrium officinalis* (Table 4.3.).

Table 4.3. Changes in occurrence of representative weed species taken from the literature.

Species	Increase (+), decline(-) or stable in central southern England 1960s – 1997 (Sutcliffe & Kay, 2000)
Alopecurus myosuroides	+
Anagallis arvensis	
Avena fatua	+
Bromus sterilis	+
Capsella bursa-pastoris	+ (post 1977)
Cerastium fontanum	
Chenopodium album	+
Cirsium arvense	+
Euphorbia helioscopia	
Fumaria officinalis	
Galeopsis tetrahit	
Galium aparine	+
Geranium dissectum	+
Lamium purpureum	
Matricaria recutita	
Myosotis arvensis	
Papaver rhoeas	+ (post 1977)
Persicaria maculosa	
Poa annua	
Polygonum aviculare	Stable
Polygonum convolvulus	Stable

Rumex obtusifolius	
Senecio vulgaris	
Sinapis arvensis	
Sonchus oleraceus	
Spergula arvensis	-
Stellaria media	
Tripleurospermum inodorum	-
Veronica persica	-
Viola arvensis	

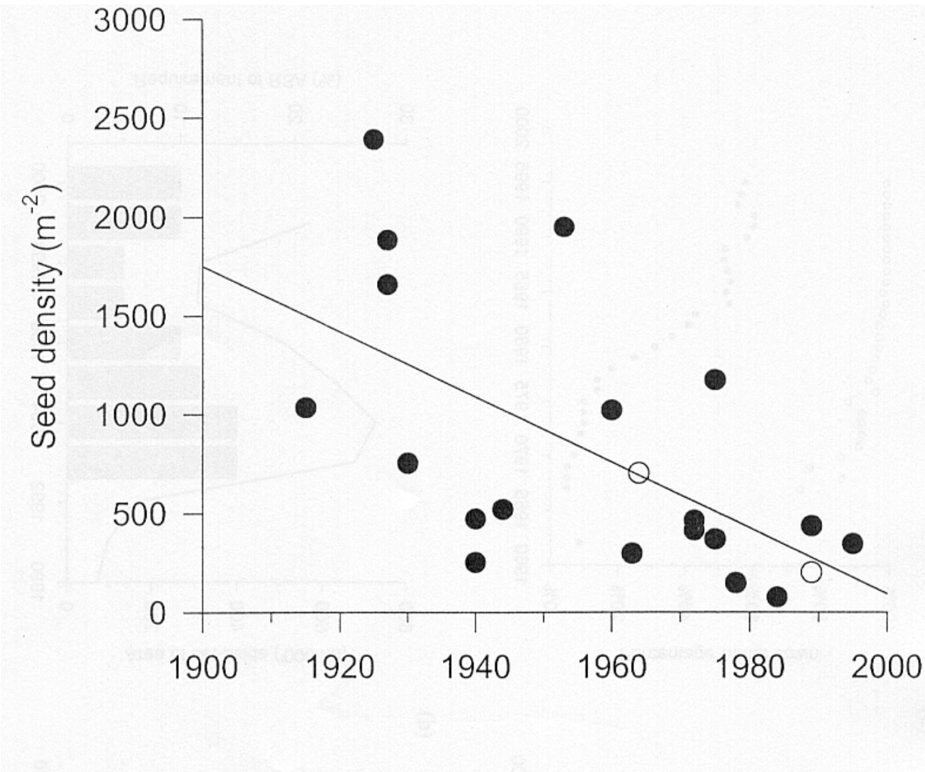
Data collated from (Brenchley, 1911, 1912, 1913) for weeds of general occurrence, or commonly found on sandy, chalk, loam or clay soils in the early 1900s are listed in Table 4.4. below.

Table 4.4. Weed species found generally distributed or associated with sand, chalk, loam or clay soils (in alphabetical order of latin names) in the early 20th century. Derived from Brenchley (1911-13).

Generalists	**Sand**	**Chalk**	**Loam**	**Clay**
Creeping bent	Bugloss	Mugwort	Corncockle	Blackgrass
Shepherd’s purse	Soft brome	Chicory	Stinking mayweed	Common orache
Common mouse-ear	Corn marigold	Smooth hawksbeard	Daisy	Dwarf spurge
Fat-hen	Viper’s-bugloss	Sun spurge	Ox-eye daisy	Cleavers
Creeping thistle	Common whitlowgrass	Common toadflax	Purple spurge	Cut-leaved cranesbill
Field bindweed	Early forget-me-not	(+ loam) Fool’s parsley	Ryegrass	Hogweed
Swine-cress	Sorrel	Common knapweed	Prickly poppy	Sharp-leaved fluellen
Wild carrot	Annual knawel	(+ sand) Basil thyme	Rough-stalk meadowgrass	Creeping cinquefoil
Couch grass	Corn spurrey	Corn chamomile	Silverweed	Corn buttercup
Field horsetail	(+loam) Common stork’s-bill	Thyme-leaved sandwort	Selfheal	Marsh woundwort
Cleavers	Small toadflax	Common orache		
Red deadnettle	Marsh cudweed	Musk thistle	Red campion	
Mayweed spp.	Yorkshire fog	Common cudweed	White mustard	
Corn mint	Common poppy	Dove’s-foot cranesbill		
Field forget-me-not	Long-headed poppy	Small-flowered cranesbill		
Greater plantain	Knotted pearlwort	Wild mignonette		
Timothy	Small-flowered catchfly	Night-flowering catchfly		
Knotgrass				
Creeping buttercup				
Wild radish				
Curled dock				
Broad-leaved dock				
Shepherd’s-needle				
Groundsel				
Field madder				
White campion				
Charlock				
Perennial sowthistle				
Chickweed				
Knotted hedge-parsley				
Green field-speedwell				
Common field-speedwell				

The lists above are not comprehensive and are derived from surveys when agricultural practice was very different to today. It is clear that it is not easy to predict the size and content of likely weed communities, given the generalist occurrence of so many species and the variation that is a natural feature of weed assemblages. The species listed in Table 4.1. are more likely to give a better picture of the weed communities now likely to be found. It is nevertheless clear that some changes have occurred over the past 75 years in the above-ground arable plant communities. Reviewing changes in biodiversity in arable land, (Robinson & Sutherland, In prep.) note that there is evidence of declining seed banks in arable land in Britain (Fig. 4.1.) (see next section). A similar trend has been reported in Denmark (Jensen & Kjellsson, 1995)]. Viable seed density declined by 50% in Danish arable fields between 1964 and 1989.

Fig. 4.1. Published estimates of seed density in arable soils. Points represent densities of dicotyledonous seed in the top lcm of soil in arable fields in Britain (filled symbols, from sources in Robinson 1997) and Denmark (open symbols, Jensen & Kjellson 1995). Studies are included only if they sampled the entire seed bank between September and November and the fields had been part of a cereal-based rotation for at least 5 years; results from adjacent fields and years have been averaged. Slope of regression through British data: - 17 seeds.m-2.yr-l, $R^2 = 0.35$. From Robinson & Sutherland (in prep.)



5. NON-TARGET WEED SPECIES IN THE SEEDBANK

This section on seedbanks concentrates on those weeds of lower economical importance but of potentially high value for wildlife that were identified earlier in the report. They are all termed non-target species, even though they might be targets for control in some circumstances. An extensive review of the literature on UK seedbanks was undertaken. The arguments and conclusions here are based on this wider literature as well as on the examples cited. The main points considered are –

- The status of the non-target species in seedbank studies between 1915 and 1997.
- The abundance and dynamics of seedbanks in response to suppression and relaxation of management.
- Community-scale features of the seedbank as comparators of sites and treatments, and the potential for modelling populations as a means of linking plant trait, field management and community.

5.1. Status of the Non-target Species

Studies of the UK arable seedbank have been sporadic and largely uncoordinated, yet in total provide a largely unambiguous account of the general frequency and abundance of the non-target species. Practitioners have used variously the extraction and germination methods (e.g. Marshall & Arnold, 1994) to detect seeds in soil. The methods generally give similar results as to the presence and broad abundance ranges of arable seedbanks in the UK. The results from the two techniques might have different implications for seedbanks as sources of food for other organisms. The extraction method probably gives a better estimate of the total contribution of seed to the underground food web, but can overestimate actual abundance of germinable seed for instance.

Frequency and ranking of non-target species in arable fields

The species of major economic importance were defined as *Alopecurus myosuroides, Avena fatua, Bromus sterilis,* and *Galium aparine.* They are the targets of much chemical weed control, and presumably because the control treatments generally succeed in reducing seed return, are not detected as frequently, or in as great an abundance, as many of the non-target species. Of the four, *A. myosuroides* and occasionally *G. aparine* reach medium abundance in some fields.

Many of the non-target species have been repeatedly recorded in studies of arable seedbanks (Table 5.1), ranging from those by Brenchley (1918) in several fields around Rothamsted Experimental Station to the more extensive surveys of Roberts and Chancellor (1986) and Warwick (1984). There have been few systematic changes and anomalies, except that *Geranium dissectum* has been seldom recorded; *Solanum nigrum* typically occurs in certain fields in abundance but is absent from many; and *Aethusa cynapium* and *Anagallis arvensis* are both absent from the surveys in Scotland (7 and 8 in Table 5.1). Taking three representative studies (Table 5.2), the species in common among the top twenty species in each are *Chenopodium album*, *Fallopia convolvulus, Myosotis arvensis, Poa annua*, *Polygonum aviculare* and *Stellaria media*. More widely, species of *Veronica* (*V. persica* and *V. arvensis* mainly) and *Capsella bursa-pastoris* are also very common.

Table 5.1. Presence of non-target species in representative seedbank studies in the UK, 1915 to 1996.

Author*	1	2	3	4	5	6	7	8	9	10
Year 19-	15	25-27	29-31	44	53-55	72-77	72-78	82	89-97	90-96
Aethusa cynapium	■	■		■	■	■			■	■
Anagallis arvensis	■	■	■	■	■	■			■	■
Capsella bursa pastoris	■	■		■	■	■		■	■	■
Cerastium fontanum	■	■	■	■		■			■	
Chenopodium album	■	■	■	■	■	■	■	■	■	■
Cirsium arvense	■	■		■			■		■	
Euphorbia helioscopia			■		■		■	■	□	□
Fallopia convolvulus	■	■	■	■	■	■	■	■	■	■
Fumaria officinalis		■	■	■	■		■	■	■	■
Galeopsis tetrahit			■				■	■		
Geranium dissectum									■	■
Lamium purpureum			■	■	■			■	■	■
Matricaria/Tripleurospermum	■	■		■	■	■	■	■	■	■
Myosotis arvensis	■	■		■		■	■	■	■	■
Papaver sp	■	■		■	■	■			■	■
Persicaria maculosa	■		■	■		■	■	■	■	
Poa annua	■	■	■	■	■	■	■	■	□	□
Polygonum aviculare	■	■	■	■	■	■	■	■	■	■
Rumex obtusifolius		■	■				■		□	
Senecio vulgaris	□	■	■	■	■	■	■		■	■
Sinapis arvensis			■	■	■	■	■	■	■	■
Solanum nigrum				■	■				□	
Sonchus oleraceus	□		■	■	■			■	■	
Spergula arvensis		■	■		■		■	■	■	
Stellaria media	■	■	■	■	■	■	■	■	■	■
Tripleurospermum inodorum	■	■		■	■					
Veronica persica	■				■	■	■	■	■	■
Viola arvensis		■	■		■	■	□	□	■	□

Notes:

1. Three common mayweeds, *Tripleurospermum inodorum* (= *Matricaria inodora* in earlier accounts), *Matricaria recutita* and *Matricaria discoidea* (pineapple weed) are difficult to separate as extracted seeds and as seedlings. The characteristics of leaf shape in Chancellor (1959) can be followed but recognition is still uncertain. *M. recutita* is seldom mentioned in the earlier sources in Table 1. Given there may have been many errors of recognition, they are classed together in the Table.
2. The open symbols in Table 1 indicate that taxa, variously as seed and seedlings, have been identified to genera, not species, e.g. *Poa*, *Euphorbia*, *Papaver*, but that the individuals were likely to have been the named species or a close relative.

*Site/author identifiers:

1. Brenchley, 1918: fields included are Geescroft Field, New Zealand Field, Long Hoos, Agdell, Barn Field.
2. Brenchley and Warrington, 1930, 1933, 1936: Rothamsted and Woburn
3. Chippendale and Milton (1934): 5 fields classed as ‘pasture formerly arable’.
4. Champness and Morris (1948): 20 lowland arable fields in England
5. Roberts (1958): one weedy field in the English midlands.
6. Roberts and Chancellor (1986): 64 fields in Oxfordshire and Warwickshire (other species may have been present).

7. Warwick (1984): 344 fields in Scotland
8. Lawson, Wright & Smoktunowicz : 100 fields in Scotland
9. MAFF (1988): set-aside experiment at ADAS Boxworth, Bridgets, Drayton, Gleadthorpe, and High Mowthorpe.
10. *TALISMAN*: Squire, Rodger & Wright (2000).

Table 5.2. The twenty species most frequently found among sites in three representative studies. The highlighted species occur in all three studies.

	Warwick (1984)	Roberts and Chancellor (1986)	MAFF (1998)
1	**Stellaria media**	**Poa annua**	**Chenopodium album**
2	*Spergula arvensis*	*Polygonum aviculare*	*Stellaria media*
3	*Polygonum aviculare*	*Stellaria media*	*Poa sp.*
4	*Persicaria maculosa*	*Fallopia convolvulus*	*Triticum aestivum*
5	*Chenopodium album*	*Aethusa cynapium*	*Fallopia convolvulus*
6	*Poa annua*	*Alopecurus myosuroides*	*Brassica spp*
7	*Fallopia convolvulus*	*Veronica persica*	*Polygonum aviculare*
8	*Atriplex patula*	*Chenopodium album*	*Anagallis arvensis*
9	*Ranunculus sp.*	*Veronica arvensis*	*Urtica sp*
10	*Hordeum vulgare*	*Capsella bursa-pastoris*	*Viola sp.*
11	*Galeopsis tetrahit*	*Anagallis arvensis*	*Veronica persica*
12	*Trifolium repens*	*Viola arvensis*	*Papaver sp.*
13	*Veronica hederifolia*	*Trifolium repens*	*Galium aparine*
14	*Myosotis arvensis*	*Myosotis arvensis*	*Veronica arvensis*
15	*Lolium sp.*	*Sonchus asper*	*Myosotis arvensis*
16	*Phleum pratense*	*Aphanes arvensis*	*Sambucus nigra*
17	*Viola sp.*	*Avena fatua*	*Trifolium repens*
18	*Brassica sp.*	*Plantago major*	*Aethusa cynapium*
19	*Fumaria officinalis*	*Chamomilla suaveolens*	*Veronica hederifolia*
20	*Dactylis glomerata*	*Atriplex patula*	*Matricaria spp.*

Notes:
1. *Capsella bursa- pastoris*: being a common weed in the area, its absence from Warwick's survey is unexplained.

5.2. Abundance and Dynamics of the Non-target Species

Many authors have meticulously recorded the abundance of seedbank species, and though the sampling methodology varies, the number of seeds per unit soil volume or per unit field area can generally be standardised and used in comparison. The abundance of a species is the result of environment and management interacting with the plants' life cycle traits. Many of the species produce large numbers of offspring if allowed to seed, to the extent that amplification rates can be 10- or 100- fold per year over a few years. However, decay rates due to predation, age and fungal attack are also large and have been well documented for many species (Rees & Long, 1993).

The potential for rapid decrease and increase therefore gives rise to a very wide range of abundance from 100 to 1000 m^{-2} in fields where seed return is largely suppressed, 10,000 m^{-2} in fields managed with a moderate intensity of management to >100,000 m^{-2} where there is little weed management but where perennials are not allowed to establish. Any form of intense management, not only chemical herbicides, can reduce total populations to within the lower of these ranges. For instance, Brenchley (1918) gives evidence of such low values resulting from several decades of hoeing and soil impoverishment. (Note that the depth of soil to which the estimates relate should be stated, such that abundances are cited as a m^{-2} to a depth of b m; most authors refer their estimates to 15 or 20 cm depth).

Several of the non-target species constitute the majority of the seedbank in many arable fields. As a somewhat subjective summary, the non-target species are categorised in terms of their relative frequency of occurrence (among sites) and their abundance per unit field area (Table 5.3). Effects of some major changes of field management on the non-target species are now summarised.

5.3. Suppressive Management – Falling Seedbanks

Roberts and Chancellor (1986) compare several previous studies from their laboratory that suggest (circumstantially) a decline in seed abundance from a median of 10,000 m^{-2} to a median of 4000 m^{-2} following the widespread use of chemical herbicides. They caution that many fields in their latest, 1972-77, survey still had >10,000 m^{-2} seeds. There have been no comparable, widespread surveys since that time, until the current farm-scale evaluations of GM crops, in which it will be important to consider the range of abundance and species number. Much of what can be surmised on the likely effect of weed suppression on the seedbank derives from work up to the late 1950s, augmented by more mechanistic studies of life cycles and population dynamics.

Several occasions have been documented when weedy arable fields were put under fallow or subject to other intense management so that seed return was eliminated or reduced. Brenchley & Warrington (1933) observed the effect of two years' fallow on weedy fields at Rothamsted and Woburn, and Roberts (1958, 1962) the effect of six years intense cultivation on a very weedy field at Wellesbourne. Roberts also compared his and Brenchley & Warrington's findings. The two studies show consistency of decay rates for several species that were common to both sites and which are in the list of non-target

Table 5.3. The non-target species categorised by frequency of occurrence among sites, and abundance per unit area in sites where they occur.

		Frequency of occurrence		
		low	*medium*	*high*
Abundance	*low*	Cerastium fontanum Euphorbia helioscopia	Cirsium arvense Galeopsis tetrahit Lamium purpureum Persicaria maculosa Rumex obtusifolius Senecio vulgaris Sonchus oleraceus	
	medium	Geranium dissectum	Aethusa cynapium Fumaria officinalis Sinapis arvensis Viola arvensis	Capsella bursa-pastoris Fallopia convolvulus Myosotis arvensis Veronica persica
	high	Papaver sp. (?) Solanum nigrum	Anagallis arvensis Spergula arvensis Tripleurospermum / Matricaria	Chenopodium album Poa annua Polygonum aviculare Stellaria media

Notes:

1. Frequency categories are subjective. Abundance categories are approximately and subjectively defined as low, 100 to 1000 m^{-2}; medium, 1000 to 5000 m^{-2}; high, >5000 m^{-2}.
2. *Tripleurospermum inodorum* and *Matricaria recutita* seem very much commoner and more abundant in recent (unpublished) seedbank studies than they appear to have been in any previous study.
3. *Papaver* sp. sometimes massively high in abundance, at other times low.

species examined here. After two years, many species had declined to less than half the initial abundance, and some species, notably *Polygonum aviculare* and *Aethusa cynapium*, to <10% of the initial. In Roberts' experiment, the total seedbank dropped to around 20% after two years and continued falling at a similar rate, to about 5% of the initial value after 6 years. In absolute numbers, the seedbanks after 6 years (i.e. by 1959) were 2000 to 4000 m^{-2} to 15 cm depth, values typical of highly managed fields in the final decade of the 20^{th} century. Species that were present in moderate or low numbers initially were only just detectable at the sampling frequency used. Subsequent information from more controlled experiments has generally confirmed the absolute decay rates and the ranking of species (Roberts & Feast, 1972; Wilson and Lawson, 1992).

Continued intense management in these experiments would probably have allowed the seedbanks to decay further, possibly to the near extinction of some species from the field. However, there is little hard information on long term persistence of a species at low frequency. Much of the evidence is circumstantial, based on discovering an arable species in a field that had once been arable but had been converted to grassland many years previously. Brenchley (1918) found many arable seeds after nine years of grass, and a few in fields under grass for >30 years. Among the latter were *P. aviculare* that the author reports was likely to have been prevalent in the past. Similarly, Chippendale and Milton (1934) found seeds of normally arable species, such as *Anagallis arvensis, Cerastium fontanum, Fumaria officinalis,* below 15 cm in grass fields that had been converted from arable up to 40 years previously. Given the depth in the soil in which they occurred, they were considered relics of past cultivation.

The weight of evidence points to a rapid decline of the non-target species in the seedbank during intense management to a small percentage of the initial value. The food value of the seedbank for invertebrates, and to a smaller degree for birds, will therefore rapidly diminish. However, the species remain in sufficient abundance after, say, 6 years to regenerate much larger seedbanks if allowed, and seed of some non-target species still exists at depth in the soil even 30 or 40 years after conversion of arable fields to pasture.

5.4. Relaxing Management – Rising Seedbanks

Very few historical cases exist of fields subjected to any relaxing of management. However, recent experiments (1989-1997) have examined the effects on the arable seedbank of de-intensifying the winter cereal rotations typical of the late 1980s.

The first instance is the *TALISMAN* experiments (Squire, Rodger & Wright, 2000), held at three ADAS sites, in which spring sown crops were introduced to the rotation and herbicide dose was about halved. After six years, most non-target species that were present had increased either in abundance or frequency of occurrence in plots at least one of the three sites (Table 5.4). The effects were particularly pronounced for spring germinating species such as *Fallopia convolvulus*, *Polygonum aviculare*, *Chenopodium album*, and *Sinapis arvensis*, and especially where the number of herbicide units was moderate (e.g. 2 to 3) at the beginning of the experiment. Several species showed no change, but no negative effects were observed. Despite the increase in species detected and their frequency of occurrence, the relaxation of management brought with it important adverse effects for crop management. First, the important weed species, *Alopecurus myosuroides* and *Galium aparine* were also stimulated to high numbers (one each at a different site); and second, several of the non-target species, notably *Papaver* sp., *Anagallis arvensis* and *Chenopodium album* increased to such massive abundances (>10,000 m^{-2}) that they would likely become economically damaging in future years. The lesson from *TALISMAN* was that encouraging the rarer species by relaxing management brought with it a logarithmic increase in the abundance of potentially competitive weed populations.

The conversion of arable fields to set aside, through sown swards or natural regeneration, (MAFF, 1998) is a form of relaxation of arable management that had more neutral or even adverse effects on the non target species, and demonstrates further that directed and skilful husbandry will be required to maintain the annual non-target broadleaves. The annuals were overtaken rapidly in the set aside and with few exceptions, such as *Matricaria* sp., hardly contributed to massive rises in the seedbank that occurred up to three years into set-aside. Some species, notably *Chenopodium album,* declined over the period (Table 5.4). The fields were converted back to arable land after 5 years, and analysis is now in progress to discover whether the non-target annual species had recovered following two years in an arable system.

Table 5.4. Effects of reducing the intensity of weed management on non-target species: (A) in the *TALISMAN* experiment, after 6 years of halving herbicide dose and introducing spring rotations (Squire, Rodger & Wright, 2000); (B) 3 years after converting arable fields to fallow or sown swards in the contemporaneous set-aside experiment (MAFF, 1998), both at ADAS sites. Up: effect of treatments predominantly increasing frequency or abundance. Down: effect predominantly decreasing; n, no change; -, not present.

Species	*(A) Talisman*	*(B) Set aside*
Aethusa cynapium	up	n
Anagallis arvensis	up	up
Capsella bursa pastoris	up	n
Cerastium fontanum	-	up
Chenopodium album	up	down
Cirsium arvense	-	n
Euphorbia helioscopia	-	n
Fallopia convolvulus	up	n
Fumaria officinalis	up	n
Galeopsis tetrahit	-	-
Geranium dissectum	up	n
Lamium purpureum	up	n
Matricaria/Tripleurospermum	up	up
Myosotis arvensis	up	up
Papaver sp	up	n
Persicaria maculosa	-	n
Poa annua	up	up
Polygonum aviculare	up	n
Rumex obtusifolius	-	-
Senecio vulgaris	-	-
Sinapis arvensis	up	n
Solanum nigrum	-	-
Sonchus oleraceus	-	n
Spergula arvensis	-	n
Stellaria media	up	n
Veronica persica	up	up
Viola arvensis	-	up

5.5. Community Features and the Potential for Modelling

Weed species form complex distribution patterns in fields caused by their interaction with soil and by variable management. Nevertheless, properties of a weed assemblage can be captured by population-scale features such as the species-accumulation curves (analogous to species-area curves widely used in ecology). The curves are derived by calculating the number of species in groups of 1, 2, 3, etc. samples selected randomly from the total samples taken at a site, and are often best described by an equation of the form $y = ax^b$, where a and b are parameters that can be used to define the community in a treatment or site. If plotted on a log-log scale, the data form a straight line. The species-area curve usefully defines the ‘rate’ at which new species are detected as the increasing amounts of soil are analysed for seed. For the same total abundance, for example, a steeper curve indicates more evenness, less dominance. The change in the curve over time gives information on the scale at which species decline (or rise) in frequency following change in management. The analysis was applied in the *TALISMAN* experiment to demonstrate consistent effects between sites (Squire, Rodger & Wright, 2000). In a falling seedbank, species do not decline equally all over the field. They are reduced more, or erased, from certain patches faster than others, so that the species number detected at small sample areas or volumes might decline while the total of species detected in the whole field does not change. If loss continues to exceed gain, this total for the field falls eventually. Scaling relations such as these also apply among fields and farming regions.

Seedbanks have rarely been examined by these community-scale properties, but they undoubtedly offer simple and quantifiable means of comparing seedbanks measured over the past century using different sampling schemes. The UK seedbank literature is extensive and would provide a valuable source of data for extending the methods used to analyse seedbanks in *TALISMAN*. A preliminary analysis of several studies in the 20^{th} century is given in Fig. 5.1. A useful reference is the weedy site examined by Roberts (1958). Most other measurements at a single site fall below the line described by his data (Fig. 5.1), whereas samples pooled from several or many sites generally lie above that line since they capture more of the rarer species in a wider range of arable habitats.

5.6. Dynamics Modelling Linking Trait to Community through Management

A more fundamental area of study is the link between the physiological traits of the seedbank species and the spatial distributions that underlie the species-area curve and other community scale features such as the species abundance distribution. Recently, progress has been made with individual based models of plant dynamics that can be used to explore the links between trait and community (Pachepsky *et al*., 2001). In the model, individual plant types, defined by physiological traits, interact over a resource to give spatial distributions of individuals that change over time. Analysis of the patterns shows the species-area relations are derived from the physiological traits of the individuals parameterised in the model. The ideas could be applied to arable seedbanks in order to search for management options that drive the seedbank community towards greater evenness and more non-target, beneficial species.

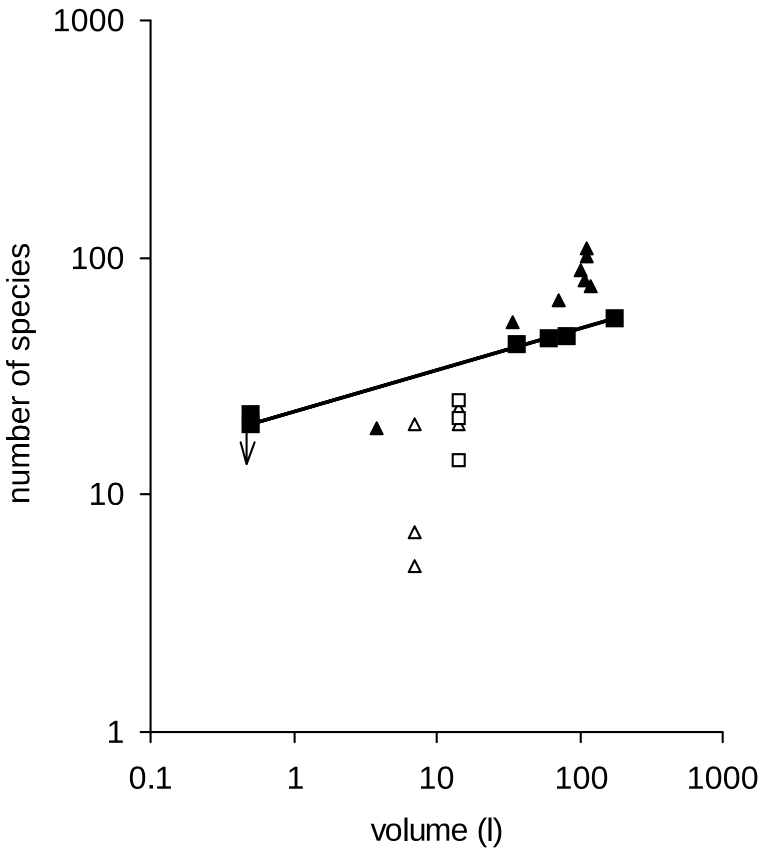


Fig. 5.1. Comparison of representative seedbank studies in the UK, expressed as number of species detected for volume of soil sampled, both on a log scale.

Site details and commentary. Closed squares, regression line and arrow: measurements within one very weedy site by Roberts (1958); the regression is the log-log plot, typical of the relation within a site; the arrow shows the extent of reduction at small sampling volume only, caused by loss of species following intensification. These data represent one of the most diverse weed assemblages in a single field ever recorded in the UK. Closed triangles: measurements at many sites by Champness & Morris (1948), Roberts & Chancellor (1986), Warwick (1984), Lawson *et al*. (1988). Open symbols show measurements each at a single site by (triangles) Brenchley (1918) and (squares) Squire *et al*. (2000), all with moderate to high intensities of management. Most values are estimated from samples of the top 0.15 cm of soil. Roberts's (1958) data and several of the studies represented by open triangles are a baseline for the UK arable seedbank before intensification.

5.7. Conclusions

- Many of the non-target species, identified as being beneficial for invertebrate and bird life, have been and still are prevalent in arable seedbanks. Their true status is uncertain, however, since there have been no broad surveys, encompassing a wide range of farms, since the 1970s. Most of the recent evidence was accumulated from various studies on experimental farms in the 1980s and 1990s.
- Among species that are particularly good hosts for invertebrates, a group can be identified that are frequent and abundant - *Chenopodium album*, *Poa annua*, *Polygonum aviculare* and *Stellaria media* (and possibly also *Tripleurospermum / Matricaria*). Other plants, that are also good hosts, are less frequent and abundant – *Cirsium arvense*, *Rumex obtusifolius*, *Senecio vulgaris*, and perhaps also *Lamium purpureum* and *Sonchus oleraceus*.
- Most of the non-target species have the potential for rapid increase in population size but also have rapid decay rates. After two years of little seed return, they may have declined to 10 to 25% of their initial value. A small fraction of their populations persists, such that their abundance after several years of suppression would still be enough to allow recovery following appropriate management.
- There are difficulties in managing arable land so as to maintain both an even balance and moderate numbers of non-target species and the presence of some rarer species. Relaxing management tends to encourage a massive rise in abundance of one or two species. Methods need to be found to cause an evening of the species-abundance relation – more species, more evenly balanced in number. Disturbance of the soil is essential to maintaining these species.
- Methods of community analysis (e.g. species accumulation curves) and modelling approaches (e.g. individual based models linking traits to community properties) could provide a general framework for investigating the dynamics of non-target and rare seedbank species.
- The current Farm Scale Evaluations of GM herbicide tolerant crops will be the most extensive seedbank survey ever undertaken in the UK, and should define the status of all the non-target species listed in Table 5.1.

6. CURRENT WEED CONTROL AND ITS IMPACT

6.1. Introduction

Weeds are primarily linked to fields, unlike pests and diseases, which are mainly associated with specific crops. However, the weed spectrum present in a crop will be greatly influenced by its sowing date and so autumn–sown crops will contain a very different selection of weed species to a spring-sown one. Thus, changes in cropping pattern can have a great effect on the weed flora, irrespective of herbicide use. For example, the decline in corn marigold (*Chrysanthemum segetum*) has been linked to the decline in spring crops over the last 20 years. So the weed flora in a field will reflect cropping practice as well as herbicide use. Pre-planting cultivations can also affect weed presence as for example the grass weeds are favoured by non-inversion tillage, whereas broad-leaved species can be favoured by ploughing. Broad-leaved weed seeds tend to have longer dormancy than grasses. Once the crop has been sown weed control practices endeavour to prevent the weeds from affecting crop yields. In practice many farmers still aim to create weed free fields. However, the financial pressures of the 1990s have forced a reduction in all inputs to crop production and the impact that this has had on weed control is to stimulate reductions in herbicide doses. The question 'how much of this product do I need to control this weed' is more frequently asked. Although many farmers are still aiming for complete weed control, the use of low doses does result in poor control in some situations and thus the retention of more weeds in fields. But, the weeds that tend to 'escape' from low dose treatments tend to be the more aggressive species.

6.2. Arable Cropping Patterns

Table 6.1 presents the changes in planting areas in the five major combinable arable crops grown in the UK.

Table 6.1 Areas of major arable crops sown in England, Wales and Scotland (GB) between 1974 and 1998 (MAFF Pesticide Usage surveys) Areas = X x 1000 ha

Year	Winter wheat	Winter barley	Spring barley	Oilseed rape	Field beans	Total (all arable crops)
1974	1172 (27)	217 (5)	1948 (45)	25 (1)	66 (2)	4352
1982	1660 (36)	872 (19)	1297 (28)	173 (4)	40 (1)	4591
1988	1878 (39)	849 (18)	982 (20)	345 (7)	153 (3)	4828
1994	1802 (45)	620 (15)	451 (11)	403 (10)	149 (4)	4030
1998	2035 (45)	760 (17)	455 (10)	505 (11)	111 (3)	4545

Figures in parentheses are % of total arable crops

As can be seen in Table 6.1 there has been a major switch away from spring barley towards the autumn sown crops (wheat, barley, oilseed rape). There are also indications that winter barley is not now as popular as it was, and that the proportion of wheat is continuing to increase. However, from the perspective of weed control, herbicide use in winter wheat and barley are not very dissimilar and so this switch would not influence usage very much. Surprisingly, there is no clear trend of increased arable cropping. This may be because in the last 10 years the arable area has been reduced by the allocation of up to 10% of land to set-aside. The predominance of cereals in British arable cropping systems is clear. Over 70% of arable crops are cereals. Consequently, herbicide use on these crops will have by far the greatest effect on the environment, whether it be herbicide residues or impacts on non-target weeds.

6.3. Herbicide Use in 1998

The most recent published survey by the MAFF Pesticide Usage Survey group was that done in 1998 (Garthwaite & Thomas, 2000). It is unlikely that major changes will have occurred between 1998 and 2001, as there have been no substantial new introductions of herbicides in the last few years. Details of the main herbicides used in the four major crops are given in Table 6.2. Major herbicides are defined as those used on more than 10% of the area of the crop. Over 94% of all four crops were treated with herbicides. All treated crops were treated at least once and many were treated twice. On average, the wheat crops received 4.6 products, the spring barley and oilseed rape 2.5, and the beans 2.1. In most crops the multiple treatments were due to separate treatments to control grass and broad-leaved weeds. Additionally, in the winter wheat the treatments tended to be split into autumn and spring applications. As a result of these multiple treatments the sum of the % of areas treated for each crop is well in excess of 100% and in the case of wheat exceeds 250%.

Table 6.2 Main herbicides used winter wheat, spring barley, oilseed rape and field beans in 1998. (main = at least 10% of the treated area / crop)

Crop	Target weed groups	Herbicide	Area treated (ha x 1000)	Area treated as % area sown
Winter wheat	grasses	graminicides *	543	26
	grasses & blws+	isoproturon	1312	64
		isoproturon + diflufenican	862	42
		Triallate	216	11
		trifluralin mixes[x]	498	24
	blws	amidosulfuron	244	12
		mecoprop	505	25
		fluroxypyr	738	36
		metsulfuron +/- others	568	28
Spring barley	grasses	tralkoxydim	49	11
	blws	ioxynil + bromoxynil mixes	139	31
		mecoprop	165	36
		metsulfuron	271	60
Oilseed rape	grasses	graminicides**	332	66
	grasses and blws	propyzamide	107	21
		trifluralin	87	17
	blws	clopyralid +/- benazolin	58	11
		metazachlor	235	47
Field beans	grasses	graminicides**	37	33
	grasses & blws	simazine	88	79
	blws	bentazone	11	10

+ blws = broad-leaved weeds
* fenoxaprop and clodinafop
x trifluralin + clodinafop, isoproturon or diflufenican
** cycloxydim, fluazifop and propaquizafop

Winter wheat

Weed control in winter wheat can be divided in two interacting ways; autumn v spring treatment and grass v broad-leaved weeds. In general the grass weed control takes place in the autumn and winter with either a pre-emergence treatment or one applied early post-emergence. This may be linked to broad-leaved weed control if the primarily grass weed herbicide is broad-spectrum (e.g. isoproturon, pendimethalin, trifluralin) or is mixed with a broad-leaved weed herbicide (e.g. isoproturon + diflufenican). The spring treatment tends to be aimed at broad-leaved weeds, though sometimes additional grass weed herbicides may be needed (Table 6.2).

The increasing problems caused by herbicide resistant annual grass weeds (wild-oats, black-grass, ryegrasses) has resulted in a greater use of sequences of grass weed herbicides and partly accounts for the appreciable areas treated with trifluralin and triallate, which are used as precursors to isoproturon and/or clodinafop and fenoxaprop. The recent release (post 1998) of flupyrsulfuron has provided another product for these resistant weeds. As a consequence there may have been some changes in the proportions of crops receiving the different herbicide products for annual grass weeds, since 1998. However, the control of grass weeds is still dominated by isoproturon and its use continues to increase year on year, despite concerns about its appearance in ground waters. It is cheap!

In recent years the mixing of diflufenican with isoproturon has become increasingly common, as it gives a ‘one shot’ treatment for the control of almost all the main weeds, except cleavers, in winter cereals. The spring treatments are targeted at the broad-leaved weeds that have survived the autumn treatments. Cleavers is the main target, as can be seen by the extensive use of mecoprop, fluroxypyr and amidosulfuron. However, a lot of farmers will add a modest quantity of metsulfuron to their cleavers herbicide to ‘tidy up’ other surviving weeds. Again, metsulfuron is inexpensive and so is attractive to use.

Spring barley

Grass weed control is less of a problem in spring barley and so use of graminicides is much lower. Also wild-oats tend to be more of a problem then black-grass. As a consequence the most widely used treatment is tralkoxydim, but even this is only applied to 11% of crops (Table 6.2). Broad-leaved weeds are much more of a problem and substantial areas are treated with ioxynil + bromoxynil mixtures and with metsulfuron either alone or with other sulfonyl ureas. Cleavers is still a problem as can be seen by the 36% of crops treated with mecoprop. It is interesting that use of mecoprop has increased appreciably since the 1970’s suggesting that cleavers are an increasing problem (Table 6.3).

Oilseed rape

The data in the Usage Surveys do not differentiate between winter and spring sown crops and although the herbicide treatments are rather different, in most years only a minor percentage of the crop is sown in spring. So the data in Tables 6.2 and 6.4 are essentially relevant to the winter crop. As with winter wheat the treatments in rape can be split into those targeted at grass weeds and those at broad-leaved species. But, the growth habit of rape does not normally permit application in the spring, so most treatments are applied before the end of January and the great majority by the end of November. The graminicides are widely used for the control of volunteer cereals, black-grass and wild-oats (66% of area treated in 1998). The market is split between cycloxydim, fluazifop and propaquizafop. The alternative product propyzamide controls a wider spectrum of weeds and can be used against herbicide resistant grass weeds, but is more slow acting and tends to be less effective than the graminicides (on non-resistant weeds). The control of broad-leaved weeds is dominated by metazachlor but trifluralin is quite often used as a cheap alternative, with the added bonus that it also controls some grass weeds. Trifluralin is the main product used in spring rape. In the past benazolin + clopyralid has been quite widely used for broad-leaved weeds. It has the advantage of a longer application window but the disadvantage that is only controls a limited range of species. It was not widely used in 1998.

Field beans
The survey data do not always distinguish between winter and spring crops, though in recent years the majority of the crop is sown in autumn. The market is dominated by simazine, which was used on nearly 80% of crops for the control of both grasses and broad-leaved weeds Table 6.2). It is inexpensive and so is favoured in this low profitability crop. A minority of crops receives a graminicide for grass weeds and bentazone for broad-leaved species, but both, especially the latter, are expensive.

6.4. Principal Changes in Herbicide Use between 1974 and 1998

This section is based on the MAFF Pesticide Usage Surveys carried out in 1974, 1982, 1988, 1994 and 1998 (Chapman, Sly & Cutler, 1977; Sly, 1986; Davis, Garthwaite & Thomas, 1990; Garthwaite, Thomas & Hart, 1996; Garthwaite & Thomas, 2000). Some information from the 1960s is presented in an earlier review (Sly, 1977).

Even in 1974 virtually all winter wheat and spring barley crops were treated with herbicides as were most field bean crops (Tables 6.3, 6.4). Oilseed rape was not a major crop in 1974, as improved cultivars did not reach the market until the early 1980s. By 1982 most rape crops were receiving herbicides (Table 4). So any changes in floral biodiversity are not associated with an increasing proportion of treated crops, but with a change in the weed spectrum of the herbicides used. This point has been already made by others (Ewald & Aebischer, 2000). Up to now it has been rare for herbicide active ingredients to disappear from the market. They have generally continued to be marketed for niche purposes. Certainly, many products with specific combinations of herbicides have disappeared, but most of the basic active ingredients still remain. One exception has been the loss of TCA in rape. As a consequence, the number of herbicides available to farmers has increased greatly over the last 20 years. The recent acceleration in the pesticide review process being implemented by the EU is anticipated to result in the loss of many of these small area treatments by 2003, leaving growers with access only to the major products. This section highlights the main changes that have occurred in the four selected crops.

It should be noted that although the first year included in these comparisons is 1974, the perception of those writing the review was that the products used then reflected those that had been used for most of the 1960s, but with the grass weed herbicides playing a less important role (Sly, 1977). Most cereal crops in the 1960s received a combination of hormone herbicides (e.g. MCPA, dicamba).

Winter wheat
In 1974 grass weed problems were less severe than they are today and so most crops did not receive a grass specific herbicides, although some triallate and benzoylprop-ethyl were

used for the control of wild-oats, and chlorotoluron had just been introduced for black-grass. Overall 10-20% of the crop received a grass-weed herbicide. Most crops were treated for broad-leaved weeds, with the hormone herbicides, MCPA, dicamba, TBA and mecoprop, as had been the case in the 1960s.

By 1982 annual grass weeds were of greater significance and the substituted urea herbicides, chlorotoluron and isoproturon were widely used. Although used primarily for grass weeds these herbicides also controlled some broad-leaved weeds. The mixture of ioxynil and bromoxynil had taken away the markets of MCPA, TBA and dicamba because of its greater crop safety and wider application window. Mecoprop still continued to be used, primarily for cleavers.

In 1988 grass weed control was similar to that in 1982 but the advent of metsulfuron had increased the treatment of broad-leaved weeds in the spring. The widespread use of isoproturon in the autumn had resulted in increases in broad-leaved species not sensitive to these herbicides, typically speedwells and field pansy. These were sensitive to metsulfuron. Fluroxypyr, the first of the cleavers herbicides to compete with mecoprop was now being marketed.

By 1994 metsulfuron had slightly reduced the ioxynil/bromoxynil market and the hormone herbicides, with the exception of mecoprop, had virtually disappeared. The increasing problems with cleavers resulting from the substantial switch from spring barley to winter barley in the 1980s provided increased market for fluroxypyr and maintained that of mecoprop. Grass weeds were still causing problems as a result of the increased winter cropping and the area treated with isoproturon continued to rise alongside the first of the new ‘graminicides’ diclofop-methyl. Diflufenican mixtures with isoproturon were now available and 24% of crops received this broad-spectrum mixture.

The situation in 1998 mirrored that of 1994. Isoproturon and the graminicides (now fenoxaprop and clodinafop) dominated grass weed control, but rising problems with herbicide resistance caused increases in the area treated with triallate and trifluralin. For the broad-leaved weeds the application of diflufenican had increased, apparently at the expense of mecoprop and metsulfuron. Fluroxypyr, with its late application window, had retained its share of the market for the control of cleavers.

This scenario is substantially the same for winter barley, although the range of grass weed herbicides is slightly more restricted due to greater crop sensitivity to some products.

Spring barley

Grass weeds, with the exception of wild-oats, are less significant in this crop and this is reflected in the herbicide treatments applied. No grass weed herbicides were used on appreciable areas of spring barley until 1998 when tralkoxydim was recorded as being used on 11% of the area. Limited amounts of triallate, barban and benzoylprop-ethyl were used in the 1970s and 1980s, succeeded by difenzoquat and flamprop-methyl in the 1980s and 1990s.

Broad-leaved weeds are more of a problem in spring barley than in winter wheat and some species are different. In 1974 most crops received a hormone herbicide, either MCPA, dicamba mixtures or mecoprop. By 1982 ioxynil/bromoxynil mixtures had taken over from the hormones, with the exception of mecoprop. Metsulfuron was widely used in 1988 but most crops were still treated with ioxynil/bromoxynil. Metsulfuron became the dominant broad-leaved weed herbicide in the 1990s, reducing the ioxynil/bromoxynil market. A modest amount of MCPA is still used.

Oilseed rape

The number of herbicides available for oilseed rape is quite limited, so the opportunities for changing products have not been great. There have bee two main changes between 1982 and 1998. Firstly, grass weed and volunteer cereal control was initially dominated by TCA. This was replaced by the more effective graminicides in 1988. Propyzamide has always been used for general grass and broad-leaved weed control, but its popularity declined once the graminicides became established. It is now having a limited resurgence as a tool for the management of herbicide resistant black-grass and wild-oats. The second change has been the increased use of metazachlor for the control of broad-leaved weeds. A certain amount of clopyralid +/- benazolin has been used in rape since 1982, but its limited weed spectrum made it less popular than the wider spectrum metazachlor, despite the latter's more restricted application window. Trifluralin is the main broad-leaved weed herbicide used in spring rape.

Field beans

Changes in herbicide use in field beans have been limited. The standard treatment since 1974 has been simazine. A minority of crops since 1988 has been treated with a graminicide for the control of volunteer cereals and grass weeds. A few crops receive bentazone to control broad-leaved weeds (e.g. volunteer rape), but it is expensive and the profitability of the crop rarely justifies such treatment.

Table 6.3 Changes in the areas treated of the major herbicides in winter wheat and spring barley between 1974 and 1998

Crop	Target weed groups	Herbicide	1974 GB†		1982 E&W		1988 E&W		1994 GB		1998 GB	
			ha x 1000	% of area	ha x 1000	% of area	ha x 1000	% of area	ha x 1000	% of area	ha x 1000	% of area
Winter wheat	Grasses	benzoylprop-ethyl	147	13								
		graminicides *							618 diclofop	34	543 fenox/clod	26
	grasses & blws	chlorotoluron	90	8	430	27	174	10	30	2		
		isoproturon			454	28	807	45	1029	57	1312	64
		isoproturon + diflufenican							425	24	862	42
		triallate	126	11	98	6	36	2	58	3	216	11
		trifluralin mixes[x]			145	9	56	3	45	3	498	24
	Blws	dicamba mixes	211	18	82	5	10	1	5	0	42	2
		fluroxypyr					229	13	611	34	738	36
		ioxynil+ bromoxynil mixes			581	36	537	30	374	21	154	8
		MCPA	262	22	195	12	116	7	65	4	48	2
		mecoprop	401	34	738	46	795	45	642	36	505	25
		metsulfuron +/-					342	19	663	37	568	28
		2,3,6 TBA mixes	127	11	6	<1						
Spring barley	Grasses	tralkoxydim									49	11
	blws	dicamba mixes	427	22	82	9	28	4	33	7	29	6
		ioxynil + bromoxynil mixes	185	10	312	35	413	62	121	26	139	31
		mecoprop	251	13	174	20	191	29	176	39	165	36
		MCPA	681	35	153	17	111	17	71	16	41	9
		metsulfuron					162	24	244	54	271	60

* diclofop, fenoxaprop and clodinafop   x trifluralin + clodinafop, isoproturon or diflufenican

[shaded box] treatments in excess of 20% of the treated area   † GB = data from England Wales and Scotland, E&W = England and Wales only

Table 6.4 Changes in the areas treated of the major herbicides in oilseed rape and field beans between 1974 and 1998

Crop	Target weed groups	Herbicide	1974 GB†		1982 E&W		1988[+] E&W		1994 GB		1998 GB	
			ha x 1000	% of area	ha x 1000	% of area	ha x 1000	% of area	ha x 1000	% of area	ha x 1000	% of area
Oilseed rape	Grasses	dalapon			16	9						
		graminicides**			2	1	171	56	169	42	332	66
		TCA			133	77						
	Grasses and blws	propyzamide			111	64	146	48	76	19	107	21
		trifluralin					5	2	45	11	87	17
	Blws	clopyralid +/- benazolin			45	26	78	26	28	7	58	11
		metazachlor					46	15	101	25	235	47
Field beans	Grasses	graminicides**					31	22	40	27	37	33
	Grasses & blws	simazine	47	71	25	62	87	63	90	60	88	79
	Blws	bentazone					14	10	22	15	11	10

\+ 1988 data on beans not available so 1990 used instead

** cycloxydim, fluazifop and propaquizafop

[shaded] treatments in excess of 20% of the treated area

† GB = data from England Wales and Scotland, E&W = England and Wales only

6.5. Changes in Weed Susceptibility to Herbicides between 1974 and 1998

In this section the changes in herbicide use have been linked to the changes in weed susceptibility. This is based on the published information on product labels and some other sources of information, such as Flint (1987) and older versions of the Weed Control Handbook, Volume 2: Recommendations (Fryer & Evans, 1968). Consequently, it is probably not exhaustive, as current labels do not always include all weeds susceptible to a particular herbicide. Therefore the numbers of susceptible species with modern herbicide presented in Tables ... may be an under-estimation. Also more information is available on moderately susceptible species (MS) for the earlier hormone herbicides MCPA and mecoprop. This category is not used very frequently with the newer products. Additionally, the older hormone herbicides (e.g. MCPA, mecoprop) were used in both cereal crops and grassland and so the information on weed sensitivities include grassland weeds, as well as weeds of arable crops. In the subsequent tables (and the appendices) weeds that tend to occur only in grassland have been deleted.

<u>Winter wheat</u>
As can be seen from the tables of changes in herbicide use (Tables 6.3 & 6.4), the greatest changes have occurred in winter wheat, the largest area crop. In the overall list for wheat (Appendix 1) 29 weed species of the total of 101 (89 broad-leaved species, 12 grasses and *Equisetum*) were sensitive to mecoprop and 25 to MCPA (Table 6.5). The introduction of ioxynil + bromoxynil in the 1980s, especially when mixed with mecoprop, as frequently occurred, raises this to 33 species. The arrival of metsulfuron and isoproturon + diflufenican in the 1990s did not seem to cause much change, as 31 and 35 species were susceptible. The widespread use of chlorotoluron and isoproturon did not impact on very many species, as the weed spectrum of these two products is much narrower. Similarly the use of graminicides has no impact on the broad-leaved weeds that are the majority of the species included. If the comparisons are restricted to broad-leaved species only, the number of species controlled by the hormone herbicides, ioxynil + bromoxynil and metsulfuron do not differ from the total weed number, as these products only control broad-leaved species. For the isoproturon and isoproturon + diflufenican the number of sensitive species declines to 14 and 28 species, respectively. So one must conclude that the selection pressure on the weed flora as a whole appears not to have increased markedly from the 1960/70s. This apparent absence of change does hide a switch in species sensitivity in the 1970s when the hormone herbicides were weak for example on *Veronica* spp., *Lamium* spp. and weeds in the Polygonaceae and the newer products do not apparently control some of the Cruciferae. However, this apparent lack of activity on the Cruciferae may be simply due to lack of data rather than actual insensitivity, as *Sinapis arvensis* and *C. bursa pastoris* are sensitive to both metsulfuron and diflufenican. Additionally, weed susceptibility data for the older products tends to be more broadly-based including species that are more common in grassland/arable systems (e.g. *Ranunculus* spp., *Bellis perennis*) than in those devoted purely to arable crops. Consequently, there may have been a slight increase in the number of purely arable species sensitive to the modern herbicides.

If the same comparisons are done using the 32 main arable species selected for this project the picture is somewhat different. A total of only 6 species are sensitive to mecoprop and 9 are reported as being sensitive to MCPA (Table 6.5, Appendix 2). Between 17 and 19 broad-leaved species are sensitive to ioxynil + bromoxynil + mecoprop, diflufenican + isoproturon and metsulfuron. Thus, the introduction of ioxynil + bromoxynil + mecoprop in the 1980s appears to have widened the weed control spectrum. This 'width' has been maintained with the newer products, metsulfuron and diflufenican. The reason for the discrepancy between the full list for wheat, which shows only a small change in species susceptibility over the last 40 years, and the 32 species project list, may lie in the fact that the project list contains many fewer species that occur in mixed arable/grassland systems. It also suggests that development programmes for new herbicide were targeted to bring forward products that could control the species that were common in the major arable crop producing areas, where the main markets were.

Table 6.5 Number of weed species susceptible to the main herbicides in winter wheat

Herbicide	Years*	Total number of susceptible species		Species in project list	
		Total spp.	Broad-leaved spp.	Total spp	Broad-leaved spp.
MCPA	1974	29	29	6	6
Mecoprop	1974-1998	25	25	9	9
ioxynil+bromoxynil	1982-1994	25	25	16	16
ioxynil+bromoxynil+mecoprop	1982-1994	34	34	19	19
Chlorotoluron	1982	19	11	13	9
Isoproturon	1982-1998	18	14	13	10
isoproturon + diflufenican	1994-1998	35	28	20	17
Metsulfuron	1988-1998	31	31	19	19
Fluroxypyr	1994-1998	10	10	8	8
fenoxaprop or clodinafop	1994-1998	6	0	2	0

* Years when herbicide was a major component of total herbicide use

Table 6.6 Number of weed species susceptible to the main herbicides in spring barley

Herbicide	Years*	Total number of susceptible species		Species in project list	
		Total spp.	Broad-leaved spp.	Total spp	Broad-leaved spp.
MCPA	1974	24	24	6	6
dicamba + MCPA +mecoprop	1974	21	21	10	10
ioxynil+bromoxynil	1982-1998	25	25	17	17
ioxynil+bromoxynil+mecoprop	1982-1998	33	33	19	19
Metsulfuron	1988-1998	31	31	19	19

* Years when herbicide was a major component of total herbicide use

Spring barley

The picture for spring barley is much the same as with winter wheat (Table 6.6). However, the increase in weed species sensitive to ioxynil+bromoxynil+mecoprop and metsulfuron, compared to MCPA alone and in combination with the other hormone herbicides, is slightly clearer. There is an increase of approximately 10 species in both the full and project lists (Appendix 3,4).

Field beans

There has been little change in herbicide use in field beans. Simazine has been the main broad-spectrum herbicide since the 1970s. The introduction of graminicides in the 1980s increased the number of sensitive grass weeds, but had no effect on the more critical broad-leaved species (Appendix 5,6)

Oilseed rape

The original herbicides used for weed control in rape were TCA and propyzamide. Since 1982 the replacement of TCA with the graminicides has not greatly changed the grass weed spectrum. Further propyzamide also control a number of grass weeds. This herbicide only controls a limited number of broad-leaved species and so its partial replacement with metazachlor has increased the number of sensitive broad-leaved species from 8 to 16 (Appendix 7). However the other broad-leaved weed products, clopyralid +/- benazolin have been used quite widely from 1982 and these products also control 12-14 species. So the increased selection pressure arising from herbicide changes has not been great. The effects on the selected species included in this project is less than for the total number of species (Appendix 8).

Conclusion

The changes in herbicide use have resulted in an increase in the number of broad-leaved species that are being controlled. This is mainly apparent for the most prominent UK crop, winter wheat, but is also evident for spring barley. The changes in herbicide use in the two broad-leaved crops have had little or no effect on species' susceptibility, but these are used on a much smaller area than the cereal crops. The main differences in the cereal crops are increased sensitivity of *Veronica* spp., *Lamium* spp. and weeds in the Polygonaceae. This increased sensitivity started with the introduction of ioxynil + bromoxynil in the early 1980s and was continued when metsulfuron and diflufenican were introduced at the end of the 1980s. Thus the greater selection against a wider range of weeds has been in place since the 1980s and is not a new phenomenon.

These conclusions are based solely on the weeds included on the herbicide labels. This is not necessarily exhaustive, especially with more modern products. More intensive investigation of field experiences could widen the list, but this is not feasible in the time-scale of this project. The herbicide data base to be included in the project developing a Weed Management Support System for winter wheat will include more information on weed susceptibility, than is currently available in published literature. This will become available in 2002-3 and will provide a more all embracing data base of sensitivities than is available at the moment.

Table 6.7 Timing of use of the major herbicides in winter wheat

Herbicide	Years*	Application window (growth stage)*	Normal application timing
MCPA	1974	30-31	March-April
Mecoprop	1974-1998	13-21, 30-31	Mainly March-April
Ioxynil+bromoxynil	1982-1994	12-32	Mainly March-April
Ioxynil+bromoxynil +mecoprop	1982-1994	13-31	Mainly March-April
Chlorotoluron	1982	Mainly pre-em	Sept-Nov
Isoproturon	1982-1998	Pre- or post-em, up to 31	Oct-April (mainly Oct-Dec)
Isoproturon + diflufenican	1994-1998	Pre- or post-em up to 32	Mainly Oct-Jan
Metsulfuron	1988-1998	12-39 (Jan. onwards)	Feb-April
Fluroxypyr	1994-1998	12-45	Mar-May
Fenoxaprop or clodinafop	1994-1998	11-39	Oct-Mar

* Zadoks growth stage

6.6. Impact of Changes in Timing of Control of Weeds on Weed Species Diversity

Change in susceptibility of weeds associated with changes in herbicide use provides only part of the picture of the impact of weed management on the weed flora of arable fields. Autumn weed control, especially with persistent soil acting products, will obviously have a much greater impact on weeds than will a late spring treatment, where the weeds could be present for an extra four months prior to treatment. Change in the timing of control is not an issue for spring barley, winter rape and winter field beans, as all treatments in the former must be in spring-summer and in the latter two crops has always been concentrated in the autumn. However, the application of herbicides in winter wheat (and winter barley) could start in September/October, with pre planting treatments and continue to the following May. How has the timing of the major herbicides used in winter wheat changed since 1974?

It is clear from Table 6.7 and from the tables included in the 1982 Pesticide Usage Survey (Sly, 1986) that few winter cereal crops in the 1970s (and in the 1960s) were treated in the autumn and most products were applied in April and May. This was mainly because the predominant hormone herbicides (e.g. dicamba, MCPA) had a very narrow window of application: restricted to application at GS30, and crops were planted later in the autumn than is the custom now. The increasing prevalence of annual grasses led to a substantial move to autumn applications in the 1980s with chlorotoluron and isoproturon, as these are most effective pre- weed emergence or when the weeds are small. These two products controlled some broad-leaved weeds but not all (Table 6.5). So although grass weeds were being controlled in the autumn many broad-leaved species were not. Because of this ‘gap’ in the weed spectrum some farmers tank mixed their isoproturon with other herbicides such as ioxynil+bromoxynil, to widen the spectrum and provide a ‘one shot’ treatment for all the main weeds. This practice was not universally adopted because the timing of the isoproturon was not always appropriate for the other products, and it failed to control spring emerging plants. So in many crops broad-leaved weeds not controlled by isoproturon were left until the spring when they received either ioxynil+bromoxynil +/- mecoprop or, at the end of the 1980s, metsulfuron +/- mecoprop. These products were applied in March – April, controlling over-wintered weeds and those newly emerged in spring. Thus, some broad-leaved weeds remained over the winter period.

The introduction of diflufenican in the late 1980s provided another tool for the ‘one shot’ autumn control of weeds, as this product, which has residual activity through the soil, when mixed with isoproturon, provided control of most common weed species, except cleavers. Thus, a common programme in the 1990s has been isoproturon + diflufenican in autumn, followed by mecoprop or fluroxypyr in the spring to control cleavers. A further refinement of this ‘recipe’ has been the addition of metsulfuron to the mecoprop or fluroxypyr, to ‘tidy up’ any residual spring weeds not sensitive to the product aimed at the cleavers. The metsulfuron is inexpensive! A further relevant aspect has been the increase in herbicide resistant grass weeds in the 1990s. The favoured programmes now used often start with pre-emergence or pre-planting applications of triallate and trifluralin both of which also control some broad-leaved weeds, as well as the target grasses.

Thus, over the last 30 years weed control in winter cereals has moved from being a predominantly spring activity, to one split between controlling grass weeds in the autumn and broad-leaved weeds in the spring, to the current situation when grass and broad-leaved species are treated in autumn and broad-leaved species are treated again in spring.

6.7. Effects of Fertilisers on Weed Communities

Whilst changes to winter cropping and concomitant herbicide use are likely to have had major impacts on weed communities, other factors will also have an influence. In other habitats, eutrophication is a major influence on community structure and biodiversity (Marrs, 1993). The relationship between increasing fertility, productivity and species richness is typified by the "hump-back" model, in which diversity rises to an asymptote and then declines. There is increasing evidence that addition of fertilisers, most notably nitrogen, in agroecosystems has a major influence on plant species composition. The Classic Experiments at Rothamsted in both grassland and cereals demonstrate profound effects on flora. The Broad Baulk experiment includes plots that have never received herbicides and plots that have remained unfertilised for over 130 years.

6.8. Overall Conclusions

Intensity of herbicide use has increased over the last 30-40 years. This has resulted in the control of a wider range of weed species. This has not necessarily been the user's intention, as most treatments are selected because of their performance against the major weeds such as black-grass and cleavers. However, other species have been controlled because of the wide selectivity of the products used particularly on broad-leaved weeds. There has also been a move away from controlling weeds in spring to controlling them in the autumn and again in the spring (see above). A further factor in the development of new herbicides has been the desire of the companies to market herbicides that control a wide range of species. This attribute has given products a marketing advantage over competitors. This applies particularly to broad-leaved weeds. The success of metsulfuron and diflufenican in current crops and of ioxynil+bromoxynil+mecoprop in the 1980s can be at least partly due to this attribute. At the moment there is little incentive for companies to market products that control only a limited range of broad-leaved species. It is easier for those making weed control decisions to choose a product that will cover most eventualities, than to have to pick and choose different products for each field.

The analyses of herbicide use indicate that the major change in the number of weed species controlled in the most important UK arable crop, winter wheat, occurred in the late 1970s, associated with the introduction of ioxynil + bromoxynil. Subsequent changes mainly relate to the timing of control, not the numbers of species controlled. Interestingly this change in herbicide use coincides quite closely with the perceived onset of the period of greatest decline in farmland birds (Chamberlain et al., 2000). However, one must be cautious about attributing causal relationships, as other farming practices were also changing over this period.

If it is assumed that the herbicide use achieves its desired aim of removing weeds, as a competitive component of the plant biomass present in fields, the conclusion must be that there are likely to be fewer weeds present in fields over the autumn/winter than there were. This should be treated with a little caution, because environmental and other factors can result in sub-optimal performance from the herbicide treatments. Crops still have weeds (wild plants) in them despite 30 years of intensive herbicide use! However, the consequence of the increased intensitivity of herbicide practice is that if control is likely to be sub-optimal, it will result in the survival of the aggressive and most well-adapted species (e.g. wild oats, black-grass, cleavers) and not those with greater biodiversity value (see sections 7, 8).

A further aspect of the timing of weed control on weed levels relates to the massive switch away from spring barley to autumn sown cereals in the 1980s. This too has the effect of reducing the availability of weeds for wildlife. Cereal stubbles were left uncultivated for longer periods in the autumn, when the next crop was spring barley, thus increasing the availability of seeds and plants for invertebrates and birds. Also research in Denmark (Hald, 1999) has clearly demonstrated increased plant and species density in spring cereals, compared with winter cereals. This work also showed that those species that were of benefit as food sources for invertebrates were commoner in the spring crops.

Any decline in weed numbers in fields can be attributed not only to changes in herbicide use, but also to changes in cropping patterns.

Appendix 1 Weed susceptibility to the main herbicides in winter wheat 1974-1998

Key: S = susceptible (1) MS = moderately susceptible (2)

MR = moderately resistant (3) R = resistant (4)

Common name	Latin name	Mecoprop		MCPA		Chloro-toluron		Iso-proturon		Met-sulfuron		isoproturon + diflufenican		Ioxynil+ bromoxynil		Fluroxypyr		Gramin-icides		Iox+bromox+ mecoprop	
Beans, volunteer	*Vicia faba*																			S	1
Bindweed, field	*Convolvulus arvensis*	R	4	MR	3																
Bindweed, hedge	*Calystegia sepium*	MR	3	MS	2																
Bird's-foot-trefoil	*Lotus corniculatus*	MS	2	MR	3																
Black bindweed	*Fallopia convolvulus*	MR	3	MR	3	S	1			MS	2			S	1	S	1			S	1
Bugloss	*Anchusa arvensis*	MR	3	MR	3									S	1	R	4				
Buttercup, corn	*Ranunculus arvensis*	S	1	S	1																
Buttercup, creeping	*Ranunculus repens*	S	1	S	1							S	1								
Cabbage, wild	*Brassica oleracea*			S	1																
Carrot, wild	*Daucus carota subsp. carota*	MR	3	MR	3																
Cat's-ear	*Hypochoeris radicata*	MS	2	MS	2																
Chamomile, corn	*Anthemis arvensis*	MR	3	MR	3																
Chamomile, stinking	*Anthemis cotula*	R	4	R	4																
Charlock	*Sinapis arvensis*	S	1	S	1	S	1	S	1	S	1	S	1	S	1	R	4			S	1
Chickweed, common	*Stellaria media*	S	1	MR	3	S	1	S	1	S	1	S	1	S	1	S	1			S	1
Chickweed, mouse-eared	*Cerastium fontanum*	S	1	MR	3							S	1							S	1
Cleavers	*Galium aparine*	S	1	R	4	R	4	R	4	R	4	S ?	1	MR	3	S	1			S	1
Clover	*Trifolium spp*																			S	1
Cornflower	*Centaurea cyanus*	S	1	S	1																
Crane's-bill, cut-leaved	*Geranium dissectum*	MR	3	MR	3			R	4												
Crane's-bill, dove's-foot	*Geraniujm molle*	S	1	MR	3			R	4	S	1										
Cress, hoary	*Cardaria draba*			MS	2																
Daisy	*Bellis perennis*	S	1	MS	2															S	1
Daisy, oxeye	*Leucanthemum vulgare*			MS	2																
Dandelion	*Taraxacum officinale*	MR	3	MR	3															S	1
Dead-nettle, henbit	*Lamium amplexicaule*	R	4	MR	3							S	1			S	1			S	1
Dead-nettle, red	*Lamium purpureum*	R	4	MR	3					S	1	S	1	S	1	S	1			S	1
Dock, broad-leaved	*Rumex obtusifolius*	S	1	MR	3					S	1									MS	2
Dock, curled	*Rumex crispus*	S	1	MS	2															MS	2
Fat-hen	*Chenopodium album*	S	1	S	1	S	1	S	1	S	1			S	1					S	1
Fiddleneck	*Amsinckia lycopsoides*													S	1						
Forget-me-not, field	*Myosotis arvensis*	R	1	MS	2					S	1	S	1	S	1	S	1			S	1
Fumitory, common	*Fumaria officinalis*	S	1	MS	2					MR	3	S	1	S	1	S?	1			S	1
Gromwell, field	*Lithospermum arvense*	MR	3	MS	2			R	4												
Groundsel	*Senecio vulgaris*	MS	2	MS	2			S	1					S	1	MR	3			S	1

Appendix 1 continued: Weed susceptibility to the main herbicides in winter wheat 1974-1998

Common name	Latin name	Mecoprop		MCPA		Chloro-toluron		Iso-proturon		Met-sulfuron		isoproturon + diflufenican		Ioxynil+ bromoxynil		Fluroxypyr		Gramin-icides		Iox+bromox+ mecoprop	
Hawkbit, autumn	*Leontodon autumnalis*	MS	2	MS	2																
Hawkweed, mouse-ear	*Hieracium pilosella*			MS	2																
Hemlock	*Conium maculatum*			MR	3																
Hemp-nettle, common	*Galeopsis tetrahit*	MS	2	S	1			S	1	S	1	S	1	R	4	S	1			MR?	3
Knotgrass	*Polygonum aviculare*	MR	3	MR	3	S	1			S	1	S	1	S	1	S?	1			S	1
Marigold, corn	*Chrysanthemum segatum*	R	4	R	4	S	1	S	1	S	1			MR	3	R	4			S	1
Mayweed, scented	*Matricaria recutita*	R	4	R	4	S	1	S	1	S	1	S	1	S	1	MR	3			S	1
Mayweed, scentless	*Tripleurospermum inodorum*	MS	2	MR	3	S	1	S	1	S	1	S	1	S	1	MR	3			S	1
Mint, corn	*Mentha arvensis*	R	4	MR	3																
Mustard, black	*Brassica nigra*	S	1	S	1																
Mustard, treacle	*Erysimum cheiranthoides*	S	1	S	1																
Mustard, white	*Sinapis alba*	S	1	S	1																
Nettle, common	*Urtica dioica*	S	1	MS	2																
Nettle, small	*Urtica urens*	S	1	S	1			S	1	S	1	S	1	S	1	S	1			S	1
Nightshade, black	*Solanum nigrum*	MS	2	MS	2																
Nipplewort	*Lapsana communis*	R	4	R	4					S	1	S	1								
Oilseed rape (volunteer)	*Brassica napus*	S	1	S	1					S	1	S	1			R	4			S	1
Orache, common	*Atriplex patula*	S	1	S	1					S	1										
Pansy, field	*Viola arvensis*	R	4	MR	3			R	4	S	1	S	1	R	4					MS	2
Parsley, cow	*Anthriscus sylvestris*	MR	3	MR	3																
Parsley, fool's	*Aethusa cynapium*	MR	3	MS	2					S	1									S	1
Parsley-piert	*Aphanes arvensis*	R	4	R	4	S	1	S	1	S	1	S	1							S	1
Penny-cress, field	*Thlaspi arvense*	S	1	S	1									S	1	R	4				
Pepperwort, field	*Lepidium campestre*			MR ?	3																
Persicaria, pale	*Persicaria lapathifolia*	MR	3	MR	3					S	1			S	1	MR	3			S	1
Pimpernel, scarlet	*Anagalis arvensis*			MS	2					S	1			S	1	R	4			S	1
Pineappleweed	*Matricaria matricarioides*	R	4	R	4					S	1										
Plantain, greater	*Plantago major*	S	1	S	1															S	1
Plantain, ribwort	*Plantago lanceolata*	S	1	S	1															S	1
Poppy, common	*Papaver rhoeas*	MS	2	S	1	S	1	S	1	S	1	S	1	S	1	R	4			S	1
Radish, wild	*Raphanus raphanistrum*	S	1	S	1							S	1	S	1	R	4			S	1
Ragwort, common	*Senecio jacobaea*			MS	2					S	1	S	1	S	1	MR	3				
Redshank	*Persicaria maculosa*	MR	3	MR	3															S	1
Shepherd's-needle	*Scandix pecten-veneris*	MR	3	MS	2																

Appendix 1 continued: Weed susceptibility to the main herbicides in winter wheat 1974-1998

Common name	Latin name	Mecoprop		MCPA		Chloro-toluron		Iso-proturon		Met-sulfuron		isoproturon + diflufenican		Ioxynil+ bromoxynil		Fluroxypyr		Gramin-icides		Iox+bromox+ mecoprop	
Shepherd's-purse	*Capsella bursa-pastoris*	S	1	S	1	S	1	S	1	S	1	S	1	S	1	R	4			S	1
Soldier, gallant	*Galinsoga parviflora*	S	1	S	1																
Sorrel, common	*Rumex acetosa*	R	4	MR	3																
Sorrel, sheep's	*Rumex acetosella*			MR	3																
Sow-thistle, perennial	*Sonchus arvensis*	MR	3	MR	3					S	1										
Sow-thistle, prickly	*Sonchus asper*	MS	2	S	1																
Sow-thistle, smooth	*Sonchus oleraceus*	MS	2	S	1							S	1	S	1						
Speedwell, common, field	*Veronica persica*	MR	3	MR	3	R	4	R	4	S	1	S	1	S	1	MR	3			S	1
Speedwell, green field	*Veronica agrestis*											S	1								
Speedwell, ivy-leaved	*Veronica hederifolia*	MR	3	MS	2	R	4	R	4	MR	3	S	1	S	1	MR	3			S	1
Speedwell, wall	*Veronica arvensis*									MR	3			S	1	MR	3				
Spurrey, corn	*Spergula arvensis*	MR	3	MR	3			S	1	S	1	S	1								
Sugar beet, volunteer	*Brassica rapa*							S	1	S	1										
Sun spurge	*Euphorbia helioscopia*									S	1										
Thistle, cotton	*Onopordum acanthium*			S	1																
Thistle, creeping	*Cirsium arvense*	S	1	MS	3															MR ?	3
Thistle, spear	*Cirsium vulgare*	MS	2	S	1															MR ?	3
Turnip, wild	*Brassica rapa*	S	1	S	1																
Venus's looking glass	*Legousia hybrida*									S	1	S	1								
Vetch, common	*Vicia sativa subsp. sativa*	S	1	MS	2																
Horse-tail, field	*Equisetum arvense*	MR	3	MS	2																
Blackgrass	*Alopecurus myosuroides*					S	1	S	1			S	1					S	1		
Brome, barren	*Anisantha sterilis*					S	1	S	1												
Canary grass, awned	*Phalaris paradoxa*																	S	1		
Meadow grass, annual	*Poa annua*					S	1	MS ?	2			S	1					S?	1		
Meadow grass, rough	*Poa trivialis*					S	1	MS ?	2			S	1					S?	1		
Rush, soft	*Juncus effusus*	MR	3	MS	2																
Rye-grass, italian	*Lolium multiflorum*					S	1	MS ?	2			S	1					MS?	2		
Rye-grass, perennial	*Lolium perenne*					S	1	MS ?	2			S	1								
Silky-bent, loose	*Apera spica-venti*					S	1	MS ?	2			S	1					S	1		
Timothy	*Phleum pratense*							S	1									S	1		
Wild-oat	*Avena fatua*					S	1	S	1			S ?	1					S	1		
Yorkshire-fog	*Holcus lanatus*							MS ?	2												
	Total susceptible species	34		25		19		18		31		35		25		10		10		33	

Appendix 2 Weed susceptibility to the main herbicides in winter wheat: project selected species

Key: S = susceptible (1) MS = moderately susceptible (2)
MR = moderately resistant (3) R = resistant (4)

Common name	Latin name	Mecoprop		MCPA		Chloro-toluron		Isoproturon		Metsulfuron		isoproturon + diflufenican		Ioxynil+ bromoxynil		Fluroxypyr		Graminicides		Iox+bromox+ mecoprop	
Bindweed black	*Fallopia convolvulus*	MR	3	MR	3	S	1			MS	2			S	1	S	1			S	1
Charlock	*Sinapis arvensis*	S	1	S	1	S	1	S	1	S	1	S	1	S	1	R	4			S	1
Chickweed, common	*Stellaria media*	S	1	MR	3	S	1	S	1	S	1	S	1	S	1	S	1	S	1	S	1
Chickweed, mouse-eared	*Cerastium fontanum*	S	1	MR	3							S	1							S	1
Cleavers	*Galium aparine*	S	1	R	4	R	4	R	4	R	4	S?	1	MR	3	S	1			S	1
Corn spurrey	*Spergula arvensis*	MR	3	MR	3			S	1	S	1	S	1								
Crane's-bill, cut-leaved	*Geranium dissectum*	MR	3	MR	3			R	4												
Dead-nettle, red	*Lamium purpureum*	R	4	MR	3					S	1	S	1	S	1	S	1			S	1
Dock, broad-leaved	*Rumex obtusifolius*	S	1	MR	3					S	1									MS	2
Fat-hen	*Chenopodium album*	S	1	S	1	S	1	S	1	S	1			S	1	R	4			S	1
Fool's parsley	*Aethusa cynapium*	MR	3	MS	2					S	1									S	1
Forget-me-not, field	*Myosotis arvensis*	R	1	MS	2					S	1	S	1	S	1	S	1			S	1
Fumitory, common	*Fumaria officinalis*	S	1	MS	2					MR	3	S	1	S	1	S?	1			S	1
Groundsel	*Senecio vulgaris*	MS	2	MS	2			S	1					S	1	MR	3			S	1
Hemp-nettle, common	*Galeopsis tetrahit*	MS	2	S	1			S	1	S	1	S	1	R	4	S	1			MS	2
Knotgrass	*Polygonum aviculare*	MR	3	MR	3	S	1			S	1	S	1	S	1	S?	1			S	1
Mayweed, scented	*Matricaria recutita*	R	4	R	4	S	1	S	1	S	1	S	1	S	1	MR	3	S	1	S	1
Mayweed, scentless	*Tripleurospermum inodorum*	MS	2	MR	3	S	1	S	1	S	1	S	1	S	1	MR	3	S	1	S	1
Nightshade black	*Solanum nigrum*	MS	2	MS	2																
Pansy, field	*Viola arvensis*	R	4	MR	3			R	4	S	1	S	1	R	4					MS	2
Pimpernel, scarlet	*Anagalis arvensis*			MS	2					S	1			S	1	R	4			S	1
Poppy, common	*Papaver rhoeas*	MS	2	S	1	S	1	S	1	S	1	S	1	S	1	R	4			S	1
Redshank	*Persicaria maculosa*	MR	3	MR	3					S	1	S	1	S	1	MR	3			S	1
Shepherd's-purse	*Capsella bursa-pastoris*	S	1	S	1	S	1	S	1	S	1	S	1	S	1	R	4			S	1
Sow-thistle, smooth	*Sonchus oleraceus*	MS	2	S	1																
Speedwell, common, field	*Veronica persica*	MR	3	MR	3	R	4	R	4	S	1	S	1	S		MR	4			S	1
Sun spurge	*Euphorbia helioscopia*									S	1										
Thistle, creeping	*Cirsium arvense*	S	1	MS	3															MS	2
Annual meadow grass	*Poa annua*					S	1	MS ?	2			S	1					S	1		
Blackgrass	*Alopecurus myosuroides*					S	1	S	1			S	1					S	1		
Brome, barren	*Anisantha sterilis*					S	1	S	1												
Wild-oat	*Avena fatua*					S	1	S	1			S?	1					S	1		
	Total susceptible species	9		6		13		13		19		20		16		8		6		19	

Appendix 3 Weed susceptibility to the main herbicides in spring barley 1974-1998

Key: S = susceptible (1) MS = moderately susceptible (2)
MR = moderately resistant (3) R = resistant (4)

Common name	Latin name	Dicamba+MCPA+ mecoprop		MCPA		Metsulfuron		Ioxynil + bromoxynil		Iox+bromox+ mecoprop	
Alkanet	*Anchusa officinalis*					MS	2				
Beans, volunteer	*Vicia faba*									S	1
Bindweed, black	*Fallopia convolvulus*	S	1	MR	3	MS	2	S	1	S	1
Bindweed, field	*Convolvulus arvensis*	MS	2	MR	3						
Bindweed, hedge	*Calystegia sepium*			MS	2						
Bird's-foot-trefoil, common	*Lotus corniculatus*			MR	3						
Bugloss	*Anchusa arvensis*			MR	3			S	1		
Bugloss, vipers	*Echium vulgare*			MR	3						
Burdock, spp	*Arctium spp*			MS	2						
Buttercup, bulbous	*Ranunculus bulbosus*	MS	2	MR	3						
Buttercup, corn	*Ranunculus arvensis*	S	1	S	1						
Buttercup, creeping	*Ranunculus repens*	S	1	S	1						
Buttercup, meadow	*Ranunculus acris*			MS	2						
Cabbage, wild	*Brassica oleracea*			S	1						
Carrot, wild	*Daucus carota*	MR	3	MR	3						
Cat's-ear	*Hypochoeris radicata*			MS	2						
Chamomile, corn	*Anthemis arvensis*			MR	3						
Chamomile, stinking	*Anthemis cotula*	R	4	R	4						
Charlock	*Sinapis arvensis*	S	1	S	1	S	1	S	1	S	1
Chickweed, common	*Stellaria media*	S	1	MR	3	S	1	S	1	S	1
Chickweed, mouse-eared, common	*Cerastium fontanum*			MR	3					S	1
Cleavers	*Galium aparine*	S	1	R	4	R	4	MR	3	S	1
Clover	*Trifolium spp*									S	1
Colt's-foot	*Tussilago farfara*	MR	3	R	4						
Cornflower	*Centaurea cyanus*	MS	2	S	1						
Crane's-bill, cut-leaved	*Geranium dissectum*	MR	3	MR	3						
Crane's-bill, dove's-foot	*Geraniujm molle*	MR	3	MR	3	S	1				
Crane's-bill, meadow	*Geranium pratense*			MR	3						
Cress, hoary	*Cardaria draba*	MS	2	MS	2						
Daisy	*Bellis perennis*	MS	2	MS	2					S	1
Daisy, oxeye	*Leucanthemum vulgare*			MS	2						
Dandelion	*Taraxacum officinale*	MS	2	MR	3					S	1
Dead-nettle, henbit	*Lamium amplexicaule*	R	4	MR	3					S	1
Dead-nettle, red	*Lamium purpureum*	R	4	MR	3	S	1	S	1	S	1
Dead-nettle, white	*Lamium album*	R	4								
Dock, broad-leaved	*Rumex obtusifolius*	MS ?	2	MR	3	S	1			MS	2
Dock, curled	*Rumex crispus*	MS ?	2	MS	2					MS	2
Fat-hen	*Chenopodium album*	S	1	S	1	S	1	S	1	S	1
Fiddleneck	*Amsinckia lycopsoides*							S	1		
Forget-me-not, field	*Myosotis arvensis*	MS	2	MS	2	S	1	S	1	S	1
Fumitory, common	*Fumaria officinalis*	MS	2	MS	2	MR	3	S	1	S	1
Gromwell, field	*Lithospermum arvense*	MS	2	MS	2						
Groundsel	*Senecio vulgaris*	MS	2	MS	2			S	1	S	1
Hawkbit, autumn	*Leontodon autumnalis*			MS	2						
Hawkweed, mouse-ear	*Hieracium pilosella*			MS	2						
Hemlock	*Conium maculatum*			MR	3						
Hemp-nettle, common	*Galeopsis tetrahit*	MS	2	S	1	S	1	R	4	MR ?	3
Hound's-tongue	*Cynoglossum officinale*			MS	2						
Knapweed, common	*Centaurea nigra*			MS	2						
Knotgrass	*Polygonum aviculare*	S	1	MR	3	S	1	S	1	S	1
Marigold, corn	*Chrysanthemum segatum*	R	4	R	4	S	1	MR	3	S	1
Mayweed, scented	*Matricaria recutita*	MR ?	3	R	4	S	1	S	1	S	1
Mayweed, scentless	*Tripleurospermum inodorum*	S ?	1	MR	3	S	1	S	1	S	1
Mint, corn	*Mentha arvensis*	MR ?	3	MR	3						
Mugwort	*Artemisia vulgaris*			MS	2						
Mustard, black	*Brassica nigra*	S	1	S	1						
Mustard, treacle	*Erysimum cheiranthoides*	S	1	S	1						
Mustard, white	*Sinapis alba*	S	1	S	1						
Nettle, common	*Urtica dioica*	MS	2	MS	2						
Nettle, small	*Urtica urens*	MS ?	2	S	1	S	1	S	1	S	1

Appendix 3 continued: Weed susceptibility to the main herbicides in spring barley 1974-1998

Common name	Latin name	Dicamba+MCPA+ mecoprop		MCPA		Metsulfuron		Ioxynil + bromoxynil		Iox+bromox+ mecoprop	
Nightshade, black	*Solanum nigrum*			MS	2						
Nipplewort	*Lapsana communis*	MS	2	R	4	S	1				
Oilseed rape (volunteer)	*Brassica napus*			S	1	S	1			S	1
Onion, wild	*Allium vineale*	R	4								
Orache, common	*Atriplex patula*	MS ?	2	S	1	S	1				
Oxtongue, bristly	*Picris echioides*	R	4								
Pansy, field	*Viola arvensis*	R	4	MR	3	S	1	R	4	MS	2
Pansy, wild	*Viola tricolor*	R	4								
Parsley, cow	*Anthriscus sylvestris*			MR	3						
Parsley, fool's	*Aethusa cynapium*			MS	2	S	1			S	1
Parsley-piert	*Aphanes arvensis*	R	4	R	4	S	1			S	1
Penny-cress, field	*Thlaspi arvense*	S	1	S	1			S	1		
Pepperwort, field	*Lepidium campestre*			MR ?	3						
Persicaria, pale	*Persicaria lapathifolia*	S	1	MR	3	S	1	S	1	S	1
Pimpernel, scarlet	*Anagalis arvensis*	MS	2	MS	2	S	1	S	1	S	1
Pineappleweed	*Matricaria matricarioides*	MR ?	3	R	4	S	1				
Plantain , greater	*Plantago major*									S	1
Plantain spp	*Plantago spp*	S	1	S	1						
Plantain, ribwort	*Plantago lanceolata*									S	1
Poppy, common	*Papaver rhoeas*	MS	2	S	1	S	1	S	1	S	1
Radish, wild	*Raphanus raphanistrum*	S	1	S	1			S	1	S	1
Ragwort, common	*Senecio jacobaea*	MR ?	3	MS	2						
Redshank	*Persicaria maculosa*	S ?	1	MR	3	S	1	S	1	S	1
Scabious, field	*Knautia arvensis*			MS	2						
Selfheal	*Prunella vulgaris*			MS	2						
Shepherd's-needle	*Scandix pecten-veneris*	MR ?	3	MS	2						
Shepherd's-purse	*Capsella bursa-pastoris*	S	1	S	1	S	1	S	1	S	1
Silverweed	*Potentilla anserina*			MR	3						
Soldier, gallant	*Galinsoga parviflora*			S	1						
Sorrel, common	*Rumex acetosa*	S	1	MR	3						
Sorrel, sheep's	*Rumex acetosella*	S	1	MR	3						
Sow-thistle, perennial	*Sonchus arvensis*	MS ?	2	MR	3	S	1				
Sow-thistle, prickly	*Sonchus asper*			S	1						
Sow-thistle, smooth	*Sonchus oleraceus*	MS	2	S	1			S	1		
Speedwell, common, field	*Veronica persica*			MR	3	S	1	S	1	S	1
Speedwell, ivy-leaved	*Veronica hederifolia*			MS	2	MR	3	S	1	S	1
Speedwell, spp	*Veronica spp*	R	4								
Speedwell, wall	*Veronica arvensis*					MR	3	S	1		
Spurrey, corn	*Spergula arvensis*	S ?	1	MR	3	S	1				
Sugar beet, volunteer	*Beta vulgaris*					S	1				
Sun spurge	*Euphorbia helioscopia*					S	1				
Thistle, cotton	*Onopordum acanthium*			S	1						
Thistle, creeping	*Cirsium arvense*	MS ?	2	MS	2					MR ?	3
Thistle, spear	*Cirsium vulgare*	MS ?	2	S	1					MR ?	3
Turnip, wild	*Brassica rapa*			S	1						
Venus's looki ng glass	*Legousia hybrida*					S	1				
Vetch, common	*Vicia sativa*			MS	2						
Vetch, spp	*Vicia sativa*	MS	2								
Yarrow	*Achillea millefolium*			MR	3						
Horse-tail, field	*Equisetum arvense*	MS	2	MS	2						
Rush, soft	*Juncus effusus*	MS ?	2	MS	2						
	Total susceptible species	21		24		31		25		33	

Appendix 4 Weed susceptibility to the main herbicides in spring barley: project selected species

Key: S = susceptible (1) MS = moderately susceptible (2)
MR = moderately resistant (3) R = resistant (4)

Common name	Latin name	Dicamba+MCPA+ mecoprop		MCPA		Metsulfuron		Ioxynil + bromoxynil		Iox+bromox+ mecoprop	
Bindweed black	*Fallopia convolvulus*	S	1	MR	3	MS	2	S	1	S	1
Charlock	*Sinapis arvensis*	S	1	S	1	S	1	S	1	S	1
Chickweed, common	*Stellaria media*	S	1	MR	3	S	1	S	1	S	1
Chickweed, mouse-eared	*Cerastium fontanum*			MR	3					S	1
Cleavers	*Galium aparine*	S	1	R	4	R	4	MR	3	S	1
Corn spurrey	*Spergula arvensis*	S ?	1	MR	3	S	1				
Crane's-bill, cut-leaved	*Geranium dissectum*	MR	3	MR	3						
Dead-nettle, red	*Lamium purpureum*	R	4	MR	3	S	1	S	1	S	1
Dock, broad-leaved	*Rumex obtusifolius*	MS ?	2	MR	3	S	1			MS	2
Fat-hen	*Chenopodium album*	S	1	S	1	S	1	S	1	S	1
Fool's parsley	*Aethusa cynapium*			MS	2	S	1			S	1
Forget-me-not, field	*Myosotis arvensis*	MS	2	MS	2	S	1	S	1	S	1
Fumitory, common	*Fumaria officinalis*	MS	2	MS	2	MR	3	S	1	S	1
Groundsel	*Senecio vulgaris*	MS	2	MS	2			S	1	S	1
Hemp-nettle, common	*Galeopsis tetrahit*	MS	2	S	1	S	1	R	4	MR ?	3
Knotgrass	*Polygonum aviculare*	S	1	MR	3	S	1	S	1	S	1
Mayweed, scented	*Matricaria recutita*	MR ?	3	R	4	S	1	S	1	S	1
Mayweed, scentless	*Tripleurospermum inodorum*	S ?	1	MR	3	S	1	S	1	S	1
Nightshade, black	*Solanum nigrum*			MS	2						
Pansy, field	*Viola arvensis*	R	4	MR	3	S	1	R	4	MS	2
Pimpernel, scarlet	*Anagalis arvensis*	MS	2	MS	2	S	1	S	1	S	1
Poppy, common	*Papaver rhoeas*	MS	2	S	1	S	1	S	1	S	1
Redshank	*Persicaria maculosa*	S ?	1	MR	3	S	1	S	1	S	1
Shepherd's-purse	*Capsella bursa-pastoris*	S	1	S	1	S	1	S	1	S	1
Sow-thistle, smooth	*Sonchus oleraceus*	MS	2	S	1			S	1		
Speedwell, common, field	*Veronica persica*	R	4	MR	3	S	1	S	1	S	1
Sun spurge	*Euphorbia helioscopia*					S	1				
Thistle, creeping	*Cirsium arvense*	MS ?	2	MS	2					MR ?	3
Annual meadow grass	*Poa annua*										
Blackgrass	*Alopecurus myosuroides*										
Brome, barren	*Anisantha sterilis*										
Wild-oat	*Avena fatua*										
	Total susceptible species	10		6		19		17		19	

Appendix 5 Weed susceptibility to the major herbicides in field beans 1974-1998

Key: S = susceptible (1) MS = moderately susceptible (2)
MR = moderately resistant (3) R = resistant (4)

Common name	Latin name	Simazine		Fluazifop		Cycloxydim		Bentazone	
Bindweed, black	*Fallopia convolvulus*	MS	2					MS	2
Black medic	*Medicago lupulina*	MS	2						
Bugloss	*Anchusa arvensis*	S	1						
Buttercup, corn	*Ranunculus arvensis*	R	4						
Campion, white	*Silene alba*							S	1
Chamomile, corn	*Anthemis arvensis*	S	1						
Chamomile, stinking	*Anthemis cotula*	S	1						
Charlock	*Sinapis arvensis*	S	1					S	1
Chickweed, common	*Stellaria media*	S	1					S	1
Chickweed, mouse-eared	*Cerastium fontanum*	S	1						
Cleavers	*Galium aparine*	MR	3					S	1
Crane's-bill, cut-leaved	*Geranium dissectum*	MR	3					S	1
Crane's-bill, dove's-foot	*Geraniujm molle*							S	1
Crane's-bill, meadow	*Geranium pratense*							S	1
Dead-nettle, henbit	*Lamium amplexicaule*	S	1					R	4
Dead-nettle, red	*Lamium purpureum*	S	1					R	4
Dwarf spurge	*Euphorbia exigua*	S	1						
Fat-hen	*Chenopodium album*	S	1					MS	2
Forget-me-not, field	*Myosotis arvensis*	S	1					S	1
Fumitory, common	*Fumaria officinalis*	MS	2					S	1
Gromwell, field	*Lithospermum arvense*	S	1					MS	2
Groundsel	*Senecio vulgaris*	S	1						
Hairy tare	*Vicia hirsuta*	MS	2						
Hemp-nettle, common	*Galeopsis tetrahit*	S	1					R	4
Knotgrass	*Polygonum aviculare*	MS	2						
Large-flowered hemp nettle	*Galeopsis speciosa*	S	1						
Long-headed poppy	*Papaver dubium*	S	1						
Marigold, corn	*Chrysanthemum segatum*	S	1					S	1
Mayweed, scented	*Matricaria recutita*	S	1					S	1
Mayweed, scentless	*Tripleurospermum inodorum*	S	1					S	1
Mustard, black	*Brassica nigra*	S	1					S	1
Mustard, treacle	*Erysimum cheiranthoides*	S	1						
Mustard, white	*Sinapis alba*	S	1					S	1
Nettle, small	*Urtica urens*	S	1					S	1
Nightshade, black	*Solanum nigrum*	S	1					S	1
Orache, common	*Atriplex patula*	MS	2					MS	1
Pansy, field	*Viola arvensis*	MS	2						
Pansy, wild	*Viola tricolor*	MS	2						
Parsley, fool's	*Aethusa cynapium*	MS	2						
Parsley-piert	*Aphanes arvensis*	S	1						
Penny-cress, field	*Thlaspi arvense*	S	1					S	1
Persicaria, pale	*Persicaria lapathifolia*	MS	2					S	1
Pimpernel, scarlet	*Anagalis arvensis*	S	1					S	1
Pineappleweed	*Matricaria matricarioides*	S	1						
Poppy, common	*Papaver rhoeas*	S	1					MS	2
Procumbent speedwell	*Veronica agrestis*	MS	2						
Radish, wild	*Raphanus raphanistrum*	S	1					S	1
Redshank	*Persicaria maculosa*	MS	2					S	1
Shepherd's-needle	*Scandix pecten-veneris*	S	1						
Shepherd's-purse	*Capsella bursa-pastoris*	S	1					S ?	1
Soldier, gallant	*Galinsoga parviflora*	S	1						
Sow-thistle, prickly	*Sonchus asper*	S	1						
Sow-thistle, smooth	*Sonchus oleraceus*	S	1						
Speedwell, common, field	*Veronica persica*	MS	2					R	4
Speedwell, ivy-leaved	*Veronica hederifolia*	MS	2					R	4
Speedwell, spp	*Veronica spp*							R	4
Speedwell, wall	*Veronica arvensis*	MS	2					R	4
Spurrey, corn	*Spergula arvensis*	S	1					S	1
Sun spurge	*Euphorbia helioscopia*	MR	3						
Thistle, cotton	*Onopordum acanthium*							MS	2
Thistle, creeping	*Cirsium arvense*							MS	2
Thistle, spear	*Cirsium vulgare*							MS	2
Turnip, wild	*Brassica rapa*	S	1						
Vetch, spp	*Vicia sativa*	MS	2						
Horse-tail, field	*Equisetum arvense*							R	4

Appendix 5 continued: Weed susceptibility to the major herbicides in field beans 1974-1998

Common name	Latin name	Simazine		Fluazifop		Cycloxydim		Bentazone	
Barren brome	*Anisantha sterilis*			S	1				
Black bent	*Agrostis gigantea*			S	1	S	1		
Blackgrass	*Alopecurus myosuroides*	S	1	S	1	S	1	R	4
Cereals, volunteer				S	1	S	1		
Common couch	*Elymus repens*			S	1	S	1		
Creeping bent	*Agrostis stolonifera*			S	1	S	1		
Fescue, red	*Festuca rubra*					R	4		
Meadow grass, annual	*Poa annua*	S	1			R	4	R	1
Meadow grass, rough	*Poa trivialis*					MR	3		
Rye-grass, italian	*Lolium multiflorum*			S	1				
Rye-grass, perennial	*Lolium perenne*			S	1				
Wild oat	*Avena fatua*	MS	2	S	1	S	1		
	Total susceptible species	38		9		6		23	

Appendix 6 Weed susceptibility to the main herbicides in field beans: project selected species

Key: S = susceptible (1) MS = moderately susceptible (2)
MR = moderately resistant (3) R = resistant (4)

Common name	Latin name	Simazine		Graminicides	
Bindweed black	*Fallopia convolvulus*	MS	2		
Charlock	*Sinapis arvensis*	S	1		
Chickweed, common	*Stellaria media*	S	1		
Chickweed, mouse-eared	*Cerastium fontanum*	S	1		
Cleavers	*Galium aparine*	MR	3		
Corn spurrey	*Spergula arvensis*	S	1		
Crane's-bill, cut-leaved	*Geranium dissectum*	MR	3		
Dead-nettle, red	*Lamium purpureum*	S	1		
Dock, broad-leaved	*Rumex obtusifolius*				
Fat-hen	*Chenopodium album*	S	1		
Fool's parsley	*Aethusa cynapium*	MS	2		
Forget-me-not, field	*Myosotis arvensis*	S	1		
Fumitory, common	*Fumaria officinalis*	MS	2		
Groundsel	*Senecio vulgaris*	S	1		
Hemp-nettle, common	*Galeopsis tetrahit*	S	1		
Knotgrass	*Polygonum aviculare*	MS	2		
Mayweed, scented	*Matricaria recutita*	S	1		
Mayweed, scentless	*Tripleurospermum inodorum*	S	1		
Nightshade, black	*Solanum nigrum*	S	1		
Pansy, field	*Viola arvensis*	MS	2		
Pimpernel, scarlet	*Anagalis arvensis*	S	1		
Poppy, common	*Papaver rhoeas*	S	1		
Redshank	*Persicaria maculosa*	MS	2		
Shepherd's-purse	*Capsella bursa-pastoris*	S	1		
Sow-thistle, smooth	*Sonchus oleraceus*	S	1		
Speedwell, common, field	*Veronica persica*	MS	2		
Sun spurge	*Euphorbia helioscopia*	MR	3		
Thistle, creeping	*Cirsium arvense*				
Annual meadow grass	*Poa annua*	S	1	R	4
Blackgrass	*Alopecurus myosuroides*	S	1	S	1
Brome, barren	*Anisantha sterilis*			S	1
Wild-oat	*Avena fatua*	MS	2	S	1
	Total susceptible species	18		3	

Appendix 7 Weed susceptibility to the major herbicides in oilseed rape 1974-1998

Key: S = susceptible (1) MS = moderately susceptible (2)
MR = moderately resistant (3) R = resistant (4)

Weed													
Common name	Latin name	TCA		Propyzamide		Clopyralid		Graminicides		Benazolin+clopyralid		Metazachlor	
Bindweed, black	*Fallopia convolvulus*			S	1	S	1			S	1	MS	2
Bindweed, field	*Convolvulus arvensis*			R	4								
Black medic	*Medicago lupulina*												
Carrot, wild	*Daucus carota subsp. carota*					S	1						
Cat's-ear	*Hypochoeris radicata*												
Chamomile, stinking	*Anthemis cotula*					S	1						
Charlock	*Sinapis arvensis*					MR	3			S	1	MR	3
Chickweed, common	*Stellaria media*			S	1					S	1	S	1
Cleavers	*Galium aparine*			MR ?	3					MS	2	MS	2
Clover	*Trifolium spp*			R	4	MR ?	3						
Colt's-foot	*Tussilago farfara*					MR ?	3						
Crane's-bill, cut-leaved	*Geranium dissectum*											S	1
Dandelion	*Taraxacum officinale*			R	4								
Dead-nettle, red	*Lamium purpureum*									S	1	S	1
Fat-hen	*Chenopodium album*			S	1	MR	3			S	1	MS	2
Forget-me-not, field	*Myosotis arvensis*			MS	2							S	1
Fumitory, common	*Fumaria officinalis*									S	1	R	4
Gromwell, field	*Lithospermum arvense*											S	1
Groundsel	*Senecio vulgaris*			R	4	S	1			S	1	S	1
Hemp-nettle, common	*Galeopsis tetrahit*											MR	3
Knapweed, common	*Centaurea nigra*					MR ?	3						
Knotgrass	*Polygonum aviculare*			S ?	1	MR	3			S	1	R	4
Marigold, corn	*Chrysanthemum segatum*					S	1			S	1	S	1
Mayweed, scented	*Matricaria recutita*			R	4	S	1			S	1	S	1
Mayweed, scentless	*Tripleurospermum inodorum*			R	4	S	1			S	1	S	1
Mustard, black	*Brassica nigra*									R	4		
Mustard, treacle	*Erysimum cheiranthoides*									R	4		
Mustard, white	*Sinapis alba*									R	4		
Nettle, small	*Urtica urens*			S ?	1							MS	2
Nightshade, black	*Solanum nigrum*			S ?	1								
Pansy, field	*Viola arvensis*									R	4	MR	3
Parsley, fool's	*Aethusa cynapium*					S	1						
Parsley-piert	*Aphanes arvensis*											S	1

Appendix 7 continued; Weed susceptibility to the major herbicides in oilseed rape 1974-1998

Weed													
Common name	Latin name	TCA		Propyzamide		Clopyralid		Graminicides		Benazolin+clopyralid		Metazachlor	
Penny-cress, field	*Thlaspi arvense*											R	4
Persicaria, pale	*Persicaria lapathifolia*					MR	3						
Pimpernel, scarlet	*Anagalis arvensis subsp. arvensis*			R	4								
Pineappleweed	*Matricaria matricarioides*					S	1						
Poppy, common	*Papaver rhoeas*									MR	3	S	1
Radish, wild	*Raphanus raphanistrum*									R	4		
Ragwort, common	*Senecio jacobaea*			R	4								
Redshank	*Persicaria maculosa*			S ?	1	MR	3			S	1	MS	2
Shepherd's-purse	*Capsella bursa-pastoris*											S	1
Soldier, gallant	*Galinsoga parviflora*			R	4								
Sow-thistle, perennial	*Sonchus arvensis*					S	1						
Sow-thistle, smooth	*Sonchus oleraceus*					S	1						
Speedwell, common, field	*Veronica persica*			MS ?	2	MR	3			R	4	S	1
Speedwell, ivy-leaved	*Veronica hederifolia*			MS ?	2					R	4	S	1
Speedwell, spp	*Veronica spp*			MS ?	2					R	4	S	1
Speedwell, wall	*Veronica arvensis*			MS ?	2					R	4	S	1
Spurrey, corn	*Spergula arvensis*			S	1							MS	2
Thistle, cotton	*Onopordum acanthium*			R	4								
Thistle, creeping	*Cirsium arvense*			R	4	S	1						
Thistle, spear	*Cirsium vulgare*			R	4	S	1						
Vetch, spp	*Vicia sativa*					S	1						
Yarrow	*Achillea millefolium*					MR	3						
Barren brome	*Anisantha sterilis*	S	1	S	1			S	1			MS	2
Black bent	*Agrostis gigantea*							S	1				
Blackgrass	*Alopecurus myosuroides*	S	1	S	1			S	1			S	1
Cereals, volunteer		S	1	S	1			S	1			MR	3
Common couch	*Elymus repens*	MS?	2					S	1				
Creeping bent	*Agrostis stolonifera*	MS?	2					S	1				
Fescue, red	*Festuca rubra*							R	4				
Meadow grass, annual	*Poa annua*	S	1	S	1			R	4			S	1
Meadow grass, rough	*Poa trivialis*							MR	3				
Rye-grass, italian	*Lolium perenne subsp. multiflorum*			S	1			S	1				
Rye-grass, perennial	*Lolium perenne subsp. perenne*			S	1			S	1				
Wild oat	*Avena fatua*	S	1	S	1			S	1			MR	3
Yorkshire fog	*Holcus lanatus*			S	1								
	Total susceptible species	5		16		14		9		12		18	
	Susceptible broad-leaved species	0		8		14		0		12		16	

Appendix 8 Weed susceptibility to the main herbicides in oilseed rape: project selected species

Key: S = susceptible (1) MS = moderately susceptible (2)
MR = moderately resistant (3) R = resistant (4)

Weed		Herbicides for use in Winter Rape											
Common name	Latin name	TCA		Propyzamide		Clopyralid		Graminicides		Benazolin+clopyralid		Metazachlor	
Bindweed black	*Fallopia convolvulus*			S	1	S	1			S	1	MS	2
Charlock	*Sinapis arvensis*					MR	3			S	1	MR	3
Chickweed, common	*Stellaria media*			S	1					S	1	S	1
Chickweed, mouse-eared	*Cerastium fontanum*												
Cleavers	*Galium aparine*			MR ?	3					MS	2	MS	2
Corn spurrey	*Spergula arvensis*			S	1							MS	2
Crane's-bill, cut-leaved	*Geranium dissectum*											S	1
Dead-nettle, red	*Lamium purpureum*									S	1	S	1
Dock, broad-leaved	*Rumex obtusifolius*												
Fat-hen	*Chenopodium album*			S	1	MR	3			S	1	MS	2
Fool's parsley	*Aethusa cynapium*					S	1						
Forget-me-not, field	*Myosotis arvensis*			MS	2							S	1
Fumitory, common	*Fumaria officinalis*									S	1	R	4
Groundsel	*Senecio vulgaris*			R	4	S	1			S	1	S	1
Hemp-nettle, common	*Galeopsis tetrahit*											MR	3
Knotgrass	*Polygonum aviculare*			S ?	1	MR	3			S	1	R	4
Mayweed, scented	*Matricaria recutita*			R	4	S	1			S	1	S	1
Mayweed, scentless	*Tripleurospermum inodorum*			R	4	S	1			S	1	S	1
Nightshade, black	*Solanum nigrum*			S ?	1								
Pansy, field	*Viola arvensis*									R	4	MR	3
Pimpernel, scarlet	*Anagalis arvensis*			R	4								
Poppy, common	*Papaver rhoeas*									MR	3	S	1
Redshank	*Persicaria maculosa*			S ?	1	MR	3			S	1	MS	2
Shepherd's-purse	*Capsella bursa-pastoris*											S	1
Sow-thistle, smooth	*Sonchus oleraceus*					S	1						
Speedwell, common, field	*Veronica persica*			MS ?	2	MR	3			R	4	S	1
Sun spurge	*Euphorbia helioscopia*												
Thistle, creeping	*Cirsium arvense*			R	4	S	1						
Annual meadow grass	*Poa annua*	S	1	S	1			R	4			S	1
Blackgrass	*Alopecurus myosuroides*	S	1	S	1			S	1			S	1
Brome, barren	*Anisantha sterilis*	S	1	S	1			S	1			MS	2
Wild-oat	*Avena fatua*	S	1	S	1			S	1			MR	3
	Total susceptible species	4		11		7		3		11		12	
	broad-leaved species	0		7		7		0		11		10	

7. EFFECTS OF MANAGEMENT OTHER THAN HERBICIDES ON FARMLAND BIODIVERSITY

Whilst this review concentrates on the impact of herbicides on biodiversity, there are a number of other factors that may have a profound effect on weed assemblages and populations and associated insect and bird species. Whilst this section is not comprehensive, a brief review of these other factors is included.

7.1. Habitat Loss

Farmland is a mosaic of crop and non-crop habitat (Marshall, 1988), so consideration of the ecology of the crop component should include the effects of the non-crop elements. Field margins and hedgerows are the commonest elements of non-crop habitat in farmland. There have been significant declines in hedgerow length in Britain (Barr et al., 1991), though the latest data from Countryside Survey indicate this loss has ceased (Haines-Young et al., 2000). These changes will have had little or no impact on the weed flora in arable fields. These species are adapted to periodic or regular disturbance regimes created by soil cultivation and are largely unconnected with the flora of the perennial margins (Marshall & Arnold, 1995). However, the same cannot be said for more mobile fauna, some of which utilise both field and margin habitats at different parts of their life cycle, for example ground beetles (Thomas et al., 2001) and birds (Vickery & Fuller, 1998). These species may well have been adversely affected by habitat loss. In the case of birds, however, there are opinions that while habitat loss has played a role in the significant declines in populations, habitat degradation is the more important factor driving losses (Chamberlain et al., 2000). A range of agricultural changes is implicated, including winter cropping, mechanisation, specialisation and loss of mixed farming and herbicides (Fuller et al., 1995).

7.2. Fertilisers and Nutrient Enrichment (see also Section 6)

One of the most important factors affecting plant diversity is nutrient availability and thus the productivity of a habitat. Both eutrophication and disturbance are implicated in the continuing decline in plant diversity recorded in the British countryside by Countryside Survey (Barr et al., 1993; Haines-Young et al., 2000). Most ecologists agree that the “hump-backed” model of productivity and diversity, in which diversity increases to an asymptote with increasing productivity and then declines with further enrichment, is a good representation. Species diversity declines as adapted species become dominant. At high productivity, tall-growing, competitive species out compete shorter subordinate species (Marrs, 1993). It is the case that more fertiliser has been used within arable systems over the past century, though recent economic pressures have encouraged targeted use (Jordan, 1998). It is likely that increased fertility within crops has encouraged more nitrophilous species. An obvious example is cleavers (*Galium aparine*), which is a weed that has increased markedly in frequency (21% in the 1960s to 88% occurrence in 1997 in central England) (Sutcliffe & Kay, 2000). This species is particularly responsive to nitrogen (Froud-Williams, 1985). Thus fertiliser use may have been an important driver in changing weed assemblages.

There is good evidence that fertiliser misplacement from field applications into field margins occurs (Rew et al., 1992; Tsiouris & Marshall, 1998) and that both fertiliser and herbicides affect margin flora (Kleijn & Snoeijing, 1997). It is apparent that fertiliser is of greater significance than herbicide drift. It is likely that the same applies within arable cropping. Associated changes in fauna, with changes in weed assemblages, might therefore be expected.

7.3. Cropping Practices

As outlined in section 6, there have been marked changes in crop type, with a huge move to winter cropping, away from spring cereals, over the past 30 years. Winter cropping will select for autumn-germinating weed species and against spring-germinating species, such as the Polygonaceae (Chancellor, 1985).

There have been a number of other changes over the last century, with increased mechanisation and increased specialisation of production. There is significantly less mixed cropping now than previously, with less grass included in crop rotations. Improved seed-cleaning techniques have had marked effects on the abundance of certain weed species (Chancellor et al., 1984). All these management factors can have selective effects on weed assemblages and populations.

8. THE IMPACT OF HERBICIDES ON INVERTEBRATES

Scope of the review

This section of the review aims to provide a balanced account of the effects of herbicides on the invertebrate fauna associated with weeds in arable cropping systems. It gives relevant background to understanding the effects and reviews the information available at the current time. While there has been a healthy literature on the effects of insecticides on non-target invertebrates, and the means of alleviating these by various management options, the recognition of the implications of herbicide use on invertebrate biodiversity in arable systems has been far less researched. Indeed, research that has been undertaken mainly focuses on community trends in field margins or conservation headlands, with very little attention to crops. There is consequently a need to draw on the ecological literature to provide a framework for the review, and to inform on the possible routes and mechanisms by which herbicides may impact on invertebrates. One of the key questions to be addressed, especially in relation to non-target weed species, relates to the importance of different weed species as a resource for invertebrates. Significant resources include provision of habitat, mainly to provide cover, and the provision of food (plant seeds and invertebrates) for a range of different insect types. As the area has received so little attention, in the context of management of pesticide use, some new dimensions are also included.

In addition to the intrinsic value of invertebrates to the biodiversity of farmland, the important services they provide in terms of pollination, biological control, nutrient cycling and the provision of resources for other organisms should not be overlooked. Section 8 mentions the latter theme in relation to invertebrates as food items for farmland birds, though data are somewhat limited.

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    - Decomposers and detritivores
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8.3 New dimensions
- Effects of herbicides on soil fauna
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8.1. Ecological Framework

8.1.1. Invertebrate Communities

Invertebrates can usefully be categorised in terms of guilds, dependent on life-history traits and feeding behaviour. The key guilds in arable systems are:

- predatory and parasitic (= parasitoid) species
- decomposers and detritivores
- phytophagous species, including nectar and pollen feeders, and herbivores
- tourists (= species with only transient association with the crop or weed communities)

The way in which these guilds interact with the weed community is important, as each has specific relationships either with a single weed species or with the weed community. It is also important to consider subterranean invertebrate communities, so often neglected (Brown & Gange 1990). Apart from key subterranean groups, such as earthworms, some soil-dwelling taxa relate closely to other stages of the species life cycle occurring above ground. For example, in many holometabolous insects, such as the Coleoptera or beetles, the immature larval stages are soil dwelling, while the adults feed on nectar or the foliage of plants.

Some insect groups, such as the ants, are seldom associated with arable land, mainly because the regular disturbance is incompatible with their behaviour. Such groups are disregarded for the purpose of this account.

8.1.2. Attributes Of Weed Communities Important To Invertebrates

Individual weed species or mixed species communities form a 'templet' (sensu Southwood 1977) both spatially and temporally, for invertebrate species and communities. The key attributes of weeds that are important to invertebrates are the species per se, the structure afforded by the plant canopy and the seasonal phenology of the species. Clearly, the interactions between these attributes are complex and particularly so in ephemeral arable crop weed communities.

Plant species composition

Phytophagous invertebrates vary in their specificity to host plants, with generalist species feeding on a wide array of plant species and specialists on few or even a single plant species and sometimes only on a particular plant structure. This specificity is normally driven by plant structural and/or chemical traits. Specialist species tend to be those with higher intrinsic biodiversity value. The abundance, local distribution and competitive interactions between different weed species, phenologies and physiological conditions are the determinants of the specialist insect communities.

Plant structure / architecture

The form of individual plant species is often neglected in favour of taxonomic or life history attributes. However, plant form is known to be very variable and particularly relevant to early successional and arable weed communities. The concept of plant structure or architecture as a determinant of insect species diversity was first mooted by Lawton & Schroder (1977). It was subsequently developed by Stinson & Brown (1983) in terms of bugs (Homoptera: Auchenorrhyncha) associated with arable weeds. Essentially, plant architecture relates to the 3-D structure of plants providing an important templet for invertebrates. In its simplest form, structurally complex species, such as herbs, tend to have more invertebrates associated with them than structurally simple species, such as grasses. At the community level, the structural complexity of the canopy provided by weeds is important for all invertebrate guilds, predators, parasitoids and decomposers, in addition to the phytophages. Before crop establishment, weeds may provide the sole means of structural modification of the habitat.

Plant phenology

The brevity of life cycles of many invertebrate species means that synchrony between insect and resource is often of critical importance in the completion of life cycles, with corresponding implications for timing of herbicide application. Mixed weed communities, as well as providing a diversity of resources, also provide a range of phenologies, thereby giving a range of plant structures for different invertebrate feeding types, throughout the growing season. The speed of population turnover of some weed species provides a regular replenishment of resources, as well as seasonal differences in diversity. Phenological relations of plants and invertebrates are generally ignored, though are of critical importance.

8.2. Effects of Herbicides on Invertebrates

The summary provided by Breeze *et al.* (1999) in PN0923 (though only referring to 7 arable weed species) is useful, since it serves to emphasise direct (toxic) and indirect effects, mediated via plant food resources or habitat modification. As emphasised in PN0923, there are few examples of direct toxic effects of herbicides on invertebrates, with many of these only being demonstrated in laboratory bioassays and at high application rates. Most effects of herbicides on invertebrates are through the indirect effects on the host plants, though there are relatively few recent studies describing more than general trends in invertebrate populations. There is certainly a need to focus more stringently on the mechanisms underpinning the interaction between invertebrates and weed communities. The indirect effects of herbicides on the interactions between arable weeds and invertebrates can be summarised in terms of modifications in invertebrate food resource and habitat (Fig. 8.1).

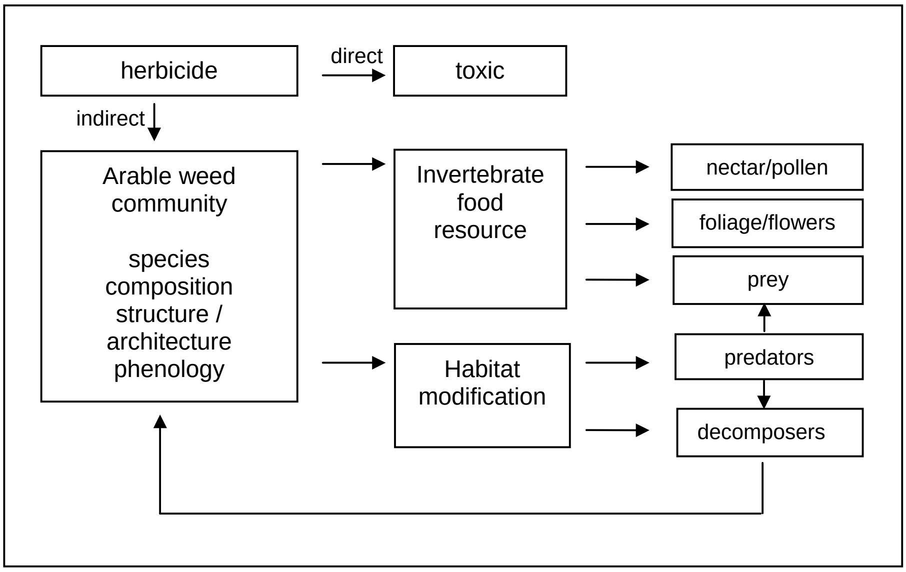


Fig. 8.1. Potential ecological effects of herbicides on invertebrates. (After Breeze *et al*. 1999).

Subsequent to studies mentioned in PN0923, Wilson *et al.* (1999) assessed the impact of agricultural intensification on the abundance and diversity of invertebrates and plants for 26 species of granivorous farmland birds in NW Europe, in the context of agricultural intensification, including pesticide usage. They have provided useful lists of key food items for different bird taxa and have shown a decline in many invertebrate taxa, though there are some inconsistencies between groups. Another review, commissioned by JNCC (Ewald & Aebischer 1999), summarises the results of the long-term Sussex study, from 1970 – 1995. Though the study includes the effects of combined herbicide, fungicide and insecticide treatments, methods of analysis have enabled some interpretation of the effects of single pesticides (Ewald & Aebischer 1999). However, correlational studies are fraught with difficulties in interpretation, especially when application times and rates of pesticides vary throughout the course of the experimental period, as crop types and management practices change (Ewald & Aebischer 2000). Even so, trends were seen in the five invertebrate groups studied (Araneae and Opiliones (spiders and harvestmen), Carabidae and Elateridae (ground beetles and click beetles), larvae of Symphyta and Lepidoptera (sawflies, butterflies and moths), Chrysomelidae and Curculionidae (leaf beetles and weevils) and non-aphid Hemiptera (bugs and hoppers). The numerical abundance of key groups of invertebrates (Araneae and Opiliones, and the beetle groups Carabidae, Elateridae, Chrysomelidae and Curculionidae) declined over the study period (*r*-values of -0.554: -0.359: -0.668 and -0.497 respectively). However, within the non-aphid Hemiptera there were no clear trends. No effect was established on the number of herbicide applications on any invertebrate group.

8.2.1. By Habitat Modification

The cover provided by the arable weed community gives important shelter to invertebrates, particularly epigeal groups, such as predatory species living on the soil surface (e.g. carabid and staphylinid beetles) and spiders, but also some decomposers (e.g. Collembola or spring tails). The lack of a plant litter layer in the crop exacerbates the importance of the cover provided. Weed cover also stimulates an appropriate microclimate, retaining moisture as well as ameliorating fluctuations in humidity and temperature. Grass cover in particular serves to enhance numbers and activity of predators (e.g. Hassall *et al.* 1992; Moreby *et al*. 1999), though detailed studies on decomposers are lacking.

Norris & Kogan (2000) suggest that the greatest effects of weed management are on polyphagous ground-dwelling predators. The interaction appears to be a combination of habitat modification, direct resource for polyphagous species that can eat plant material and, for strictly predaceous species, the prey living on weeds. For example, Speight & Lawton (1976) found the number of carabid beetles was linearly related to the presence of *Poa annua* and the cover provided (Fig. 8.2). Interestingly, the extent of prey removal also increased as *Poa annua* cover increased.

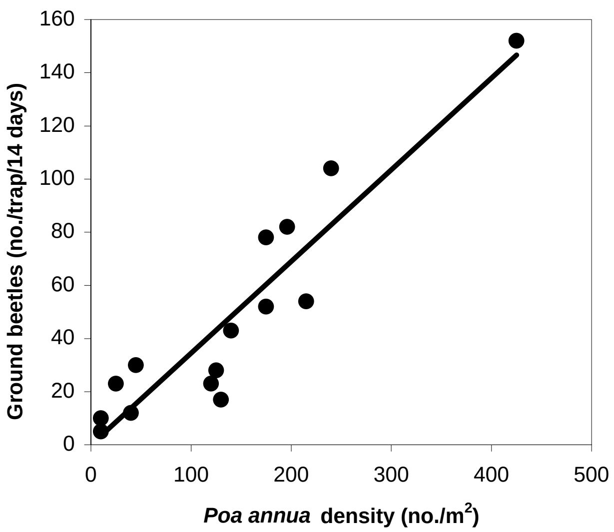


Fig. 8.2. Relationship between frequency of *Poa annua* and the numbers of ground beetles in pitfall traps over 14 days. Y= 1.12 + 0.77X; r = 0.72, P>0.001. (From Norris & Kogan 2000).

Effects on predatory species

Spiders

Little is known of the effects of herbicide application on spiders, relative to information on insecticides (but see Asteraki *et al*. 1992). Spiders are particularly affected by vegetation structure, where a variable structure is important for the provision of web spinning sites, prey capture and a suitable micro-climate. In recent work on field margins, Haughton *et al*. (1999) compared the application of 3 different rates of herbicide (glyphosate). Although the total number of spiders was reduced, there were interesting differences between the wandering and web-spinning prey-capture guilds and the two most abundant species (*Gonatium rubens* and *Lepthphantes tenuis*). The highest rates of glyphosate consistently reduced the total number of spiders, the numbers of web spinners and the two common species, but not the number of wandering spiders. Thus, herbicide use may not only reduce the diversity and predatory function in these communities, but may modify the community composition, by differential effects. Ewald & Aebischer (1999) demonstrated a positive relationship between herbicide use and the densities of spiders and Opiliones, although this may be more closely tied to the amount of dead vegetation and reduction in prey items. A time lag in the response of predatory groups that rely on vegetation structure (e.g. spiders) to herbicide application may be expected, as dead plant material persists for some time, continuing to provide the structural component, before finally collapsing and decomposing (Smith & Macdonald 1992). Other, indirect, delayed effects may occur via prey species that depend more on plant species composition than on architectural complexity.

Ewald & Aebischer (1999) also found that spring and summer herbicide application enhanced populations of Araneae and Opiliones rather more than autumn/winter applications that were more common at the beginning of the study period. The interpretation of these differences may be similar to those cited above.

Predatory beetles

Carabidae and Elateridae were positively related to autumn/winter herbicide treatment and to that in the previous year (Ewald & Aebischer 1999), again possibly because of the amount of dead vegetation and reduction in prey items. However, these responses may also relate to the use of pitfall traps. Higher numbers of large beetles have been captured in cereal crops with few weeds, suggesting that clean herbicide-treated crops are easier for the beetles to colonise (Powell, Dean & Dewar 1985). Movement is also easier in clean crops and therefore capture enhanced. Since pitfall trapping is a poor method of collection for Elateridae and Carabidae, the results should be treated carefully (Sunderland *et al.* 1995; Borges & Brown, submitted MS). As in spiders, Krooss & Schaefer (1998) also found responses differed between species of staphylinid beetles in winter wheat, under different farming systems, again suggestive of herbicide treatment modifying community structure.

Dispersal ability and overwintering strategy of species are important traits to understand. Some species withdraw to crop margins, especially overwinter, while others remain in the cropped area throughout and tend to be more vulnerable, especially to early season applications when there is little weed cover.

Effects on tourists and parasitoids

Many insects, commonly referred to as ‘tourists’, have no specific relationship with the vegetation, but use it for shelter, sustenance (e.g. honey dew from aphids), basking or sexual display. These groups are mainly the adults of smaller Acalyptrate Diptera and Hymenoptera (Parasitica). The latter group, or parasitoids, (particularly the Chalcidoidea, Braconidae and Ichneumonoidea) serve an important biocontrol function. However, since many species are specific to one particular host, trends in overall numbers should be viewed with caution. Many tourist taxa are important components of diversity, e.g. species-specific leaf miners, which commonly use weed communities as staging posts. Tourists and parasitoids often require water, nectar, or aphid honeydew as a source of food (Jervis *et al.* 1993). These resources are commonly plentiful in the weed canopy.

Effects on decomposers and detritivores

Changes in micro-climate produced by weed canopies are significant to those groups that are moisture sensitive (e.g. Collembola). The moist microclimate provided by a dense cover of broad-leaved species is particularly advantageous to such primitive insects that are unable to conserve water by having an impermeable cuticle. Collembola are key organisms in decomposition and therefore nutrient cycling. The effects of herbicides on this group are virtually unknown (but see Wardle *et al.* 1999a) and the area requires further work. The results from the Boxworth study throw little light on this area in respect of herbicide application alone (Frampton *et al*. 1992) and other work has been inconclusive or contradictory. In some studies, increases in numbers of springtails have been observed after herbicide applications, caused by an increased rate of litter input to the soil (e.g. Conrady 1986). However, some herbicides may also have direct adverse effects on springtails (e.g. Edwards & Stafford 1979). In the Boxworth study, it is possible that cumulative effects of successive applications may have contributed to the overall effect of the full insurance regime (Frampton *et al.* 1992).

Effects on molluscs

Similarly, the behaviour of slugs will be influenced by the effects of vegetation on microclimate and soil moisture. Encouragement of certain weeds may play a part in Integrated Pest Management, providing alternative food sources for slug pests (Cook, Bailey & McCrohan 1997; Kozlowski & Kozlowska 2000). However, weeds and other non-crop plants may also act as refuges for pest species. Studies of slug populations in crops adjacent to sown wildflower strips have shown that slug pests may use such areas as refuges (Frank 1998; Friedli & Frank 1998). Other studies in the same system have shown that the presence of weeds may protect crops (Frank & Barone 1999). The key factor in determining whether weedy vegetation will have a positive or negative effect on crop damage is the palatability of the crop relative to that of the weeds (Cook, Bailey & McCrohan 1996; Briner & Frank 1998; Kozlowski & Kozlowska 2000). Other factors determining the outcome of the interaction are the relative densities of crop and weed, and the timing of their growth in relation to the lifecycle of the slug (Cook *et al*. 1997; Frank & Barone 1999). Thus, herbicides have the potential to indirectly affect slug abundance in arable fields, and the outcome may be positive or negative in terms of crop damage (e.g. Wilby & Brown 2001). The review by Wilson *et al.* (1999) cited herbicides only once as having a detrimental effect on molluscs. Molluscs are likely to be key predators of weed seedlings and will therefore impact on weed population dynamics quite extensively.

8.2.2. <u>By Prey Resources</u>

Though predators mainly rely on the structural attributes of the vegetation, prey items (e.g. aphids) are commonly more species specific, and thus there will be direct feedback to prey availability. Slugs and Collembola, representing key food items for predatory beetle groups (e.g. Carabidae and Staphylinidae), are less affected by the species diversity of the weed community, though the shelter it provides is important.

8.2.3. By Plant Food Resources

Pollen and nectar feeders

Weeds are an important source of pollen and nectar for invertebrates. Further, traits of annual weeds, to produce large numbers of flowers often over a short period of time, make them important, though often temporally separated resources. The diversity of weed communities can provide a regular supply of these resources, particularly for generalist feeders. It is significant that flower and nectar feeding does not necessarily imply pollination, since many weed species are either obligatorily or facultatively self-pollinating. Weed species are also often flexible in their pollination strategy, even to the extent of population differences (Ollerton, pers. comm.). In addition to the obvious role of insects in pollination (see PN0923), adult parasitic wasps and syrphid flies, important in biological control as larvae, commonly feed on nectar sources (Wratten & van Emden 1995; Norris & Kogan 2000). Some key aphidophagous species rely heavily on weeds for supplies of nectar.

Appendix 8.1 gives a summary of a thorough, though not exhaustive, literature search for the main pollen and nectar-feeding groups associated with the key 34 weed species included in this review. It includes information on 25 species additional to those included in PN0923. In most cases, data are only available to the insect family level, though species information is provided by some authors (e.g. Saure 1996; Westrich 1996). Unfortunately, one of the key reference sources is Knuth (1906, 1908, 1909), which means that the data may have little current relevance, while other sources tend to be rather anecdotal and widely spread. Indeed, the exercise highlights the need for more up to date treatment of this guild of invertebrates.

Flower and nectar-visiting insect groups include solitary and bumble bees, butterflies and moths, hoverflies and other Diptera and less frequently wasps (both species and the larger parasitic groups (Ichneumonidae)) and beetles. Weed species appear to vary in the diversity of insects visiting them, though this is also likely to be attributable to recorder bias and to the apparency of the plant. Generally, members of the Asteraceae, such as *Cirsium arvense*, *Centaurea cyanus*, *Chrysanthemum segetum*, *Matricaria recutita*, *Senecio vulgaris* and *Tripleurospermum inodorum*, are the species supporting the largest diversity of nectar and pollen feeding insects.

Syrphidae and bumble bees (*Bombus* species) are the most common insect groups visiting arable weeds, though the taller herbs, such as *Cirsium arvense*, are commonly visited by butterflies (mainly the Satyridae or Browns) (Feber, Smith & Macdonald 1994, plus pers. obs.). It should be mentioned, however, that within the crop the ‘apparency', sensu Feeny (1976), of weeds to these larger flower-visiting species would be very limited. Crop type and timing will be significant in this context.

Although grasses are wind pollinated, their flowers are visited for pollen by some beetle groups, e.g. Cantharidae and Malachidae (Harde & Hammond 1984). Thrips or Thysanoptera, not mentioned in PN0923, are also frequent visitors to the flowers of a wide range of arable weeds, where the Terebrantia, in addition to sucking sap from leaves, many flower dwelling species swallow pollen grains or suck their contents. Lewis (1973) lists species in the genera *Aeolothrips*, *Odontothrips*, *Oxythrips, Taeniothrips*, *Thrips* and *Haplothrips* whose larvae and adults suck the liquid contents from pollen grains of many flowers, including *Convolvulus, Anthemis, Sonchus* and *Centaurea.*

Appendix 8.1 also includes information of the breeding system of the 31 species (from Clapham, Tutin & Moore 1987; Stace 1997). This information is included to indicate dependency on the insect community for pollination services, even though species are very variable.

Foliage, flower and seed feeders
26% of insect species are phytophagous (Strong, Lawton & Southwood 1984). Thus, interactions between weed communities and insects are highly significant in terms of biodiversity, and probably far more so than is generally accepted. Arable weeds belong to a large number of plant families (the species in this review belong to 17 plant families). They exhibit a range of specific structural attributes and chemical properties, which have led to a spectrum of different host-plant relations in terms of level of specialism. All life stages of plants provide food resources for insects. Seedlings are important, because of their low levels of defence compounds, and high nutrient content. Likewise, all plant structures are exploited, with flowers and seeds being favoured by many specialist insects because of their high nutrient quality (Prestidge & McNeill 1983). Seed-feeding insects, their interaction and effects on weed host plants and their population dynamics, are not well researched.

Herbivorous insects feed on plants by chewing tissues or feeding on sap. Lepidoptera and sawfly (Hymenoptera: Symphyta) and some Diptera only feed on plant tissue as larvae, though adult Lepidoptera feed extensively on nectar. Some Coleoptera, especially Chrysomelidae (leaf beetles) and Curculionoidea (weevils) feed on plants as larvae and adults, though sometimes there is a host plant switch between stages, even to the extent that the adult will feed on a dicotyledonous herb and the larvae on grass roots (Brown & Hyman 1986, 1995). Plant tissue may be taken externally or internally, within leaf mines and plant galls. Hemiptera (Homoptera and Heteroptera) and Thysanoptera (thrips) are the main sap-feeding insects, feeding on the phloem, xylem or, in the case of thrips, cell contents of the mesophyll. Orthoptera (grasshoppers) are rare in arable crops, with the group declining in farmland in general. However, undisturbed bare ground in crop margins provides a suitable habitat for oviposition of *Chorthippus brunneus* (Brown 1983), and weeds are a source of food. This group is also of particular importance in the diet of some species of farmland birds.

Specific relations of folivorous insects and arable weeds
In assessing the importance of different weed species to invertebrates, it is essential to have information on host plant relationships that is reliable and relevant. In reality, this can only be obtained by targeted work in the field on single weed species. Unfortunately, such studies are seldom undertaken, though work on the arable weed communities at Silwood Park by Brown & colleagues have provided insight into the potential of this approach (Brown *et al.* 1987; Brown & Hyman 1995). Literature records seldom differentiate between occasional records and those that are common, and they are often dated. Undoubtedly, in the UK, the Phytophagous Insect Data Base (PIDB) developed by Lena K. Ward, Centre for Ecology and Hydrology (CEH), is of

outstanding value in terms of a collation of host plant records and a unique resource (see Ward 1988; Ward & Spalding 1993).

The PIDB holds information on linkages between insects and plants compiled from the literature, fro museum collections and from unpublished sources. The linkages are based on feeding records, but do not include nectar or pollen feeders. The PIDB is extensive (45,000 linkages or more), though suffers from the disadvantages already cited. These apart, its interrogation was highly appropriate to determine the relative importance of the target and non-target weed species, included in this review (see page 4), for phytophagous insects. Access to the database was agreed between MAFF and CEH and interrogation and synthesis undertaken by the author. Data on only 3 non-target species (*Centaurea cyanus, Chrysanthemum segetum*, *Fallopia convolvulus*) were not available.

The following relationships were assessed for the insect fauna associated with individual weed species:

- number of families of insects
- number of species of insects (generalist or specialist)
- number of insect species dependent on the weed species for completion of life history (mainly host specific species)
- number and identity of rare (Red Data Book) species
- number of pest species.

The species identity of the last three categories is also given. Figure 8.3 gives information on the number of insect families and species associated with the target weed species. The number of families provides only a course assessment of biodiversity value, but is likely to be robust. In terms of both families and species, three target species (*Stellaria media, Poa annua and Polygonum aviculare*) support a high diversity of insects. Two other points worthy of mention are the low diversity of insect species associated with two target grass species (*Avena sativa, Alopecurus myosuroides*) and a similarly low number associated with the two species of smaller stature (*Myosotis arvensis, Viola arvensis*) supporting the structural concept mentioned previously. Figure 8.4 provides similar information for 23 non-target weed species, grouped according to family. Weed species again vary in the diversity of insect species supported. However, the Asterceae have a particularly rich fauna with *Senecio vulgaris* and *Cirsium arvense* having around 50 insect species associated with them. *Sonchus oleraceus, Tripleurospermum inodorum and Sinapis arvense* (latter in Brassicaceae) are also species rich. Only *Rumex obtusifolius* (a species of only local importance in arable cropping systems) supports levels of insect diversity similar to those of two target species (*Stellaria media and Polygonum aviculare*).

Clearly, weed species associated with host important or specific insects are of particular biodiversity value. Of the target species (Fig. 8.5), *Stellaria media, Chenopodium album, Polygonum aviculare*, *Galium aparine* and the grass *Poa annua* supports four or more host-important insect species. Among the non-target weed species (Fig. 8.6), those species with rich faunas mentioned in relation to species and family richness also have the highest number of host specific species. The identity of these species is given in Appendix 8.2.

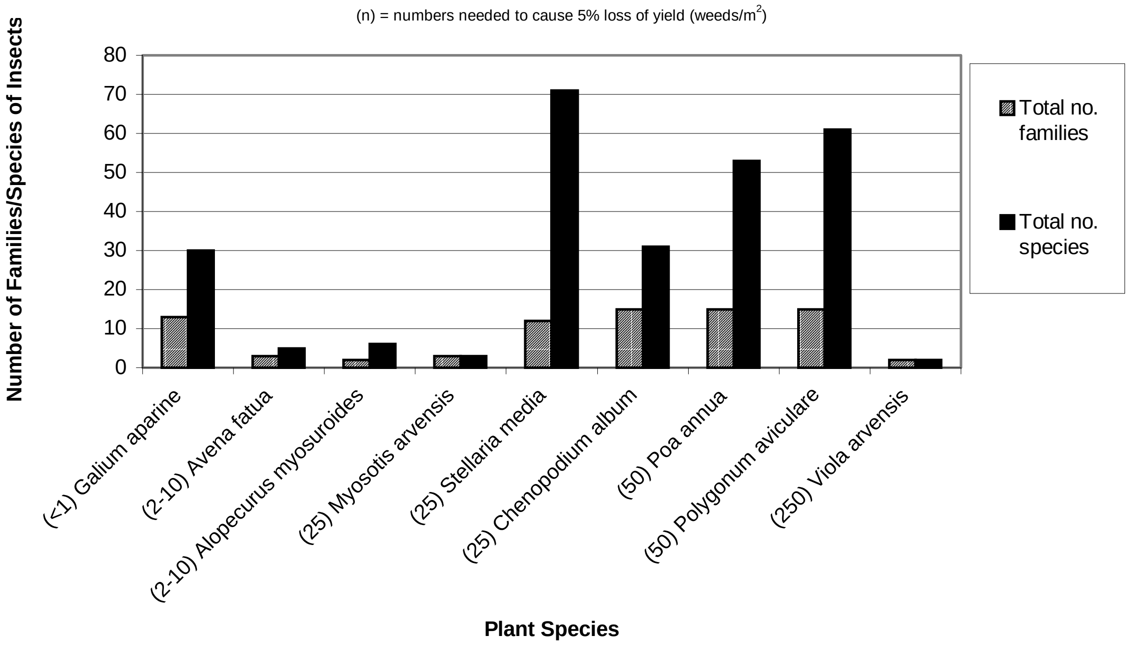
The arable weed community is associated with a number of rare Red Data Book species that feature in the UK Biodiversity Action Plan as meriting special conservation effort.

Two target and six non-target weed species have one or more Red Data Book species associated with them. Such species are generally highly host specific (Fig. 8.7). *Poa annua* has the most (3), while *Polygonum aviculare* and *Tripleurospermum inodorum* have two species each. Significantly, two target weed species (*Poa annua*, *Polygonum aviculare*) between them support five Red Data Book species. The identity of these species is given in Appendix 8.3. The insect species belong to a range of families within the Heteroptera (bugs), Chrysomelidae (leaf beetles) and Lepidoptera (moths), as well as two aphid species.

It is well known that certain weed species act as hosts to crop pest species. It is therefore important to consider potential pest status in any management decisions that may be made, as well as biodiversity value. Of the target species, six are recorded as hosts for pest species (Fig. 8.8). *Galium aparine*, *Chenopodium album* and *Poa annua* each have four species recorded, while *Stellaria media*, *Polygonum aviculare*, *Alopecurus myosuroides* three, three and two respectively. However, the proportion of insects in this category is very low (4.2% *Stellaria media*, 4.9% *Polygonum aviculare*). Appendix 8.4 gives the identity of these species. Non-target species also host a range of pest species with *Sinapis arvense* having 13 pest species (26%) associated with it (Fig. 8.9). Clearly, this species serves as an alternative host to many pests of crops in the Brassicaceae, undoubtedly mainly rape.

Figure 8.3: Number of: Insect families and species associated with target weed species

(n) = numbers needed to cause 5% loss of yield (weeds/m^2)



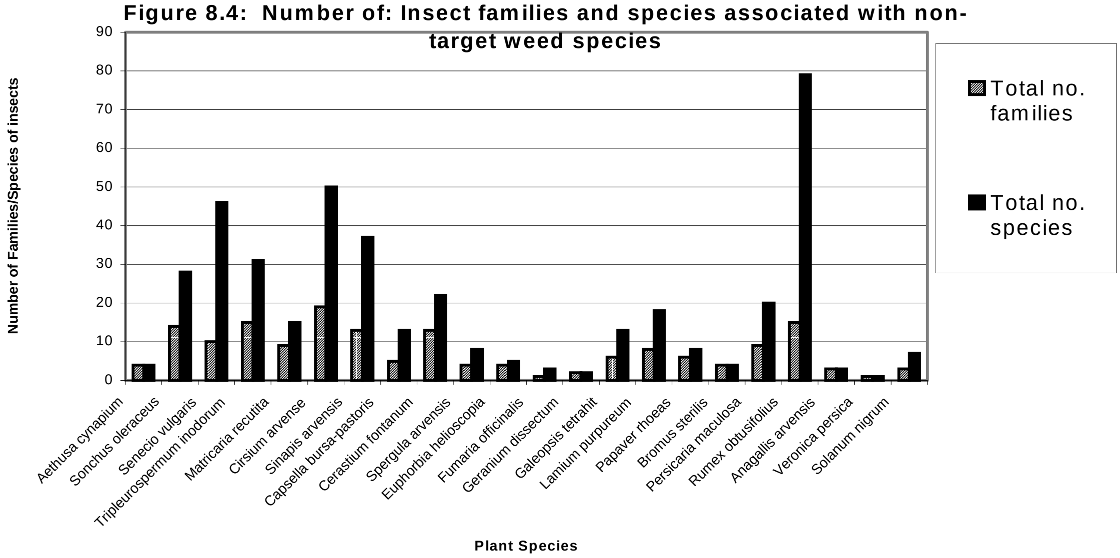


Figure 8.5: Number of: Host specific insect species associated with target weed species
(n) = numbers needed to cause 5% loss of yield (weeds/m^2)

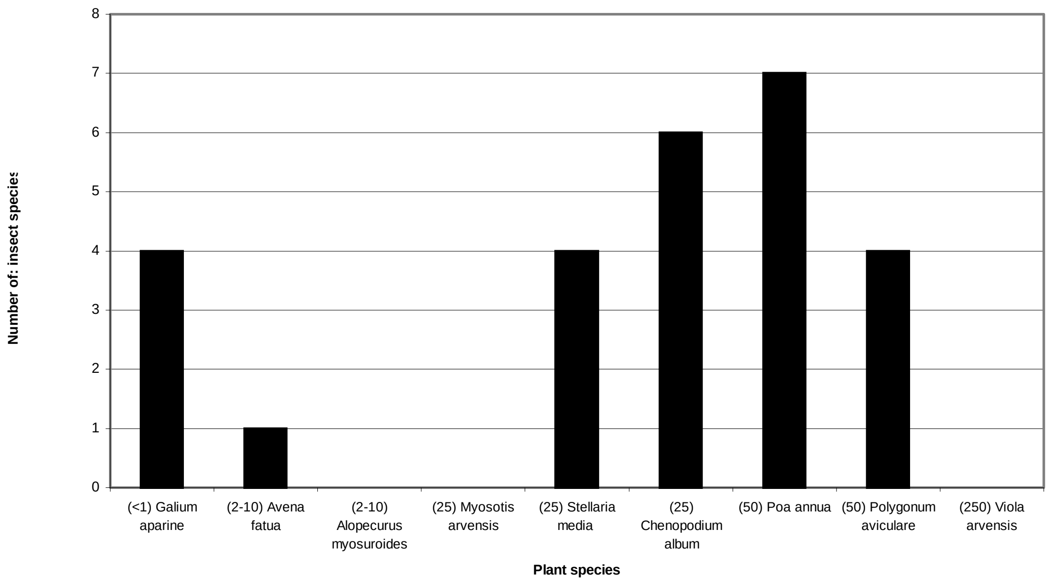


Figure 8.6: Number of: host specific insect species associated with non-target weed species

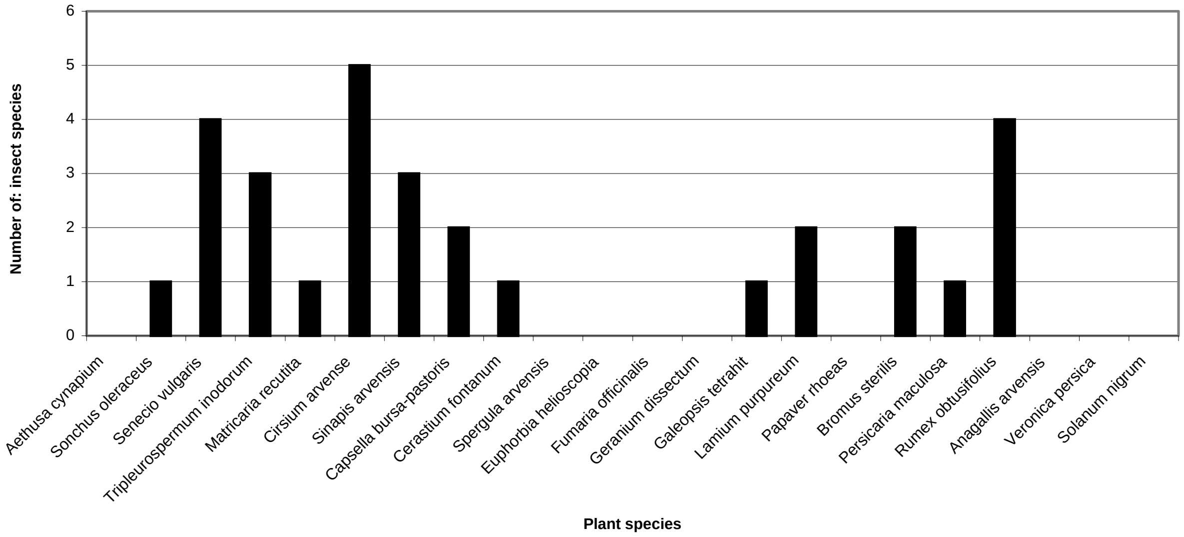


Figure 8.7: Number of: rare (Red Data Book species) associated with specific weed species

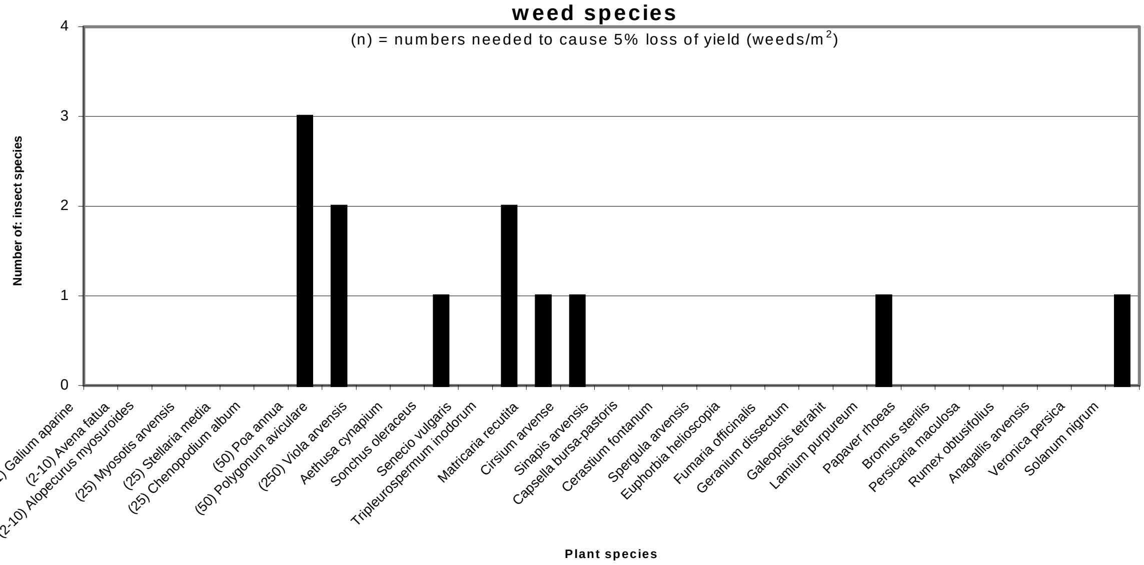


Figure 8.8: Target weed species that act as alternate hosts for pest species

(n) = numbers needed to cause 5% loss of yield (weeds/m²)

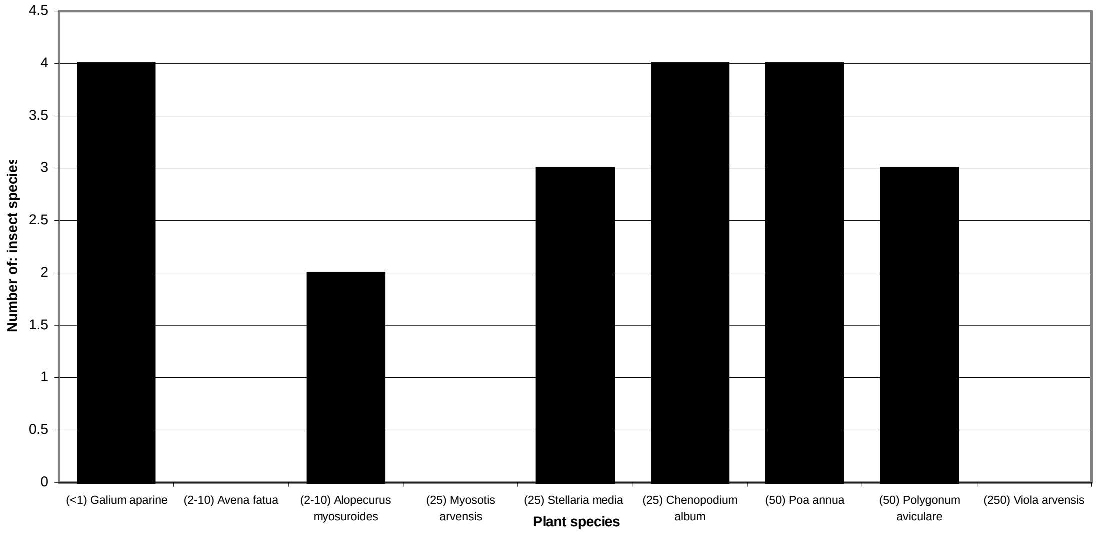
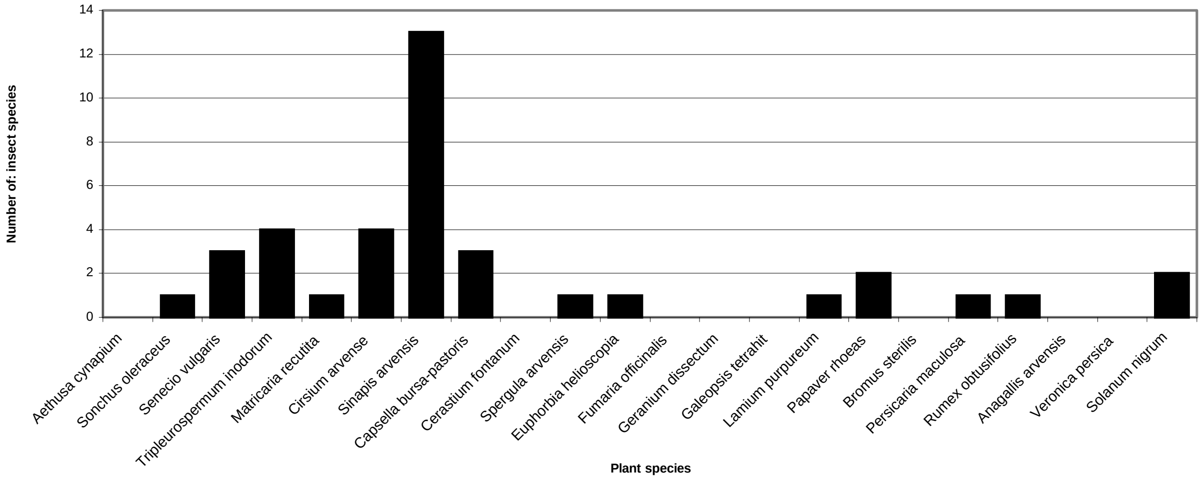


Figure 8.9: Non-target weed species that act as alternate hosts for pest species



The PIDB has the potential for far greater interrogation of the insect fauna in terms of life history traits and feeding strategies (chewers, sap feeders, leaf miners) and plant structural preferences (leaves, stems, flowers, seeds etc). Analysis of these trends was beyond the scope of this review. Relevant to this review would be information on the seasonality of life cycles in respect of timing of herbicide application. Unfortunately, these data are not available in the PIDB and thus further primary interrogation of the literature would be needed. Targeted work in the field would be eminently preferable.

Clearly, in determining the biodiversity significance of a particular weed species, we are interested in the number of invertebrate species it supports, their degree of 'rarity', balanced against the potential for the species to host pest insect species. What the PIDB does not take into account is the value of the species as a source of pollen or nectar for pollinating species, or as a host for parasitic or predatory species that may afford a level of biocontrol. However, there are likely to be strong correlations particularly in the case of parasitoids. A synthesis of these various attributes is given in Table 8.1.

Table 8.1 An estimate of the relative importance of the selected plant species for invertebrates, based on the available datasets. *** = very important, ** = important, * = moderately important, - = little importance or inadequate data available, nd = no data available.

Selected weed Species					
			Value for invertebrates		
Common Name	**Plant Species**	**Family**	**Value for invertebrates**	**No. Red Data Book species**	**No. Pest species**
Grasses					
Annual Meadow-grass	*Poa annua*	Festuceae	***	3	4
Barren Brome	*Bromus sterilis*	Bromeae	-	0	0
Black-grass	*Alopecurus myosuroides*	Agrostidae	*	0	2
Wild-Oat	*Avena fatua*	Aveneae	-	0	0
Forbs					
Black Nightshade	*Solanum nigrum*	Solanaceae	*	1	2
Black-bindweed	*Fallopia convolvulus*	Polygonaceae	nd	nd	nd
Broad-leaved Dock	*Rumex obtusifolius*	Polygonaceae	***	0	1
Charlock	*Sinapis arvensis*	Brassicaceae	***	0	13
Cleavers	*Galium aparine*	Rubiaceae	***	0	4
Common Chickweed	*Stellaria media*	Caryophyllaceae	***	0	3
Common Field-speedwell	*Veronica persica*	Scrophulariaceae	-	0	0
Common Fumitory	*Fumaria officinalis*	Fumariaceae	-	0	0
Common Hemp-nettle	*Galeopsis tetrahit*	Lamiaceae	**	0	0
Common Mouse-ear	*Cerastium fontanum*	Caryophyllaceae	**	0	0

Common Poppy	*Papaver rhoeas*	Papaveraceae	*	0	2
Corn Marigold	*Chrysanthemum segetum*	Asteraceae	nd	nd	nd
Corn Spurrey	*Spergula arvensis*	Caryophyllaceae	*	0	1
Cornflower	*Centaurea cyanus*	Asteraceae	nd	nd	nd
Creeping Thistle	*Cirsium arvense*	Asteraceae	***	1	4
Cut-leaved Crane's-bill	*Geranium dissectum*	Geraniaceae	-	0	0
Fat-hen	*Chenopodium album*	Chenopodiaceae	***	0	4
Field Forget-me-not	*Myosotis arvensis*	Boraginaceae	-	0	0
Field Pansy	*Viola arvensis*	Violaceae	-	0	0
Fool's Parsley	*Aethusa cynapium*	Apiaceae	-	0	0
Groundsel	*Senecio vulgaris*	Asteraceae	***	0	3
Knotgrass	*Polygonum aviculare*	Polygonaceae	***	2	3
Red Dead-nettle	*Lamium purpureum*	Lamiaceae	**	1	1
Redshank	*Persicaria maculosa*	Polygonaceae	**	0	1
Scarlet Pimpernel	*Anagallis arvensis*	Primulaceae	-	0	0
Scented Mayweed	*Matricaria recutita*	Asteraceae	**	1	1
Scentless Mayweed	*Tripleurospermum inodorum*	Asteraceae	***	2	4
Shepherd's-purse	*Capsella bursa-pastoris*	Brassicaceae	**	0	3
Smooth Sow-thistle	*Sonchus oleraceus*	Asteraceae	***	1	1
Sun spurge	*Euphorbia helioscopia*	Euphorbiaceae	*	0	1

Insect criteria based on number of insect species associated with particular weeds: 0-5 species -; 6-10 *; 11-25 **; 26+ ***. It must be appreciated that not all weed species have received equal data input in the PIDB.

The PIDB does not afford a measure of abundance. Consequently, for assessing the value of species in terms of resources for birds and small mammals, the data have to be viewed with some caution. However, it does provide taxonomic and functional categories of insect species to be determined (e.g. insects feeding externally or internally in plant tissues, flower or seed feeders etc), which are of clear relevance to the known preferred diet of farmland bird species.

8.3 New Dimensions

8.3.1. <u>Effects Of Herbicides On Soil Fauna</u>

There have been very few studies of the effects of herbicides on the soil fauna. This is an important and surprisingly neglected area. It is also of considerable relevance, since nutrient dynamics in the soil are strongly influenced by the soil meso- and micro-fauna, as well as the microbes. Apart from earthworms, meso-faunal groups most commonly represented in the soil include Collembola (springtails) and Acari (mites), which though of small individual biomass can be very abundant. The larvae of some holometabolous insect groups (e.g. Diptera and Coleoptera) can also be locally abundant, depending on extent and timing of insecticide applications. Furthermore, as adults on the foliage, these species provide an important component of biodiversity, as well as food resources for birds and small mammals. The complex network of biotic interactions in the soil is given in Fig. 8.10.

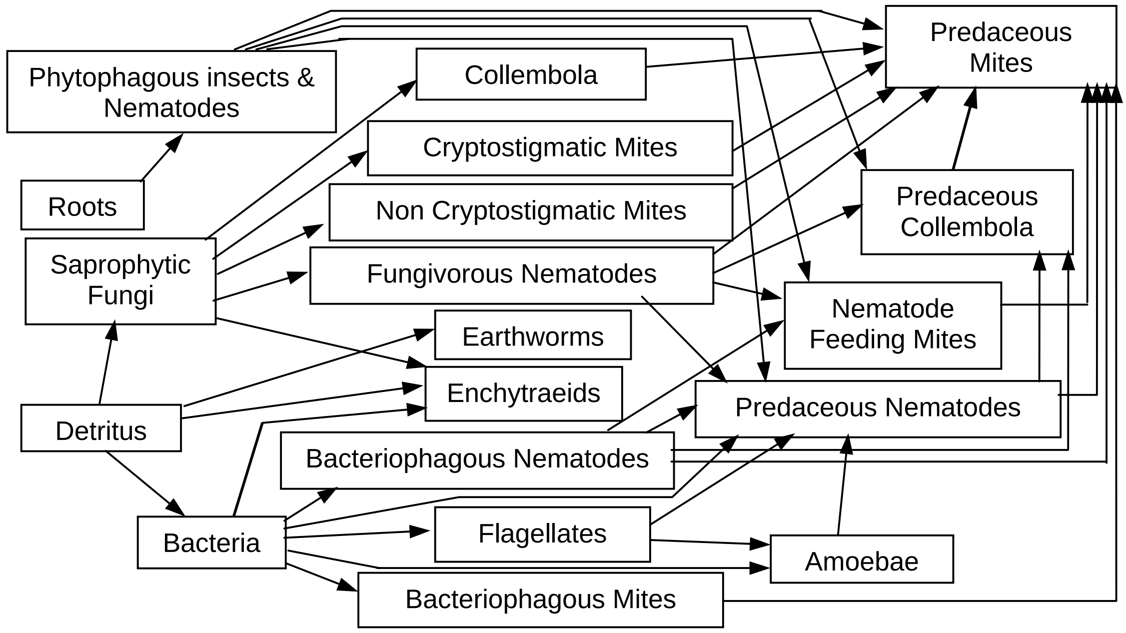


Fig. 8.10. Complex food web in soil (Hooper *et al.* 2000).

European Directive 91/414/EC requires that plant protection products should be evaluated for their potential effects on the decomposition of organic matter, to protect soil fertility and the biodiversity of soil organisms, and thereby the general 'health' of the environment. To date, herbicide-induced changes in litter decomposition processes have been attributed to (i) direct toxic effects of herbicides on soil and litter biota or (ii) indirect effects resulting from altered chemical composition of the litter or microclimate of the decomposition subsystem. Hendrix & Parmelee (1985) used a litterbag experiment to investigate the influence of atrazine, paraquat and glyphosate on decomposition of grass litter in a fallow field in Georgia, USA, to explore inconsistencies in the literature. At ten times the recommended concentrations, decomposition processes were significantly changed by direct application of the herbicide. This was attributed to (i) the promotion of microbial utilisation of the herbicide as a carbon source, (ii) increasing the importance of micro-arthropod grazing relative to comminution, (iii) eliminating or reducing the importance of predatory micro-arthropods, and (iv) increasing the rate of nutrient loss from the litter via microbial and micro-arthropod activity. It appears that decreased decomposition rates most often result from direct treatment of plant residues, where herbicide effects are exerted through direct action on the soil and litter biota. On the other hand, accelerated decomposition rates most often result from treatment of living vegetation and subsequent alteration of litter composition or the abiotic environment (Wardle *et al.*1999b). The effects of herbicide treatment on the quality of the litter and therefore the dynamics of decomposition are not known.

Wardle *et al*. (1993; 1999a), working in New Zealand, have investigated the effects of agricultural intensification (including the effects of two herbicides: terbumeton / terbuthylazine and bromacil) on the soil fauna in an annual cropping system (maize) and a perennial system (asparagus) over a seven-year period. Generally, soil arthropods were positively correlated with weed biomass, as a result of vegetation structure above and below ground, host plant availability for specialist species and more favourable microclimatic conditions (Krooss & Schaefer 1998). Consequently, these groups showed significant declines in populations following herbicide application. Direct effects due to toxicity were difficult to determine in the field.

Wardle (e.g. Wardle *et al*. 1999c) is currently attempting experimental manipulations involving the removal of representatives of different plant functional groups on the diversity of soil biota and decomposition processes. The implications of this, and related purely ecological work, are high in terms of understanding effects of herbicides on non-target weed species.

PN0938 is currently reviewing the effects of pesticides on non-target soil organisms, especially those involved in the decomposition of organic matter. However, the main focus is on the microbial processes involved in the decomposition of organic matter, the impact and role of the meso- fauna still requires attention. Indeed, there is urgent need for research to explore the direct effects of herbicides on the soil biota, but more especially the indirect effects, mediated via physiological changes in the host plant impacting on decomposition. For example, the effects of herbicides on symbiotic organisms (mycorrhizal fungi and nitrogen-fixing bacteria) are virtually unknown. Such experiments need to be long term, as there appears to be a time lag in changes in the dynamics of the soil biota compared to that of the weed community. This has been demonstrated under another MAFF-funded project, BD1434 on arable reversion.

8.3.2. Sub-Lethal Effects Of Herbicides On Invertebrates

Sub-lethal effects of herbicide application on invertebrate populations may be direct, by modifying the fecundity of the species, or indirect, by altering the physiology of the plants as hosts for invertebrates, thereby influencing their behaviour or population dynamics.

There are already some examples of herbicide application impacting negatively on insect fecundity. Chiverton & Sotherton (1991) showed that carabid fecundity, in terms of higher mean egg number, was found in untreated plots. They also demonstrated, by dissection of the alimentary canal, that the untreated species had taken significantly more meals / food biomass, suggesting that herbicide application reduces the number of cereal aphids consumed. Interestingly, there were no treatment differences in pitfall trap catches of carabids, though there were more females of *Agonum dorsale*. Although further work may be of interest, the potential for indirect sub-lethal effects, mediated via changes in the physiology of the plant, is more wide ranging and likely to be more relevant.

The responses of herbivorous insects to plants treated with sub-lethal doses of herbicide have received very little attention (but see Campbell 1988). However, the effects on crop plants can be to increase insect pest populations (Oka & Pimentel 1976). It is also known that herbicides can affect populations of insect herbivores living on surviving weed plants in treated fields or plants in uncultivated habitats subjected to herbicide deposition. These positive herbivore populations appear to be related to the higher nutritional value of the foliage when the plant is stressed (Masters, Brown & Gange 1993). The latter work showed that drought stress, or that imposed by root pruning or herbivory, resulted in higher N/C ratios in the foliage, thereby inducing higher fecundity in foliar-feeding insects and higher population levels. (Higher populations of invertebrates may also occur as a result of reduced densities and efficiency of predators or parasitoids as a result of direct effects of herbicide application). The increased levels of free amino acids in the phloem, derived from reallocation of resources from storage organs to actively growing plant parts, particularly favours sap-sucking insects or those feeding on meristematic tissues. Indeed, it would appear that insects chewing the leaves of plants respond rather differently. For example, populations of the beetle *Gastrophysa viridula* declined when feeding on Asulam-treated *Rumex obtusifolius* (Speight & Whittaker 1987), a trend that was explained by the lower nutrient quality of treated leaves. Interestingly, the timing of application in relation to the life cycle of the beetle was more important than the concentration of the Asulam. A similar response, to the application of a sub-lethal dose of Chlorsulfuron to *Polygonum* (=*Fallopia*) *convolvulus*, was found in *Gastrophysa polygoni*, which reduced beetle survival (Kjær & Elmegaard 1996). The herbicide is non-toxic to the insect when applied directly and only caused significant effects when mediated via the host plant. However, clear effects were seen on the performance of the beetle on whole plants, relating to the changes in host plant quality, which were measured in terms of larval survival, development time and pupal weight. Survival of the beetles decreased with increasing herbicide rate and development time was prolonged for surviving larvae. Also, dry weight of the pupae (a surrogate for insect fecundity) was inversely correlated with the rate of application. The results are suggestive of an induced plant response mechanism with the threshold being lowered when the plants are stressed. Indeed, there was a clear density-dependent effect on survival caused by the herbivore-density-dependent production of induced chemicals. However, the effect of Chlorsulfuron on plant-insect interactions is probably rather specific and not applicable to herbicides with different phytotoxic properties (Kjær & Elmegaard 1996).

If this kind of herbivore-induced disturbance of plant-insect interactions is significant in the field, it is important when considering the management of crop plants. It also is of significance to environmental protection in regard to deposition of herbicides on uncultivated vegetation. The results are of particular interest to conservation and wildlife management, when evaluating the value of non-target weed species as basic links in food chains of the agro-ecosystem, particularly when reduced herbicide rates are applied. It would appear that herbicide-treated plant material is of limited value as a food resource for some herbivorous insects, particularly at high densities.

Acknowledgements
The author wishes to thanks Dr Jeff Ollerton for guidance in sourcing data on insect pollinators and Dr Lena Ward for personal assistance with explanation of the PIDB. Thanks to Alex Brook for technical assistance in processing the information from the PIDB.

Appendix 8.1 Summary of information on key pollen and nectar-feeding insect groups, including 25 species additional to PN0923. From: [1]Clapham *et al*. 1987. [2]Colyer & Hammond 1968. [3]Cowgill, Wratten & Sotherton 1993. [4]Free & Butler 1959. [5]Free 1993. [6]Fussell & Corbet 1992. [7]Knuth (1906, 1908, 1909). [8]Proctor & Yeo 1973. [9]Saure 1996. [10]Stace 1997. [11]Westrich 1996. The flower visitor abbreviations used are as follows: BB = Bumblebees; SB = Solitary bees; HF = Hoverflies; BF = Butterflies; F = Flies; M = Moths; B = Beetles; W = Wasps (including sphecids, ichneumonids, etc.)

Common Name	Plant Species	Plant Family	Insect Taxon (common name)	Breeding In/Out
Grasses				
Annual Meadow-grass	*Poa annua*	Poaceae	Wind pollinated	In
Barren Brome	*Bromus sterilis*	Poaceae	Wind pollinated	In/sometimes Out
Black-grass	*Alopecurus myosuroides*	Poaceae	Wind pollinated	?
Wild-oat	*Avena fatua*	Poaceae	Wind pollinated	?
Forbs				
Black Nightshade	*Solanum nigrum*	Solanaceae	Bees, HF [7]	?
Black-bindweed	*Fallopia convolvulus*	Polygonaceae	Mainly selfing, occasional SB & HF.[7]	In/Out
Broad-leaved Dock	*Rumex obtusifolius*	Polygonaceae	Wind pollinated.[8]	In/Out
Charlock	*Sinapis arvensis*	Brassicaceae	Bees: (*Andrena agilissima Osmia brevicornis*)[11] Honeybees (on *Sinapis alba*)[5] (B, F, HF, BB, SB, BF, M) [7] Freely visited by flies and bees.[1]	In/Out
Cleavers	*Galium aparine*	Rubiaceae	F, HF, W, but mainly selfing?[7] Sparingly visited by small insects.[1]	In/sometimes Out
Common Chickweed	*Stellaria media*	Caryophyllaceae	Honeybees (*Stellaria spp.*)[5] (F, HF)[7] Visited by numerous flies and small bees, etc, automatically self-pollinated.[1]	In/sometimes Out
Common Field-speedwell	*Veronica persica*	Scrophulariaceae	Bees: *Andrena viridescens*.[11] Visited by various insects, often selfed.[1]	In/sometimes Out
Common Fumitory	*Fumaria officinalis*	Fumariaceae	(BB, SB) [7] Visited by bees.[1]	In/sometimes Out
Common Hemp-nettle	*Galeopsis tetrahit*	Lamiaceae	Bees: *Osmia andrenoides*[11] Bumblebees (on Laminaceae family)[4] (BB, SB) [7]	In
Common Mouse-ear	*Cerastium fontanum*	Caryophyllaceae	(F, HF) [7] Visited chiefly by flies.[1]	In/Out
Common Poppy	*Papaver rhoeas*	Papaveraceae	Bees[5] (B, F, HF, BB, SB) [7]	Out
Corn Marigold	*Chrysanthemum segetum*	Asteraceae	Syrphidae (Hoverflies)[2] Bees: *Andrena denticulate*[11] Visited freely especially by flies[1].	Out
Corn Spurrey	*Spergula arvensis*	Caryophyllaceae	(F, HF, SB) [7] Visited occasionally by Syrphids and some other insects.[1]	In/sometimes Out

Cornflower	*Centaurea cyanus*	Asteraceae	*Bombus spp.* (Bumblebees)[4] Syrphidae (Hoverflies). Bees: *Andrena denticulate*[11] Bees: *Heriades crenulatus*[9] (HF, F, SB, BB, M, BF)[7] Freely visited by flies and bees.[1]	Out
Creeping Thistle	*Cirsium arvense*	Asteraceae	*Bombus spp.* (Bumblebees)[5] Satyridae (Butterflies/Browns)3 Syrphidae (Hoverflies)[3] Bees: *Andrena denticulate*[11] Bees: *Heriades crenulatus*[9] (F, B, SB, BB, M, BF)[7] Visited freely by a great variety of insects[1].	Out/sometimes In
Cut-leaved Crane's-bill	*Geranium dissectum*	Geraniaceae	(SB, F, HF) [7] Few insect visitors.[1]	In/sometimes Out
Fat-hen	*Chenopodium album*	Chenopodiaceae	Mainly wind pollinated?	In/Out
Field Forget-me-not	*Myosotis arvensis*	Boraginaceae	-	In/sometimes Out
Field Pansy	*Viola arvensis*	Violaceae	Mainly selfing ?[8] Pollinated by various insects, often selfed.[1]	In/Out
Fool's Parsley	*Aethusa cynapium*	Apiaceae	Bees: *Andrena proxima*[11] (HF, F, SB, BB, M)[7]	In
Groundsel	*Senecio vulgaris*	Asteraceae	Bees: *Andrena denticulate*[11] (HF, F, SB)[7] Little visited by insects and normally self pollinated.[1]	In/sometimes Out
Knotgrass	*Polygonum aviculare*	Polygonaceae	Syrphidae (Hoverflies)[3] mainly selfing, occasional HF.[7]	In
Red Dead-nettle	*Lamium purpureum*	Lamiaceae	Bees: *Osmia andrenoides*[11] Bumblebees (on Laminaceae family)[4] (BB, SB) [7]	In/Out
Redshank	*Persicaria maculosa*	Polygonaceae	(F, HF, SB, BF) [7] Visited by numerous insects , especially bees.[1]	Out
Scarlet Pimpernel	*Anagallis arvensis*	Primulaceae	Mainly selfing, occasional SB.[7]	In/sometimes Out
Scented Mayweed	*Matricaria recutita*	Asteraceae	Syrphidae (Hoverflies)[3] Bees: *Andrena denticulate*[11] Freely visited by flies and some small bees[1].	Out
Scentless Mayweed	*Tripleurospermum inodorum*	Asteraceae	Bees: *Andrena denticulate*[11] (F, B, HF, SB, BB, W, BF) [7]	Out/sometimes In
Shepherd's-purse	*Capsella bursa-pastoris*	Brassicaceae	Bees: (*Andrena agilissima* *Osmia brevicornis*) [11] (F, SB, HF) [7] Visited by small insects and automatically self-pollinated.[1]	In
Smooth Sow-thistle	*Sonchus oleraceus*	Asteraceae	Tachinidae (parasite flies)[1] Bees: *Andrena denticulate*[11] (F, SB, BB, HF, BF)[7] Visited by various insects, especially bees and hoverflies.[7]	In/sometimes Out
Sun Spurge	*Euphorbia helioscopia*	Euphorbiaceae	(F, HF, occasional SB & W) [7]	In

Appendix 8.2 Insect species with specific or important hosts (data from Phytophagous Insect Data Base, CEH, 2001).

Common Name	**Important host plant species**	**Plant Family**	**Insect Family**	**Insect species with important plant hosts.**
Grasses				
Annual Meadow-grass	*Poa annua*	Festuceae	Agromyzidae	*Phytomyza milii* Kaltenbach
			Chaitophoridae	*Sipha maydis* Passerini
			Noctuidae	*Mesapamea secalis* (L.) *Pachetra sagittigera* (Hufnagel)
			Pyralidae	*Agriphila poliellus* (Treitschke)
			Satyridae	*Aphantopus hyperantus* (L.) *Coenonympha pamphilus* (L.) *Lasiommata megera* (L.) *Maniola jurtina* (L.)
Barren Brome	*Bromus sterilis*	Bromeae	Elachistidae	*Elachista argentella* (Clerck) *Eriophyes tenuis Nalepa*
Wild-oat	*Avena fatua*	Aveneae	Aphididae	*Sitobion avenae* (F.)
Forbs				
Broad-leaved Dock	*Rumex obtusifolius*	Polygonaceae	Aphididae	*Dysaphis radicola* (Mordvilko) II *Apion violaceum* Kirby, W.
			Chrysomelidae	*Gastrophysa viridula* (Degeer)
			Noctuidae	*Xestia c-nigrum* (L.)
Charlock	*Sinapis arvensis*	Brassicaceae	Aeolothripidae	*Melanthrips fuscus* (Sulzer)
			Pieridae	*Pieris napi* (L.) *Anthocharis cardamines* (L.)
			Aphididae	*Dysaphis pyri* (Boyer de Fonscolombe) II
			Eriophyidae	*Cecidophyes galii* (Karpelles)
			Miridae	*Polymerus nigritus* (Fallen)
			Noctuidae	*Naenia typica* (L.)
Common Chickweed	*Stellaria media*	Caryophyllaceae	Aphididae	*Myzus cymbalariellus* Stroyan
			Arctiidae	*Diaphora mendica* (Clerck)
			Noctuidae	*Xestia baja* (Denis & Schiffermuller) *Xestia c-nigrum* (L.)
Common Hemp-nettle	*Galeopsis tetrahit*	Lamiaceae	Aphididae	*Cryptomyzus galeopsidis* (Kaltenbach) II
Common Mouse-ear	*Cerastium fontanum*	Caryophyllaceae	Rhopalidae	*Rhopalus parumpunctatus Schilling*
Creeping Thistle	*Cirsium arvense*	Asteraceae	Agromyzidae	*Phytomyza spinaciae* Hendel
			Cecidomyiidae	*Dasineura gibsoni* Felt
			Chrysomelidae	*Lema cyanella* (L.)
			Nymphalidae	*Cynthia cardui* (L.)
			Tephritidae	*Urophora cardui* (L.)
Fat-hen	*Chenopodium album*	Chenopodiaceae	Aphididae	*Aphis fabae* Scopoli II
			Chrysomelidae	*Cassida nebulosa* (L.)
			Coccinellidae	*Subcoccinella vigintiquattuorpunctata* (L.)
			Coleophoridae	*Coleophora sternipennella* (Zetterstedt)
			Curculionidae	*Chromoderus affinis* (Schrank)
			Miridae	*Orthotylus flavosparsus* (Sahlberg)
Groundsel	*Senecio vulgaris*	Asteraceae	Agromyzidae	*Napomyza lateralis* (Fallen)
			Arctiidae	*Callimorpha dominula* (L.)
			Geometridae	*Orthonama obstipata* (F.)
			Noctuidae	*Xestia c-nigrum* (L.)

Knotgrass	*Polygonum aviculare*	Polygonaceae	Aphalaridae	*Aphalara maculipennis* Low
			Chrysomelidae	*Gastrophysa polygoni* (L.) *Chaetocnema concinna* (Marsham)
			Coleophoridae	*Augasma aeratella* (Zeller)
			Geometridae	*Orthonama obstipata* (F.)
			Noctuidae	*Lacanobia contigua* (Denis & Schiffermuller)
Red Dead-nettle	*Lamium purpureum*	Lamiaceae	Aphididae	*Cryptomyzus galeopsidis* (Kaltenbach) II
			Arctiidae	*Diaphora mendica* (Clerck)
Redshank	*Polygonum persicaria*	Polygonaceae	Geometridae	*Orthonama obstipata* (F.)
Scented Mayweed	*Matricaria recutita*	Asteraceae	Aphididae	*Aphis vandergooti* (Borner, C.)
Scentless Mayweed	*Tripleurospermum inodorum (=Tripleurospermum maritimum ssp. inodorum*	Asteraceae	Agromyzidae	*Phytomyza pullula Zetterstedt* *Napomyza lateralis* (Fallen)
			Noctuidae	*Noctua janthina* (Denis & Schiffermuller) *Heliothis peltigera* (Denis & Schiffermuller)
Shepherd's-purse	*Capsella bursa-pastoris*	Brassicaceae	Aphididae	*Aphis fabae* Scopoli II *Aphis frangulae* Kaltenbach II
Smooth Sow-thistle	*Sonchus oleraceus*	Asteraceae	Rhopalidae	*Liorhyssus hyalinus* (F.)

Appendix 8.3 Red data book species (data from Phytophagous Insect Data Base, CEH, 2001).

Common Name	Plant species	Plant Family	Insect Family	RDB insect species
Grasses				
Annual Meadow-grass	*Poa annua*	Poaceae	Chaitophoridae	*Sipha maydis* Passerini
			Noctuidae	*Pachetra sagittigera*
			Pyralidae	*Agriphila poliellus*
Forbs				
Black Nightshade	*Solanum nigrum*	Solanaceae	Chrysomelidae	*Epitrix pubescens* (Koch)
Creeping thistle	*Cirsium arvense*	Asteraceae	Aphididae	*Dysaphis lappae* (Koch, C.L.)
Knotgrass	*Polygonum aviculare*	Polygonaceae	Aphalaridae	*Aphalara maculipennis* Low
			Coleophoridae	*Augasma aeratella*
Red Dead-nettle	*Lamium purpureum*	Lamiaceae	Aphididae	*Aphis lamiorum* (Borner, C.)
Scented Mayweed	*Matricaria recutita*	Asteraceae	Lygaeidae	*Metopoplax ditomoides* (Costa)
Scentless Mayweed	*Tripleurospermum inodorum*	Asteraceae	Chrysomelidae	*Chrysolina marginata (L.)*
			Lygaeidae	*Metopoplax ditomoides* (Costa)
Smooth Sow-thistle	*Sonchus oleraceus*	Asteraceae	Rhopalidae	*Liorhyssus hyalinus*

Appendix 8.4 Pest species associated with arable weed species (Data from Phytophagous
Insect Data Base, CEH, 2001).

Common Name	**Plant Species**	**Plant Family**	**Insect Family**	**Pest insect species**
Grasses				
Annual Meadow-grass	*Poa annua*	Poaceae	*Aphididae*	*Myzus ascalonicus Doncaster* *Macrosiphum fragariae* (Walker)
			Chloropidae	*Oscinella frit* (L.)
			Noctuidae	*Mesapamea secalis* (L.)
Black-grass	*Alopecurus myosuroides*	Poaceae	Cecidomyiidae	*Dasineura alopecuri* (Reuter) *Sitodiplosis mosellana* (Gehin)
Forbs				
Black Nightshade	*Solanum nigrum*	Solanaceae	Chrysomelidae	*Leptinotarsa decemlineata* (Say)
			Miridae	*Lygocoris pabulinus*
Broad-leaved Dock	*Rumex obtusifolius*	Polygonaceae	Curculionidae	*Rhinoncus pericarpius* (L.)
Charlock	*Sinapis arvensis*	Brassicaceae	Aphididae	*Lipaphis erysimi* (Kaltenbach) *Myzus persicae* (Sulzer)
			Cecidomyiidae	*Contarinia nasturtii* (Kieffer) *Dasineura brassicae* (Winnertz)
			Chrysomelidae	*Phyllotreta cruciferae* (Goeze) *Phyllotreta atra* (F.) *Phyllotreta undulata* Kutschera *Phyllotreta nemorum* (L.)
			Curculionidae	*Ceutorhynchus quadridens* (Panzer) *Ceutorhynchus pleurostigma* (Marsham) *Baris laticollis* (Marsham)
			Nitidulidae	*Meligethes aeneus* (F.)
			Thripidae	*Thrips angusticeps* Uzel
Cleavers	*Galium aparine*	Rubiaceae	Aphididae	*Aphis fabae* Scopoli II *Macrosiphum fragariae* (Walker) *Sitobion avenae* (F.)
			Cecidomyiidae	*Hybolasioptera cerealis* (Lindeman)
Common Chickweed	*Stellaria media*	Caryophyllaceae	Aphididae	*Myzus ascalonicus* Doncaster *Aulacorthum solani* (Kaltenbach)
			Curculionidae	*Hypera arator* (L.)
Common Poppy	*Papaver rhoeas*	Papaver rhoeas	Agromyzidae	*Phytomyza horticola* Goureau
			Curculionidae	*Stenocarus umbrinus* (Gyllenhal)
Corn Spurrey	*Spergula arvensis*	Caryophyllaceae	Curculionidae	*Hypera arator* (L.)
Creeping Thistle	*Cirsium arvense*	Asteraceae	Aphididae	*Aphis fabae* Scopoli II
			Miridae	*Lygocoris spinolai* (Meyer-Dur) *Lygocoris pabulinus* (L.)
			Thripidae	*Thrips angusticeps* Uzel
Fat-hen	*Chenopodium album*	Chenopodiaceae	Aphididae	*Aphis fabae* Scopoli

			Miridae	*Lygocoris pabulinus* (L.) *Lygus maritimus* Wagner *Lygus rugulipennis* Poppius
Groundsel	*Senecio vulgaris*	Asteraceae	Agromyzidae	*Napomyza lateralis (Fallen)*
			Aphididae	*Brachycaudus cardui* (L.)
			Miridae	*Lygocoris pabulinus* (L.)
Knotgrass	*Polygonum aviculare*	Polygonaceae	Aphididae	*Aphis nasturtii* Kaltenbach
			Chrysomelidae	*Chaetocnema concinna* (Marsham)
			Noctuidae	*Discestra trifolii* (Hufnagel)
Red Dead-nettle	*Lamium purpureum*	Lamiaceae	Aphididae	*Cryptomyzus galeopsidis* (Kaltenbach) II
Redshank	*Persicaria maculosa*	Polygonaceae	Aphididae	*Aphis nasturtii* (Kaltenbach)
Scented Mayweed	*Matricaria recutita*	Asteraceae	Aphididae	*Aphis fabae* Scopoli II
Scentless Mayweed	*Tripleurospermum inodorum (=Tripleurospermum maritimum ssp. inodorum*	Asteraceae	Agromyzidae	*Napomyza lateralis* (Fallen)
			Miridae	*Adelphocoris lineolatus* (Goeze) *Calocoris norvegicus* (Gmelin) *Lygus rugulipennis* Poppius
Shepherd's-purse	*Capsella bursa-pastoris*	Brassicaceae	Aphididae	*Aphis nasturtii Kaltenbach Lipaphis erysimi* (Kaltenbach) *Myzus persicae* (Sulzer)
Smooth Sow-thistle	*Sonchus oleraceus*	Asteraceae	Thripidae	*Thrips angusticeps* Uzel
Sun Spurge	*Euphorbia helioscopia*	Euphorbiaceae	Aphididae	*Macrosiphum euphorbiae* (Thomas, C.A.)

9. RELATIONSHIPS BETWEEN WEEDS, HERBICIDES AND BIRDS

9.1. Introduction

It is now well established that many species of farmland birds are undergoing long term population declines and range contractions (Fuller *et al.*, 1995; Siriwardena *et al.*, 1998). Baillie *et al*. (2001) provide the most recent data on population declines. Among farmland birds, grey partridge *Perdix perdix*, turtle dove *Streptopelia turtur*, skylark *Alauda arvensis*, song thrush *Turdus philomelos*, spotted flycatcher *Muscicapa striata*, starling *Sturnus vulgaris*, house sparrow *Passer domesticus*, tree sparrow *Passer montanus*, linnet *Carduelis cannabina*, bullfinch *Pyrrhula pyrrhula*, yellowhammer *Emberiza citrinella*, reed bunting *Emberiza schoeniclus* and corn bunting *Miliaria calandra* have declined by over 50% between 1968 and 1998, based on Common Bird Census (CBC) data. Several species have experienced major declines over the ten years 1988-1998, including tree sparrow (63% decline), spotted flycatcher (55%), turtle dove (42%), yellowhammer (40%) and starling (30%). The causes of these declines are not fully understood in most cases, though there is strong evidence that concurrent changes in agricultural practices are largely responsible. Potential mechanisms are reviewed by Fuller (2000), and include pesticides, though only for one species, the grey partridge, has a relationship between pesticide use and population decline been conclusively demonstrated (Burn, 2000; Campbell *et al.*, 1997).

Herbicides can affect birds either by affecting the structure of their habitat, particularly nesting habitat, or by affecting food supply. Direct effects (i.e. toxicity) are not considered important, though they can be for other classes of pesticides such as insecticides, molluscicides and rodenticides (Burn, 2000). Campbell *et al*. (1997) considered that herbicide impacts on nesting habitat were unlikely to be significant, though they make the point that for crop-nesting species which prefer short or open crops, such as stone curlew *Burhinus oedicnemus* and skylark, herbicide use may make the habitat more attractive for nesting. Selective application of herbicide to small areas of arable crops has been used to create bare patches to enable stone curlews to rear second broods, and a similar approach is currently being investigated for skylarks in winter cereals by the RSPB. Non-crop nesting habitats were reviewed in a previous report (Breeze *et al.*, 1999).

Herbicide effects on the food supply of birds may be of two kinds:

(i) through reduction in seeds and other plant food

(ii) reduction in numbers or availability of invertebrate food by removal of invertebrate host plants

Seeds are particularly important for granivorous species during the winter although some depend on them all year. Chicks of most species, even those which are granivorous as adults, require invertebrate food, though there are some exceptions e.g. linnet, turtle dove. Recent reviews of the diet of farmland birds include Buxton *et al*., 1996; Wilson *et al*., 1996 and Wilson *et al*., 1999 (see also Appendix 9.2). In this section the importance of different weed species in the diet of birds is analysed, and the potential impact of herbicide use is considered.

9.2. The Diet Of Farmland Birds

Weeds

Arable plants (mostly regarded as “weeds”) form a major part of the diet of many farmland birds (see Appendix 9.2, Table D). However, weed species vary considerably in terms of their relative importance in bird diet. Weed species have been categorised in terms of their importance to birds as seeds as described below. Weeds are also important as host plants for arthropods which are eaten by birds, but there is insufficient information to classify their relative importance for birds in these terms because, in addition to difficulties in distinguishing preference from availability, and the absence of knowledge of the relative food value of different taxa (which also apply to weed seeds; see below), it is not generally known to what extent arthropod taxa are dependent on any specific plant species (but see below for some examples where dependency can be demonstrated). Indeed, for many arthropods, vegetation density and structure may be more important than botanical composition (see section 8).

Method

Plants from the list of representative common weed species given in Table 9.1 were classified as important or present in the diet of each bird species. Data were derived from previous reviews (Breeze *et al.*, 1999; Buxton *et al.*, 1998; Wilson *et al.*, 1996). The level of taxonomic specification for plants varied, so information was compiled at family, genus and species level depending on the information available. However, there were few records for individual species and the results are included only for completeness (Appendix 9.1).

There are considerable difficulties in deriving quantitative assessments of importance in the diet where information is from many sources, because different methods have been used to derive data and taxonomic specificity varies considerably. Measurements of importance in the diet may be recorded by observation of feeding or by analysis of gut contents or faecal matter. Data may be presented either as an overall biomass across many individuals, or as a frequency of occurrence. Furthermore, preference is impossible to define since few studies detail the availability of food sources. The distinction between presence and importance in the diet is therefore subjective. Wilson *et al*. (1996) defined a food item as important if it comprised a mean of more than 5% of the diet over all quantitative studies reviewed or if the authors stated that they considered it to be important at some point in the year. However, this report does not give details to the species level, only for selected families and genera. Some more specific data were derived from Buxton *et al*. (1998) where importance was defined at the 10% level in any study. There were few conflicting results and most of the differences reflected absences from each dataset.

Bird species considered were those identified by Breeze *et al*. (1999) (Appendix 3.2.1), excluding those that are recorded as feeding exclusively on invertebrates. Frequency data (number of bird species for which each plant taxon was ‘present’ or ‘important’ in the diet) were derived at each taxonomic level for birds in the following groups: all seed/plant-eating species, BAP priority species (Anon 1998) and CBC rapidly or moderately declining species (Baillie *et al.*, 2001) (Table 9.1). Plant family, genus and species were then ranked in order of importance for each grouping, sorted by importance then presence in the diet (see Appendix 9.1). These rankings were then used to group the taxa into four categories: “very important”, “important”, “present” and “nominally present”.

Table 9.1. Bird species for which the importance of various weed taxa in the diet was assessed. * identifies BAP priority species or species in rapid or moderate decline.

Latin name	Common name	BAP Priority	CBC Rapid Decline	CBC Moderate Decline
Alectoris rufa	Red-legged Partridge			
Perdix perdix	Grey Partridge	*	*	
Coturnix coturnix	Common Quail			
Phasianus colchicus	Common Pheasant			
Burhinus oedicnemus	Stone Curlew			
Pluvialis apricaria	European Golden Plover			
Vanellus vanellus	Northern Lapwing			*
Columba oenas	Stock Dove			
Columba palumbus	Common Wood Pigeon			
Streptopelia decaocto	Eurasian Collared Dove			
Streptopelia turtur	European Turtle Dove	*	*	
Alauda arvensis	Skylark	*	*	
Anthus pratensis	Meadow Pipit			*
Troglodytes troglodytes	Winter Wren			
Prunella modularis	Hedge Accentor (Dunnock)			*
Erithacus rubecula	European Robin			
Turdus merula	Common Blackbird			*
Turdus pilaris	Fieldfare			
Turdus philomelos	Song Thrush	*	*	
Turdus iliacus	Redwing			
Turdus viscivorus	Mistle Thrush			*
Sturnus vulgaris	Common Starling		*	
Passer domesticus	House Sparrow		*	
Passer montanus	Tree Sparrow	*	*	
Fringilla coelebs	Chaffinch			
Carduelis chloris	European Greenfinch			
Carduelis carduelis	European Goldfinch			
Carduelis cannabina	Common Linnet	*	*	
Pyrrhula pyrrhula	Common Bullfinch	*	*	
Emberiza citrinella	Yellowhammer		*	
Emberiza cirlus	Cirl Bunting	*		
Emberiza schoeniclus	Reed Bunting	*	*	
Miliaria calandra	Corn Bunting	*	*	

Results

Table 9.2. The importance of families and genera containing common weed species in bird diet (See Appendix 9.1 for derivation)

Very Important	Important	Present	Nominally Present
Family			
Poaceae	Compositae	Boraginaceae	Papaveraceae
Polygonaceae	Labiatae	Euphorbiaceae	Primulaceae
Chenopodiaceae	Boraginaceae	Solanaceae	Umbelliferae
Caryophyllaceae	Violaceae	Fumariaceae	
Cruciferae		Scrophulariaceae	
		Geraniaceae	
		Rubiaceae	
Genus			
Stellaria	*Cerastium*	*Sonchus*	*Euphorbia*
Chenopodium	*Sinapis*	*Centaurea*	*Galeopsis*
Polygonum	*Viola*	*Capsella*	*Lamium*
	Poa	*Cirsium*	*Matricaria*
	Rumex	*Fumaria*	*Myosotis*
	Senecio	*Spergula*	*Avena*
			Bromus
			Galium
			Geranium

Rankings of plant taxa did not vary greatly whether the assessment was based on all seed-eating birds or subsets of declining species (Appendix 8.1). A number of families were identified as important or very important, but within these families genera varied in importance; e.g. within the Polygonaceae *Polygonum* spp. were more important than *Rumex*; the Poaceae were considered very important but whilst the genus *Poa* was eaten by a number of bird species, *Bromus* and *Avena* were recorded as present in the diet of only one species and important for none. Within the Compositae, *Cerastium* appeared in the diet of many bird species, *Sonchus* and *Cirsium* in few whilst *Matricaria* appeared to be of minor importance.

Ideally the assessment would be carried to species level but the data were not robust enough to give meaningful results at this level, because dietary information was often not recorded to species. The available information was analysed and is presented in Appendix 9.1 (Table C) for completeness. For some genera, there is only one common weed species so it can be inferred that this is the species concerned in most records, e.g. chickweed, *Stellaria media*. In other cases several species could be involved e.g. the genus *Polygonum*, which contains knotgrass *P. aviculare,* black-bindweed *P. convolvulus* (now *Fallopia convolvulus*), and redshank *P. persicaria* (now *Persicaria maculosa*) among others. (N.B. Although some of these species are now considered to belong to different genera, most records of occurrence in bird diet are likely to have considered them all as “polygonums”.)

Invertebrates

Some farmland birds feed mainly or entirely on invertebrates throughout their lives, but many species, including a large proportion of those which are currently in decline, feed largely on seeds and other plant material as adults, but require invertebrate food to nourish their growing chicks. Wilson *et al*. (1996) give a detailed account of the diet of farmland birds, species by species (see Appendix 8.2, Table E). Invertebrate taxa which they found to be important components of the diet of a wide range of bird species included spiders and mites (Arachnida), especially spiders (Araneae); beetles (Coleoptera), especially ground beetles (Carabidae, and weevils (Curculionidae); grasshoppers, crickets, bush crickets etc. (Orthoptera); flies (Diptera), especially crane flies and their larvae (leatherjackets) (Tipulidae); bugs (Hemiptera), especially aphids (Aphididae); ants, bees, wasps and sawflies (Hymenoptera), especially ants (Formicidae); and butterflies, moths and their larvae (Lepidoptera). Three groups were identified as showing evidence of association with declining bird species: ground beetles, (Carabidae); grasshoppers, bush-crickets and crickets (Orthoptera); and larvae of butterflies and moths (Lepidoptera).

Wilson *et al*. (1999) reviewed the abundance and diversity of invertebrate (and plant) foods of 26 granivorous bird species of northern Europe. When they considered invertebrate orders which were '*present'* or' *important*' (i.e. comprised a mean of at least 5% of the diet over all studies reviewed) in the diet of at least 12 of the 26 species, only (Orthoptera) were *present* in the diet of a significantly greater proportion of declining that non-declining species, but Orthoptera, Hymenoptera and Arachnida were *important* in the diet of a significantly greater proportion of declining than non-declining species. Invertebrates were then considered at sub-order or family level as *present* or *important* in the diet of two or more bird species. Grasshoppers (Orthoptera: Acrididae) and leaf beetles (Coleoptera: Chrysomelidae) were *present* in the diet of a significantly greater proportion of declining than non-declining species, whilst spiders (Arachnida: Araneae), grasshoppers and sawflies (Hymenoptera: Symphyta) were *important* in the diet of a significantly greater proportion of declining than non-declining species.

It is known that herbicides can reduce the availability of invertebrate food for birds (e.g. Moreby & Southway, 1999), but this may be due to effects on food plants of herbivores, changes in microclimate or vegetation structure, and in many cases the mechanisms are not fully understood. An example of a species for which herbicide effects have been demonstrated is the knotgrass beetle, *Gastrophysa polygoni*. This beetle feeds on knotgrass *Polygonum aviculare* and black-bindweed *Fallopia convolvulus* and appears to have poor powers of dispersal. Sotherton (1982) found that larvae feeding on host plants or egg cases sprayed with 2-4 D herbicide suffered significantly higher mortalities than larvae that fed on untreated material. Treatment of spring barley with 2-4 D + CMPP significantly reduced mean densities of the food plants and egg batches on sprayed areas compared to unsprayed areas, and in fields treated with a herbicide mixture containing dicamba and dichlorprop, which were more effective against the host plants, no knotgrass beetles were found.

9.3. Relationships Between Food Abundance And Bird Populations

In order to model effects of herbicides on birds, a number of questions need to be answered:

i. How do herbicides affect the abundance of bird food items, i.e. weed seeds and invertebrates?
ii. What is the relationship between food abundance and either (a) breeding performance or (b) adult mortality?
iii. Is there a relationship between (a) or (b) and population trend?

Point (i) has been addressed in previous sections. Note that in order for birds to be affected, it is not necessary to demonstrate long term declines in populations of the plants or invertebrates on which they feed (though there is indeed evidence for such declines, e.g. Sotherton & Self, 2000); short term reductions in abundance may be sufficient to have an impact on bird populations if achieved on a sufficient scale. For example, Southwood & Cross (1969) found that spraying barley fields with herbicide (MCPA, MCPB or 2,4-DP+MCPA) reduced arthropod numbers by about half and biomass by two thirds. Vickerman (1974) showed that control of rough meadow-grass *Poa trivialis* in winter barley with metoxuron + simazine reduced the biomass of insects eaten by partridge chicks by 43% compared to control of broad-leaved weeds only with mecoprop. Chiverton & Sotherton (1991) also found large differences in densities of gamebird chick-food arthropods between plots treated with a mixture of mecoprop, ioxynil and bromoxynil or untreated. Points (ii) and (iii) are considered below.

<u>Relationship between food abundance and breeding performance</u>

Of all farmland birds, the grey partridge has been the most studied and is the best understood in terms of its population dynamics and reasons for its decline. The key factor contributing to its decline is reduced chick survival during the first six weeks of life (Potts, 1980; 1986; Potts & Aebischer, 1991; 1995), which is related to the availability of invertebrate prey(Green, 1984; Potts, 1980; 1986; Southwood & Cross, 1969). Southwood & Cross (1969) showed that over the years 1959-1966, almost 90% of the variation in partridge breeding success could be accounted for by variations in insect abundance. Potts (1980) found that nearly 80% of chick survival could be explained by the densities of the insect groups Tenthredinidae (sawflies) and Lepidoptera larvae, larger Hemiptera (mostly Heteroptera and Jassidae), beetles from the families Curculionidae, Chrysomelidae and Carabidae, and smaller Hemiptera (mostly aphids) in cereal crops at median chick hatch date. Relationships between chick mortality or chick survival and insect abundance are given by Potts (1986) and Potts & Aebischer (1991). Green (1984) radiotracked grey partridge broods and found that they foraged almost entirely in cereal fields, especially at the edges where both weeds and arthropods were more abundant. Chick survival was related to density of the arthropod groups Aphididae, other Hemiptera, Lepidoptera & Tenthredinidae larvae, and Acalypterate Diptera.

Experimental evidence of herbicide effects on chick survival was provided by Rands(1985; 1986). Replicated blocks of fields on a large (11 km^2) farm were sprayed as normal (fully sprayed) or left unsprayed with pesticides on the outer six metres from 1 January (unsprayed headlands), over two years (1983 and 1984). In practice this meant that spring applied herbicides and fungicides were omitted from winter cereals, whilst spring cereals received no herbicide (or fungicide). No insecticides were applied to either treatment in 1983, but winter wheat received insecticide in 1984 though winter and spring barley did not. Chick food insects were more abundant in unsprayed headlands than where they were fully sprayed, and partridge brood sizes were significantly greater in both years in fields with unsprayed headlands. In the second year the same treatments were also applied to eight farms in East Anglia, and brood size was higher on seven of the eight, being on average twice as high where unsprayed headlands were present. Although fungicides and insecticides were omitted as well as herbicides, insecticides were used on only some of the fully sprayed fields in only one of the two years, and evidence from other studies suggests that fungicide use does not have major effects on arthropod abundance. Further trials in 1985 and 1986 produced similar results in terms of brood size for grey partridge, and also for pheasant *Phasianus colchicus* (Sotherton & Robertson, 1990).

Hill (1985) showed that survival of pheasant chicks was also related to arthropod densities, which explained 75% of variation in chick survival. Chick survival was highest in broods that had ingested the highest biomass of insects, as determined by faecal analysis. Carabid beetles, chrysomelid beetles and the larvae of sawflies and Lepidoptera explained 67% of between-year variation in chick survival rates.

Aebischer & Ward (1997) found that the density of nesting corn buntings was positively related to the number of caterpillars in cereal crops. Brickle *et al.* (2000) found no relationship between brood size of corn buntings and food availability, but chick weight was positively correlated with the abundance of chick-food invertebrates. The probability of nest survival also increased with invertebrate availability. The authors conclude that “even if reductions in chick food did not cause the decline, they seem likely to hamper population recovery”.

Evans *et al*. (1997) found that chicks from early broods often died of starvation or predation, which was thought to be linked to increased begging, caused by food shortage. Chick survival increased markedly later in the season when grasshoppers and bush crickets (Orthoptera) became available.

No instances of direct evidence for relationships between food abundance and breeding performance were found for other species, though indirect evidence suggests that for some species such a link may exist, but studies of breeding success have not been accompanied by assessment of food availability. For example, skylark densities were higher on organic farms and set-aside, and nest survival rates were higher on set-aside, than on intensively managed cereals. Poulsen (1996) found that skylarks foraged preferentially on set-aside, and arthropod food density was greater on set-aside than other crop types, though he did point out that the set-aside in his study area may not have been typical of set-aside in general.

Linnets and other cardueline finches are unusual in feeding their chicks mainly on seeds rather than invertebrates. Linnets declined by 50% between 1968 and 1987, followed by some recovery. Linnet nestling diet in the 1960s included a variety of weed seeds such as dandelion *Taraxacum* spp., chickweed *Stellaria media,* charlock *Sinapis arvensis* and thistles *Cirsium* spp. (Newton 1967). In a study carried out in 1996, only dandelions were still major components of nestling diet, the balance being predominantly oilseed rape *Brassica napus*, a crop which was not widely grown at the time of Newton's study (Moorcroft *et al*., 1997). Moorcroft & Wilson (2000) suggest that the observed demographic trends could be explained by declines in availability of weed seeds, and the rise in oilseed rape growing with rape seeds replacing weed seeds in the diet. Linnet abundance in the UK could therefore now be dependent on the availability of oilseed rape, with potential negative consequences should the amount of rape grown decline.

Another species that depends almost entirely on seeds is the turtle dove. A recent study has identified changes in the diet of this species compared with earlier studies, similar to those observed for linnet. Murton *et al*. (1964) found that weed seeds made up over 95% of the food eaten by adult turtle doves in the 1960s, and about 80% of nestling diet. In contrast, Browne & Aebischer (2001) found that in the late 1990s, weed seeds formed only 40% of adult diet and 30% of nestling diet. The balance consisted of crop seeds, mainly wheat and oilseed rape, which the authors considered less satisfactory due to restricted availability, lower food quality and longer travelling distances required to find grain. The number of young fledged per pair was 1.3 in the 1990s study compared to 2.1 in the 1960s, partly due to a difference in fledging success (69% compared to 81%) and partly to a difference in the number of clutches produced per pair (1.6 compared to 2.9). This reduction in breeding performance was more than sufficient to explain the observed population decline if it were nationally representative.

<u>Relationship between seed abundance and adult mortality</u>

Adult mortality is very difficult to measure for most species, and data indicating direct relationships with food availability are even more sparse than for breeding success. Potts (1986) found no effect of seed availability on winter mortality of grey partridge, in spite of observed declines in weed seed availability during the period of his study.

Circumstantial evidence for the importance of seed availability over the winter period exists for the cirl bunting *Emberiza cirlus*. This species suffered a severe decline in numbers and range between the 1940s and 1980s, so that by 1989 they were virtually confined to a small area in South Devon (Evans, 1992). Studies showed that cirl buntings preferred to forage in winter on stubble fields, specifically those containing broadleaved weeds (Evans, 1997a). As a consequence, in the early 1990s, action was taken to increase the number of weed-rich stubbles available in the area where they still occurred, and since that time the population has increased substantially from 118-132 pairs in 1989 to over 370 in 1995 (Evans, 1997b). This evidence strongly suggests that the availability of weed seeds was limiting the population through effects on over-winter survival.

Other birds, including corn bunting, grey partridge, skylark, linnet and reed bunting have also been found to show preferences for feeding on stubbles and set-aside in winter (Evans 1997a). Draycott *et al*. (1997) surveyed the incidence of grain and weed seeds on stubbles and concluded that the availability of seed on arable fields in spring was insufficient to maintain food resources for seed-eating birds. Set-aside contained higher numbers of seeds, but numbers in many set-aside fields were still very low. Robinson & Sutherland (1999) found great variation in seed densities (0-28,000 per m^2, but stubbles held more than winter cereals or grass leys.

Brickle & Harper (2000) found that corn buntings preferred stubbles between October and mid-December, grass fields with cattle (where they ate cattle food) plus stubbles and brassicas from mid-December to mid-February, and freshly drilled spring barley from mid-February to the end of March. The main food items were cereal grain and seeds of the Polygonaceae. However, grain is not essential to corn buntings as large flocks occur on oilseed rape stubbles (Watson & Rae, 1997). Donald & Forest (1995) and Shrubb (1997) considered that reduced winter food supply resulting from fewer winter stubbles was the most likely cause of the decline in corn buntings.

9.4. Relationship between Breeding Performance and Population Trend

Potts (1980, 1986) and Potts and Aebischer (1991, 1995) developed a model based on many years of monitoring grey partridge populations in West Sussex that showed that the major factor associated with the decline of this species was chick survival, particularly in the absence of nest predation control. Annual variation in population density was related to changes in chick mortality caused by fluctuations in the invertebrate food supply. The grey partridge is the only species for which relationships have been demonstrated between pesticides and food availability, between food availability and breeding performance, and between breeding performance and population size.

Such population models have not been developed for other species, but demographic studies have been used to indicate potential causes of declines (Siriwardena *et al*., 1998, 2000a). Changes in fledgling production per nesting attempt only appeared to be significantly related to population change for one species, the linnet, and this pattern was caused by an increase in nest failure rate at the egg stage (Siriwardena *et al*., 2000a). In contrast, several species (turtle dove, skylark, tree sparrow, yellowhammer and corn bunting) showed higher fledgling production during periods of population decline (Siriwardena *et al*., 2000a). The authors point out that post-fledging survival rates and/or number of breeding attempts may be implicated in declines. However, these analyses did not take into account possible density dependence, which can make changes in demographic rates difficult to detect (Green, 1999).

Siriwardena *et al*. (2000b) suggested that nidifugous species (i.e. those in which the nestlings leave the nest soon after hatching) were more likely to have been affected by changes in fledgling production. Like the grey partridge, lapwing *Vanellus vanellus* chicks are nidifugous, feed on invertebrates and their foraging time is limited by the need for brooding by parents to maintain body temperature (Beintema & Visser, 1989; Beintema *et al*., 1991). Peach *et al*. (1994) found that neither adult or first year survival showed changes which were likely to explain the decline in lapwing numbers, but a review of the literature showed that in only 8 of 24 studies were sufficient fledglings produced to maintain the population. Galbraith (1988) found that productivity was sufficient to maintain the population on rough grazing areas, but not on arable land, due to egg losses during cultivation and poor chick survival. Similarly Baines (1989) found that productivity was greater on unimproved grassland (0.86 chicks per pair) than on improved grassland (0.25 chicks per pair), with arable land intermediate (0.56 chicks per pair). Chick survival was similar on improved grassland and arable land. Only on unimproved grassland was productivity at the levels of 0.83-0.97 estimated by Peach *et al*. (1994) to be sufficient to maintain the population. However, Baines (1989) considered that predation was more important than chick food availability in his study as a cause of low productivity

Other species for which breeding productivity have contributed to declines are stone curlew and corncrake *Crex crex*, but for these species agricultural operations have been the main cause of low productivity Aebischer *et al*. (2000). However, a recent study has identified availability of chick food as a potential cause of poor breeding success of stone curlews in south Cambridgeshire, which has resulted in a decline to virtual extinction in this area during the 1990s (Shardlow, 2001)

9.5. Relationship between Adult Mortality and Population Trend

In a survey of studies of 21 stable and 13 declining populations of the grey partridge worldwide, Potts (1986) found that winter losses were similar for stable and declining populations. Annual over-winter survival rates in West Sussex increased during the period 1968-1993 whilst the population declined from 21 to under 4 pairs per km^2 in spring (Potts & Aebischer, 1995).

However, adult survival rates may be more important in determining population changes for nidicolous species (those whose chicks remain in the nest during the fledging period) (Siriwardena *et al*., 2000b). Siriwardena *et al*. (1999) analysed variations in annual survival rate for six seed-eating species (bullfinch, chaffinch *Fringilla coelebs*, goldfinch *Carduelis carduelis*, greenfinch *Carduelis chloris*, linnet and house sparrow), and found that only for goldfinch and house sparrow could they have been sufficient to explain population changes. However, Siriwardena *et al*. (2000b) concluded that changes in survival rate could have been an important mechanism behind population change for at least 13 of 28 farmland bird species considered, and recommend further research in this area, as well as post-fledging survival rates and numbers of breeding attempts.

Thompson *et al*. (1997) found that changes in survival of first year song thrushes could explain the population decline in this species, but were unable to distinguish between immediate post-fledging survival and survival over winter.

Peach *et al*. (1999) showed that changes in first year survival and adult survival could explain the observed decline in numbers of reed buntings, and that breeding performance was actually higher during the period of decline. They considered that the most likely cause of the decline was a reduction in food availability outside the breeding season, due to more efficient herbicides and a reduction in the availability of winter stubbles. Survival rates of first year reed buntings increased during the 1990s, and since 1983, numbers of reed buntings have been relatively stable. The authors suggest that this could reflect an increased availability of winter food due to the introduction of set-aside.

Evidence linking the population decline and subsequent increase in numbers of cirl buntings to the availability of weedy stubbles and set-aside has been considered above. Siriwardena *et al*. (2000b) note that their estimates of yellowhammer survival rates suggest a fall during its decline, which could explain the decline if estimates of breeding success from recent field studies are representative.

9.6. Relationship between Food Density and Foraging

Impacts of food abundance on bird breeding performance and survival depend not only on food availability, but also on birds foraging behaviour and their efficiency in locating and utilising food resources.

Nidicolous bird species have a limited foraging range defined by the nest location, though for some species this can be quite large (e.g. up to 11 km for turtle doves; Browne & Aebischer, 2001). However, where parent birds have to travel large distances to find food, this can affect breeding performance. For example, the weight of corn bunting chicks was related to the distance at which parents foraged, which in turn was related to invertebrate abundance close to the nest (Brickle *et al*., 2000). The probability of nest survival was also related to the abundance of chick-food invertebrates close to the nest. Parents were able to distinguish between good and poor feeding habitat; the most common chick-food items were more abundant in samples from foraging areas than from non-foraging areas, and the foraging distance was negatively correlated with food availability. Where they had a choice, parents foraged preferentially in areas that had received fewer pesticide applications, and the abundance of preferred invertebrates was negatively correlated with the number of pesticide applications.

Nidifugous species can take their chicks to good feeding areas, though the distance that they need to travel can affect chick survival. Lapwings nesting on arable land tended to move their chicks to pasture where invertebrate densities were higher, but those which had to move a long distance had a lower probability of survival (Galbraith, 1988). Similarly, chick survival of grey partridges was related to the mean distance between successive roost sites (Rands, 1986). Broods with access to unsprayed cereal headlands had smaller home range sizes, and the home range contained a greater proportion of headland (i.e. the outer 6 m of crop), than for those in fields with fully sprayed headlands (Rands, 1986).

Outside the breeding season birds can, and do, travel long distances to find food, mobility varying between species. A number of studies have shown preferences among seed-eating birds for feeding on stubbles and set-aside in winter (e.g. Evans, 1997a), but recently Robinson & Sutherland (1999) have also studied feeding behaviour within fields. They found that the distribution of skylarks, grey partridges, and red-legged partridges was related to weed seed density, whilst yellowhammer distribution was related to the density of grain. However, there were also species preferences for certain parts of fields in relation to cover: skylarks avoided foraging close to hedgerows, whilst yellowhammers preferred to feed near hedges. Boatman *et al*. (2000) showed that where food was supplied in the form of “wild bird cover” grown on set-aside, very few birds were seen on farm crops, with feeding activity being almost entirely confined to the wild bird cover. Within wild bird cover areas, birds showed preferences for different seed types.

Such studies of foraging behaviour are few, but indicate that birds do respond to food abundance, and it is not therefore necessary for food to be evenly distributed across the landscape. Indeed, as intake is related to food density (e.g. Robinson & Sutherland, 1997), it may be advantageous for food to be available in small areas of high food density. This may have implications for management aimed at increasing food supplies for birds, particularly in winter.

9.7. Other Causes Of Bird Declines

This section has concentrated on relationships between food abundance and bird populations, and the potential effects of herbicides on these relationships. It will be clear from the foregoing review that the impact of herbicide use on birds is still by no means clear in most cases, due to a lack of available evidence. The strongest evidence for the role of pesticides, including herbicides, in the decline of any species is for the grey partridge, but Campbell *et al*. (1997) in their review of the indirect effects of pesticides on birds considered that indirect effects could be implicated in the declines of 11 other species, and could not be ruled out for a further eight. One problem is that a number of changes have taken place in agriculture over the same period, and it is therefore extremely difficult to disentangle their effects. For example, the cirl bunting has apparently been affected by the switch from spring to winter crops, resulting in fewer over-winter stubbles, but it has been shown that they prefer to feed on weedy stubbles and the use of herbicides has almost certainly rendered remaining stubbles less attractive to birds because of reduced feeding opportunities.

Gillings & Fuller (1998) divided the effects of agricultural intensification into two categories: habitat loss and habitat degradation. They compared changes in bird populations on farms that had undergone extensive removal of habitats such as hedgerows and ponds, with farms where there had been little change in the amount of such habitats. They found that all 11 farms studied had significant numbers of declining species and that there were no significant effects of habitat loss on population trends. They concluded that habitat loss was of secondary importance in causing farmland bird declines, though it may have locally exacerbated declines caused by other processes such as habitat degradation. Fuller (2000), reviewing relationships between agricultural changes and bird populations, suggested that although the loss of hedgerows since the 1940s had been substantial, it did not appear to have been a principal driver of recent (i.e. post-1970) declines in farmland bird populations. Factors resulting from agricultural intensification on arable farms identified by Fuller (2000), which have implications for birds, include increased mechanisation, increased use of inorganic fertilisers and less farmyard manure, reduction in spring sowing of cereals, simplification of rotations and decline in mixed ley farming, and changes in cropping patterns, in addition to increases in pesticide use.

It is still not certain for the majority of species which factors are driving population changes. For species with small populations confined to a limited area such as cirl bunting, stone curlew and corncrake, it is possible to test hypotheses about the factors underlying population changes by changing agricultural management in the area concerned and observing population changes, as has been done successfully for all three of these species (Aebischer *et al.*, 2000). Even in these cases, conservation action has tended to address more than one potential causal factor, so that the relative importance of individual factors is often to some extent obscured. Furthermore, it is important to remember that *population recovery does not necessarily depend on reversing the original cause(s) of decline*, a point which is often forgotten. Ultimately, population dynamics are about gains and losses to the population over time, and if losses due to one cause can be more than balanced by gains from another, the population will increase. An example is provided by the apparent substitution of weed seeds by seeds of oilseed rape in the diet of nestling linnets (Moorcroft *et al.*, 1997). Acceptance of this premise allows a greater degree of lateral thinking about solutions. For example, although the reduced availability of seed-rich stubbles may have contributed to the decline of some seed-eating bird species, it may not be necessary to reintroduce stubbles on a large scale if the necessary food can be provided in other ways (Boatman *et al.*, 2000). Work by the Game Conservancy Trust in partnership with the Allerton Research and Educational Trust at Loddington in Leicestershire has shown that populations of some declining species can be increased on a local scale by appropriate management on a commercial farm with autumn sown crops without major changes to crop management practices (Boatman *et al.*, 2000). This approach did however involve the provision of substantial areas of nesting and feeding habitat by pro-active management of set-aside and field margins.

9.8. Conclusion

In conclusion, it is generally agreed that agricultural intensification is primarily responsible for the declines in farmland birds which have been observed over the last three decades, and the available evidence suggests that a reduction in the availability of food, either during the breeding season or the winter period, or both, is likely to have been a crucial factor for a many of these declining species. Weed seeds are known to be important in bird diets, and herbicides directly diminish their availability. It has also been shown that the use of herbicides reduces the availability of invertebrates important in the diet of chicks at the crucial time of year, although the relationships between weeds and chick-food invertebrates are poorly understood and there is a pressing need for research in this area. Thus, although the evidence is incomplete, it is highly probable that herbicide use has contributed to farmland bird declines. There is a need for further studies relating bird food supply to demographic parameters to establish the extent and significance of such effects.

APPENDIX 9.1.

Importance of weed taxa by family, genus and species in bird diet

The data in the following tables represent the number of bird species for which weed taxa are classified as important (i) or present (p) under the categories "all seed-eaters", "BAP priority species", "CBC rapid decline" and "CBC moderate decline" (see main text for further details)

Table A. Plant families

Family	All seed-eaters			CBC moderate decline			CBC rapid decline			BAP priority		
	p	i	rank	p	i	rank	p	i	rank	p	i	rank
Poaceae	29	25	1	15	13	1	11	11	1	9	9	1
Polygonaceae	25	14	2	13	8	2	10	7	2	9	6	2
Caryophyllaceae	25	13	3	13	7	3	11	6	3	8	6	3
Chenopodiaceae	20	12	4	12	6	4	10	6	4	9	5	4
Compositae	20	11	5	11	4	6	10	4	6	8	4	6
Cruciferae	24	9	6	15	5	5	12	5	5	9	5	5
Labiatae	15	4	7	10	2	7	9	2	7	6	2	7=
Violaceae	13	3	8	8	2	9	7	2	9	6	2	7=
Boraginaceae	13	2	9	8	2	8	8	2	8	6	2	7=
Euphorbiaceae	14	1	10	7	1	11	6	1	10	4	1	10
Solanaceae	14	1	11	9	0	14	8	0	13	7	0	12
Scrophulariaceae	13	1	12	9	1	10	7	0	14	6	0	13
Rubiaceae	10	1	13	4	0	17	4	0	16=	3	0	16=
Geraniaceae	7	1	14	5	1	12	4	1	11	3	0	16=
Fumariaceae	4	1	15	3	1	13	3	1	12	3	1	11
Papaveraceae	7	0	16	6	0	15	5	0	15	4	0	14=
Primulaceae	7	0	17	5	0	16	4	0	16=	4	0	14=
Umbelliferae	4	0	17	1	0	17	1	0	17	1	0	17

Table B. Plant genera

Genus	All seed-eaters			CBC moderate decline			CBC rapid decline			BAP priority		
	p	i	rank	p	i	rank	p	i	rank	p	i	rank
Polygonum	21	12	1	12	7	1	9	6	1	7	5	3
Stellaria	20	12	2	11	6	2	9	5	3	9	5	1
Chenopodium	17	9	3	11	5	3	9	5	2	7	5	2
Sinapis	8	7	4	3	3	6	3	3	4	3	3	5
Poa	13	6	5	8	4	5	6	3	5	5	2	7
Cerastium	15	5	6=	8	5	4	6	4	6	4	3	4
Rumex	15	5	6=	7	2	8	6	2	8	5	2	8
Senecio	9	4	8	4	2	9	3	2	10	4	2	9
Viola	13	3	9	8	2	7	7	2	7	6	2	6
Spergula	12	2	10	5	1	11	4	0	14=	3	0	14=
Centaurea	9	2	11	4	0	15	4	0	14=	3	0	14=
Sonchus	6	2	12	4	2	10	4	2	9	3	2	10
Cirsium	5	2	13	2	1	13	1	1	12=	1	1	12=
Capsella	5	1	14	3	1	12	3	1	11	3	1	11
Fumaria	1	1	15	1	1	14	1	1	12=	1	1	12=
Euphorbia	2	0	16	1	0	16=	1	0	16=	1	0	16=
Galeopsis	1	0	17=	1	0	16=	1	0	16=	1	0	16=
Geranium	1	0	17=	1	0	16=	1	0	16=	0	0	21
Lamium	1	0	17=	1	0	16=	1	0	16=	1	0	16=
Matricaria	1	0	20=	1	0	16=	1	0	16=	1	0	16=
Myosotis	1	0	20=	1	0	16=	1	0	16=	1	0	16=
Avena	1	0	20=	0	0	22=	0	0	22=	0	0	22=
Bromus	1	0	20=	0	0	22=	0	0	22=	0	0	22=
Galium	1	0	20=	0	0	22=	0	0	22=	0	0	22=

Table C. Plant species

Species	All seed-eaters			CBC moderate decline			CBC rapid decline			BAP priority		
	p	i	rank	p	i	rank	p	i	rank	p	i	rank
Sinapis arvensis	7	7	1	3	3	2	3	3	2	3	3	2
Stellaria media	11	5	2	5	3	1	4	3	1	4	3	1
Senecio vulgaris	4	4	3	2	2	3	2	2	3	2	2	3
Persicaria maculosa	5	2	4	2	1	4=	2	1	4=	2	1	4=
Capsella bursa-pastoris	3	1	5	2	1	4=	2	1	4=	2	1	4=
Fallopia convolvulus	3	1	6	1	0	9	1	0	9	1	0	9
Chenopodium album	2	1	7	1	1	6=	1	1	6=	1	1	6=
Fumaria officinalis	1	1	8=	1	1	6=	1	1	6=	1	1	6=
Cirsium arvense	1	1	8=	0	0	13=	0	0	13=	0	0	13=
Polygonum aviculare	3	0	10	2	0	8	2	0	8	2	0	8
Poa annua	2	0	11=	1	0	10=	1	0	10=	1	0	10=
Sonchus oleraceus	2	0	11=	1	0	10=	1	0	10=	1	0	10=
Spergula arvensis	2	0	11=	1	0	10=	1	0	10=	1	0	10=
Avena fatua	1	0	14	0	0	13=	0	0	13=	0	0	13=

APPENDIX 9.2.

Presence of invertebrate and plant taxa in the diet of farmland birds

Table D. Presence of invertebrate taxa and vertebrates in the diet of farmland birds. Bird species are arranged in order of magnitude of population change with the species in greatest decline on the left. Unshaded: not known to be taken as food; grey: present, but not an important dietary component; and black: an important component.

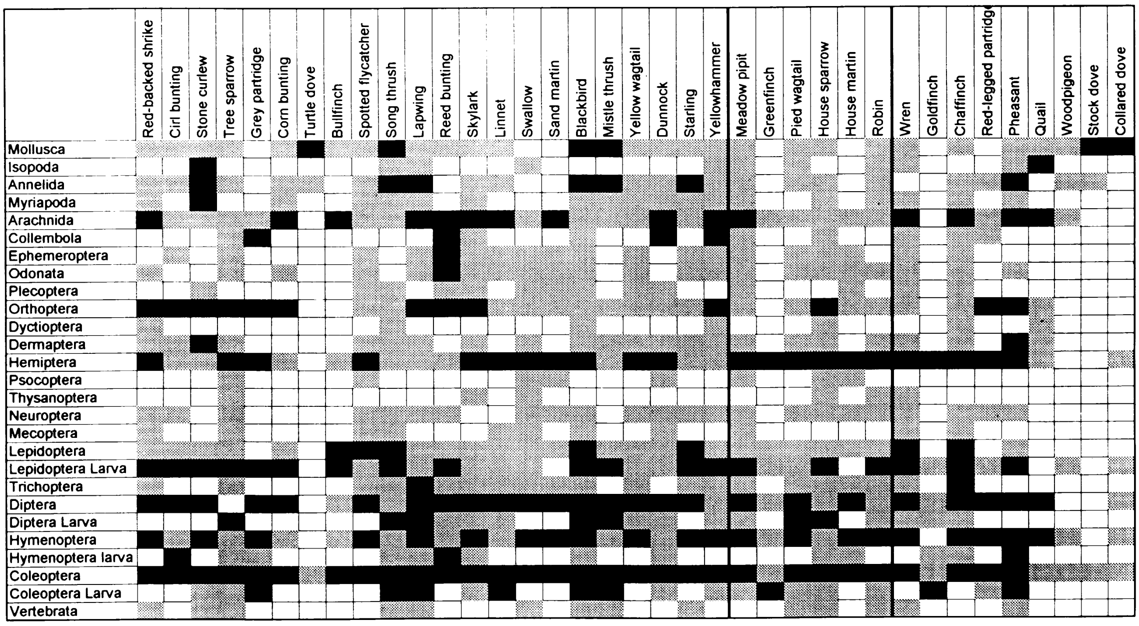
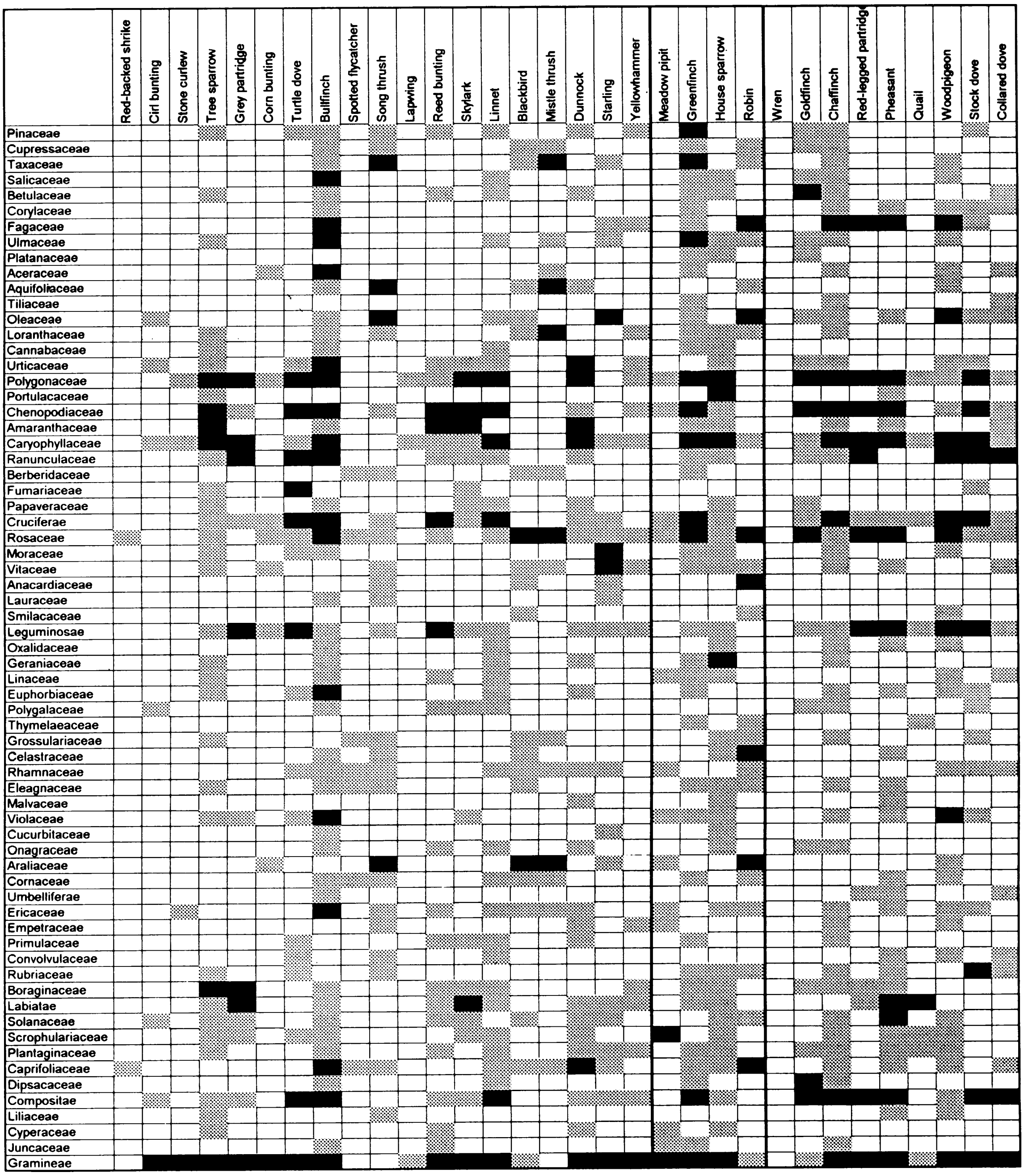


Table E. Presence of plants in the diet of farmland birds.

Bird species are arranged in order of magnitude of population change with the species in greatest decline on the left. Unshaded: not known to be taken as food; grey: present, but not an important dietary component; and black: an important component.



Tables D and E reproduced from: Campbell, L.H., & Cooke, A.S. (eds.). 1997. The indirect effects of pesticides on birds. 18pp. Peterborough, Joint Nature Conservation Committee.

10. RISK ASSESSMENT FOR NON-TARGET PLANTS WITHIN CROPS

Pesticide risk assessment is usually made by examining likely damage from their use and likely exposure to target and non-target flora and fauna. In practice, this is usually achieved with measures of toxicity and an evaluation of exposure factors, followed by calculation of toxicity exposure ratios (TERs).

An extensive review of "Options for Testing and Risk Assessment" was included in the review PN0923 (Breeze et al., 1999). Suggestions as to methods of assessing exposure and risk were presented, including the use of probabilistic methods of quantifying uncertainty. A tiered regulatory framework was outlined, noting that significant development work would be required, particularly as sub-lethal effects on plants might have effects on key regenerative life stages. It was suggested that acceptable levels of risk would be higher within target areas, due to the need to control weeds. In the present study (see below), an attempt has been made to identify the weed species that might represent those that are particularly important for non-target effects on higher tropic levels.

Considerations of regulatory approaches to non-target plants have been made extensively in Canada. Comparisons of data on sensitivity of species to herbicides have indicated that insufficient numbers of species were included in the current regulatory process (Boutin & Rogers, 2000). It is suggested that an extended database on plant sensitivities is necessary in order to refine risk assessments for non-target plants. This, though, is particularly aimed at non-target plants outside the crop area.

Advances in non-target risk assessment have also been made in Europe, aimed at assessing the risks to off-field flora particularly from drift events (Full et al., 2000; Hewitt, 2000). (Full et al., 2000) report that the German Federal Environmental Agency has developed a tiered approach to assessing the effects of plant protection products on non-target plants. A higher tier test based on different plant life stages has been proposed by (Zwerger & Pestemer, 2000). These approaches are entirely suitable for non-target situations for "off-field" movement of herbicides. **However, the main challenge of this current study is to assess the practicality of non-target plant risk assessment within the target crop area**.

The principles for regulatory testing of non-target arthropods with plant protection products using semi-field and field experiments have been outlined by (Candolfi et al., 2000). Modifications to take account of real exposure in plant canopies, where total area deposition is over three-dimensional surfaces, and for multiple applications have been suggested (Gonzalez-Valero et al., 2000).

In considering regulatory schemes, a practical approach to non-target plants within fields must be the identification of species that are likely to be important for biodiversity and also only of intermediate concern regarding crop losses. In this project a representative number of weed species have been examined in terms of their competitivity and importance for invertebrates and birds within crops. At present, approaches to risk assessment for plants within the crop area are at the preliminary stage. The data for weed competitive ability, birds and invertebrates indicate that it should be possible to identify those weed species that are only moderately competitive and support important numbers of invertebrates and birds. The list of common weed species considered is given in Table 10.1 below, from which eleven species important for within-crop biodiversity have been identified. This offers the possibility of selecting weed assemblages for regulatory testing for toxicity. These species might be targeted for Tier 1 dose-response toxicity testing, with more detailed examination in higher Tiers. Nevertheless, it should be pointed out that these are not necessarily the most important species, as they have been selected from the list of representative species selected in the initial stages of the project. The selected species are representative of such species.

Having considered toxicity, then estimating exposure is the other part of risk assessment. *The major problem with this risk assessment is simply that these non-target plants occur within the target area and are likely to have maximum exposure to the field application rate, if conventional delivery systems are being considered.* There might be some potential for risk avoidance (see next section), depending on modes of action, timing etc.

Over-riding these considerations, there is the question of how the regulatory process will address the legitimate argument that these species can be targets for weed control, if their populations are above particular levels. Under these conditions, the herbicide should be effective. In practice, perhaps a higher proportion of the population that is killed, derived from probabilistic dose-response assessment, would be acceptable for non-target species within the crop.

The indications are that there are significant causal links between herbicide use and decline in farmland biodiversity. This may require a radical reappraisal of crop management. Requirements to modify herbicide practice may result, with the need for much more specific herbicide chemistry and/or specific application technology. If more selective chemistry were required, then conventional regulatory testing on selected weed species that are important for biodiversity would be appropriate. Nine arable weed species have been identified that have moderate to low competitivity against arable crops and are important for invertebrate and bird species (Table 10.1). A further two plant species, broad-leaved dock and creeping thistle, fulfil these characteristics, but are more abundant in grassland and are also listed weeds under the 1959 Weeds Act.

Table 10.1. The importance of a representative list of common weed species for invertebrates and birds and their economic importance in terms of crop yield loss.
[1.] An estimate of the relative importance of the selected plant species for invertebrates, based on the available datasets. Insect criteria based on number of insect species associated with particular weeds: 0-5 species -; 6-10 *; 11-25 **; 26+ ***
[2.] Importance of the plant genus for seed-feeding birds. *** = important for >8 bird species; ** = important for 3-8 species; * = 1 or 2 species; - = not important.
[3.] Figures in (brackets) are expert opinion.

Pale highlight – arable species that are important for in-field biodiversity
Dark highlight – grassland/arable species important for biodiversity

Common name	[1.] Value for invertebrates	No. Red Data Book species	No. pest species	[2.] Importance for seed-eating birds	[3.] Competitive index	%fields infested
Annual Meadow-grass	***	3	4	**	0.10	79
Barren Brome	-	0	0	-	(1.0)	13
Black Nightshade	*	1	2	a		
Black-bindweed				***	0.30	
Black-grass	-	0	2	a	0.40	38
Broad-leaved Dock	***	0	1	**		
Charlock	***	0	13	**	0.40	36
Cleavers	***	0	4	-	3.00	58
Common Chickweed	***	0	3	***	0.20	94
Common Field-speedwell	-	0	0		0.08	72
Common Fumitory	-	0	0	*	0.08	17
Common Hemp-nettle	**	0	0	-		
Common Mouse-ear	**	0	0	**	(0.20)	
Common Poppy	*	0	2	a	0.40	18
Corn Marigold				a		
Corn Spurrey	*	0	1	*		
Cornflower				b**		
Creeping Thistle	***	1	4	*	0.30	
Cut-leaved Crane’s-bill	-	0	0		0.08	11
Fat-hen	***	0	4	***	0.20	13
Field Forget-me-not	-	0	0	-	0.20	
Field Pansy	-	0	0	**	0.02	45
Fool’s Parsley	-	0	0			

Groundsel	***	0	3	**	0.06	
Knotgrass	***	2	3	***	0.10	
Red Dead-nettle	**	1	1	-	0.08	47
Redshank	**	0	1	***	(0.20)	
Scarlet Pimpernel	-	0	0	a	0.05	
Scented Mayweed	**	1	1	-	0.40	67
Scentless Mayweed	***	2	4	a	0.40	67
Shepherd's-purse	**	0	3	*	0.10	23
Smooth Sow-thistle	***	1	1	*	0.10	
Sun Spurge	*	0	1	-		
Wild-oat	-	0	0	-	1.00	42

a: no information at genus or species level
b: due to the rarity of cornflower, it is highly likely that references in the literature refer to other members of this genus e.g. black knapweed *C. nigra*, greater knapweed *C. scabiosa*

11. PRACTICAL WEED CONTROL, BIODIVERSITY AND RISK AVOIDANCE

11.1. Weed Control And Biodiversity

The data for weed competitive ability and importance for birds and invertebrates of different weed species (summarised in Table 10.1) indicate that it should be possible to identify those species that are only moderately competitive and support important numbers of invertebrates and birds. This offers the possibility of selective management of weed assemblages towards desired endpoints of species and populations. The practicality of this will need further work and may ultimately be difficult to achieve. Nevertheless, the impact of weed control on reducing insect biodiversity within the crop has been demonstrated by (Schellhorn & Sork, 1997). Several initiatives, notably for integrated crop management, indicate there are implications for biological diversity within fields from different approaches to weed control (Clements et al., 1994; Mayor & Dessaint, 1998; Palmer & Maurer, 1997; Van der Putten et al., 2000). The protection of the farmers' investment and avoidance of risk have been the driving forces for efficient weed control in the past. However, an emerging new paradigm is to match crop production with conservation of biological resources (Paoletti et al., 1992) and the development of more sustainable systems. This may require the maintenance of some weeds within fields.

Weed assemblages have changed to some degree in the UK over recent decades. Over a similar period, herbicide use has also changed and the pattern of arable cropping has altered. However, causal links are extremely difficult to prove. With better information, it should be possible to identify the important components of weed assemblages for biological diversity, and therefore the likely impacts of particular herbicides with varied spectra of activity, alongside the effects of crop type, management, etc. The results of the present study indicate that the weed species listed in Table 11.1 have intermediate competitive abilities and are important for insects and bids in farmland.

Table 11.1. Weed species of importance for invertebrates and birds and with intermediate abilities to compete with arable crops.

Arable weeds	Arable weeds	Arable/grassland weeds
Annual Meadow-grass	Knotgrass	Broad-leaved Dock
Charlock	Redshank	Creeping thistle
Common Chickweed	Scentless Mayweed	
Fat-hen	Smooth Sow-thistle	
Groundsel		

Maintenance of non-competitive populations of these species may allow a balance to be struck between maintaining biological diversity and profitable cropping. There remains a need to assess the biodiversity value of other common weeds not included in this study.

Weed management systems

Recent research, now carried into practice to some degree, has considered the management of weeds within the crop rotation as a whole, rather than simply in single crops. Economic pressures have also forced farmers and growers to consider the number of herbicide applications made and the dose of active ingredients used. Reduced dose applications have become common. These and other approaches contribute to “integrated weed management”.

However, “*devising integrated weed management strategies that address a diversity of weed species with a diversity of life history traits is difficult*” (Mortensen et al., 2000). A sound understanding of species, population and community ecology can contribute to weed management. Advances include population equilibria, density-dependent effects, crop competition models and integration with herbicide dose-response studies (Mortensen et al., 2000). (Jones & Medd, 2000) suggest that rather than taking the economic threshold approach to weed control, there are advantages in using population management. Application of natural resource economics, with the aim of reducing the stock of weed seed and based on dynamic modelling, can give better weed control. Herbicide dose-response studies also have the potential for recommendations for appropriate (and reduced rate) herbicide mixtures for mixed weed populations (Kim et al., In press).

Simple cropping systems and reliance on herbicides have resulted in herbicide resistance in some weed species. A combination of crop rotation, including spring crops, a range of cultural practices including delayed sowing, and effective herbicides, can reduce populations of herbicide resistant blackgrass, *Alopecurus myosuroides* (Chauvel et al., 2001).

Novel approaches to weed control

A variety of novel approaches to weed control have been examined experimentally. For example, “living mulches” or bi-cropping with companion crops to reduce weeds have been examined in maize (Ammon & Muller-Scharer, 1999; Drinkwater et al., 2000) and in wheat (Clements et al., 1995). Selective biological weed control may be a useful adjunct to integrated weed control (Ammon & Muller-Scharer, 1999). Legume cover crops reduced weed growth in maize in Mexico, apparently showing an allelopathic effect (Caamal-Maldonado et al., 2001). There is also some evidence in the UK that oats are allelopathic to weeds (Wilson et al., 1999).

Whilst not novel, manipulation of crop architecture shows some potential for weed suppression. A series of studies have shown that different cultivars and species of crop have differing abilities to suppress weeds. Factors such as row spacing and sowing density can have marked effects particularly in combination with herbicides, e.g. (Blackshaw et al., 2000) (Kirkland et al., 2000). Crop row spacing can influence weed impact on the crop, for example shown by (Conley et al., 2001) in potatoes.

Mechanical weed control

Inter-row hoeing in cereals has been developed in Finland (Lotjonen & Mikkola, 2000), but wider row spacing will reduce overall crop yield in barley. Thus there is a trade-off between weed control and crop yield. Nevertheless, mechanical weed control can allow reduced rates of herbicide to be used in combination, resulting in more consistent control

(Forcella, 2000). Combinations of tillage and timing of cultivation can also allow reduced rates of herbicides to be used (Bostrom & Fogelfors, 1999).

Future weed management for biodiversity

Current integrated weed management programmes might be further developed and modified to maintain adequate populations of the most important weed species, while controlling the most damaging.

The data on weed seed banks (Section 5) illustrate the dynamic nature of weed populations and the ability of weeds to produce high seed return, if control is relaxed. This offers some possibility of relaxing weed control either rotationally or in limited areas of crops, as with conservation headlands. Nevertheless, the major constraint is that the most fecund and often the most competitive weed species respond best to simple relaxation of management. Therefore, relaxed weed control would need to be managed carefully to allow the less common and less competitive species to increase, while controlling the competitive species. This may indicate a new approach to weed management, with the explicit aim of maintaining specific weed assemblages. These might be more traditional assemblages that were common 100 years ago, or tailored to maintaining beneficial invertebrate species, or for biodiversity. An understanding of the selection pressures applied by management, including the use of herbicides, and their effects on diversity, ranging from genetic to community levels, is needed.

The key to risk avoidance must be in targeting only those species or populations that require control. This means that precision in chemistry, i.e. selectivity of herbicide, and precision of application, i.e. only to the target plants, offers the most robust way forward. This needs to be within a sound forecasting and decision-support framework. The requirement for greater specificity of herbicide action runs against the trend for more broad-spectrum products produced by the manufacturers. In order to cover the high costs of product development, manufacturers require products that will sell into large, usually global, markets. This has resulted in herbicides with wide weed spectra coming to market, with more selective products rarely being commercialised. Whilst greater herbicide selectivity would be the sound ecological development, it is not without practical and financial difficulties. The inertia of commercial development could only be mobilised by legislative and regulatory requirements, possibly backed up by redirected farm support to growers. In addition, there could be difficulties if there are insufficient product options, associated with the development of herbicide resistance.

11.2. Risk Management and Avoidance

Risk management needs to address susceptibility and exposure. Exposure can be most easily manipulated for "off-field" non-target effects and rather less easily for non-target species within the application target area. Susceptibility is unlikely to be modified, except by selecting narrow spectrum chemicals or using protectants. Risk avoidance for non-target species can be based on application techniques, timing of operations and by exploiting spatial methods. The following areas ought to be considered in order to reduce risk:

1. Choice of pesticide. Use compounds with high specificity, rather than broad-spectrum; use pesticides with low mobility in soils; low volatility

2. Optimum dose. Reduced doses may be adequate to achieve commercial control levels, leaving non-target species

3. Timing of application. Herbicides might be applied at specific times to give selectivity between targets and non-targets, e.g. GMHT crops might allow late weed control.

4. Selective application. Patch spraying, rather than overall; weed detection; weed wiping, etc.

5. Application technology. Air-assistance, electrostatic, droplet production

6. Formulation. Adjuvants to increase effectiveness and reduce doses; protectants, if possible

6. Spatial methods. It is possible that rather than changing management wholesale within arable fields, it may be sufficient for biodiversity enhancement to modify management in sacrifice areas on farms. The maintenance and management of set-aside has been shown to encourage biodiversity (Firbank, 1998; Firbank & Wilson, 1995; Henderson et al., 2000). The best practical example of the spatial approach is the Conservation Headland, described below.

Conservation Headlands

One approach to reducing the effects of herbicide use on biodiversity is the use of "Conservation Headlands". This technique was developed by the Game Conservancy Trust, originally in response to concerns about the potential impact of pesticides on invertebrates eaten by grey partridge chicks (Rands, 1985; 1986), and involved modifying pesticide use on the outer six metres, or half spray boom width, of cereal crops. Grey partridges were known to prefer cereals as foraging habitat for broods (Green, 1984), and it was hypothesized that withholding pesticides from a small proportion of cereal fields would increase the availability of invertebrate food and, as a result, chick survival. Replicated field experiments using large blocks of land, each consisting of several fields with fully sprayed or "unsprayed" headlands, confirmed this hypothesis, with chick survival of grey partridge and pheasant increasing in response to increased abundance of chick-food arthropods (Rands, 1985; 1986; Sotherton & Robertson, 1990). Further work showed that butterfly numbers were also increased where headlands were left untreated (de Snoo *et al.*, 1998; Dover *et al.*, 1990), whilst wood mice (*Apodemus sylvaticus*) and blue-headed wagtail *Motacilla flava flava* selected untreated blocks as feeding habitat (de Snoo *et al.*, 1994; Tew *et al.*, 1992). Observations of rare and declining members of the arable flora in untreated headlands indicated the potential of this approach as part of a strategy for rare "weed" conservation (Wilson *et al.*, 1990), especially as, where such species do survive in the seed bank, they are most abundant at the field edge (Wilson & Aebischer, 1995).

Initially, the prescription was to leave the outer six metres of cereal crops untreated with any pesticide after 1 January, so that spring sown crops received no pesticides at all, whereas autumn-sown crops received residual herbicides in autumn but no spring herbicides, fungicides or insecticides. However, it was soon realised that the use of autumn-applied residual herbicides suppressed the broad-leaved weed species that were considered beneficial (Boatman, 1987), whilst the exclusion of all pesticides in spring, particularly fungicides, was not essential to achieve the aims of the technique. Guidelines were drawn up specifying the use of selective herbicides for the control of grass weeds (Anonymous, 1997), and cereal field edges managed according to these guidelines were termed “conservation headlands” (Sotherton, 1991). Initially, effective control of black-grass *Alopecurus myosuroides* in conservation headlands depended on the use of a sequence of tri-allate followed by diclofop-methyl, the timing of which was crucial (Boatman, 1987). Later, the advent of more effective foliar applied herbicides such as tralkoxydim, clodinafop propargyl and fenoxaprop-P-ethyl widened the choice and increased the ease of achieving effective selective control of grass weeds (Boatman *et al.*, 1999; Canning *et al.*, 1993; Varney *et al.*, 1995). Cleavers *Galium aparine* were also considered unacceptable in conservation headlands because of their high competitive ability, but presented a more intractable problem in terms of selective control. Fluroxypyr proved less than ideal, being effective against species such as *Polygonum* weeds that were desirable as hosts for chick-food insects (Boatman *et al.*, 1988), and quinmerac, which showed considerable promise (Boatman, 1989), was not released as a single ingredient product. Eventually however, the approval of amidosulfuron provided a product with the required properties for selective control of cleavers (Boatman *et al.*, 1999). As well as providing a good degree of selectivity in terms of susceptibility, amidosulfuron has two additional advantages: it can be used early in the spring, before the main germination period of the April-germinating *Polygonums*, and it suppresses desirable but competitive over-wintered species such as chickweed (*Stellaria media*), which are stunted temporarily but then recover so that they remain beneath the crop canopy and are less competitive than if completely untreated.

Replicated experiments have been carried out to assess the impact of conservation headland management on crops (Boatman, 1992 and unpublished data), and the cost to the farm in terms of income foregone in the UK (Boatman *et al.*, 1999; Boatman & Sotherton, 1988) and the Netherlands (de Snoo, 1994). Conservation headland costings and guidelines have been adopted as the basis for prescriptions in several Environmentally Sensitive Areas and the pilot Arable Stewardship Scheme.

12. KNOWLEDGE GAPS AND RESEARCH NEEDS

Consideration of non-target effects of herbicides within crops and the related development of more sustainable crop management systems are important challenges for agriculture and horticulture. Both raise questions regarding cause and ecological effect, what objectives should be pursued and how these might be practically achieved. In the following section, areas where information is lacking and research is required are briefly discussed. These are broken down into topic areas related to weeds, insects and birds for simplicity, but the inter-disciplinary nature of the ecology requires integrated research to develop the requisite understanding of the intertrophic interactions.

Overall, work is needed to classify the competitive ability of a wider range of weed species under different cropping conditions. The trends shown from data derived from the Phytophagous Insect Database linking plants to insect herbivores must be confirmed. There is a clear need for better knowledge of the status of weed populations and a system which would provide information against which future weed changes could be measured. Similarly, there is a need for quantitative as well as qualitative data on the importance of particular weeds for invertebrates and birds. The interactions between weeds, invertebrate fauna and most birds, including those that are insectivorous at the chick stage, are also poorly understood. Greater understanding of the functioning of the agricultural ecosystem would allow clearer causal links between population change and agronomic practice to be identified, against which to better judge the impact of herbicides. In particular, the nature and effect of selection within agroecosystems is poorly understood at genetic, individual, population and community levels. A major challenge is to develop weed management systems that allow biodiversity to be maintained in the crop.

12.1. Weeds and Weed Management

- Status of weed flora associated with cropping

Information on the status of the weed flora in the UK is patchy. There is a need to be able to assess changes in the flora of arable and horticultural fields, both for weed control and biodiversity reasons. Occasional comprehensive surveys that cover all crop types, soils and farming systems are needed.

- Competitive ability of weed species

An understanding of the impacts of weeds on crops and crops on weeds is a basic requirement for the development of practical weed management systems. The competitive ability of some weeds is known, but this needs extending to a much wider range of species. The factors affecting weed competition need to be quantified, including the impacts of weed density of different species in a wider range of crops. Competitivity in most horticultural crops is poorly known.

- Population cycles of weeds, including seed losses

More complete population models for a wider range of weed species are needed. These can be used to understand and simulate changes in cropping management, are useful for predicting management interventions and might be used to start investigating the effects of selection pressures.

- Understanding selection

There is an important need to understand the impacts of selection pressures within agroecosystems. Selection is likely to be rapid in annual cropping systems, but is poorly researched at the genetic, individual, population or community level, at all of which there may be important effects on diversity.

- Herbicide effects on flowering, fecundity and herbivory (including sub-lethal doses)

Herbicides can have a range of effects on plants ranging from complete kill to enhanced growth depending on susceptibility, dose etc. Reduced doses may have subtle effects on plant morphology and phenology. Most annual plants are dependent on seed for regeneration. Subtle effects on seed production and flowering may have more profound impacts on populations over time, particularly for species with short-lived seeds. Indirect effects on herbivore species may result from changes in plant defences and palatability, as well as effects on flowering.

- Factors affecting the spatial behaviour of weeds

Whilst not all weed species are patchily distributed, many are. Field-to-field variation in weed assemblages is poorly understood, but is a key feature of weed ecology. An understanding of the spatial variability and patch behaviour of weeds may be useful for reducing herbicide use and for gaining an insight into weed movement and re-introduction dynamics. The reasons for within-field spatial variability of weeds have been recently investigated in Iowa, USA, using multivariate analyses of spatially-referenced weed occurrence and soil environment data (Dieleman et al., 2000). The approach is applicable to UK conditions and is an important area to enhance our understanding of weed occurrence and to develop work on patchiness and spatial behaviour of weeds.

- Interactions between weeds, invertebrates and birds, especially for chick food

Whilst good information on the interactions between weeds, invertebrates and grey partridge populations exist, there is a need for better understanding of the tritrophic interactions affecting other farmland bird species. Data on the importance of the full range of common weeds for invertebrates and farmland birds is required.

- Selectivity of herbicides

Information on the susceptibilities of weeds to existing herbicides is not easily obtained, except for limited data on herbicide labels. There is a need for a) easier access to existing information and b) much more comprehensive dose-response data on the range of weed species commonly found.

Legislative and regulatory frameworks need to encourage manufacturers to develop and growers to use narrow-spectrum herbicides, targeted at those weed species that need to be controlled, rather than the broad-spectrum, low risk approach currently deployed. How this might be achieved requires development.

- Selective precision delivery systems

Selectivity of herbicide action can be achieved by precision application to target weed species. How this might be achieved within crops requires research and innovation. Target recognition may be a key area of future development.

- Weed management systems, including DSS

To reduce herbicide use, farmers and growers need information on which to objectively judge the need for interventions. That judgement needs to consider not only the existing crop, but future rotations, population responses (including any seed bank) and likely herbicide efficacy on weed species and populations present. Decision support systems, incorporating such data, are required. If weed management is to move to one that incorporates aspects of biodiversity support, with greater potential risk to production, information-rich systems will be needed to support farmers.

- Practical approaches to managing crops for biodiversity

Practical approaches to crop management for biodiversity need to be designed and field tested. Targets for control need to be objectively identified and strategies developed to deal with non-target weeds that become targets at particular population levels. Systems development within Integrated Crop Management would be a practical start.

The targeting of particular weed assemblages and the development of practical means of maintaining such associations is an important priority for R&D.

- Spatial techniques, sacrifice areas

It is possible that sufficient resources can be provided for plants, invertebrates and farmland birds by managing particular areas or parts of fields in particular ways. This requires rigorous testing, as spatial scale will be key to the dynamics. One example is Conservation Headlands for increasing gamebirds (and incidentally invertebrates and songbirds). Perennial vegetation island areas within arable crops are being examined by the Farmed Environment company and CEH. The technique could be modified for the arable flora.

- Economic implications

A number of management scenarios are implied by the challenge to maintain biodiversity with crops. Each requires an economic evaluation and methods of support need to be investigated. Yield foregone might be useful for support for specific management prescriptions for limited areas.

12.2. Invertebrates

- Status of invertebrates associated with cropping

Very little information is available on the status of the invertebrate fauna of arable and horticultural fields. Nevertheless, some species are Biodiversity Action Plan targets or Red List species. More comprehensive data on status and change over time is required, taking account of different cropping, soils, etc.

- Confirmation of trends shown by PIDB for weed-invertebrate associations

Invertebrate / weed species interactions are of key importance in balancing herbicide input and biodiversity concerns. Field research is needed to clarify trends indicated in the Phytophagous Insect Database used here. Quantitative ecological investigations of the use of key weed species by invertebrates should be developed first.

The PIDB is concerned with insect herbivores only. Information on the other guilds, including pollinators and predators, is also need and should also be obtained by field research.

- Feeding preferences and food value of weeds and seeds

Closely allied to the above, information on the feeding preferences of different invertebrates on weeds is required, particularly for the insect species that are of most importance for farmland birds. Information on the nutritive values of weeds for these species would inform the selection of species for targeted management.

- Seed-feeders and weed population dynamics

Interactions between weed species and seed-feeding insects – pre and post dispersal – may have profound effects on population cycles. This requires detailed research. Some data on seed predation is becoming available, but further work is required, particularly in relation to seed availability for birds at key times of year. Evidence exists that pre-emergence seedling mortality, by invertebrates, is very high and again requires experimental verification for a range of species.

- Interactions between soil fauna, weeds and herbicides

Few studies have been made of the effects of herbicide use on below-ground fauna. Effects of herbicides on soil organisms and processes, e.g. decomposition and collembolan and mycorrhizal functioning, may have profound influences within agroecosystems. The relative importance of these effects should be quantified.

- Sub-lethal effects on invertebrates

Herbicides may have both direct and indirect effects on key insect groups and species. Little is known of these. Likewise, synergy between pesticides is known (Norris & Kogan 2000) but its likely importance is not.

12.3. Birds

Effects of herbicides on birds

Figure 12.1 gives a model framework for the assessment of risks presented by herbicide use for birds.

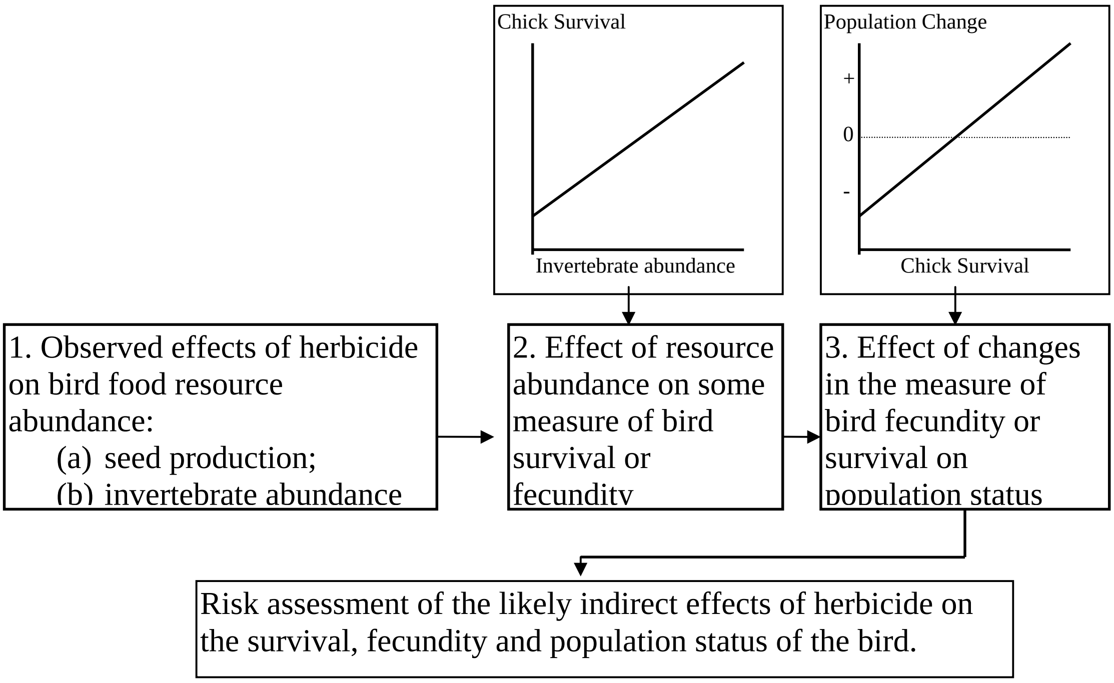


Figure 12.1. Schematic representation of a deterministic risk assessment process to assess the likely indirect effects of herbicide application on a bird population, with examples of relationships established for the grey partridge.

Research is required in the following areas:

Box 1(a):

- Further work on feeding preferences, food value of different weed species and potential for substitution
- Effects of sub lethal doses of herbicide on weed seed production
- The implications of providing weed seeds in "sacrifice areas" (e.g. field margins) compared to provision throughout crops, for farm productivity and profitability, bird utilisation and feeding behaviour

- The impact of other seed predators on seed availability for birds

Box 1(b):

- Further work on feeding preferences, availability, and food value of invertebrate taxa
- Invertebrate/weed interactions for key weed species
- Effects of sub lethal herbicide doses on weed-feeding invertebrates

Box 2:

- Effect of weed seed abundance or invertebrate abundance on appropriate life stage for bird species of conservation concern (where not already known)

Box 3:

- Identification of life stages which are critical in causing population change (where not already known)

12.4. Priority Research Areas

1. classification of the competitive ability of a wider range of weed species under different cropping conditions
2. confirmation of the trends shown from data derived from the Phytophagous Insect Database linking plants to insect herbivores by ecological field study
3. assessment of the biodiversity importance of common weeds not included in this study
4. surveys of the status of weed and invertebrate populations
5. quantification of the importance of particular weeds for invertebrates and birds, including preferences and resource values
6. investigation of the interactions between weeds, invertebrate fauna and birds, including those that are insectivorous at the chick stage
7. modelling the functioning of the agricultural ecosystem to identify clearer causal links between population change and agronomic practice
8. investigation of the nature and effect of selection pressures within agroecosystems at genetic, individual, population and community levels
9. development of weed management systems that allow biodiversity to be maintained in the crop
10. tests of spatial methods of herbicide risk avoidance at appropriate spatial scales

EXECTIVE SUMMARY AND CONCLUSIONS

In considering non-target plants within arable fields, the majority of plant species that are found are of only minor concern to farmers, unless present at high population density. Under horticultural conditions, it can be argued that all weeds are targets, providing some difficulty for formal risk assessment. In arable, there are a number of key weed species that are typically controlled irrespective of density. In contrast, rare arable weeds may require specific conservation protection; these species may be non-targets under almost all conditions. The majority of species usually present can be both targets and non-targets and are most likely to be of greatest significance for biological diversity within fields, as they occur frequently and with moderate abundance.

Data on farmland birds and invertebrates indicate that there have been significant reductions in populations and ranges over the past thirty years. In the case of the grey partridge, there is good evidence that herbicides have played a significant role in their decline. Whilst *habitat loss* and fragmentation may play a role in bird declines, the evidence indicates that *habitat degradation* is of greater importance. Changes in farming practice in general are the cause of most population declines of farmland birds. Whilst the exact causal links are not known for most species, herbicides are implicated.

This review has shown that there have been changes in weed assemblages over the past century, with some species becoming less common, other increasing in frequency and others remaining static. Studies of weed seed banks indicate little change in weed seed abundance or a slight trend for reduced densities. Where weed control has been relaxed, either as set-aside or where herbicide use has been halved, weed seed banks can increase rapidly. However, the commonest and most competitive weed species tend to become the most abundant, under these conditions. Rare species may not recover.

Analysing changes in cropping and herbicide use, the move from spring to winter cropping since the 1970s has been a dramatic change in cropping practice. Co-incident with the change to winter cropping, there have been major changes in the pattern of herbicide use. In the 1970s, herbicides were used primarily for broad-leaved weed control and on only about 50% of fields. Today, herbicides are used on most fields and are targeted on grass weeds as well as dicotyledonous species. An examination of the weed spectra controlled by the herbicides in use over the past 25 years indicates that on average today’s herbicides control more weeds. Broader spectrum products were introduced in the early 1980s. Factors other than herbicides may play an important role in changing weed assemblages, particularly fertilisers and cropping pattern.

Data collected from the literature and from the Phytophagous Insect Database demonstrate close links between invertebrates and a range of representative weed species. Different weed species support differing numbers of insect herbivores, with some species hosting numbers of rare species, as well as pest species. The data indicate that a number of weed species that are particularly important for insect biodiversity in the arable habitat can be selected.

Data on the use of weed species by birds has also been examined. Whilst, as with the invertebrate data, there is some lack of quantitative information on preferences, it is clear that bird species of conservation importance utilise particular genera of weeds. Thus it is possible to identify genera that are of greater importance for farmland birds.

The data indicate that herbicides, by controlling weeds and modifying abundance and species assemblages, have impacted on wildlife in arable land. These non-target effects need to be considered for regulatory reasons, particularly with the requirements under EU Regulation 91/414. With such dramatic changes in biodiversity, there are also calls for more sustainable production methods. The challenge will be to grow crops and maintain an appropriate population of weed species to support farmland wildlife. Under horticultural conditions, this may be difficult, in terms of crop quality protection. Nevertheless, under arable and horticultural production, there may be opportunities to develop sacrifice areas, such as conservation headlands, or to develop much greater selectivity of herbicide action, either through selective chemistry or application or a combination of these.

In terms of regulatory needs, the approach of selecting representative weeds and assessing their importance for biodiversity has been successful. A shortlist of species has been identified. The approach can now be applied to other weed species, to check the most important species have been identified. Regulatory approaches reviewed in PN0923 can be applied as non-target protocols, with adjustment of acceptable risk to achieve control where required.

There are a number of areas where knowledge is lacking. These are briefly reviewed and a priority list for research and development is given below:

1. classification of the competitive ability of a wider range of weed species under different cropping conditions
2. confirmation of the trends shown from data derived from the Phytophagous Insect Database linking plants to insect herbivores by ecological field study
3. assessment of the biodiversity importance of common weeds not included in this study
4. surveys of the status of weed and invertebrate populations
5. quantification of the importance of particular weeds for invertebrates and birds, including preferences and resource values
6. investigation of the interactions between weeds, invertebrate fauna and birds, including those that are insectivorous at the chick stage
7. modelling the functioning of the agricultural ecosystem to identify clearer causal links between population change and agronomic practice
8. investigation of the nature and effect of selection pressures within agroecosystems at genetic, individual, population and community levels
9. development of weed management systems that allow biodiversity to be maintained in the crop
10. tests of spatial methods of herbicide risk avoidance at appropriate spatial scales

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