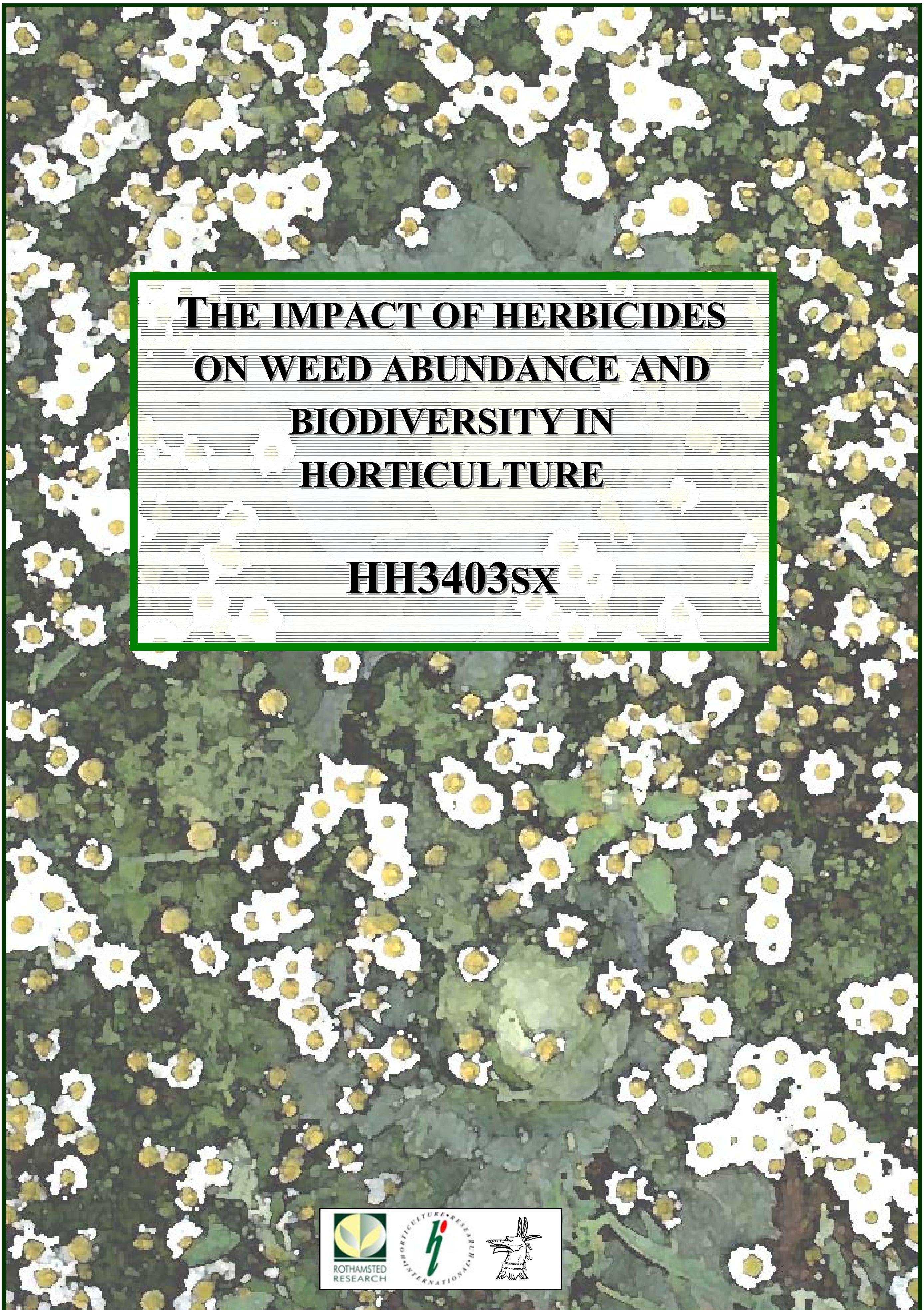

THE IMPACT OF HERBICIDES ON WEED ABUNDANCE AND BIODIVERSITY IN HORTICULTURE

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ROTHAMSTED RESEARCH

HORTICULTURE RESEARCH INTERNATIONAL

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EXECUTIVE SUMMARY

This desk study has confirmed that achieving a balance between production and biodiversity in horticulture presents a number of interesting and complicated challenges compared with arable systems. As with much of agriculture, there is a lack of baseline survey data by which any positive management towards increasing biodiversity can be measured. This is particularly true for horticulture where we can only extrapolate from the collation and interpretation of the similarly disjointed and uncoordinated collection of surveys made in arable crops.

There has been a decline of more than 38% in the horticultural crop area since 1977 (excluding potatoes), compared with a 100% increase in wheat. The area of potatoes grown is the largest in the 'horticulture' sector, but in 2000 this was 5.3% of the wheat area. Despite the relatively small environmental "footprint" of horticulture, the combination of soil types, wide range of crops and crop architectures, diverse weed species and spring cropping provide a number of opportunities to complement and enhance strategies already in place in cereal crops. However, horticultural crops are much higher value than winter wheat and the purchasers of horticultural crops put stringent quality requirements on growers. These quality requirements are such that growers cannot risk leaving weeds as it may result in complete crop rejection and thus huge loss of income. The same is not true for cereals where there may simply be a modest reduction in price. Therefore, whilst there are different production systems for all horticultural crops there is a common aim throughout: from the aspects of quality, yield and harvesting, weeds within the crop area are simply not tolerated and all weed species are targets for control. This intolerance of the majority of horticultural crops to weeds, make the relaxation of weed management and use of thresholds within the crop less attractive than in arable systems.

Hedges, field margin refuges, mulches and over winter stubbles would appear to be the most practically achievable way of enhancing biodiversity within horticultural systems. However, it will be necessary to examine whether these approaches will deliver all the desired biodiveristy benefits or whether there are certain organisms/groups of organisms that will not respond measure also being located within the field centres. Importantly, any such strategies that actually take land out of production could not be entered into without appropriate compensation to growers. This is because many of the horticultural crops, particularly vegetables, are grown on valuable high-grade land. In contrast to cereals, there is currently no EU area aid payment for horticulture (although this will change). If growers were compensated for loss of production and management of land for environmental benefits, there would need to be a benchmark against which improvement could be measured.

Managing such areas would need to be carefully tailored so that the biodiversity encouraged was beneficial (e.g. source of pollinators and biocontrol of pests) and did not conflict with the management of crop itself. For example, by introducing the "wrong combination of flora" that actually attracts or harbours potentially threatening crop pests. As in arable crops, most of these interactions between weeds in horticultural systems and the associated bird and invertebrate populations are poorly understood. A better understanding (and quantification) of the establishment, ecology and population dynamics of these flora and their trophic interactions may help towards developing suitable management prescriptions adjacent to specific horticultural crops. Knowledge of the specific biology and ecology of many of these beneficial or rare arable weed species are also lacking which hinders their establishment and management.

Many of the common horticultural weeds have already been identified within arable systems as being beneficial in encouraging biodiversity. However, whilst simply reducing herbicides or doses alone could encourage some of the common beneficial species, it is unlikely to improve populations of the rare arable weed species. Without selectively sowing desirable species followed by a combination of appropriate chemical and cultural management, succession will generally lead to the establishment of less beneficial perennial species and more grasses.

Ironically, whilst it is generally accepted that the widespread use of herbicides has contributed to the depletion of biodiversity in the last 50 years, in horticulture, the loss of products may in itself remove a tool to help us manage for biodiversity in the future. The decline of herbicides in horticulture is a result of the EU pesticide review and the economic disincentive to the agrochemical industry to develop new products. The reliance on a small number of largely broad-spectrum products in horticulture provides little scope for selective management for specific weed species, either within the crop (in the few examples where they can be tolerated) or even the designated sacrificial margins.

Importantly, the reliance on a small (and still decreasing) number of products also compromises efforts to prevent the development of herbicide resistance, which should underpin all good chemical weed management programmes. The worst-case scenario resulting from the loss of products could be that certain horticultural crops could no longer be grown in the UK. There are no easy answers to reversing this decline in products. In most horticultural crops the cost of alternative non-chemical methods are often more expensive and can themselves have negative and still largely unquantified impacts on biodiversity. Therefore, the development of more cost effective, reliable and novel methods of non-chemical control will be an important complementary method of weed management in horticulture in the future. However, non-chemical methods alone are unlikely to be able replace the continuing need for herbicides to meet market demands and we can expect very few new herbicides for horticulture in the future. New products being developed for cereals and other major crops may have potential for use in horticulture, but exploring these possibilities needs facilitating and sufficient support.

The remit of this study has raised a wide range of complex issues and research needs relating to the impact of herbicides and weeds on biodiversity in horticulture. It has also highlighted many of the concerns (such as loss of herbicides) constraints (such as crop quality demands) and knowledge gaps (such as lack of baseline information and understanding of trophic interactions) for the future of sustainable weed management in horticulture. As a results a number of specific research needs have been identified and a priority list constructed. These research gaps fall within four broad themes; namely 1) baseline monitoring, 2) practical measures for encouraging biodiversity, 3) underpinning weed biology and ecology and 4) improving long-term sustainable weed management strategies for horticulture. Ultimately the integration of properly researched tactical management approaches is essential to prevent the development of impractical or conflicting strategies in horticulture.

Knowledge gaps and research needs:

Baseline monitoring:

1. Survey current weed flora of horticultural systems to provide baseline data.
2. Field survey bird utilisation of all horticultural crops for nesting and foraging through the year and also evaluate and extract data of bird occurrence in horticulture from BBS and CBC datasets
3. Survey cropping patterns that precede different horticultural crops
4. Identify weed species that contribute to winter seed supply in different crop stubbles.
5. Develop measurable indicators of biodiversity for horticulture.

Practical measures for encouraging biodiversity:

6. Evaluate crop management factors that favour particular birds, particularly crop structure, mulching and timing of operations
7. Can partial disruption of refuge habitat force natural enemies into the crop and enhance biological control?
8. Evaluation of annual and perennial margin strips and wildflower seed mixtures for a range of horticultural crops.
9. Investigate the effectiveness of selected surface mulches/manures for increasing natural enemy abundance and biological pest control within horticultural crops whilst respecting hygiene and harvesting protocols.
10. Determine optimal understorey species and management practices for use in orchards.
11. Is there scope for increasing weed tolerance levels (species and abundance)?

Underpinning weed biology and ecology:

12. Understand the relative time of emergence of crops and weeds within the changing seedbed environment to improve weed control strategies that rely on crop/weed growth-stage differentials to be effective.
13. Improve our understanding of weed seed dormancy (e.g. to improve our ability to predict weed survival and emergence through a rotation and target control techniques more effectively).
14. Understand the germination ecology and management requirements for desirable and rare arable weeds for the establishment and maintenance of beneficial margins.
15. Improve estimates of critical stages in weed population dynamics (e.g. seed production, seed predation and seed persistence).

Improving long-term sustainable weed management strategies for horticulture:

16. Integrate models of weed biology and ecology to help predict the long-term outcome of weed management strategies and shifts in the weed flora. These should also include weed species identified as rare or having specific beneficial properties.
17. How will horticultural crops and weed populations respond to long-term climate change so we can plan for future sustainable weed management?
18. Are there opportunities for using influence diagrams as a framework for understanding complex interactions and risks associated with the future of weed management and biodiversity in horticulture?
19. Improve the reliability and cost-effectiveness of existing non-chemical and novel weed management techniques to complement and integrate with herbicides
20. Prioritise future weed management needs on crops where gaps for herbicide weed control will exist after 2007 and examine whether new products developed for cereals and other major crops have potential use for horticulture.

CONTENTS

CHAPTER 1

INTRODUCTION

1.1 Purpose of the desk study

Weeds represent a significant and ongoing constraint to horticultural production. Over the last 50 years significant reductions have taken place in the biodiversity and abundance of both the flora and fauna in agroecosystems and herbicides have been implicated in these changes both directly and indirectly. The extent of the impact of herbicides and weed management on biodiversity in horticulture is not fully understood. In addition weed management in horticulture itself faces an uncertain future and many challenges. Without such information appropriate strategies to promote biodiversity and sustainable weed management cannot be developed. The Defra weeds programme therefore seeks to consider these future challenges whilst also taking into account relevant publications such as the Sustainable Food and Farming Strategy, Review of Agri-environment Schemes, the Biodiversity Strategy for England, the UK Biodiversity Action Plan and the Public Service Agreement (PSA) target for farmland birds. Therefore, the purpose of desk study is to facilitate Defra in identifying key areas for consideration in the future weeds programme.

1.2 Weed control in horticulture in 2003

In comparison with arable crops, horticultural crops leave a very small 'footprint' on land use. The area of potatoes grown is the largest in the 'horticulture' sector, but in 2000 this was 5.3% of the wheat area. Surveys show that the area of potatoes, most vegetables (except onions and lettuce), soft fruit and top fruit have suffered a dramatic decline of 40% or more in the last 25 years. Only the area of bulbs and hardy nursery stock has increased. However, horticultural crops are high-value compared with winter wheat and currently, in contrast to cereals, there is no EU area aid payment, although there will be changes in support mechanisms in the future.

Horticultural crops are diverse, as is their associated weed flora. Most are sown in the spring and on lighter soils, which tend to be associated with a greater diversity of weed species. The crops themselves also have diverse architectures. There are different production systems for all these crops, but there is a common aim: from the aspects of quality, yield and harvesting, weeds are generally not tolerated. Thus, unlike the situation for arable crops as reviewed by PN 0940, all weed species are targets for control. It is possible in a cereal crop to retain a threshold of weed and to still achieve an acceptable marketable crop yield. For many horticultural crops, in addition to yield loss, purchasers put stringent quality requirements on growers and small amounts of weed may cause rejection of the whole crop on grounds on quality and there are no payments to mitigate such catastrophic losses to growers. In particular, quality assurance is important to the fruit and vegetable consumer - produce must be free from toxic and other weedy contaminants, which can occur where pesticides are not used.

A major weed control issue for most growers is the small range of herbicides that will be available in future. This is a combination of the EU pesticide review and the economic disincentive to the Agrochemical industry to develop new products. The extent of herbicide development by Crop Protection companies in crops other than cereals is a reflection of crop area and there is thus a wide range of herbicides for crops such as sugar beet and wheat. In contrast, growers of many minor crops have few herbicides at their disposal, since development cost is high, sales small and a damage claim in a high value crop could be considerable. Reliance has been placed on materials approved for other crops and in the UK there is a system for Off-Label use in some situations. Specific Off-Label Approvals (SOLAs) may be granted by the UK Pesticide Safety Directorate, usually for a minor use. For edible crops, residues data are usually a requirement.

1.3 Biodiversity in horticulture

Many changes have been documented in the flora and fauna of agricultural ecosystems in the UK and one of the most concerning is a reduction in biodiversity (Leake, 2002). Biodiversity has been shown to be important since it performs crucial functions within ecosystems (Altieri, 1999). Whilst habitat fragmentation is important in many of the changes we observe today in agricultural ecosystems, it is changes in farming practice, in which herbicides play a major role, that are thought to be the major driver behind many of these modifications (Marshall *et al.*, 2001). Currently there are no specific baseline surveys of the weed flora and of biodiversity made in horticultural crops.

Herbicides impact both directly and indirectly on the weed flora, invertebrates and bird populations. The weed flora itself is changing both above ground (Sutcliffe & Kay, 2000) and in the seedbank (Squire *et al,* 2000). However, it is the trophic interactions of weeds, both as a primary source of food and habitat structure, that make them particularly significant to biodiversity (Marshall, 2002). For example, whilst there is little evidence for direct phytotoxic effects of herbicides on invertebrates (Breeze *et al,* 1999) one of the major causes for their reductions in numbers has been linked to loss of weed seeds that provide an important food source (Ewald & Aebischer, 1999). Databases such as PIDB provide a useful demonstration of the close links that exist for a number of invertebrates with weed species (Ward & Spalding, 1993). Declines in farmland birds have also been noted in a number of studies (Baillie *et al,* 2001), and again it is thought that loss of weeds seeds and the invertebrates that subsequently feed on them is a critical factor both during the breeding season and winter periods (Wilson *et al,* 1999).

In achieving a balance between production and biodiversity, horticultural systems provide a number of interesting challenges and complications compared with arable systems.

- Firstly, the large number of crops and their associated systems, make generic guidelines for horticulture difficult to achieve. The diversity of crops types therefore necessitates consideration on an individual basis.

- Secondly, within horticultural systems there are the potential conflicts between achieving biodiversity and crop quality. For example, growers might argue that high market demands for quality and the need to avoid weed contamination result in few circumstances where weeds can be considered as non-target and left within the crop (Marshall *et al.*, 2001). The area immediately outside the cropped area may therefore become particularly crucial to achieving biodiversity in horticultural systems.

- Thirdly, all this is set against a backdrop of continually declining herbicides for use in horticulture. With a lack of products to deal with every weed in every crop situation, some weeds may become uncontrollable in certain crops. This reliance on a narrow range of active ingredients will increase problems, such as development of a tolerant weed flora and herbicide resistance (Knott, 2002). Integration of mechanical weed control and other novel strategies may become increasingly important. Ironically, the loss of products and the fact that those that remain are largely broad spectrum may in itself remove flexibility of control to manage for biodiversity in the future.

- Finally, changes in our climate towards milder but wetter springs may further compound weed management options in horticulture on a number of accounts (Grundy, 2002).

Therefore, in any risk assessment on the impact of herbicides, all these factors need to be taken into account when defining appropriate weed management strategies to meet with the UK's commitments to maintaining or enhancing biodiversity.

1.4 Principle objectives of the desk study

The main objectives of the desk study are to:

1. To **review the known effects of herbicides** on weed populations and communities within horticultural crops and the subsequent indirect effects on fauna.

2. To **summarise the impact of weeds** on horticultural crops.

3. **Identify gaps in knowledge**, to prioritise research needs and to examine potential approaches to:
    a) Risk assessment for non-target plants in fields
    b) Practical means of maintaining appropriate weed cover in crops.

Within these main objectives, other *specific* objectives will be to:

1. Define non-target plants in crop situations.
2. Review indirect effects of herbicides and other weed management techniques in the terrestrial environment.
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 horticultural 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.
9. To help with development of new ROAME A in line with Defra's aims and objectives.

For the purpose of the desk study, the diversity of horticultural crops and their associated weed flora made it necessary to rationalise the crops and weed species studied. A consolidated list of crop and weed species selected for this study are summarised in Tables 1.1 and 1.2 respectively.

The crops were selected as a minimum baseline to ensure that all the major horticultural commodities were covered. However, in many cases where relevant information has been available additional crops have been included in the study. Excluding potatoes, the highlighted horticultural crops in Table 1.1 account for around 110,000 ha out of a total of 190,000 ha of horticultural production. The total area of potatoes and horticultural production in 2000 was approximately 360,000 ha. Therefore, *all* the highlighted crops in Table 1.1 account for approximately 280,000 ha, or just over 2/3rds of the total, so they give very good representative coverage of; crop area; different crop types; geographical areas where horticulture is important. The rationale for choosing specific crops are given as footnotes to Table 1.1

Table 1.1 List of crops used as a representative basis for the desk study. Numbers refer to rationale used for choosing typical horticultural crops for purpose of this study.

CROP	AREA (HA)	RATIONALE	COMMENTS
POTATOES	170,000	1,2	(serious weed in its own right as volunteers in other crops).
FIELD VEGETABLES	150,000		
BRASSICAS	30,000		
CAULIFLOWER	12,000	4, 1	picked as typical brassica
LEGUMES	60,000		
VINING PEAS MACHINE HARVESTED & PROCESSED	40,000	1, 6	contaminants, some toxic.
ROOTS & ONIONS	35,000		
ONIONS, BULB & SALAD	12,000	4, 5	Very poor weed competitor
CARROTS & PARSNIPS	15,000	5	Poor early competitors often rented land crops
SALAD S & HERBS	17,000		
LETTUCE	6,000	6,9 (short season)	Interfere with manual harvesting (nettles, thistles)
FLOWERS & BULBS & HONS	13,000		
NARCISSI	4,000	8	Local importance representative of non edibles
TOTAL FRUIT	28,000		
STRAWBERRIES	4,000	3	Hand harvested thistles nettles unwelcome short perennial
Top fruit orchards desert culinary & cider	18,000	2, 3, 7, 8, 9 (long-term)	Tree crops understorey possible cider apples picked from orchard floor

The list is based on:

1. planted area, - the most obvious environmental footprint
2. economic importance
3. crop diversity in production and architecture - perennial vs annual crops, trees vs herbaceous
4. differing abilities of crops to compete with weeds - (eg onions very poor, brassicas ok)
5. herbicide use and weed tolerance per unit area - (onions very high use, low tolerance)
6. specific crop issues - (eg weed seed/plant parts tolerance separation)
7. how intensive
8. high local impact
9. short season or long-term crop

An important consideration for this chapter, and indeed the whole desk study, is that to the best of our knowledge there have been no co-ordinated or widespread surveys made of either the horticultural weed flora or its associated biodiversity. Therefore, the weeds species in Table 1.2 have been chosen based on the list of non-target weeds with potential beneficial associations highlighted in PN0940. The list has also been expanded to include the main problematic weeds in specific commodities based on personal communication with specialist advisors in the industry.

Table 1.2 List of typical horticultural weed species used as a representative basis for the desk study. Competitive index for cereals; the 10+ most frequently mentioned weeds in some crops because they commonly occur or are difficult to control ** also wild mignonette & mugwort in carrots; **all grasses & perennials field bindweed, horsetail; in orchards Canadian fleabane, dandelion, creeping buttercup, silverweed, nettle; # HNS hairy bittercress*

Common name	**Latin name**	**Competitive index (w. cereals)**	**Potatoes**	**Spring cabbage**	**Vining Peas**	**Dwarf Beans**	**Onions Carrots ***	**Bulbs**	**Straw berries**	**Bush& ** cane fruit**	**Top fruit ****	**HNS #**	**Overall weed rating**
Grass weeds										√	√	√	
Annual Meadow-grass	*Poa annua*	0.1	√	√	√	√	√	√	√	√	√	√	10
Barren Brome	*Bromus sterilis*												0
Black-grass	*Alopecurus myosuroides*	0.4											0
Common couch	*Elytrigia repens*		√						√	√	√	√	5
Wild-oat	*Avena fatua*	1.0											0
Broad-leaved weeds													
Black Nightshade	*Solanum nigrum*					√							1
Black-bindweed	*Fallopia convolvulus*	0.3	√		√	√						√	4
Broad-leaved Dock	*Rumex obtusifolius*								√	√	√		3
Charlock	*Sinapis arvensis*	0.4		√				√					2
Cleavers	*Galium aparine*	3.0	√							√			2
Common Chickweed	*Stellaria media*	0.2		√	√			√	√			√	5
Common Field speedwell	*Veronica persica*	0.08		√					√				2
Common Fumitory	*Fumaria officinalis*	0.08					√						1
Common Hemp-nettle	*Galeopsis tetrahit*												0
Common Mouse-ear	*Cerastium fontanum*												0
Common Poppy	*Papaver rhoeas*	0.4			√								1
Corn Marigold	*Chrysanthemum segetum*												0
Corn Spurrey	*Spergula arvensis*												0
Cornflower	*Centaurea cyanus*												0
Creeping Thistle	*Cirsium arvense*	0.3	√	√	√			√	√	√	√	√	8
Cut-leaved Crane's-bill	*Geranium dissectum*	0.08											0
Fat-hen	*Chenopodium album*	0.20	√	√	√	√	√	√	√	√	√	√	10
Field Forget-me-not	*Myosotis arvensis*	0.2											0
Field Pansy	*Viola arvensis*				√				√				2
Fool's Parsley	*Aethusa cynapium*						√						1
Groundsel	*Senecio vulgaris*	0.06		√			√		√	√	√	√	6
Knotgrass	*Polygonum aviculare*	0.1	√		√	√	√		√	√	√		7
Pineappleweed	*Matricaria discoidea*				√	√	√	√					4
Red Dead-nettle	*Lamium purpureum*	0.08											0
Redshank	*Persicaria maculosa*		√			√	√	√					4
Scarlet Pimpernel	*Anagallis arvensis*	0.05											0
Scented Mayweed	*Matricaria recutita*	0.40		√	√	√	√	√					5
Scentless Mayweed	*Tripleurospermum inodorum*	0.40		√	√	√	√	√					5
Shepherd's-purse	*Capsella bursa-pastoris*			√									1
Small nettle	*Urtica urens*			√		√		√	√				4
Smooth Sow-thistle	*Sonchus oleraceus*		√							√	√	√	4
Sun Spurge	*Euphorbia helioscopia*												0
Willowherbs	*Epilobium* spp.									√	√	√	3
Volunteer potatoes	*Solanum tuberosum*		√		√	√	√	√					5
Volunteer oilseed rape	*Brassica napus*		√		√								2
Perennial spp.**									√	√	√	√	4

1.5 References

ALTIERI, M.A. (1999). The ecological role of biodiversity in agroecosystems. *Agriculture Ecosystems & Environment* **74**, 19-31.

BAILLIE, S.R., CRICK, H.Q.P., BALMER, D.E., BASHFORD, R.I., BEAVEN, L.P., FREEMAN, S.N., MARCHANT, J.H., NOBLE, D.G., RAVEN, M.J., SIRIWARDENA, G.M., THEWLIS, R., & WERNHAR, C.V. (2001*). Breeding birds in the wider countryside: their conservation status 2000,* Rep. No. 252. British Trust or Ornithology, Thetford.

BREEZE, V.G., MARSHALL, E.J.P., HART, A., VICKERY, J.A., CROCKER, J., WALTERS, K., PACKER, J., KENDALL, D., FOWBERT, J., & HODKINSON, D. (1999). *Assessing pesticide risks to non-target terrestrial plants.* Report to MAFF Pesticides Safety Directorate, Commissioned No. PN0923.

EWALD, J.A. & AEBISCHER, N.J., (1999). *Pesticide use, avian food resources and bird densities in Sussex.* JNCC Report No. 296, Joint Nature Conservation Committee, Peterborough.

GRUNDY, A.C. (2002). Extreme weather and weeds: can we realistically predict weed emergence and how useful would that information be*? BCPC 39th Annual Review of Weed Control .* 32-35

KNOTT, C.M. (2002). Weed control in other arable and field vegetable crops. In: *Weed Management Handbook* (ed RE Naylor) 9th edition, British Crop Protection Council, Blackwell Science Ltd. Oxford. UK

LEAKE, A.R. (2002). Biodiversity in different farming systems. *British Crop Protection Conference – Pests & Diseases* 2002. 949-956.

MARSHALL, E.J.P. (2002) Weeds and biodiversity. In: *Weed Management Handbook* (ed. RE Naylor) 9th edition, British Crop Protection Council, Blackwell Science Ltd. Oxford. UK

MARSHALL EJP, BROWN V, BOATMAN N, LUTMAN P & SQUIRE G (2001) *The impact of herbicides on weed abundance and biodiversity.* PN0940. A report for the UK Pesticides Safety Directorate. IACR-Long Ashton Research Station, UK

SQUIRE, G.R., RODGER, S. & WRIGHT, G. (2000). Community-scale seedbank response to less intensive rotation and reduced herbicide input at three sites. *Annals of Applied Biology* **136**, 47-57.

SUTCLIFFE, O.L. & KAY, Q.O.N. (2000). Changes in the arable flora of southern England since the 1969's. Biological Conservation **93**, 1-8.

WARD, L.K. & SPALDING, D.F. (1993). Phytophagous British Insects and mites and their foodplant families – total numbers and polyphagy. *Biological Journal of the Linnean Society*, **49**, 257-276.

WILSON, J.D., MORRIS, A.J., ARROYO, B.E., CLARK, S.C., & BRADBURY, R.B. (1999). A review of the abundance and diversity of invertebrate and plant foods of granivorous birds in northern Europe in relation to agricultural change. *Agriculture Ecosystems and Environment*, **75**, 13-30.

CHAPTER 2

CROP/WEED INTERACTIONS

An important consideration for this chapter, and indeed the whole desk study, is that apart from a survey of field vegetable seedbanks made in the mid 1970s, to the best of our knowledge there have been no co-ordinated or widespread surveys made of either the horticultural weed flora or its associated biodiversity. Therefore, it is difficult to quantify whether or not biodiversity has declined in horticultural systems. This also means that we have no baseline for future comparisons.

2.1 Time of sowing and soil type

The weed spectrum in a field is linked to soil type and within a crop it is dependent on time of sowing. Cultivations stimulate weed seed germination, and affect weed emergence and species (Roberts & Dawkins, 1967). The frequency of these cultivations exhausts the buried seedbank at differing rates and the decline is specific to species: in a soil cultivated four times a year, chickweed, an important species for bird feed (Chapter 5), declines at a rate of 56% p. a. but fat-hen 28%. Therefore there are implications for non-chemical v. chemical weed control in terms of the effects of repeated soil disturbance. The weeds that emerge from the seedbed are generally a poor reflection of the species diversity of weed seeds buried in the soil. There has been considerable research on seedbanks in arable cropping systems but there is less information for horticultural crops (see Chapter 7).

Weeds are usually associated with particular soil types, e.g. bugloss, corn marigold, fumitory, mayweeds, common orache, corn spurry, cranesbill spp., wild mignonette, white campion are found on sands; on chalk mugwort, sun spurge, common toadflax; on loam, common poppy, mayweeds, fool's parsley. Knotgrass, fat-hen, cleavers, charlock, chickweed, speedwells, groundsel, shepherds purse, creeping thistle, perennial sowthistle and docks are found on most soils (data from Table 4.4 of PN0940 derived from Brenchley & Warrington, 1933). Most horticultural crops (vegetables and flowers) are sown/planted mainly in spring on lighter soils (Table 2.1), in contrast to the major UK crop winter wheat which is autumn sown on a wide range of soil-types, including heavier ones. It is generally accepted that numbers of weeds and species are far greater on finely cultivated seedbeds on sandy soils, for example those for carrot and onion production, than those on cloddy, heavy soil types. Silt soils however are prone to capping after heavy rainfall and the solid surface impedes emergence of small-seeded weeds (and crops).

Research by Roberts and Potter (1980) on a sandy loam soil suggested that the numbers of weed species and densities emerging in the autumn were lower than those emerging in late spring and summer but were also related to rainfall, and thus spring-sown horticultural crops in Great Britain may be more likely to suffer weed problems than those sown in autumn. This is supported by research in Denmark that has shown that the number of weed species and density is greater in spring-sown compared with autumn-sown cereals in Denmark (Hald, 1999). Winter hardiness of weed species is important for autumn or summer planted crops: for example, chickweed survives winter frosts and has been shown to have a great effect on yield of spring cabbage (Table 2.2).

Weed emergence is also related to rainfall and can be delayed or extended in dry conditions. Roberts and Potter, (1980) also found that the weed species composition is affected by soil temperature and moisture and hence on timing of cultivations. This sort of information is useful for forecasting weed problems – for example, black-nightshade is more likely to affect late-drilled vining pea crops. Information on time of emergence and maturity of weed species related to time of sowing and harvesting crops is given in Chapter 7.

Table 2.1 Main sowing (s) / transplanting (t) times, methods, typical soil types and rotations for a range of horticultural crops

Crop	Sowing/Planting time, drilled seed (s)/transplants (t)/sets/bulbs	Soil type/texture	Rotation type (minimum years between crop) or age
Potatoes	March - April	Light - medium	Arable (4)
Cauliflower, cabbage	March – August (t)	Medium - light moisture retentive	Arable (4)
Brussels sprouts	March - June (t)	Medium - light moisture retentive	Arable (4)
Calabrese	March – August (t)	Medium - light moisture retentive	Arable (4)
Swedes, turnips	March – July; Scotland March – early June	Medium - light clay loammoisture retentive	Arable (5)
Vining peas	February – end May (s)	Light - medium	Arable (4 - 6)
Broad beans	February – end May (s)	Light - medium	Arable (4)
Dwarf French beans	mid May – June (s)	Light - medium	Arable (4 - 6)
Runner beans	Mar – April (s) & (t)	Medium	Continuous (1)
Carrots, parsnips	Autumn & Feb – May (s)	Sandy – light, organic	Arable (4 - 6)
Celery	Spring (t)	Organic, some light	(5)
Onions, bulb & salad	Feb – March (s), (t), some sets; salad (s) Feb-Sept	Light - medium	Arable (4-6)
Leeks	Spring (s), early & late harvest (t)	Light - medium	Arable (4)
Lettuce	Continuous: (t) modules/blocks, (s) a few	Light	Continuous (1)
Red beet	Feb - June	Light	Arable (4)
Spinach	Spring (s), continuous baby leaf	Light - medium	Arable (4), continuous
Sweetcorn	May (s) & (t)	Light - medium	Continuous (1)
Bulbs	August – Sept bulbs	Light - medium	Arable (4 - 6), up to 3 yrs
Flowers	April – May (s) & (t)	Light - medium	Arable (4)
Strawberries	Spring, summer, autumn	Various	Perennial 2-3 yr
Cane and bush fruit	Autumn/winter, spring, spring planted in Scotland	Various	Perennial 5-8 yr
Top fruit	Autumn/winter, spring	Various	Perennial 2-45 yr
Hardy Nursery Stock	Autumn/winter-late spring	Various	Perennial 1-8 yrs herbaceous-Christmas trees

2.2 Rotations

The weed spectrum in a field is also dependent on the cropping rotation. In the 19th Century the introduction of rotations of crops with different timing of cultivations, sowing, harvest and type of crop canopy, meant that no one weed species could benefit from a consistently favourable environment and become dominant as a result. Broad-leaved 'cleaning' crops where mechanical weed control was possible - potatoes or turnips, were grown after cereals. Field beans, grown to feed horses before tractors replaced them, were also part of the rotation. In the 1920s sugar beet was introduced and peas were included later. This meant that although weeds were rarely absent in these crops, they were seldom overwhelming.

Now, horticultural vegetables are frequently a constituent of mainly arable rotations which may include winter wheat, sugar beet, potatoes, oilseed rape and pulses, although crops of the same family would not be a part (e.g. oilseed rape not in rotation with brassicas, or pulses with vegetable legumes). Set-aside is not likely to form part of the rotation on fertile soils. Where horticultural crops are grown in a rotation that includes several cereal crops they inherit cereal weeds. These appear to have increased as a result of reducing herbicide doses to minimise costs of growing cereals (Lutman, 2001). If weeds escape control with low herbicide doses in cereals, weed seeds can return to infest other crops in the rotation. This is not true for the short season vegetables harvested before weed seeds mature and spring sown horticultural crops offer an important break in a cereal rotation where grass weeds have increased.

Volunteer crops, particularly potatoes, are also a serious problem in vegetable rotations because herbicides (if indeed they are safe to the crop) can only offer suppression or, in peas, prevent formation of toxic potato berries. Other volunteers include: cereals, easily controlled with graminicides; oilseed rape, a widespread and persistent problem and linseed, which now occurs infrequently because of the reduction in area and poor survival of its seed.

The weed spectra in perennial fruit crops and hardy nursery stock are more static because obviously rotations are not possible, the land is not cultivated annually and they will not include volunteers from other crops.

2.3 Impact of weeds and weed species on quality and harvesting of horticultural crops - zero tolerance

Horticultural crops are high-value compared with winter wheat and at present there is no EU area payment, although there will be changes in support in the future. Incomes per hectare are in the region of £600 for winter wheat but for lettuce £10,500, leeks £10,000, carrots £5,175/ha, calabrese £4,950, maincrop potatoes £3,575, bulb onions £3,150, vining peas £1,200, dessert apples £5,650, strawberries £13,500 and raspberries £11,250 (Nix, 2002). As a consequence high standard of weed control is therefore the target in most crops.

The main markets for fruit and vegetable produce are through retailers and processors, and growers are not eligible unless they are members of Assurance Schemes (NFU/Retailer Assured Produce scheme www.assuredproduce.co.uk or EUREP Gap) and in the UK 218,000 ha (77% of the cropped area) are included in the Assured Produce Scheme. The aim is crop traceability and to assure the consumer that the produce is safe, and regular audits on farm are carried out. These schemes are based on Integrated Crop Management, which includes efforts to prevent weed problems so that some herbicide applications in the crop can be avoided. For example: allowing shed seeds of oilseed rape to germinate in autumn rather than ploughing them down. Non-approved use of pesticides is an offence under the Control of Pesticide Regulations 1986. Retailers also have their own restricted lists of pesticides for crops and these differ between individual retailers. Importantly, these lists are only for pesticides not production systems.

Within most horticultural annual crops the policy is zero tolerance of weeds for reasons of reduced quality and the possibility of total crop rejection where potentially toxic contaminants are present (Knott, 1997), as well as yield reduction and harvesting difficulties (Table 2.2 & Table 2.3). The impact of weeds is often dependent on harvesting method: nettles and thistles will deter pickers of hand-harvested crops; intake of weedy contaminants, some toxic, by machine-harvesters reduce quality; some weeds e.g. fat-hen, volunteer oilseed rape, knotgrass slow down machine harvesting. The effects of weeds on quality and harvesting for horticultural crops are shown in Table 2.2. Table 2.3 shows the effect of individual weed species on quality and harvesting for a few vegetable crops and differences are also highlighted between effects on the same crop species (onions, lettuce and carrots) grown using different production systems, different harvesting methods and for different markets.

Table 2.2 Impact of weeds on crop quality and harvesting

Crop	Quality	Harvesting & other operations
Potatoes	Tuber size and uniformity	Machine slower work rate (fat-hen, redshank), higher cost and harvest losses (volunteers in other crops).
Brussels sprouts	Size, disease	Machine slower work rate, higher cost and harvest losses; interfere with manual harvest (nettles, thistles)
Cauliflower, Cabbages, Calabrese	Contaminants seeds & berries, Size & weight (calabrese, cabbage(4)), large internode distance cabbage (4)	Interfere with manual harvest (nettles, thistles)
Dry harvested peas processed	Microclimate favours Botrytis ('chalky peas') reduced quality.	Crop lodging (black-bindweed, cleavers), delayed maturity, harvesting difficulties (volunteer oilseed rape) and desiccant (diquat) needed in weedy crops cost £27/ha.
Vining Peas machine harvested & processed	Weed parts contaminants, some toxic. Cost cleaning £50/t	Slower work rate, higher cost and harvest losses, by-passed crops.
Broad Beans machine harvested &processed	Weed parts contaminants, some toxic. Cost cleaning £50/t	Slower work rate, higher cost and harvest losses, by-passed crops.
Dwarf Beans machine harvested & processed	Weed parts contaminants, some toxic. Cost cleaning £50/t	Slower work rate, higher cost and harvest losses, by-passed crops.
Picking peas, broad and dwarf beans	Weed parts contaminants, some toxic.	Interfere with manual harvest (nettles, thistles)
Runner Beans	Contaminants, some toxic.	Interfere with manual harvest (nettles, thistles)
Onions, bulb & salad	Disease risk, reduce air flow, uneven size grades (8)	Severe harvesting difficulties; Drying & storage (bulb) problems
Leeks	Reduced air flow, Disease risk (Phytopthora porri & Cladosporium spp.)	Harvesting difficulties
Carrots & Parsnips	Size uneven or reduced. Harvesting damage	Slower work rate, higher cost and harvest losses
Celery	Weed seeds contaminants	Interfere with manual (nettles, thistles)
Herbs, culinary	Contaminants, some toxic	Separation from weeds impractical & uneconomic
Lettuce	Chlorosis of leaves, abnormal leaf elongation. Seeds lodge in petioles	Interfere with manual harvest (nettles, thistles)
Spinach	Contaminants, some toxic	Separation from weeds impractical & uneconomic
Bulbs	Lower flower yield. Longer, weaker stems; forcing performance reduced. Size reduced by 10% (12)	Clog bulb lifting machinery & slow down work rate. Interfere with manual picking of flowers
Flowers	Longer, weaker stems	Interfere with manual picking (nettles, thistles)
Strawberries	Size fruit reduced; weeds hosts for nematode, fungal Black spot (Colletotrichum acutatum) & virus diseases; shelter vermin & insect pests	Interfere with manual harvest (nettles, thistles); adverse impression on PYO customers
Bush fruit	Size fruit reduced, weeds hosts for nematode, fungal & virus diseases; shelter weevil	(12) Interfere with manual harvest (nettles, thistles) and pruning, machine harvesting (field bindweed, cleavers)
Cane fruit	(12) Size fruit reduced; weeds hosts for nematode, fungal & virus diseases; shelter vermin, weevils; compete for pollination by insects.	(12) Interfere with manual harvest (nettles, thistles) and pruning (field bindweed, cleavers)
Top fruit	(12) Tree growth and size fruit reduced; shelter mice & voles, which damage trunks; dandelion etc. compete for pollination by insects.	Weeds hide cider apples/perry pears picked from orchard floor. (12) Interfere with manual harvest (nettles, thistles, bindweed spp.).
Hardy Nursery Stock	Affect plant shape; size stock reduced; thin trunks, poor development of lower branches, presence of weed roots & rhizomes reduce quality	Slow down the lifting of stock, perennial weeds disrupt crop management, adverse impression on customers.
Numbers in parentheses see reference below. Many comments from crop specialists		

References to Tables 2.2 and 2.4 (number in parentheses)

(1)ROBERTS HA, BOND W & HEWSON RT (1976) Weed competition in drilled summer cabbage. *Annals of Applied Biology* **84** (1), 91-95

(2)MILLER AB & HOPEN HJ (1991) Critical weed-control period in seeded cabbage *Brassica oleracea* var Capita. *Weed Technology* **5,** (4), 852-857.

(3)LAWSON HM (1971) Weed competition in transplanted spring cabbage. *Acta Horticulturae (Wageningen)* **2** (23), 254-267

(3)ROBERTS HA (1976) Weed competition in vegetable crops. *Annals of Applied Biology* **83** (2), 321-324

(4)LAWSON HM (1972) Weed competition in transplanted spring cabbage. *Weed Research* **12**, 254-267.

(5)BROWN A (1966) Herbicides in brassica crops. *Experimental Horticulture* **16,** 102-111.

(6)HEWSON RT, ROBERTS HA & BOND W (1973) Weed competition in spring sown broad beans. *Horticultural Research* **13** (1), 25-32.

(7)TEI F, BAUMANN DT, BLEEKER PO *et al.* (1999) Weeds and weed management in carrots – a review. In: *The 11th European Weed Research Society Symposium 1999,* Basel. Switzerland. (URL http://www.agr.unipg.it/ewrsveg)

(8)BOND W, BURSTON S, BEVAN JR & LENNARTSSON MEK (1998) Optimum weed removal timing in drilled salad onions and transplanted bulb onions grown in organic and conventional systems. *Biological Agriculture and Horticulture* **16,** 191-201.

(9)ROBERTS HA, HEWSON RT & RICKETTS ME (1977) Weed competition in drilled summer lettuce. *Horticultural Research* **17** (1), 39-46.

(10)HEWSON RT & ROBERTS HA (1973) Effects of weed competition for different periods on the growth and yield of red beet. *Journal of Horticultural Science* **48** (3), 281-292.

(11)WOOD J & HOWICK SJ (1958) Experiments with herbicides on beds of narcissus and tulips 1955-58. In: *Proceedings 4th British Weed Control Conference,*112-115

(12)LAWSON HM (1974) The effects of weeds on fruit and ornamental crops. *Proceedings of the 12th British Weed Control Conference, Brighton,* 1159-1169

(13)LAWSON HM & WISEMAN JS (1976) *Weed Investigations*. In: Annual Report. Scottish Horticultural Research Institute 1972, 24-25

(14)LAWSON HM & WISEMAN JS (1976) Weed competition in spring planted strawberries. *Weed Research* **16** (5), 345-354

(15)LAWSON HM & WISEMAN JS (1976) Weed competition in spring planted raspberries. *Weed Research* **16** (3), 155-162

(16)WILBOURN TA & RAUCH FD (1972) Weed competition in container grown nursery stock. *Hortscience* **7** (3), 37.

In Tables 2.3 and thereafter common weed names are according to Dony *et al.(*1986); Latin names according to Stace (1997)

Table 2.3 A representative list of common weed species that may be both targets for weed control using herbicides or non-chemical means. All weed species will have some effect on yield. *R risk crop rejection (quality); Q direct effect on quality (all species may have an indirect effect e.g. on size of carrots for processing); H harvesting difficulties*

Common name	**Latin name**	**Potatoes**	**Onions, Bulb**	**Onions Salad**	**Herbs culinary, Spinach Baby leaf lettuce**	**Carrots bunching**	**Carrots processing**	**Lettuce mature**	**Cauliflower Calabrese**	**Cabbage**	**Vining Peas**	**Dwarf beans**
Grass weeds												
Annual Meadow-grass	*Poa annua*		QH									
Barren Brome	*Bromus sterilis*											
Black-grass	*Alopecurus myosuroides*											
Common couch	*Elytrigia repens*	H	QH			H	H					
Wild-oat	*Avena fatua*											
Broad-leaved weeds												
Black Nightshade	*Solanum nigrum*			R	R	R		Q	Q	Q	R	R
Black-bindweed	*Fallopia convolvulus*	H	QH	Q	QH	QH	H			H	H	H
Broad-leaved Dock	*Rumex obtusifolius*			Q	Q	Q						
Charlock	*Sinapis arvensis*			Q	Q	Q			QH	H		
Cleavers	*Galium aparine*	H	QH	Q	QH	QH	H					
Common Chickweed	*Stellaria media*			Q	Q	Q		Q				
Common Field speedwell	*Veronica persica*			Q	Q	Q						
Common Fumitory	*Fumaria officinalis*		QH	Q	Q	Q						
Common Hemp-nettle	*Galeopsis tetrahit*		QH	Q	Q	Q						
Common Mouse-ear	*Cerastium fontanum*			Q	Q	Q						
Common Poppy	*Papaver rhoeas*			Q	Q	Q					Q	
Corn Marigold	*Chrysanthemum segetum*		QH	Q	Q	Q					Q	
Corn Spurrey	*Spergula arvensis*			Q	Q	Q						
Cornflower	*Centaurea cyanus*			Q	Q	Q						
Creeping Thistle	*Cirsium arvense*		QH	QH	QH	QH	H	H	H	H	Q	
Cut-leaved Crane's-bill	*Geranium dissectum*			Q	Q	Q						
Fat-hen	*Chenopodium album*	H	QH	QH	QH	QH	H		H	H		H
Field Forget-me-not	*Myosotis arvensis*			Q	Q	Q						
Field Pansy	*Viola arvensis*		QH	Q	Q	Q						
Fool's Parsley	*Aethusa cynapium*		QH	Q	Q	Q						
Groundsel	*Senecio vulgaris*			Q	Q	Q		Q				
Knotgrass	*Polygonum aviculare*	H	QH	Q	Q	QH	H					H
Pineappleweed	*Matricaria discoidea*		QH	Q	Q	Q					Q	
Red Dead-nettle	*Lamium purpureum*			Q	Q	Q						
Redshank	*Persicaria maculosa*	H	QH	Q	QH	QH	H					H
Scarlet Pimpernel	*Anagallis arvensis*			Q	Q	Q						
Scented Mayweed	*Matricaria recutita*		QH	Q	Q	Q					Q	
Scentless Mayweed	*Tripleurospermum inodorum*		QH	Q	Q	Q					Q	
Shepherd's-purse	*Capsella bursa-pastoris*		QH	Q	Q	Q		Q	Q			
Small nettle	*Urtica urens*	H	QH	QH	Q	QH	H	H	H	H		H
Smooth Sow-thistle	*Sonchus oleraceus*		QH	QH	Q	QH					Q	
Sun Spurge	*Euphorbia helioscopia*			Q	Q	Q						
Volunteer potatoes	*Solanum tuberosum*	Q	QH	Q	Q	QH	H		QH	QH	R	R
Volunteer oilseed rape	*Brassica napus*	H	QH	Q	Q	Q	H		H	H	Q	

2.4 Impact of weeds and weed species on yield of horticultural crops

The ability of horticultural crops to compete with weeds for water, nutrients, and, where the crop is shaded by weeds, for light, will vary considerably depending on time and speed of establishment, crop plant size, morphology (architecture), planting arrangement, plant population and system of production. Horticultural crops range from perennial fruit trees to short season lettuce, and even within the Brassica crops, Brussels sprouts are likely to differ from calabrese, as the former are more vigorous. Onions are very uncompetitive, particularly if grown from seed, as they are slow to emerge, have a narrow leaf profile and do not form a dense leaf canopy to suppress weed growth. The growing systems for the same crop species may also differ, for example carrots can be grown on wide rows or alternatively at high density on a close-row bed system, depending on the intended market. Thus, weed problems and the impact of weeds vary greatly between crops and also within crops, depending on the production system. Because, in general, horticultural crops are vulnerable to competition from weeds, and because the weeds may also impact on harvesting and crop quality, growers have tended to have a low or 'zero' tolerance (see Section 2.3). However, the national goal of reducing the use of pesticides (Re National Pesticide Plan) may in future impact on horticultural growers either specifically through the requirements of Assurance Schemes or more generally through environmental incentives developed nationally or associated with the recent CAP Review.

Consequently, an increased tolerance of weeds may be required for economical, environmental and social reasons. How could this be done? One option is to assess the anticipated impact of the weed, which will depend on the crop, the weed species, their density, and their time of emergence relative to the crop. When weeds are expected to damage the crop, treatments should be applied. Assuming the weeds are anticipated to reduce yields the next question is what method of control should be used and when should it be done? Chapter 4 reviews methods of control, but this Chapter will consider when should weeds be controlled, and for how long should the crop be kept free of weeds. The answers to these questions will be influenced by the weed species and by their density. There are two basic questions; how long can the weeds be left in the crop without causing irretrievable loss of yield and secondly having controlled the weeds once, how long must the crop be kept weed free so that any subsequently emerging weeds do not reduce yields? Linking these two together leads to the concept of 'critical periods. – how long must the crop be free of weeds to prevent unacceptable impacts on yield, quality or harvestability. Most critical period studies tend to focus solely on yields and occasionally consider the economic consequences. This is because the concept was originally developed for maize and soyabeans, where effects of weeds on crop quality is not a major issue. However, in horticultural crops quality and harvesting efficiency are major concerns. Most critical period studies do not address this though the work of Dunan *et al.* (1995, 1996*)* does explore the effects of weeds on the quality of the onion crop (see below). The concept of critical periods also assumes that tools are available to control weeds at the desired times, which may not always be the case.

2.4.1 Competition, thresholds, critical periods, and herbicide dose responses

A literature search shows that appreciable numbers of studies on weed competition in horticultural crops were done in the early 1970s. More recent work is less common. One problem with using data from the 1970s is that systems of production have changed (eg strawberries and raspberries) and so the older data are no longer fully relevant. Some data from published research and trials quantifying yield loss is shown in Table 2.4. Much of the research simply measured the amount of weed present, either in terms of density, ground cover or biomass, and often identification of the role of individual species was sparse. If more targeted management were to be attempted, more detailed information on the competitive abilities of individual weed species would be needed. Some more detailed information on effects of weeds is given in Chapter 3.

Table 2.4 Impact of weeds on yield of horticultural crops

Crop	Yield reduction	Species mainly responsible
Potatoes	Reduction, early varieties growth check, competition for moisture.	
Cabbage, summer drilled	(1) 47-100% weeds 50-540 pl/m2 (3) 25-100% weeds 100 pl/m2 (2) USA study 52-76% fat-hen 1.2 pl/m2; 71-92% fat-hen 3.6 pl/m2 in	(2)# fat-hen
Spring Cabbage transplanted3	(4) 33%, 26%, 68% marketable yield (5) 20%	(4) over-wintered chickweed dominated weed flora in spring and shaded crop, Annual meadow-grass, speedwell, shepherds-purse little effect (5) annual meadow-grass
Dry harvested peas processed	Reduction up to 30% #	
Vining Peas machine harvested & processed	Up to 30% (average 17%)#. Cleaning losses 3%/t. Crop rejection 100%.	
Broad Beans machine harvested & processed	Up to 30%, average 19%. # Cleaning losses 3%/t. Crop rejection 100%.	
Broad Beans	(6) 13% weeds104 pl/m2; 27% weeds 580 pl/m2 80% weeds 440 pl/m2 drought	
Dwarf Beans machine harvested & processed	Up to 87% in trials #, average 20% more if fat-hen present (3). Cleaning losses 3%/t. Crop rejection loss 100%.	Fat-hen, small nettle, redshank
Picking peas, dwarf beans	Up to 100%	
Runner Beans	Up to 100%	
Onions, bulb & salad	High levels complete crop failure, # 10% even low weed numbers.. (8) Salad conventional 45%, 67%, 77%; organic73%, 79%, 64% Transplanted bulb conventional 55%; organic 34%	
Leeks	#Up to 35%; even low weed numbers	
Carrots	(7) Up to 100%	
Celery	#Reduction 20 – 30% even in protected celery, Up to 100%	
Herbs, culinary	Up to 100%	
Lettuce drilled summer	(9) 100% weeds 65-315 pl/m2	
Red beet	(10) 45-98%, weeds15-240 pl/m2	
Bulbs (Narcissi)	#4–17% bulbs (11) 13% bulbs (12) 15-24% for lifted bulbs after 1 yr, 2 yr 64% fewer shoots; 22-25% fewer flowers; 15% bulbs	Overwintered chickweed; in spring fat-hen, hemp-nettle & fumitory. (11) Mayweeds (12) Competition effects greatest in June
Strawberries spring planted	Competition moisture and nutrients (13) (14) If not weeded in first 8 weeks after planting 13% loss in yr 2, in first 14 weeks 34%, 21 weeks 54%, 29 weeks 67%	(12) Common couch (14) Uncontrolled strawberry stolons similar effect on yield
Bush fruit	Competition for moisture and nutrients: growth reduction	(12) Best to remove weeds in autumn Common couch, hogweeds (Scotland)
Raspberries, spring- planted in Scotland	Competition for moisture and nutrients: growth reduction. (15) Competition effects greatest in June. Yr 1 high mortality, reduction cane number & height; yr 2 95% crop loss; Yr 3 weeded 30-40% mortality; (12) Yr 2 50% crop loss	Common couch and other grasses, thistle, dock, willowherb, fleabane, hogweeds (Scotland)
Top fruit	Competition moisture and nutrients. (12) Trees most vulnerable during establishment yr 1 (no yield), but this has impact on yield in year 2 and up to yr 5. Reduction in shoot production & girth: 1st yr apples growth reduction up to 60%; June 20-40% reduction later yrs	Most annual weeds year 1. Perennials from year 2. Common couch and other grasses, thistle, dock, willowherb.
Hardy Nursery Stock container grown	Competition for moisture and nutrients: growth reduction	USA study (16) hairy bittercress had no effect on yield.
Numbers in parentheses see reference below Table 2.3; # unpublished herbicide trials data		

The initial concept of weed critical periods was published in 1968 by Nieto *et al.*, working on the timing of weed control in maize. Their work showed firstly that weeds needed to be removed from the crop 10-12 days after germination and then secondly that weeds emerging 30 days after germination had little impact. Thus the crop had a critical weed free period lasting from 10-30 days after germination. A diagrammatic example of a study showing a critical period of 20-35 days is given in Fig 2.1. The shape of the curves has been reviewed in some detail in a recent paper by Knezevic *et al* (2002). They concluded that a logistic curve should be used to describe the response to the increasing period of weed competition, and a Gompertz curve for the increasing length of the weed free period. The timing and length of the critical period will be influenced to some extent by the weed density and species present. This approach has been studied in many crops, especially soyabeans and maize. Some have a very long critical period whilst others do not exhibit one at all (Roberts, 1976). The latter arises when any weed emergence after a single weeding to avoid irretrievable yield loss, has no impact on quality or yields. This is frequently the situation in winter wheat in the UK.

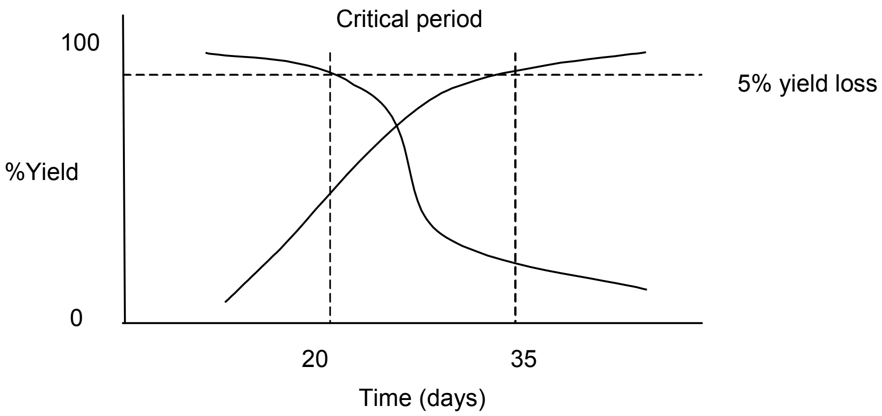

Fig. 2.1 Diagrammatic example of yield losses due to weeds where weeds are removed for increasing periods of time or are left in the crop for increasing time, resulting in the identification of a 'critical period' (to avoid more than 5% yield loss) of 20 –35 days after crop emergence.

The critical period of weed control is not just a characteristic of the crop but is a characteristic of the crop/weed environment and so will vary from field to field and year to year. It will also be influenced to some extent by the weed species present and by their density. However, this concept can be useful in determining a general view as to when weed control should be started and for how long it should be continued. It does, of course, assume that appropriate tools are available to control weeds at the desired dates. In practice, the extent of the critical period should be based on economics, not simply on yield losses. The cost of control needs to be balanced by loss of income due to reductions in yield and also quality and perhaps include additional harvesting costs. Few economics based studies have been reported, though Dunan *et al* (1995) calculated economic thresholds and critical periods for the application of herbicides to control weeds in onions.

Published data on critical periods in horticultural crops are limited as most papers focus on maize and soyabeans. Two reviews, one by Van Heemst (1985) and the other by Turner *et* *al,* (1999) endeavor to pull together relevant publications on critical periods for a range of horticultural crops. The former paper includes a high proportion on Asian and N. American papers and consequently the weed species may not always be relevant to the UK (and has been included because there is very little UK data) whereas the latter concentrates on UK-based research.

2.4.1.1 Critical period for potatoes

Most 'critical period' studies indicate that one treatment to remove weeds is generally adequate to prevent yield loss, assuming that it achieves a high level of control. Turner *et al.,* (1999) reported that the critical period was from 2-6 weeks after emergence and this is confirmed by Baziramakenga & Leroux (1994). However, the latter commented that the end of the critical period was more variable than the start. Other work quotes 4-6 weeks and 6-9 weeks after planting (Thackral *et al.*, 1989; Saghir & Markoulis, 1974), so assuming 3 weeks for the potatoes to emerge, this equates to 1-6 weeks after emergence, similar to the previous data. Thus, one must conclude that weeds need to be removed from the crop within two weeks of crop emergence. The crop then needs to be kept clean for the next four weeks. A single herbicide treatment applied within two weeks of crop emergence would probably prevent subsequent weed emergence within the subsequent critical four weeks.

2.4.1.2 Critical period for field vegetables

In a review of thresholds for weed control in field-grown vegetables, concentrating on leeks, carrots, red beet and onions, Baumann *et al.,* (1993) concluded that weeds could be tolerated in these crops until the 2 leaf stage, though in some situations weeds can be left longer. The end of the critical period varied between the crops and depends at least in part on the length of the growing period. They concluded that, in general, weeds emerging in the second half of the growth period do not greatly affect yield and quality. Depending on the competitive ability of the crop, weeds have to be removed for 1-4 weeks over the middle of the growth period.

Brassicas.

The critical period for Brassica crops will depend on the type of crop, the planting system (drilled vs transplanted, row spacings etc) and the date of sowing, so 'standardised' conclusions for 'Brassicas' are not possible. In reality, competition studies have tended to focus on cabbages. For drilled cabbage, there is some agreement that weed control needs to start 2-3 weeks after crop emergence and that there is either no need for a subsequent weeding or the crop needs to be kept clean for only the following 2 weeks (Miller & Hopen, 1991; Roberts *et al.*, 1976). For transplanted cabbage, one of the critical issues is when the crop is planted. In spring cabbage (sown in autumn) weeds can be left through the winter but must be removed in spring (April) (Lawson, 1972). For spring planted cabbages, the weeds should be removed about 3 weeks after transplanting and there was no critical period, similar to the drilled cabbage (Weaver, 1984). This work also showed that varying row spacing from 0.75 m to 2 m failed to impact greatly on the critical period. Data from Turner *et al.,* (1999) indicated that weeds need to be removed 3-8 weeks after transplanting. Thus, overall for both types of cabbage, weeds can be left for about 3 weeks after crop emergence or transplanting and provided weed control is good, no subsequent treatment is needed. The delay in control can be longer in autumn transplanted cabbages. Late emerging weeds seem not to be a problem in this crop, as ground cover by the crop is high. Turner *et al.*, (1999) concluded that the requirements of swedes and turnips were similar to cabbage though they do comment that turnip is more competitive than swede and so control can be delayed a little longer with this crop.

Peas and beans

There is a dearth of information on the critical period for weed control in peas, though several researchers have explored the competitive impact of weeds on this crop (Lawson, 1983, Harker *et al.*, 2001). This lack of data may in part reflect the zero tolerance of growers to weeds in this crop. The work of Harker *et al.,* (2001), demonstrated that delaying weed control beyond two weeks after crop emergence could lead to irretrievable yield loss, but they did not study the impact of later emerging weeds and so a critical period could not be identified. Research on the impact of a N. American nightshade (*Solanum ptycanthemum*) also confirmed that weed removal was needed two weeks after pea emergence and then goes on to conclude that later emerging weeds do also need removing before harvest, mainly because of the effect of the weed on harvesting and crop quality (Croster & Masiunas, 1998). This work must be treated with caution as the UK black-nightshade does not emerge in peas until June. However, the principle that control can be delayed is still valid (control can not be delayed in peas because herbicides must be applied before enclosed bud stage). Van Heemst (1985) estimated the end of the critical period for peas to be 0.21 through the growth period of the crop and so assuming a cropping period of 15 weeks the end of the critical period would be about 3 weeks post-emergence. Research on the associated broad bean crop indicated that weeds needed to be removed 3 weeks after crop emergence (Hewson *et al.*, 1973) but that subsequently emerging weeds did not impact on yields. Thus, there was no critical period. On limited evidence weeds need to be removed from this crop 2-3 weeks after crop emergence. Evidence for the need for a subsequent treatment to retain crop yield is scarce and so it is hard to produce a valid conclusion. However, as effects of weeds on harvesting and quality may actually be more important than their effects on yields, the practical view would be that weeds arising from subsequent emergence should be controlled, so that weed survival to harvest is minimised.

Onions

This crop is extremely uncompetitive and often receives sequences of herbicide treatments and/or hand weeding. Van Heemst (1985) and Baumann *et al.*, (1993) classify it as one of the crops most susceptible to weeds. Because of this, it has had more attention from weed biologists. Impact of weeds will depend on whether the crop is sown as seed or is transplanted, and whether its end use will be salad or bulb onions. All the published data seems to relate to the spring-planted crops but a minority is also planted in the autumn, where the impact of weeds will be very different.

The studies on spring sown bulb onions give slightly conflicting results. Work by Hewson & Roberts (1971) and Roberts (1976) suggests that there was a critical period of 6-8 weeks after crop emergence, indicating that provided techniques to remove weeds were available that weeds could be left in the crop for up to 5 weeks without incurring a yield reduction. If a single effective control strategy was used, a further treatment was unnecessary, provided new weeds did not establish before week 7. This does not agree with the work reported by Wicks *et al.*, (1973) where they showed yield losses from weeds not removed even 2 weeks after emergence and concluded that the critical period stretched for 0 – 12 weeks after crop emergence. The more physiological approach of Dunan *et al.* (1996) indicated that the crop needed to have experienced over 100 thermal units (base temperature 7.2^{o}C) before significant yield losses occurred, indicating that the onset of competition did not start at emergence, like that reported by Wicks *et al* (1973). Van Heemst (1985) concludes that the critical period for weeds in onions starts 0.15 through the growth cycle and ends 0.53 through the cycle. Thus, assuming spring planted bulb onions are in the ground for 20 weeks, the critical period stretches from 3-11 weeks. The studies reported by Bond *et al.,* (1998) with drilled salad onions indicated that weeding could be delayed for 4 weeks after crop emergence, but no longer. There was no need for subsequent weeding. Experiments by the same authors with transplanted bulb onions, showed that, because the onions were initially larger than the emerging weed seedlings, weed control could be delayed until 5-7 weeks after planting. Again a single weeding was adequate to prevent yield losses.

Thus, the overall conclusion for this crop is that weed control in spring sown onions can be delayed for probably 4 weeks and that one weeding is often adequate to prevent subsequent loss of yield. However, there may be a short critical period up to about week 7-12 (after emergence), if a later flush of weeds emerge. If weeds are particularly aggressive (as in the Wicks paper) this delay may have to be shortened. The limited data on transplanted bulb onions would indicate that weed control can be delayed longer than 4 weeks. This, of course, assumes that 'tools' are available to remove weeds from onions at this time. In reality herbicide treatments and hand weeding may have to start sooner because of the more effective control/removal of smaller weeds.

Carrots

Information on critical periods for weed control in carrots appears to be very limited. Only three references have been identified, which explore this topic. Baumann *et al.* (1993) conclude that this crop is quite tolerant of weeds, a conclusion not supported by Van Heemst (1985) who concludes it as vulnerable to weeds as onions and has a similar critical period lasting from 3 to 11 weeks, assuming a crop growth period of 20 weeks. The length of the growing season varies depending on the intended market and so if the growing period is longer, so will the critical period. The general review by Baumann *et al.* (1993) concluded that in several crop species, including carrot that weeds could be left until the crop reached the 2-leaf stage. Similarly, Turner *et al,* (1999) concluded in their review that weeds in carrots needed to be removed 4 weeks after emergence. Turner's own work (Turner *et al*, 2001) also concluded that weeds could be left for 3-5 weeks. This work did not identify the end of the critical period but some work reported by Benoit & Watson (1987) concluded that the critical period was from 3-6 weeks after emergence. Thus, most work indicates that the period was relatively short and so one effective weed removal, either with a herbicide or by hand, would be acceptable. A second weeding might be needed in some years to remove the later cohort of weeds.

Lettuce

There is very little published data on the effects of weeds on this crop. Turner *et al.,* (1999) in their review of critical periods concluded that weeds needed to be removed 3 weeks after crop emergence. Because of the short growing period of this crop, there was no need for a subsequent treatment. It is not clear whether current practices such as modular planting and growing under fleece will increase or decrease the crop's vulnerability to weeds. Modular planting should decrease the crop's susceptibility to weeds in the same way that transplanted onions are less vulnerable than drilled onions.

2.4.1.3 Critical period for flowering bulbs (daffodils etc)

Bulbs planted in autumn do not suffer greatly from the presence of weeds during the winter period. However, weeds present during the early summer can seriously reduce crop vigour and thus reduce bulb growth for the final harvest. Conclusions from 6 experiments reported by Lawson (1976) were that weed control should aim to remove weeds from the crop during the period of flower initiation and bulb increase (i.e. from early May to the end of June).

2.4.1.4 Critical period for soft fruit

The concept of critical periods for weed control does not apply to perennial crops such as soft fruit in the same way as it does to annual crops. However, it is clear that weed control is particularly 'critical' during the period of crop establishment. For example, research reported by Lawson & Wiseman (1976a) in raspberries clearly demonstrated the need to prevent weed competition during cane emergence of the newly sown crop in June/July. Weeds left during this period seriously affected production in the following year. Earlier emerging weeds had little effect, provided they were removed by June. If weeds were left after late June, considerable cane mortality occurred. Thus, to optimise production weeds need to be removed during the June/July growth period.

A study in strawberries by Lawson & Wiseman (1976b) reached similar conclusions to those found in raspberries, though the results were more variable. Weeds left in the crop during mid-summer reduced fruit production in the following year in one experiment but not in a second. Most serious competition occurred from weeds present during mid-summer but there was some evidence that those present earlier in the season also had adverse effects. This conclusion is supported by some American studies, which showed that newly planted strawberries were particularly sensitive to early weed competition, as weeds remaining the crop for the first month reduced yields the following summer. Leaving weeds in the crop later in the season (late summer/autumn) had much less effect. There was a strong linear relationship between weed biomass in the planting year and yield in the following one (Pritts & Kelly, 2001). Practioners support the need for both early and late weed control as weeds are a particular problem in strawberries right from planting (problems with competition) through to harvest (problems with access), (N Hipps pers. com.).

These UK studies were done in the 1970s with 'traditional' production systems. The conclusions may not be appropriate for crops grown using current management practices. For example, with current practices, weed control in winter can be particularly important because there are few chemicals available or effective for summer control in soft fruit (N. Hipps pers. com.).

2.4.1.5 Critical period for top fruit

The same issues raised with soft fruit also apply to top fruit, as weeds present during establishment can reduce subsequent fruiting. Additionally the presence of weeds (and other plants) between and within the rows of fruit such as apples can also reduce fruit production. Lawson (1974) reviewed the impact of weeds on top fruit and concluded that young crops were particularly vulnerable to the presence of weeds, whilst establishing. Yields in the following years could be appreciably reduced. But there was little information on the importance of the timing of weed removal. The issue with established crops is whether to allow vegetation (weeds and grasses) to grow between and within rows. Stott (1976) recorded clear reductions in apple yields arising from the presence of uncut grass around three year old trees. Current practices are to have a bare soil weed free strip round trees with grass alley-ways in between. Now only cider apples have grass round tree bases.

2.4.1.6 Overview of critical periods

The 'traditional' approach to critical period research is to design an experiment with increasing periods of weediness and increasing periods without weeds and plot the appropriate response curves (Knezevic *et al,* 2002). In reality much of the research has not followed this structured approach and has primarily explored the onset of competition, assuming that later emerging weeds from early weed control are not significant. In many situations one application of a herbicide (provided it is fully effective) or a hand weeding has been found to be adequate, as emergence of subsequent weeds was delayed beyond the end of the critical period, especially if dry conditions prevailed at the time of application. This makes it difficult to define the end of the critical period.

The following table (Table 2.5) endeavours to summarise the data that has been published on critical timings of weed control in the main annual horticultural crops. As concluded in the introduction, weed control needs to start 2-4 weeks after crop emergence and then the crop needs to be kept weed free for the following 2-6 weeks, depending on the crop. This means that in many crops, one weed control 'event' is sufficient, provided it is fully effective. However, from a crop safety point of view (in for example onions and carrots), herbicides are often applied over a period of time as repeat split reduced doses.

Table 2.5 Critical periods for weed absence in potatoes and horticultural vegetable crops

Crop	Production method	Critical period of weed absence* (weeks post-emergence or -planting)
Potatoes	planted	2-4 weeks
Spring-sown cabbages	drilled	2-4 weeks
Spring-sown cabbages	transplanted	3-8 weeks
Peas	drilled	2-3 weeks
Spring planted bulb onions	drilled	4-8 weeks
Spring planted bulb onions	transplanted	5-7 weeks
Spring planted salad onions	drilled	4-? weeks
Carrot	drilled	3-6 weeks
Lettuce	drilled	3-? weeks

* This period defines the time when weeds need to be absent from the crop to ensure optimum yields. This may be achieved by a single or by multiple treatments for weed control.

One weakness in Table 2.5 is that these critical periods do not in general address any impact that the weeds may have on quality or harvesting, as few studies explored these aspects. These may need addressing in future. One issue that does emerge is that several papers conclude that the time of removal is more important than the level of weed infestation. It is more important to get the timing correct than to worry about how much weed is present. However, in practice, lack of appropriate 'tools' to control weeds at the appropriate time is inhibiting the implementation of such approaches. Either herbicide-based weed management has to be based on pre-emergence treatment, rather than post-emergence ones, because of the lack of good products, or mechanical weeding has to be done whilst the weeds are very small (large weeds are not easily controlled). In future there may also be MRL issues to consider. In some crops early and repeat low dose herbicide applications control small weeds and are also safe to the crop.

If intensity of weed management in horticultural crops is to be reduced, one option may be to consider omitting late control practices, done after the end of the critical period, when surviving weeds would not impact on yields. It is a pity that most trials have focussed on the start rather than its end and so sound data on when to stop control practices is limited. More data may be needed to clarify the ends of critical periods where multiple weed control applications are being used. However, although 'leaving' weeds in the crop at the end of the season may not impact greatly on yields, these surviving weeds could affect aspects of crop quality and harvesting. As already shown in Tables 2.2 & 2.3, many weeds are unacceptable in horticultural crops because of these effects.

The issue of critical periods in perennial horticultural crops is rather different. All the evidence indicates the need for good weed management is during crop establishment, especially during the crop's first summer. The crop needs to be kept free of weeds during this time, otherwise yields will be depressed in the following year(s). This applies equally to soft and top fruit. In subsequent years the need for weed control is less and the questions relate more to 'what level of weed is tolerable' (eg grass strips between or within rows of top fruit) rather than a specific critical period issue.

2.4.2 Relative competitive effects of weeds

Weed species differ in their competitive impact on the crops. Some crops are more vulnerable than others but with similar sowing dates, the 'peck order' for weed competition probably will not change. The different crops will have different species that are not acceptable because of their effects on crop quality or harvesting. Thus black-nightshade is much more important in peas and broad beans, than might be predicted from its competitive impact, because of the risk of contamination from the berries. The grower's perception of the importance of a weed species is also influenced by how easy it is to control. A weed that is difficult to manage will be perceived to be more important than its impact on the crop really justifies.

A list of the top ten most frequently mentioned weeds in horticultural crops is presented in Table 2.6. Those highlighted in grey are most frequently mentioned in several crops and could be considered the 'worst weeds' for horticulture, i.e. they occur in most crops, or are difficult to control with the herbicides available. However they do not include species where the presence of only a few could reduce quality and cause crop rejection (Table 2.2). Table 2.6 also includes the relative competitive abilities of the species in winter wheat. Most of these values are based on research studies, though some are estimated by expert opinion. It is probable that some of these values are not relevant to spring–sown horticultural crops. However, data for relevant spring crops is very sparse. A ranking of weed species based on their competitive abilities was used by Dunan *et al.,* (1996) in their predictions of the competitive effects of weeds in onions. This was done in the USA and so most species are not relevant to UK. The most damaging weed was volunteer sunflower (Competitive index (CI) = 1.0). Fat-hen was assigned 0.6 and black-nightshade 0.35. This already indicates that the winter wheat value for fat- hen is too low for spring-sown crops. Because of this lack of data, key weeds for horticulture have been assigned 'star ratings' to indicate their competitive abilities (Table 2.7). Chickweed has a low competitive effect (index) compared with many species but in spring cabbage (also sown in autumn) it can reduce yields by up to 68%. This emphasises the difficulty of amalgamating information across the range of differing horticultural crops. Yield loss is dependent on weed species/crop combination and height differential. Tall weed species, which shade the crop, e.g. fat-hen in dwarf French beans, have a greater effect than short low-growing species. It is clear that the weed competitive ranking from winter cereals is not totally appropriate for spring-sown horticultural crops.

Despite its limitations, the estimations of competitive effects do help to prioritise weed control treatments. Clearly creeping thistle and fat-hen are of major concern as, not only are they competitive, they are also serious problems (for this and other reasons) in many horticultural crops. Volunteer potatoes are also very damaging but unlike most 'true' weeds will only occur when potatoes are grown in the same rotation as the affected horticultural crops, and so if necessary could be avoided. Interestingly, the most widely identified problem weed, annual meadow-grass is one of the less competitive ones, but it is a very common weed.

It would be possible to develop threshold based weed management systems for horticultural crops, including elements of critical period requirements, but a considerable amount of R&D would be needed to develop reliable predictions. This work could be linked into the current LINK project developing a weed management support system for winter wheat (WMSS) (Collings *et al.*, 2003), as a key element of the project is to predict the economic impact of the weeds and balance this with the cost of control. However, the crucial importance of the effects of weeds on harvesting and crop quality in horticulture would greatly increase the work needed to predict the economic consequences. Indeed, unless growers and retailers etc. are persuaded to move away from a 'zero tolerance' attitude to weeds, such work would be unproductive. One way forward could be to pick a crop where weeds are more tolerable and develop such a threshold management approach using this crop as a model example.

Table 2.6 Competitive index for cereals; the 10+ most frequently mentioned weeds in some crops because they commonly occur or are difficult to control * *also wild mignonette & mugwort in carrots; **all grasses & perennials field bindweed, horsetail; in orchards Canadian fleabane, dandelion, creeping buttercup, silverweed, nettle; # HNS hairy bittercress*

Common name	**Latin name**	**Competitive index (w. cereals)**	**Potatoes**	**Spring cabbage**	**Vining Peas**	**Dwarf Beans**	**Onions Carrots ***	**Bulbs**	**Straw berries**	**Bush& ** cane fruit**	**Top fruit ****	**HNS #**	**Overall weed rating**
Grass weeds										√	√	√	
Annual Meadow-grass	*Poa annua*	0.1	√	√	√	√	√	√	√	√	√	√	10
Barren Brome	*Bromus sterilis*												0
Black-grass	*Alopecurus myosuroides*	0.4											0
Common couch	*Elytrigia repens*		√						√	√	√	√	5
Wild-oat	*Avena fatua*	1.0											0
Broad-leaved weeds													
Black Nightshade	*Solanum nigrum*					√							1
Black-bindweed	*Fallopia convolvulus*	0.3	√		√	√						√	4
Broad-leaved Dock	*Rumex obtusifolius*								√	√	√		3
Charlock	*Sinapis arvensis*	0.4		√				√					2
Cleavers	*Galium aparine*	3.0	√							√			2
Common Chickweed	*Stellaria media*	0.2		√	√			√	√			√	5
Common Field speedwell	*Veronica persica*	0.08		√					√				2
Common Fumitory	*Fumaria officinalis*	0.08					√						1
Common Hemp-nettle	*Galeopsis tetrahit*												0
Common Mouse-ear	*Cerastium fontanum*												0
Common Poppy	*Papaver rhoeas*	0.4			√								1
Corn Marigold	*Chrysanthemum segetum*												0
Corn Spurrey	*Spergula arvensis*												0
Cornflower	*Centaurea cyanus*												0
Creeping Thistle	*Cirsium arvense*	0.3	√	√	√			√	√	√	√	√	8
Cut-leaved Crane's-bill	*Geranium dissectum*	0.08											0
Fat-hen	*Chenopodium album*	0.20	√	√	√	√	√	√	√	√	√	√	10
Field Forget-me-not	*Myosotis arvensis*	0.2											0
Field Pansy	*Viola arvensis*				√				√				2
Fool's Parsley	*Aethusa cynapium*						√						1
Groundsel	*Senecio vulgaris*	0.06		√			√		√	√	√	√	6
Knotgrass	*Polygonum aviculare*	0.1	√		√	√	√		√	√	√		7
Pineappleweed	*Matricaria discoidea*				√	√	√	√					4
Red Dead-nettle	*Lamium purpureum*	0.08											0
Redshank	*Persicaria maculosa*		√			√	√	√					4
Scarlet Pimpernel	*Anagallis arvensis*	0.05											0
Scented Mayweed	*Matricaria recutita*	0.40		√	√	√	√	√					5
Scentless Mayweed	*Tripleurospermum inodorum*	0.40		√	√	√	√	√					5
Shepherd's-purse	*Capsella bursa-pastoris*			√									1
Small nettle	*Urtica urens*			√		√		√	√				4
Smooth Sow-thistle	*Sonchus oleraceus*		√							√	√	√	4
Sun Spurge	*Euphorbia helioscopia*												0
Willowherbs	*Epilobium* spp.									√	√	√	3
Volunteer potatoes	*Solanum tuberosum*		√		√	√	√	√					5
Volunteer oilseed rape	*Brassica napus*		√		√								2
Perennial spp.**									√	√	√	√	4

Table 2.7 The competitive abilities of weeds in winter cereals and estimated competitive importance of the ten most frequently identified serious weeds of horticultural crops (taken from Table 2.6)

Common name	Latin name	*Competitive index (w. cereals)*	Importance rating	Estimated competitive impact[+]
Annual Meadow-grass	*Poa annua*	0.1	10	*
Black-bindweed	*Fallopia convolvulus*	0.3	4	***
Common Chickweed	*Stellaria media*	0.2	5	**
Creeping Thistle	*Cirsium arvense*	0.3	8	****
Fat-hen	*Chenopodium album*	0.20	10	***
Groundsel	*Senecio vulgaris*	0.06	6	*
Knotgrass	*Polygonum aviculare*	0.1	7	**
Mayweeds	*Matricaria recutita Tripleurospermum inodorum*	0.40	5	**
Common couch	*Elytrigia repens*		5	***
Volunteer potatoes	*Solanum tuberosum*		4	****

+ **** Most competitive

2.5 Avoiding weed competition

There are few options for the grower to avoid weed competition and more detail is given in Chapters 3 and 4. For vegetables they include the use of stale seedbeds, herbicides, steam and flame weeding, plastic and mechanical weed control (where row width allows). Opportunities to suppress weeds by increasing seed rates, manipulation of row widths, time of sowing or planting and choice of variety may be available for cereals, but not usually for horticultural crops (although there are some for organic production). This is because the growing system adopted is to achieve the required size of produce, to suit precision drills for expensive seed and specialist harvesting equipment (or hand pickers), the time of harvest and continuity of supply is vital and the varieties selected are dictated by the market, i.e. the retailer, processor and ultimately the consumer.

For perennial crops (orchards and soft fruit), wood chips, straw or plastic mulches, and mowing are methods used. Plastic mulches are used routinely in soft fruit.

2.6 Interactions between crops and weeds: interactions with other pests

As well as having direct effects on the crop, through competition, weeds can also have indirect effects. Companion planting has been used to reduce pest infestations in horticultural crops, especially in organic systems, for many years (Dempster & Coaker, 1974; Smith, 1976). The species associated with the crop can be a weed (in other circumstances). Recent studies have shown that just the number, size and spatial arrangement of green objects (such as weeds) surrounding a host plant can reduce pest insect attack (Finch & Collier, 2000). Indeed, keeping a crop completely weed free surrounded by bare soil can as a result expose the crop to maximum pest attack (Billiald, 2001). Possibilities for managing weeds to reduce pest numbers is complicated by the need to balance benefits vs. potential loss. Whilst it is known from the work on critical periods that weeds can be tolerated in the crop for a period of time with no loss to yield (see earlier in this chapter), it is not fully understood whether the necessary time for weeds to be present to deliver pest reduction benefits contradict weed management recommendations. Combining models of weed competition (e.g. Benjamin & Aikman, 1995) and pest insect attack (e.g. Finch *et al.,* 1996) may help gain insight into these strategies and represents an approach more closely aligned to the multiple decision making that growers face on a daily basis. Onions and carrots would be too sensitive to weed competition, so it is likely that such strategies could only be considered for the more competitive species such as cabbage. Importantly, crop quality would also need to be incorporated into the scenario.

Conversely, weeds can also act as hosts for fungal, virus and nematode-borne diseases that subsequently infect the crop. For example, weeds in the Brassicaceae (e.g. Shepherd's purse) carry *Sclerotinia* diseases that can affect Brassicas and several other crops. Volunteers such as oilseed rape can be a particular problem in transmitting diseases such as *Alternaria* to related Brassica crops (Maude *et al,* 1986). Similarly weeds can provide an environment suitable for the multiplication of diseases and pests. The damp conditions created by an understory of weeds in some vegetables, will increase infection of crops with *Botrytis* and weed control is often considered as part of the cultural strategy for reducing pathogens and pests in susceptible crops (for example strawberries, Daugaard, 2000).

2.7 Changes in weed spectra in horticulture for the future

Changes in weed spectra for horticulture in the future are discussed in Chapter 4. They will depend on:

- changes in cropping, including winter cereals in arable rotations
- the loss of herbicides for some crops
- weed spectrum shifts, and possible development of resistant weeds because of a limited range of herbicides left for horticultural crops
- weed population shifts as a result of climate change
- invasive aliens have always had an impact and some, e.g. common field speedwell and pineappleweed, introduced in the 19th century, are now frequently found in Horticultural crops
- volunteers from “new” or Industrial crops
- volunteers from GM and other Herbicide-Tolerant crops
- reduced use of residual herbicides in perennials (top fruit) will result in more annual weed problems

2.8 Summary & Conclusions

1 There are no recorded weed surveys in horticultural crops for Great Britain, therefore we do not know whether weed biodiversity has declined or not. If growers are to be compensated for loss of production and management of land for environmental benefit there may need to be a benchmark so that improvement can be measured. Much information could be gained from efficacy trials data submitted to the Pesticide Safety Directorate, Defra for herbicide product Approval, where comparisons are made with plots untreated with herbicides.

2 The weed spectrum in a field is linked to soil type and within a crop it is dependent on time of sowing. Cultivations can also affect weed emergence and species. Most horticultural crops (e.g. vegetables, bulbs and flowers) are sown/planted mainly in spring on lighter soils, in contrast to the major UK crop winter wheat which is autumn sown on a wide range, including heavy soils. Weed numbers and biodiversity are greater in spring crops and this may offer opportunities.

3 The weed spectrum in a field is also dependent on the cropping rotation. Where horticultural crops are grown in a rotation that includes mainly cereals they inherit cereal weeds. These may be a combination of missed spraying opportunities because of a) decreases in labour and equipment and b) attempting to reduce herbicide doses to minimize costs. Thus any biodiversity schemes for leaving weeds within the wheat crop will have a knock-on effect in horticultural crops in the rotation.

4 Weeds affect quality, yield and harvestability – quality is the most important factor (Tables 2.2 and 2.3)

- *Quality:* Weedy contaminants reduce quality in many crops - machine harvested herbs, spinach, dwarf French beans, broad beans and peas; weed seeds in lettuce, calabrese, cauliflower. Where separation is difficult or impossible, and where the contaminant is toxic (black-nightshade, volunteer potatoes) the crop is rejected because it poses a risk to the consumer. The quality standards have been raised in some products to what amounts to “nil tolerance”, for example “one piece of contaminant per tonne of peas (for freezing)” compared with 2% some years ago. The presence of weeds, or other, contaminants will adversely affect consumer confidence.

  Weeds can also affect quality in terms of size grade and uniformity of crop (a standard usually specified by the retailer), of all soft fruit, top fruit, bulbs, potatoes, carrots for processing and fresh, onions etc. They also affect plant shape in hardy nursery stock. Failure to meet specifications results in crop rejection or no sales.

  Quality assurance is important to the fruit and vegetable consumer - produce must be free from toxic and other weedy contaminants. The main markets for fruit and vegetable produce are through retailers and processors, and growers have to be members of Assurance Schemes.

- *Harvesting:* The impact of weeds on harvesting depends on the method. In hand harvested crops cider apples, strawberries, lettuce, celery etc. weeds, particularly nettles and thistles, deter pickers. In machine harvested crops the effect varies with the weed species and machine: for example woody, tough stemmed species slow down and clog up bulb and potato lifters; black-bindweed wraps round picking reels of pea/broad bean harvesters and there are also harvest losses to consider. In all cases weedy crops slow down work rate and increase costs.

- *Yield:* Weeds also cause yield loss and the impact depends on weed numbers and weed species present and the crop concerned. The ability of horticultural crops to compete with weeds for water, nutrients, and, where the crop is shaded by weeds, for light, will vary considerably depending on time and speed of establishment, crop plant size, morphology (architecture), planting arrangement, plant population and system of production. In horticulture there is an extremely diverse range of crop architecture: annual (onion – Brussels sprouts), perennial (strawberries – apples). Some crops are more vulnerable than others: the competitive effect of onions is poor compared with Brussels sprouts, and most are less competitive than winter wheat.

5. For all the above reasons the policy within most horticultural annual crops is zero tolerance of weeds. Chapter 4 shows there will be a decreasing number of tools to control them.

6. There are some studies on time of removal of weeds (critical periods) and the effect on yield for some fruit and vegetables, but these are often from the 1970s and production systems have changed. The conclusions are that for most vegetable crops and strawberries it is critical that fields are kept weed-free during the first two to six weeks after planting to prevent serious yield losses, but in perennial crops soft and top fruit, weed control is needed in the first year during crop establishment otherwise yields will be depressed in the following years. In subsequent years the need for weed control is less. Could weeds emerging later than the critical period perhaps be left within the crop to achieve environmental benefits? This will depend on whether there are benefits at all during this time. In addition it would be unacceptable to the grower in many crops (vegetables, strawberries, some hardy nursery stock) to risk quality defects and consequent price deductions or crop rejection. These weeds may be less of an issue in orchards.

7. Economic thresholds for weed control and herbicide dose responses have not been developed in horticultural crops, probably because the major impact of weeds is on quality. Extrapolations from winter wheat data are unlikely to be valid, although relative competitive effects of different weed species could be estimated.

8. Practical implementation of more targeted weed management is difficult because of concerns of the impact of weeds on crop quality and the lack of reliable tools, which are safe to the crop, to control the weeds at the relevant time (growth stage). Pre- and post-emergence herbicides do not give consistently reliable control and mechanical control is often in effective on large weeds. There are also crop safety/Minimum Harvest Interval / MRL issues to consider.

9. In conclusion, horticultural crops are much higher value than winter wheat and a high standard of weed control is essential to achieve quality and economic yield. There are different production systems for all these crops but there is a common aim: from the aspects of quality, yield and harvesting, weeds within the crop area are not tolerated. Thus all weed species are targets for control. Field margins managed for biodiversity would perhaps be a sensible alternative for horticulture and acceptable to the grower if there was compensation for loss of production.

2.9 References

ASSURED PRODUCE - The NFU/Retailer partnership. Internet URL http://www.assuredproduce.co.uk

BAUMANN DT, POTTER CA & MULLER-SCHARER H (1993) Zeitbezogene schadenschwellen bei der Intergrierten Unkrautbekampfung in Freilandgemusebau. *Proceeding 8th EWRS Symposium Quantitative approaches in weed and herbicide research and their practical application,* Braunschweig, 807-813.

BAZIRAMAKENGA R. & LEROUX GD (1994) Critical period of quackgrass (*Elytrigia repens*) removal in potatoes (*Solanum tuberosum*). *Weed Science* **42**, 528-533.

BENJAMIN LR & AIKMAN DP (1995). Predicting growth in stands of mixed species from that in individual species. *Annals of Botany* **76**, 31-42

BENOIT DL & WATSON AK (1987) Identification of the critical period of competition for weeds growing among carrots in organic soil. *Phytoprotection* **68,** 132-133.

BILLIALD H (2001). The effect of diverse backgrounds on host plant selection by two fly pests of field vegetable crops. Msc Thesis, University of London, Imperial Collage. 85pp.

BOND W, BURSTON S, BEVAN JR & LENNARTSSON MEK (1998) Optimum weed removal timing in drilled salad onions and transplanted bulb onions grown in organic and conventional systems. *Biological Agriculture and Horticulture* **16**, 191-201.

BRENCHLY WA & WARRINGTON K (1933) The weed seed population of arable soil. II. Influence of crop, soil and methods of cultivation upon the relative abundance of viable seeds. *Journal of Ecology* **21**, 103-127.

COLLINGS L V, GINSBURG D, CLARKE JH, MILNE AE, PARSON DJ, WILKINSON DJ, BENJAMIN LR, MAYES A, LUTMAN PJ, DAVIES DHK (2003) WMSS: Improving the precision and prediction of weed management strategies in winter dominant rotations. *Proceedings BCPC International Congress Crop Science and Technology,* (in press).

CROSTER MP & MASIUNAS JB (1998) The effect of weed-free period and nitrogen on Eastern black nightshade. *Horticultural Science* **33,** 88-91.

DAUGAARD, H (2000) Effect of cultural methods on the occurrence of grey mould (*Botrytis cinerea* Pers.) in strawberries. *Biological Agriclture & Horticulture* **18,** 77-83.

DEMPSTER JP & COAKER TH (1974) Divesrification of crop ecosystems as a means of controlling pests. In: *Biology in Pest and Disease Control* (eds D Price Jones & ME Solomon) John Wiley & Sons, New York, 106-114.

DONY JG, JURY SL & PERRING FH (1986) *English Names of Wild Flowers*, 2nd edn. The Botanical Society of the British Isles.

DUNAN CM, WESTRA P, SCHWEIZER EE, LYBECKER DW & MOORE F (1995) The concept and application of early economic period threshold - the case of DCPA in onions (*Allium cepa*). *Weed Science* **43**, 634-639.

DUNAN CM, WESTRA P, MOORE F & CHAPMAN P (1996) Modelling the effect of duration of weed competition, weed density and weed competitiveness on seeded, irrigated onions. *Weed Research* **36**, 259-269.

FINCH S & COLLIER RH (2000) Host-plant selection by insects – a theory based on "appropriate/inaapropriate landings" by pest insects of cruciferous plants. *Entomologia experimentalis et applicata*, **96**, 91-102.

FINCH S & COLLIER RH & PHELPS K (1996). A review of work done to forecast pest insect attacks in UK horticultural crops. *Crop Protection* **15**, 353-357.

HALD AB (1999a) The impact of changing the season in which cereals are sown on the diversity of the weed flora in rotational fields in Denmark *Journal of Applied Ecology,* **36**, 24-32.

HARKER KN, BLACKSHAW RE & CLAYTON GW (2001) Timing weed removal in field pea (*Pisum sativum*). *Weed Technology* **15**, 277-283,

HEWSON RT & ROBERTS HA (1971) The effect of weed removal at different times on the yield of bulb onions. *Journal of Horticultural Science* **46**, 471-483.

HEWSON RT, ROBERTS HA & BOND W (1973) Weed competition in spring-sown broad-beans. *Horticultural Research* **17**, 25-32.

KNEZEVIC SZ, EVANS SP, BLANKENSHIP EE, VAN ACKER RC & LINDQUIST JL (2002) Critical period for weed control; the concept and data analysis. *Weed Science* **50**, 773-786.

KNOTT C M (1997) Achieving Quality in Legume crops with Agrochemicals. In: *Crop Protection and Food Quality – meeting consumer needs.* British Crop Protection Council, University of Kent, Canterbury, UK.

LAWSON HM (1972) Weed competition in transplanted spring cabbage. *Weed Research* **12,** 254-267.

LAWSON HM (1974) The effects of weed on fruit and ornamental crops. *Proceedings British Weed Control Conference,* 1159-1169.

LAWSON HM (1983) Competition between annual weeds and vining peas grown at a range of population densities: effects on the crop. *Weed Research* **23**, 27-38.

LAWSON H M (1976) The effects of spring-germinating weeds on narcissus. *Annals of Applied Biology* **83**, 324-327.

LAWSON HM & WISEMAN JS (1976a) Weed competition in spring-planted raspberries *Weed Research* **16**, 155-162.

LAWSON HM & WISEMAN JS (1976b) Weed competition in spring-planted strawberries. *Weed Research* **16**, 345-354.

LITTERICK AM, REDPATH J, STEEL W & LEIFERT C (1999). An evaluation of weed control strategies for large-scale organic potato production in the UK. *Brighton Crop Protection Conference - Weeds:* 951-956.

LUTMAN PJW (2001). Current weed control and its impact. In: *The impact of herbicides on weed abundance and biodiversity: A report for the UK Pesticide Safety Directorate PN0940* (eds EJP Marshall, V Brown, ND Boatman, PJW Lutman & G Squire). pp 134. IACR Long Ashton Research Station, UK

MAUDE RB, BAMBRIDGE JM & SPENCER A (1986) Diseases of brassicas – biology, resistance and control. In: *36th Annual Report for 1985 National Vegetable Research Station*, Wellesbourne, Warwick: 56-60.

MILLER AB & HOPEN HJ (1991) Critical weed-control period in seeded cabbage *Brassica oleracea* var Capita. *Weed Technology* **5,** (4), 852-857.

NIETO JH, BRONDO MA & GONZALEZ JT (1968) Critical periods of the crop growth cycle for competition from weeds. *PANS (C)* **14**, 159-166.

NIX J (2002) *Farm Management Pocketbook 33rd edition 2003*. Imperial College Wye, Andersons Centre, Melton Mowbray, UK.

PRITTS MP & KELLY MJ (2001) Early season weed competition reduces yeild in newly planted matted row strawberries. *Horticultural Science* **36**, 729-731.

ROBERTS HA (1976) Weed competition in vegetable crops. *Annals of Applied Biology* **83** (2), 321-324.

ROBERTS HA & DAWKINS PA (1967) Effect of cultivation on the numbers of viable weed seeds in the soil. *Weed Research* *7***,** 290-301.

ROBERTS HA, BOND W & HEWSON RT (1976) Weed competition in drilled summer cabbage. *Annals of Applied Biology* **84** (1), 91-95.

ROBERTS HA & POTTER ME (1980) Emergence patterns of weed seedlings in relation to cultivation and rainfall. *Weed Research* **20**, 377–386.

SAGHIR AR & MARKOULLIS G (1974) Effect of weed competition and herbicides on yield and quality of potatoes. *Proceedings British Weed Control Conference,* 533-539.

SMITH JG (1976) Some effects of crop background on the populations of aphids and their natural enemies on Brussels sprouts. *Annals of Applied Biology* **63**, 326-330.

STACE C (1997) *New Flora of the British Isles 2nd edition*. Cambridge University Press, Cambridge, UK.

STOTT K (1976) The effects of competition from ground covers on apple vigour and yield. *Annals of Applied Biology* **83**, 327-330.

THACKRAL KK, PANDITA ML, KHURANA SC. & KALLOO,G. (1989) Effect of time of weed removal on growth and yield of potato. *Weed Research* **29**, 33-38.

TURNER RJ, LENNARTSSON MEK, BOND W, GRUNDY AC & WHITEHOUSE D (1999) Organic weed control – getting it right in time. *Proceedings 1999 Brighton Conference – Weeds,* 969-974.

TURNER RJ, LENNARTSSON MJ, HESKETH M, GRUNDY AC & WHITEHOUSE D (2001) Weed control in organically grown- carrots. *Proceedings of the BCPC Conference – Weeds,* 291-296.

VAN HEEMST HDJ (1985) The influence of weed competition on crop yield. *Agricultural Systems* **18**, 81-93.

WEAVER SE (1984) Critical period of weed competition in three vegetable crops. *Weed Research* **24**, 317-525.

WICKS GA, JOHNSTON DA, NULAND DS & KINBACHER EJ (1973). Competition between annual weeds and sweet Spanish onions. *Weed Science* **21**, 436-439.

CHAPTER 3

CROP AREAS AND WEED MANAGEMENT IN HORTICULTURE

3.1 Changes in horticultural crop areas and location

The changes in horticultural crop areas grown in Great Britain are shown in the following Tables, (source Pesticide Usage Survey Reports published by MAFF now Defra and the Scottish Agriculture and Fisheries Department) and we acknowledge the help of Miles Thomas and David Garthwaite, Central Science Laboratories, who undertake these surveys.

In comparison with arable crops, horticultural crops leave a very small 'footprint' (Table 3.1). There has been a decline of more than 38% in the horticultural crop excluding potatoes (about 32% including potatoes) area since 1977, compared with a 100% increase in wheat. Under the current CAP regime wheat has been supported with area aid for many years, horticultural crops have not.

Table 3.1 Comparison of the area (x 1'000 hectares) grown of arable and wheat crops (GB) 1977 – 2000 (England and Wales 1988, 1990)$ compared with horticultural crops (UK)# and potatoes

Crop	1977	1988 E & W	1990 E & W	1992	1994	1998	2000
Total area grown – all arable crops **GB** [1]	4,045	3,886	3,906	4,400	3,875	4,697	4,097
Wheat GB	*w* 1,046	1,779	1,894	2,057	*1,802	*2,035	*2,078
Total horticultural field crops[2, 3] **UK**	292	228	230	217	205	198	182
Total potatoes GB	214	139	139	169	154	158	161

[1] Excludes set-aside and potatoes;
[2] excluding potatoes;
[3] 1977 for fields includes headlands, ditches etc., other years are cropped area
w = winter wheat;
**= winter & spring wheat*
 # Defra Basic Horticultural Statistics for the UK; $ Defra Pesticide Usage Survey Reports

Potatoes were not part of the arable crops study (PN 0940) and are included here with horticultural crops. Table 3.2 shows that the area of potatoes grown is the largest in the 'horticulture' sector, but in 2000 was 5.3% of wheat.

In 2000 (Table 3.2), the total herbicide treated area of wheat was over 7.3 million ha, 354 % of the crop (3 to 4 passes) which far exceeded the herbicide input for the largest horticultural crop, potatoes. The area of potatoes treated with herbicides is small (2 passes), and only 4.6%, in comparison with winter wheat.

In Great Britain cereals are grown on most farms and on most soil types. In contrast, horticultural crops are grown in many regions but are restricted to the most suitable soil types and climatic conditions. The main growing areas are mentioned for the following horticultural crops:

- **Potatoes:** the majority is now grown on light to medium textured soils with irrigation. In 2000 the main area of the ware crop was in Eastern England (38%), and also the Midlands and Western region (24%) and 16% in the North. Seed potatoes are nearly all still grown in Scotland.

- **Outdoor Vegetables:** are grown on soil types suited to production. Vegetables for fresh market are grown in several areas but processed crops, in particular vining peas, are grown near processing factories to avoid deterioration after harvest. The first factories were sited on the East coast for fish. Later, vegetables were processed as well and factories have opened in other areas since. However, there have also been several factory closures in recent years. Peas are still grown on lighter soils mainly in Eastern England, some in the North and in a decreasing area in Scotland.

- Over the years there has been a shift to lighter sandy soils for **carrots, parsnips, onions and leeks,** which are mainly grown in the Eastern region. There has been little move to other production areas for the following crops. **Cabbages, calabrese, cauliflower and Brussels sprouts** are grown in all areas, but most are in Eastern England on moisture retentive soils. **Swedes and turnips** are more suited to cooler, wet conditions and are mainly grown in Scotland and South-west and West England. The largest area of **lettuce** is in Eastern England. **Sweetcorn** requires warm weather and is concentrated in the South Eastern region and so are cucurbits.

- **Bulbs and Outdoor Flowers:** in the most recent 2001 survey, approximately 52% of the total area of outdoor bulb and flower crops were grown in the Eastern Region, 31% in South Western Region. These were mainly narcissi, the largest area of these crops

- **Soft fruit:** most of the area of all soft fruit is concentrated in the South East and East, except for raspberries. The main crops are now strawberries (East and South East), blackcurrants (in the Eastern region for processing), raspberries (in Scotland), and grapevines (South East). The decline in raspberries is reflected by a 71% reduction of the main production area in Scotland between 1990 and 2001, only 44% of the crop was grown in Scotland in 2001.

- **Orchard crops:** the established growing areas for perry pears and cider apples are in the Midlands and Western region, and some in the South West; dessert apples, pears and cherries in South East England and plums in the Midlands, Western and South Eastern regions. There has been little shift except for a decline of orchards in the East of England.

- **Hardy Nursery Stock:** the area of Christmas trees and ornamentals account for the largest total area. Most hardy nursery stock is grown in Midlands & Western, Eastern and South Eastern England.

3.2 Potatoes (Table 3.2)

3.2.1 Changes in the cropped area of potatoes

The area of potatoes grown for ware and seed has declined since the late 70's. In 2000 the total was 25% less than in 1977. This is a reflection of change in the national diet and competition from imports. The area of ware potatoes has moved, where irrigation is available, to lighter soils and most of the seed crop is still grown in Scotland. Despite an increase in ware potato area of 2% since 1998 the area grown in 2000 was still less than the area grown in 1977. The seed potato area decreased considerably from 1977, but since 1990 has continued to rise and the area grown in 2000 was 3% greater than that grown in 1998. Annual fluctuations in the areas grown, are due to the removal of the quota system in 1996 and the consequent opportunity for growers to determine their own planting areas. The herbicide treated area has increased by 125% since 1977, when cultivations of ridges were used, but there are signs that this method is becoming popular again.

Table 3.2 Comparison of the area (x1000 hectares) grown and treated with herbicides (excluding potato desiccants) of potatoes with wheat in Great Britain, 1977 – 2000 (England and Wales 1988, 1990)

Crop	1977	1988 E & W	1990 E & W	1992	1994	1998	2000
Wheat	**w 1,046**	**1,780**	**1,895**	**2,058**	***1,802**	***2,036**	***2,079**
Total wheat herbicides	**w 1,671**	**4,385**	**4,297**	**4,897**	***5,182**	***6,843**	***7,368**
Ware potatoes	188	N/A	N/A	154	140	142	145
Seed potatoes	26	N/A	N/A	15	14	16	17
Total potatoes	**214**	**139**	**139**	**169**	**155**	**158**	**161**
Total potato herbicides	**200**	**172**	**205**	**282**	**299**	**359**	**342**
Herbicide % potato area	94	124	147	167	193	227	212

* winter & spring wheat; w winter wheat

3.2.2 Weed management in potatoes

Potatoes are grown on ridges on wide rows, stone and clod separators are now frequently used. Early potatoes are produced under protection of clear floating plastic film or woven fleece. The crop offers good weed suppression once established, but yields are reduced by severe infestations. Weeds also influence tuber size and affect rate and ease of harvesting, particularly species with a strong stem e.g. fat-hen and volunteer oilseed rape.

Although potatoes are considered to be one of the more competitive horticultural crops, they are still extremely vulnerable to competition from weeds. This is not only due to the overall decrease in yields that weeds can cause but also to the reduction in tuber size and consequent greater loss of marketable tubers. Yield losses from weeds can be very high. In the 1960s Neild and Proctor (1962) recorded a mean loss of 36% from a series of trials and other work has reported 40-43% (Thackral *et al.*, 1989, Ivany, 2002) and 54% (Nelson & Thoreson, 1981). Obviously, competitive effects will depend on weed density and weed species, as some weeds are more aggressive than others. Research exploring the relative competitive effects of different weed species is rare and often the species studied are not relevant to the UK (e.g. VanGessel & Renner, 1990a). Thus, it is not possible to quantify the relative effects of different species on potato yields. However, subjective views would indicate that tall vigorous or scrambling species are likely to be more competitive (e.g. *C. album, S. arvensis, G. aparine*, volunteer oilseed rape, *F. convolvulus, C. arvense*) (see Table 2.6).

The key to weed control in potatoes is to minimise the effects of early-emerging weeds, which are clearly potentially the most damaging. Later emerging weeds are of less importance, as the crop canopy can suppress these more effectively. Nelson & Thoreson (1981) showed that although early emerging weeds reduced yields by 54%, the fewer later emerging ones only reduced yields by 16%. Consequently, most 'critical period' studies indicate that one treatment to remove weeds is generally adequate to prevent yield loss, assuming that it achieves a high level of control. Further details regarding the critical periods for weed control in potatoes are discussed elsewhere (see 2.4.1.1 to 2.4.1.7).

Competition studies endeavouring to link weed infestations with yield loss, tend to be based on comparing weed/crop vigour (dry weights) in summer, with tuber yields at harvest (e.g. Nelson & Thoreson, 1981; VanGessel & Renner, 1990a). There are some sound comparisons, but such information cannot be used predictively and the densities and species composition of the weed infestations are rarely identified in adequate detail. Thus, threshold management approaches would be difficult to introduce, as there are inadequate data on which to base predictions.

Traditionally, potatoes were considered a 'cleaning' crop, as the wide row planting system provided an opportunity for repeated mechanical weeding and re-ridging, which kept the crop relatively free of weeds. However, following the development of selective herbicides for this crop in the 1960s, intensive comparisons showed that the root pruning and other soil effects resulting from the mechanical weeding could cause reductions in yield (Lutman, 1992). Less intensive soil disturbance can minimise this, but there is then a risk of inadequate levels of weed control. Over the last 30 years herbicides have become the 'standard' tools for weed management, sometimes supported by re-ridging and limited mechanical weeding (see Chapter 4).

Non-chemical weed control in potatoes is now increasing, with the greater production of organically grown potatoes. This crop is one of the easier ones to grow without the use of herbicides (Litterick *et al.*, 1999). If possible the land is ploughed early to encourage a weed flush, and the weeds be killed by a stone separation/ridging operation. Potatoes are planted into ridges and, as close to emergence as possible, the ridges are thermally weeded to remove any weed flush. During the season some kind of inter-row cultivator is used to loosen the soil on the ridge sides followed by ridging bodies to ridge up and smother the weeds. The ridges are harrowed and re-ridged, as necessary. Hand rogueing of large weeds which have escaped weeding may be employed but generally potatoes require little casual labour.

A recent paper by Ivany (2002) discusses the potential for reducing herbicide use in potatoes by band spraying the row and then using a tine weeder to remove the weeds between the row. This seemed to work satisfactorily and may offer a tool to reduce the impact of weed control on the arable ecosystem. The weeds between rows could be left untreated for longer, providing food for invertebrates and birds. It is not clear from the paper, how essential the subsequent cultivation was. A further tool to assist managing weeds is the planting of more vigorous cultivars. Several studies have shown that more aggressive cultivars will reduce weed growth and will incur less yield loss (VanGessel & Renner, 1990b).

3.3 Outdoor vegetables (Table 3.3)

3.3.1 Changes in the cropped area of outdoor vegetables

Outdoor vegetables represent the next largest horticultural area after potatoes. Most outdoor vegetables are grown in Eastern England on light or medium soil types, with the exception of sweetcorn and cucurbits, which are mainly grown in the South East England.

Table 3.3 Comparison of the area (ha) of outdoor vegetables grown and treated with herbicide (and as a % area grown) in Great Britain 1977 – 1999 (1981 England & Wales E & W).

Crop	# 1977	#1981 E & W	1986	1991	1995	1999
Brassicas	56,472	47,805	50,330	43,832	40,828	34,743
Root crucifers	8,056	3,849	5,012	5,274	4,171	4,237
Peas, beans	121,192	93,569	76,653	54,769	51,966	45,365
Onions, leeks	12,391	10,945	12,428	11,670	13,477	16,289
Carrots, parsnips, celery	24,055	17,129	18,198	18,981	16,469	15,851
Lettuce, endive etc.	6,955	5,319	3,848	8,646	6,855	5,858
Sweetcorn	3,237	1,005	1,197	1,533	2,025	1,690
Other root vegetables	3,293	2,666	2,316	2,426	2,513	1,760
Cucurbits	1,210	380	1,029	970	950	1,112
Other vegetables	1433	inc pots 12,255	2,487	4,600	3,088	4,861
Total vegetables	259,482	194,923	173,498	152,701	142,342	131,766
Herbicides area treated (ha)	387,250 excl desic	315,336 excl desic	340,937	351,513	410,566	449,423
Herbicides as % area grown	149	162	197	230	288	341

includes early potatoes but excludes use of desiccants

Details of the 1972 E & W survey are not shown in Table 3.3 but the total area of vegetables was 221,000 ha and from 1972 to 1977 there was an overall increase of 15%. There was a 75% increase in bulb onions as growing the crop, particularly weed control, became more developed. Peas and beans had a 41% increase and there were also increases in carrots and herbs.

The total area of vegetable crops has declined considerably, by nearly 50% or more since the late 1970s, partly because of increased efficiency of UK growing and marketing, but also because of competition from imports. Retailers now source produce from all over the world, all year round. The total area has continued to decline over the past ten years, with overall reductions of 24% compared with 1986, and by 7% since 1995. However since 1986 the area of onions & leeks, lettuce, endive etc., sweetcorn, cucurbits and root crucifers have shown increases of 31%, 52%, 41%, 8% and 2% respectively. The area of "other vegetable crops", mainly outdoor herbs, has doubled over the same period. Since 1977 there has been a dramatic decline in the area of peas and beans and all other crops have shown a fall in the area grown.

The range of some species has increased, e.g. lettuce types Lollo Rosso, Oakleaf etc., and time of harvest e.g. for 'baby leaf' salads and 'baby-sweetcorn', and these innovations are retailer and consumer driven.

The earlier pesticide usage surveys for vegetables included early potatoes: 1972, 1977 (21,045 ha) and 1981 E & W (10,014 ha) and bulbs in 1972 and 1977 (2,158 ha). These are included in Table 3.3 but desiccants for these crops are not, and in the surveys herbicides are not discussed separately. In 1977 and 1981 the "other root vegetables" were beetroot, "other vegetables" included spinach. In 1972, 229,482 ha of vegetables were treated with herbicides i.e. 104% of the area grown. The extent of herbicide usage decreased by 19% between 1977 and 1986 in E & W but was virtually unchanged between 1981 and 1986. By 1999 it had risen to 341%.

3.3.2 Weed management in outdoor vegetables

Much of the following information on management is from the Weed Management Handbook (Knott, 2002)

3.3.2.1 Brassicas (leaf and root) (Table 3.3)

<u>*Brassicas*</u>

Brassicas (leaf and root), including cabbage, cauliflower, Brussels sprouts, calabrese and sprouting broccoli, are grown throughout the country on a range of soil types; the most suitable are moisture retentive, alkaline, mineral soils. Production of cauliflower and cabbages is all year round and clear perforated plastic film is used for their early production and for early calabrese. Most brassica crops are grown on wide rows from transplants raised in modular trays or blocks. Bare root transplants are used less frequently. Where produce of small size is required: Brussels sprouts for processing, baby cauliflower and calabrese for small spear production are precision drilled in the field at high density on narrow rows, and the crop canopy closes early. Weeds compete with brassicas for nutrients and water and can delay maturity. Good weed control is essential to maximise yield and to achieve crop uniformity and quality.

Horticultural brassicas are grown in arable rotations and inherit the weeds of previous arable crops and the crop volunteers (potatoes, oilseed rape and cereals). The long season brassicas, Brussels sprouts and cabbage, are the worst affected by weeds. Where brassicas are intensively grown there may be a build up of weeds tolerant to herbicides, for example, shepherd's purse - a serious spring weed. Weeds emerging in large numbers in autumn, annual meadow-grass, common chickweed and mayweeds are the main problems in brassicas, which are transplanted or drilled from July to September. Tall species, such as fat-hen interfere with mechanical harvesting of Brussels sprouts; small nettle is unpleasant for hand pickers in calabrese and cauliflower. Black-nightshade and volunteer potatoes affect quality of brassicas. Weed seeds of shepherd's purse for example sometimes contaminate produce when the crop is wet.

Swedes and turnips

Swedes and turnips grown for culinary use are more suited to moister, cooler areas. Early crops are harvested in July, maincrops from September through to April. They are usually precision drilled on wide rows and are sometimes grown on raised beds, which are sometimes de-stoned. Some crops are grown under cover to achieve earliness for the ware market, and a few are covered with 'enviromesh' to exclude cabbage root fly after revocation of chlorfenvinphos. Weeds interfere with mechanical harvesting.

3.3.2.2 Weed management in Brassicas (leaf and root)

Perennial species, common couch, docks and thistles, should be controlled prior to planting. Where brassicas are transplanted, weeds are removed by cultivations or herbicides prior to transplanting and rapid establishment allows the early use of post-planting treatments. The key period for weed control is the first four weeks after transplanting.

Herbicide use can be reduced by using a 'stale seedbed' technique: the soil is cultivated and prepared several weeks in advance of cropping and the flush of weeds is killed just prior to planting with a non-selective herbicide, ensuring a weed-free start.

In most brassica crops, weed control is achieved with a pre- or post-planting application of a residual herbicide. Trifluralin, soil incorporated pre-sowing/planting is cheap, has been used for many years, but controls a limited weed spectrum. Modular or block transplants are particularly sensitive to herbicide damage and some labels include warnings that care must be taken not to introduce treated soil to the root zone. Herbicides which are persistent in the soil may be unsuitable in short term brassicas. Foliar-acting herbicides, which may also have some residual activity, are applied to emerged problem weeds and sometimes cultivations are used as well. Several brassica herbicides are safe on all the main crop species, but some post-emergence materials are less safe on calabrese and cauliflower which have less well-developed leaf wax. Maintaining adequate harvest intervals after foliar acting herbicides may be difficult in short season crops. Grass weeds are controlled with post-emergence graminicides.

Swedes and turnips

Weed problems in these crops are similar to other brassicas but sewdes and turnips are less effective at covering the ground and are thus more susceptible to weed competition, particularly for the first 8 weeks after emergence. Weeds also interfere with mechanical harvesting. A sequential programme of trifluralin incorporated pre-sowing, followed by a residual treatment are used. Most brassica herbicides are approved for use in swedes and extrapolated to turnips from swedes under the Long Term Arrangements for Extension of Use (LTAEU). Foliar acting treatment for broad-leaved weeds is limited to clopyralid. A graminicide is used for volunteer cereals and some grass weeds. Blemishes or malformation of swede and turnip roots caused by herbicides or mechanical methods are unacceptable in crops for human consumption.

Organic brassicas

For organic production, these crops are normally grown from transplants to give the crop a competitive edge over the weeds. A stale seedbed is ideally used and the crop planted in rows, spaced according to market size requirements. It is possible to use a broad- spectrum weed control implement, for example a flexible tine weeder, across the entire bed when the transplants are well rooted. Mechanical weeders are used later for crops on wide rows to control weeds between the rows: steerage hoes, brush or finger weeders and several new implements have been developed. The aim is to give minimal soil disturbance in dry conditions and the soil is lightly thrown around the base of the stem to smother seedling weeds. Number of passes and equipment choice will depend on composition and severity of weed flushes. Hand hoeing or hand weeding may be needed. Early crops are more difficult, as establishment is slower, so they are often covered with fleece, which encourages weed growth. Mechanical weeding is not possible where crops are grown under cover. Swedes and turnips, are drilled, ideally into stale seedbed. The crop is inter-row weeded when the rows are visible and repeated as necessary during the season.

3.3.2.3 Peas and Beans (Table 3.3)

In Table 3.3 peas and beans represent the largest crop area after potatoes. This group includes vining peas (the largest area 52,016 ha in 1977), broad beans and dwarf French beans grown for quick-freezing or canning, or for fresh market; runner beans for fresh market only and in some surveys, peas harvested dry for processing (but not animal feed). Peas harvested dry, and processed for human consumption declined from 40,335 ha in 1977 to 14,376 ha in 1991 and was 18,400 ha in 1999 but there is now a downward trend. Very few dwarf French or broad beans are grown in Great Britain and there has been a considerable decline since 1977.

Vining peas

The growing season is short, about four months. Sowing programmes ensure continuity of supply, and for vining peas begin in February and finish in early June. Peas are grown on a range of soils: sands, light and medium soil types.

Broad beans

For the fresh market broad beans are sown mainly in spring but some are overwintered to achieve earliness. Row widths are 300 - 450 mm. Spring-sown broad beans grow rapidly and achieve better weed suppression than most vegetable crops.

Dwarf French beans

Dwarf beans grown for quick-freezing, canning and much of the fresh market crop, are mechanically harvested. The optimum row width for yield is 200 mm or less, but many crops for processing are still sown on 400 mm rows. Sowing programmes, beginning in mid-May outdoors, are used to achieve continuity of supply.

3.3.2.4 Weed management in Peas and Beans

Peas and broad beans for processing
These are sown on optimum row widths of 200 mm or less, and mechanical weeding is not used so the grower relies entirely on herbicides to control weeds. Vining peas are harvested with specialist pea harvesters with reels, which pick up the vine and pods are thrashed to shell peas. Although weeds are less likely to interfere with this operation than the old method (pre-1980) of harvesting the whole crop, weedy contaminants such as flower or seed heads of creeping thistles, mayweeds, common poppy, fragments of volunteer oilseed rape and linseed capsules are difficult to separate from produce and pineappleweed also causes taints. Vining pea crops are sometimes rejected to avoid risk of poisonous berries of black nightshade or volunteer potatoes in produce. A very high standard of weed control is therefore necessary in the processed crop to avoid quality problems in the factory.

Broad beans for processing
In machine harvested crops the main weed problems are volunteer oilseed rape and potatoes, because these weedy contaminants affect produce quality. Black-bindweed causes severe difficulties where direct harvesting is attempted because it entwines round the picking reel.

Dwarf French beans
Successive weed flushes can be encouraged to germinate in this crop by cultivations before sowing. Weeds are controlled with herbicides but there are very few left for this crop. Competition against weeds is not very effective in the early stages of growth. The crop plants are short and many weed species as well as volunteer potatoes can grow above the canopy and cause substantial yield reduction. Woody-stemmed and bushy weeds such as redshank and fat-hen interfere with machine harvesting. The presence of poisonous weedy contaminants in machine-harvested produce can result in crop rejection and stalks of volunteer potatoes and black-nightshade (which germinates in late June) are frequent problems. In the past, wide rows accommodated mechanical weeders, but green beans are shallow rooting and damage. In addition there was soil build-up round the stems which interfered with mechanical harvesting and contaminated pods.

For hand-picked peas and beans, contaminants are not such a problem, but as with other crops, thistles and nettles are unpleasant for pickers.

There are no guidelines as yet for organic production for peas or beans for processing, however peas and broad beans at both early and late growth stages are able to withstand weeding with flexible tines. Peas and beans are generally deeply drilled, beans often being ploughed in. The flexible tine weeder would be used as required, typically as early and aggressively as possible.

3.3.2.5 Onions (bulb and salad) and leeks (Table 3.3)

Bulb onions
These constitute over 80% of the onions grown in the UK. The vast majority is spring sown/planted in February/March. Approximately 70% of the spring sown onion crop is direct-drilled; the remaining 30% are planted as sets. Onion sets grow much more rapidly

than drilled crops and are therefore generally at a more advanced stage than the weed, thus aiding herbicide selectivity. A small proportion of the crop is grown overwinter, almost exclusively from October planted sets. Shelter rows of barley are drilled between rows of (drilled) onion where peat or sand soil blowing can cause crop injury or loss, and the shelter also improves onion vigour and growth.

Salad onions

Salad onions account for about 20% of the onion crop and they are sown in succession from February to September. They occupy the ground for a much shorter time than bulb onions and are grown at higher plant densities, thus weed control may be less of a problem.

Leeks

Leeks are mainly drilled to a stand, but early and late crops are often transplanted. Cultivations which ridge up soil along crop rows are frequently used to provide a better blanch and this also reduces the number of herbicides required.

3.3.2.6 Weed management in onions and leeks

Onions

Onions are relatively slow growing, have an upright foliage habit and they do not form a dense canopy, making them very susceptible to weed competition. Poor weed control can therefore result in significant yield and quality loss. Heavy weed infestations restrict airflow through the crop leading to increased incidence of fungal diseases. Weeds may also hinder bulb ripening. In addition weeds cause harvesting difficulties and severe storage problems in bulb onions

The main problem weeds are mayweeds, fat-hen, *Polygonum* spp, fumitory, volunteer potatoes and oilseed rape and annual meadow-grass. Volunteer cereals are often a problem in overwintered crops which are usually established after cereals. Rotations and cultural practices can minimise 'volunteers' in onions. Onions are extremely sensitive to weed competition (Chapter 2, Table 2.4). Repeat low dose herbicide applications are the key to weed control in onions.

After drilling/planting, residual herbicides are applied. The spring-drilled crops are slow to emerge typically taking 3 - 4 weeks; weeds appearing before crop emergence are controlled with a non-selective herbicide based on glyphosate or paraquat. Post-emergence applications of a residual herbicide are commonly used in conjunction with a contact herbicide, such as ioxynil up to the second true leaf stage. There is no technique for late (after 6-8 weeks) removal of weeds within rows. Crop safety to all post-emergence herbicide applications, particularly prior to the three true leaf stage, depends on adequate leaf wax. All post-emergence contact herbicide programmes are based on the principle of repeat low dose applications beginning as early as loop stage. Graminicides are used to kill grass weeds, volunteer cereals and shelter rows of barley.

Organic production of bulb onions

These can be drilled, modular raised or planted as sets. The farmer chooses the cropping method best suited to his system. Drilled onions require close attention, as they are poor competitors with weeds and are only used on soils with low weed pressure. The onions are drilled into a stale seedbed and weeded inter-row when the plants are strong enough to withstand the operation. The crop can be post-emergence flame weeded and inter-row weeded when required with a hand weeding in the crop rows. Onions raised in modules to produce 4-5 grouped plants are planted out at a spacing to allow long handled hoeing within the crop row. Onions grown from modules or sets are inter-row weeded when necessary. Sets can produce strong early plants that compete well with weeds. Large sets, planted late (early-mid-May) for harvest the third week in July, require less hoeing.

Salad onions

Weed control strategy in this crop is similar to bulb onions. However, particular care should be taken to observe harvest intervals and avoid herbicide damage to the leaf which can render the produce unmarketable.

Organically grown salad onions are a relatively quick summer crop. They are drilled into a stale seedbed and when the onions are strong enough, they are mechanically weeded between the rows. The crop is harvested early and weeding is not as costly as for bulb onions.

Leeks

Leeks suffer from similar weed problems to onions. Drilled leeks are slow to emerge and a contact-acting herbicide kills weeds, which emerge before the crop. A pre-emergence residual herbicide is used and post-emergence herbicides are applied early, from 1 - 3 true leaf stage of the crop, often as split doses. Onion herbicides are used, but since leeks have a larger 'funnel' type of leaf and there is less 'run-off' they are more sensitive to the post-emergence herbicides. Leeks may also collect more pesticide residues than onions and this restricts the use of some chemicals.

Organic leeks are usually grown from bare root transplants. They are inter-row weeded and when strong enough, an implement with a ridging effect can be used to throw soil in the crop row smothering weeds and also covering the plant stem to aid blanching. A finger weeder achieves some mechanical intra-row weed control.

3.3.2.7 Carrots, parsnips and celery (Table 3.3)

Carrots

These are sown on wide rows where top-lifting harvesters are used up till late October; baby carrots for processing are drilled at high populations on a bed system and are share-lifted from the end of August onwards. Early fresh market carrots are seeded at low density in late autumn or winter and the beds are covered in clear film plastic or non-woven fleece. Main season and late crops are drilled from February to May for harvest from August and into the following year when they may be protected in the field, by covering with deep straw or black polythene.

Parsnips
Parsnips are grown on a bed system on sand soils where roots can develop without restriction and mechanical stone separation may be needed. They are drilled in spring from February to early June for harvest June to early April. (The early harvest (from late May) crop is covered in clear plastic film)Parsnips are slow to emerge, but at 4-5 leaf stage can compete with weeds. Their growing season is long.

Celery
Early and late 'self-blanching' crops harvested from July to November are grown at high density on narrow rows from transplants mainly on organic, but some on mineral soils. Self-blanching celery has a short growing season.

3.3.2.8 Weed management in carrots, parsnips and celery

Carrots
Like onions, carrots are extremely sensitive to weed competition (Chapter 2, Table 2.4) and a high standard of weed control is needed to avoid yield loss and to maintain quality and desired size grade particularly for baby carrots. Volunteer potatoes are particularly competitive. Knotgrass, annual meadow-grass and common couch interfere with mechanical harvesting and tall species such as fat-hen and mayweeds are a nuisance where top-lifting harvesters are employed. Nettles are unpleasant where carrots are hand pulled for bunching. Species closely related to carrots are difficult to control: hemlock and wild carrot cannot be controlled with herbicides and must be removed by machine topping, or with inter-row hoes. For later drillings a stale seedbed technique helps to control fool's parsley and wild mignonette, which occur on sandy soils.

Repeat low dose herbicide applications are the key to weed control in carrots. Weed control is achieved with a combination of pre- and post-emergence herbicides and occasionally machine or hand hoeing or hand weeding. Repeat low dose programmes and tank-mixes are usually necessary to cover the weed spectrum. Linuron pre- or post-emergence has been widely used in carrots for annual meadow-grass and broad-leaved weeds for many years. On organic soils residual herbicides are not effective and shallow A blade hoes may be used. Annual and perennial grasses, cereals as volunteers or where they are sown as cover to prevent damage from soil blows, are removed with a range of post-emergence graminicides.

Carrots grown under plastic cover are more difficult to keep weed-free because these conditions favour emergence and growth of weeds as well as crop. Residual herbicides are used after drilling and before covering the crop. The cover is removed when seedlings are well developed in April or May. However contact herbicides applied when growth is soft may damage the crop as well as the weed.

For organic production, the crop is drilled into a stale seedbed and pre-emergence flamed. Other techniques such as using pulses of light to stimulate early germination of some weeds (fat-het) is also being used in some organic (and conventional) crops. Inter-row weeding takes place as early as possible often followed by a bed weeder (a platform for people to lie prone and weed attached to the back of the tractor). A hand weeding is usually required once or twice during the season and inter-row weeding as dictated by weed severity.

Parsnips
Parsnips are affected by similar weed problems to carrots. Herbicides with a label approval for carrots can be extrapolated for use in parsnips. The larger parsnip leaves retain more herbicide than carrots and parsnips are less tolerant of post-emergence herbicides. For crop safety, herbicides are applied at half dose rates and/or at a more advanced growth stage than carrots, but bearing in mind harvest intervals. Any cultivations must be done with care to avoid damage to parsnip crowns.

For organic production, a "topping" technique is used after the crop is established at 4-5 true leaf stage. The leaves and weeds are cut down, this controls species such as groundsel, and the crop is irrigated. Cleavers are removed with a flexible tine weeder.

Celery
Weed numbers are reduced with a stale seedbed technique. Use of a contact herbicide before planting may mean fewer herbicide applications to the crop and is essential on organic soils. A few herbicides used in carrots are suitable for celery. After transplants have established, a residual/contact acting herbicide is applied up to 2 rough leaf stage only) but there will be a little residual activity on organic soils. If weed control is achieved during the first six weeds celery is then very competitive and no further treatment is required. The morphology of the celery plant is different from other crop species and larger amounts of pesticides may be retained, resulting in higher levels of residues. Thus there are no minor-use extrapolations to celery and the number of label recommendations is likely to remain small.

3.3.2.9 Outdoor lettuce (Table 3.3)

Outdoor lettuce is grown from transplants in blocks or modules. The early lettuce crop is frequently grown under the protection of fleece. Continuous lettuce production is carefully planned and any crop check or maturity delay caused by weed competition or herbicide must be avoided. Lettuce crops are short-term crop so several are grown on the same land in a single season. Crop rotation would reduce weed problems, but many factors influence field lettuce production and often breaks of only one year are achieved. Block/module transplants of early maturing varieties do not usually suffer from severe weed infestation but in later maturing, and in all drilled crops, problems can be acute. There is zero tolerance of weeds whose seed contaminants reduce product quality or hinder hand harvesting.

3.3.2.10 Weed management in outdoor lettuce

Continuous cropping on the same land and the short term crop are limiting factors for weed control: propyzamide, is a widely used pre-emergence residual herbicide, but it has a six week harvest interval and it is persistent in the soil, so care should be taken in respect of following crops. Some herbicides cannot be used on transplanted lettuce. The risk of damage to tender leaves prevents the use of later herbicide applications and often mechanical or hand weeding supplements chemical weed control, usually to remove weed species not controlled by the herbicides.

Most of the herbicides are safe to the types of lettuce mentioned but new varieties of speciality lettuce are constantly introduced and there may be differences in tolerance. There are extrapolations from the few herbicides approved for use in lettuce to several other minor but important uses. Lamb's lettuce, frisée, radicchio, escarole, cress and leaf herbs. If approvals in lettuce are not maintained these other crops would be affected.

A soil fumigant is sometimes used to kill weed seeds particularly in the production of 'baby leaf' lettuce, which has become popular. Dazomet granules are incorporated in the soil which is then covered with polythene. Steam sterilisation is often used in "baby leaf" lettuce before planting. This method is successful, but slow at 40 - 100 h/ha. The use of a dry heat system which sterilises 2 - 5 ha/day has also been investigated..

Organic lettuce is generally be grown as a transplanted crop. Inter-row weeding performed as necessary with mechanical tine, brush or 'A' blade weeders or hand weeding (typically 2 passes) where lettuce are grown on a 250 mm row spacing or hand weeding. Another option is to grow organic lettuce on close spacing to crowd out weeds, together with hand weeding. The crop spacing would allow intra-row hoeing by hand.

3.3.2.11 Sweetcorn (Table 3.3)

A small area of sweetcorn is drilled or transplanted, in late April/May on very wide rows 750 mm if grown for hand-picking. Sweetcorn is slow growing initially when temperatures are low and it seldom forms a complete canopy before the end of July. Spring emerging annual weeds can smother sweetcorn at early growth stages and perennial species, particularly common couch, can cause suppression. Even when mature, the canopy allows light penetration and weeds grow beneath it. Sweetcorn is often grown continuously on the same sheltered field and repeated use of atrazine leads to a build-up of black-nightshade.

3.4 Bulbs and other outdoor flowers (Table 3.4)

3.4.1 Changes in cropped area of bulbs and outdoor flowers

The 2001 survey shows that there has been very little change in the total area of outdoor bulbs and other flowers for cutting grown in Great Britain since 1993. When outdoor bulb crops alone are considered, the area grown has increased by 10% since 1997. However, the area of other flowers for cutting has fallen by 48% since 1993 and by 27% since the previous survey in 1997.

Narcissi accounted for 96% of the total area of bulb crops grown, dahlia and gladioli for 1%, and other bulb crops each less than one percent. Other bulb crops included tulips, iris, anemone, lilies, *Agapanthus*, *Brodiaea* and *Crocosmia*. The narcissus crop (both dry bulbs and bulbs for flowers) is high quality and much of it is exported to Europe and North America. Narcissi, are grown for up to three years or more, most other bulbs are grown on an annual basis. Forty-three percent of narcissi were in their first year, 47% in their second year with the remainder (expected to rise in future) being three years or older. Flowers were picked from 71% of first year narcissi, from 97% of second year crops and from all crops three years and older – the emphasis has changed to a more dual-purpose crop and this exacerbates weed problems. With the exception of one third of the tulip area, flowers were picked from all other bulb crops. Overall, 50% of the narcissus area grown in 2001 was harvested as bulbs for replanting, as were 94% of tulips and 20% of gladioli.

Thirty-four specific crops were included in the category "other flowers for cutting" in the 2001 survey. Major crops included in this category were 'natural season' chrysanthemum, accounting for 18% of the area grown where a crop was specified, *Eucalyptus* 15%, aquatic plants 7%, paeony 6%, sweet peas 6%, gypsophila 5%, cornflower 5%, larkspur 4%, sweet William 4%, aster 4%, holly 4% and wallflower 4%. Fashions change rapidly and currently sunflower, delphinium and stock are also popular. All crops were grown for cut flowers/foliage but the length of time that a crop was grown varied both between and within crops. Over half (51%) of all crops were grown on an annual basis, 5% as biennials and the remainder as perennials, which also have more weed problems.

Table 3.4 Comparison of the area (ha) of bulbs and outdoor flowers grown and treated with herbicide (and as a % area grown) in Great Britain 1977 – 2001 (Scotland is excluded for earlier years)

	1977	1982	1993	1997	2001
Outdoor bulbs	GB 2,158 (E & W # 1,949)	GB 4,615 (E & W 4,425)	4,759	4,715	5,237
Herbicides area treated (ha)	(E & W # 4,863)	GB 10,405 (E & W 10,064)	10,153	14,404	22,134
Herbicides as % area grown	(E & W # 250)	GB 225 (E & W 227)	199	288	422.6
Other flowers for cutting			1,033	741	540
Herbicides area treated (ha)			1,101	952	539
Herbicides as % area grown			106	128	99.8

 # South West England was excluded in 1977

3.4.2 Weed management in bulbs and outdoor flowers

Bulbs are grown on ridges and cultivations (running tines down furrows etc.) play a part in weed control early in the season. Weeds can reduce bulb size and consequently flower yield and forcing quality i.e. smaller bulbs and fewer, smaller flowers, and also impede harvesting by clogging machinery. Therefore control of all weeds is the aim. Bulbs are planted in August or September and over-wintered weeds, for example chickweed and weeds that grow up with the crop in spring are the most damaging (Lawson, 1976; Lawson & Wiseman, 1978), and so are weed species that shade the crop until late June. The presence of nettles and thistles is not acceptable to flower pickers; fat-hen, redshank, knotgrass and common couch cause problems with bulb–lifting machinery. Herbicides are used at four stages (ADAS, 1985): total herbicides, mainly glyphosate, are used in the autumn/winter period before the crop emerges to remove over-wintered weeds; a residual herbicide is then applied as late as possible but before the crop emerges; a contact-acting/residual herbicide is applied post-emergence before the bulb shoots are about 10 cm tall, and after flowering. Weed control is difficult at the last stage - the post-flowering period, because the new flower initials being formed at this time may be damaged by herbicides, and the senescing foliage falls over, shielding the soil, and trampling of flower-pickers will have destroyed any residual herbicide seal.

The very large proportion of narcissus bulbs grown has an overwhelming influence on the total use of herbicides on all outdoor bulb and flower crops, and in 2001 narcissus received over 4 herbicide sprays, but other flowers for cutting were only treated once possibly because of lack of knowledge on which herbicides would be safe to the crop.

3.5 Soft fruit crops (Table 3.5)

3.5.1 Changes in cropped area of soft fruit crops

Between 1975 and 2001 there has been a reduction of 45% in the total area of soft fruit grown in Great Britain. The total area of soft fruit crops in 2001, 9,432 ha, remained virtually unchanged since 1998 but 38% less than in 1990. Much of the decline since 1990 is due to a reduction in the desire of the general public for pick-your-own (PYO) fruit and an increase in the quantities of lower priced fruit imported into Great Britain.

The areas of individual crops grown had changed markedly and since 1975 only vines have increased, but very few gooseberries are now grown. Despite recent changes in the production systems for strawberries, the area grown in 2001 was 37%, (2,236 ha) less than in 1990. However, since 1998, the area grown had remained relatively stable. A very large area of strawberries is grown under polythene.

Blackcurrants, including those for fresh market and processing, have shown a substantial decrease since 1975. However, between 1998 and 2001 there was a 96% increase, reflecting changes in the processing industry and a renewed interest in the crop.

Table 3.5 Comparison of the area (ha) of soft fruit crops grown and treated with herbicide (and as a % area grown) in Great Britain, 1975 – 2001

Crop	1975	1980	1990	1994	1998	2001
Strawberry	6,797	8,037	6,001	5,081	3,887	3,765
Blackcurrant	4,146	4,251	3,257	2,918	1,368	2,683
Gooseberry	1,199	1,196	491	415	261	258
Raspberry	4,085	4,336	3,875	2,778	2,488	1,530
Vine	196	349	838	981	865	745
Other soft fruit	852	972	640	410	561	451
Total - all soft fruit	**17,277**	**19,140**	**15,102**	**12,520**	**9,430**	**9,432**
Herbicides area treated (ha)	**35,711**	**47,175**	**42,460**	**41,054**	**29,185**	**26,092**
Herbicides as % area grown	**207**	**247**	**281**	**283**	**309**	**277**

The area of raspberries continues to decline and the area grown in 2001 was 63% less than in 1975 and 61% less than in 1990. The decline in raspberries is reflected by a 71% reduction of the main production area in Scotland between 1990 and 2001. The change to protecting raspberries under poly-tunnels, a requirement driven by retailers to reduce the effects of wet weather and improve quality, may also have reduced wastage.

The area of grapevines, was small in 1975, then increased dramatically but has since fallen and is now 11% less than in 1990. Half the vines grown in 1975 were for wine-making and in England there was also an increase in PYO soft fruit which may have meant these crops had to be kept weed free. In 1971 (not shown) in E & W approx 13,000 ha were grown.

3.5.2 Weed management in soft fruit crops

Soft fruit includes strawberries, blackcurrants, redcurrants and whitecurrants, gooseberries, raspberries, blackberries, hybridberries and grapevines. Although the effect of weeds on competition is important, effects on quality and in strawberries, maturity, are also considered. All weeds are targeted in soft fruit crops. Failure to control annual weed species can result in rapid increase. Knotgrass, speedwells and pansies are reported problems in strawberries. Perennials thistles and common couch frequently occur in soft fruit and field-bindweed, though less common, is difficult to control. Willowherbs and hogweed (in Scotland) are found in some plantations and these were not previously considered weeds of cropped areas. In perennial crops, any weeds that survive can develop and seed.

Individual plants of perennial fruit are planted close together within rows but have clear alleyways between. Strawberries are often grown in plastic covered beds, with strawed alleys. Alternatively they are grown under mypex mulch. Weeds in alleys are controlled with applications of residual herbicides early, followed by contact-acting or translocated herbicides later in the growing season. Spawn (primocanes) in raspberries are controlled with a herbicide, sodium monochloroacetate, which will be withdrawn in 2007.

Organically grown soft fruit such as strawberries need at least a 4-year rotation and should not planted after solonaceous crops (tomato, potato) to reduce volunteer weeds and particularly disease problems. Weed control is frequently seen as vital towards the minimisation of pathogens and pests. Systems of mechanical weeding are being developed to reduce the use of polythene. Finger-harrowing is often used, primarily for weed control but also claimed to affect the occurrence of *Botrytis* (the most common disease of strawberries). Few conclusions could be drawn about organic cane and bush fruit production as there are very few growers in the UK with significant areas of soft fruit (see specific recommendations on the HDRA web site). (http://www.hdra.org.uk/research/ires_ofp.htm).

3.6 Orchard crops (Top fruit) (Table 3.6)

3.6.1 Changes in the cropped area of orchards crops (top fruit)

There has been a continual decrease in the area of orchard crops grown and from 1979 to 2000 an overall decline of 47%. From the surveys in 1996 until 2000 the overall area was still declining by 8%. With the exception of cider apples and perry pears, all crops surveyed showed reductions in the area grown. The area of cider apples & perry pears increased since the 1980's, by 39% in 2000, and still shows an increase of 23% from 1996 to 2000. There are few orchards in Scotland. The majority of cider apples and perry pears are grown in the Midlands, West and some in the South West; other apples, pears and cherries in the South East; plums in the Midlands, West and South East. The age of trees varies with most between 4 – 25 years. Top fruit is grown on a wide range of soils.

3.6.2 Weed management in orchard crops (top fruit)

All weeds are targets in top fruit. With long-season perennial crops, it is essential to protect growth throughout the growing season in order to ensure the production of high quality fruit. The effect on tree growth is shown in Table 2.4 Chapter 2. The tree base must be kept weed-free to avoid competition for moisture and nutrients.

Growers may manage orchard floors in a number of different ways. Orchards can be grassed over completely, as is common in cider and plum orchards, or the ground may be maintained completely bare through cultivation or the use of herbicides. Most orchards are now grown with weed-free tree-bases, most often in the form of bare strips along the rows with grass alleyways in between. Mulching is uncommon. Unsprayed areas are potential reservoirs of weeds – for example: creeping buttercup, bents, clover and silverweed can spread from grassed alleys into bare strips. Weed seeds dispersed by wind will spread greater distances.

Organic weed management in orchards uses a combination of mechanical weeding, hand-labour, mulching (straw, plastic, mypex) and use of cover crops (both permanent and rapidly growing green manures sown late summer and mechanically removed to avoid shelter for mice) (as described by the Organic Top Fruit Group, 2001 http://www.hri.ac.uk/site2/research/eastmall/organics/topfruitguidelines.pdf).

Table 3.6 Comparison of the area (hectares) of orchard crops grown and treated with herbicide (and as a % area grown) in Great Britain 1979 – 2000 (small area in Scotland, excluded 1979,1983 and 1987)

	1979 (E&W)	**1983** (E&W)	**1987** (E&W)	**1992**	**1996**	**2000**
Dessert apples (Cox)			*9,168*	*8,198*	*5,934*	*4,542*
Dessert apples (others)			*5,268*	*3,944*	*3,791*	*3,772*
Total dessert	17,084	15,002	14,436	12,142	9,735	8,314
Culinary apples (Bramley)			*6,028*	*5,335*	*4,067*	*3,864*
Culinary apples (others)			*886*	*567*	*342*	*254*
Total culinary	8,862	7.464	6,914	5,902	4,409	4,118
Cider apples & perry pears	4,383	4,072	3,921	3,976	4,591	5,652
Pears	4,718	4,114	4,028	3,533	3,228	2,555
Plums	4,483	3,488	2,624	2,229	1,702	1,316
Cherries	1,426	1,121	904	808	698	498
Other top fruit (incl. nuts)	Nuts 200	Nuts 180	248	161	145	142
Total - all orchard crops	**42,926**	**35,443**	**33,085**	**28,751**	**24,498**	**22,595**
Herbicides area treated (ha)	**125,817**	**128,157**	**128,394**	**61,680**	**74,282**	**56,356**
Herbicides as % area grown	**293**	**362**	**388**	**215**	**303**	**249**

3.7 Hardy Nursery Stock (Table 3.7)

3.7.1 Changes in the cropped area of Hardy Nursery Stock

Hardy nursery stock includes stock plants as well as those grown for resale. In the most recent survey in 2001, Christmas trees accounted for 33% of the total area of crops grown in the survey, ornamental trees for a further 24%, mixed areas 20%, roses 8%, fruit stock 7%, herbaceous perennials 5% and shrubs etc. the remainder. Approximately 78% of the area of hardy nursery stock was grown in three regions, Midlands & Western, Eastern and South Eastern England.

Since 1981, there had been a 21% increase in the total area of hardy nursery stock grown, though in 2001 the area grown has declined by 10% since the previous survey in 1997. However, since 1997, the relative areas of some crop groups had changed. The areas of shrubs, fruit stock, roses and mixed areas decreased by 70%, 34%, 31% and 23% respectively. However, the areas of Christmas trees grown increased by 31% since 1997, that of ornamental trees by 20% and herbaceous plants by 4%.

Fruit stock included stone and pome fruit, bush fruit, cane fruit and strawberries for runner production. Sixty one percent of fruit for stock plants or for sale, and 87%, of ornamental trees were over one year old. Roses are grown on a two-year system with lifting occurring in the second year. Shrubs etc. included a wide variety of plant types and hundreds of species including conifers, hedging plants, ornamental shrubs and ericaceous plants and most of these (62%) were over one year old. Herbaceous plants included wild flowers, paeonies, iris, delphiniums and hundreds of species of annual, biennial and perennial plants, mainly propagated from seed or rootstocks and about 86% were less than one year old. The crop group "mixed areas" included container-grown crops from possibly thousands of species, and small areas of field grown crops from all other categories. Almost two thirds, 64%, of the mixed areas recorded were less than one year old. Christmas trees and other ornamental trees were mainly over a year old. With the exception of mixed areas, all other crops were grown in field situations.

3.7.2 Weed management in Hardy Nursery Stock

In containers well watered, fertile conditions are ideal for weed germination and weeds reduce crop growth and render plants unsaleable under some accreditation schemes. “Zero tolerance” is therefore the aim. In field production weeds compete with moisture and nutrients and reduce growth rate, affect budding in rootstock and dense stands encourage rodent damage.

Willowherb, groundsel, creeping thistle, sowthistle (all sources of wind blown seeds), chickweeds, annual meadow-grass, are the main problems; in addition creeping buttercup, bindweeds, small nettle and horsetail (*Equisetum*), grass weeds (Christmas trees) in a field situation; hairy bittercress, groundsel, pearlwort, moss and liverwort in container grown stock.

Hand weeding is prohibitive – about 30 times more expensive than a herbicide programme (J Atwood, pers.com) thus weed control is mainly based on herbicides. There are few on-label recommendations but, under the Long Term Arrangements for Extension of Use, herbicides approved for any growing crop may be used on Hardy Nursery Stock where neither the seed nor any part of the plant is to be consumed by animals or humans, as long as usage restrictions are complied with. However the wide range of species means that herbicides must be carefully chosen to ensure crop safety as well as effective weed control. Herbaceous plants are shallow rooting and can be damaged by residual herbicides and they are generally less tolerant of herbicides than woody stock. A small area of ornamentals is treated with chemical soil sterilants. Nursery hygiene is essential to eliminate sources of weeds from uncropped areas and standing beds, irrigation water and for container-grown stock, dirty pots, and contaminated compost.

Weed management differs for container grown and field grown systems (HDC, 2001). In field grown crops, weeds, particularly perennial species, are controlled with glyphosate in the year before planting, often during a years fallow. Perennials within the growing crop are removed by spot treatment or directed herbicide sprays. Stale seedbed techniques are often used for trees and shrubs grown from seed and a total herbicide paraquat, or paraquat/diquat is applied to kill weeds emerging before the crop. A residual herbicide is applied post-planting, followed by a summer treatment to control autumn germinating weeds, and another the next spring when there is more choice for a less sensitive established crop. For container grown stock, total herbicides are used to clean up standing areas. Most herbicides used in nursery stock production have persistent residual soil activity, and, depending on the crop species, some do not damage the crop foliage. Otherwise granular herbicide formulations are widely used.

Table 3.7 Comparison of the area (hectares) of Hardy Nursery Stock grown and treated with herbicide (and as a % area grown) in Great Britain, 1980/81 –2000/2001 growing seasons. 1993 # included Christmas trees, 1981 survey details not available.

	1981		**1993**		**1997**		**2001**	
	Crop	**Herbicides**	**Crop**	**Herbicides**	**Crop**	**Herbicides**	**Crop**	**Herbicides**
Fruit stock			799	1,743	776	4,520	512	**2,513**
Roses			862	2,671	860	2,398	592	**2,058**
Ornamental trees			1,842	4,919	1,527	3,287	1,839	**5,097**
Shrubs etc			#2,240	5,373	1,203	3,635	359	**547**
Herbaceous plants			304	379	351	674	364	**804**
Mixed areas			2,215	6,027	2,010	5,023	1,556	**4,477**
Christmas trees					1,978	5,555	2,584	**5,537**
Total Hardy Nursery Stock	**6,465**		**8,172**		**8,706**		**7,806**	
Herbicides area treated (ha)		**20,047**		**21,113**		**25,092**		**21,032**
Herbicides as % area grown		**310**		**258**		**288**		**269**

There is increasing interest in non-chemical weed control, which is useful for herbicide sensitive plants and may also be an important selling point for some retailers. In container grown plants the following methods exclude light to reduce weed seed germination for up to 12 months: *pot toppers*, a covering mat fitted round the base of the plant to form a mulch over the surface of the compost; *mulches* of bark chips for example.

In field grown nursery stock the use of cultivations is integrated with herbicides and a wide range of mechanical weed control equipment (hoes, brush and finger weeders) is available to remove weeds within and between rows of stock. Flame weeding, soil sterilisation with steam can also be used although the latter is slow and costly. Mulches (black polythene, black woven polypropylene or bark chippings) have been successfully used for many years.

3.8 Implications of GM technology for weed management and biodiversity in horticulture

Whilst genetically modified herbicide tolerant (HT GM) arable crops, such as oilseed rape, have already been released in a number of countries and are in the process of being tested in the UK, this technology is some way behind in horticulture. Globally, one of the few examples for horticultural crops is the recent application for field-testing to evaluate the environmental impact of onions that have been modified for tolerance to the herbicide glyphosate. However, it is questionable at present whether similar developments in herbicide tolerance for horticultural crops are commercially attractive, given their relatively small commodity size compared with arable crops in the UK. Despite the fact that herbicide tolerant field vegetable crops are not on the immediate horizon in the UK, GM technology for herbicide tolerance may well have an indirect impact where GM HT crops form part of a rotation that also includes horticultural crops. Therefore the potential implications of GM HT on weed populations and biodiversity need to be acknowledged within the context of this study.

Currently, the majority of herbicides can only be applied within a relatively small window during the crop-growing season. This is either because of lack of weed control efficacy beyond a certain weed size, or because of potential crop damage outside a recommended crop growth stage. In addition, timing of herbicide application is further constrained by prevailing weather conditions and so failure to apply herbicides at the correct time can sometimes lead to catastrophic crop losses. GM HT crops, such as HT oilseed rape, enable the use of broad-spectrum herbicides (glyphosate and glufosinate) to be used without fear of damage to the crop and providing good weed control efficacy over a wide timescale. This is because these herbicides are generally capable of removing larger weeds and much later in the growing season. Therefore the technology has the potential to provide both greater flexibility in application time and, because the herbicides are broad-spectrum, the potential for reducing the number of herbicides needed and so the number of applications. In addition, the herbicides used in GM HT technology are generally regarded as less environmentally damaging than many products in terms of, for example, their biodegradability and persistence in the soil.

Numerous studies support the general acceptance that agricultural intensification and are implicated in the loss of biodiversity in the last 50 years (Robinson & Sutherland, 2002). For example, the change towards increased winter cropping in arable rotations and the use of increasingly broad-spectrum herbicide combinations that lead to cleaner (weed free) crops (Marshall *et al,* 2003). Some recent studies have suggested that the flexibility that is offered by GM HT crops (described above), could also provide new opportunities for reintroducing this biodiversity back into cropped fields. This is because weeds may be allowed to remain in the crop much longer than possible with conventional technology, hence providing a vital source of food to birds and beneficial insects (Dewar *et al*, 2003). The technology may also reduce reliance on cultural control methods and favour reduced tillage and minimise soil erosion etc. (Firbank & Forcella, 2000). However, in many field vegetable crops, whilst increased flexibility in herbicide application time would undoubtedly have weed management benefits, its use as a tool for retaining weeds long enough in the crop to actually deliver biodiversity benefits is unlikely to be practical. This is because many field vegetable crops, particularly those such as carrots and leeks, are very uncompetitive compared with their arable counterparts. Weeds cannot be tolerated by these crops for any length of time and they start to compete after a matter of just a few weeks (see section on critical periods 2.4.1.1 to 2.4.1.7). The detrimental effects of these weeds on yield and quality in such high value crops are therefore unlikely to be tolerated. The long-term implications for the build up of future weed infestations are also unquantified.

There is currently no long-term evidence from studies on potential shifts in the weed flora (or the seedbank) over time resulting from the use of this technology. Most suggestions are based on model simulations or theoretical extrapolation. For example, Watkinson *et al*., (2000) used a model to demonstrate the potential for weed populations to be significantly reduced, and in the case of some species even eradicated. Other researchers have proposed that the weed flora would be skewed towards later germinating species that emerge (and go on to subsequently shed seed) after herbicide application, or early germinating species capable of completing their life cycle prior to treatment (Derksen *et al* 1999; Forcella, 1999). Changes in the weed flora may also result from the development of herbicide resistance. Resistance may evolve over time if a herbicide, or group of herbicides, with the same mode of action are repeatedly used and same situation would be true of the herbicides used in GM HT crops if ease of use were to lead to over-reliance. Examples of glyphosate tolerance in volunteer oilseed rape have already been reported in Canada after a relatively short period following the introduction of HT oilseed rape (Downey, 1999). However, sensible management such as use of rotations, herbicides with alternative modes of action and different cultural methods all contribute towards delaying the development of resistance (Orson, 2002) and minimising weed population shifts. Again, whilst there are currently no GM HT field vegetable crops in the UK, there may be long-term implications for weed populations and weed management in horticultural crops where GM HT arable crops have formed part of the same rotation. The diminishing number of herbicides available for horticulture may increase problems. Oilseed rape resistant to glyphosate in particular would be more difficult to manage in horticultural crops.

Clearly, the long-term effects of GM HT crops on weed populations in arable crops and their impact on biodiversity and weed management in associated horticultural crops are poorly understood at present. As such “the ability to understand and predict weed shifts associated with widespread use of broad-spectrum herbicides over growing crops” has already been identified as a significant gap in knowledge as part of the GM science review first report.

3.9 Summary & Conclusions

1. The information on horticultural crop areas makes depressing reading. There has been a decline of more than 38% in the horticultural crop area (excluding potatoes) since 1977, compared with a 100% increase in wheat. Under the current CAP regime wheat is supported with area aid but horticultural crops are not.

2. In comparison with arable crops, horticultural crops leave a very small 'footprint'. In 2000 the total area of arable crops excluding potatoes, was 4,097,514 ha (GB), the potato area 161,502 ha (UK), and the total area of other horticultural field crops (UK) was only 181,662 ha.

   - The area of **potatoes** grown for ware and seed has declined: in 2000 The decline in potato area is 25% since 1977 – (less than most crops) - a reflection of change in the national diet and competition from imports. The crop offers good weed suppression and once established, weeds emerging early are the most competitive and damaging. Yields are reduced by severe infestations. Weeds also influence tuber size and affect rate and ease of harvesting, particularly species with a strong stem e.g. fat-hen and volunteer oilseed rape.

   - **Outdoor vegetables** represent the next largest horticultural area after potatoes. The total area has declined considerably, by more than 40% since the late 1970s, partly because of increased efficiency of UK growing and marketing, but also because of competition from imports. Retailers now source produce from all over the world, all year round. The few areas increasing include herbs, onions and Christmas trees. There has been a dramatic decline in the area of peas and beans. In many of these vegetables weeds have an impact on quality and weedy crops may be rejected. Weeds also affect harvesting. Weed control is with herbicides, with several repeat low doses in the less competitive crops onions and carrots.

   - Between 1975 and 2001 there has been a reduction of 45% in the total area of **soft fruit** grown in Great Britain. The decline in raspberries in Scotland, which was the main production area, between 1990 and 2001 was 71%. The effect of weeds on competition is important, effects on quality and in strawberries, maturity, are also considered. All weeds are targeted in soft fruit crops. Perennials weed species, particularly those which seed, are a problem. Individual plants of perennial fruit are planted close together within rows but have clear alleyways between. Strawberries are often grown in plastic covered beds, with strawed alleys. Alternatively they are grown under mulch. Weeds in alleys are controlled with applications of residual herbicides early, followed by contact-acting or translocated herbicides later in the growing season.

   - There has been a continual decline in the total area of **orchard crops** grown and from 1979 to 2000 an overall decline of 47%. Cider apples and perry pears are the exception. All weeds are targets in top fruit. With long-season perennial crops, it is essential to protect growth throughout the growing season in order to ensure the production of high quality fruit. The tree base must be kept weed-free to avoid competition for moisture and nutrients and this is through cultivation or the use of herbicides.

- Since 1981, there had been a 21% increase in overall area of **hardy nursery stock** grown. In containers weeds reduce crop growth and render plants unsaleable. In field grown nursery stock the use of cultivations is integrated with herbicides and mechanical weed control. Hand weeding is prohibitive – about 30 times more expensive than a herbicide. Thus weed control is mainly based on herbicides. There is increasing interest in non-chemical weed control. Mulches have been successfully used for many years.

3. Horticultural crops may only occupy a small area in comparison with cereals but the crops are very diverse with a wide range of crop architectures and the spring drilled crops in particular offer opportunities for biodiversity:

   - Weed species are more diverse because of spring cultivation and light soil type

   - Leaving cereal stubble over winter may be acceptable on light sandy soils (silts are generally autumn ploughed)

   - Crops are more open and more attractive to some bird species (skylarks)

4. There are different production systems for all horticultural crops but there is a common aim: from the aspects of quality, yield and harvesting, weeds are not tolerated. Thus all weed species are targets for control.

5. Horticultural crops are in general less competitive with weeds than cereals. Therefore, strategies based on reduced doses of herbicides could leave the more aggressive weed species, which are likely to have a greater effect on many vegetable crops than on cereals.

6. There are few options for the grower to avoid weed competition and virtually all horticultural crops are dependent on a diminishing number of herbicides.

7. It is possible to control weeds by non-chemical methods. However, organic production is small and many growers are reverting back to conventional growing. In most horticultural crops the costs of alternative weed control methods are higher than for weed control with herbicides. Hand labour has now become expensive and also scarce - producers of horticultural crops are dependent on workers from abroad. A USA study NCAFP (2003) concluded that even with an additional 7 million hand-weeders and increased mechanical cultivations, overall crop production would decline by 21%, and that herbicides are essential to maintain current yields. This is probably true for the UK as well. Non-chemical methods are also aimed at controlling all weeds and repeated cultivations may, in addition, have adverse effects on biodiversity by depleting the seedbank and have adverse effects on soil structure and ground-nesting birds. Flame or steam-weeding will have negative effects on invertebrates.

8. There are few options for the grower to manipulate weed populations and species within most horticultural crops. Changing seed rates, manipulation of row widths, time of sowing or planting and choice of variety may be available for cereals, but not usually for many horticultural crops. This is because the growing system adopted suits

precision drills for expensive seed and specialist harvesting equipment (or hand pickers) and has to achieve the required size of produce and maximum yield. The time of sowing is planned for time of harvest and continuity of supply – this is vital. Weeds must not affect crop maturity. The varieties of most fruit, vegetables (and flowers) grown are selected for the market outlet, usually by the retailer or processor, for quality, i.e. flavour, colour etc., and to cover a range of maturities to extend the season. There is little scope to choose vigorous varieties where the main attribute is to suppress weeds.

9. There has been much discussion on "what (weeds) shall we leave" in arable crops, but little research world wide on weed thresholds in horticultural crops and none in the UK. The UK research on winter-sown cereals cannot be directly extrapolated to crops with different morphology and time of sowing. However, the sensitivity of the crop to weeds, its high value (compared with cereals) and the effect of only a few weeds on quality in some crops are likely to make thresholds for most horticultural crops impractical.

10. If certain weeds listed in Table 5.5, Chapter 5 as beneficial for bird food (e.g. chickweed) are able to be left to flourish within horticultural crops, the question is whether this can be done by selective herbicide application to leave certain species, or by reducing herbicide doses to leave a range of species? Again, the practicality of achieving this in vegetables would be difficult, either with herbicides, or non-chemical means, to selectively leave these species without leaving other species with the potential to contaminate harvested produce and in some cases cause crop rejection. This is because most herbicides used in horticulture are broad-spectrum. For example, Chickweed (identified as a potentially beneficial species) is also one of the most susceptible weeds to herbicides; it is only tolerant to two, oxadiazon and fomesafen (which will soon be lost) and mechanical hoeing would certainly remove it. An additional complication is that a pre-emergence herbicide is used in all vegetables crops (except those on organic soils) and this may be essential in future if there are requirements to reduce residues in the produce.

11. Potatoes are vulnerable to competition from early emerging weeds but critical period and other studies would indicate that later emerging ones matter less. Thus, supplementary, late post-emergence treatments may often be unnecessary and could be omitted. But, avoidance of such treatments may deliver few wildlife benefits, because of the vigour of the crop. There is virtually no information on the relative importance of different weed species in potatoes. Manipulating row spacings or tuber density seems not to be useful, but selecting vigorous cultivars may have potential to reduce the need for weed control. Environmental benefits from potato production seem most likely to arise from not planting the crop on headlands, which yield less anyway, and then 'farming' these for wildlife objectives.

12. If strips within a field were left untreated and weedy, this crop area could not be harvested because of contaminant risk.

13. Crops where there may be possibilities are top fruit and cane and bush fruit, and some growers are already addressing this, but even here the areas of beneficial flora are along hedges or shelter-belts, where competition for moisture is less, or unlikely. Beneficial flora could perhaps be sown with the grass in alleys, but this has not been tested yet.

14. Areas specially "set-aside" on the farm and linked to margins along field edges and water-courses could be the most suitable means of achieving environmental benefits. Vegetable, strawberry and bulb crops are usually grown in arable rotations – field margins could link with those in adjacent arable crops.

15. Many of the horticultural crops, particularly vegetables are grown on valuable high-grade land. Buffer zones near water-courses have already been taken out of production and consultations are taking place regarding buffer zones near housing. Field margin biodiversity areas could perhaps combine with these buffer zones. However, if more areas were to be taken out of production and managed for biodiversity and compensation would be needed.

3.10 References

PESTICIDE USAGE SURVEYS. Reports are by Central Science Laboratories, Sand Hutton, York and a list of reports and some summaries can be viewed on the Internet URL http://www.csl.gov.uk. Copies of the more recent reports for England & Wales, or Great Britain are obtainable from Defra Publications, London SE99 7TP, data relating specifically to Scotland, from the Scottish Agriculture and Fisheries Department. Many of the older reports used in this study are no longer available.

ADAS (1985) *Narcissus Bulb Production. Booklet* 2150. MAFF (Publications), Alnwick, UK

DERKSEN DA, HARKER KN & BLACKSHAW RE (1999). Herbicide tolerant crops and weed population dynamics in western Canada. In: *Proceeding of Brighton Crop Protection Conference – Weeds* 1999, 417-424.

DEWAR AM, MAY MJ, WOIWOD IP, HAYCOCK LA, CHAMPION GT, GARNER BH, SANDS RJ, QI A & PIDGEON JD (2003). A novel approach to the use of genetically modified herbicide tolerant crops for environmental benefit. *Proceedings of the Royal Society of London*, B, 270, 335-340.

DOWNEY RK (1999). Gene flow and rape – the Canadian experience. In: *BCPC Symposium Proceedings No. 72: Gene flow and agriculture: relevance for transgenic crops.* British Crop Protection Council: Farnham 105-116.

FIRBANK LG & FORCELLA F (2000). Genetically modified crops and farmland biodiversity. *Science* **289**, 1481-1482.

FORCELLA F (1999). Weed seed bank dynamics under herbicide tolerant crops. In: *Proceeding of Brighton Crop Protection Conference – Weeds* 1999, 409-416.

HDRA (http://www.hdra.org.uk/research/ires_ofp.htm).

HORTICULTURAL DEVELOPMENT COUNCIL (HDC) (2001) *Practical weed control for nursery stock*. (eds J Atwood, M Scott & J Adlam)., East Malling, Kent, UK

IVANY JA (2002) Banded herbicides and cultivation for weed control in *potatoes (Solanum tuberosum* L.) *Canadian Journal Of Plant Science* **82**: 617-620

KNOTT CM (2002) Weed Control in Arable and Field Vegetable Crops. In: *Weed Management Handbook.*(ed. RL Naylor) 359-398. British Crop Protection Council, Blackwell Science Ltd., Oxford, UK

LAWSON HM (1976) The effects of spring-germinating weeds on narcissus. *Annals of Applied Biology* **83**, 324-327.

LAWSON HM & WISEMAN JS (1978) The effect of weeds on the growth and development of narcissus. *Journal of Applied Ecology* **15**, 257-272.

MARSHALL, E. J. P., V. K. BROWN, N. D. BOATMAN, P. J. W. LUTMAN, G. R. SQUIRE AND L. K. WARD. (2003). The role of weeds in supporting biological diversity within crop fields. *Weed Research*

NATIONAL CENTER FOR FOOD & AGRICULTURAL POLICY (NCFAP) (2003) *The value of herbicides in U. S. crop production* (eds LP Gianessi & S Sankula). NCFAP, Washington DC, USA.

NEILD JRA & PROCTOR JM (1962). Chemical weed control in potatoes *Procedings 6th British Weed Control Conference*: 697-712.

NELSON DC & THORESON MC (1981). Competition between potato (*Solanum tuberosum*) and weeds. *Weed Science* **29**: 672-677.

ORGANIC TOP FRUIT GROUP (2001) http://www.hri.ac.uk/site2/research/eastmall/organics/topfruitguidelines.pdf

ORSON J (2002). Gene stacking in herbicide tolerant oilseed rape: lessons from the North American Experience. *English Nature Research Report* No. 443, English Nature, Peterborough, UK

ROBINSON RA & SUTHERLAND WJ (2002) Post-war changes in arable farming and biodiversity in Great Britain. *Journal of Applied Ecology*, **39**,157-176.

THACKRAL KK, PANDITA ML, KHURANA SC & KALLOO G (1989) Effect of time of weed removal on growth and yield of potato. *Weed Research* **29**, 33-38.

VAN GESSEL MJ & RENNER KA (1990a) Redroot Pigweed (*Amaranthus retroflexus*) And Barnyardgrass (*Echinochloa crus-galli*) Interference In Potatoes (*Solanum tuberosum*) *Weed Science* **38**: 338-343

VAN GESSEL MJ & RENNER KA (1990b). Effect of soil type, hilling time, and weed interference on potato (*Solanum tuberosum*) development and yield. *Weed Technology* **4:** 299-305.

WATKINSON AR, FRECKLETON RP, ROBINSON RA & SUTHERLAND WJ (2000). Predicting biodiversity responses to GM-herbicide-tolerant crops. *Science* **289**, 1554-1556.

CHAPTER 4

HERBICIDES IN HORTICULTURE

4.1 Herbicides in horticulture

From 1930 weeds in a substantial area of cereals were controlled with sulphuric acid. Mineral oils were introduced in 1949 and tractor-vapourising oil (TVO) was used in carrots for many years until it was found to give taints in the processed crop. In the 1940s the first of the new, more selective herbicides were developed for cereals: nitrophenols (DNOC, dinoseb-ammonium, dinoseb) - now withdrawn; salts of phenoxy-acetic acids MCPA - still widely used today in some horticultural crops. Soil-acting herbicide simazine was introduced in 1956, and was used in fruit and other horticultural crops in the 1960s; other residual herbicides were developed later. The labour force decreased and farmers became dependent on herbicides, and the area (and yield) of cereals increased. As a result there was an increase in grass weeds and in the 1970s several grass-weed killers were developed - some for broad-leaved crops. Although herbicides continued to be developed for cereals, only a few were selective in vegetables, but several were suitable for use in orchards. Oilseed rape was grown in the 1970s and the area increased in the 1980s. Selective herbicides were introduced for rape (propyzamide, metazachlor) and these were also suitable for horticultural brassicas.

The availability of herbicides for other vegetables in the early 1970s and the development of mechanical harvesters enabled production of vegetables to progress from market garden to field scale production, in some cases for processing. Wide rows were no longer needed to accommodate tractor hoes and this meant that crop yields could be maximized by using narrow rows, with a more square planting arrangement.

Particular difficulties in control arise when the prevalent weeds are botanically related to the crop, e.g. where *Cruciferae* occur in brassica crops or *Compositae* in lettuce. There are often few, or no, herbicides selective in such circumstances.

Herbicide costs are not normally an issue for the grower except perhaps for the large-scale crops for processing with lower gross margins. The problem for most growers is the small range of herbicides available in future. The extent of herbicide development by Crop Protection companies in crops other than cereals is a reflection of crop area and there is thus a wide range of herbicides for oilseed rape and sugar beet. However, growers of many minor crops have few herbicides at their disposal, since development cost is high, sales small and a damage claim in a high value crop could be considerable. Reliance has been placed on materials approved for other crops. Resources for independent evaluation of herbicides in minor crops have also been reduced.

In addition to pesticide use approved on a label for major crops there is a UK system for Off-Label use in some situations. Specific Off-Label Approvals (SOLAs) may be granted by the UK Pesticide Safety Directorate, usually for a minor use. For edible crops, residues data are usually a requirement. Such pesticides are applied at growers risk and there is no guarantee of crop safety. These SOLAs are sought by growers and funded by growers levy, in the case of several for horticulture, from the Horticultural Development Council.

Under the 'Long Term Arrangements for Extension of Use' (LTAEU), an on-label use for a pesticide for one crop can sometimes be extrapolated to another, minor one, provided the crop morphology, harvest time and other factors are similar. For example, swedes can be extrapolated to turnips.

Both of these Off-Label arrangements are of tremendous benefit to growers, and without them some crops could either not be grown, or it would be uneconomic to do so.

For non-edible crops and plants, under the Off-Label Arrangements, pesticides approved for any growing crop may be used. For example, in HNS, bulbs and flowers, where no part of the plant or seed is to be consumed by humans or animals. This also applies to nursery fruit trees, bushes, canes, vines and strawberries before final planting out provided any fruit harvested within 12 months is destroyed, and that fruit is not present when applications are made.

In the past very few Maximum Residue Limits (MRLs) have been set nationally for herbicides for edible crops. Under the EC Review, pesticides which achieve listing on Annex 1 of directive 91/414/EEC will have MRLs set for the crop uses (usually major ones) which were supported through the review, and currently a 4 year period is then given to provide extra data for re-registration of existing (usually minor horticultural) uses. This will not be the case in future. There is now a Commission proposal to simplify and consolidate existing Community legislation on EU MRLs into one Regulation. The new European Food Safety Authority (EFSA) would have the role of assessing data and recommending MRLs, which would then be set at Community level. Member States would no longer be able to set national MRLs pending harmonised Community levels. However there is also a proposal that a default MRL of 0.01 mg/kg (the limit of determination (LOD); effectively zero) should apply unless specific data are available to support a different MRL – this regulation is forecast to come into force on 1 January 2005. This means there is very little time to submit MRL data.

Unless amendments can be negotiated into the proposal, there is likely to be a considerable impact on Horticulture - where no data are available, or where data were generated using old analytical techniques for some SOLAs. Important uses could be lost and it might not be possible to grow some crops.

Table 4.1 *Comparison of herbicide treated areas and GB crop area (Pesticide Usage Survey), crop value and gross margins (* J Nix, Farm Management Pocketbook, 2002; # UK Basic Horticultural Statistics 2002, Defra) for a range of some important horticultural crops*

Crop	Date last Pesticide Usage survey	GB Crop area ha last survey	% Herbicide treated area last survey	Crop value £/ha *2003	Gross Margin £/ha * 2003
Potatoes	2000	161,502	212	3,575 maincrop	1,600
Bulbs & flowers	2001	5,777	393	4,450#	N/A
Total vegetables	***1999***	***131,766***	***341***		
Brassicas	1999	34,743	164	3,600 cauliflower	1,100
Peas & Beans	1999	45,365	241	1,200 vining peas	960
Onions & leeks	1999	16,289	946 (split doses)	3,150 bulb onions	1,025
Carrots, parsnips & celery	1999	15,851	520 (split doses)	5,175 maincrop	1,425
Lettuce	1999	5,858	253	10,500	3,250
Total soft fruit	***2001***	***9,432***	***277***		
Strawberries	2001	3,765	341	13,500	4,750
Blackcurrants processing	2001	2,429	272	3,250	2,225
Raspberry	2001	1,530	272	11,250	4,800
Total top fruit	***2000***	***22,595***	***249***		
Dessert apples Cox	2000	8,314	340	5,650	3,475
Total HNS	***2001***	*7,806*	***269***	***4,333#***	***N/A***

A comparison, for a range of fruit and vegetables, (Table 4.1) of herbicide treated area as a percentage crop area indicates the number of passes required to try to produce a weed-free crop. There are more than nine herbicide applications for onions, over five for carrots. It shows that onion and carrot crops are the most vulnerable to weed competition and must be kept weed free and also that these crops are rather sensitive to some herbicides particularly at early growth stages, so lower, split doses are used early during the critical period for competition. Potatoes, with two applications, are less vulnerable to weed competition in comparison. However, the figures should also be considered in relation to the length of growing season – lettuce is a short-season crop, but longer-term control is required for perennial crops, soft and top fruit.

4.2 Herbicides for Horticulture in the Future

The EC Review 91/414 of pesticides registered in 1993, or before, has been undertaken by the European Commission to ensure that older pesticides meet modern safety standards. Many of the herbicides for horticulture are "old" but have been used without obvious adverse effects on consumer or environment for the last 25 years. Where there are concerns about water quality, dose rates have been reduced and the impact from field applications is less compared with run-off from hard surfaces.

Table 4.2 *List of active substances and products permitted in the UK, for the following 'Essential Uses' only, until 31 Dec 2007*

Active Substance	Crop Use
Cyanazine	Dry harvest & vining pea;
	Calabrese/Broccoli, Cauliflower, Cabbage
	Bulb Onion, Salad Onion, Leek
	Narcissi
Fenuron	Runner beans, Spinach
Fomesafen	Dry harvest and Vining Pea (spring sown) Broad Bean (spring sown)
	Dwarf French bean, Runner bean
Metoxuron	Carrots & parsnips
Pentanochlor	Celeriac, Celery, Carrot, Parsnip
	Ornamentals
	Parsley & Herbs (outdoor & protected)
Prometryn	Bulb & Salad Onion (outdoor)
	Leek (transplanted)
	Leek (direct drilled & transplanted)
	Carrot, Parsnip
	Celery, Parsley, Herbs, all (outdoor & protected)
Sodium mono-chloroacetate	Bulb & Salad Onion, Leek
	Cabbage,Brussels sprout, Calabrese/ Broccoli, Cauliflower
	Hops
	Raspberry, Blackberry, Loganberry, Hybrid berries
Terbacil	Herbs (outdoor & protected)
Terbutryn	Dry harvest, Vining, Edible Podded Pea, Broad Bean,

Many herbicide active substances in the review have not been supported by Agrochemical Companies, mainly for commercial reasons. The minor markets and the high cost of generating modern data packages for many of the older chemicals could not be justified. Thus several on-label registrations were revoked on 25 July 2003, many herbicides became unavailable before that date, and as a result SOLA's and extrapolations for minor crops for these herbicides will also cease. There will be a grower use-up period only until 31 December 2003.

Requests for derogations for 'Essential Uses' were made by Member States to the European Commission to continue use of a few active substances after 2003. Submissions had to include details of: economic impact on crop production if these actives were withdrawn, that there were no other alternatives and evidence that alternatives were being sought. The European Parliament voted to allow a few 'Essential Uses', the Commission then decided in June 2002 to extend the use of 49 pesticide active substances to continue until the end of 2007, to allow time to develop alternatives. For the UK, these included 9 key herbicides for vegetables (Table 4.2). However, there is no guarantee that these products will continue to be manufactured until 2007.

Growers have serious concerns about impending losses of herbicides in 2003 or, for those with 'Essential Use' derogations, 2007, and whether the minor uses in horticulture for those herbicides achieving Annex 1 status will be supported. Even where active substances are supported in the EC Pesticide Review not all uses will be supported. For example: chlorpropham in round 1 of the Review has been supported as a sprout suppressant in potatoes but only as a herbicide in flowers and bulbs. There are currently herbicide approvals for chlorpropham in 14 other crops including, importantly, lettuce. There are also concerns about losses resulting from the new Commission proposals on MRLs (Section 4.1) Where possible, applications for SOLAs will be made, and residues data generated (which takes 2 years).

The Horticulture Industry, through the levy body the Horticulture Development Council (HDC) have funded work on GAP Analysis (identification of future gaps in control of pests, diseases and weeds) for 35 fruit and vegetable crops, and in hardy nursery stock, bulbs, flowers etc. with the aim of prioritizing research work, SOLA applications and residues data URL http://www.hdc.org.uk.

EU harmonisation and 'Mutual Recognition' once a pesticide achieves Annex 1 status could mean that herbicides used in other Member States may become available in the UK, but this is still dependent on Crop Protection Companies.

The fundamental problem now is the high cost of registration and development by Crop Protection Companies relative to small sales for minor crops. This means that we can expect very few new pesticides, particularly broad-leaved weed killers, which, for reasons of safety, are more crop-specific.

Crop Protection Companies now consider all EU crops except wheat are of minor importance, but broad-leaved herbicides for wheat are usually damaging to broad-leaved crops. In the past there were spin-offs from soya herbicides to broad-leaved crops, but because of the development of herbicide-tolerance, soya is not included in primary herbicide screens. Development of Genetically Modified Herbicide-Tolerant minor crops seems unlikely in there near future because of EU consumer opposition. There is more optimism for fungicides, insecticides and graminicides because they can be used on a wide range of crop species. New herbicides are likely to be developed for brassicas as long as oilseed rape is an important crop unless Herbicide-Tolerant rape is grown, although these will not necessarily be safe for use in all horticultural brassicas.

A crisis threatens EU production of not only important high value crops grown on a small area, but some major ones as well. A study by the USA National Center for Food & Agricultural Policy (NCFAP, 2003) concluded that if US farmers employed an additional 7 million hand-weeders and increased mechanical cultivations, overall crop production would decline by 21%, and that herbicides are essential to maintain current yields. This is probably applicable to the UK as well.

Reliance on a narrowing range of active ingredients in a widening range of crops will increase the problem of developing tolerant weed flora and increase the risk of herbicide resistance occurring (see next section 4.3).

4.3 Resistance to a limited range of herbicides

Repeated use of a particular herbicide, or family of herbicides, it know to eventually lead to the possible development of herbicide resistance in previously susceptible species (Heap, 2001; Powles & Shaner 2001). In arable crops this has occurred with the so-called "fop" and "dim" graminicides and acetolactate synthase (ALS) inhibitors and the concept, mechanisms and implications of herbicide resistance are more fully reviewed elsewhere (Moss, 2002). Some of the well-documented resistant grass weeds from cereal crops are being carried over into the following horticultural crops, which emphasises the need to consider weed management (including resistance management) within the whole rotation. Of the important horticultural weeds identified in Table 2.6 (Chapter 2), groundsel acquired high levels of resistance within a relatively short time of triazine herbicides, such as simazine, being introduced (Frey *et al.,* 1999).

In addition to the several-fold increase in tolerance that is found when full resistance develops, it is possible that a gradual change in herbicide susceptibility may occur unnoticed, particularly where reduced doses of herbicide are applied. Subsequent generations of the weeds that survive, either through an evolving partial resistance or delayed emergence, may become less susceptible to the herbicide following regular use over several years. This "creeping resistance" from the gradual selection pressure of low input strategies may eventually lead to a level of herbicide resistance that results in failure of even a full rate of chemical (Gressel, 1995). Despite these concerns, there still havt been no examples of resistance reported so far from the regular use of reduce dose herbicide strategies for more than 20 years in carrots.

In any crop, the development of resistance is a serious problem, and the usual response is to turn to an alternative product with a different mode of action. However, in many horticultural crops where the range of available a.i's are more limited than in arable crops, such alternative herbicide options could be restrictive and likely to decline further in the future (Gillott, 2001). A limited number of alternative herbicides inevitably makes resistance management difficult to achieve. Studies in the USA have estimated the impact of the loss of important herbicides used in apple production and the potential resistance problems associated with growers being left with a single predominant replacement (Derr, 2001). For example, diuron is important for rotation with simazine for resistance management in apple orchards (both are still key products used on >10% of the crop in the UK, Table 4.7), so the loss of either product would compromise the resistance management strategy (Derr, 2001).

4.4 Non-chemical alternatives to herbicides

It is possible to control weeds in some horticultural crops by non-chemical methods and this is discussed in Chapter 3. Stale seedbeds, flame weeding, mechanical hoe, tine and brush weeders, hand weeding and polythene mulch are all methods that are employed. In close row crops e.g. baby carrots, peas and self-blanching celery, non-chemical weed control is more difficult.

In organic fruit and vegetables yields expected are half those for conventional production, although sometimes yields are too low, or quality too poor to make harvesting worthwhile.
An example strategy for organic carrot production (Tei *et al.,* 1999) (URL http://www.agr.unipg.it/ewrsveg) is:

- Stale seedbed
- Sown on single rows 0.5 m width
- Pre-emergence flaming (50 to 80 kg gas ha^{-1})
- Crop 2-3 leaves brush weeding
- 5 to 8 passes intra-row mechanical control (hoeing, rotary cultivation, finger weeding)
- Hand weeding on 'weed beds' 100-500 hours ha^{-1}

In most horticultural crops the costs of alternative weed control methods are higher than for weed control with herbicides. Hand labour has now become expensive: Nix (2002) in the Farm Management Pocketbook estimates £191.49/week for a 19 year-old to £258.57/week for a Grade 1 worker in 2003. There are no details for costs of weeding, and on conventional farms hand labour is used for transplanting and harvesting, but only for weeding as a rescue operation, for example removing volunteer potatoes in dwarf French beans where there is a risk of a contaminant problem. Hand labour is also scarce - producers of horticultural crops are dependent on workers from abroad. It was estimated in the NCFAP study in the USA (NCFAP, 2003) that most fruit and vegetable crops were projected to use 50 to 148 hours of hand weeding per hectare. All these methods are also aimed at controlling all weeds and repeated cultivations may, in addition, have adverse effects on soil structure and ground-nesting birds. Flame and steam weeding will have negative effects on invertebrates.

4.5 Current Herbicide Use

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For most edible crops only a limited range of herbicides is available, and growers have serious concerns about impending losses (in blue text) in 2003 or, for those 'Essential Uses' with derogations only until the end of 2007 (Table 4.2, section 4.1). Whether the minor uses of those herbicides achieving Annex 1 status in the EC Review will be supported by Agrochemical companies is also a major concern. Retailers also impose restrictions on some herbicides used in some crops, where there could be consumer concerns (real or perceived). There is more choice for non-edible crops and plants and pesticides approved for any growing crop may be used in HNS, bulbs and flowers, where no part of the plant or seed is to be consumed by humans or animals. Thus a number of herbicides can legally be used as shown in 'other herbicides' underneath Tables 4.5 and 4.8.

4.5.1 Potatoes (Table 4.3)

Potatoes are grown on ridges on wide rows; stone and clod separators are now frequently used. Weeds growing in rows of collected stones and clods are controlled with foliar applied herbicides.

Table 4.3 *Usage of herbicides on potatoes grown in Great Britain, 2000 (spray hectares). Herbicides used on 10% of the crop or more in red; herbicides not supported in the EC Review in blue.*

Herbicides	**Potatoes**
Crop area	161,502
Total weeds	
Glyphosate	23,602
Diquat/paraquat	68,672
Paraquat	53,839
Grasses	
Clodinafop-propargyl	290
Cycloxydim	2,791
Propaquizafop	2,462
Broad-leaved weeds	
Cyanazine	1,190
Clopyralid	8
Linuron & monolinuron	66,150
Mecoprop	1,482
Metribuzin	41,619
Pendimethalin	243
Herbicides area treated (ha) excl diquat & sulphuric acid (desiccants)	**342,032**
Herbicide excl desiccants as % area grown	**212**

Early potatoes produced under protection of clear floating plastic film or woven fleece are sprayed early pre-emergence before covering, but weeds which escape control cannot be removed with late pre-emergence herbicides or with cultivations.

Table 4.3 shows the range of herbicides used on the potato area in 2000, the most recent survey year published. It does not include desiccants sulphuric acid and diquat. The targets are broad-leaved weeds, controlled pre-emergence with contact-acting total herbicides paraquat or diquat/paraquat, usually applied in tank-mix with residual linuron. Ware potatoes receive at least 2 sprays, a total herbicide (diquat/paraquat or paraquat) and a residual linuron (15% of the herbicide treated area) or metribuzin (11%). Metribuzin and/or a small area of bentazone is applied post-emergence. Grower uptake of the new sulfonylurea for rimsulfuron, which has systemic foliar activity, controls cleavers and volunteer oilseed rape has, so far, been small. Graminicides are only used on a small area of potatoes.

4.5.2 Vegetables (Table 4.4)

A combination of non-selective herbicides and cultivations removes weeds before planting. For spring crops over-wintered weeds include autumn germinating cleavers and black-grass.

Most crops are treated with a residual pre-emergence herbicide unless it is not safe to the crop (on sands) or activity would be reduced (on organic soils).

Post-emergence there is more risk of crop damage and possible quality reduction. Damage to foliage of herbs, spinach or salad onions for example, may render them unmarketable. In some seasons there are also few spray windows of suitable weather, and Minimum Harvest Intervals (MHI) must be observed. A post-emergence herbicide is used for weed species, which are not susceptible to the pre-emergence product.

Onions and carrots are sprayed with herbicide programmes of repeat low doses to control weeds in these uncompetitive crops.

Table 4.4 *Usage of herbicides on vegetable crops grown in Great Britain, 1999 (spray hectares). Herbicides used on 10% of the crop or more in red; herbicides not supported, or which did not achieve Annex 1 listing in the EC Review in blue; herbicides no longer manufactured or withdrawn in green.*

Herbicides	**Brassicas etc.**	**Root crucifers**	**Peas & beans**	**Onions & leeks**	**Carrots etc.**	**Lettuce endive etc**	**Sweetcorn**	**Other root vegetables**	**Cucurbits**	**Other vegetables**	**All crops**
Crop area	**34,743**	**4,237**	**45,365**	**16,289**	**15,851**	**5,858**	**1,690**	**1,760**	**1,112**	**4,861**	**131,766**
Herbicides Total weeds											
Diquat/paraquat	998	67	1,335	2,649	2,442	776	60	200	268	625	**9,419**
Glyphosate	4,234	263	14,941	4,694	3,931	595	404	317	419	1,638	**31,437**
Paraquat	473	135	428	1,225	372	50	14	8	55	709	**3,469**
Herbicides grasses											
Cycloxydim	338	170	2,356	922	75	0	0	9	0	0	**3,871**
Fluazifop-P-butyl	0	0	145	2,689	1,958	0	0	86	0	0	**4,877**
Propaquizafop	13	0	0	5,708	4,231	0	0	63	0	392	**10,407**
Herbicides Broad-leaved & grass weeds											
Atrazine	0	0	0	28	0	0	2,085	0	0	0	**2,113**
Bentazone	141	0	1,132	3,089	0	0	0	0	0	0	**4,363**
Bentazone/MCPB	0	0	15,907	0	0	0	0	0	0	0	**15,907**
Chloridazon	0	0	0	9,606	0	0	0	4	0	4	**9,614**
Chloridazon/propachlor	0	0	0	1,417	0	0	0	0	0	0	**1,417**
Chlorpropham	0	0	0	4,019	37	3,254	0	0	0	179	**7,489**
Chlorthal-dimethyl	553	0	153	814	0	0	0	0	22	2	**1,544**
Clopyralid	1,835	65	0	2,979	0	0	15	895	0	115	**5,903**
Cyanazine	647	0	26,526	14,911	0	0	0	0	0	0	**42,085**
Ethofumesate	0	0	0	2,035	0	0	0	1,341	0	10	**3,386**
Fluroxypyr	0	0	0	8,275	0	0	0	0	0	0	**8,275**
Fomesafen	0	0	1,549	0	0	0	0	0	0	0	**1,549**
Fomesafen/terbutryn	0	0	4,843	0	0	0	0	0	0	0	**4,843**
Ioxynil	7	0	0	45,931	26	0	0	0	0	1	**45,966**
Linuron	0	0	0	1,105	28,992	0	0	12	17	624	**30,750**
MCPA/MCPB	0	0	10,766	0	0	0	0	0	0	0	**10,766**
MCPB	0	0	3,445	0	0	0	0	0	0	0	**3,445**
Metamitron	0	0	0	0	0	0	0	2,195	0	112	**2,307**
Metazachlor	13,937	2,261	0	37	26	0	0	0	0	0	**16,261**
Metoxuron	0	0	0	0	17,056	0	0	0	0	0	**17,056**
Metribuzin	0	0	0	0	2,029	0	0	0	0	0	**2,029**
Monolinuron	0	0	1,049	70	0	0	0	0	0	10	**1,129**
Pendimethalin	853	0	138	17,114	10,683	316	138	0	0	155	**29,397**
Pentanochlor	0	0	0	0	5,450	0	0	0	0	13	**5,463**

Table 4.4 *Usage of herbicides on vegetable crops grown in Great Britain, 1999 (spray hectares) (cont)*

	Brassicas etc.	Root crucifers	Peas & beans	Onions & leeks	Carrots etc.	Lettuce endive etc.	Sweetcorn	Other root vegetables	Cucurbits	Other vegetables	All crops
Phenmedipham	0	0	0	11	0	0	0	3,686	0	49	**3,746**
Prometryn	7	0	5	3,512	2,922	0	0	1	0	101	**6,548**
Propachlor	12,238	1,076	47	19,224	26	5,820	0	0	0	248	**38,678**
Propyzamide	0	0	0	0	0	3,759	0	0	20	224	**4,003**
Pyridate	1,126	0	0	153	0	0	738	0	0	0	**2,016**
Simazine	0	0	210	0	0	0	4	0	0	1,013	**1,226**
Sodium monochloroacetate	711	0	0	1,053	0	0	0	0	0	0	**1,764**
Terbuthylazine/terbutryn	0	0	22,428	0	0	0	0	0	0	0	**22,428**
Trifluralin	16,668	3,220	98	0	520	241	0	0	0	1,469	**22,217**
Other herbicides	2,127	257	1,837	859	1,633	3	655	1,112	29	1,267	**9,777**
Herbicides area treated (ha)	**56,906**	**7,514**	**109,339**	**154,130**	**82,409**	**14,814**	**4,112**	**9,927**	**830**	**8,960**	**448,939**
Herbicide as % area grown	**164**	**177**	**241**	**946**	**520**	**253**	**244**	**564**	**75**	**184**	**341**

Other herbicides includes aziprotryne, benazolin/clopyralid, benazolin/dimefuron, bromoxynil, bromoxynil/prosulfuron, chlorbufam/chloridazon, chlorpropham/diuron/propham, chlorpropham/fenuron, chlorpropham/pentanochlor, cyanazine/pendimethalin, desmedipham/ethofumesate/phenmedipham, desmedipham/phenmedipham, desmetryn, dichlobenil, diquat, ethofumesate/phenmedipham, glufosinate-ammonium, isoxaben, isoxaben/terbuthylazine, lenacil, MCPA, mecoprop, pendimethalin/prometryn, sethoxydim, simazine/trietazine, tebutam, terbacil, terbutryn/trietazine, triflusulfuron-methyl and unspecifie

4.5.3 Outdoor bulbs and outdoor flowers (Table 4.5)

The very large proportion of narcissus bulbs grown greatly influences the total use of herbicides on all outdoor bulb and flower crops. Bulbs are grown on ridges and cultivations play some part in weed control. Cultural methods can be used to control some weed species, such as volunteer potatoes but this is often ineffective. Chemical control is particularly required during the early season to control weeds that grow up with the bulb crop, causing serious competition.

Table 4.5 *Usage of herbicides (ha) on outdoor bulb and flower crops grown in Great Britain 2001. Herbicides used on 10% of the crop or more in red; herbicides not supported, or not achieving Annex 1 listing in the EC Review in blue; herbicides no longer available in green.*

Herbicides	**Outdoor bulbs**	**Other flowers for cutting**	**Total all outdoor bulb and flower crops**
Crop area	**5,237**	**540**	**5,777**
Total weeds			
Diquat	147	.	**147**
Diquat/paraquat	2,043	.	**2,043**
Glyphosate	5,104	208	**5,313**
Paraquat	916	67	**984**
Grasses			
Fluazifop-P-butyl	469	.	**469**
Broad-leaved weeds			
Bentazone	1,950	.	**1,950**
Chlorpropham	1,604	4	**1,608**
Chlorpropham/linuron	179	3	**182**
Cyanazine	2,275	.	**2,275**
Diuron	536	.	**536**
Isoxaben	157	.	**157**
Lenacil	1,072	.	**1,072**
Linuron	2,680	.	**2,680**
Metamitron	1,911	.	**1,911**
Pendimethalin	531	22	**552**
Simazine	274	70	**345**
Herbicides area treated (ha)	**22,134**	**539**	**22,673**
Herbicides as % area grown	**422.6**	**99.8**	**392.5**

The 2001 survey (Table 4.5) showed that glyphosate was the most extensively used herbicide on bulbs, accounting for 23% of the herbicide treated area. This was followed by linuron (12%), cyanazine, (10%), diquat/paraquat (9%), bentazone (9%) and metamitron (9%). Pentanochlor (Essential Use only until Dec 2007) was used for a small area. Some of the more widely used active substances occur in more than one formulation.

On other flowers for cutting (Table 4.5), glyphosate was applied to 39% of the herbicide treated area, The next most widely used herbicides were simazine (13%), paraquat (12%) and pendimethalin (4%).

For bulbs, total herbicides glyphosate or diquat/paraquat are extensively used to clean-up weeds before planting, to clean up planted ridges before crop emergence, and in the dormant season between years. Glyphosate and clopyralid are applied, sometimes with a weed-wiper, to control thistles or suppress volunteer potatoes, but not in the growing crop. Broad-leaved weeds are controlled with residual herbicide linuron alone, or in the 2001 survey with a product containing chlorpropham/linuron mixture. This product is no longer manufactured, so now a tank-mix of chlorpropham + linuron is used pre-emergence and it is effective on knotgrass and other polygonums. Monolinuron featured in the 1997 survey but later, did not achieve Annex 1 listing in the EC Review and was revoked. Diuron is used before crop-emergence to control willowherbs.

However, these residual herbicides are not effective against annual small nettle, an important and invasive weed, and knotgrass sometimes escapes control, so cyanazine is applied during late winter/early spring, post-emergence of the crop when height is 7-10cm. Chlorpropham + linuron, and cyanazine are effective on groundsel. Isoxaben + metamitron can also be used post-crop emergence although only metamitron has contact action, controlling fat-hen and annual meadow-grass. Post-flowering treatment with a tank-mix of residual herbicides isoxaben + metazachlor is used to control several annual weeds including black-grass, annual meadow-grass, mayweeds and groundsel (possibly simazine-resistant strains) which can be a particular problem in the second and third year of cropping. The loss of post-emergence cyanazine, which cannot be used on bulbs after 2007, will leave a large gap in weed control for bulbs and charlock and small nettle will not be controlled unless an alternative is found.

For other flowers for cutting, total herbicide glyphosate is used pre-planting/sowing. Simazine and pendimethalin were the most widely used residual herbicides in the 2001 survey, and also chlorpropham, alone or in mixture with linuron. Small areas were treated with chlorthal-dimethyl, which is expensive, and also with propachlor. Currently there is little information for growers on crop safety of herbicides on the very wide range of flower species thus there are trial and error applications.

4.5.4. Soft fruit (Table 4.6)

Bush and cane fruit have a dormant period in winter when they are less vulnerable to damage from total herbicides. All weeds are targets in soft fruit and non-selective “total” herbicides are widely used - they are the main method of weed control for the very small area of vineyards.

Simazine is still the major residual herbicide in tolerant soft fruit crops (Table 4.6) – it is cheap and controls most annual broad-leaved weeds and grasses. However, programmes were developed later, partly to control simazine - and paraquat – resistant species. In soft fruit simazine can be part of a programme with: dichlobenil, oxadiazon and diuron (blackcurrants), with napropamide, isoxaben, bromacil, oxadiazon (raspberries) and napropamide, pendimethalin, isoxaben, propyzamide (strawberries) and several of these control perennial weeds as well. The 2001 Pesticide Usage survey shows this (Table 4.6).

The largest herbicide use in 2001 was for strawberries, but some paraquat was used to control strawberry runners as well as weeds. Strawberries are the only soft fruit where there is an overall application of a contact-acting herbicide - phenmedipham is used for control of seedling weeds. Thistles are targeted with translocated herbicide clopyralid. The 2001 survey showed that selective graminicide fluazifop-p-butyl was needed to control grass weeds in strawberries as well as residuals propyzamide or simazine. Graminicides were rarely used in other crops probably because the non-selective weed killers fulfilled this requirement.

Table 4.6 *Usage of pesticides (hectares) on soft fruit crops grown in Great Britain, 2001. Herbicides used on 10% of the crop or more in red; herbicides not supported or which did not achieve Annex 1 listing in the EC Review in blue.*

Herbicides	**Strawberry**	**Blackcurrant fresh market**	**Blackcurrant processing**	**Redcurrant & whitecurrant**	**Gooseberry**	**Raspberry**	**Blackberry**	**Hybridberry**	**Vine**	**All crops**
Crop area	**3,765**	**254**	**2,429**	**169**	**258**	**1,530**	**107**	**175**	**754**	**9,432**
Total weeds										
Diquat/paraquat	1,173	36	782	11	38	794	53	31	.	**2,918**
Glufosinate-ammonium	559	10	381	6	8	205	9	4	146	**1,328**
Glyphosate	346	18	714	6	22	78	3	32	566	**1,784**
Paraquat	954	39	221	17	48	531	20	23	178	**2,031**
Grasses										
Fluazifop-P-butyl	661	9	54	10	10	55	4	4	.	**806**
Broad-leaved & grasses										
Bromacil	19	4	.	1	.	194	28	30	.	**277**
Chlorthal-dimethyl	119	.	.	.	.	17	.	1	.	**137**
Clopyralid	789	1	.	.	7	68	.	.	.	**866**
Dichlobenil	.	43	1,393	32	74	112	7	25	.	**1,685**
Diuron	28	3	443	4	19	.	.	.	19	**516**
Isoxaben	1,063	22	156	20	57	206	8	14	.	**1,547**
Lenacil	216	.	.	.	.	8	.	2	.	**226**
MCPB	6	4	140	.	5	13	.	1	.	**169**
Napropamide	1,353	19	103	4	9	503	47	28	.	**2,068**
Oxadiazon	15	27	464	6	16	170	2	8	26	**734**
Pendimethalin	1,212	20	99	14	43	148	28	18	.	**1,582**
Phenmedipham	643	.	.	.	.	.	.	.	.	**643**
Propachlor	900	3	.	1	4	18	.	.	.	**926**
Propyzamide	573	52	172	9	24	109	10	7	.	**954**
Simazine	1,869	65	1,370	21	52	661	26	27	21	**4,113**
Sodium monochloroacetate	.	.	10	.	.	168	1	2	.	**181**
Herbicide area treated (ha)	**12,848**	**384**	**6,596**	**165**	**467**	**4,159**	**247**	**258**	**968**	**26,092**
Herbicide as % area grown	**341**	**151**	**272**	**98**	**181**	**272**	**231**	**147**	**128**	**277**

[1]Other herbicides include 2,4-D, 2,4-D/dicamba/mecoprop, 2,4-D/dichlorprop/MCPA/mecoprop, amitrole, asulam, atrazine, bromoxynil/ioxynil, clopyralid/triclopyr, cycloxydim, dicamba/MCPA/mecoprop-P, diquat, ethofumesate, fluroxypyr, MCPA, mecoprop, metsulfuron-methyl, propaquizafop, sethoxydim, tepraloxydim, trifluralin and unspecified herbicides.

4.5.5 Orchard crops (Top fruit) (Table 4.7)

Like soft fruit, all weeds are targets in top fruit. Docks, nettles, thistles, cleavers, bindweed, willowherb, grasses, brambles, other woody weeds and triazine-resistant species (groundsel) were mentioned in the survey.

The tree base must be kept weed-free during the growing season to avoid competition for moisture and nutrients. In organic orchards with poor weed control, trees suffer from nitrogen deficiency. This means that the majority of crops receive some degree of treatment, with susceptible crops, such as Cox apples and pears, receiving the most treatments (3) in 2000. Cox apples are now being replaced with other varieties.

The most recent survey, in 2000, showed simazine was still the most widely used residual herbicide for annual weeds. Perennial broad-leaved weeds were controlled with combinations of cereal 'hormone' herbicides: dicamba, MCPA, mecoprop and dichlorprop (not supported in the EC Review and now replaced with mecoprop P and dichlorprop P respectively). There was wider use of non-selective total herbicides than in soft fruit, mainly glyphosate, which is cheap.

Table 4.7 *Usage of herbicides (spray hectares) on top fruit crops grown in Great Britain, 2000. Herbicides used on 10% of the crop or more in red; not supported or which did not achieve Annex 1 listing in the EC Review in blue.*

Herbicides	**Dessert apples**		**Culinary apples**		**Pears**	**Cider apples & Perry pears**	**Plums**	**Cherries**	**Other top fruit inc. nuts**	**Total all top fruit**
	Cox	**Others**	**Bramley**	**Others**						
Crop area	**4,542**	**3,772**	**3,864**	**254**	**2,555**	**5,652**	**1,316**	**498**	**142**	**22,595**
Total weeds										
Diquat/paraquat	241	213	93	53	120	83	11	59	.	**873**
Glufosinate-ammonium	1,295	977	956	40	907	418	172	154	1	**4,919**
Glyphosate	4,010	3,096	2,443	226	2,253	3,006	590	245	85	**15,954**
Paraquat	148	180	48	3	95	1,271	55	.	23	**1,822**
Broad-leaved weeds & grasses										
2,4-D	517	651	352	11	215	163	7	31	1	**1,947**
2,4-D/dichlorprop/MCPA/mecoprop	1,294	956	1,123	21	798	41	110	21	68	**4,433**
Amitrole	1,153	755	952	15	921	155	46	74	.	**4,071**
Dicamba/MCPA/mecoprop	1,115	874	718	54	578	237	6	36	.	**3,617**
Dicamba/MCPA/mecoprop-P	704	382	355	22	347	1,082	26	22	1	**2,939**
Diuron	1,155	872	665	61	543	450	8	15	.	**3,770**
Pendimethalin	660	465	256	21	224	84	87	99	.	**1,895**
Propyzamide	460	235	124	10	103	.	89	63	.	**1,084**
Simazine	2,161	1,541	1,044	61	883	1,968	128	12	53	**7,850**
Herbicide area treated (ha)	**15,443**	**11,474**	**9,241**	**653**	**8,092**	**8,957**	**1,352**	**890**	**255**	**56,356**
Herbicides as a % crop area	**340**	**304**	**239**	**257**	**317**	**158**	**103**	**179**	**180**	**249**
Other herbicides used include clopyralid/triclopyr, fluazifop-**p**-butyl, fluroxypyr, isoxaben, MCPA, MCPB, mecoprop-P, oxadiazon, triclopyr										

4.5.6 Hardy Nursery Stock (Table 4.8)

In the most recent survey of Hardy Nursery Stock in 2001, herbicides were used on over 94% of roses, 90% of fruit stock, 74% of ornamental trees, 65% of shrubs etc. and 59% of both mixed areas and Christmas trees. Usage of herbicides was most intensive on treated herbaceous plants, which received five sprays, seven products but 47%, probably the more sensitive species, were not treated. Fruit stock also received nearly 5 herbicide sprays. Christmas trees received the lowest number of herbicide applications with only two sprays.

Table 4.8 *Usage of pesticides on hardy nursery stock grown in Great Britain, 2001 (spray hectares). Herbicides used on 10% of the crop or more in red; herbicides not supported or which did not achieve Annex 1 listing in the EC Review in blue*

Herbicides	**Fruit stock**	**Roses**	**Ornamental trees**	**Shrubs etc.**	**Herbaceous plants**	**Mixed areas**	**Christmas trees**	**All crops**
Crop area	**512**	**592**	**1,839**	**359**	**364**	**1,556**	**2,584**	**7,806**
Total weeds								
Diquat/paraquat	99	30	1,187	25	66	383	.	**1,791**
Glufosinate-ammonium	90	3	633	7	89	305	1	**1,127**
Glyphosate	26	48	657	221	98	843	2,283	**4,175**
Paraquat	115	107	416	36	10	305	83	**1,072**
Grass weeds								
Fluazifop-P-butyl	.	5	12	.	20	23	11	**71**
Broad-leaved (& grasses)								
Atrazine	.	341	14	8	.	9	297	**669**
Clopyralid	216	163	11	.	18	42	309	**760**
Cyanazine	.	.	.	.	17	.	121	**138**
Dichlobenil	21	.	.	.	.	48	60	**128**
Diuron	8	30	65	3	14	139	738	**998**
Isoxaben	335	99	393	10	157	809	167	**1,971**
Lenacil	.	4	.	17	75	46	.	**142**
Metazachlor	164	536	516	63	33	317	14	**1,643**
Napropamide	100	.	15	.	.	45	13	**173**
Oxadiazon	69	26	237	35	.	647	129	**1,143**
Pendimethalin	222	.	208	33	.	.	448	**911**
Phenmedipham	500	70	12	2	.	50	6	**639**
Propachlor	63	.	60	.	83	.	.	**206**
Propyzamide	73	46	187	1	82	171	324	**884**
Simazine	355	437	421	42	1	145	523	**1,923**
Herbicide area treated	**2,513**	**2,058**	**5,097**	**547**	**804**	**4,477**	**5,537**	**21,032**
Herbicides as a % crop	**491**	**348**	**277**	**152**	**221**	**288**	**214**	**269**

[1]Other herbicides include 2,4-D, amitrole, amitrole/2,4-D/diuron, amitrole/diquat/paraquat/simazine, bromacil, bromoxynil, clopyralid/triclopyr, dicamba/MCPA/mecoprop, dicamba/MCPA/mecoprop-P, diflufenican/trifluralin, diquat, diuron/paraquat, isoproturon, isoxaben/trifluralin, linuron, MCPA, mecoprop-P, metamitron, metsulfuron-methyl, propaquizafop, pyridate, sethoxydim, triclopyr and trifluralin.

In 2001 glyphosate, used mainly in Christmas trees, was the most frequently used herbicide on 20% of the treated area, isoxaben 9%, simazine 9%, diquat/paraquat 9% and metazachlor on 8%. Isoxaben was the most popular herbicide in mixed areas, fruit stock and herbaceous plants, metazachlor in roses and ornamentals and simazine on Christmas trees, roses and ornamentals. In the 2001 survey, in fruit stock, phenmedipham, and clopyralid, were used post-emergence for weeds escaping control with pre-emergence simazine or isoxaben. In roses, metazachlor, simazine and atrazine were the most widely used residual herbicides, with metazachlor targeting groundsel, which was perceived as resistant to triazines. In ornamentals metazachlor, simazine, isoxaben, oxadiazon and others were the most popular residual herbicides. Total herbicides, glyphosate and paraquat, were used on beds prior to standing down plants in containers in "mixed areas". A very wide range of herbicides were used on the container surface because of the diversity of crop species, but isoxaben and oxadiazon were the most widely used, to control bittercress, but oxadiazon has a major weakness on common chickweed (Appendix 9). Glyphosate was used in nearly all the Christmas tree crop, and other important residual herbicides were diuron, which controls willowherb, simazine, atrazine and clopyralid (thistles) was also widely used.

Simazine and atrazine may not achieve Annex 1 listing in the EC Review and even if Essential Uses are granted, they will be lost probably in 2007. Diuron is also under threat.

4.6 Changes in herbicide use between 1977 and 2001

Herbicide usage surveys were carried out more frequently for potatoes (in the arable crops survey) than for other vegetable, fruit and ornamental crops. Years of surveys did not necessarily coincide, so comparisons between crops/years are not possible. The majority of the herbicide active substances used in horticultural crops has remained unchanged since the 1970's, for example terbutryn/terbuthylazine and MCPB for peas; cyanazine for peas, onions and brassicas; ioxynil for onions; trifluralin and propachlor for brassicas; simazine for topfruit and soft fruit. Fomesafen was one of the very few active substances introduced specifically for a UK horticultural crop.

Cereal "hormone" herbicides are not tolerated by many broad-leaved species. Sulfonylureas are widely used in cereals now but only two are available for horticultural crops, rimsulfuron for potatoes and until recently prosulfuron for sweetcorn (a spin-off from the French maize market) but approval has now lapsed.

The first post-emergence graminicides for broad-leaved crops were developed in the 1970's, to control volunteer cereals, wild oats and blackgrass and there have been several more since. The newer ones, propaquizafop and tepraloxydim, have claims for some control of annual meadow-grass. Tri-allate had a recommendation for several vegetables but will not be manufactured after 2003.

The introduction of the Specific Off-label Approval (SOLA) scheme has enabled growers to use programmes with a wider range of herbicides to control problem weed species

There have been many losses of useful herbicides: TCA, dinoseb, methazole, tebutam, desmetryne, monolinuron in the past and several more will go (in blue text in the Tables). It is possible that in 2003, atrazine and simazine will not achieve Annex 1 status. Perhaps a few "Essential Uses" may be granted for a limited time period. The loss of simazine would affect the viability of several crops.

4.6.1 Potatoes (Table 4.9)

In the past, common couch was one of the main weed problems in potatoes but the crop area has shifted to lighter soils where it is less likely to occur. In the Scottish seed crop, potato volunteers are a problem. Most herbicide applications are for control of broad-leaved weeds, in particular cleavers, reported to be increasing (possibly a legacy from cereals). Species such as creeping thistle and coltsfoot can be problems in maincrop potatoes.

Potatoes were traditionally regarded as a cleaning crop and in the past weeds were controlled with repeated cultivations, which caused root damage and some yield loss. Now weed control is mainly achieved with herbicides. Herbicide use in potatoes increased considerably to two applications in 2000 from one application in 1974, when cultivations of ridges were used, but there are signs that cultivations are becoming popular again. Recently environmental concerns and the need to examine costs have generated renewed interest in mechanical weed control and new methods may appear attractive to growers on weedy land, especially where highly organic soil limits herbicide options. These mechanical methods are often integrated with chemical control.

Paraquat, available since the late 1950's was the main herbicide used in 1974, but now other total herbicides are used as well: diquat/paraquat and glyphosate. Total herbicides were, and still are, used to kill weed seedlings emerging before the crop. Damage to any emerged potatoes is often only temporary. Diquat/paraquat and paraquat were very widely used pre-crop emergence in 1998 and 2000, with an increase in paraquat in 2000. They are still used in tank-mixes with residual herbicides linuron and monolinuron.

Linuron and monolinuron (introduced in the 1960s) alone or in mixtures were the main residuals used in 1977 and continued to be popular in 1998 and 2000. Linuron also has contact activity but causes crop effects. Monolinuron became less popular because of cost, and it was revoked in 2000, with a grower use-up period untl September 2001, following the failure to achieve Annex 1 status in the EU Review. Linuron's main weakness is on fumitory.

Metribuzin was introduced in 1973 and has been widely used pre- and post- crop emergence for ware potatoes. It has contact and residual activity, and is the most persistent of the currently recommended residual herbicides. Metribuzin controls oilseed rape volunteers Appendix 1), but there are varietal restrictions especially post-emergence of the crop. It was the most popular herbicide in 1998 but there was a reduction in use in the 2000 survey and now it is only used for 0.1% of the herbicide treated area.

Table 4.9 *Usage of herbicides (spray hectares) on total potato area (ware and seed) grown in Great Britain, 1977 - 2000. Desiccants sulphuric acid, diquat, glufosinate ammonium excluded. Herbicides used on 10% of the crop or more in red; herbicides not supportedor lost in the EC Review in blue.*

Crop year	**1977**	**E&W 1988**	**E&W 1990**	**1992**	**1994**	**1998**	**2000**
Crop area	**213,893**	**139,017**	**138,687**	**169,031**	**154,851**	**158,382**	**161,502**
Herbicides Total weeds							
Glyphosate		617	2,239	6,581	4,071	24,766	23,602
Diquat/paraquat				28,113	33,805	67,206	68,672
Paraquat	97,237	45,703	50,858	70,869	82,924	37,268	53,839
Herbicides Grasses							
Cycloxydim				652	1,969	2,251	2,791
Propaquizafop						2,462	2,462
Sethoxydim		822	2,012				
Herbicides Broad-leaved weeds							
Bentazone			6,316	4,456	4,516	8,159	
Cyanazine		1,322		10,004			1,190
Clopyralid							8
Linuron	#78,924	23,816	#	46,014	37,779	51,142	66,150
Metribuzin	37,259	38,947	51,901	53,342	61,826	68,140	41,619
Monolinuron/paraquat		25,526	#				
Pendimethalin		2,208	1,075	130	1,163	266	243
Terbutryn/terbuthylazine		9,805	13,632	14,582	10,907		
Herbicide area treated (ha)	**200,392**	**172,015**	**204,663**	**281,759**	**298,702**	**358,979**	**342,032**
Herbicide as % area grown	94	124	147	167	193	227	212
# monolinuron and linuron alone and in mixtures no separate data							

These residuals controlled most species except cleavers and later, contact-acting bentazone, also with varietal retrictions, was used (for ware crops only) post-emergence where they occurred. The sulfonylurea rimsulfuron was registered in 1997 for the ware crop. Rimsulfuron has systemic foliar activity, is safe on all varieties and controls cleavers, volunteer oilseed rape and a range of late emerging broad-leaved and grass weeds but grower uptake has so far been limited. Since the last survey, pre-emergence clomazone, which controls cleavers and a few other species, was approved in 2002.

Hence it is now possible to control all the common broad-leaved weeds in ware potatoes, but the options for the seed crop are limited because any effects on foliage caused by the post-emergence herbicides mask symptoms of virus and are not approved.

Post-emergence graminicides are applied to only a small percentage of the crop, and now most growers rely on glyphosate, applied pre-harvest or in stubble of a preceding cereal crop to reduce perennial grass weed problems.

4.6.2 Vegetables (Table 4.10)

In 1981 and 1986 pesticide usage was only surveyed for England and Wales and the 1991 survey for Scotland is not available.

Table 4.10 *Treated area in vegetables (ha) from 1977 – 1999 for the top ten herbicides for broad-leaved-weed control; the top herbicide for grass weeds; the top for total weeds*

# 1977 GB	1981 E&W	1986 E&W	1991 GB	1995 GB	1999 GB
Broad-leaved weeds					
dinoseb 42,848	terbutryn/ terbuthylazine 42,392	propachlor 33,691	propachlor 39,372	cyanazine 42,772	ioxynil 45,966
linuron 33,660	propachlor 34,611	linuron 29,286	linuron 33,526	propachlor 39,524	cyanazine 42,048
terbutryn/ terbuthylazine 29,732	trietazine/ simazine 28,728	terbutryn/ terbuthylazine 27,286	trifluralin 31,355	ioxynil 35,365	propachlor 38,678
trietazine/simazine 29,168	trifluralin 23,272	trifluralin 22,557	cyanazine 31277	linuron 33,000	linuron 30,750
trifluralin 29,395	linuron 18,865	ioxynil 15,600	terbutryn / terbuthylazine 19,520	trifluralin 26,975	pendimethalin 29,397
propachlor 24,451	dinoseb 18,245	metoxuron 15,452	ioxynil 16,014	terbutryn/ terbuthylazine 26,414	terbutryn/ terbuthylazine 22,428
cyanazine 14,873	chlorthal-dimethyl 13,725	trietazine/simazine 13,132	metoxuron 16,693	bentazone/MCPB 23,820	trifluralin 22,217
metoxuron 11,426	metoxuron 10,538	dinoseb 12,871	chlorbufam/ chloridazon 12,703	pendimethalin 19,202	metoxuron 17,056
chlorpropham 7,766	desmetryne 9,538	metoxuron 12,761	bentazone/MCPB 11,969	metoxuron 15,124	metazachlor 16,261
desmetryne 6,518	cyanazine 5,727	cyanazine 12,249	pendimethalin 9,772	metazachlor 12,594	bentazone/MCPB 15,907
Grasses					
tri-allate 30,567	tri-allate 19,332	tri-allate 3,774	fluazifop-p-butyl 8,229	fluazifop-p-butyl 6,412	fluazifop-p-butyl 4,877
Total weeds					
paraquat 31,523	paraquat 17,490	paraquat 12,482	paraquat 9,138	glyphosate 12,960	glyphosate 31,437

The extent of herbicide usage decreased by 19% between 1977 and 1986 in E & W but was virtually unchanged between 1981 and 1986. The most extensively used herbicides for all vegetables in 1986 were propachlor, linuron, terbuthylazine/terbutryn, trifluralin and ioxynil; in 1991, by far the largest use was with propachlor, linuron, cyanazine, trifluralin, terbutryn/terbuthylazine, ioxynil and metoxuron.

In 1999 (Table 4.10) the top ten herbicides used in vegetables were: glyphosate pre-planting, ioxynil (repeat low doses), cyanazine, propachlor (also repeat low dose), linuron (pre- and post carrots), terbutryn/terbuthylazine, trifluralin, metoxuron, metazachlor and bentazone/MCPB (peas only). As shown by the coloured text, many for broad-leaved weeds are no longer available or will soon be lost.

4.6.2.1 Brassicas (Leaf & Root) (Table 4.11)

The surveys show that over the last 25 years the herbicide treated area for brassicas has more than doubled, possibly because programmes are used with herbicides controlling complementary weed spectra. Brassicas (leaf and root) now receive on average 2 herbicide sprays. Tractor-hoeing is an alternative for brassicas grown on wide rows. Post-emergence graminicides are seldom used in brassicas. Where brassicas are transplanted, weeds are removed by cultivations or herbicides prior to transplanting and rapid establishment allows the early use of post-planting treatments.

Trifluralin was introduced in 1967 and to this day is the most widely used herbicide for leaf and root brassicas. It is soil-incorporated pre-sowing/planting. Trifluralin is cheap and is effective on resistant-blackgrass, but there are several gaps in its weed spectrum: cruciferous species including shepherd's purse and charlock; corn marigold, mayweeds and groundsel (Appendix 2) and fumitory is only moderately susceptible. These species are frequently found in the main brassica growing areas. Propachlor became available a few years later and closed some of these gaps, e.g. shepherd's purse (Appendix 2), with the exception of charlock and fumitory. Polygonum species and fat-hen are both resistant to propachlor. Propachlor is applied soon after drilling or after crops have 3 - 4 true leaves, or to hardened off transplants. Desmetryne was also used post-emergence in the 70's and was popular up till 1995, but subsequently became unavailable. Chlorthal-dimethyl first appeared in the 1981 survey, until 1995 but there was a problem with availability in 1999, but not now. It must be applied pre-emergence of weeds, it can be used on drilled crops or any time after transplanting, and it has a wider weed spectrum than propachlor. Metazachlor applied pre-emergence or after the 3 true-leaf stage of the drilled crop or to well established transplants, was used after the 1980's to include control of shepherds-purse, groundsel and mayweeds (Appendix 2).

The 1995 survey shows that there was also some post-emergence use of clopyralid for specific weeds thistles, mayweeds and volunteer potatoes; pyridate (approved only for use on cabbage and sprouts) for cleavers and cyanazine, which has a SOLA for some leaf brassicas (cabbage, cauliflower and calabrese), was used to control charlock. Pyridate will not be available after 2003; cyanazine and the only brassica herbicide to control field pennycress, sodium monochloroacetate, were not supported in the EC review and cannot be used after 2007.

In root brassicas, culinary swedes and turnips, sequential programmes of trifluralin incorporated pre-sowing, followed by a residual treatment are used. Most brassica herbicides are approved for use in swedes and extrapolated to turnips from swedes under the arrangement for minor uses. Foliar-acting treatment for broad-leaved weeds is limited to clopyralid.

In 1977, and before then, the main herbicides for leaf and root brassicas were trifluralin and propachlor. In 1995 and 1999 the most important active substances were trifluralin, metazachlor and propachlor and the reasons for the majority of herbicide applications were for general weed control. Herbicide usage in 1999 for leaf brassicas decreased by 21% since 1995, but there was an overall increase since 1977. In contrast there has been a decrease in weight applied reflecting the move to lower rates of application. The herbicide treated area in root brassicas has shows a steady increase since 1977.

Table 4.11 *Usage of herbicides (spray hectares) on brassicas grown in Great Britain, 1977 – 1999, England and Wales 1981, 1986. Herbicides used on 10% of the crop or more in red; herbicides not supported in the EC Review in blue; no longer available green*

	Brassicas etc	Root crucifers	Brassicas etc	Root crucifers	Brassicas etc	Root crucifers	Brassicas etc	Root crucifers	Brassicas etc	Root crucifers	Brassicas etc	Root crucifers
Crop year	**#1977**	**#1977**	**1981 E&W**	**1981 E&W**	**1986 E&W**	**1986**	**1991**	**1991**	**1995**	**1995**	**1999**	**1999**
Crop area	**56,472**	**8,056**	**47,805**	**3,849**	**E&W 47,968 GB 50,330**	**E&W 3,621 GB 5,012**	**43,832**	**5,274**	**40,828**	**4,171**	**34,743**	**4,237**
Herbicides Total weeds												
Diquat/paraquat					461		294	27	387	317	998	67
Glyphosate			1,675	391	480		936	25	1,856	117	4,234	263
Paraquat	2,028	391	4,394	908	1534		734	317	793	7	473	135
Herbicides Grasses												
Alloxydim-sodium												
Cycloxydim							220		146	59	338	170
Fluazifop-P-butyl				169			5				0	0
Propaquizafop									120		13	0
Herbicides Broad-leaved & grass weeds												
Aziprotryne					1,939		1,076	12	2,158			
Bentazone											141	0
Chlorthal-dimethyl			5,544	534	4,774		2,050	98	4,291	30	553	0
Chlorthal-dimethyl / propachlor					1,219							
Clopyralid					3,925		1,031	15	2,139	164	1,835	65
Cyanazine					835		76		590		647	0
Desmetryne	7,233	26	9,400		8,059		4,778		4,538			
Metazachlor					3,346		5,570	1,265	10,619	1,965	13,937	2,261
Pendimethalin							102		479		853	0
Propachlor	16,547	2,294	21,833	1,529	23,378		22,214	1,453	19,918	595	12,238	1,076
Pyridate									159		1,126	0
Sodium monochloroacetate					845		593		834		711	0
Tebutam							1,932	804	1,150	310		
Trifluralin	21,620	3,036	15,000	2,081	17,177		16,884	4,386	21,521	3,265	16,668	3,220
OtherTranslocated			1,894									
Other Soil acting			9,285									
Other herbicides									466	-	2,127	257
Herbicide area treated (ha)	**48,267**	**6,100**	**61,654**	**5,930**	**GB 72,066**	**GB 6,501**	**59,100**	**8,509**	**72,163**	**6,829**	**56,906**	**7,514**
					E&W Brassicas (leaf & root) 71,531						**57,081**	**7,553**
Herbicide as % area grown	**85**	**76**	**129**	**124**	**143**	**130**	**135**	**161**	**177**	**164**	**164**	**178**

4.6.2.2 Peas and Broad Beans (Table 4.12)

Grasses, usually wild-oats, were the main target weeds (as perceived by the grower) in the 1972 and 1977 survey, and before then. Tri-allate was applied pre-sowing and incorporated as a blanket 'insurance' spray, but later, graminicides (alloxydim-sodium, sethoxydim and then fluazifop-butyl) were developed for post-emergence application if the grass weeds emerged, thus spraying for grass weeds declined.

In 1977 and before, over-wintered weeds were killed with paraquat. Residual pre-emergence herbicides simazine/trietazine and terbutryn/terbuthylazine were introduced in the early 1970s and appeared in the 1972 survey and the area treated increased by the 1977 survey. Since then, triazines have formed the basis for residual control and, given adequate soil moisture, they are very effective on most species except cleavers, fool's parsley and ivy-leaved speedwell (Appendix 3). Simazine/trietazine was not manufactured after 2001. Simazine is still used in broad beans but is not safe to peas at these doses. Dinoseb had been used since the 1950s, was the most widely used post-emergence herbicide for broad-leaved weeds in peas in 1977 - it was banned in 1986.

The old method of harvesting of cutting the crop before picking it up to go through a pea viner, meant that large bulky weed material such as wild-oats slowed down harvesting. In 1976 a new harvester was introduced with a picking reel, which combed through the weeds, so a whole mass of plant material did not enter the podder. By 1980 about 80% of the vining pea area was harvested by these machines. However weedy contaminants are still frequent problems in processing factories.

The area treated with herbicides for broad-leaved weed control has increased over the last 25 years – perhaps a reflection of the 'nil weed contaminant in frozen produce' policy adopted by buyers. Mayweed, poppy, sowthistle, and campion heads can be a problem in machine-harvested vining peas and broad beans, but the most serious are toxic black-nightshade, potato berries and linseed capsules, which are a similar size, colour and shape to peas and are therefore difficult and costly to remove.

With the increasing area of oilseed rape grown there was a new volunteer problem causing contaminants in vining peas and beans, and harvesting difficulties in dry harvested peas. Control is with the active ingredient fomesafen, pendimethalin (only registered for dry harvest peas) and the post-emergence hormones MCPB and MCPA and bentazone (Appendix 3).

Clomazone, a cleavers killer, was not approved for use in peas and broad beans (under the Long Term Arrangements for Extension of Use) until 2001 but it has a limited weed spectrum.

In 1999, and now, growers kill over-wintered weeds with glyphosate, and follow with a pre-emergence residual herbicide still mainly terbutryn/terbuthylazine, and some fomesafen/terbutryn. In peas a post-emergence herbicide tank-mix of bentazone/MCPB plus cyanazine, or cyanazine plus MCPB/MCPA, is used for weeds escaping control. The latter is used to suppress formation of potato berries.

In the 1999 survey the main targets were for general weed control (55%) or broad-leaved weeds (30%), with volunteers and grass weeds comprising a further 13% and 3% respectively. The most important herbicides were cyanazine, 24% of the herbicide treated area, terbuthylazine/terbutryn 21%, bentazone/MCPB 15% and glyphosate 14%. The herbicide treated area showed a 6% decrease on 1995 and an 11% reduction when compared with 1986. Cyanazine, terbutryn and fomesafen were not supported in the EC Review and these 'Essential Uses' are permitted until December 2007. After then there will be no broad-spectrum pre-emergence herbicide for vining peas.

Table 4.12 *Usage of herbicides (spray hectares) on total area peas (excludes peas harvested dry for stock feed), broad beans, dwarf French beans grown in Great Britain, 1977,1995, 1999; England and Wales 1981,1986. Excludes desiccant use. Herbicides used on 10% of the crop or more in red; herbicides not supported or which did not achieve Annex 1 listing in the EC Review in blue; no longer available green*

Crop year	**1977**	**1981 E&W**	**1986 E&W**	**1991**	**1995**	**1999**
Crop area	**121,192**	**93,571**	**E&W 72,306 GB 76,653**	**54,769**	**51,966**	**45,365**
Herbicides Total weeds						
Diquat	267	1,322	1,215	308		
Diquat/paraquat			1,206	2,504	1,669	1,335
Glyphosate			1,299	4,282	6,191	14,941
Paraquat	15,576		4,166	2,834		428
Herbicides grasses						
Alloxydim-sodium			144			
Cycloxydim				1,035	1,731	2,356
Fluazifop-P-butyl			1,766	1,002	641	145
Sethoxydim			1,152			
Tri-allate	27,944	18,345	3,729			
Herbicides Broad-leaved & grass weeds						
Bentazone	6,234		5,354	5,229	4,362	1,132
Bentazone/MCPB				11,969	23,820	15,907
Chlorthal-dimethyl			293	412	392	153
Cyanazine	12,916		7,791	25,019	30,535	26,526
Dinoseb etc. (+ dinoseb in oil)	49,136	17,953	19,734			
Fomesafen						1,549
Fomesafen/terbutryn					2,048	4,843
MCPA/MCPB			2,407	8,690	6,975	10,766
MCPA			2,043			
MCPB			5,191	5,315	1,723	3,445
Monolinuron			2,816	2,097	2,066	1,049
Simazine	687			386		
Simazine/trietazine	29,168	28,728	13,132	8,395	1,130	
Terbuthylazine/terbutryn	27,375	38,945	27,286	19,520	26,414	22,428
Terbutryn/trietazine				3,661	2,820	
Terbutryn/ prometryn		2,566				
Trifluralin	5,620		2,956	1,714	566	98
Translocated (inc barban)	11,267	5,311				
Other contact		10,009				
Other soil acting	6,093	16,516				
Herbicide area treated (ha)	**211,853**	**131,867**	**E&W 109,872 GB 122,967**	**109,084**	**116,409**	**109,339**
Herbicide excl desiccants as % area grown	175	141	E&W 152 GB 160	199	224	241

In dwarf French beans trifluralin soil-incorporated pre-sowing was used for many years but rarely now because of concerns about loss of moisture during the cultivations. Stale seedbed techniques are widely used and volunteer potatoes emerging before the crop are killed with glyphosate. Monolinuron pre-emergence was popular, but it did not achieve Annex 1 listing in the EC Review and it was revoked in 2001. Early application of fomesafen is extremely useful for control of a wide weed spectrum including volunteer oilseed rape, but will be lost after 2007. Only the expensive pre-emergence residual chlorthal-dimethyl with a limited weed spectrum and post-emergence bentazone will remain.

4.6.2.3 Onions (salad and bulb) and leeks (Table 4.13)

All weeds are targets in these uncompetitive crops. The main problem weeds are mayweeds, fat-hen, Polygonums, fumitory, volunteer potatoes and annual meadow-grass. Volunteer cereals are often a problem in over-wintered onions, which are usually established after cereals. In the 1999 survey general/broad-leaved weed control was the aim for most of the crop but volunteers were specified (8%), grass weeds (6%) and 1% to destroy pre-drilled cover crops.

The spring established crops are slow to emerge, and weeds appearing before the crop are controlled with a non-selective herbicide. This was mainly paraquat in 1977, by 1999, glyphosate. In 1977 residual herbicides applied after drilling/planting were propachlor, or chlorbufam/chloridazon on mineral soils and chlorpropham plus propachlor on organic soils were widely used. Propachlor does not control knotgrass or cruciferous species; chlorpropham has a narrow weed spectrum and neither control fumitory (Appendix 4). Pendimethalin (SOLA) was introduced later and by 1999 the area treated was nearly as large as propachlor – they are often used in combination. Post-emergence applications of propachlor, pendimethalin (SOLA) and chloridazon (SOLA) are now commonly used in conjunction with a contact herbicide such as ioxynil up to the second true leaf stage. Methazole was withdrawn.

Ioxynil post-emergence, developed in the 1970s, is still the mainstay of onion control programmes and there are several low dose applications. Several post-emergence contact/translocated herbicides were then developed in the 1990s to target specific weeds. Ioxynil is usually used now in combination with other contact herbicides such as cyanazine for control of Polygonums; fluroxypyr (SOLA) for control of volunteer potatoes and cleavers; bentazone (SOLA) for control of mayweeds and clopyralid for control of thistles and other Compositae. All post-emergence contact herbicide programmes are based on the principle of repeat low dose applications.

Surveys suggest that grass weeds, volunteer cereals or shelter barley are more recent targets, in 1991 34% of fluazifop-**p**-butyl was used for cover crop destruction; in 1995, controlled with post-emergence graminicides such as cycloxydim (bulb and salad onions), fluazifop-**p**-butyl or propaquizafop (bulb only). In 1999 propaquizafop was used predominantly.

Onion herbicides are used in leeks, but since leeks have a larger 'funnel' type of leaf and there is less 'run-off' they are more sensitive to the post-emergence herbicides. A pre-emergence residual herbicide is used and post-emergence herbicides are applied early, often as split doses.

As a result of the adoption of repeat low dose programmes there has been a huge increase in the number of herbicide applications over the period 1977 to 1999, from more than 3 to between 9 and 10. However, the total weight of active substances increased by only 19% since 1986. Usage of ioxynil increased dramatically since 1977, and it was still the most important herbicide in the 1995 and 1999 surveys. Usage of propachlor, pendimethalin, cyanazine and chloridazon was also extensive in both surveys.

Table 4.13 *Usage of herbicides (spray hectares) on total area onions and leeks grown in Great Britain, 1977 – 1999. Herbicides used on 10% of the crop or more in red; herbicides not supported in the EC Review blue; no longer available green*

Crop year	**1977**	**1981 E&W**	**1986 E&W**	**1991**	**1995**	**1999**
Crop area	**12,391**	**10,944**	**E&W 12,231 GB 12,428**	**E&W 11,500 GB 11,670**	**13,477**	**16,289**
Herbicides Total weeds						
Diquat/paraquat			219	825	2,311	2,649
Glyphosate			643	632	1,699	4,694
Paraquat	6,611	3724	3,632	3,008	1,641	1,225
Herbicides grasses						
Alloxydim-sodium			850	8		
Cycloxydim						922
Fluazifop-P-butyl			1,906	3,156	3,065	2,689
Propaquizafop					2,916	5,708
Sethoxydim			591			
Herbicides Broad-leaved & grass weeds						
Aziprotryne			113	556	458	
Bentazone			499	988	1,590	3,089
Chlorbufam/chloridazon	6,478	2,578	9,973	12,677	4,843	
Chloridazon					2,182	9,606
Chloridazon/propachlor					1,309	1,417
Chlorpropham	5,703	1815	3,876	3,219	5,209	4,019
Chlorthal-dimethyl		7,653	3,237	1,764	1,863	814
Clopyralid			1,622	899	1,589	2,979
Cyanazine	3,192	-	3,592	6,182	11,617	14,911
Ethofumesate				31	1,498	2,035
Fluroxypyr					5,053	8,275
Ioxynil	1,241	2,095	15,600	15,491	35,365	45,931
Ioxynil/linuron	2,287	2,533	2,263			
Linuron				154	81	1,105
Methazole	4,870	2,845				
Pendimethalin			2,058	5,102	8,650	17,114
Prometryn				1,768	1,886	3,512
Propachlor	7,691	11,249	9,543	11,679	14.443	19,224
Pyridate						153
Sodium monochloroacetate			493	294	288	1,053
Herbicide area treated (ha)	**40,301**	**38,655**	**E&W 62,725 GB 63,353**	**69,722**	**110,066**	**154,130**
Herbicides as % area grown	325	353	E&W 513 GB 510	597	817	946

4.6.2.4 Carrots, parsnips and celery (Table 4.14)

Carrots were the first vegetable crop in which effective chemical weed control was achieved with the introduction of mineral oils (TVO) in the late 1940's. However the oil caused taints in the processed crop. Linuron, with residual and contact action, was introduced in the early 60's and has been widely used pre- and post-emergence in carrots to control annual meadow-grass (pre-emergence only) and broad-leaved weeds for many years; trifluralin (pre-sowing incorporated) was also applied but use is rare now. Metoxuron was developed in the 1970's for post-emergence control of species resistant to post-emergence linuron and trifluralin such as mayweeds (Appendix 5). Linuron + metoxuron tank-mix remains the standard for post-emergence control of broad-leaved weeds and suppression of volunteer potatoes.

Since the 1986 survey, several other herbicides have been developed to solve specific weed problems: knotgrass with post-emergence pentanochlor, fool's parsley and wild mignonette with metribuzin (SOLA) and fumitory and other weeds with prometryn (Appendix 5). Pendimethalin has also become an increasingly popular pre-emergence residual herbicide. Volunteer potatoes are usually hand-pulled and there are moves to avoid them in the rotation. Hemlock and wild carrot cannot be controlled with herbicides. The 1999 survey shows a much wider use of non-selective herbicides glyphosate and diquat/paraquat, used to kill overwintered weeds pre-cultivation, on stale seedbeds or pre-emergence of the crop. Repeat low dose programmes and tank-mixes are usually necessary to cover the weed spectrum. In 2007, the loss of Essential Uses, there will be gaps for control of mayweeds and volunteer potato suppression with metoxuron, and fumitory with prometryn.

Table 4.14 *Usage of herbicides (spray hectares) on total area carrots, parsnips, celery etc. grown in Great Britain, 1977 – 1999, herbicide details for E & W1986. Herbicides used on 10% of the crop or more in red; herbicides not supported in the EC Review in blue; no longer available green*

Crop year	**1977**	**1981 E&W**	**1986**	**1991**	**1995**	**1999**
Crop area	**24,055**	**17,129**	**E&W 17,288** **GB 18,198**	**18,981**	**16,469**	**15,851**
Herbicides Total weeds						
Diquat/paraquat			248	656	588	2,442
Glyphosate			49	175	225	3,931
Paraquat	1,962	1,538	1,097	342	308	372
Herbicides grasses						
Alloxydim-sodium		1,920	67			
Cycloxydim					85	75
Dalapon						
Fluazifop-P-butyl			1,079	3,701	2,620	1,958
Propaquizafop					1,623	4,231
Sethoxydim			63			
Herbicides Broad-leaved & grass weeds						
Chlorbromuron		4,904				
Chlorpropham				169		37
Chlorpropham/pentanochlor				2,210	2,584	
Ioxynil						26
Linuron	32,916	18,471	28,859	32,550	31,887	28,992
Metoxuron	11,396	10,583	12,716	16,559	15,124	17,056
Metribuzin						2,029
Pendimethalin				3,922	9,663	10,683
Pentanochlor				2,020	1,126	5,450
Prometryn			1,184	1,832	2,214	2,922
Propachlor						26
Trifluralin	1522	1109	1,735	2,884	849	520
Herbicide area treated (ha)	**54,153**	**44,521**	**E&W 49,103** **GB 52,920**	**67,415**	**69,476**	**82,409**
Herbicides as % area grown	**225**	**260**	**E&W 284** **GB 291**	**355**	**422**	**520**

Grass weeds are controlled with post-emergence graminicides: the first was alloxydim-sodium in 1977, then fluazifop-p-butyl which was replaced in popularity by propaquizafop, perhaps with the expectation of some annual meadow-grass control. In 1991, 29% of fluazifop-**p**-butyl was used for destruction of cereal crop cover.

Surveys do not specify herbicide usage on parsnips or celery, and weeds are controlled with herbicides developed for the carrot crop. The larger parsnip leaf retains more herbicide than carrots and thus parsnips are less tolerant of post-emergence herbicides. For crop safety herbicides are applied at half dose rates and/or at a more advanced growth stage than carrots, but bearing in mind Minimum Harvest Intervals. In celery a few herbicides used in carrots are suitable. Use of a contact herbicide before planting may mean fewer herbicide applications to the crop and is essential on organic soils.

Herbicides with a label approval for carrots can be extrapolated for use in parsnips and pendimethalin, linuron, linuron + metoxuron and graminicides are used. The morphology of the celery plant is different from other crop species and larger amounts of pesticides may be retained, resulting in higher levels of residues. There are therefore no minor-use extrapolations to celery and the number of label recommendations is likely to remain small. After transplants have established, a residual/contact acting herbicide is applied such as chlorpropham alone, chlorpropham/pentanochlor or linuron (up to 2 rough leaf stage only) but there will be a little residual activity on organic soils.

The herbicide area treated in these crops increased by 231% from the 1977 survey to 1999 (from 2 applications to over 5. The increase was 19% from 1995 - 1999 and by 56% since 1986, however the weight applied increased by only 7% and 15% respectively, reflecting the increased use of repeat low dose applications. Linuron was the most important herbicide in both years, accounting for almost double the area treated by metoxuron, the second most extensively used herbicide in both years. Pendimethalin and pentanochlor were the third and fourth most used herbicide active substances in both the last two surveys, but propaquizafop replaced fluazifop-**P**-butyl at number five in 1999.

4.6.2.5 Lettuce, endive, Chinese cabbage etc. (Table 4.15)

Most of the herbicides mentioned are safe to the major types of lettuce but new varieties of speciality lettuce are constantly introduced and there may be differences in tolerance. Propachlor causes a growth check but the delay in maturity is usually 'built into' the sequence of croppings. Continuous cropping on the same land and the short-term crop are limiting factors thus there are few herbicide options. Propyzamide has a six-week harvest interval and it is persistent in the soil, so care should be taken in respect of following crops. Chlorpropham can also be used pre-emergence on drilled lettuce, but not on sands or very light soils, and it can be damaging. Trifluralin soil incorporated before drilling or transplanting is less safe to the crop and is seldom used now.

In surveys, general weed control was the aim in all years. Propyzamide and chlorpropham (in mixture with sulfallate in 1977) were the main herbicides used on these crops in the 1977 survey (Table 4.15) and they were still extensively used in 1999. There are no details for lettuce in the 1981 and 1986 E & W surveys because lettuce was included in "other vegetables" and occupy the largest area in this sector but from these data it appears that propyzamide, followed by chlorpropham, alone or in formulation, were the main herbicides used, but propachlor use was small (only 770 ha for all "other vegetables"). In 1999 propachlor had begun to replace propyzamide, the principal herbicide active substance applied since 1977 and before then. Propachlor (SOLA) can be used pre- or post-emergence for Compositae. The only other important active substance applied in both 1995 and 1999 was chlorpropham. Tank-mixes of propachlor with propyzamide or chlorpropham at reduced dose rates are also used now. Only a narrow range of weeds is susceptible to chlorpropham (Appendix 4); propyzamide does not control mayweeds (Appendix 9); propachlor does not kill cruciferous species or Polygonums (Appendix 4). However, lettuce is a short-season crop and long-term control is not required.

Table 4.15 *Usage of herbicides (spray hectares) on total area lettuce, endive etc. grown in Great Britain, 1977 - 1999. Herbicides used on 10% of the crop or more in red; no longer available green*

Crop year	**1977**	**1981 E&W**	**1986**	**1991**	**1995**	**1999**
Crop area	**6,955**	**5,319**	**E&W 3,463 GB 3,848**	**8,539**	**6,855**	**5,858**
Herbicides Total weeds						
Diquat/paraquat				465	70	776
Glyphosate				68	1,415	595
Paraquat				676	211	50
Herbicides Broad-leaved & grass weeds						
Chlorpropham	520	+	+	1,149	2,359	3,254
Chlorpropham/sulfallate	2,728					
Pendimethalin				203	205	316
Propachlor			+	3,758	4,500	5,820
Propyzamide	3,860	+	+	5,704	4,839	3,759
Trifluralin		+	+	1,417	448	241
Herbicide area treated (ha)	**8,155**	**No details**	**No details GB 5,988**	**13,485**	**14,094**	**14,814**
Herbicides as % area grown	**117**		**GB 156**	**146**	**206**	**253**

There is currently no herbicide with a label recommendation for lettuce to control mayweed or groundsel, although propachlor (SOLA) does help to control Compositae.

Table 4.15 shows a steady increase in herbicide use from 1977, when one treatment was applied, compared with more than 2 in 1999. The increase was 5% between 1995 and 1999. Three herbicides accounted for 86% of the herbicide treated area, propachlor (39%), propyzamide (25%) and chlorpropham (22%) in 1999. There has also been increased use of non-selective total herbicides glyphosate or paraquat, to clean up before transplanting.

A soil sterilant is sometimes used to kill weed seeds particularly in the production of 'baby leaf' crops. Dazomet granules are incorporated in the soil, which is then covered with polythene. The usage of soil sterilants in 1999 had increased by 27% in terms of the area treated since the 1995 survey. In 'baby leaf' lettuce steam sterilisation is also used before planting. This method is successful, but slow.

4.6.2.6 Sweetcorn (Table 4.16)

Virtually all sweetcorn is grown in the south of England. Atrazine has been the most widely used herbicide for many years. Atrazine is residual and foliar acting and controls a wide range of annual broad-leaved weeds (43 including black-nightshade) and grasses (12), cleavers and knotgrass are moderately resistant. To protect water, atrazine now has restrictions on permitted use - the high dose rate for common couch is no longer approved. Some retailers no longer permit the use of atrazine. Other alternatives are: simazine but this also has restricted use to protect water; cyanazine, a less persistent herbicide can be used for annual meadow-grass and broad-leaved weeds; pendimethalin alone SOLA, and where sweetcorn has been grown continuously a tank-mix of atrazine plus pendimethalin is recommended.

Strains of annual meadow-grass and groundsel have become resistant to triazines. Black-nightshade has become a problem on some fields where sweetcorn is frequently grown, and was often mentioned as a target in 1986, but was only a target for 2% of the crop in the 1999 survey. Other herbicides have therefore been developed and herbicide use in sweetcorn has increased to between 2 and 3 applications. There were several other post-emergence options to solve most weed problems: bromoxynil or bromoxynil/prosulfuron for black-nightshade and other annual broad-leaved weeds; pyridate for black nightshade and cleavers; clopyralid for creeping thistle and mayweeds.

In 1999 (Table 4.16) atrazine was used on 51% of the herbicide treated area, pyridate (18%), bromoxynil (16%) and glyphosate (10%). Usage of herbicides declined by 29% between 1995 and 1999 but more than doubled between 1986 and 1999. Atrazine was the principal active substance applied from 1977 to 1999. Usage of clopyralid and pyridate, principal second and third herbicides in 1995, declined in 1999 with atrazine accounting for 51% of the herbicide treated area in the 1999 survey.

Pyridate and bromoxynil/prosulfuron are no longer available for sweetcorn. Failure of atrazine and simazine to achieve Annex 1 status in the EC Review will leave a serious gap for sweetcorn weed control.

Table 4.16 *Usage of herbicides (spray hectares) on total area sweetcorn grown in Great Britain (all in England), 1977 - 1999. Herbicides used on 10% of the crop or more in red; herbicides not supported or which did not achieve Annex 1 listing in the EC Review in blue; no longer available greenor not achieving Annex 1*

Crop year	**1977**	**1981**	**1986**	**1991**	**1995**	**1999**
Crop area	**1000**	**1005**	**1,197**	**1,533**	**2,025**	**1,690**
Herbicides Total weeds						
Diquat/paraquat					75	60
Glyphosate		+		47	491	404
Paraquat					42	14
Herbicides Broad-leaved & grass weeds						
Atrazine	1000	975	1258	1,828	2,034	2,085
Bromoxynil						660
Clopyralid				48	1,739	15
Cyanazine					31	
Pendimethalin						138
Pyridate				+	1,406	738
Simazine		+				4
Herbicide area treated (ha)	**No details**	**No details**	**1,989**	**2,635**	**5,817**	**4,126**
Herbicides as % area grown			**166**	**172**	**287**	**244**

4.6.2.7 Cucurbits (Table 4.17)

These transplanted crops rapidly cover the ground and suppress weed growth thus herbicide use is small, mainly for a clean-up pre-planting, with paraquat in 1981 and glyphosate the most popular by 1999 (Table 4.17). Some dinoseb was also used in 1981. The use of soil sterilants is increasing.

Table 4.17 *Usage of herbicides (spray hectares) on total area cucurbits grown in Great Britain (all in England and Wales), 1977 - 1999. Herbicides used on 10% of the crop or more in red.*

Crop year	**1977**	**1981 E&W**	**1986**	**1991**	**1995**	**1999**
Crop area	**1210**	**379**	**GB 1,029**	**970**	**950**	**1,112**
Herbicides Total weeds						
Diquat/paraquat			+	17	147	268
Glyphosate			+	20	61	419
Paraquat	+	21	+	84	323	55
Herbicides Broad-leaved & grass weeds						
Chlorthal-dimethyl						22
Linuron					33	17
Propachlor					20	
Propyzamide						20
Herbicide area treated (ha)	No details	No details	506	257	603	830
Herbicides as % area grown			49	26	63	75

4.6.2.8 Other root vegetables (Table 4.18) and other vegetables (Table 4.19)

The crops included in this category have changed over the years and some crops have moved from one survey category to another, thus for small area crops, details of herbicides are not mentioned here. In some machine-harvested crops such as spinach and herbs, weed contaminants may mean rejection, nettles are obnoxious to hand pickers of asparagus and beetroot, therefore in all cases control of all weeds was the aim.

'Other vegetables' in the 1977 survey of 3,643 ha included marrow, sweetcorn and very small areas of herbs, rhubarb and asparagus with atrazine, paraquat and simazine the main herbicides used for general weed control on 2,915 ha sprayed. Details for sweetcorn and marrow have been included in the Tables 4.16 and 4.17, beetroot in Table 4.18. Beetroot (3,239 ha) and, in England, spinach (222 ha) were then in another category and weeds were controlled mainly with lenacil pre-emergence, phenmedipham post-emergence and others (a total of 8,676 ha) sprayed. First-early potatoes (21,045 ha) were also surveyed and non-selective paraquat was used followed by residual herbicides monolinuron and terbutryn/terbuthylazine to control broad-leaved weeds and annual meadow-grass, a total of 19,914 ha.

In the E & W 1981 survey, beetroot 2,666 ha, first-early potatoes, marrow, courgette, sweetcorn, lettuce and other minor vegetables and herbs were grouped under the 'other vegetable' category. Details have been included in the Tables of data for each specific crop. Phenmedipham was the main beet herbicide (3,205 ha sprayed) also lenacil, ethofumesate, metamitron, propham and paraquat with tri-allate for grass weeds; terbutryn/terbuthylazine and paraquat in first-early potatoes, chlorpropham, propyzamide and trifluralin in lettuce, paraquat in marrows; atrazine, simazine and glyphosate in sweetcorn.

Table 4.18 *Usage of herbicides (spray hectares) on total area other root vegetables grown in Great Britain, 1977 - 1999. Herbicides used on 10% of the crop or more in red*

Crop year	**Beetroot & spinach 1977**	**Beetroot 1981 E&W**	**Beetroot celeriac, chicory 1986 E&W**	**1991 E & W**	**1995**	**1999**
Crop area	**32,396 & 222**	**2,666**	**E&W 2316 GB 2,316**	**2,426**	**2,513**	**1,760**
Herbicides Total weeds						
Diquat/paraquat						200
Glyphosate				274	715	317
Paraquat		95		11	78	8
Herbicides grasses						
Cycloxydim				10	10	9
Fluazifop-P-butyl				354	59	86
Propaquizafop					58	63
Herbicides Broad-leaved & grass weeds						
Chloridazon		+			37	4
Clopyralid			*498*	1,251	541	895
Ethofumesate		+	*937*	3,025	1,221	1,341
Lenacil	626					
Linuron				50	211	12
Metamitron		+	*4,274*	2,299	1,950	2,195
Phenmedipham	3,697	3205	*2,529*	6,592	4,728	3,686
Propyzamide				62	164	
Trifluralin				19	98	
Herbicide area treated (ha)	**8,676**	**No detail**	**GB 10,326**	**E &W 14,734**	**10,481**	**9,927**
Herbicides as % area grown	**266**		**GB 446**	**607**	**417**	**564**

The E & W 1986 survey included the same crops as in 1981 except early potatoes, (which were included from then on in the arable crops surveys). There are no details for individual crops but the main active substances used for sweetcorn, beetroot are clear and are added to relevant tables.

Table 4.19 ***Table 4.19*** *Usage of herbicides (spray hectares) on total area other vegetables grown in Great Britain, 1991 – 1999. Herbicides used on 10% of the crop or more in red; not supported or which did not achieve Annex 1 listing in the EC Review in blue.*

Crop year	**1991**	**1995**	**1999**
Crop area	**E&W 2,678**	**3,088**	**4,861**
Herbicides Total weeds			
Diquat	246		
Diquat/paraquat	39	185	625
Glyphosate	469	190	1,638
Paraquat	1,130	726	709
Herbicides grasses			
Propaquizafop			392
Herbicides Broad-leaved & grass weeds			
Chlorpropham		91	179
Chlorpropham/pentanochlor	173	278	?
Clopyralid	39	132	115
Linuron	635	788	624
Metamitron	46		112
Pendimethalin	193	46	155
Pentanochlor	243	292	?
Phenmedipham	7	97	49
Prometryn	81	274	101
Propachlor	160	47	248
Propyzamide	265	252	224
Simazine	923	?	1,013
Trifluralin	9	213	1,469
Herbicide area treated (ha)	**E&W 5,604**	**4,628**	**8,960**
Herbicides as % area grown	**E&W 209**	**150**	**184**

There were two categories in later surveys: one for '**other root vegetables'**, another for **'other outdoor vegetables'.** The earlier years are therefore excluded from Table 4.19 because comparisons cannot be made. **'Other root vegetables'** beetroot, celeriac, chicory and Jerusalem artichoke, received on average 3 herbicide sprays in 1995 and the 1999 surveys. In 1995 broad-leaved weed control was the most commonly stated reason for the use of herbicides. Three herbicides accounted for 73% of the herbicide treated area, phenmedipham (37%), metamitron (22%) and ethofumesate (14%). The herbicide treated area in 1999 was 5% less than in 1995, the weight applied decreased by 39% reflecting the increased use of phenmedipham, metamitron and ethofumesate at lower rates. The herbicide treated area decreased by 4% since 1986 whilst the weight applied fell by 51% over the same period. Apart from the three active substances specified above, clopyralid was also encountered in the principal five in the two most recent surveys. All major herbicide active substances were used in both years on beetroot, the most important crop in this category. Non-selective herbicides were used with a change from paraquat to glyphosate.

'Other outdoor vegetables' which included a range of herbicide active substances for: asparagus (simazine,), mustard (trifluralin), parsley, raddichio, rhubarb (simazine), spinach (phenmedipham, metamitron), outdoor tomatoes and watercress. Non-selective herbicides were widely used, with a change from paraquat in 1995 to glyphosate in 1999. Weed control for herbs, a rapidly expanding crop area, is based on SOLAs for several herbicides – the main ones in 1999 were simazine, chlorpropham/pentanochlor, pentanochlor, trifluralin and for parsley: chlorpropham/pentanochlor, pentanochlor and trifluralin.

Table 4.20 *Usage of herbicides (spray hectares) bulbs and outdoor flowers grown in Great Britain (Scotland is excluded for1977 & 1982, #1977 excludes SW Engand), 1977 – 2001. Herbicides used on 10% of the crop or more in red, herbicides not supported or which did not achieve Annex 1 listing in the EC Review in blue.*

Crop year	**#1977 E & W**	**1982 E & W**	**1993**	**1993**	**1993**	**1997**	**1997**	**1997**	**2001**	**2001**	**2001**
	Bulbs	**Bulbs**	**Bulbs**	**Flowers**	**Total bulbs flowers**	**Bulbs**	**Flowers**	**Total bulbs flowers**	**Bulbs**	**Flowers**	**Total bulbs flowers**
Crop area	**1,949**	**4,425**	**4,759**	**1,033**	**5,792**	**4,715**	**741**	**5,456**	**5,237**	**540**	**5,777**
Herbicides Total weeds											
Diquat			181		1,576	226		226	147		147
Diquat/paraquat			1,356	39	1,925	2,077	57	2,135	2,043		2,043
Glufosinate-ammonium					6	48	33	81			
Glyphosate		1,094	1,896	29	1,925	3,184	211	3,395	5,104	208	5,313
Paraquat	1362	3,505	948	131	2,473	1,772	119	1,891	916	67	984
Herbicides Grasses											
Cycloxydim					17	114		114			
Fluazifop **p** butyl									469		469
Broad-leaved weeds											
Bentazone									1,950		1,950
Chlorpropham			229		1,054	373	10	384	1,604	4	1,608
Chlorpropham/diuron			107								
Chlorpropham/linuron	1719	2,190	690		690	309		309	179	3	182
Chlorthal-dimethyl				202	194		113	113			
Cyanazine			2,620		2,620	2,820	13	2,833	2,275		2,275
Diuron			358		465	230		230	536		536
Isoxaben			358	65	423	456	8	464	157		157
Lenacil						546	7	554	1,072		1,072
Linuron & monolinuron			304		994	828	6	834	2,680		2,680
MCPA			61		61	72		72			
Metamitron					31	299	1	299	1,911		1,911
Metazachlor				57	57	110	57	167			
Oxadiazon				127	127						
Pendimethalin			448		448	515	40	555	531	22	553
Propachlor				168	167		85	85			
Simazine			403	76	479	355	6	360	274	70	345
Herbicides area treated (ha)	**#4,863**	**10,064**	**10,153**	**1,101**	**11,254**	**14,404**	**952**	**15,356**	**22,134**	**539**	**22,673**
Herbicides % area grown	**#250**	**227**	**199**	**106**	**194**	**288**	**128**	**281**	**422.6**	**99.8**	**392.5**

4.6.3 Outdoor bulbs and other other flowers for cutting (Table 4.20)

Sulphuric acid and, in 1977, dinoseb in oil (banned in 1986) were used as desiccants prior to lifting bulbs and are not included in Table 4.20. Sulphuric acid was used for 328 ha in 2001.

In 1977, bulbs were part of the arable pesticide usage survey and only data for the main herbicides are given. General weed control was the aim and most bulbs were treated pre-emergence with paraquat or, with residual herbicides chlorpropham alone, which has several gaps in the weed spectrum or in mixture with linuron (Appendix 6). At this time the post-emergence use of cyanazine was small.

By 1982 paraquat use increased and was the most widely used herbicide, but glyphosate had begun to make an impact – both total weed killers, and chlorpropham/linuron (pre- or post-emergence) and other mixtures of chlorpropham with diuron or fenuron were popular residual herbicides. A very small area was treated post-emergence with bentazone or cyanazine. In 1993 the use of paraquat had begun to decline in favour of cheaper glyphosate, and by then cyanazine had become widely used. In 1997 weed control in the majority of bulbs was with glyphosate pre-planting, followed by linuron alone or with chlorpropham pre-emergence. Pendimethalin was also used in bulbs pre-emergence from 1993 to 2001, and lenacil pre-emergence nearly doubled from 1997 to 2001.

The area treated with cyanazine post-emergence increased from 1993, but decreased slightly in 2001. Cyanazine has contact and residual activity and it is usually applied post-emergence although it can also be applied pre-crop emergence. It is particularly effective against emerged annual small nettle (Appendix 6), which often escapes control with linuron. The loss of cyanazine after 2007 will leave a gap in weed control for bulbs. In 2001 bentazone, not popular in previous years, was nearly as widely used post-emergence as cyanazine but it was probably used post-harvest.

There have been few surveys of outdoor flowers, and herbicide use is low on these sensitive crops, mainly glyphosate pre-sowing. Use of residual herbicide simazine, recorded in the 1993, 1997 and the 2001 surveys and pendimethalin in the last two, are suitable for some flower crops. Residuals chlorthal-dimethyl (safer on more sensitive species) or propachlor were used in 1993 and 1997, but chlorthal-dimethyl became scarce and did not feature in the 2001 survey – it is now available again. Chlorpropham/pentanochlor was popular in chrysanthemums in 1993 but pentanochlor use will be revoked in 2007.

Soil sterilants were used on 78 ha of bulb and otherflower crops in 1993, none were recorded in 1997, and only 42 ha were treated in 2001. Grass weeds are seldom targets in bulbs or flowers and the use of graminicides is small.

Over the period 1982 to the most recent survey in 2001 the area of bulbs treated with herbicides has nearly doubled, an increase from 2 sprays per crop to more than 4, with a 70% increase between 1993 and 1997. However, between 1993 and 2001, there has been a 32% reduction in the average dose rate of herbicides applied.

On flower crops, the area treated as a percentage of the area grown increased from 1993 to 1997 (although the average rate of application dropped), and area treated declined again in the 2001 survey. Other flowers for cutting are generally treated only once, because they are sensitive to many herbicides and there is little information on crop safety.

4.6.4 Soft Fruit (Table 4.21)

Herbicide use has increased from 2 sprays in 1975 to about 3 averaged overall soft fruit in 2001, with strawberries the most intensively treated crop in 2001 but some paraquat use was for control of strawberry runners as well as weeds.

Herbicide usage in soft fruit in 1971 (not shown) and 1975 was for general weed control, with simazine and paraquat used extensively. The use of simazine increased in 1975 by 1800 ha in England and Wales and paraquat, dichlobenil and chlorthiamid was also increasing. Propyzamide and glyphosate were not available in 1971 but appeared in the 1975 survey. Residual hebicides lenacil until 1990 and propyzamide until 1998 were important.

Table 4.21 *Usage of pesticides on soft fruit crops grown in Great Britain, 1975 - 2001 (spray hectares). Herbicides used on 10% of the crop or more in red; herbicides not supported or which did not achieve Annex 1 listing in the EC Review in blue; no longer available green*

Crop year	**1975**	**1980**	**1990**	**1994**	**1998**	**2001**
Crop area	**17,277**	**19,140**	**15,102**	**12,520**	**9,430**	**9,432**
HerbicidesTotal weeds						
Diquat			3,308	3,697	3,513	
Diquat/paraquat		575		(3,646)	3,477	2,918
Glufosinate-ammonium				257	1,487	1,328
Glyphosate	266		751	979	1660	1,784
Paraquat	7,823	7,168	7,269	(3922) 7,568	2,791	2,031
Grasses						
Fluazifop-P-butyl			725	1,466	674	806
Herbicides Broad-leaved weeds & grasses						
Bromacil	1,337	1416	1,314	1,019	913	277
Chlorthal-dimethyl		657	518	641	205	137
Chlorthiamid	2,213	908				
Clopyralid			1,387	1,552	1,140	866
Dichlobenil	2,108	1,557	860	1,280	683	1,685
Diuron	242	469		1,085	407	516
Isoxaben			2,269	2,976	1,947	1,547
Lenacil	2,603	3,717	1,717	738	226	226
MCPA	313	412				
MCPB	1,672	1,308		489		169
Napropamide			2,091	2,277	1,888	2,068
Oxadiazon		1,064	767	1,250	495	734
Pendimethalin		168	1,330	2,073	1,722	1,582
Phenmedipham	337		1,973	1,287	582	643
Propachlor		663	1,680	2,181	1,326	926
Propyzamide	2,861	2,947	2,737	2,193	1,368	954
Simazine	10,691	14,025	11,563	8,402	4,605	4,113
Mainly primocane removal						
Dinoseb +/- oil	119	1,377				
Diquat/paraquat		575				
Sodium monochloroacetate			20	607	702	181
Herbicide treated area (ha)	**35,711**	**47,175**	**42,460**	**41,054**	**29,185**	**26,092**
Herbicides as % area grown	**207**	**247**	**281**	**283**	**309**	**277**

In 1975 some of the paraquat was used for runner control in strawberries (and up to 2001) and particularly in Scotland for primocane control in raspberries but sodium monochloroacetate is used for this purpose now and after 2007 there is no obvious alternative. The 1980 survey shows chlorthiamid use had decreased and it was later withdrawn. MCPB declined in popularity from 1975 and after 1980, was seldom used.

After more than 30 years simazine is still the most widely used residual herbicide in tolerant crops (Table 4.21) – it is cheap and controls most annual broad-leaved weeds and grasses (Appendix 7). However triazine- resistant groundsel and willowherb occur in fruit crops and other weeds have also become resistant to simazine (see section 4.3). Resistance to paraquat has also been reported in some species. In soft fruit from about 1990 simazine became part of a programme with: dichlobenil, oxadiazon and diuron (blackcurrants), with napropamide, isoxaben, bromacil, oxadiazon (raspberries) and napropamide, pendimethalin, isoxaben (strawberries) and several of these control perennial weeds as well. In addition, for strawberries, post-emergence phenmedipham was used from 1975 but is less important in recent surveys and a post-emergence graminicide, fluazifop-p-butyl, was used to control grass weeds from 1990.

4.6.5 Orchard crops (Top fruit) (Table 4.22)

Table 4.22 *Usage of herbicides (spray hectares) on top fruit crops grown in Great Britain 1979 – 2000, small area in Scotland, excluded 1979 (95 ha) and 1983. Herbicides used on 10% of the crop or more in red; not supported or which did not achieve Annex 1 listing in the EC Review in blue; withdrawn green.*

Crop year	**1979 (E & W)**	**1983 (E & W)**	**1992**	**1996**	**2000**
Crop area all top fruit	**42,916**	**35,443**	**28,751**	**24,498**	**22,595**
Herbicides Total weeds					
Diquat/paraquat		1,634	1,404	1,056	873
Glufosinate-ammonium			1,628	5,813	4,919
Glyphosate	7,402	4,485	1,714	13,097	15,954
Paraquat	16,654	8,894	1,805	1,903	1,822
Herbicides Broad-leaved weeds (& grasses)					
2,4-D	7,264	2,337		9,369	1,947
2,4,5-T	3,809				
2,4-D/dichlorprop/MCPA/mecoprop	4,226	17,496	10,483	8,861	4,433
Amitrole (and mixtures 79 & 83)	30,354	37,769	15,112	10,192	4,071
Dicamba/MCPA/mecoprop	6233	3,372	1,675	5,079	3,617
Dicamba/MCPA/mecoprop-P					2,939
Dicamba//2,4-D/2,4,5-T	2,772				
Dicamba/mecoprop/2,4,5-T	4,080				
Dinoseb in oil		5,691			
Diuron	2,081		8,401	7,443	3,770
MCPA	3,752				
Mecoprop	4,522	1,863			
Oxadiazon	1,010				
Pendimethalin			535	1,822	1,895
Propyzamide	1,251	1,813	718	844	1,084
Simazine	25,935	32,306	14,121	14,997	7,850
Triclopyr			719	562	+
Herbicide treated area (ha)	**125,817**	**128,157**	**61,680**	**74,282**	**56,356**
Herbicides as % area grown	**293**	**362**	**215**	**303**	**249**

In 1979 and 1983, surveys showed amitrole, alone or mixture was the main herbicide, closely followed by simazine. Dinoseb in oil was used on 16% of top fruit in 1983, but use was revoked in 1986. Surveys for 1996 show that there were several herbicide applications, approximately three per year for general weed control usually as applications at the base of the tree and this decreased to 2.5 in the 2000 survey. Cider apples and perry pears are less intensively treated than other top fruit. Specific weed problems mentioned were: field-bindweed, controlled with 2,4-D/dichlorprop/MCPA/mecoprop, dicamba/mecoprop/MCPA and glyphosate; docks, nettles and thistles were controlled with 2,4-D/dichlorprop/MCPA/mecoprop (Appendix 8) and glufosinate, brambles with triclopyr used for 562 ha in 1996 and thistles with clopyralid. In some situations groundsel had become resistant to simazine. The top ten active substances remained the same from 1979 to 1996, except for 2,4,5-T, which was withdrawn in 1986 and was replaced by dichlorprop.

The 2000 survey shows a reduction in treated area with only 35% of the crop treated with simazine, compared with 61% in 1996, and also a substantial reduction in diuron. In 2000 there was an increase in glyphosate use of 20%. Glyphosate, introduced in the 1970s, is cheap and has now by far the greatest use for total weed control. The growing system has changed since the 1970s and 80s when the use of residual herbicides overall was widely advised. Now, top fruit are grown with weed free strips round the tree base, and grass alleys between - consequently the area treated with simazine, although still important, has declined considerably and orchards are more likely to be treated with glyphosate now.

There have been changes to herbicide isomers: mecoprop to mecoprop P and although dichlorprop will go in 2003, it will be replaced by dichlorprop P. Changes are also due to availability: glufosinate-ammonium was not available till 1987 and began to replace paraquat.

4.6.6 Hardy Nursery Stock (Table 4.23)

Since 1981, there has been a 21% increase in the total area of hardy nursery stock grown, though the area has declined by 10% since the previous survey in 1997. However, the areas of Christmas trees increased by 31% since 1997, that of ornamental trees by 20% and herbaceous plants by 4%.

In 2001 the greatest herbicide use was in fruit stock (nearly 5 applications), the least in Christmas trees and some herbaceous plants were not treated at all. Overall herbicide usage increased slightly over the last two decades, by about five percent since 1981, though usage in 2001 decreased by 16% since 1997. However herbicide use as % of the area grown decreased since 1981. The total weight of herbicides applied to hardy nursery stock has also declined by 35% since 1981. Usage of the two of the main herbicides in 2001, glyphosate and diquat/paraquat, had increased since the last survey. Glyphosate has tended to replace other herbicides for total vegetation control, partly because it is cheaper than it was in 1993. Other herbicides showing major increases in use were diuron and pendimethalin, used mainly around Christmas trees. There were major increases from 1993 to 1997 for pre-emergence isoxaben, post-emergence phenmedipham, used mainly in fruit stock; clopyralid used primarily for Compositae in Christmas trees and fruit stock but in the 2001 survey these had all declined as had several others. Simazine has been the main residual herbicide for nursery stock since the 1970s but after 1981 there has been a significant decline in simazine usage. Oxadiazon, used on mixed areas and fruit stock, does not control chickweed (Appendix 9) and has become less popular since 1993.

__Table 4.23__ Comparison of herbicide usage on hardy nursery stock 1981 - 2001, area treated (ha). Herbicides used on 10% of the crop or more in red; not supported or which did not achieve Annex 1 listing in the EC Review in blue.

Crop year	**1981**	**1993**	**1997**	**2001**
Crop area	**6,465**	**8,172**	**8,706**	**7,806**
Herbicides Total weeds				
Diquat/paraquat	503	1,314	559	1,791
Glufosinate-ammonium	-	243	1,012	1,127
Glyphosate	2,268	1,989	3,477	4,175
Paraquat	3,856	2,484	1,553	1,072
Grasses				
Cycloxydim			152	
Fluazifop-P-butyl		192	206	71
Propaquizafop			192	
Herbicides Broad-leaved (& grasses)				
2,4-D/dicamba/triclopyr			72	
Atrazine	687	583	884	669
Chlorthal-dimethyl			105	
Clopyralid		114	1,101	760
Cyanazine			275	138
Dichlobenil	326	283	430	128
Diphenamid	230	1,852	+	
Diuron	17	310	387	998
Isoxaben	-	1,434	2,572	1,971
Lenacil		177	331	142
Linuron			94	
Linuron/trifluralin			76	
Metazachlor	-	2,322	1,835	1,643
Napropamide		196	319	173
Oxadiazon	599	2,154	1,657	1,143
Pendimethalin	118	709	689	911
Phenmedipham	52	219	1,253	639
Propachlor		123	433	206
Propyzamide	1,010	1,141	1,563	884
Simazine	5,555	2,576	3,236	1,923
Trifluralin			212	
Herbicide area treated (ha)	**20,047**	**21,113**	**25,092**	**21,032**
Herbicides as % area grown	**310**	**258**	**288**	**269**
Soil sterilants area treated (ha)	**202**	**119**	**95**	**43**

Over the last 20 years additional herbicides have been developed for use in programmes, for example with simazine to complement the weed spectra to control triazine-resistant groundsel (metazachlor) (Appendix 9) or solve other problems such as hairy bittercress (isoxaben), thistles (clopyralid). In 1981 metazachlor and isoxaben were not available. Diphenamid, a residual herbicide widely used in 1993 became unavailable and is no longer approved in GB.

The use of soil sterilants, mainly used on shrubs and herbaceous plants, has declined and the area applied in 2001 was less than half that used in 1981. Usage of dazomet increased, whilst that of methyl bromide, (which is to be phased out by 2005) and metam-sodium decreased.

4.7 Weed species: susceptibility to the main herbicides

The susceptibility of weeds shown on labels often covers only the species shown in the Tables. There may be more information, but fewer trials are done in minor crops in comparison with winter wheat. A non-selective herbicide such as glyphosate can achieve 100% weed control under favourable conditions, but it is rare for a selective herbicide to consistently achieve 100% weed kill of a “susceptible” species. The requirement to claim susceptibility on a label for UK registration is that there is at least 85% control in 5 trials where the population on untreated plots is at least $5m^{-2}$. The resistant species, i.e. those where control would be less than 60%, are often not shown on labels by the manufacturer.

Labels for the same active substance sometimes differ significantly between the amounts of information given. For example, simazine: Gesatop, from the company which discovered it, states “for pre-emergence control of most annual weeds”, the label for Atlas Simazine mentions 43 Susceptible/Moderately Susceptible species and 12 Moderately Resistant/Resistant species.

Very few of the rare arable flowers on the UK Biodiversity Action Plan (BAP) Lists, the Cereal Field Margin Habitat Biodiversity Action Plan or surveyed under the Botanical Society of the British Isles Scarce Plant Project are mentioned on these labels precisely because they are rare and have not been found on untreated plots in trials on horticultural land. The only ones are:

Pendimethalin	S = corn buttercup *(Ranunculus arvensis)* (Appendix 4)
Simazine	S = field gromwell *(Lithospermum arvense)*; R = corn buttercup (Appendix 7)
MCPA	S = corn buttercup, cornflower *(Centaurea cyanus)*, field gromwell, shepherd’s-needle *(Scandix pectin-veneris)* (Appendix 8).

There are no recorded weed surveys in horticultural crops. However, much information could be gained from efficacy trials data submitted to the Pesticide Safety Directorate Defra, for herbicide product Approval, where comparisons are made with plots untreated with herbicides. From personal experience, in over 25 years of trials, weed numbers and diversity do not appear to have declined. There is some information on cleavers from a limited informal survey in a range of crops (BCPC Weed Review, 1999). Crop specialists/Agronomists have knowledge of weed problems and contributed to information in vegetables in the Weed Management Handbook (2002). They report common occurrence of fumitory and knotgrass on light soils, fools parsley and also corn marigold. On fields where there is a history of brassica growing and as a result of frequent use of trifluralin, groundsel, cruciferous weeds (e.g shepherd’s purse) and mayweeds often occur. Mayweeds in carrots account for the large area sprayed with metoxuron. Other weeds occur as a result of too frequent use of some herbicides on the same field (black-nightshade in sweetcorn, simazine–resistant groundsel in orchards). Perhaps the only declining weed species in horticultural crops are wild-oats and common couch - these are not often quoted now as target species in surveys or in advisory calls.

Volunteer potatoes and oilseed rape, both of them widespread and persistent problems, have attracted more attention. A survey in 1992 by processors of the incidence of volunteer potatoes in peas and beans showed that the area affected had increased since a similar survey in 1974, despite the decline in potato area, and that 46% of vining peas, 68% of dwarf French beans needed control measures to avoid reduction of quality (Knott, 1993). Results from the same survey showed oilseed rape volunteers infested 25% of vining peas and 100% of broad beans. These volunteers are troublesome in onions, carrots and several other crops. Borage is also a good survivor, but linseed capsules fortunately do not appear to remain viable for long.

Surveys in some crops (bulbs) show an increase in post-emergence use of the same herbicide. This may suggest that weed seedbanks are increasing or it may be a result of poor performance of residual herbicides in dry seasons.

4.8 Weed management for the future

- **Cropping**: weed spectra on fields are very dependent on cropping. Thus changes in weed spectra could occur, if for example, there is a reduction in winter-cropping of cereals (as a result of changes in EU policy), or if some vegetables or fruit are no longer produced as a result of falling consumer demand, competition from imports or if they are no longer economically viable because of pesticide losses.

- **Climate change** will also influence the crops grown, composition and competitive ability of associated weed flora (Patterson, 1995). Temperature increases of 2-4 °C over the next 50 years, perhaps greater seasonal rainfall, wetter milder winters, hotter drier summers, and erratic weather patterns are predicted. Weed population shifts as a result of global climate change caused by the "greenhouse effect" (Froud-Williams, 1996) are also likely. Winter hardy weeds and crops suited to a cool wet climate are likely to shift north; crops which are more tolerant of a drier, hotter climate and their associated summer weeds adapted to these conditions, could be introduced from Southern Europe. There has already been an expansion of forage maize grown in England. Red-root pigweed (*Amaranthus retroflexus*) common in Mediterranean countries has now appeared here. Most of the world's worst weeds are efficient users of water, but many crops are less efficient. Elevated CO_2 levels are also predicted and increased CO_2 has different effects depending on crop and weed species concerned.

  Herbicides used in warmer climate crops will affect weed species composition as a result of the weed spectra they control.

  There are likely to be implications of climate change for herbicide efficacy and impact. Already, milder GB winters appear to be changing the time of emergence of some weed species, for example more competitive, earlier emerging cleavers will complicate herbicide programmes. Weeds requiring warm temperatures before germination occurs, e.g. black-nightshade, may emerge and mature earlier, thus increasing problems with toxic berries. Crop sowing programmes may need to change. Other scenarios are suggested by Froud-Williams (1996). Herbicide persistence is dependent on temperature and rainfall. There is already evidence (Bailey, 2003) that some herbicides, e.g. isoproturon, are breaking down more rapidly in recent years in England due to warmer winters and are becoming less effective. Higher rainfall will increase herbicide leaching into groundwater. The effect of temperature, light and humidity on foliar applied herbicide increases performance in some cases, but moisture stress reduces efficacy, while high humidity and temperature increase penetration. Climate change could restrict opportunities to apply some herbicides e.g. bentazone - labels carry a warning of crop damage if it is applied at temperatures over 21°C.

- **Loss of herbicides** for some horticultural crops will result in an increase in populations of some species hitherto controlled: mayweeds (metoxuron) and common fumitory (prometryn) in carrots; charlock in brassicas (cyanazine). If there is a restricted range of herbicides we will also see an increase of weed species tolerant to those herbicides (for example groundsel and mayweeds not controlled by pendimethalin). Where mechanical or other **non-chemical methods** are used, species more easily removed (speedwells, chickweed) may decrease, while those with a strongly developed or wiry taproot (charlock, oilseed rape volunteers and black-bindweed) are more likely to remain.

- The **limited range of herbicides** left for horticultural crops will also increase the risk of herbicide resistance (section 4.3). The frequent use of herbicides to control certain weeds is causing problems with herbicide-resistant biotypes in many parts of the world and this has occurred with several herbicide groups. Herbicide-resistant black-grass in cereals are already spreading to vegetable crops where they were controlled with graminicide 'fops' and 'dims'. A gradual change in resistance will be buffered to some extent by the soil weed seedbank. This is because post-harvest cultivations will tend to bury the freshly shed seed from treated plants and bring to the surface seed from previous years (Grundy *et al,* 1999). Therefore, under commercial cropping, it is difficult to determine how serious a problem creeping resistance is likely to be and may take several years to reach a measurable level. Recent studies of baseline weed sensitivities to herbicides in cereals have already noted that natural variation in weed populations is poorly quantified and hence relatively small changes in response to a herbicide are therefore likely to be extremely difficult to identify in the very early stages (Collings *et al.*, 2001). With repeated use of a limited range of products the balance of the weed floral composition will also change over time, as species repeatedly controlled by a product may allow other, species less susceptible to that product, gain a foothold.

- **Sub-lethal applications of herbicides** may also possibly contribute to changes in the flora through subtle effects on the germination, competitive ability or fecundity of the progeny of treated maternal plants. Sometimes these effects are only expressed in the very early growth stages of an individual. A study of the effects of sub-lethal rates of fluroxypyr on field speedwell reported that seed size was negatively correlated with herbicide application rate, possibly as a result of earlier senescence and incomplete seed fill or even the mobilization of seed reserves (Champion *et al.,* 1998). Furthermore, the smaller seeds had significantly reduced germination percentage compared with the larger seeds. Therefore, not only was the herbicide application rate influencing the distribution of seed sizes produced by the maternal plants, but also the germination profile of those seeds. Sub-lethal rates herbicides applied to the maternal generation may even effect the fecundity of the progeny themselves (Grundy *et al.,* 1995). However, it is likely that there is a complex relationship between timing of herbicide application (Andersson, 1996) and the weed species/herbicide combination. Clearly, the relative importance of these maternal effects is largely unknown and further information is required to fully interpret the many implications of reduced herbicide applications on subsequent weed population shifts.

- If **Genetically Modified Herbicide-Tolerant crops** are grown commercially in the UK in the future, volunteers could be difficult to manage with or without herbicides.

- **Invasive aliens** have always had an impact and many are now commonly found in UK horticulture, for example common field speedwell introduced from Western Asia (probably 1825), gallant soldier from South America (1860) and pineappleweed from North East Asia (1871) (Mortimer, 1990). More recent examples are dodder (*Cuscuta* spp) introduced in carrot seed, red root pigweed (*Amaranthus retroflexus*) in maize seed and feed, and *Cyperus* spp. in some bulbs/corms such as gladioli.

4.9 Summary & Conclusions

Weed control in horticultural crops

1. Economic loss of high value horticultural crops can occur if failure to control weeds results in reduced quality and crop rejection (Table 2). In all conventionally grown horticultural crops weed control is mainly with herbicides (Chapter 3)

2. The total herbicide treated area of wheat in 2000 was over 7.3 million ha, 354 % of the crop area (3 to 4 passes), which far exceeded the herbicide input for the largest horticultural crop, potatoes. The area of potatoes treated with herbicides was small in comparison 342,032 ha, 212% of the potato area (2 passes).

3. Pesticide Usage Survey data shows that for perennial crops, top fruit, bulbs and HNS where long-term weed control is required, the number of (up to 3) herbicide applications of mainly total weed killers remained the same over the last 20 years. However, the percentage area of other horticultural crops treated with herbicides has increased considerably. In 1972, 104% of the vegetable area was treated with herbicides; by 1999, this had increased to 341%, (3 to 4 passes). There are several possible reasons for this:

   - Repeat low dose programmes are used in some crops (onions 9+, carrots 5+) - although number of applications has increased the total amount of herbicide has not

   - The demand for quality i.e. pressure from the consumer, retailer and/or processor to deliver produce free from weedy contaminants

   - Cost-cutting and reduced herbicide dose rates in winter cereals has led to an increase in grasses, cleavers and other weeds appearing in horticultural crops grown in arable rotations

   - Availability of additional herbicides to widen the weed spectrum

   These data may also suggest, that the weed populations in some horticultural crops are not declining and many frequently escape control measures.

5. Pesticide usage surveys show that from the 1980s the use of non-selective glyphosate in orchards and hardy nursery stock, or pre-sowing of vegetables and bulbs, increased and glyphosate is by far the most widely used herbicide. Linuron (potatoes, carrots) is the most important selective residual/contact-acting herbicide.

6. Over the last 25 years or more, the core herbicides for horticultural crops have remained the same but additional herbicides have been developed and SOLAs granted, to control specific problem weeds (e.g. clopyralid for thistle control in brassicas) so that it is possible to control a wider weed spectrum. The situation is changing quickly. There will be several herbicide losses 2003/2007 as a result of lack of support in the EC Review. These include three of the top ten most important herbicides for vegetables.

7. The high cost of pesticide registration and development in Europe, relative to small sales for horticultural crops means in future we can expect very few new herbicides, particularly broad-leaved weed killers, which, for reasons of safety, are more crop-specific. Lack of alternatives for weed control will mean that some crops will becomes uneconomic to grow here or in the rest of the EU. Crops identified as having important gaps for weed control after 2007 (HDC GAP Analysis, URL http://www.hdc.org.uk) are carrots, celery, herbs, dwarf French beans, vining peas. If simazine does not achieve Annex 1 status, then broad beans, sweetcorn, soft fruit, top fruit, HNS will also be severely disadvantaged.

8. In most horticultural crops the costs of alternative weed control methods are higher than for weed control with herbicides. Hand labour has now become expensive and scarce. In future there are likely to be more weeds in these crops. Therefore, non-chemical methods are unlikely to deliver sufficiently to "replace" herbicides and thus to be able to meet the general demands of the market. It was estimated in the NCFAP study in the USA that most fruit and vegetable crops were projected to use 50 to 148 hours of handweeding per hectare because herbicides will become unavailable.

9. Factors which may affect weed flora composition in future are: -

    - Reliance on a limited range of herbicide active ingredients in a widening range of crops will increase the problem of developing tolerant weed flora, not necessarily rare or other desirable species, and will increase the risk of herbicide resistance occurring.
    - Weed spectra are very dependent on cropping - changes could occur if there is a reduction in winter-cropping of cereals, or if some vegetables or fruit are no longer produced as a result of falling consumer demand, competition from imports or if they are no longer economically viable because of pesticide losses.
    - Climate change will influence the crops grown, herbicides used if available, and composition and competitive ability of associated weed flora. Weed population shifts as a result of global climate change are predicted.
    - Introduction of invasive aliens.
    - Some genetically modified herbicide-tolerant crop volunteers could be difficult to manage with or without herbicides.

Implications for Biodiversity

1. Like herbicides, non-chemical methods are also aimed at controlling all weeds. Where mechanical weed control methods are used, species more easily removed (chickweed) may decrease, while those with a strongly developed or wiry taproot (charlock, oilseed rape volunteers and black-bindweed) are more likely to remain. Flame and steam weeding and repeated cultivations may, in addition to removing weeds, also have adverse effects on soil structure, ground-nesting birds and invertebrates.

2. Very few of the rare arable flowers are mentioned on herbicide labels (data generated over 25 years in many cases) because they have not been found on untreated plots in trials on horticultural land, i.e. precisely because they are rare. This suggests that reduction of herbicide use or doses, or non-chemical weed control is unlikely to

improve the populations of these rare species. However, there are no specific baseline surveys in horticultural crops to be able confirm this.

3. Reliance on a narrowing range of active ingredients in a widening range of crops will increase the problem of developing tolerant weed flora, not necessarily rare or other desirable species. For example, cruciferous weeds have built up after continual use of trifluralin in brassicas in the rotation.

4. Reduced doses of a limited number of herbicides is likely to result in a build up of species classed as moderately susceptible, or moderately resistant, on the label (see Appendices). These are often aggressive undesirable species (cleavers) rather than "beneficial" weeds.

5. If certain weeds beneficial for insects and hence bird food, such as chickweed and knotgrass are left to flourish within horticultural crops, how can this be done? For vegetables it would be difficult, either with herbicides, or non-chemical means, to selectively leave these species without leaving others as potential contaminants of harvested produce. Information in Appendices shows weed susceptibility for the herbicides used in each crop – virtually all control common chickweed. If strips within a field were left untreated and weedy, the crop could not be harvested because of contaminant risk.

4.10 References

PESTICIDE USAGE SURVEYS. Reports are by central science laboratories (CSL), sand hutton, york and a list of reports and some summaries can be viewed on the internet URL http://www.csl.gov.uk. Copies of the more recent reports for England & Wales, or Great Britain, are obtainable from Department for Environment, Food and Rural Affairs (Defra), Defra publications, London SE99 7TP, data relating specifically to scotland, from the Scottish Agriculture and Fisheries Department. Many of the older reports used in this study are no longer available.

ANDERSSON L (1996). Seed production and seed weight of six weed species treated with MCPA. *Swedish Journal of Agricultural Research* **24:** 95-100.

BAILEY SW (2003) climate change and decreasing herbicide persistence. *Pest Management Science*, (in press).

BRITISH CROP PROTECTION COUNCIL (BCPC) (1999) biology and control of cleavers. In: *BCPC 36th Annual Review of Weed Control*. British crop protection council, farnham, uk.

CHAMPION GT, FROUD-WILLIAMS RJ & HOLLAND JM (1998). The effect of reduced rates of fluroxypyr on the seed size and germination of common field speedwell *Veronica persica*. *Aspects of Applied Biology 51, Weed Seedbanks: etermination, dynamics & manipulation.* 143-146.

COLLINGS LV, BLAIR AM & CLARKE JH (2001). Establishing background sensitivities of a range of herbicide treatments. *Brighton Crop Protection Conference- weeds* 583-588.

DEPARTMENT FOR ENVIRONMENT, FOOD AND RURAL AFFAIRS (Defra), (2002) *basic horticultural statistics for the uk, calendar and crop years 1991/92 – 2001/2002.* Defra publications, London, UK.

DERR JF (2001) Biological assessment of herbicide use in apple production - II. Estimated impacts following loss of specific herbicides. *Horttechnology* **11**: 20-25

DONY JG, JURY SL & PERRING FH (1986) *English names of wild flowers*, 2nd edn. The Botanical Society of the British Isles, UK.

FREY JE, MULLER-SCHARER H, FREY B, FREI D (1999) Complex relation between triazine-susceptible phenotype and genotype in the weed Senecio vulgaris may be caused by chloroplast DNA polymorphism. *Theoretical and Applied Genetics* **99**: 578-586

FROUD-WILLIAMS RJ (1996) weeds and climate change:implications for their ecology and control. *Aspects of Applied Biology* **45,** *Implications of "Global Environment Change" for Crops in Europe,* 187-196

GILLOTT I (2001). Herbicide use in minor crops: an agronomist's view. *Brighton Crop Protection Conference - weeds* 799-802

GRESSEL J (1995). Creeping resistances: the outcome of using marginally-effective or reduced rates of herbicide. *Brighton Crop Protection Conference- weeds* 587-590.

GRUNDY AC, FROUD-WILLIAMS RJ & BOATMAN ND (1995). Maternal effects in progeny of field pansy (*viola arvensis*) subjected to different herbicide and nitrogen rates. *Annals of applied biology* **127:** 343-352.

GRUNDY, AC, MEAD, A. & BURSTON, S. (1999). Modelling the effect of cultivation on seed movement with application to the prediction of weed seedling emergence. *Journal of Applied Ecology*, **36**, 663-678.

HEAP I (2001). International survey of herbicide-resistant weeds. Internet site: hhttp://www.weedscience.com

HORTICULTURAL DEVELOPMENT COUNCIL (HDC) (2003) *Gap Analysis.* Internet online url http://www.hdc.org.uk

KNOTT CM(1993). Volunteer crops in legumes for processing. *Aspects of Applied Biology* **35** *Volunteer Crops as Weeds,* 207-213.

KNOTT CM (2002) weed control in arable and field vegetable crops. In: *weed Management Handbook.*(ed. RL Naylor) 359-398. British Crop Protection Council, Blackwell Science Ltd., Oxford, UK.

MORTIMER AM (1990) the biology of weeds. In: *Weed Management Handbook, Principles, 8th edn.* (eds RJ Hance & K Holly)1-42. British Crop Protection Council, Blackwell Scientific Publications, Oxford, UK.

MOSS SR (2002) herbicide–resistant weeds. In: *Weed Management Handbook* (ed REL Naylor) 9th edn, published for the British Crop Protection Council by Blackwell Science, Oxford UK.

NATIONAL CENTER FOR FOOD & AGRICULTURAL POLICY (NCFAP) (2003) *The value of herbicides in U. S. Crop production* (eds LP Gianessi & S Sankula). NCFAP, Washington DC, USA.

NIX J (2002) *Farm Management Pocketbook 33rd edition 2003*. Imperial College Wye, Andersons Centre, Melton Mowbray, UK.

PATTERSON DT (1995). Weeds in a changing climate. *Weed Science* **45**, 685-701.

POWELS SB & SHANER DL (2001). *Herbicide resistance in world grains*. CRC Press: Boca Raton, Florida, USA.

STACE C (1997) *New Flora of the British Isles 2nd edition*. Cambridge University Press, Cambridge, UK.

TEI F, BAUMANN DT, BLEEKER P *ET AL.* (1999) Weeds and weed management in carrots – a review. In: *the 11th European Weed Research Society Symposium 1999,* Basel. Switzerland. Summary on internet online url http://www.agr.unipg.it/ewrsveg

All weed names in Chapter 4 text and appendices, Dony *et al.* (1986), English; Stace (1997), Latin

Appendix 1 Weed Susceptibility to the main herbicides in Potatoes.

Key: S = susceptible; MS = Moderately Susceptible; R = Resistant; MR = Moderately Resistant

		linuron	**bentazone**	**metribuzin**	**metribuzin**
		pre	**post**	**pre**	**post**
Common name	**Latin name**				
Bindweed black	*Fallopia convolvulus*	S	MS	MS	S
Bugloss	*Anchusa arvensis*	S		S	S
Charlock	*Sinapis arvensis*	S	S	S	S
Chickweed, common	*Stellaria media*	S	S	S	S
Chickweed, mouse-eared	*Cerastium fontanum*				
Cleavers	*Galium aparine*	MR	S	R	R
Corn marigold	*Chrysanthemum segetum*	S	S		MS
Corn spurrey	*Spergula arvensis*	S	S	S	S
Crane's-bill, cut-leaved	*Geranium dissectum*		S		
Deadnettle, henbit	*Lamium amplexicaule*		MS	S	S
Dead-nettle, red	*Lamium purpureum*	S	MS	S	S
Dock, broad-leaved	*Rumex obtusifolius*				
Fat-hen	*Chenopodium album*	S	MS	S	S
Fool's parsley	*Aethusa cynapium*		S		
Forget-me-not, field	*Myosotis arvensis*	S	S	S	S
Fumitory, common	*Fumaria officinalis*	R	MS	S	S
Gallant -soldier	*Galinsoga parviflora*	S			
Groundsel	*Senecio vulgaris*	S	MS	S	S
Hemp-nettle, common	*Galeopsis tetrahit*	S	MR	S	S
Knotgrass	*Polygonum aviculare*	MS	MR	S	MS
Mayweed, scented	*Matricaria recutita*	S	S	S	S
Mayweed, scentless	*Tripleurospermum inodorum*	S	S	S	S
Nettle, small	*Urtica urens*	S	S	S	S
Nightshade black	*Solanum nigrum*	S	S	S	S
Orache, common	*Atriplex patula*	S	MS	S	S
Pansy, field	*Viola arvensis*	S	R	S	MS
Parsley piert	*Aphanes arvensis*				
Pennycress, field	*Thlaspi arvense*	S	S	S	S
Persicaria, pale	*Persicaria lapathifolia*	S	S	S	S
Pimpernel, scarlet	*Anagalis arvensis*	S	S	S	S
Pineappleweed	*Matricaria discoidea*	S	S		
Poppy, common	*Papaver rhoeas*	S	MS		
Redshank	*Persicaria maculosa*	S	S	S	S
Shepherd's-purse	*Capsella bursa-pastoris*	S	S	S	S
Sow-thistle, smooth	*Sonchus oleraceus*	S	MS	S	MS
Speedwell, common, field	*Veronica persica*	S	MS	S	S
Speedwell, ivy-leaved	*Veronica hederifolia*		MR	S	S
Sun spurge	*Euphorbia helioscopia*			S	
Thistle, creeping	*Cirsium arvense*	R	suppr		
Wild radish	*Raphanus raphanistrum*	S	S	S	S
Annual meadow grass	*Poa annua*	MS	R	S	S
Blackgrass	*Alopecurus myosuroides*		R	S	MS
Brome, barren	*Anisantha sterilis*				
Wild-oat	*Avena fatua*	R			
Vol OSR	*Brassica napus*		S	S	S
Vol Potatoes	*Solanum tuberosum*				

Diquat/paraquat; paraquat; glyphosate total herbicides widely used

Appendix 2 Weed Susceptibility to the main herbicides for Brassicas (Leaf and Root).

In 1977 desmetryne was widely used

Key: S = susceptible; MS = Moderately Susceptible; R = Resistant; MR = Moderately Resistant

		trifluralin	propachlor	cyanazine	metazachlor	clopyralid
		presow	pre	post	pre	post
Common name	**Latin name**					
Bindweed black	*Fallopia convolvulus*	S	R	S		MS
Bugloss	*Anchusa arvensis*			S		
Charlock	*Sinapis arvensis*	R	R	S		
Chickweed, common	*Stellaria media*	S	S	S	S	
Chickweed, mouse-eared	*Cerastium fontanum*					
Cleavers	*Galium aparine*	R	S	R	MR	
Corn marigold	*Chrysanthemum segetum*	R	S			R
Corn spurrey	*Spergula arvensis*	MS	S			
Crane's-bill, cut-leaved	*Geranium dissectum*			MR	MR	
Deadnettle, henbit	*Lamium amplexicaule*	S	MS	S		
Dead-nettle, red	*Lamium purpureum*	MS	S	S	S	
Dock, broad-leaved	*Rumex obtusifolius*					
Fat-hen	*Chenopodium album*	S	MR	S		
Fool's parsley	*Aethusa cynapium*			S		
Forget-me-not, field	*Myosotis arvensis*			S	S	
Fumitory, common	*Fumaria officinalis*	MS	R	S	R	
Gallant -soldier	*Galinsoga parviflora*		S			
Groundsel	*Senecio vulgaris*	R	S	S	S	S
Hemp-nettle, common	*Galeopsis tetrahit*	S	S	S		
Knotgrass	*Polygonum aviculare*	S	R	S	R	
Mayweed, scented	*Matricaria recutita*	R	S	S	S	S
Mayweed, scentless	*Tripleurospermum inodorum*	R	S	S	S	S
Nettle, small	*Urtica urens*	MS	S	S		
Nightshade black	*Solanum nigrum*	R	MS	S		
Orache, common	*Atriplex patula*	MS	MR	S		S
Pansy, field	*Viola arvensis*		S	S	R	
Parsley piert	*Aphanes arvensis*			MR	S	
Pennycress, field	*Thlaspi arvense*	R	R		R	
Persicaria, pale	*Persicaria lapathifolia*	S		S		M
Pimpernel, scarlet	*Anagalis arvensis*	S		S		
Pineappleweed	*Matricaria discoidea*	R	S	S		
Poppy, common	*Papaver rhoeas*			S	MS	
Redshank	*Persicaria maculosa*	S	R	S		MR
Shepherd's-purse	*Capsella bursa-pastoris*	R	S	S	S	
Sow-thistle, smooth	*Sonchus oleraceus*	R	MS			S
Speedwell, common, field	*Veronica persica*	S	S	S		
Speedwell, ivy-leaved	*Veronica hederifolia*			S		
Sun spurge	*Euphorbia helioscopia*		R			
Thistle, creeping	*Cirsium arvense*	R				S
Wild radish	*Raphanus raphanistrum*	R	R	S		
Annual meadow grass	*Poa annua*	S	S	S	S	
Blackgrass	*Alopecurus myosuroides*	S	S	MS	S	
Brome, barren	*Anisantha sterilis*			MS		
Wild-oat	*Avena fatua*	MS	R	R		
Willowherbs	*Epilobium* spp					
Vol OSR	*Brassica napus*					
Vol Potatoes	*Solanum tuberosum*					

Appendix 3 Weed Susceptibility to the main herbicides for Peas and Beans

Key: S = susceptible; MS = Moderately Susceptible; R = Resistant; MR = Moderately Resistant

		simazine/ trietazine	terbutryn/ terbuthylazine	fomesafen/ terbutryn	bentazone	cyanazine	bentazon/MCPB + cyanazine
		pre	pre	pre	post	post	post
Common name	**Latin name**						
Bindweed black	*Fallopia convolvulus*	MS	S	S	MS	S	S
Bugloss	*Anchusa arvensis*			S		S	
Charlock	*Sinapis arvensis*	S	S	S	S	S	S
Chickweed, common	*Stellaria media*	S	S	S	S	S	S
Chickweed, mouse-eared	*Cerastium fontanum*			S			
Cleavers	*Galium aparine*	R	R		S	R	MS
Corn marigold	*Chrysanthemum segetum*				S		
Corn spurrey	*Spergula arvensis*		S	MS	S		
Crane's-bill, cut-leaved	*Geranium dissectum*			MS	S	MR	
Deadnettle, henbit	*Lamium amplexicaule*			S	MS	S	
Dead-nettle, red	*Lamium purpureum*	S	S	S	MS	S	S
Dock, broad-leaved	*Rumex obtusifolius*						
Fat-hen	*Chenopodium album*	S	S	S	MS	S	S
Fool's parsley	*Aethusa cynapium*	S	R	(S)	S	S	MS
Forget-me-not, field	*Myosotis arvensis*			S	S	S	S
Fumitory, common	*Fumaria officinalis*	MS	S	S	MS	S	S
Gallant -soldier	*Galinsoga parviflora*						
Groundsel	*Senecio vulgaris*	S	S	S	MS	S	S
Hemp-nettle, common	*Galeopsis tetrahit*	MS	S	MS	MR	S	MS
Knotgrass	*Polygonum aviculare*	S	S	S	MR	S	MR
Mayweed, scented	*Matricaria recutita*	S	S		S	S	S
Mayweed, scentless	*Tripleurospermum inodorum*	S	S	S	S	S	S
Nettle, small	*Urtica urens*	S	S	S	S	S	S
Nightshade black	*Solanum nigrum*	MS	?	S	S	S	MS
Orache, common	*Atriplex patula*	MS		S	MS	S	S
Pansy, field	*Viola arvensis*	MS	S	S	R	S	S
Parsley piert	*Aphanes arvensis*	S				MR	S
Pennycress, field	*Thlaspi arvense*	S			S		
Persicaria, pale	*Persicaria lapathifolia*	S	S	S	S	S	S
Pimpernel, scarlet	*Anagalis arvensis*	S		S	S	S	
Pineappleweed	*Matricaria discoidea*	S			S	S	S
Poppy, common	*Papaver rhoeas*	S	S	S	MS	S	
Redshank	*Persicaria maculosa*	S	S	S	S	S	S
Shepherd's-purse	*Capsella bursa-pastoris*	S		S	S	S	S
Sow-thistle, smooth	*Sonchus oleraceus*	S		S	MS		MS
Speedwell, common, field	*Veronica persica*	S	S	S	MS	S	S
Speedwell, ivy-leaved	*Veronica hederifolia*	S	R	MS	MR	S	S
Sun spurge	*Euphorbia helioscopia*	MS		MR			
Thistle, creeping	*Cirsium arvense*		R	R	suppr		
Wild radish	*Raphanus raphanistrum*	S		S	S	S	
Annual meadow grass	*Poa annua*	MS	S	MS	R	S	R
Blackgrass	*Alopecurus myosuroides*	MS			R	MS	R
Brome, barren	*Anisantha sterilis*					MS	R
Wild-oat	*Avena fatua*	R				R	R
Vol OSR	*Brassica napus*		R	S	S		S
Vol Potatoes	*Solanum tuberosum*						

dinoseb revoked 1986, post-emergence control of most broad-leaved weeds except mustards
simazine/trietazine no longer available S =treacle mustard; MS = white campion
bentazone/MCPB + cyanazine; cyanazine; bentazone: S = black & white mustard
fomesafen/terbutryn: S = white campion

Appendix 4 Weed Susceptibility to the main herbicides for Onions & Leeks

Key: S = susceptible; MS = Moderately Susceptible; R = Resistant; MR = Moderately Resistant

		chloridazon	chlorpropham	cyanazine	propachlor	ioxynil	prometryn
		pre	pre	post	pre	post	pre/post
Common name	**Latin name**						
Bindweed black	*Fallopia convolvulus*	S	S	S	R	S	(Spre)
Bugloss	*Anchusa arvensis*			S		S	
Charlock	*Sinapis arvensis*	S	MR	S	R	S	(MSpre)
Chickweed, common	*Stellaria media*	S	S	S	S	S	S
Chickweed, mouse-eared	*Cerastium fontanum*		S				
Cleavers	*Galium aparine*	MR	R	R	S		R
Corn marigold	*Chrysanthemum segetum*	S	R		S		
Corn spurrey	*Spergula arvensis*	S	S		S		S
Crane's-bill, cut-leaved	*Geranium dissectum*		R	MR			
Deadnettle, henbit	*Lamium amplexicaule*		R	S	MS		
Dead-nettle, red	*Lamium purpureum*	S	R	S	S	S*	
Dock, broad-leaved	*Rumex obtusifolius*						
Fat-hen	*Chenopodium album*	S	MS	S	MR	S	S
Fool's parsley	*Aethusa cynapium*		R	S			
Forget-me-not, field	*Myosotis arvensis*			S			
Fumitory, common	*Fumaria officinalis*	MS	MS	S	R	S*	S
Gallant -soldier	*Galinsoga parviflora*		R		S		
Groundsel	*Senecio vulgaris*	MS	R	S	S	S	MS(Spre)
Hemp-nettle, common	*Galeopsis tetrahit*	S	S	S	S	S*	S
Knotgrass	*Polygonum aviculare*	S	S	S	R		(Spre)
Mayweed, scented	*Matricaria recutita*	S	R	S	S	S	(Spre)
Mayweed, scentless	*Tripleurospermum inodorum*	S	R	S	S	S	(Spre)
Nettle, small	*Urtica urens*	S	S	S	S	S*	S
Nightshade black	*Solanum nigrum*	S	R	S	MS	S	S
Orache, common	*Atriplex patula*	S	MS	S	MR	S	S
Pansy, field	*Viola arvensis*	MR	R	S	S		
Parsley piert	*Aphanes arvensis*		R	MR			
Pennycress, field	*Thlaspi arvense*	S	S		R		
Persicaria, pale	*Persicaria lapathifolia*		S	S		S*	S
Pimpernel, scarlet	*Anagalis arvensis*	MS	R	S			MS(Spre)
Pineappleweed	*Matricaria discoidea*	S	R	S	S	S	
Poppy, common	*Papaver rhoeas*	S	S	S			S
Redshank	*Persicaria maculosa*	S	S	S	R	S*	S
Shepherd's-purse	*Capsella bursa-pastoris*	S	MS	S	S	S	S
Sow-thistle, smooth	*Sonchus oleraceus*	MR	R		MS		(Spre)
Speedwell, common, field	*Veronica persica*	S	S	S	S	S	S
Speedwell, ivy-leaved	*Veronica hederifolia*	S	MS	S		S	S
Sun spurge	*Euphorbia helioscopia*	MR			R		
Thistle, creeping	*Cirsium arvense*		R			R	R
Wild radish	*Raphanus raphanistrum*	S	MR	S	R	S	Mspre
Annual meadow grass	*Poa annua*	S	S	S	S	R	(Spre)
Blackgrass	*Alopecurus myosuroides*		S	MS	S	R	
Brome, barren	*Anisantha sterilis*			MS		R	
Wild-oat	*Avena fatua*	R	MS	R	R	R	R
Vol OSR	*Brassica napus*						
Vol Potatoes	*Solanum tuberosum*						

methazole, chlorbufam/chloridazon no longer available

ioxynil: swinecress S

Appendix 5 Weed Susceptibility to the main herbicides for Carrots, Parsnips & Celery

Key: S = susceptible; MS = Moderately Susceptible; R = Resistant; MR = Moderately Resistant; rare BAP species in red text

		trifluralin	linuron		metoxuron	prometryn	pentanochlor	pendimethalin	metribuzin
		presow	pre	post	post	pre/post	pre	post	post
Common name	**Latin name**								
Bindweed black	*Fallopia convolvulus*	S	S	S	S	(Spre)	S	S	S
Bugloss	*Anchusa arvensis*		S	MR				S	S
Charlock	*Sinapis arvensis*	R	S	S	S	(MSpre)		S	S
Chickweed, common	*Stellaria media*	S	S	S	S	S	S	S	S
Chickweed, mouse-eared	*Cerastium fontanum*								
Cleavers	*Galium aparine*	R	MR	R	S	R	?	R	R
Corn marigold	*Chrysanthemum segetum*	R	S	R	S		S	MS	MS
Corn spurrey	*Spergula arvensis*	MS	S	S	S	S		S	S
Crane's-bill, cut-leaved	*Geranium dissectum*								
Deadnettle, henbit	*Lamium amplexicaule*	S					S	S	S
Dead-nettle, red	*Lamium purpureum*	MS	S	MR	S		S	S	S
Dock, broad-leaved	*Rumex obtusifolius*								
Fat-hen	*Chenopodium album*	S	S	S	S	S	S	S	S
Fool's parsley	*Aethusa cynapium*								
Forget-me-not, field	*Myosotis arvensis*		S	S	S		S	S	S
Fumitory, common	*Fumaria officinalis*	MS	R	R		S	MS	S	S
Gallant -soldier	*Galinsoga parviflora*		S	S					
Groundsel	*Senecio vulgaris*	R	S	MR	MS	MS(Spre)		S	S
Hemp-nettle, common	*Galeopsis tetrahit*	S	S	S	MS	S	S	S	S
Knotgrass	*Polygonum aviculare*	S	MS	MR	R	(Spre)		MS	MS
Mayweed, scented	*Matricaria recutita*	R	S	R	S	(Spre)	MS	S	S
Mayweed, scentless	*Tripleurospermum inodorum*	R	S	R	S	(Spre)	MS	S	S
Nettle, small	*Urtica urens*	MS	S	S	S	S	S	S	S
Nightshade black	*Solanum nigrum*	R	S	MR		S	S	S	S
Orache, common	*Atriplex patula*	MS	S	S		S	S	S	S
Pansy, field	*Viola arvensis*		S	S	S		S	MS	MS
Parsley piert	*Aphanes arvensis*						S		
Pennycress, field	*Thlaspi arvense*	R	S	S				S	S
Persicaria, pale	*Persicaria lapathifolia*	S	S	S	S	S		S	S
Pimpernel, scarlet	*Anagalis arvensis*	S	S	S		MS(Spre)	S	S	S
Pineappleweed	*Matricaria discoidea*	R	S	R	S		MS		
Poppy, common	*Papaver rhoeas*		S	S	S	S	S		
Redshank	*Persicaria maculosa*	S	S	S	S	S	S	S	S
Shepherd's-purse	*Capsella bursa-pastoris*	R	S	S		S	S	S	S
Sow-thistle, smooth	*Sonchus oleraceus*	R	S	S		(Spre)	S	MS	MS
Speedwell, common, field	*Veronica persica*	S	S	S	R	S	S	S	S
Speedwell, ivy-leaved	*Veronica hederifolia*					S	S	S	S
Sun spurge	*Euphorbia helioscopia*								
Thistle, creeping	*Cirsium arvense*	R	R	R	R	R			
Wild radish	*Raphanus raphanistrum*	R	S	S		Mspre		S	S
Annual meadow grass	*Poa annua*	S	MS	MR	small	(Spre)	S	S	S
Blackgrass	*Alopecurus myosuroides*	S			R		S	MS	MS
Brome, barren	*Anisantha sterilis*								
Wild-oat	*Avena fatua*	MS	R	R	suppr	R			
Vol OSR	*Brassica napus*						MS	S	S
Vol Potatoes	*Solanum tuberosum*								

pendimethalin: S = corn buttercup
pentanochlor: S = wild mignonette

Appendix 6 Weed Susceptibility to the main herbicides for Bulbs & Outdoor Flowers

Key: S = susceptible; MS = Moderately Susceptible; R = Resistant; MR = Moderately Resistant

		chlorpropham	chlorpropham/ linuron	linuron	linuron	cyanazine
		pre	pre or post	pre	post	post
Common name	**Latin name**					
Bindweed black	*Fallopia convolvulus*	S		S	S	S
Bugloss	*Anchusa arvensis*			S	MR	S
Charlock	*Sinapis arvensis*	MR	S	S	S	S
Chickweed, common	*Stellaria media*	S	S	S	S	S
Chickweed, mouse-eared	*Cerastium fontanum*	S				
Cleavers	*Galium aparine*	R	S	MR	R	R
Corn marigold	*Chrysanthemum segetum*	R	S	S	R	
Corn spurrey	*Spergula arvensis*	S		S	S	
Crane's-bill, cut-leaved	*Geranium dissectum*	R				MR
Deadnettle, henbit	*Lamium amplexicaule*	R				S
Dead-nettle, red	*Lamium purpureum*	R	S	S	MR	S
Dock, broad-leaved	*Rumex obtusifolius*					
Fat-hen	*Chenopodium album*	MS	S	S	S	S
Fool's parsley	*Aethusa cynapium*	R				S
Forget-me-not, field	*Myosotis arvensis*			S	S	S
Fumitory, common	*Fumaria officinalis*	MS	S	R	R	S
Gallant -soldier	*Galinsoga parviflora*	R		S	S	
Groundsel	*Senecio vulgaris*	R	S	S	MR	S
Hemp-nettle, common	*Galeopsis tetrahit*	S	S	S	S	S
Knotgrass	*Polygonum aviculare*	S	S	MS	MR	S
Mayweed, scented	*Matricaria recutita*	R	S	S	R	S
Mayweed, scentless	*Tripleurospermum inodorum*	R	S	S	R	S
Nettle, small	*Urtica urens*	S	S	S	S	S
Nightshade black	*Solanum nigrum*	R	S	S	MR	S
Orache, common	*Atriplex patula*	MS	S	S	S	S
Pansy, field	*Viola arvensis*	R		S	S	S
Parsley piert	*Aphanes arvensis*	R				MR
Pennycress, field	*Thlaspi arvense*	S		S	S	
Persicaria, pale	*Persicaria lapathifolia*	S		S	S	S
Pimpernel, scarlet	*Anagalis arvensis*	R	S	S	S	S
Pineappleweed	*Matricaria discoidea*	R	S	S	R	S
Poppy, common	*Papaver rhoeas*	S		S	S	S
Redshank	*Persicaria maculosa*	S	S	S	S	S
Shepherd's-purse	*Capsella bursa-pastoris*	MS	S	S	S	S
Sow-thistle, smooth	*Sonchus oleraceus*	R		S	S	
Speedwell, common, field	*Veronica persica*	S	S	S	S	S
Speedwell, ivy-leaved	*Veronica hederifolia*	MS	S			S
Sun spurge	*Euphorbia helioscopia*					
Thistle, creeping	*Cirsium arvense*	R		R	R	
Wild radish	*Raphanus raphanistrum*	MR		S	S	S
Annual meadow grass	*Poa annua*	S	S	MS	MR	S
Blackgrass	*Alopecurus myosuroides*	S	S			MS
Brome, barren	*Anisantha sterilis*					MS
Wild-oat	*Avena fatua*	MS	S	R	R	R
Willowherb	*Epilobium* spp.					
Vol OSR	*Brassica napus*					
Vol Potatoes	*Solanum tuberosum*					

Appendix 7 Weed Susceptibility to the main herbicides for Soft Fruit.

In 1977 simazine, dichlobenil, lenacil, propyzamide, chlorthiamid & MCPB were popular

Key: S = susceptible; MS = Moderately Susceptible; R = Resistant; MR = Moderately Resistant; rare BAP species red text

		propyzamide	lenacil	dichlobenil	napropamide	isoxaben	simazine	pendimethalin
		pre	pre 2 - 5L	pre/post	pre 5 to 7l/ha	pre 2L	pre 2 to 3L	pre 5L
Common name	**Latin name**							
Bindweed black	*Fallopia convolvulus*	S	S				S	S
Bugloss	*Anchusa arvensis*							
Charlock	*Sinapis arvensis*	S	S	S	R	S	S	
Chickweed, common	*Stellaria media*	S	S	S	S	S	S	S
Chickweed, mouse-eared	*Cerastium fontanum*			S		S		
Cleavers	*Galium aparine*	MS	S		MS	MR	MS/MR	?S
Corn marigold	*Chrysanthemum segetum*		S	S	R	S		S
Corn spurrey	*Spergula arvensis*		S	S	S	S		
Crane's-bill, cut-leaved	*Geranium dissectum*							
Deadnettle, henbit	*Lamium amplexicaule*							S
Dead-nettle, red	*Lamium purpureum*		MS			S	S	S
Dock, broad-leaved	*Rumex obtusifolius*							
Fat-hen	*Chenopodium album*	S	MS	S	S	S	S	S
Fool's parsley	*Aethusa cynapium*						MR	
Forget-me-not, field	*Myosotis arvensis*				S	S		S
Fumitory, common	*Fumaria officinalis*	MS	S				MS	MS
Gallant -soldier	*Galinsoga parviflora*							
Groundsel	*Senecio vulgaris*	R	MS	S	S	MS	S	
Hemp-nettle, common	*Galeopsis tetrahit*		R				S	S
Knotgrass	*Polygonum aviculare*	S	S		S	S	MS	
Mayweed, scented	*Matricaria recutita*	R	S	S	S	S	S	MS
Mayweed, scentless	*Tripleurospermum inodorum*	R	S	S	S	S	S	MS
Nettle, small	*Urtica urens*	S	MS	S	MS	S	S	S
Nightshade black	*Solanum nigrum*	S	R		R		S	S
Orache, common	*Atriplex patula*		S	S		S	MS	S
Pansy, field	*Viola arvensis*		R		MS	S		S
Parsley piert	*Aphanes arvensis*				R	S		S
Pennycress, field	*Thlaspi arvense*		S		R			
Persicaria, pale	*Persicaria lapathifolia*		S		MS			
Pimpernel, scarlet	*Anagalis arvensis*		S			S	S	S
Pineappleweed	*Matricaria discoidea*			S	S	S	S	MS
Poppy, common	*Papaver rhoeas*		S	S	S	S	S	S
Redshank	*Persicaria maculosa*	S	S		MS	S	MS	S
Shepherd's-purse	*Capsella bursa-pastoris*		S		MS	S	S	S
Sow-thistle, smooth	*Sonchus oleraceus*		S	S	MS			S
Speedwell, common, field	*Veronica persica*	S	MS		S		S	S
Speedwell, ivy-leaved	*Veronica hederifolia*	S	R			S		S
Sun spurge	*Euphorbia helioscopia*							
Thistle, creeping	*Cirsium arvense*	R					R	
Wild radish	*Raphanus raphanistrum*		S			S		
Annual meadow-grass	*Poa annua*	S			S		S	S
Blackgrass	*Alopecurus myosuroides*	S	R	S	S		S	S
Brome, barren	*Anisantha sterilis*	S						
Wild-oat	*Avena fatua*	S	R	S				
Willowherbs	*Epilobium* spp				S	MS		
Vol OSR	*Brassica napus*	R				S	R	MS
Vol Potatoes	*Solanum tuberosum*							

diquat/paraquat; paraquat; glyphosate total herbicides widely used
isoxaben: S = hairy bittercress, pearlwort, ribwort plantain, greater plantain
oxadiazon: S = hairy bittercress
simazine: S = black, treacle & white mustard, field gromwell, long-headed poppy, shepherds needle; MS = wall speedwell, willowherb; MR = creeping buttercup, dandelion, hairy tare, common vetch; R = corn buttercup, deep rooted perennials

Appendix 8 Weed Susceptibility to the main herbicides for Top Fruit.

Key: S = susceptible; MS = Moderately Susceptible; R = Resistant; MR = Moderately Resistant; rare BAP species red text

		simazine	**diuron**	**amitrole**	**MCPA**	**mecoprop**	**dicamba /MCPA /mecoprop P**	**2,4-D/ dichlorprop/ MCPA/mecoprop**
		pre 2 - 3L	**pre**	**post**	**post**	**post**	**post**	**post**
Common name	**Latin name**							
Bindweed black	*Fallopia convolvulus*	S	S			MR	S	
Bugloss	*Anchusa arvensis*					MR		
Charlock	*Sinapis arvensis*	S	S	S	S	S	S	
Chickweed, common	*Stellaria media*	S	S	S	R	S	S	S
Chickweed, mouse-eared	*Cerastium fontanum*		S			S		
Cleavers	*Galium aparine*	MS/MR	S		R	S	S	S
Corn marigold	*Chrysanthemum segetum*			S		R	R	
Corn spurrey	*Spergula arvensis*		S				S	
Crane's-bill, cut-leaved	*Geranium dissectum*					MR		
Deadnettle, henbit	*Lamium amplexicaule*		S					
Dead-nettle, red	*Lamium purpureum*	S	S			MS	R	
Dock, broad-leaved	*Rumex obtusifolius*		S	S		SP	S	S
Fat-hen	*Chenopodium album*	S	S	S	S	S	S	S
Fool's parsley	*Aethusa cynapium*	MR	S					
Forget-me-not, field	*Myosotis arvensis*					R		
Fumitory, common	*Fumaria officinalis*	MS			S	MS	S	
Gallant -soldier	*Galinsoga parviflora*		S					
Groundsel	*Senecio vulgaris*	S	S			MR	S	S
Hemp-nettle, common	*Galeopsis tetrahit*	S			S	MR	S	
Knotgrass	*Polygonum aviculare*	MS	S			MR	S	MS
Mayweed, scented	*Matricaria recutita*	S	S	S	R	R	S	MS
Mayweed, scentless	*Tripleurospermum inodorum*	S	S	S	R	MR	S	MS
Nettle, small	*Urtica urens*	S	S	S	S	S		S
Nightshade black	*Solanum nigrum*	S				MR		
Orache, common	*Atriplex patula*	MS	S		S	MS		S
Pansy, field	*Viola arvensis*					R	R	
Parsley piert	*Aphanes arvensis*						R	
Pennycress, field	*Thlaspi arvense*		S		S	S		
Persicaria, pale	*Persicaria lapathifolia*					MR		
Pimpernel, scarlet	*Anagalis arvensis*	S	S			MR	S	
Pineappleweed	*Matricaria discoidea*	S	S	S	R			MR
Poppy, common	*Papaver rhoeas*	S	S		S	MR	S	
Redshank	*Persicaria maculosa*	MS		S		MR	S	
Shepherd's-purse	*Capsella bursa-pastoris*	S	S		S	S	S	S
Sow-thistle, smooth	*Sonchus oleraceus*		S	S	S	MR	S	MS
Speedwell, common, field	*Veronica persica*	S				MS	R	
Speedwell, ivy-leaved	*Veronica hederifolia*					MS	R	
Sun spurge	*Euphorbia helioscopia*			S				
Thistle, creeping	*Cirsium arvense*	R		S	S	SP	S	S
Wild radish	*Raphanus raphanistrum*		S		S	S	S	
Annual meadow-grass	*Poa annua*	S	S	S			R	
Blackgrass	*Alopecurus myosuroides*	S					R	
Brome, barren	*Anisantha sterilis*			S			R	
Wild-oat	*Avena fatua*						R	
Vol OSR	*Brassica napus*							
Vol Potatoes	*Solanum tuberosum*	R		S		S		

diquat/paraquat; paraquat; glyphosate total herbicides widely used

MCPA: S = corn buttercup, cornflower, treacle mustard, wild cabbage, field gromwell, shepherds needle, creeping buttercup, hoary cress, perennial sowthistle, field horsetail, plantains, spear thistle; MS = dandelion, common ragwort, soft rush

mecoprop: S = treacle, black and white mustard, plantains; MS = wild turnip, doves-foot cranesbill; SP = white campion, creeping buttercup, perennial sowthistle

diuron: S = corn chamomile, creeping buttercup, mustards

Appendix 9 Weed Susceptibility to the main herbicides for Hardy Nursery Stock

Key: S = susceptible; MS = Moderately Susceptible; R = Resistant; MR = Moderately Resistant; rare BAP species in red text

		simazine	isoxaben	metazachlor	propyzamide	oxadiazon	phenmedipham
		pre	pre	pre	pre	pre & post	post
Common name	**Latin name**						
Bindweed black	*Fallopia convolvulus*	S			S	S	MS
Bugloss	*Anchusa arvensis*						
Charlock	*Sinapis arvensis*	S	S		S	S	
Chickweed, common	*Stellaria media*	S	S	S	S	R	S/MS
Chickweed, mouse-eared	*Cerastium fontanum*		S				
Cleavers	*Galium aparine*	MS/MR	MR	MR	MS		R
Corn marigold	*Chrysanthemum segetum*		S				
Corn spurrey	*Spergula arvensis*		S			S	
Crane's-bill, cut-leaved	*Geranium dissectum*			MR			
Deadnettle, henbit	*Lamium amplexicaule*						
Dead-nettle, red	*Lamium purpureum*	S	S	S		S	S
Dock, broad-leaved	*Rumex obtusifolius*						
Fat-hen	*Chenopodium album*	S	S		S	S	S/MS
Fool's parsley	*Aethusa cynapium*	MR					
Forget-me-not, field	*Myosotis arvensis*		S	S			MR
Fumitory, common	*Fumaria officinalis*	MS		R	MS		S
Gallant -soldier	*Galinsoga parviflora*						
Groundsel	*Senecio vulgaris*	S	MS	S	R	S	S
Hemp-nettle, common	*Galeopsis tetrahit*	S				R	S
Knotgrass	*Polygonum aviculare*	MS	S	R	S	S	S/MS
Mayweed, scented	*Matricaria recutita*	S	S	S	R	S	
Mayweed, scentless	*Tripleurospermum inodorum*	S	S	S	R	S	MR
Nettle, small	*Urtica urens*	S	S		S	S	S
Nightshade black	*Solanum nigrum*	S			S		
Orache, common	*Atriplex patula*	MS	S				S
Pansy, field	*Viola arvensis*		S	R			S
Parsley piert	*Aphanes arvensis*		S	S			
Pennycress, field	*Thlaspi arvense*			R			
Persicaria, pale	*Persicaria lapathifolia*						MS
Pimpernel, scarlet	*Anagalis arvensis*	S	S			R	S
Pineappleweed	*Matricaria discoidea*	S	S			S	
Poppy, common	*Papaver rhoeas*	S	S	MS			
Redshank	*Persicaria maculosa*	MS	S		S	S	MS
Shepherd's-purse	*Capsella bursa-pastoris*	S	S	S		S	S
Sow-thistle, smooth	*Sonchus oleraceus*					S	R
Speedwell, common, field	*Veronica persica*	S			S	S	S
Speedwell, ivy-leaved	*Veronica hederifolia*		S		S	S	MS
Sun spurge	*Euphorbia helioscopia*					S	
Thistle, creeping	*Cirsium arvense*	R			R		
Wild radish	*Raphanus raphanistrum*		S			S	
Annual meadow-grass	*Poa annua*	S		S	S		R
Blackgrass	*Alopecurus myosuroides*	S		S	S	R	
Brome, barren	*Anisantha sterilis*				S		
Wild-oat	*Avena fatua*				S		
Willowherbs	*Epilobium* spp.	MS	MS				
Vol OSR	*Brassica napus*	R	S		R		
Vol Potatoes	*Solanum tuberosum*						

diquat/paraquat; paraquat; glyphosate total herbicides widely used
isoxaben: S = hairy bittercress, pearlwort, ribwort plantain, greater plantain
oxadiazon: S = hairy bittercress *Cardamine hirsuta*
simazine: S = black, treacle & white mustard, field gromwell, long-headed poppy, shepherds needle; MS = wall speedwell, MR = creeping buttercup, dandelion, hairy tare, common vetch; R = corn buttercup, deep rooted perennials

CHAPTER 5

RELATIONSHIP BETWEEN WEEDS AND BIRDS IN HORTICULTURE

5.1. Birds in UK farmland: status and factors affecting population and range

Common birds in farmland have shown significant declines in population size (Table 5.1) and some also show declines in geographical range over the period 1970 – 1995 (Fuller *et al.*, 1995). Agricultural intensification, in both arable and grassland areas of the UK, has been shown to play an important part in those declines (Baillie *et al.*, 2001; Chamberlain & Fuller, 2000; Chamberlain *et al.,* 2000; Siriwardena *et al.,* 2000; Siriwardena *et al.*, 2001a). Baillie *et al.* (2001; 2002) 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).

Whilst a series of agricultural changes are implicated in adverse effects on biodiversity (Breeze *et al.,* 1999; Marshall *et al.,* 2001; Robinson & Sutherland, 2002; Stoate *et al.,* 2002), causal links are nevertheless difficult to prove. For birds, three stages during the life cycle appear to be particularly vulnerable. These are nesting success, nestling survival and adult survival over winter. Data for individual bird species indicate that some or all of these have been adversely affected, and most often by changes in habitat availability, habitat quality and food availability. The factors most often cited as affecting bird populations are:

- The move to winter sowing of arable crops, from spring drilling
- Silage cutting, rather than later hay making
- Habitat loss, e.g. hedgerow and woodland removal
- Grassland intensification, i.e. loss of species-rich meadows
- Loss of winter stubbles
- Improved weed control

The diets of farmland birds have been reviewed extensively in recent time, e.g. (Moreby & Stoate, 2001; Wilson, Arroyo & Clark, 1996a; Breeze *et al.,* 1999; Fuller, 2000; Marshall *et al.*, 2001; Vickery, Carter & Fuller, 2002b; Vickery & Fuller, 1998). Some species are seed and plant eaters; others are insectivores. A number of species that feed on plant material as adults feed their young on insects, for example the grey partridge. Assessment of available information has allowed a simple description of the different groups most commonly found in bird diets (Breeze *et al.*, 1999) (Appendix 5.1). Similarly the genera and species of weeds most often taken as seeds by birds have been listed (Table 5.2) .

Table 5.1. Changes in farmland bird populations between 1974 and 1999 recorded in the BTO Common Bird Census plots. Taken from: http://www.bto.org/birdtrends/appendix71b.htm#cbcfarm25

Species	Plots (n)	Change (%)	Lower limit	Upper limit	Comment
Linnet	73	-46	-58	-30	
Lapwing	38	-45	-69	-31	Unrepresentative
Moorhen	55	-43	-52	-29	
Treecreeper	29	-42	-68	-11	
Yellowhammer	73	-42	-53	-32	
Dunnock	93	-40	-51	-27	
Goldcrest	27	-37	-54	-6	
Blackbird	96	-34	-41	-27	
Cuckoo	50	-26	-45	-2	
Tree Sparrow	34	-93	-97	-86	
Corn Bunting	17	-90	-95	-80	Small sample
Grey Partridge	40	-83	-88	-77	
Turtle Dove	25	-81	-90	-67	
Spotted Flycatcher	31	-75	-86	-60	
Bullfinch	47	-71	-79	-61	
Snipe	7	-70	-96	-53	Small sample
Song Thrush	82	-66	-73	-57	
Redshank	9	-60	-82	-19	Small sample
Reed Bunting	49	-58	-71	-44	
Starling	65	-55	-68	-38	
Skylark	83	-54	-60	-44	
Mistle Thrush	59	-51	-61	-43	

The weed genera most important in the diet of bird species include the spring-germinating weeds of the Polygonaceae, several members of the Chenopodiaceae and Carophyllaceae and *Poa annua*, annual meadow grass. The term "bird diet species" has been coined to describe these important weeds.

The most recently published work on bird diet in farmland reports the contents of hen harrier pellets (Clarke *et al.* 2003). These raptors take a number of passerine species close to the ground, such as linnet and buntings. Within the pellets, the contents of the prey gizzards include a number of common weed species, including Chenopodium and Polygonum species. The study clearly demonstrates that weeds, and spilt grain, are important for a number of farmland bird species.

Information on the diet of farmland birds have alse been recently re-reviewed, confirming the data reported previously and that noted in Table 5.2. (Sutherland, 2003).

Weed control practices and changes in cropping patterns, especially autumn sowing, rather than spring planting, have affected the prevalence of some weeds at a national scale (Marshall *et al.*, 2001). Such changes may influence food availability for birds through the year. Not only are weeds and seeds eaten in the growing crop, but seeds present in crop stubbles over winter are important for many birds (Vickery, Atkinson & Marshall, 2002a). With the move to winter cropping, stubbles are less common in the landscape in autumn and winter. This in part is the reason that set-aside fields have been shown to be useful for birds

(Donald *et al.*, 2001; Firbank, 1998; Firbank *et al.*, 2003b; Moorcroft *et al.*, 2002; Watson & Rae, 1997).

Table 5.2. The importance of plant genera in the diet of farmland birds. 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" (from (Marshall *et al.,* 2001)

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=

For insectivorous birds and nestlings, the supply of invertebrates is important for survival (Moreby & Stoate, 2001). A number of these invertebrates are dependent on particular weed species. For example, the knotgrass beetle, *Gastrophysa polygoni* (L.), is closely associated with Polygonum species (Sotherton, 1982). If these species are absent, the beetle, a species taken by partridges, is likely to be absent as well. The success of conservation headlands in supporting gamebird populations is in major part due to the encouragement of dicotyledonous weeds and their associated insects (Rands, 1985; Sotherton, Rands & Moreby, 1985). A comparison of sprayed and unsprayed arable crop edges has shown significant indirect and adverse impacts of herbicides on chickfood insects (Moreby & Southway, 1999). Weed removal often results in less abundant and less diverse fauna in the crop.

The UK government, as part of the initiatives on public accountability, sustainability and co-ordination between departments, has published a series of Public Service Agreements (PSA). These have published aims and targets, each with headline indicators that measure progress towards the targets. ***Headline indicator 13: Wildlife***, which is associated with PSA 1 – promoting sustainable development and PSA 3- care for our natural heritage, has as its objective reversing the long-term decline in populations of farmland and woodland birds. A population index of farmland and woodland birds has been created, based on breeding bird surveys. Changes in these indices are illustrated in Fig. 5.1. Current assessments indicate positive effects on woodland birds, though little change in farmland species. The PSA target will have been achieved when the long-term trend in the index and the associated upper and lower confidence limits (using a 95% confidence interval) are all positive.

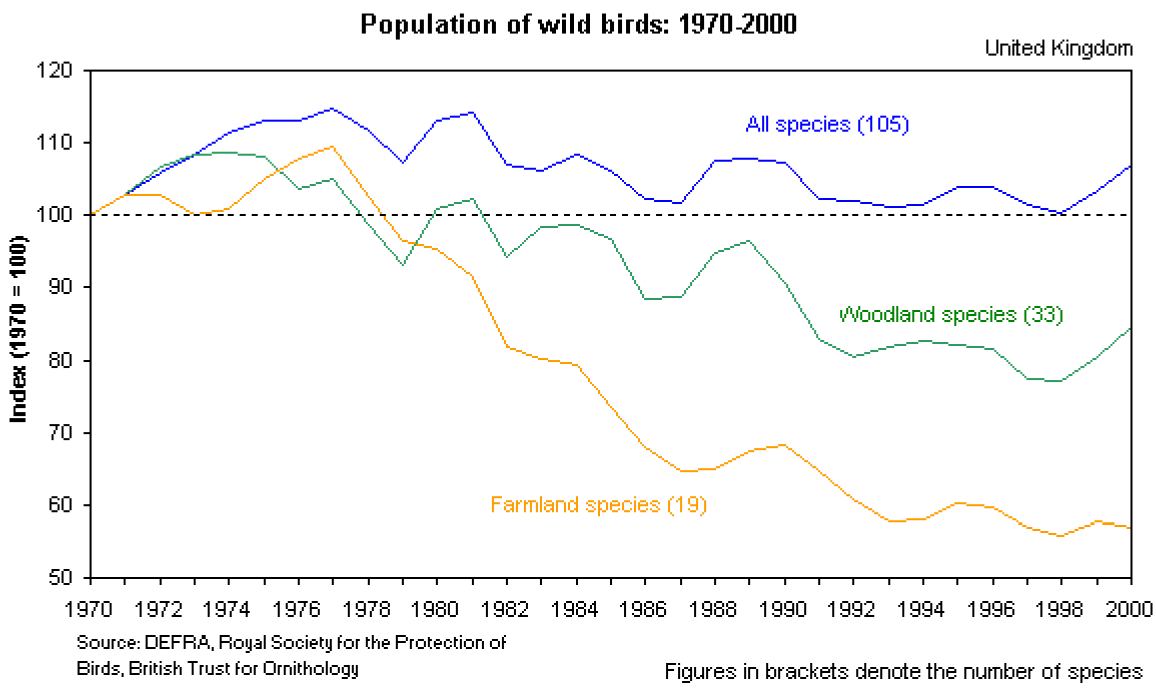


Fig. 5.1. Changes in farmland and woodland bird population indices from 1970 to 2000. Data from: http://www.sustainable-development.gov.uk/indicators/headline/h13.htm

The questions to be addressed in this chapter of the review are:

- Do horticultural crops affect farmland bird populations and *vice versa*?
- Is any influence significant at local, regional or national scales within the UK?
- Are there opportunities to mitigate potentially negative management operations in horticulture for birds?

5.2. Birds as crop pests

There are very few species of birds in the UK that are regarded as pests by farmers and growers. The exceptions are the wood pigeon and perhaps, in the past, the bullfinch. Wood pigeons feed on plant material, including buds, shoots, seeds, nuts and berries. They can have significant physical and economic impact on crops of cabbages, Brussels sprouts, peas, field and broad beans, oilseed rape and grain crops. The species has shown a steady increase in population size since the mid 1960s, according to CBC data. The increase in intensive arable cultivation, especially of oilseed rape, may explain the rise in its numbers (Gibbons, Reid & Chapman, 1993).

The bullfinch, *Pyrrhula pyrrhula*, was regarded as a pest in some fruit growing areas, as it took fruit buds from commercial orchards in spring. There was once a legal culling programme in parts of Kent and Worcestershire. The birds eat seeds and buds, but also take insects to feed their young. The species has shown marked declines in populations, by up to 65% in farmland since 1965, the reasons for which are not clearly established (Siriwardena, Freeman & Crick, 2001b). Subtle changes in habitat quality that affect nesting success and survival are probably the cause. The comparative rarity of the species now, means it should not be regarded as a pest.

5.3. Birds use of horticultural crop fields

Whilst adverse impacts of birds on horticultural crops may be limited to pigeon feeding, is there much information on inoffensive or even beneficial use of horticultural fields by birds? The published literature for the UK is very limited, indicating that there is a need for much more directed observations. There are some extensive data sets on bird populations in the UK. Therefore there may also be opportunities to examine such existing data sets, notably the Breeding Bird Survey and possibly the Common Bird Census, to extract appropriate information relevant to horticulture.

Casual observations from staff of RSPB and BTO report contrasting extremes of abundant farmland birds in weedy fallow areas and crops rich in insects and seeds with situations of no birds in apparently sterile crops (R Winspear; R Fuller Pers. comm.). One study in East Anglia (Mason & Macdonald, 2000) suggests that yellow wagtails *Motacilla flava* showed particular preference for potatoes, peas, beans and salad crops. Skylarks *Alauda arvensis* showed weaker preferences for potatoes, peas, salad crops and other spring-sown crops. These data on yellow wagtails concur with the results from the first year of fieldwork from a PhD study involving UEA, EN, RSPB and BTO, i.e. that potatoes (and to some extent peas and field beans) are favoured nesting habitats for this species in the latter half of the breeding season (June onwards) (. G Anderson Pers. comm). There is also anecdotal evidence that yellow wagtails will also nest in strawberry crops.

As regards other horticultural crops, there are unpublished reports by BTO on pea fields (Henderson, 2003). The results from this study, part of the Birds Eye Walls: Partnership for Sustainability project, show the importance of pea crops for lapwing and skylark (I. Henderson Pers. comm.). Whilst there are marked farm-to-farm and regional differences in populations of the species, lapwing and skylark nesting is encouraged in peas. Lapwings favour bare ground for nesting. The fact the crop is spring sown, provides appropriate structure at nesting time. Skylarks favour short vegetation for nesting (Chamberlain *et al.*, 1999; Donald *et al.*, 2001; Poulsen, Sotherton & Aebischer, 1998; Wilson *et al.*, 1997); pea crops are shorter and more open than cereals through the year, but especially in June and July when second broods are raised.

The value of pea crops for certain farmland birds illustrates the potential biodiversity value of other horticultural crops. In landscapes dominated by winter crops, horticultural crops might have a disproportionately greater importance for farmland birds species than might be expected simply in terms of land area. However, little information is available for the majority of horticultural crops, many of which are intensively managed.

5.4. Crop management and birds

The three factors limiting farmland bird populations are suitable nesting habitat, food for nestlings and winter food supplies for adults. The type, structure, timing of establishment and subsequent management of different horticultural crops will impact on each of these factors. Aspects of the establishment and management of horticultural crops were explored in Chapter 2. A brief examination of crop establishment timing is repeated here. Apart for perennial crops, bulbs and those that are continuously planted, the majority of crops considered in this review are established in spring (Table 5.3). Thus they differ from the majority of arable crops that are winter sown. As they are established at a different time of year, most horticultural crops will contribute to heterogeneity in landscape mosaics in those areas where they occur. Spring cropping has been shown to be important for nesting in a number of farmland bird species, notably skylark and yellow wagtail. Being spring-sown, such crops may indirectly contribute to over-winter food supplies in preceding stubbles, if these are allowed to maintain weeds over winter (Project BD1610) (Vickery *et al.*, 2002a). In addition, such crops encourage the germination of spring-sown weed species, many of which are favoured bird food species, such as the Polygonaceae. Thus, many horticultural crops have the potential to indirectly aid the over-winter survival of a number of farmland birds, notably the finches and buntings, by providing winter stubble fields.

5.4.1. Nesting habitat for farmland birds

Aspects of the impacts of weed control on farmland birds were reviewed by (Breeze *et al.,* 1999). As noted in that review, nesting habitat of the majority of farmland birds is amongst trees, shrubs and hedges. Whilst top fruit may provide such environments, most field crops do not. Nevertheless, there are a number of ground-nesting species, notably *Red-legged and Grey Partridge, Pheasant, Stone Curlew, Lapwing, Skylark, Meadow Pipit, Corn Bunting, Yellowhammer and Yellow Wagtails* that nest amongst ground vegetation and could utilise horticultural crops. The gamebirds nest in tall ground vegetation, especially grasses, often along field margins (Hinsley & Bellamy, 2000; Rands & Sotherton, 1987). According to (Breeze *et al.*, 1999) :

"*Corn Buntings nest in tangled grass or shrubs in arable fields or in pasture in a clump of thick weeds. Yellowhammers almost always nest on, or very close, to the ground, well hidden amongst grass or herbage. They tend to nest in herbaceous vegetation in the field margins rather than in the shrubby vegetation on the hedge itself (Stoate, Moreby & Szczur, 1998). Typically they will nest against the bank or base of a hedge, small tree or bush or well inside Bramble. Yellow Wagtails usually nest in a tussock of vegetation often close to water. Skylark, Meadow Pipit, Lapwing and Stone Curlew tend to nest in more open habitats. Lapwings nesting on grassland prefer fields which have short and tussocky swards and irregular surface topography. Meadow Pipits also favour thick ground vegetation. Skylarks favour open ground* *in growing or short vegetation such as grass or growing crops. Lapwing often nest on small hummocks or in grass tussocks whilst Stone Curlew favour open, flat ground with short vegetation."*

There is good evidence that skylarks prefer shorter crops for nesting in, and tall cereals are avoided, particularly for second broods in the summer (Chamberlain & Gregory, 1999; Chamberlain *et al.*, 1999; Odderskaer *et al.,* 1997; Wilson *et al.,* 1997).

Table 5.3 Main sowing (s) / transplanting (t) times, methods, typical soil types and rotations for a range of horticultural crops

Crop	**Sowing/Planting time, drilled seed (s)/transplants (t)/sets/bulbs**	**Soil type/texture**	**Rotation type (minimum years between crop) or age**
Potatoes	March – April	Light - medium	Arable (4)
Cauliflower, cabbage	March – August (t)	Medium - light moisture retentive	Arable (4)
Brussels sprouts	March – June (t)	Medium - light moisture retentive	Arable (4)
Calabrese	March – August (t)	Medium - light moisture retentive	Arable (4)
Swedes, turnips	March – July; Scotland March – early June	Medium - light clay loammoisture retentive	Arable (5)
Vining peas	February – end May (s)	Light - medium	Arable (4 - 6)
Broad beans	February – end May (s)	Light - medium	Arable (4)
Dwarf French beans	mid May – June (s)	Light - medium	Arable (4 - 6)
Runner beans	Mar – April (s) & (t)	Medium	Continuous (1)
Carrots, parsnips	Autumn & Feb – May (s)	Sandy – light, organic	Arable (4 - 6)
Celery	Spring (t)	Organic, some light	(5)
Onions, bulb & salad	Feb – March (s), (t), some sets; salad (s) Feb-Sept	Light - medium	Arable (4-6)
Leeks	Spring (s), early & late harvest (t)	Light - medium	Arable (4)
Lettuce	Continuous: (t) modules/blocks, (s) a few	Light	Continuous (1)
Red beet	Feb – June	Light	Arable (4)
Spinach	Spring (s), continuous baby leaf	Light - medium	Arable (4), continuous
Sweetcorn	May (s) & (t)	Light - medium	Continuous (1)
Bulbs	August – Sept bulbs	Light - medium	Arable (4 - 6), up to 3 yrs
Flowers	April – May (s) & (t)	Light - medium	Arable (4)
Strawberries	Spring, summer, autumn	Various	Perennial 2-3 yr
Cane and bush fruit	Autumn/winter, spring, spring planted in Scotland	Various	Perennial 5-8 yr
Top fruit	Autumn/winter, spring	Various	Perennial 2-45 yr
Hardy Nursery Stock	Autumn/winter-late spring	Various	Perennial 1-8 yrs herbaceous-Christmas trees

The remaining farmland birds nest amongst trees, shrubs and scrub, some constructing nests amongst branches and some, such as the sparrows, starling, martins and to a lesser extent wren and robin, using holes in trees, walls and banks. For these bird species, the horticultural crop is not of importance for nesting, but potentially for foraging habitat. The field boundary is known to be used by many birds and avoided by few species (Vickery & Fuller, 1998). Species that avoid field margins are the golden plover, and breeding lapwings and skylarks. Vickery & Fuller (1998) suggest that diverse and well-managed field margins may provide suitable food resources through the nesting and summer period, when birds may be constrained in their foraging distances. In winter, field centres are of greater importance for flocks of buntings, finches and plovers. The provision of seed-rich winter stubbles is of particular importance for a number of farmland birds (Vickery *et al.,* 2002a).

5.4.2. Horticultural crop structure: nesting and food resources

Other factors that will affect the use of horticultural crops by birds include the structure of the crop and the levels of weed control. The majority of horticultural crops are grown in rows. This allows some open ground during the growing season, which may allow some of the ground-nesting species to fledge young. The closed canopy of winter cereal crops are not favoured by many bird species (Robinson & Sutherland, 1999; Wilson, Taylor & Muirhead, 1996b), though curlews may prefer taller vegetation at certain times (Berg, 1992). As an example, the rare stone curlew *Burhinus oedicnemus* needs bare ground for nesting (Bealey *et al.*, 1999; Green & Griffiths, 1994; Green, Tyler & Bowden, 2000). In addition, it may be possible to tolerate a level of weed cover in the between row areas to provide food for some birds. However, there needs to be further work to quantify how much of which weed species can be tolerated in which crops. In general, crop quality is paramount and there is zero tolerance of weeds in most horticultural crops. Other factors, such as ease of harvesting, predicate against allowing weeds within the crop.

Lack of weeds during the period that crops are grown will result in a lack of plant and seed material for herbivorous birds. Further, the insects associated with different weeds will be absent. Insect diversity is closely related to plant diversity in many habitats, e.g. (Thomas & Marshall, 1999; Wright & Samways, 1998). Thus monoculture crops tend to have low faunal diversity; where herbicides are used, insect diversity is often reduced (Buckelew *et al.*, 2000; Moreby & Southway, 1999). Whilst pest insects may achieve high biomass and provide potential food resources for birds, crop quality and yield requirements for horticultural crops result in intensive pesticide programmes to prevent pest damage. Resources for birds are therefore likely to be poor in most horticultural crops, except in cane and top fruit, where inter-row vegetation is allowed to grow.

Many horticultural crops are short in stature compared with most cereals and oilseed rape, a factor that affects nest site selection of several species, such as the skylark, which seeks shorter vegetation (Chamberlain *et al.*, 1999; Donald *et al.*, 2001; Wilson *et al.*, 1997). Some horticultural crops are mulched, for example soft fruit. This may provide suitable short nesting cover for some farmland bird species, though information is generally lacking in this area.

5.4.3. Horticultural crops and weeds for birds

It may be possible to rank the range of horticultural crops according to their potential benefit to birds. Similarly, it may be possible to rank the usefulness of weeds for farmland birds, based on their contribution to diet. An assessment of the likely contribution of horticultural crops to birds is presented in Table 5.4. A summary of the known use of birds is given, together with the potential for preceding winter stubbles (for spring established crops). An indication of weed tolerance during crop growth is used to estimate the potential for the presence of weeds (and indirectly on insects) for birds. Finally, a subjective assessment of likely nesting use of the different crops is given.

Table 5.4. Horticultural crop types and their likely importance for birds

Crop	Farmland birds known to use the crop	Can be preceded by winter stubble	Weeds and seeds in summer	Ground nesting habitat
Potatoes	+	+	-	+
Cauliflower, cabbage		-	-	-
Brussels sprouts		+	-	-
Calabrese		+	-	-
Swedes, turnips				
Vining peas	+	+	-	+
Broad beans	+	+	-	+
Dwarf French beans		+	-	-/+
Runner beans		+	-	-
Carrots, parsnips		-	-	+
Celery		+	-	-
Onions, bulb & salad		+/-	-	-
Leeks		+	-	-
Lettuce		-	-	-
Red beet		+	-	?
Spinach		+	-	-
Sweetcorn		+	-	-
Bulbs		-	-	-
Flowers		+	-	-
Strawberries	+	-	-	+
Cane and bush fruit		-	+	+
Top fruit		-	+	+
Hardy Nursery Stock		-	+	+

Currently, most horticultural crops have little in the way of plant and insect food resources during crop growth. Nevertheless, there is some opportunity for providing cover for ground nesting birds and for facilitating winter stubbles in preceding crops. Clearly, there is a need for further studies of crop utilisation by birds.

The list of representative horticultural weeds noted in Chapters 1 and 2, have varying importance for birds (see section 5.2; Appendix 5.1). An examination of the status of these species in the flora of Great Britain is given in Table 5.5, together with a subjective summary of their importance for birds based on diet content. A relatively small number of weed species have the highest importance. Most weeds that appear to be of benefit to birds are common and have distribution ranges that are stable. A limited amount of information is available on the weeds that are able to grow in autumn and winter and set seed during the extended stubble phase prior to spring crop establishment. Further work is needed here, as these species may be of particular importance in enhancing adult bird survival over winter.

Table 5.5. Status of common horticultural weeds and their importance for birds. Data on status taken from the 2002 Atlas of the British and Irish flora (Preston, Pearman & Dines, 2002). Species seeding in winter stubbles from (Vickery *et al.,* 2002a).

Common name	Latin name	Status (increasing, stable (O) or decreasing) in comparison with 1962 Atlas	No. 10x10-km grid squares recorded in GB between 1987-99	Bird diet species	Species seeding in winter stubbles
Annual meadow grass	*Poa annua*	O	2737	++	+
Bindweed black	*Fallopia convolvulus*	-	1687	+++	
Bitter-cress, hairy	*Cardamine hirsuta*	O	2303		
Blackgrass	*Alopecurus myosuroides*	+	874		
Brome, barren	*Anisantha sterilis*	O	1717		
Bugloss	*Anchusa arvensis*	-	1018		
Charlock	*Sinapis arvensis*	-	1902	++	
Chickweed, common	*Stellaria media*	O	2671	+++	
Chickweed, mouse-eared	*Cerastium fontanum*	O	2784	++	+
Cleavers	*Galium aparine*	+	2584		
Corn marigold	*Chrysanthemum segetum*	-	887		
Corn spurrey	*Spergula arvensis*	-	1805	+	
Crane's-bill, cut-leaved	*Geranium dissectum*	+	2016		
Deadnettle, henbit	*Lamium amplexicaule*	-	1024		
Dead-nettle, red	*Lamium purpureum*	O	2154		
Dock, broad-leaved	*Rumex obtusifolius*	O	2652	++	
Fat-hen	*Chenopodium album* agg.	O	2092	+++	
Fools parsley	*Aethusa cynapium*	-	1388	+++	
Forget-me-not, field	*Myosotis arvensis*	O	2383		
Fumitory, common	*Fumaria officinalis*	O	1621		
Gallant -soldier	*Galinsoga parviflora*	+	276		
Groundsel	*Senecio vulgaris*	O	2426		+
Hemp-nettle, common	*Galeopsis tetrahit sensu lato.*	O	2167		
Knotgrass	*Polygonum aviculare*	O	2435	+++	
Mayweed, scented	*Matricaria recutita*	O	1361		
Mayweed, scentless	*Tripleurospermum inodorum*	O	2001		
Nettle, small	*Urtica urens*	O	1440		
Nightshade black	*Solanum nigrum*	O	1137		
Orache, common	*Atriplex patula*	O	1990	+	
Pansy, field	*Viola arvensis*	O	1742	++	
Parsley piert	*Aphanes arvensis* agg.	O	1964		
Pennycress, field	*Thlaspi arvense*	+	1243		
Persicaria, pale	*Persicaria lapathifolia*	O	1560	+++	
Pimpernel, scarlet	*Anagallis arvensis*	-	1632		
Pineappleweed	*Matricaria discoidea*	O	2554		
Poppy, common	*Papaver rhoeas*	O	1508		
Redshank	*Persicaria maculosa*	O	2341	+++	
Shepherd's-purse	*Capsella bursa-pastoris*	O	2452	+	+
Sow-thistle, smooth	*Sonchus oleraceus*	O	2149	+	
Speedwell, common, field	*Veronica persica*	O	1976		
Speedwell, ivy-leaved	*Veronica hederifolia*	O	1756		
Sun spurge	*Euphorbia helioscopia*	-	1769		
Thistle, creeping	*Cirsium arvense*	O	2682	+	
Vol OSR	*Brassica napus*	+	1493	++	
Vol Potatoes	*Solanum tuberosum*	O	549		
Wild radish	*Raphanus raphanistrum*	-	951		
Wild-oat	*Avena fatua*	+	1337		
Willowherbs	*Epilobium spp*				

With regard to weed control, Chapters 2 and 3 demonstrate that most horticultural crops have particular requirements for weed control. In such typically high value crops, threats to quality and yield are not usually tolerated, and many crops are virtually weed-free. Thus opportunities to provide food in the form of plant material, seeds and associated insects are currently limited. However, there may be opportunities to manage horticultural crops, that allow the benefits of spring cropping and winter stubbles to be realised, or that allow nesting and food resources in limited sacrificial areas.

5.4.4. Horticultural impacts within the farmed landscape

What proportion of the farmed landscape is under horticultural crops? Data from Chapter 3 and previous reviews (Marshall *et al.,* 2001) (Table 5.6) indicate that only potatoes, peas and beans and all vegetables have areas over 1% of the total arable acreage. The proportion of all horticulture only amounts to 7.45% of the arable area. Thus, the land area concerned is small and it might be assumed that there is a relatively small environmental "footprint" from horticulture. However, if these crop areas are potentially important for farmland birds, then attention needs to be paid to them as part of the strategy for achieving PSA targets for farmland birds. In particular, the potential benefits associated with winter stubbles prior to horticultural cropping, may mean that horticulture has a larger positive "footprint" than has been previously supposed.

Table 5.6. Areas (ha) of different horticultural and arable crops in Great Britain (England, Scotland & Wales).

Crop	Date	Crop area ha	Proportion (%) of total arable
Potatoes	2000	161,502	3.55
Bulbs & flowers	2001	5,777	0.13
Total vegetables	***1999***	***131,766***	***2.90***
Brassicas	1999	34,743	0.76
Peas & Beans	1999	45,365	1.00
Onions & leeks	1999	16,289	0.36
Carrots, parsnips & celery	1999	15,851	0.35
Lettuce	1999	5,858	0.13
Total soft fruit	***2001***	***9,432***	***0.21***
Strawberries	2001	3,765	0.08
Blackcurrants processing	2001	2,429	0.05
Raspberry	2001	1,530	0.03
Total top fruit	***2000***	***22,595***	***0.50***
Dessert apples Cox	2000	8,314	0.18
Total HNS	***2001***	*7,806*	***0.17***
Winter wheat	1998	2,035,000	44.77
Winter barley	1998	760,000	16.72
Spring barley	1998	455,000	10.01
Oilseed rape	1998	505,000	11.11
Field beans	1998	111,000	2.44
Total arable crops	***1998***	***4,545,000***	

5.5. Mitigating adverse impacts of weed control

It must be accepted that weeds are likely to be tolerated in only a small number of horticultural crops (see Table 2.2), though further work is required to refine this. If the potential benefits of horticultural crops to birds, in providing nesting cover and weed and insect food, are to be realised, then mitigation measures need to be practical, easy to implement and manage and have positive economic implications for growers. Nevertheless, whilst there are generally positive assessments of some mitigation measures in arable situations, data for horticultural crops are generally lacking. Thus this area requires further investigation.

In arable land, a number of procedures supported within agri-environment schemes have positive effects on wildlife (Marshall & Moonen, 2002). For example, conservation headlands can have positive impacts on grey partridge populations (Rands, 1985; Sotherton *et al.*, 1985). Sown grassland strips at arable field edges may also be beneficial for farmland birds (Vickery *et al.,* 2002b) and can have agronomic benefits in terms of weed control in field boundaries, as well as enhancing plant diversity (Moonen & Marshall, 2001). Unsown, but tilled, strips at arable field edges have been used in the Breckland to encourage the conservation of rare arable weeds (Critchley, 1994; Critchley, 1996). Such sacrificial areas might be used to balance weed control requirements within the main horticultural crop and provision of weed cover for birds. Current Countryside Stewardship Scheme (CSS) prescriptions include 2 m or 6m strips at arable field edges, while 20 m wide set-aside strips can also be created

Possible mitigation measures might include:

- Margin weed strips
- Strips within main horticultural fields
- Reduced overall weed control
- Modified timing of weed control

Sacrificial strips may be the simplest form of mitigation measure to develop, though they need some field assessment in different horticultural crops to assess the management implications of their introduction. Reduced overall weed control is likely to be feasible in only a few crops. Modified weed control, in terms of timing, for example, has been proposed as a potential benefit of herbicide tolerant crops, e.g. in sugar beet (Dewar *et al.*, 2000; Volkmar *et al.*, 2003). However, it has also been argued that simply delaying weed control and then removing the resource later might be worse for birds that have sited nests in the locality. The general introduction of herbicide tolerant crops might have good or bad effects on birds, depending on patterns of uptake (Watkinson *et al.,* 2000). We wait upon the results of the Field Scale Evaluation of GMHT crops (Firbank *et al.*, 2003a), but note that three of the four crops to be assessed are spring sown and perhaps most representative of horticultural cropping patterns.

The potential provision of winter food supplies in winter stubbles prior to horticultural cropping needs attention. Recent work (Vickery *et al.*, 2002a) in arable crop stubbles concluded that benefits for birds required:

(i) reduced herbicide programmes in preceding crops,
(ii) restrictions on the use of pre-harvest glyphosate,
(iii) promotion of barley (especially spring barley) over wheat and linseed,
(iv) reduced or no stubble cultivation

Such factors might influence the subsequent management of horticultural crops rather more than following arable crops, in terms of increased weed control, but more data is needed. It is clear that whilst the above prescriptions may be practical on some soils, others, notably clays and silts, need to be ploughed before winter frosts to allow weathering. Under such conditions, the value of the stubbles for birds may be lower.

The patterns of land ownership associated with horticultural cropping will also need to be understood. A significant proportion of horticultural crops are grown on rented land, within other cropping rotations. In some cases, horticultural crops might be grown on land already supported by the Countryside Stewardship Scheme. In Table 5.7, the potential impact on birds of different prescriptions within the current Countryside Stewardship Scheme designed for arable farmers is derived from likely effects on nesting habitat, plant and insect provision as food during crop growth and during winter.

Table 5.7. Countryside Stewardship Scheme arable farming prescriptions and their likely impact on farmland birds.

CSS prescription	Nesting habitat	Summer food resources	Winter food resources
2 m margins & beetle banks	+	+	?
6 m margins	+	+	?
Arable reversion	+	+	?
Overwintered stubble (3)	-	-	+
Conservation headlands (2)	?	+	-
Wildlife mixtures (2)	?	+	+

For mitigation purposes, it would seem that habitat creation at field edges is likely to provide the best resources for birds and least compromise to crop quality and yield and a low threat of crop rejection. The best options are likely to be margin strips of varying vegetation cover. Sown margin strips with diverse herbaceous vegetation should provide nesting cover and summer foraging for plant material, seeds and insects. Specific wildlife mixtures can provide winter food resources (Henderson, Vickery & Carter, 2001). Under some circumstances, tilled but undrilled margin strips will provide open nesting habitat and allow annual weeds to grow and seed. These may be of particular value to stone curlew and skylark.

5. 6. Summary & Conclusions

1. Common farmland birds have shown significant population declines over the past 30 years. A group of these species now form part of a Headline Indicator for the achievement of more than one government Public Service Agreement. The reasons for the declines are associated with changes in agriculture, notably the move to winter cropping, silage cutting in grassland and intensification of management, including the use of herbicides.

2. The life history stages of birds that have been affected by agricultural change are nesting (habitat loss and change in habitat quality), nestling survival (reduced amounts of weeds and insects) and adult survival over winter (reduced food availability).

3. A number of weeds are important components of the diet of farmland birds. These include the Polygonaceae, some Chenopodiaceae, Carophyllaceae and annual meadow grass (*Poa annua)*.

4. There is very limited data on the utilisation of horticultural crops by birds for nesting or foraging. Crops of peas, field beans and potatoes are important habitats for some ground nesting birds, notably yellow wagtail and skylark.

5. The majority of horticultural crops are spring sown or established in spring. There is an opportunity that such crops may indirectly benefit farmland birds by providing stubbles over winter. Crop stubbles can be important for providing seeds for adult birds over winter, though reduced weed control may be required in the preceding crop to achieve sufficient seeding. However, retention of such winter stubbles may not always be possible, for example silt soils need to be ploughed in autumn to ensure frost breakdown to get a good spring seedbed.

6. A number of horticultural crops are shorter and more open than winter cereals. Thus they may provide suitable nesting habitat for a number of bird species, especially for second nest broods in mid-summer.

7. The imperative to control weeds in most of horticulture is such that few such crops provide seeds and insects for birds during the crop growth period. Perennial crops have greater opportunity to provide food, if they support an associated perennial ground flora. Nevertheless, most horticultural fields do not provide food resources for birds.

8. As horticulture is only a very small part of the agricultural acreage (7%), the environmental "footprint" of the industry might be assumed to be small. However, the indirect benefits of the industry to birds, especially the growth of spring crops and the provision of stubbles, may mean that the industry benefits birds far greater than previously supposed.

9. Mitigating the current approaches to weed control in horticultural crops is most likely to be best achieved by creating habitat at field edges. There is little opportunity to reduce weed control within fields, as the risk of crop rejection is high if there is contamination or quality is compromised. Margin strips of diverse perennial herbaceous vegetation, or in some circumstances allowing the annual weed flora to

develop, or creating specific winter bird food mixtures, appear to be the most practical and beneficial prescriptions.

5.7 References

BAILLIE SR, CRICK HQP, BALMER DE, BASHFORD RI, BEAVEN LP, FREEMAN SN, MARCHANT JH, NOBLE DG, RAVEN MJ, SIRIWARDENA GM, THEWLIS R & WERNHAR CV (2001) Breeding birds in the wider countryside: their conservation status 2000. Report No. 252. British Trust for Ornithology, Thetford.

BEALEY CE, GREEN RE, ROBSON R, TAYLOR CR & WINSPEAR R (1999) Factors affecting the numbers and breeding success of Stone Curlews Burhinus oedicnemus at Porton Down, Wiltshire. *Bird Study* **46,** 145-156.

BERG A (1992) Habitat Selection By Breeding Curlews *Numenius arquata* On Mosaic Farmland. *Ibis* **134,** 355-360.

BREEZE VG, MARSHALL EJP, HART A, VICKERY JA, CROCKER J, WALTERS K, PACKER J, KENDALL D, FOWBERT J & HODKINSON D (1999). Assessing pesticide risks to non-target terrestrial plants. A desk study. Commission PN0923. MAFF Pesticides Safety Directorate.

BUCKELEW LD, PEDIGO LP, MERO HM, OWEN MDK & TYLKA GL (2000) Effects of weed management systems on canopy insects in herbicide-resistant soybeans. *Journal of Economic Entomology* **93,** 1437-1443.

BURN AJ (2000) Pesticides and their effects on lowland farmland birds. In *Ecology and Conservation of Lowland Farmland Birds* (ed. N. J. Aebischer, A. D. Evans, P. V. Grice and J. A. Vickery), pp. 89-104. British Ornithologists' Union, Tring.

CAMPBELL LH, AVERY MI, DONALD P, EVANS AD, GREEN RE & WILSON JD (1997) A review of the indirect effects of pesticides on birds. Report No. 227. Joint Nature Conservation Committee, Peterborough.

CHAMBERLAIN DE & FULLER RJ (2000) Local extinctions and changes in species richness of lowland farmland birds in England and Wales in relation to recent changes in agricultural land-use. *Agriculture, Ecosystems & Environment* **78,** 1-17.

CHAMBERLAIN DE, FULLER RJ, BUNCE RGH, DUCKWORTH JC & SHRUBB M (2000) Changes in the abundance of farmland birds in relation to the timing of agricultural intensification in England and Wales. *Journal of Applied Ecology* **37,** 771-788.

CHAMBERLAIN DE & GREGORY RD (1999) Coarse and fine scale habitat associations of breeding Skylarks Alauda arvensis in the UK. *Bird Study* **46,** 34-47.

CHAMBERLAIN DE, WILSON AM, BROWNE SJ & VICKERY JA (1999) Effects of habitat type and management on the abundance of skylarks in the breeding season. *Journal of Applied Ecology* **36,** 856-870.

CLARKE R, COMBRIDGE P & MIDDLETON N (2003) Monitoring the diets of farmland winter seed-eaters through raptor pellet analysis. *British Birds* **96**, 360-375

CRITCHLEY CNR (1994) Relationship between vegetation and site factors in uncropped wildlife strips in Breckland Environmentally Sensitive Area. In *Field Margins: Integrating Agriculture and Conservation* (ed. ND Boatman), pp. 283-288. British Crop Protection Council, Warwick.

CRITCHLEY CNR (1996) Monitoring as a feedback mechanism for the conservation management of arable plant communities. In *Vegetation Management in Forestry, Amenity and Conservation Areas. Aspects of Applied Biology, 46*, pp. 239-244. AAB, Warwick.

DEWAR AM, HAYLOCK LA, BEAN KM & MAY MJ (2000) Delayed control of weeds in glyphosate-tolerant sugar beet and the consequences on aphid infestation and yield. *Pest Management Science* **56,** 345-350.

DONALD PF, EVANS AD, BUCKINGHAM DL, MUIRHEAD LB & WILSON JD (2001) Factors affecting the territory distribution of Skylarks Alauda arvensis breeding on lowland farmland. *Bird Study* **48,** 271-278.

FIRBANK L (1998) Agronomic and environmental evaluation of set-aside under the EC Arable Area Payments Scheme. Final Report. Volumes 1-4. Report to MAFF. ITE: Merlewood.

FIRBANK LG, HEARD MS, WOIWOD IP, HAWES C, HAUGHTON AJ, CHAMPION GT, SCOTT RJ, HILL MO, DEWAR AM, SQUIRE GR, MAY MJ, BROOKS DR, BOHAN DA, DANIELS RE, OSBORNE JL, ROY DB, BLACK HIJ, ROTHERY P & PERRY JN (2003a) An introduction to the Farm-Scale Evaluations of genetically modified herbicide-tolerant crops. *J Appl Ecology* **40,** 2-16.

FIRBANK LG, SMART SM, CRABB J, CRITCHLEY CNR, FOWBERT JW, FULLER RJ, GLADDERS P, GREEN DB, HENDERSON I & HILL MO (2003b) Agronomic and ecological costs and benefits of set-aside in England. *Agriculture Ecosystems & Environment* **95,** 73-85.

FULLER RJ (2000) Relationships between recent changes in lowland British agriculture and farmland bird populations: an overview. In: *The Ecology and Conservation of Lowland Farmland Birds* (ed. N. J. Aebischer, A. D. Evans, P. V. Grice and J. A. Vickery), pp. 5-16. British Ornithologists' Union, Tring.

FULLER RJ, GREGORY RD, GIBBONS DW, MARCHANT JH, WILSON JD, BAILLIE SR & CARTER N (1995) Population declines and range contractions among farmland birds in Britain. *Conservation Biology* **9,** 1425-1441.

GIBBONS DW, REID JB & CHAPMAN RA (1993) *The New Atlas of Breeding Birds in Britain and Ireland: 1988-1991*. Poyser, London.

GREEN RE & GRIFFITHS GH (1994) Use of preferred nesting habitat by stone curlews *Burhinus oedicnemus* in relation to vegetation structure. *Journal Of Zoology* **233,** 457-471.

GREEN RE, TYLER GA & BOWDEN CGR (2000) Habitat selection, ranging behaviour and diet of the stone curlew (Burhinus oedicnemus) in southern England. *Journal of Zoology* **250,** 161-183.

HENDERSON IG (2003) Birds Eye Walls: Partnership for Sustainability. Progress report on the use of pea fields by birds. 2000. BTO Report No. 237. 56.

HENDERSON IG, VICKERY JA & CARTER N (2001) *The Relative Abundance of Birds on Farmland in Relation to Game-Cover and Winter Bird Crops*. British Trust for Ornithology.

HINSLEY SA & BELLAMY PE (2000) The influence of hedge structure, management and landscape context on the value of hedgerows to birds: A review. *Journal of Environmental Management* **60,** 33-49.

MARSHALL EJP & MOONEN AC (2002). Field margins in northern Europe: their functions and interactions with agriculture. *Agriculture Ecosystems & Environment* **89,** 5-21.

MARSHALL J, BROWN V, BOATMAN N, LUTMAN P & SQUIRE G (2001) The impact of herbicides on weed abundance and biodiversity. PN0940. A report for the UK Pesticides Safety Directorate, pp. 134 pp. IACR-Long Ashton Research Station.

MASON CF & MACDONALD SM (2000) Influence of landscape and land-use on the distribution of breeding birds in farmland in eastern England. *Journal of Zoology, London* **251,** 339-348.

MOONEN AC & MARSHALL EJP (2001) The influence of sown margin strips, management and boundary structure on herbaceous field margin vegetation in two neighbouring farms in southern England. *Agriculture, Ecosystems & Environment* **86,** 187-202.

MOORCROFT D, WHITTINGHAM MJ, BRADBURY RB & WILSON JD (2002) The selection of stubble fields by wintering granivorous birds reflects vegetation cover and food abundance. *Journal of Applied Ecology* **39,** 535-547.

MOREBY SJ & SOUTHWAY SE (1999) Influence of autumn applied herbicides on summer and autumn food availability to birds in winter wheat fields in southern England. *Agriculture, Ecosystems & Environment* **72,** 285-297.

MOREBY SJ & STOATE C (2001) Relative abundance of invertebrate taxa in the nestling diet of three farmland passerine species, Dunnock *Prunella modularis*, Whitethroat *Sylvia communis* and Yellowhammer *Emberzia citrinella* in Leicestershire, England. *Agriculture, Ecosystems & Environment* **86,** 125-134.

ODDERSKAER P, PRANG A, POULSEN JG, ANDERSEN PN & ELMEGAARD N (1997) Skylark (*Alauda arvensis*) utilisation of micro-habitats in spring barley fields. *Agriculture Ecosystems & Environment* **62,** 21-29.

POULSEN JG, SOTHERTON NW & AEBISCHER NJ (1998) Comparative nesting and feeding ecology of skylarks *Alauda arvensis* on arable farmland in southern England with special reference to set-aside. *Journal of Applied Ecology* **35,** 131-147.

PRESTON CD, PEARMAN DA & DINES TD (2002). *New Atlas of the British and Irish Flora*. Oxford University Press, Oxford.

RANDS MRW (1985) Pesticide use on cereals and the survival of grey partridge chicks: a field experiment. *Journal of Applied Ecology* **22,** 49-54.

RANDS MRW & SOTHERTON NW (1987) The management of field margins for the conservation of gamebirds. In *Field Margins. BCPC Monograph No. 35* (ed. JM Way and PW Greig-Smith), pp. 95-104. British Crop Protection Council, Thornton Heath, Surrey, UK, London.

ROBINSON RA & SUTHERLAND WJ (1999) The winter distribution of seed-eating birds: habitat structure, seed density and seasonal depletion. *Ecography* **22,** 447-454.

ROBINSON RA & SUTHERLAND WJ (2002) Post-war changes in arable farming and biodiversity in Great Britain. *Journal of Applied Ecology* **39,** 157-176.

SIRIWARDENA GM, BAILLIE SR, CRICK HQP & WILSON JD (2000) The importance of variation in the breeding performance of seed-eating birds in determining their population trends on farmland. *Journal of Applied Ecology* **37,** 128-148.

SIRIWARDENA GM, BAILLIE SR, CRICK HQP & WILSON JD (2001a) Changes in agricultural land-use and breeding performance of some granivorous farmland passerines in Britain. *Agriculture, Ecosystems & Environment* **84,** 191-206.

SIRIWARDENA GM, FREEMAN SN & CRICK HQP (2001b) The decline of the Bullfinch *Pyrrhula pyrrhula* in Britain: is the mechanism known? *Acta Ornithologia* **36**.

SOTHERTON NW (1982) The effects of herbicides on the chrysomelid beetle Gastrophysa polygoni (L.) in the laboratory and field. *Zeitschrift fur angewandte Entomologie* **94,** 446-451.

SOTHERTON NW, RANDS MRW & MOREBY SJ (1985) Comparison of herbicide treated and untreated headlands on the survival of game and wildlife. In *1985 British Crop Protection Conference - Weeds*, pp. 991-998. British Crop Protection Council, Thornton Heath, Surrey, UK, Brighton.

STOATE C, BOATMAN ND, BORRALHO RJ, CARVALHO CR, SNOO GRD & EDEN P (2002) Ecological impacts of arable intensification in Europe. *Journal of Environmental Management* **63,** 337-365.

STOATE C, MOREBY SJ & SZCZUR J (1998) Breeding ecology of farmland Yellowhammers *Emberiza citrinella*. *Bird Study* **45,** 109-121.

SUTHERLAND WJ (ed.) (2003) *Modelling the effects of farmland food webs of herbicide and insecticide management in the agrocultural ecosystem*. Unpublished report to Defra. Defra EPG 1/5/188. http://www.defra.gov.uk/environment/gm/research

THOMAS CFG & MARSHALL EJP (1999) Arthropod abundance and diversity in differently vegetated margins of arable fields. *Agriculture, Ecosystems and Environment* **72,** 131-144.

VICKERY J, ATKINSON P & MARSHALL EJP (2002a) The effects of different crop stubbles and straw disposal methods on wintering birds and arable plants. Project BD1610. BTO, Marshall Agroecology Ltd.

VICKERY J, CARTER N & FULLER RJ (2002b) The potential value of managed cereal field margins as foraging habitats for farmland birds in the UK. *Agriculture Ecosystems & Environment* **89,** 41-52.

VICKERY JA & FULLER RJ (1998) Use of cereal fields by birds: A review in relation to field margin management. British Trust for Ornithology, Thetford.

VOLKMAR C, HUSSEIN ML-A, JANY D, HUNOLD I, RICHTER L, KREUTER T & WETZEL T (2003) Ecological studies on epigeous arthropod populations of transgenic sugar beet at Friemar (Thuringia, Germany). *Agriculture Ecosystems & Environment* **95,** 37-47.

WATKINSON AR, FRECKLETON RP, ROBINSON RA & SUTHERLAND WJ (2000) Predictions of biodiversity response to genetically modified herbicide-tolerant crops. *Science* **289,** 1554-1557.

WATSON A & RAE R (1997) Some effects of set-aside on breeding birds in northeast Scotland. *Bird Study* **44,** 245-251.

WILSON JD, ARROYO BE. & CLARK SC (1996a) The diet of bird species of lowland farmland: a literature review. BBSRC-NERC Ecology & Behaviour Group, University of Oxford, Oxford.

WILSON JD, EVANS J, BROWNE SJ & KING JR. (1997). Territory distribution and breeding success of skylarks *Alauda arvensis* on organic and intensive farmland in southern England. *Journal of Applied Ecology* **34,** 1462-1478.

WILSON JD, MORRIS AJ, ARROYO BE, CLARK SC & BRADBURY RB (1999) A review of the abundance and diversity of invertebrate and plant foods of granivorous birds in northern Europe in relation to agricultural change. *Agriculture, Ecosystems & Environment* **75,** 13-30.

WILSON JD, TAYLOR R & MUIRHEAD LB (1996b) Field use by farmland birds in winter - an analysis of field type preferences using resampling methods. *Bird Study* **43,** 320-332.

WRIGHT MG & SAMWAYS MJ (1998). Insect species richness tracking plant species richness in a diverse flora: gall-insects in the cape Floristic Region, South Africa. *Oecologia* **115,** 427-433.

Appendix 5.1

Presence of invertebrate and plant taxa in the diet of farmland birds
Data from (Breeze *et al.*, 1999) and based on (Wilson *et al.*, 1996a; Wilson *et al.*, 1999).

Table A. 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.

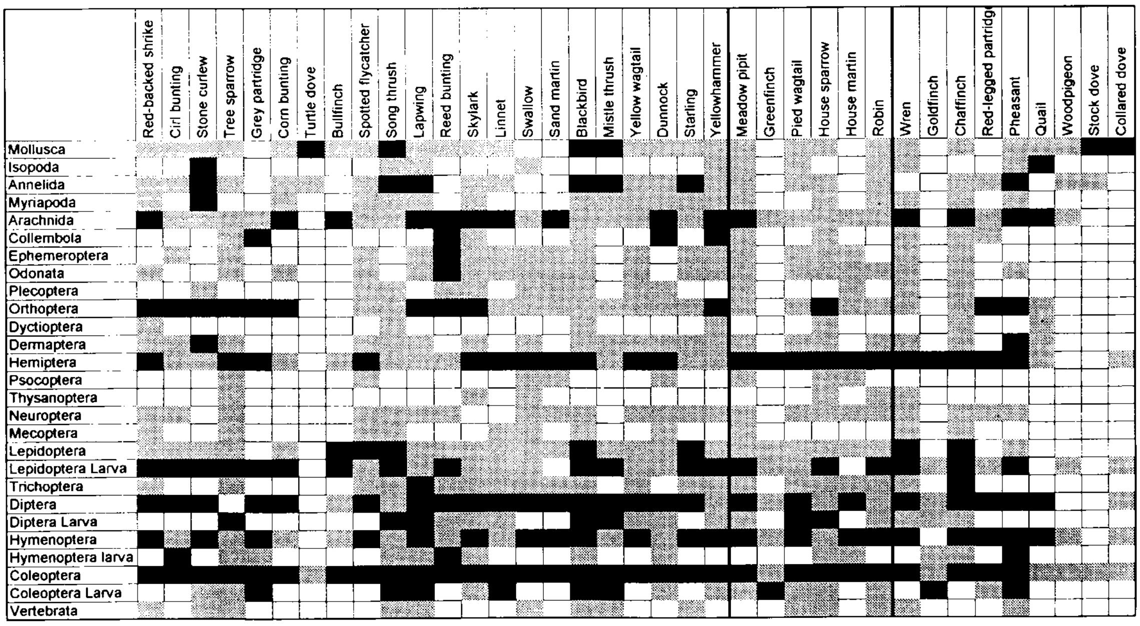
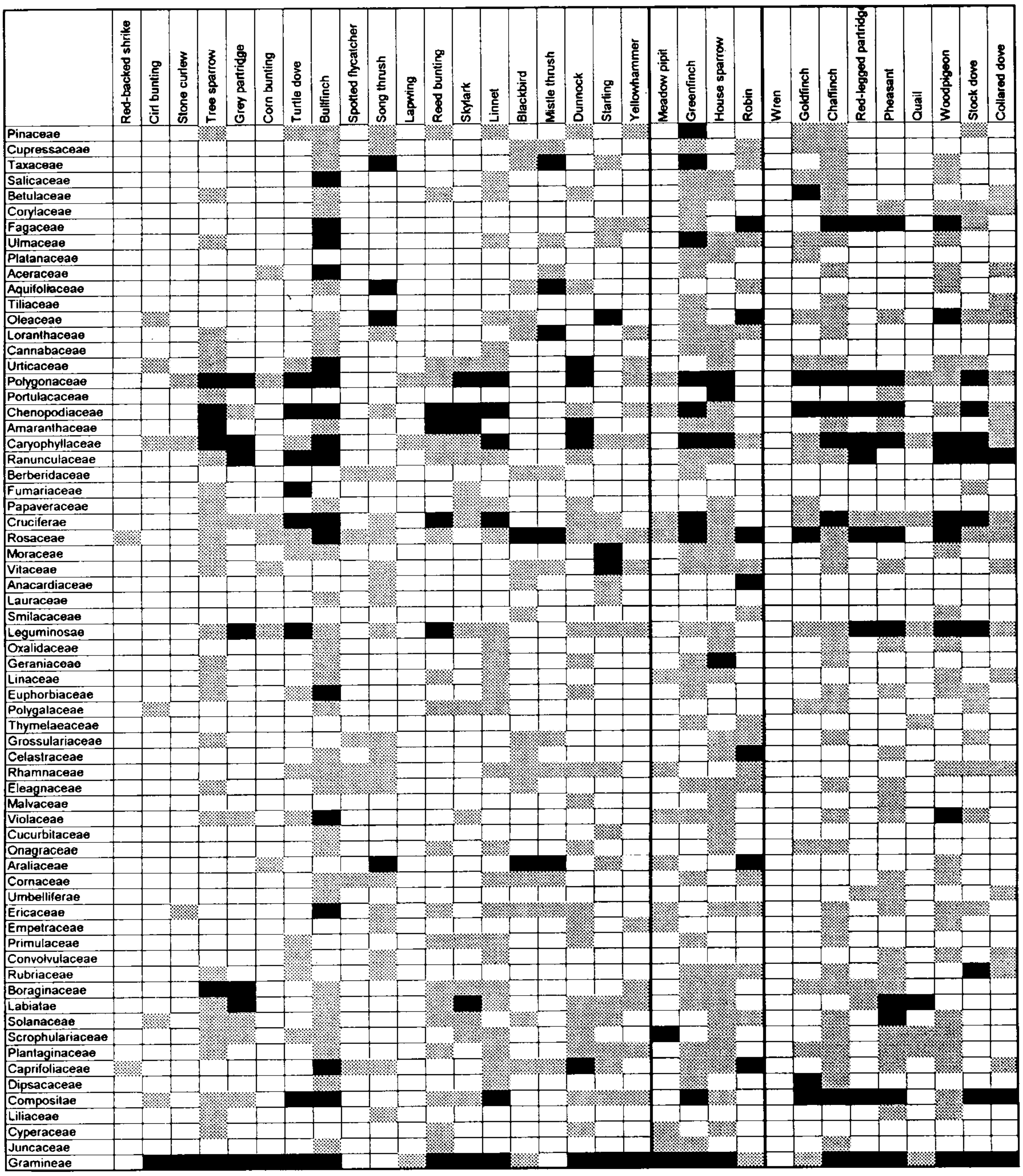


Table B. Presence of plants in the diet of farmland birds.

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

CHAPTER 6

THE RELATIONSHIPS BETWEEN WEEDS AND INVERTEBRATES IN HORTICULTURE

6.1 Introduction

There are few situations in horticulture where weeds can be tolerated (e.g. orchards, blackcurrants, hardy nursery stock). This is because horticultural crops are of high value per unit area and weeds reduce profitability drastically through effects on yield, quality, ease of harvesting, and marketability (see details in Chapter 2). High quality standards are necessary for producers to meet the criteria of a plethora of assured produce schemes (Parker, 2002). Various systems of companion planting (e.g. undersowing, intercropping) in brassicas, even when effective in reducing pest damage on the target crop, can run the risk of reducing crop yield because of competition for soil moisture (Hooks & Johnson, 2003). Similarly, the use of trap crops (e.g. strips of pest-attracting plants running through the crop to divert pests off the crop) in brassicas have so far produced mixed results, sometimes reducing the pest burden on the crop, but at other times increasing it (Bigger & Chaney, 1998; Hooks & Johnson, 2003). Two potential strategies that may avoid the above problems, yet sustain biodiversity and beneficial ecosystem services in the absence of weeds in the crop are i) manage the farm to have weeds (and/or other sown vegetation) near to the crop in refuge areas (see 6.3), and/or ii) apply dead organic mulches or manures to the soil surface within the crop field (see 6.4). Areas of weediness (habitat diversification), as reservoirs of invertebrates, could be fostered at field edges, or in uncropped strips within the field. The potential benefits and disbenefits of this strategy to horticulture and farmland biodiversity are explored in this chapter. The distinction between agriculture and horticulture in this regard becomes blurred because horticultural crops are often grown on rented ground (e.g. approximately half of the carrot acreage is grown on rented ground each year), on different land from year to year, and often on land previously used for agricultural crops. Therefore habitat diversification adjacent to agricultural crops may benefit horticulture in a subsequent year, and vice versa. In addition, pests and natural enemies have spatial dynamics operating at larger scales than field or farm (Fry, 1995) and so a myopic interpretation of the factors affecting horticultural production (in a reduced-pesticide era) would be inappropriate. Both the regional abundance and biodiversity of arthropods, including the pool of predators and parasitoids that can impact on horticultural and agricultural pests, are known to be increased by high landscape complexity (e.g. high proportion of landscape consisting of uncropped semi-natural habitats) (Kareiva, 1990; McLaughlin & Mineau, 1995; Marino & Landis, 1996; Colunga-Garcia *et al.*, 1997; Menalled *et al.*, 1999; Duelli & Obrist, 2003; Gurr *et al.*, 2003). Species richness of natural enemies is affected more by landscape structure than by farming practice (e.g. organic versus conventional), and is maximised in complex heterogeneous landscapes (Estevez *et al.*, 2000; Weibull *et al.*, 2003). Modelling and other studies suggest that pest control is improved by increased habitat and natural enemy diversity (Speight, 1983; Altieri, 1999; Loreau, 2000; Wilby & Thomas, 2002), so the interests of conservation and pest control coalesce in the desire to protect and enhance arthropod abundance and biodiversity at the landscape scale. There is a need to understand the mechanisms whereby biodiversity favours biological control of pests (Gurr *et al.*, 2003). One possibility is that species diversity facilitates interspecific interactions, often via indirect routes (Cardinale *et al.*, 2002), that render the prey resource more available to the natural enemy assemblage as whole. An example would be synergistic predation mediated by vertical redistribution of the pest population (Losey & Denno, 1999). Beyond pest control, advantages of diversifying the agricultural landscape include reduction of soil erosion (by wind and water), and the creation of an aesthetically pleasing farmscape to the benefit of tourism and local recreation (Gurr *et al.*, 2003).

Many predators need refuges to hide from inimical physical conditions during daytime. Such refuges could be provided by thick weed cover, but, since this would seriously compete with the crop, the protective function of weeds could be substituted by dead mulches/manures lying on the ground surface. Such mulches would also provide extra food for predators and protection for vulnerable stages in their life cycle. The prospects and potential of this strategy are evaluated in Section 6.4.

6.2 Weeds within crops

Weeds within arable fields are a valuable resource for natural enemies, including generalist predators (with wide dietary ranges), such as spiders and carabid beetles (Speight & Lawton, 1976; Powell *et al.*, 1985, 1986; Pfiffner & Luka, 2003). Unfortunately, weeds cannot normally be tolerated in horticultural crops. Sengonca *et al.* (2002) planted, in a lettuce crop, weeds (wormwood *Artemisia vulgaris*, tansy *Tanacetum vulgare*, stinging nettle *Urtica dioica*) that are attractive to polyphagous predators (ladybirds and lacewings). Predator abundance on lettuce plants in plots containing these weeds was significantly greater and aphid populations were significantly reduced. In plots of broccoli with and without interplantings of 34 genera of nectar-producing flowers, however, caterpillar pests (*Pieris rapae* and *Plutella xylostella*) were more abundant in plots containing flowers than in control plots (Zhao *et al.*, 1992). In both of these studies the authors provided no data on the yield, quality, ease of harvesting or marketability of plants in weedy versus weed-free plots, nor on levels of contamination with invertebrates. Any invertebrates (moths, beetles, flies, bees, wasps, slugs, bugs) in ready-to-eat salad packs, for example, are unacceptable at a rate of 5 per 100,000 packs (Parker, 2002). Although methods are being developed to manage crop systems so that some weeds can be retained, but without significant negative impacts on crop yield and quality (Liebman *et al.*, 2001), currently few weed species can be tolerated in few horticultural crops. A possible exception is underplanting in orchards.

6.2.1 Weeds in orchards

Bare ground was compared with natural vegetation and sown vegetation (ryegrass, mustard and clover) understorey in a pear orchard. Arthropod assemblages in trees varied according to the type of understorey. Predatory bugs (Anthocoridae) predominated above sown inter-rows, predatory flies (Empididae) above natural vegetation, earwigs (Forficulidae) above bare ground, and predatory bugs (Miridae) above all three. The ratio of natural enemies to phytophages (including pests) was lowest over bare ground. This suggests that understorey manipulation can be a tool for tailoring natural enemy community composition in orchard trees to optimise biocontrol of pests that dominate in specific regions (Rieux *et al.*, 1999). Care is needed, however, to ensure that underplantings do not compete with the crop. When apple was underplanted (in alternating single-species strips) with dill (*Anethum graveolens*), buckwheat (*Fagopyrum escelentum*), dwarf sorghum (*Sorghum bicolor*) and rape (*Brassica napus*), both yield and quality of apples suffered compared with apples taken from a conventional orchard with bare earth below trees. Competition for water and nutrients between trees and ground cover was suspected. This underlines the need for detailed knowledge and careful management to optimise the benefits of underplanting (Brown & Glenn, 1999).

Adults, larvae and pupae of the ladybird *Coccinella 7-punctata* were recorded on weeds infested with the aphid *Aphis fabae* under trees in an apple orchard. This was the dominant ladybird species in the canopy too (Radwan & Lövei, 1982). Weed strips were sown between trees in an apple orchard and this area was compared with a control part of the orchard. More aphidophagous predators (spiders, bugs, Coccinellidae, Chrysopidae) were recorded on the trees above the weed strips (especially when they were flowering) than on trees in control areas. Apple aphids were less abundant in the weed-strip part of the orchard (Wyss, 1995; Wyss *et al.*, 1995). In contrast, in an unreplicated experiment, the pest aphid *Dysaphis plantaginea* was more abundant on apple trees above a mixture of flowering plants than above grass. *D. plantaginea* is an early species which built up its population before the understorey came into flower, and before natural enemies were attracted to the area (Vogt & Weigel, 1999). The aphids *Myzus persicae* on fallen peach leaves are eaten by ground beetles, which reduces the number of aphids returning to trees to oviposit (Bugg & Waddington, 1994). Carabid beetles were more abundant on the ground in an apple orchard where no-till weedy areas remained, than in cultivated areas (Holliday & Hagley, 1984). Altieri & Schmidt (1986) found high numbers of predators on cover crops under apple trees; these sometimes (e.g. spiders), but not always, translated into higher numbers of predators on the trees. The authors suggested investigating whether mowing the cover crop would force natural enemies into the trees.

Fitgerald & Solomon (2003 under review) tested fourteen species of flowering plants and found that corn chamomile (*Anthemis arvensis*), cornflower (*Centaurea cyanus*) and corn marigold (*Chrysanthemum segetum*) were most attractive to insects. These three species were sown in some plots of an apple and pear orchard and compared with unsown control plots. Predatory anthocorid bugs were significantly more numerous on trees above undersown plots, but otherwise there were no significant differences between treatments in numbers of predators or pests. However, when Solomon *et al.* (1999) put out potted pear trees bearing eggs and larvae of pear psylla (*Cacopsylla pyricola*) in plots sown with a mixture of the above three flowering plants psyllids were reduced in flower plots to half the level observed in bare earth plots over a period of two weeks. Fye (1983) found that small grain cereals as cover crops were successful (but inconsistent) in retaining predators of pear psylla in pear orchards, because the cereals supplied alternative prey such as cereal aphids (*Schizaphis graminum*). Stephens *et al.* (1998) planted buckwheat (*Fagopyrum esculentum*) under apple trees and found significantly higher levels of parasitism of leafroller larvae above these buckwheat plots than above herbicide-treated control areas.

Valuable weeds in terms of harbouring natural enemies include common knotgrass (*Polygonum aviculare*) and chickweed *(Stellaria media*), which provides nectar to parasitoids. Cover crops can be strip managed, i.e. strips can vary in terms of floristic composition or tillage and alternate strips can be mown so that natural enemies can retain refuges. Strip management can be a means of reducing competition between trees and cover crop whilst maintaining inoculum of natural enemies. It will also maximise diversity (Bugg & Waddington, 1994).

Re-analysis of data of Leius (1967) showed that parasitism of codling moth larvae was significantly greater in apple orchards with a diverse understorey of flowering plants such as buttercup, dandelion and many others (Bugg & Waddington, 1994).

Predatory phytoseiid mites have high fecundity on apple pollen, but grass pollen (potentially obtained from a grass understorey) can enhance survival (Ouyang *et al.*, 1992). Liang & Huang (1994) reported that whiteweed (*Ageratum conyzoides*; Asteraceae) has many positive attributes as an orchard understorey weed. It is shallow-rooted and does not compete with trees for water and nutrients, yet it is vigorous and suppresses growth of pernicious weeds. Orchards underplanted with this species have temperatures 10 °C lower and humidities 5% higher than in control bare-earth orchards, and these modified microclimates are more suitable for predatory mite (*Amblyseius* spp.) enemies of spider mites (*Panonychus* spp.). Fourteen species of *Amblyseius* were found on trees, twelve on *A. conyzoides*, and eleven were common to both. Natural enemies migrated from weeds to trees. This weed is highly valued in China and forms an understorey in 135,000 ha of citrus orchard there.

6.3 Invertebrate refuges: benefits and disbenefits to horticulture and wildlife

Field "margin" is defined as the crop edge plus any margin strip present plus the semi-natural habitat associated with the boundary (Marshall & Moonen, 2002; Marshall *et al.*, 2002).

6.3.1 Benefits

The benefits of invertebrate refuges at field margins (or as habitat strips running through fields) relate to them being reservoirs of walking and flying natural enemies (predators and parasitoids) that could colonise the crop and contribute to the biological control of invertebrate pests on the crop. They may also provide foci of survival of these natural enemies during winter, and also during episodes of perturbation within the fields caused by farming practices such as ploughing and the application of insecticides. They may act as sources of food (such as pollen and aphids) that fly or are blown from the edge into fields and that can then be a significant energy source for generalist predators in the field, improving their efficiency in the biocontrol of pests. Additionally, they are an important resource for pollinators, which are of great economic significance because of their services in pollinating crop plants. They make a major contribution to farmland biodiversity through provision of floristic diversity which, in turn, supports a rich fauna, including seed-eating invertebrates, small mammals and a range of farmland birds (insectivores, herbivores and omnivores), many of which are in decline. These various benefits are discussed below. They also protect adjacent terrestrial and riparian habitats from pesticide drift and surface run-off (Boatman, 1998; Marshall *et al.*, 2002).

6.3.1.1 Enhancement of biocontrol

Field edges and conservation headlands:
Conservation headlands (receiving some, but limited, pesticide applications) are beneficial to invertebrates and birds (Moreby & Southway, 1999). Abundance of aphid-feeding predators in field edges is positively correlated with general arthropod diversity and both are favoured by a high proportion of tussock-forming grasses (Dennis & Fry, 1992). Both complex and simple field border habitats support abundant and diverse populations of carabid beetles (Varchola & Dunn, 2001). Holland *et al.* (2001) surveyed carabid beetles across 66 ha of arable land, including six fields and their boundaries, and found that patches of greatest carabid diversity were near field boundaries. The abundance of carabid beetles was significantly greater in conservation headlands than in crops or fully-sprayed headlands (Cardwell *et al.*, 1994). Abundance of predators such as ladybirds and hoverflies was greater in unsprayed than sprayed

edges (de Snoo & de Leeuw, 1996), but not significantly greater in 6 m-wide compared to 3 m-wide unsprayed edges (de Snoo, 1996). Field edges can be sites of rich spider biodiversity. In a study of 97 field margins characterised by herbs and grasses, Barthel (1997) recorded 75 species of spider. Frank (2000) found a mean of 2.5 spider species per edge compared with a mean of 0.5 per sample within fields. McLachlan & Wratten (2003) found 25 spider species (at 316 m^{-2}) in field edges, compared with 13 species (at 53 m^{-2}) in fields. Reduction of pesticide inputs to field edges and conservation headlands results in increases in abundance and species richness of generalist predators, probably mediated mainly through changes in abundance of prey (Chiverton & Sotherton, 1991; Hassall *et al.*, 1992; Raskin, 1993; White & Hassall, 1994; Hawthorne, 1995; Hawthorne & Hassall, 1995; Baines *et al.*, 1998). Other management practices can also affect the composition and abundance of predator communities in field edges. Lycosid spiders were more numerous in margins sown with grass, or grass and wildflowers, than in naturally regenerating margins (Thomas & Marshall, 1999). Spring and summer mowing caused considerable reductions in abundance and species richness of spiders, especially Linyphiidae (Feber *et al.*, 1995; Baines *et al.*, 1998). Mowing in spring and autumn every two years, and leaving the mown hay *in situ*, was the least damaging management regime for spiders (Haughton *et al.*, 1999a). Wildflower mixtures did not increase the abundance of staphylinid beetles (Feber *et al.*, 1995), and sometimes (Baines *et al.*, 1998) but not always (Feber *et al.*, 1995) increased the abundance and species richness of spiders. Applications of glyphosate reduced the abundance of all predators, but spiders were more severely affected than carabid beetles (Haughton *et al.*, 1999b). Within the Araneae, however, web-making spiders were more affected by glyphosate than were wolf spiders (Lycosidae), which hunt on the ground surface and do not make webs (Haughton *et al.*, 1999c). The direct effect of glyphosate on web-spiders is small (Haughton *et al.*, 2001a), but it has a deleterious effect by reducing the availability of suitable microsites for web attachment (Bell *et al.*, 2002a,b; Haughton *et al.*, 2001a,b). Although herbicides have little or no direct effect on natural enemies, some herbicide active ingredients can boost pest populations (e.g. aphids and caterpillars) by increasing the protein content of host plants (Oka & Pimentel, 1976).

Beetle banks:

Beetle banks are narrow, raised and vegetated banks within fields. They harbour natural enemies and one of their main aims is to reduce field size to enable predators that disperse by walking (e.g. the carabid beetles *Demetrias atricapillus* and *Agonum dorsale*) to colonise fields more easily in spring, and so be present at the earliest stages of pest immigration and increase (Holland, 1994; Sotherton, 1995; Wratten & Van Emden, 1995; Collins *et al.*, 2003a). Establishment cost of a 400 m beetle bank was less than £80 in 1995, with annual maintenance cost of less than £30. They now attract a grant of £600 ha^{-1} under the Countryside Stewardship Scheme (Anon., 2001, 2002). Beetle banks provide a valuable refuge for polyphagous predators, especially in the tussocks of sown cocksfoot (*Dactylis glomerata*) and Yorkshire fog (*Holcus lanatus*), and their density within the bank is up to 1500 m^{-2} (Sotherton, 1995), which is ten to twenty times greater than in the open field (Wratten & Thomas, 1990; Thomas *et al.*, 1991, 1992a). This refuge effect can last for at least a decade (Thomas *et al.*, 2002). Collins *et al.* (2003a) tested the suitability of five grasses (*Arrhenatherum elatius*, *Dactylis glomerata*, *Phleum pratense*, *Festuca rubra* and *Cynosurus cristatus*) for beetle banks and concluded that *A. elatius* and *D. glomerata* supported the highest predator (27 species of ground beetle, 2 species of rove beetle and 25 species of spider) densities.

Field margin and within-crop weed strips:

Weed strips created within crops are similar to beetle banks, except that they are not necessarily raised above the crop and are not dominated by grasses (they are floristically diverse with a high proportion of dicotyledonous weeds). In this context the term "weed" does not necessarily denote a plant that is harmful to horticulture and agriculture; it includes plant species that are neutral, or even valuable, because of the services they provide for beneficial invertebrates. Weed strips within fields (at a spacing of 50 m to 100 m (Nentwig *et al.*, 1998), that have the potential to influence conservation biological control and farmland biodiversity) occupy about 5% of the field area; the consequent financial losses need to be taken into account by the farmer, or in government compensation schemes (Nentwig, 1998). Wildflower areas or weed strips at field margins, initially created by sowing a wildflower mixture of 25 herbaceous species, gained, after four years, a further 28 grass species and 77 herb species from the regional species pool (Barone & Frank, 2003). Predator densities (and often species richness) were higher within weed strips than in the adjacent crop (Kemp & Barrett, 1989; Rodenhouse *et al.*, 1992; Lys, 1994; Lys & Nentwig, 1994; Lys *et al.*, 1994; Zangger, 1994; Zangger *et al.*, 1994; Frank & Nentwig, 1995; Frank, 1996; Jmhasly & Nentwig, 1995; Frank, 1997; Lemke & Poehling, 1998; Nentwig *et al.*, 1998; Fench & Elliott, 1999; Menalled *et al.*, 2001). About 70 predators m^{-2} were found on borage (*Borago officinalis*), blue knapweed (*Centaurea cyanus*) and poppy (*Papaver rhoeas*) in weed strips (Nentwig, 1998). Ladybirds are especially attracted to stinging nettle (*Urtica dioica*), alfalfa (*Medicago sativa*), evening primrose (*Oenothera biennis*), carrot (*Daucus carota*), white mustard (*Sinapis alba*), comfrey (*Symphytum officinale*) and mullein (*Verbascum densiflorum*) in weed strips (Nentwig, 1998). More species of carabid beetle were found in strips than in adjacent field areas (Nentwig *et al.*, 1998). Zangger *et al.* (1994) showed that the egg complement of a representative predatory carabid (*Poecilus cupreus*) was significantly greater in weed strips than in adjacent fields, and Barone & Frank (2003) showed that the mean egg complement of this species was 11 in one-year-old strips, but significantly greater at 16 in four-year-old strips. The reproductive period of carabids was also prolonged in strips (Nentwig *et al.*, 1998). This means that well-established strips support a higher rate of beetle reproduction than occurs in fields, which increases their value as potentially potent sources of predators for surrounding farmland. Denys & Tscharntke (2002) also found that predator density and predator-prey ratios were significantly greater in 6-year-old than in 1-year-old margin strips.

<u>*Sources or sinks ?:*</u>
Arthropods in agricultural landscapes tend, in general, to be very dispersive. Along a 5 km transect taking in a range of habitats including crop fields, Duelli & Obrist (2003) caught 222,812 arthropods of 2229 species, but only 6% of species were confined to a single habitat. This means that a wide range of species emanating from refuge habitats have at least a chance to sample crop fields. Duelli *et al.* (1990) collected 30 spider species in a crop field and distribution patterns suggested that 60% would have been absent but for the neighbouring semi-natural habitats; in contrast only 22% of rove beetle species (Staphylinidae) and 16% of ground beetle (Carabidae) species seemed to be in the field because of adjacent land. The situation may be different, however, where hedgerows dominate field edges. Toft & Lövei (2000) identified 71 species of spider under hedges, but only four species were characteristic of adjacent fields.

Some species of carabid are known to make a spring migration from field edge overwintering sites into the field proper (Wratten, 1988; Paoletti, 2001). These include *Agonum dorsale* (Pollard, 1968; Coombes & Sotherton, 1986; Jensen *et al.*, 1989; Welling, 1990; Kromp & Steinberger, 1992; Booij *et al.*, 1995; Kromp & Nitzlader, 1995; Idinger *et al.*, 1996; Hawthorne *et al.,* 1998), *Demetrias atricapillus* (Coombes & Sotherton, 1986; Thomas *et al.*, 1991), *Harpalus rufipes* (Wallin, 1986), *Brachinus explodens* (Kromp & Steinberger, 1992), *Asaphidion flavipes* (Idinger *et al.*, 1996), *Bembidion lampros* (Wallin, 1985; Coombes &

Sotherton, 1986; Kromp & Steinberger, 1992; Idinger *et al.*, 1996; Hawthorne *et al.*, 1998), *Carabus* spp., *Loricera pilicornis*, *Harpalus affinis* and *Amara* sp. (Welling, 1990). Grids of pitfall traps encompassing hedgerow and field showed that *Amara* spp. and *Harpalus rufipes* had distributions focussed on hedgerows, and that *Nebria brevicollis* aestivated in the hedgerow during summer and then moved out into the field in autumn (Fernández García *et al.*, 2000; Thomas *et al.*, 2001). The within-field distribution of *Amara* spp. and *Bembidion lampros* appeared to be influenced by the field edge, since the majority of individuals were caught within 60 m of the edge (Holland *et al.*, 1999b). *Demetrias atricapillus* also migrated from beetle banks to at least 60 m into the field during spring (Wratten & Thomas, 1990), and catches from grids of pitfall traps showed carabid aggregations in the crop alongside beetle banks (Thomas *et al.*, 2000). Movement of carabids into fields is sometimes inferred from the spatio-temporal pattern of catches along a transect running from the edge towards the middle of a field (Wallin, 1985; Klinger, 1987; Thomas *et al.*, 1991; Kromp & Steinberger, 1992; Booij *et al.*, 1995; Frank, 1996; Idinger *et al.*, 1996 Thomas *et al.*, 1997), but has also been demonstrated in mark-release-recapture experiments (Pollard, 1968; House & All, 1981; Coombes & Sotherton, 1986; Wallin, 1986; Jensen *et al.*, 1989; Welling, 1990; Kajak & Lucasiewicz, 1994; Kromp & Nitzlader, 1995; Winstone *et al.*, 1997). A comparison of crop areas containing weed strips with strip-free control areas suggests that the abundance and species richness of carabids (Nentwig, 1989; Lys & Nentwig, 1992; Lys, 1994)) and some other predators (Altieri & Todd, 1981; Rodenhouse *et al.*, 1992) in the crop can be augmented by the presence of weed strips. Carabid abundance in the crop was greater adjacent to conservation headlands than adjacent to fully-sprayed headlands (Cardwell *et al.*, 1994) and 8% more predators were caught up to 100m into fields adjacent to set-aside strips (with kale, millet, *Phacelia*, quinoa, triticale, sunflowers and clover) than in control fields (Holland *et al.*, 2003). Directional pitfall traps showed that more carabids (especially *Bembidion lampros*) were moving out of conservation headlands in the spring than were moving back in the opposite direction (Hawthorne *et al.*, 1998). Few flying carabids are caught in window traps in fields (Wallin, 1985) and most individuals probably walk into fields. The larger carabids can disperse 7 – 15 m day^{-1} (Welling, 1990; Lys & Nentwig, 1991; Thomas *et al.*, 1997), and *Pterostichus melanarius* moved up to 73 m day^{-1} (Lys & Nentwig, 1992). In contrast, many staphylinid beetles can fly, and large numbers are caught in 12.2 m suction traps in spring and autumn (Sunderland, 1992). Thus, they can enter fields from many sources over extensive areas and evidence for field edges being significant resevoirs of field staphylinids is not very strong (Coombes & Sotherton, 1986).

Spider dispersal into fields has been inferred from catches along transects (Alderweireldt, 1999; Thomas *et al.*, 1990; Frank, 1996; Hausammann, 1996; Vangsgaard, 1996; Tóth & Kiss, 1997; Lemke & Poehling, 1998; Nentwig *et al.*, 1998; Sigsgaard, 2000) and demonstrated by mark-release-recapture (Kajak & Lucasiewicz, 1994). The linyphiid spiders *Bathyphantes gracilis* (Alderweireldt, 1989) and *Oedothorax apicatus* (Thomas *et al.*, 1990; Lemke & Poehling, 2002) colonise fields by walking in from edges, but the majority of linyphiids disperse by ballooning (Freeman 1946; Dean & Sterling, 1985; Greenstone *et al.*, 1987; Sunderland 1987, 1991) and have the capacity to travel long distances through the air before alighting into crops and other habitats (Bishop & Riechert, 1990; Crawford & Edwards, 1986; Crawford *et al.*, 1995; Toft 1995a). On a day with 6 h of suitable weather, linyphiid spiders can disperse a mean distance of 30 km downwind (Thomas *et al.*, 2003).

Perennial grasses in field margin strips are likely to also be a source of parasitoids of crop pests. These parasitoids are expected to move out of margin strips and into fields in the spring, but this remains to be fully investigated (Wratten *et al.*, 1998).

A proportion of carabid individuals of the those species found in fields during the summer remain in or very near field edges during the summer (Desender & Alderweireldt, 1988; Klimes & Sechterova, 1989; Wallin, 1989; Dennis, 1991; Kromp & Steinberger, 1992; Kiss *et al.*, 1993; Bedford & Usher, 1994; Kajak & Lucasiewicz, 1994; Hawthorne, 1995; Bujaki *et al.*, 1996 Thomas *et al.*, 1997; Holland *et al.*, 2001). This principle also applies to predatory Heteroptera (Altieri & Todd, 1981), staphylinid beetles (Dennis, 1991) and spiders (Raatikainen & Huhta, 1968; Nyffeler & Benz, 1980; Altieri & Todd, 1981; Klimes & Sechterova, 1989; Glück & Ingrisch, 1990; Maelfait & De Keer, 1990; Kromp & Steinberger, 1992; Nyffeler & Breene, 1992; Alderweireldt, 1993; Kiss *et al.*, 1993; Bedford & Usher, 1994; Kajak & Lucasiewicz, 1994; Luczak, 1995; Bujaki *et al.*, 1996; Downie *et al.*, 1996; Huusela-Veistola, 1998). Wolf spiders (Lycosidae) are more numerous at the edges than centres of fields, but the reverse can sometimes be true for money spiders (Linyphiidae) (Sunderland, 1987; Klimes & Sechterova, 1989; Maelfait & De Keer,1990; Nyffeler & Breene, 1992; Holland *et al.*, 1999b). This may be because lycosids are more susceptible to mechanical disturbances (Huusela-Veistola, 1998). Spider abundance and species richness were also greater within a couple of metres of a weed strip than at 13 m or more into the field (Frank & Nentwig, 1995; Jmhasly & Nentwig, 1995; Lemke & Poehling, 2002). Some predators, such as carabid beetles (Lys, 1994; Nentwig *et al.*, 1998), anthocorid bugs (Kemp & Barrett, 1994) and dictynid spiders (Heidger & Nentwig, 1989) have been found to move from the crop into weed strips, so these strips may sometimes act as sinks rather than sources (Corbett, 1998). Even the larvae of spring migrators, such as the carabid *Agonum dorsale*, can be found at considerable density in field edges during the summer (Desender & Alderweireldt, 1988), and carabid larvae are more abundant in conservation headlands than in sprayed headlands (Coombes & Sotherton, 1986; Hawthorne *et al.*, 1998). Edges may be more attractive than crops to generalist predators because they often harbour a rich diversity of prey, including Diptera, Hymenoptera, Auchenorryncha and Heteroptera (Huusela-Veistola & Kurppa, 1996). Nettles (*Urtica dioica*) at edges may support aphids and psyllids (Perrin, 1975). Fungivorous Diptera (Lauxaniidae, Drosophilidae, Lonchopteridae) and Coleoptera (Corylophidae, Lathridiidae, Phalacridae, Cryptophagidae, Staphylinidae), which can be alternative foods for predators, are also abundant in field edges (Reddersen, 1995). Sown weed strips at the edge of fields contained a high density of spiders and predatory Heteroptera, but these predators did not move out into the field in summer (Bugg *et al.*, 1987). Similarly, the large carabids monitored by Frampton *et al.* (1995) remained in a grassy bank at the field edge. More carabids were caught at 2 m into fields adjacent to strips of *Sinapis alba* and *Phacelia tanacetifolia* than adjacent to controls, but this effect did not extend out as far as 7 m, and staphylinids and spiders were unaffected by the treatment (Klinger, 1987). Kienegger & Kromp (2001) found that carabids did not disperse out into broccoli from commercial annual wildflower strips. Predatory heteropteran bugs (Nabidae, Geocoridae and Anthocoridae) were extremely abundant in field borders sown with candytuft (*Iberis umbellata*) but failed to move out into the adjacent cabbage crop (Bigger & Chaney, 1998). When carabids and spiders were marked at field edges, less than 5% moved up to 5 m out of the habitat where they were marked (Kajak & Lucasiewicz, 1994). It is possible that some natural enemies are repelled from immigrating into the crop by toxic pesticide residues remaining from earlier spray applications (Gurr *et al.*, 1998), but this topic is liitle researched. Predator populations overwintering at field edges were calculated to constitute only 9% of summer populations within fields (Desender *et al.*, 1989). For edge populations to account for densities observed during summer within fields, reproduction would have to be extremely high, and it is more likely that summer field populations are derived from a variety of sources of which field edges are just one (Sunderland & Samu, 2000).

Effects on pests:
Evidence for depression of pest populations within fields due to predators moving out from edges into crops is still somewhat sparse (Kromp, 1999), but this phenomenon is difficult to study. Researchers tend to look for greater pest reductions in areas of crop adjacent to diversified edge habitats, and such effects have been recorded in a few cases up to about 10 m into the crop (Chambers *et al.*, 1982; Welling & Kokta, 1988; Kemp & Barrett, 1989; Riedel, 1991; Raskin, 1994 (in Kromp, 1999); Hawthorne & Hassall, 1995; Lemke & Poehling, 1998; Marshall & Moonen, 2002; Marshall *et al.*, 2002). Collins *et al.* (2002) showed that polyphagous predators (Carabidae, Staphylinidae, Lycosidae, Linyphiidae) moved out of beetle banks into the crop, and that depression of aphid populations in the crop on some dates was greater up to 33 m into the crop than at 58 m and 83 m. It should also be noted, however, that many predators are rapid dispersers (Van Emden, 1981; Wissinger, 1997),including by flight and ballooning. These highly dispersive edge-overwintered predators may join the regional pool of predators which is a source of predators colonising fields in the region as a whole. It is predicted that diversified or complex landscapes (with a high proportion of predator refuge areas) should harbour larger regional populations of predators than simple (i.e. with a high proportion of cropped land) landscapes (Sunderland & Samu, 2000). This hypothesis is difficult to test experimentally, but modelling studies tend to support its plausibility (Topping & Sunderland, 1994ab; Halley *et al.*, 1996; Thomas, 1996; Topping, 1997, 1999; Thomas *et al.*, 2003). Östman *et al.* (2001ab) found that high condition indices (length, biomass, fat content) of carabid beetles in fields and low numbers of pest aphids establishing in crops, were associated with abundant field margins and a high proportion of perennial crops in the landscape. Parasitoid abundance and parasitism of pests in fields may also be related to habitat complexity. Mean percentage parasitism of armyworm (*Pseudaletia unipuncta*), a caterpillar pest of cereals, was significantly greater in complex landscapes than in simple landscapes in some regions (Marino & Landis, 1996), but not in others (Menalled *et al.*, 1999).

Edge habitats may also be reservoirs for parasitoids of pests. Thies *et al.* (1997) (cited in Frank, 2000) found that percentage parasitism of pollen beetle (*Meligethes* spp.) by an ichneumonid wasp (*Tersilochus heterocerus*) was twice as great within 2 m of the field edge compared to 12 m into the fields. Thies & Tscharntke (1999) showed that parasitism was greater and crop damage less in complex landcapes (i.e. with high percentage of non-crop area in the landscape) than in landscapes that were predominantly composed of large crop fields with little natural refuge edge habitat.

Given that suitably-managed edge/strip habitats (and orchard understoreys –section 6.2.1) are extremely hospitable habitats for natural enemies, and that because of this some individuals may not move out into adjacent crops, it is possible that periodic partial destruction of the habitat (e.g. by mowing) would force natural enemies out into the crop and improve biological control of pests there. This practice has been suggested quite often (e.g. Altieri & Schmidt, 1986; Bigger & Chaney, 1998; Mensah, 1999) and there is some evidence to support this general principle in a variety of cropping systems (Perrin, 1975; Ali & Reagan, 1985; Bugg *et al.*, 1991; Settle *et al.*, 1996), but it does not appear to have been investigated yet in horticulture.

Might this principle (of using short-term floral biodiversity to build up natural enemies, then flushing the natural enemies onto the crop by removing the floral biodiversity) also be applied *within* horticultural crops, rather than just in refuge areas? In theory, if genetically modified herbicide tolerant horticultural crops are eventually grown in the UK, more flexibility will be available in the choice of timing of applications (because broad-spectrum herbicides can be used). This means that weeds could be left for longer in the crop, which would enhance natural enemies (Dewar *et al.*, 2003), and subsequent herbicide applications might then divert these natural enemies onto the crop plants, thus improving biocontrol of pests. In practice, however, weed tolerance levels in horticultural crops are so low, and periods of tolerance so short (see details in Chapter 3), that this strategy is unlikely to be practicable; it may also be detrimental to farmland bird populations (Chapter 5).

6.3.1.2 Flowers provide food for pollinators and flying natural enemies

Pollinators, adult parasitoids and flying predators feed on floral and extrafloral nectar and on pollen from flowers in refuge habitats (Jervis & Kidd, 1996; Landis *et al.*, 2000). They also consume honeydew excreted by Hemiptera (e.g. aphids and whiteflies) feeding on the plants (Idris & Grafius, 1995; Jervis & Kidd, 1996). Sugars obtained directly and indirectly from refuge plants increase the searching capacity, fecundity and longevity of parasitoids, nectar promotes egg maturation of Ichneumonidae parasitoids (Schneider-Orelli, 1945) and pollen enhances egg maturation of hoverflies (Gurr *et al.*, 1998). This might increase their impact on crop pests (providing that they also disperse out from refuge areas and into fields). Flowers in refuge habitats are an important source of food for honeybees and bumblebees (Apidae), which are needed for pollination of about forty UK crop species (Osborne & Williams, 1996).

<u>Field margins:</u>

More parasitic Hymenoptera were caught in flower-rich field margins than in crop fields (Van Emden, 1963). Parasitic Diptera (especially Tachinidae) are also commonly recorded feeding at flowers (Van Emden 1965b). Examples can be found where increased parasitism of pests in crops is attributable to the influence of nectar-producing plants at the edge of crops (Powell, 1986). Field margins sown with flowering perennials (Asteraceae, Fabaceae, Lamiaceae) attracted nine species of Hymenoptera, seven species of Diptera and three species of Lepidoptera (Carreck *et al.*, 1999). These authors also investigated (in plot trials) the attraction of various annual flowering plants (that might be sown as invertebrate refuges) to pollinators. The most attractive species were phacelia (*Phacelia tanacetifolia*), borage (*Borago officinalis*), marigold (*Calendula officinalis*), buckwheat (*Fagopyrum esculentum*), mallow (*Malva sylvestris*) and cornflower (*Centaurea cyanus*). These species attracted sixteen species of Hymenoptera (including the honey bee and fourteen species of bumble and solitary bees), seventeen species of Diptera (sixteen species being hoverflies) and six species of Lepidoptera. Perennial flowering plants in field margins produce more energetic nectars than annuals (Corbet, 1995) and are better nectar sources for bumblebees (Fussell & Corbet, 1992; Dramstad & Fry, 1995). Bumble-bees are economically more important as crop pollinators since the accidental introduction to the UK of *Varroa destructor*, a parasitic mite attacking honey bees (Fussell & Corbet, 1992), but they have undergone a decline, caused, in part, by agricultural intensification (Williams, 1982, 1986; Osborne *et al.*, 1991; Corbet, 2000). Significantly more bees were found to visit naturally regenerated field margins than cropped field margins managed as conservation headlands (Kells *et al.*, 2001). Bumblebees (*Bombus terrestris*, *Bombus lapidarius*) preferred different flower species to honeybees (*Apis mellifera*), emphasising the need for floral diversity in refuge habitats (Kells *et al.*, 2001). Melilot (*Melilota alba*) was found to be especially attractive to honey-bees and flies (excluding Syrphidae) and red clover (*Trifolium pratense*) to bumble-bees. When a bee-hive was placed at the field margin, and pollen sampled in a pollen trap, it was shown that pollen collected by bees came mainly from rape (*Brassica napus* and *Brassica rapa*), melilot, red clover, hoary plantain (*Plantago media*), meadow sweet (*Filipendula ulmaria*) and burdock (*Arctium tomentosum*) (Lagerlöf *et al.*, 1992). When the activities of seven species of bumblebee were monitored in refuge areas at field edges, only nine out of 78 flowering plant species were observed to receive a significant number of bee visits (Dramstad & Fry, 1995).

Although appropriately-managed field margins are excellent refuges for predators, such as spiders (section 6.3.1.1), and pollinators can be killed by predators on flowering plants (Suttle, 2003), this negative interaction is slight compared to the overall density-enhancing effect of margins on both predators and pollinators.

The common aphidophagous hoverfly, *Episyrphus balteatus,* visited 27 flower species at the edges of fields, but preferred flowers of autumn hawkbit *(Leontodon autumnalis)*, fool's parsley (*Aethusa cynapium)*, wild carrot (*Daucus carota)* and white campion (*Silene alba)* (Cowgill *et al.*, 1993a). More recently, with funding from SAPPIO LINK (3D Farming Project), this species was shown to concentrate its feeding visits not only on white campion but also on yarrow (*Achillea millefolium*), cow parsley (*Anthriscus sylvestris*) and hogweed (*Heracleum spondylium*)(Northing,2003; http://www.csl.gov.uk/science/organ/environ/entom/3DFarming). *Episyrphus balteatus* was significantly more abundant in florally-rich field margins than in impoverished margins, and dispersed away from the latter more rapidly (MacLeod, 1999). It was significantly more abundant in unsprayed headlands than in headlands treated with herbicide, and there was a significant positive correlation between number of hoverfly eggs per aphid and weed density (Cowgill *et al.*, 1993b). Hoverfly eggs were 1.5 times more numerous on Brussels sprouts near a flower-rich edge than in the centre of the field, and dissection showed that adult female hoverflies had fed on flower pollen. Aphid density (*Brevicoryne brassicae*) near the edge was half that in the centre of the field (Van Emden, 1965a). The 3D Farming project (above) also showed that aphid populations in fields opposite flower-rich margins were half as numerous as those opposite flower-denuded control areas, and this effect may reach 100 m into the field.

Weed and flower strips:

Pollen and nectar are nutritionally valuable for egg development by hoverflies (Diptera: Syrphidae), including species with aphidophagous larvae (Schneider, 1969), and a valuable source of energy. Hoverfly adults have mouthparts and alimentary canal adapted for intake and digestion of pollen and nectar (Zimina, 1957 cited in Van Emden 1965b). In theory, hoverflies might oviposit in weed and flower strips, thus denying this valuable source of predators (the hoverfly larvae) to the crop. In practice, however, this does not appear to be a problem; Salveter (1998) recorded over ten times fewer larvae (mainly the of the aphidophagous *Episyrphus balteatus*) in weed strips compared to numbers found in the adjacent crop. The importance of weed strips to hoverflies is, therefore, as a food source for flying adults. The abundance of adults of aphidophagous syrphids was greater in sown weed strips (containing about 25 species of weeds) running through fields than in the fields themselves (Frank, 1996,1999). Fewer aphids per syrphid larva were found at 3 m from the weed strip than at 10 m (Hausammann, 1996), suggesting that pest control was very locally enhanced due to adult syrphids ovipositing in the crop near to the weed strip. Harwood *et al.* (1992,1994) also found significantly more adult aphidophagous syrphids (*Metasyrphus corollae*, *Melanostoma corollae*, *Platycheirus* spp.) in crops opposite margin strips sown with grass and wild flowers than opposite unmanaged control margins. Kienegger & Kromp (2001) observed many adult syrphids in commercial annual wildflower strips running through a broccoli crop, but few actually on the broccoli plants. Strips of coriander (*Coriandrum sativum*) and phacelia (*Phacelia tanacetifolia*) were more attractive to hoverflies than were strips of quinoa (*Chenopodium quinoa*) or borage (*Echium lycopis*) (Lövei *et al.*, 1993a). Using distinctive phacelia and coriander pollen in hoverfly guts as a marker, it was shown that individual *Melanostoma fasciatum* dispersed at least 15 m from the strips into the crop (Lövei *et al.*, 1993b), but not usually more than 20 m (Lövei *et al.*,1998). Hickman & Wratten (1996) sowed field edges with strips of phacelia (an annual from North America) which is a good source of pollen for hoverflies. Significantly more hoverfly eggs were found in fields with *Phacelia* edges than in control fields and aphids were later (when large hoverfly larvae were present) reduced to lower levels in fields with *Phacelia* edges at up to 50 m into the field (Hickman & Wratten, 1996). Similarly, more hoverflies were recorded up to12 m into a cabbage crop opposite *Phacelia* edges than opposite control edges, and there were significantly fewer pest aphids in the crop opposite *Phacelia* edges (White *et al.*, 1995). Lövei *et al.* (1992) recorded 3-8 times more adult hoverflies in fields containing *Phacelia* strips than in control fields, and the enhancement effect extended for 10 m from the strip.

Sown weed strips contained significantly greater numbers of wild bees and Sphecidae wasps than did adjacent field habitats (Frank, 1996). Blue knapweed (*Centaurea cyanus*) is a valuable component of strips because it has extrafloral nectaries excreting a sweet fluid (75% sugar) which attracts ladybirds, hoverflies, wasps, ants and Ichneumonidae parasitoids (Nentwig, 1998). Other predators visiting flowers include flies (Dolichopodidae, Empididae, Rhagionidae) and lacewing (Neuroptera) adults (Van Emden, 1965b).

Beetle banks:
Beetle banks increase in floral diversity over time, gradually providing more nectar and pollen resources for mobile predators and parasitoids (Thomas *et al.*, 2002).

6.3.1.3 Overwintering

Field edges and Conservation Headlands:
Very few pollinators, predators or parasitoids survive the winter in open cultivated fields, especially during harsh winters (McLaughlin & Mineau, 1995), and so refuge habitats become essential if these beneficials are to be available to repopulate fields in the spring. Some species of spiders (Maelfait & De Keer, 1990; Harwood *et al.*, 1994; Dinter, 1997), carabid (Pollard, 1968; Best *et al.*, 1981; Desender *et al.*, 1981; Desender, 1982; Sotherton 1984, 1985; Desender & Alderweireldt, 1988; Wallin, 1989; Riedel, 1995) and staphylinid beetles (Sotherton 1984, 1985; Riedel, 1995), that are found in fields during the summer, have been shown to overwinter in field edges. Species richness of predators is much greater in margins (22 carabid species, 36 staphylinids, 17 spiders) than in fields (4 carabids, 7 staphylinids, 1 spider) during winter (Pfiffner & Luka, 2000). Overwintering carabid densities at field edges are usually greater than summertime densities in crops, and can even exceed 1000 m^{-2} (Lövei & Sunderland, 1996). Wiedemeier & Duelli (2000) found a carabid density of 162 m^{-2} in field edges compared with only 11 m^{-2} within fields; equivalent data for staphylinids were 400 m^{-2} and 100 m^{-2}, and for spiders190 m^{-2} and 20 m^{-2}. Andersen (1997) recorded carabid densities of 8.3 m^{-2} to 22.8 m^{-2} within ploughed fields and grass fields, but 62.6 m^{-2} to 119.0 m^{-2} at field edges. Differences for staphylinids were even greater (20.8 – 28.9 m^{-2} in fields, but 187.4 – 199.0 m^{-2} at the edge – Andersen,1997). Mortality of carabids and staphylinids during winter can exceed 90% (Petersen *et al.*, 1996) unless they find protective microhabitats such as occur in field boundaries (Riedel & Steenberg, 1998). Survival rates of the carabid *Demetrias atricapillus* and the staphylinid *Tachyporus hypnorum* were greater in tussocks of the grass *Dactylis glomerata* during winter than in less

well vegetated parts of field boundaries (Dennis *et al.*, 1994). Field edge management practices can affect the suitability of this habitat for overwintering. For example, carabids (Pollard, 1968; Desender, 1982) and lycosid spiders (Bayram & Luff, 1993) favour a deep sod layer and plentiful tussocks, and linyphiid spiders prefer edges sown with wildflowers compared to unsown edges (Harwood *et al.*,1994). Invertebrate abundance (including carabid and staphylinid beetles) during winter was significantly greater in field margins sown with a mixture of grasses and wildflowers than in natural unsown margins (Thomas *et al.*, 1994). Arthropods used margins sown with grass as an overwintering habitat within one year of establishment (Marshall *et al.*, 2002).

Weed and wildflower strips:
Numbers of overwintering linyphiid spiders were significantly greater in sown grass and wildflower margin strips than in unmanaged control margins (Harwood *et al.*, 1994). Linyphiid densities within wildflower strips were 212 m^{-2} compared with < 10 m^{-2} in the adjacent field (Lemke & Poehling, 1998, 2002) and 240 spiders m^{-2} hibernated under comfrey (*Symphytum officinale*) in the strips (Nentwig, 1998). Three times more carabid beetles overwintered in sown weed strips than in adjacent fields (Lys, 1994) and densities varied from 60 m^{-2} under cornflower (*Centaurea cyanus*) to 250 m^{-2} under chamomile (*Matricaria chamomilla*) (Bürki & Hausammann, 1993 cited in Kromp, 1999) and yarrow (*Achillea millefolium*) (Nentwig, 1998). Total density of predatory beetles (Cantharidae, Carabidae, Coccinellidae and Staphylinidae) was 847 m^{-2} in sown weed strips compared to185 m^{-2} in the field, and, for spiders, 118 m^{-2} in the strips compared to only 9 m^{-2} in the field (Bürki & Pfiffner, 2000). Fourteen carabid species overwintered in strips compared with only two in fields adjacent to strips (Lys, 1994). Ladybirds do not hibernate within crop fields, but 180 m^{-2} were found hibernating in sown weed strips under lesser burdock (*Arctium minus*) (Nentwig, 1998). Larvae of soldier beetles (Cantharidae) were present at 110 m^{-2} in strips compared with 10 m^{-2} in fields (Nentwig, 1998). 17 families of parasitic Hymenoptera were found on the vegetation in weed strips and 13 of these families hibernated in strips, with 100 – 160 parasitoids m^{-2} under comfrey (*Symphytum officinale*) and yallow (Nentwig, 1998). Overwintering shelter for predators in orchards can be provided by retaining vegetable debris below trees (Deng *et al.*, 1988) and by provision of refugia on tree trunks (Tamaki & Halfhill, 1968)

Beetle banks:
Overwintering densities of predators in one-year-old beetle banks were greater than in the field but less than at the field edge (Chiverton, 1989; Riedel, 1991). Over a five-year period, densities in beetle banks were similar to or greater than those in hedgebanks (Collins *et al.*, 2003b) and there was a slight shift of the beetle bank predator community from dominance by open-field colonist species towards species that typically use boundary habitats as overwintering sites (Thomas *et al.*, 1992a) . Microhabitats within tussock-forming grasses (*Dactylis glomerata* and *Holcus lanatus*) had more stable temperatures during winter than did microhabitats within mat-forming species (*Agrotis stolonifera* and *Lolium perenne*), which may be one of the reasons why carabid and staphylinid beetles aggregate in tussocks (Thomas *et al.*, 1992b).

6.3.1.4 Refuge from pesticides and cultivations

After treating a field with an insecticide (dimethoate), Duffield & Aebischer (1994) noted that the spatial pattern of recovery in numbers of polyphagous predators (carabid and staphylinid beetles and linyphiid spiders) was consistent with a progressive invasion of the field from refuge habitats at the field margin. This phenomenon was also observed previously in the context of other studies (Smart *et al.*, 1989; Jepson & Thacker, 1990; Thomas *et al.*, 1990). Pests (such as aphids) usually recover more rapidly in the centre of the field soon after spraying, and Duffield *et al.* (1996) showed that this was due to predation being greater near the margins as a wave of predators moves out of margin refuges into the field. Asteraki *et al.* (1995) showed that hedgerow margins in southwest England sheltered a greater number of carabid species (63 species) to re-invade insecticide treated or ploughed fields than did post and wire fence margins (48 species). Such carabids are not directly affected by herbicides in the field, apart from sometimes a short-term repellent effect (Brust, 1990), but some are killed by insecticides (Jepson, 1989) and survivors may leave the field when their activity level increases greatly in response to hunger, because their prey populations have been temporarily decimated by the insecticide (Chiverton, 1984). They may reinvade the field from the refuge later, when prey populations (Trumper & Holt, 1998) recover in the field (Boivin & Hance, 2003). In manipulative field experiments Lee *et al.* (2001) demonstrated that carabid abundance in crop areas previously treated with insecticide was significantly higher when adjacent to refuge strips. Linyphiid spiders will also reinvade the field from edge habitats during a period of several months after insecticide application to the field (Thomas *et al.*, 1990). Simulations suggested that in organic farming systems provision of refuge areas where spiders were protected from agricultural operations had the greatest effect on spider population size in the agricultural landscape (Topping, 1997).

6.3.1.5 Source of allochthonous foods

Allochthonous resources are energetic resources that enter into a habitat from a separate more productive habitat (Huxel *et al.*, 2002). There could be considerable quantities of aerial flotsam (e.g. pollen and non-pest aphids) drifting into fields from edge habitats. In 1976, a 1.8 m high suction trap was run continuously in the middle of a winter wheat field from May to July (Sunderland, unpublished). It caught 4587 aphids of 97 species (identified by Dr A.M. Dewar). Only three species were capable of feeding on wheat, and, since the crop was virtually free of weeds, the remaining 94 species can be considered as allochthonous foods. Ten of these 94 species (*Aphis fabae, Brachycaudus helichrysi*, *Brevicoryne brassicae*, *Cavariella aegopodii*, *Cryptomyzus galeopsidis*, *Macrosiphum euphorbiae*, *Macrosiphum rosae*, *Macrolophium carnosum*, *Myzus persicae*, *Rhopalosiphum insertum*) were represented by more than fifty individuals. Allochthonous alternative foods such as these would provide an energy and nutrient subsidy to generalist predators within crops thus enhancing their capacity to control pests. The importance of such "imported" allochthonous foods to predator-prey dynamics is very well established in other ecological systems (Polis & Hurd, 1995,1996; Polis *et al.*, 1996,1997; Strong *et al.,* 1996; Huxel & McCann, 1998), especially in relation to interchange between terrestrial and aquatic habitats (Nakano *et al.*, 1999; Nakano & Murakami, 2001), but it has been little studied in agriculture and horticulture. Duelli & Obrist (2003) caught 222,812 arthropods of 2229 species in a 5 km transect of an agricultural landscape, but only 6% of species were confined to a single habitat. The transect included crop fields which were recipients of a wide range of arthropods (e.g. thrips, heteropteran bugs, phorid flies) "leaking out" of nearby semi-natural habitats. A proportion of these accidental dispersers could be a valuable food resource for generalist predators within crop fields. Grasses in orchards provide wind-blown pollen which are an allochthonous alternative food for predatory mites (Phytoseiidae) on fruit trees (Smith & Papacek, 1991; Bugg & Waddington, 1994). Increasing the proportion of semi-natural refuge areas within a landscape is likely to increase the choice and rate of supply of allochthonous foods to generalist natural enemies within crops. It is likely that this would improve the efficiency of biocontrol of pests because natural enemies would be more likely to remain and breed in the crop and would suffer a lower mortality than in crops where allochthonous foods were scarce. On the other hand, there is a danger that natural enemies may prefer the allochthonous foods to the pests (some species of pest aphid, for example, are poor quality foods for beetle and spider predators, and some predators even develop a temporary aversion to these aphids – Bilde & Toft, 1994; Toft, 1995b, 1996, 1997; Bilde & Toft, 1997ab; Toft & Nielsen, 1997; Bilde & Toft, 1999, 2001; Nielsen & Toft, 2000), which would result in a reduced efficiency of biocontrol. Only well-planned, careful and rigorous research will resolve this issue.

6.3.1.6 Source of seed-eaters

Epigeaic seed predation contributes to suppression of annual weeds (Cromar *et al.*, 1999), and seed predators may emanate from uncropped refuge areas. Seed consumption by invertebrates has greater potential to exert weed control than does consumption by vertebrates, because the former have their greatest food demand soon after the peak of weed seed shed (Westerman *et al.*, 2003). Many adult predatory carabid species will also consume plant material, including seeds. In the laboratory, seeds of *Capsella bursa-pastoris* were completely eaten by 13 species of adult carabid, seeds of *Poa annua* by 15 species and seeds of *Taraxacum* sp. by 8 species (Goldschmidt & Toft, 1997). Larvae of the predatory carabid *Harpalus rufipes* feed mainly on weed seeds, which they cache in their burrows (Luff, 1980). Seeds were found to be of greater value than insects in supporting development and enhancing fecundity of *H. rufipes* (Jorgensen & Toft, 1997a). Larvae of the carabid *Amara similata* have also recently been shown to be granivorous (Jorgensen & Toft, 1997b). Relative preferences of various carabid species for seeds of a range of weed species can be determined in cafeteria-style experiments in the laboratory (Johnson & Cameron, 1969; Lund & Turpin, 1977), and results of these experiments are reviewed in Tooley & Brust (2002). Even when a relatively small proportion of seeds are consumed in the field, selective seed predation by carabids can affect competitive interactions between weed species. For example, carabids often prefer seeds of broad-leaved weeds to those of grasses and this may help grasses to dominate fields and edges that have dense carabid populations (Brust, 1994b).The predatory carabid beetle *Pterostichus madidus* ate seeds of greater knapweed (*Centaurea scabiosa*), lady's bedstraw (*Galium verum*), ox-eye daisy (*Leucanthemum vulgare*), and cowslip (*Primula veris*), in laboratory trials, and 80% of these seeds placed out at the edge of a wheat field were eaten in a week (but slugs may also have contributed) (Hurst & Doberski, 2003). Invertebrates (mainly carabids) were responsible for half to two thirds of losses of seeds of common grass and dicotyledonous weed species from dishes placed out in fields in Leicestershire and Hampshire (Tooley *et al.*, 1999). Losses were as great at 40 m into the field as at the edge, suggesting that invertebrates could have an impact on the weed seedbank throughout fields (Tooley *et al.*, 1999). In an earlier study in Oxfordshire, carried out in the same way, small mammals had a greater impact than invertebrates on losses of seeds of annual grass weeds (*Alopecurus myosuroides*, *Avena fatua* and *Bromus sterilis*) put out in field margins (Povey *et al.*, 1993), suggesting considerable temporal or regional variation in taxonomic composition of seed predators. Rates of seed removal, and the relative importance of vertebrates and invertebrates as seed predators, also varies greatly between fields in the same region (Marino *et al.*, 1997; Menalled *et al.*, 2000). Weed seed removal is greater in field margin strips than in the field (Menalled *et al.*, 2001), but the distribution of seed consumption (by both vertebrates and invertebrates) within the field is usually unrelated to proximity of the field margin (Marino *et al.*, 1997; Westerman *et al.*, 2003). Seed predation is rarely quantified and so its role is not adequately considered in weed population models (Chapter 7). Seed-eaters also remove seeds from sown wildflower strips. Kollmann & Bassin (2001) showed that 10-51% (depending on plant species) of wildflower seeds in such strips were eaten per week, mainly by slugs and rodents. Wildflower seeds can also be eaten while still part of the flower head by invertebrates such as tephritid flies and microlepidoptera. 67% of flower heads of brown knapweed (*Centaurea jacea*) were damaged in this way, and damage increased significantly with the proportion of the landscape consisting of semi-natural habitats (Steffan-Dewenter *et al.*, 2001). For information on seed-eating by birds, see Table 5.2.

6.3.1.7 Source of invertebrates for birds

Discussion of the effects of herbicides and weeds on farmland birds that are unrelated to invertebrates can be found in Chapter 5. This section is confined to consideration of effects on birds that are mediated by invertebrate foods. Some farmland birds are primarily insectivorous throughout their lives. Other species, which feed on seeds and plant material as adults, nevertheless have a a crucial few weeks as chicks when invertebrate food is vital for survival (Wilson *et al.*, 1999). Chicks of the grey partridge (*Perdix perdix*), for example, require invertebrate food (especially heteropteran bugs, caterpillars of moths and sawflies, leafbeetles and weevils) in the first few weeks of life (Rands, 1985). Boatman (2001) lists 31 species of farmland bird for which invertebrates are an important food source. These include grey partridge (*Perdix perdix*), corn bunting (*Miliaria calandra*), song thrush (*Turdus philomelos*), reed bunting (*Emberiza schoeniclus*), skylark (*Alauda arvensis*), blackbird (*Turdus merula*), yellowhammer (*Emberiza citrinella*), pied wagtail (*Motacilla alba*), wren (*Troglodytes troglodytes*), chaffinch (*Fringilla coelebs*) and pheasant (*Phasianus colchicus*). Moreby (1997) adds to this list whitethroat (*Sylvia communis*) and dunnock (*Prunella modularis*). Major invertebrate food types in the diets of most of these species are Hemiptera, Lepidoptera larvae, Diptera, Hymenoptera and Coleoptera (Boatman, 2001). Invertebrates most important in the food of declining bird species are grasshoppers, sawflies, leaf beetles and spiders, which are all very sensitive to insecticide applications. The indirect effects of herbicides on these invertebrate food sources are little studied (Wilson *et al.*, 1999).

Habitat generalist bird species (e.g. carrion crow, *Corvus corone*, and wren, *Troglodytes troglodytes*) increased between 1968 and 1995, but examination of the UK Common Birds Census showed that 13 species of farmland specialists (e.g. skylark, *Alauda arvensis*, and corn bunting, *Emberiza calandra*) underwent decline (Siriwardena *et al.*, 1998; see also Fuller *et al.*, 1995; Marshall *et al.* (2003) and Table 5.1 of this review). It is estimated that, in the last twenty years, ten million breeding individuals of ten species of farmland birds have disappeared from the British countryside. 116 species of farmland birds (a fifth of the European avifauna) are now of conservation concern (Krebs *et al.*, 1999). There has been a 40% decline in UK farmland birds since the1970's, and, in a long-term study in Sussex, invertebrates in fields were shown to be declining at a rate of 4.2% per year (Leake, 2002). General extensification of farming practices is considered necessary if these declines are to be reversed (Chamberlain *et al.*, 2000; Chamberlain & Fuller, 2001). Evidence from some studies suggests that refuges for birds and invertebrates, in the form of beetle banks, conservation headlands and similar landscape diversification methods within agri-environment schemes, can reverse these trends (Wilson *et al.*, 1999; Leake, 2002; Stoate, 2002; Benton *et al.*, 2003). Beetle banks were found to be an important foraging habitat for skylarks (Murray *et al.*, 2002). Defra has a public service agreement to reverse the decline in a suite of farmland bird species by 2020 and a Biodiversity Action Plan target to increase the area of cereal field margin under conservation management. The Sustainable Arable LINK Programme "Sustainable Arable Farming for an Improved Environment (SAFFIE)" (2002-2006) aims to investigate within-field manipulation of crop architecture and a range of sown grass-based vegetation at crop margins to enhance biodiversity in general, and to aid recovery of populations of farmland birds in particular.

Invertebrates (including carabid and staphylinid beetles, lycosid and linyphiid spiders) that are a food source for farmland birds were greatest in field edges and within 60 m of field edges (Holland *et al.*, 1999a; Moreby *et al.*, 1999). Sawfly larvae (Tenthredinidae), which are an important food of the chicks of grey partridge (*Perdix perdix*) and corn bunting (*Miliaria calandra*) (Potts, 1986; Aebischer & Ward, 1997) were at least four times more abundant in sown grass strips (both at the field edge and as beetles banks running through fields) than in cereal fields (Barker & Reynolds, 1999). Field edges are a more suitable habitat than field centres for the majority of larvae of Lepidoptera, especially when they are protected from insecticidal spray drift (Cilgi & Jepson, 1995), and these caterpillars are a valuable component of the diet of birds such as the yellowhammer, *Emberiza citrinella* (Stoate *et al.*, 1998). Densities of Lepidoptera larvae were found to be significantly greater in 20 m wide than in 6 m wide buffer zones at field edges (Chiverton, 1999). Yellowhammer chicks are dependent on invertebrates, and fields sprayed with insecticides are not perceived as being profitable foraging areas by these birds (Morris *et al.*, 2002). Unsprayed foraging areas at field edges (perhaps funded under the Countryside Stewardship Scheme) should provide food for birds such as yellowhammers and help to reverse their decline in abundance (Morris *et al.*, 2002). Mean brood size of the grey partridge (Rands,1985), and abundance of chick food insects (Moreby, 1997), were significantly higher in unsprayed headlands than in headlands receiving applications of herbicides and fungicides.

6.3.1.8 Enhancing farmland biodiversity

Intensive management of farmland has caused appreciable reduction in the biodiversity of flora (Andreasen *et al.*, 1996) and invertebrates (Aebischer, 1991; Robinson & Sutherland, 2002), and well-managed refuge habitats could help to restore these losses without compromising agricultural productivity and profitability. The Countryside Stewardship Scheme and the Arable Stewardship Scheme both recognise the importance of field margin refuge habitats for conserving farmland biodiversity (MAFF 1998, 1999).

Most flowering plants in weed strips accommodate 1-300 arthropods m^{-2} but poppy (*Papaver rhoeas*), rape (*Brassica napus*), buckwheat (*Fagopyrum esculentum*) and tansy (*Tanacetum vulgare*) harbour more than 500 m^{-2}, and 48-80% of these are phytophages (Nentwig, 1998). Few species of phytophage are associated with some species of weed, such as speedwell (*Veronica persica*), but others, such as chickweed (*Stellaria media*) are host to more than 70 species (Marshall *et al.*, 2003). 86 aphid species were found in weed strips (Nentwig *et al.*, 1998). It is important to note that very few of the 850 aphid species in Europe are serious pests, the rest make an important contribution to biodiversity (by their own diversity, as food for aphidophages, and also by producing sugary honeydew that is an energy fuel helping to support a large number of additional arthropod species – Monsrud & Toft, 1999). Similary, amongst the twelve species of leafhoppers (Cicadellidae) and nine species of sawflies (Tenthredinidae) living in the weed strips, few were pest species (Nentwig *et al.*, 1998). Beetle species composition and diversity varies considerable from one field edge to another, and maintenance of this variation will contribute to overall biodiversity at the farm and landscape scales (Beard & Mauremootoo, 1994). Lethmayer *et al.* (1997) recorded 22 species of leaf beetle (Chrysomelidae) and 47 species of weevil in sown weed strips, and these were not considered to constitute a pest problem to adjacent fields.

There has been a marked decline in the abundance of butterflies in Europe over the last half century (Thomas, 1995; De Snoo *et al.*, 1998), but reduction of pesticide applications to field edges may help to restore populations to former levels. Sympathetically-managed field edges can contain up to twenty species of butterfly (a third of the British list)(Feber *et al.*,1996; Dover, 1999). Abundance of butterflies was significantly greater in unsprayed than sprayed edges, but not significantly greater in 6 m-wide compared to 3 m-wide unsprayed edges (de Snoo, 1996). Species richness was also significantly greater in unsprayed edges, and the large white (*Pieris brassicae*) and common blue (*Polyommatus icarus*) were observed only in unsprayed edges (de Snoo *et al.*, 1998). Conservation headlands seem able to underpin population increases of some species, such as Meadow Brown (*Maniola jurtina*) and Gatekeeper (*Pyronia tithonus*) (Dover *et al.*, 1990). These butterflies were observed to spend less time flying and more time feeding in conservation headlands than in fully-sprayed control headlands (Dover, 1997). Studies of population trends of butterflies in conservation headlands suggest that increases there are due to reproduction and survival rather than just local redistribution (Dover, 1999). Edge management to promote habitat diversity (e.g. by mowing some, but not all, of the margin) will maximise abundance and diversity of butterflies. For example, the small tortoiseshell (*Aglais urticae*) prefers to oviposit on short nettle (*Urtica dioecia*) plants, but the peacock (*Inachis io*) prefers to oviposit on tall ones. The abundance of both species is also affected by availability of nectar sources, such as thistles (*Carduus* spp., *Cirsium* spp.), field scabious (*Knautia arvensis*) and knapweed (*Centaurea* spp.) (Feber *et al.*, 1996,1999). Mowing edges in summer reduced butterfly abundance and diversity (and was more detrimental than not mowing, or mowing in spring and autumn) because adults were ovipositing and larvae were feeding at that time (Feber *et al.*, 1996). Buys (1995)(reported in Marshall & Moonen, 2002) found that butterfly species richness and abundance was greater in sown margin strips of legumes than in sown grass and clover strips. Sowing with a grass and wildlower mixture can, however, increase butterfly abundance and also reduce abundance of noxious weeds, such as creeping thistle (*Cirsium arvense*). Sown edges had a greater proportion of perennial flowering plants and these were better nectar sources than annuals for butterflies (Feber *et al.*, 1996). Nectar increases the fecundity and longevity of butterflies (Stern & Smith, 1960; Murphy 1983; Murphy *et al.*, 1983; Wiklund & Karlsson, 1984). Sown weed strips within fields also contained more species of butterfly than did the adjacent field habitat, and butterflies were observed to use the weed strips for feeding, mating and oviposition (Frank, 1996).

Pseudoscorpions (small predators preying mainly on Collembola, and not of significance for biocontrol), such as *Cthonius ischnocheles* and *C. orthodactylus*, were most abundant in old unmanaged field margins, favouring the accumulation of litter that occurs in such habitats (Bell *et al.*, 1999).

Orb-web spiders (Araneidae) are not important predators in fields because they are not numerous there, but they are more abundant and species rich in the vegetation of field edges. They are sensitive to insecticidal spray drift because their large vertical webs are efficient collectors of fine spray droplets, and webs are periodically eaten by the spiders which then receive a relatively high dose of insecticide (Samu *et al.*, 1992). Buffer strips of unsprayed headland would help to protect these spiders. Similarly, such buffer strips reduce mortality of butterfly larvae in the boundary (Longley & Sotherton, 1997; Longley *et al.*, 1997).

Unsprayed vegetated field margins are valuable habitats for small mammals (Tew *et al.*, 1994). Tussock-forming grasses (such as *Dactylis glomerata*) characteristic of beetle banks have been found to provide excellent nesting habitat for harvest mice (*Micromys minutus*). Nest densities on beetle banks were 47 km^{-1} compared to 5 km^{-1} in field magins (Bence *et al.*, 1999). Tussocks can also be used as suitable nest sites by bumblebees (Alford, 1975).

6.3.2 *Disbenefits*

Potential negative effects associated with uncropped refuge areas are not fully understood (Wratten *et al.*, 1998) but include i) weeds may move into the crop, ii) weeds may harbour pests (e.g. slugs, aphids) that could migrate into the crop, and iii) refuge areas might act as barriers inhibiting the dispersal of natural enemies from field to field.

Habitat diversification may be favourable for the regional build up of polyphagous pests (Gurr *et al.*, 1998). Uncropped areas may provide alternative food (including pollen and nectar) for pests before and after the crop is available (Van Emden, 1965b; Van Emden, 1981).

Nearly 40 years ago, Van Emden (1965b) wrote "*Almost every advantage offered to beneficial insects by uncultivated land is at least to some extent offset by a similar advantage to pests. It is obvious that a balance sheet is needed but this is not yet possible owing to the lack of quantitative data on the economic aspects of various relationships*". Today, although much more data are available on specific aspects, this synthesis has still not been carried out. It would be extremely valuable to now draw up this "balance sheet" and use it to develop a general-purpose edge/strip refuge system that has no major disbenefits (e.g. seriously problematical source of disease for a particular crop) to both horticultural and agricultural crops, yet many benefits.

6.3.2.1 Source of crop weeds

In surveys in different years, and at different times of year, seeds and seedlings of 11 – 17 common species of weed were shown to decrease with increasing distance from the field margin into the field, often with a sharp decline in abundance at 1 m up to 4m from the edge (Wilson & Aebischer, 1995). This result is not necessarily due only to spread of seeds from the edge, but might also represent improved weed survival (with less competition) where there is soil compaction and crop damage due to machinery turning near the headland (Wilson & Aebischer, 1995). Migration of weeds into the crop from the field edge or from beetle banks can be prevented by a sterile strip between bank and crop, and contact grass weed herbicides can be used as spot treatments against wild oats, blackgrass and barren brome where necessary (Thomas *et al.*, 2002). Minimising disturbance to the field margin and encouraging perennial plants will also reduce ingress of noxious weeds (Marshall & Moonen, 2002). After a four year study of management of uncropped field edges, Smith *et al.* (1999) concluded that such edges are very unlikely to cause weed problems within the crop, and that risks of weed invasion coming from edges degraded by herbicide use are greater.

6.3.2.2 Source of invertebrate crop pests

Slugs, such as *Arion lusitanicus*, find wildflower strips to be a good refuge habitat. They move between strip and adjacent crop and can cause crop damage up to 1 m into the crop (Frank, 1998a). Although they can be controlled with metaldehyde (Frank, 1998b), there is also potential for diverting their attack away from crop plants and onto highly attractive and palatable weed species, such as chickweed (*Stellaria media*) and shepherd's-purse (*Capsella bursa-pastoris*) (Frank & Barone, 1999; Frank & Friedli, 1999). Dipterous pests such as cabbage root fly (*Delia radicum*) and carrot fly (*Psila rosae*) roost in the vegetation of field edges at night, and during inclement weather, and crop damage caused by their larvae is often greater near to headlands than in the centre of fields (Van Emden, 1981), presumably because adults tend to oviposit close to roosting sites. Coaker & Finch (1973) calculated that eight cow parsley plants (*Anthriscus sylvestris*) per metre of field edge could sustain at least 2000 adult cabbage root fly during the pre-oviposition period.

Aphids and thrips were found to be more numerous in crop fields than in field edges (Huusela-Veistola & Kurppa, 1996). Carrot fly (*Psila rosae*)(Wainhouse & Coaker, 1981), cereal leaf beetle (*Oulema* spp.)(Kiss *et al.*, 1993; Thomas & Marshall, 1999), blossom beetles (*Meligethes* spp.)(Lagerlöf & Wallin, 1993) and others (Altieri, 1994) may overwinter or breed in field edges to some extent, but the economic threat to farmers is not considered to be great (Lagerlöf & Wallin, 1993) and farmers are generally willing to incorporate edge habitat diversification into production systems (Van Emden, 1990). The general public consider diversified field margins and hedgerows to be important components of the British landscape and worth preserving under schemes such as designated Environmentally Sensitive Areas (Marshall *et al.*, 2002).

Borders sown with candytuft *(Iberis umbellata*, Brassicaceae) were not found to be reservoirs of cabbage pests and did not threaten adjacent cabbage crops (Bigger & Chaney, 1998). Various pest aphids were found by Lethmayer (2000) on weeds in sown weed strips; *Brachycaudus cardui* (transmits plum pox virus) on *Tripleurospermum inodorum* and *Achillea millefolium*; *Aphis fabae* (polyphagous pest and aphid vector) on *A. millefolium*, *Cirsium vulgare*, *Pastinaca sativa*, *Papaver rhoeas* and *Oenthera biennis*; *Macrosiphum euphorbiae* (pest of potato and virus vector) on *Lactuca serriola*; *Hyperomyzus lactucae* (blackcurrant and lettuce pest and virus vector) on *Sonchus* sp.; *Cavariella aegopodii* (pest of carrots and celery and virus vector) on *P. sativa*; *Dysaphis pyri* (pear pest) on *Galium* sp; and *Aphis grossulariae* (pest of gooseberry and virus vector) on *Epilobium* sp. However, aphid density was not increased in the crop due to the proximity of a sown weed strip, but was more likely to be reduced (Nentwig *et al.*, 1998). De Snoo & de Leeuw (1996) found significantly more cereal aphids (*Sitobion avenae*, *Metopolophium dirhodum* and *Rhopalosiphum padi*) in unsprayed than in sprayed edges, but they did not invade the crop from these unsprayed reservoirs. It should also be noted that individuals (and their offspring) of a given pest species feeding on weeds will not necessarily be able to transfer and prosper on crop plants. The pest species may be subdivided into a number of genetically distinct host races (Drès & Mallet, 2002) adapted to different plant species. Information on this subject is sparse, and results appear to be case-specific. The pea aphid (*Acyrthosiphon pisum*), for example, is divided into host races (Via, 1991, 1999; Via *et al.*, 2000), but the cabbage aphid (*Brevicoryne brassicae*) does not appear to exhibit such genetic subdivision (Miller *et. al.*, under revision).

Sown weed strips also harboured fairly large populations of blossom beetle (*Meligethes* spp.) in late June and early July, but they did not host high numbers of other pests (such as weevils and leaf beetles) and were considered, in general, to not play a role in enhancing pest abundance on adjacent crops (Lethmayer *et al.*, 1997; Nentwig, 1998). In general, there is a need to determine which refuge plants are entirely beneficial, or that can at least be tolerated, with respect to specific crops (Chaney, 1998; Marshall *et al.*, 2003), and which are potentially threatening (for example as sources of crop diseases vectored by insects from wild plants to the crop – Van Emden, 1965b). Commercial wildflower seed mixes have not been evaluated in this respect (Bugg & Waddington, 1994). The Phytophagous Insect Data Base (Ward & Spalding, 1993) could be a valuable resource for identifying crop pest species associated with species of wild plant characteristic of refuge areas. Brassicaceae should be avoided for weed strips because they provide pollen for blossom beetle pests (Nitidulidae) at times when oilseed rape is unsuitable (in the pod stage) (Lethmayer *et al.*, 1997). Baggen & Gurr (1998) showed that, although strips of dill, borage and coriander growing adjacent to a potato field increased parasitism of the potato moth (*Phthorimaea operculella*), the strips also increased fecundity of the pest, and the net effect was increased crop damage in the proximity of the strips. In a later paper (Baggen *et al.*, 1999), the authors demonstrated that phacelia (*Phacelia tanacetifolia*) and nasturtium (*Tropaeoleum majus*) benefited only the encyrtid parasitoid (*Copidosoma koehleri*) of potato moth, and were thus wholly beneficial for conservation biological control. This underlines the need for careful selection of refuge plants. Refuge plants may themselves be reduced or even eliminated by pests. Frank (2003), for example, showed that blue knapweed *(Centaurea cyanus*), which is a very valuable plant for fostering predators (6.3.1.1) and pollinators (6.3.1.2) can be completely destroyed by the slug *Arion lusitanicus*. Knowledge of this sort is valuable in relation to the establishment and management of refuge habitats. Initial seed rates can be increased for valuable refuge plant species which are under threat from pests (Frank, 2003).

6.3.2.3 Barriers to dispersal of natural enemies

For walking predators that are incapable of aerial dispersal, such as some species of carabid beetle, linear features in the landscape (hedges, ditches, banks, fences, tracks, roads, railways) may act as barriers to inter-field dispersal (Duelli *et al.*, 1990; Thomas *et al.*, 2002). Carabids are more likely to move along such linear features than to cross them (Mader *et al.*, 1990; Joyce *et al.*, 1999). The carabid *Pterostichus melanarius* is a highly mobile species but, in spite of this, only 3-6% of individuals marked and released on one side of a hedge were subsequently (over periods of four to ten weeks) recaught on the other side (Thomas *et al.*, 1997,1998). *Pterostichus madidus* was better able to disperse through hedges and 7% of marked individuals crossed three hedgerows during a three month study (Holland *et al.*, 2002). For other large carabids, 16%-30% fewer beetles were caught on the other side of a hedge during 21 days after release (Mauremootoo *et al.*, 1995). Grassy banks (such as "beetle banks" running across fields) can also reduce movement between fields during the summer. Movement of the carabids *Harpalus rufipes*, *Pterostichus melanarius* and *Pterostichus niger* was slower through a 1.3 m-wide and 0.3 m-high grassy bank than through a barley crop (Frampton *et al.*, 1995). Surprisingly, even flying natural enemies can be inhibited by "apparent barriers" that constitute no acutal physical impediment to movement. Adult hoverflies, for example, are very reluctant to fly over areas of bare ground (ploughed fields, dirt tracks, asphalt roads), and so field edges and weed or wildflower strips should not be separated from crops by strips of bare earth if it is desired to use such refuge habitats to boost hoverfly abundance within the crop (Lövei *et al.*,1998). Hoverfly dispersal is also inhibited by tall hedges, but not by post-and-wire fences (Wratten *et al.*, 2003).

6.4 Mulches and manures on soil surface of crop

In addition to boosting the abundance of natural enemies and non-pest alternative prey (see below), mulching horticultural crops can i) suppress weeds by physical and/or phytotoxic (suppressed weed germination) effects (Ozores-Hampton *et al.*, 2001; Pinamonti & Sicher, 2001), ii) improve soil structure, iii) improve water economy, iv) stabilise soil temperature and v) and often contribute to fertilising the crop (He *et al.*, 2001; Pinamonti & Sicher, 2001; Sikora & Szmidt, 2001). Organic fertiliser-induced changes in plant physiology could affect the crop's ability to resist insect attack. Eigenbrode & Pimentel (1988) found significantly fewer flea beetles attacking brassicas fertilised with manure (compared to brassicas treated with inorganic fertilser), but the mechanism underlying this result was not determined. Unlike weediness and undersowing, mulching does not compete with the crop (Hellqvist, 1996). In fruit production, mulches can be used as preplant applications, maintenance dressings, or applied in strips beneath fruit trees or in alleys between tree rows. Compost mulches can be superior to polyethylene mulches in several respects (Pinamonti & Sicher, 2001) but can cause problems with mechanical harvesting in some crops. Increased yields due to compost have been reported in onion, lettuce, brassicas, spinach, cucumber, eggplant and tomato (Roe, 2001). In certain cases, composted wastes may also suppress plant disease (*Rhizoctonia*, *Fusarium* and powdery mildew) and composts can be as effective as fungicides for control of *Phytophthora* root rots. Composts have replaced methyl bromide in the USA ornamentals industry (Hoitink *et al.*, 2001). Cruciferous mulches can suppress root rot of peas (Chan & Close, 1987; Muehlchen *et al.*, 1990) and fodder rape mulches are active against stem canker of potato (Lootsma & Scholte, 1997, 1998). Vermicomposts (produced by the action of earthworms and microorganisms on organic wastes) have been shown to suppress plant diseases (*Pythium, Rhizoctonia* and *Verticillium*) and plant-parasitic nematodes in horticultural crops (Arancon *et al.*, 2002; Chaoui *et al.*, 2002). The high temperature phase of conventional composting kills seeds, plant pathogens, human pathogens (Epstein, 2001) and beneficial microorganisms (e.g. *Bacillus*, *Enterobacter*, *Flavobacterium balustinum*, *Pseudomonas* spp., *Streptomyces* spp., *Penicillium* spp., *Trichoderma* spp., *Gliocladium virens*), but the latter reinvade the cooling compost and may contribute to disease biocontrol (Hoitink *et al.*, 2001). Vermicomposting shows promise as a procedure for reducing human pathogens in organic wastes to safe levels (Eastman *et al.*, 2001). Composts produced from onion wastes contain a compound that causes sclerotia of *Allium* white rot (*Sclerotium cepivorum*) to germinate (ungerminated sclerotia can survive in soils in the absence of host plants for 20 years), and after germination they cannot survive without the live host. White rot can cause severe plant wilting and death, and it can reduce yields to uneconomic levels in four successive years of cropping. So onion-based composts (which remain biologically active for over a month) can be used to rid land of this disease before planting with onions. This also provides a means of disposing of packhouse onion wastes and avoiding landfill tax (Coventry *et al.*, 2002abc). Green composts may also find a place as one of the components in new growing substrates for ornamentals (e.g. lilies) to replace peat (Hanks *et al.*, 2002). Naturally, all new composts require efficacy testing, because, for example, some immature composts can cause crop injury (Ozores-Hampton *et al.*, 2001). There is also a danger that composts may cause build up of some nutrients and metals in the soil which may then result in dangerous levels in crop plants. This requires monitoring and research (Roe, 2001).

Applications of dead organic mulches or manures to the soil surface are also likely to increase the abundance and diversity of predators by (i) increasing their food supply through provision of detritivorous alternative foods such as springtails (Collembola) and small flies, (Holland & Luff, 2000) (ii) improving the microclimate (e.g. many predators are nocturnal and must avoid the hot, dry, desiccating conditions found on unprotected soil surfaces during daytime in summer), and (iii) providing a structurally more complex physical milieu that, for example, increases the density of websites for spiders (including spring immigrants that might otherwise fail to settle in the crop - Riechert, 1998), enables small predators to hide from larger ones (avoidance of intraguild predation promoting coexistence and maximising species richness), and offers protection during risky life functions such as moulting, oviposition and pupation.

There are plentiful sources of inexpensive waste vegetable material and organic matter that might be suitable for mulching (after appropriate processing and screening to safeguard human health in relation to heavy metals and human pathogens – see for example guidelines laid down under the Safe Sludge Matrix, however many crop are excluded from this matrix; www.adas.co.uk/matrix; EU Ecolabel UNI EN ISO 9002; Pinamonti & Sicher, 2001; and the EPA 503 Rule in the USA; Chaney *et al.*, 2001; Epstein, 2001; Walker, 2001). Tritrophic transfer of trace metals from sewage sludge through agricultural food chains has been demonstrated (Winder *et al.*, 1999). Compost applications also need to be checked to ensure that they are not an environmental pollution hazard due to uncontrolled leaching by rain and runoff to water courses (Sikora & Szmidt, 2001). Fodder radish soil amendments, however, reduced the risk of N leaching losses and increased N uptake by the subsequent crop (Thorup-Kristensen,1994; Thorup-Kristensen & Nielsen, 1998). Primary sources of material for mulches and manures include cereal straw (Grossbard, 1979), societal and agro-industrial wastes (Lee, 1997), and sewage sludge (Lübben, 1989; Pimentel & Warneke, 1989; Larink, 1997; Lee, 1997). 210 million tons of biodegradable municipal solid waste (MSW) was produced in 1996 in USA (Criner *et al.*, 2001), and it is estimated that 5 million tonnes of MSW is disposed of per year in UK (Barker, 2000). Onions and root vegetables alone account for more than 30,000 tonnes of waste annually coming from packhouses, at landfill disposal costs of more than £500K (Noble *et al.*, 2000; Coventry *et al.*, 2002c). Research is underway to develop techniques for converting MSW into a product suitable for agricultural use (Barker, 2000), and to convert onion wastes into stable fertilising composts that are free of pests and pathogens (Noble *et al.*, 2000). The U.S. Environmental Protection Agency estimated that composting can handle 30-60% of a community's waste stream and the estimated market size for compost in U.S. agriculture is 684 million cubic metres, but there is currently less than 2% market penetration (Criner *et al.*, 2001). In the UK in 1999, 90 operators running 197 sites processed 833,044 tonnes of waste (mainly from MSW) into compost, and the number of processing sites is growing at a rate of 25% per annum (Slater *et al.*, 2001). This trend is set to continue in order to meet the requirements of the EU Landfill Directive i.e. to reduce MSW sent to landfill to 35% of 1995 levels by 2020 (Spillett, 2000; http://www.environment-agency.gov.uk). 3.2 million tonnes per year must be diverted from landfill to meet the first target date of the UK Government policy document "A Way with Waste" (Barker, 2000). Accelerating increases in landfill tax provide an incentive to develop innovative schemes of waste management (Potter & Colvin, 2000). In USA a quarter of compost produced is used for growing food crops (Criner *et al.*, 2001).

6.4.1 Effects on the alternative prey of predators

Mulches have been found to greatly increase the abundance of a range of detritivores, including Acari, Lumbricidae, Coleoptera and Diptera, but especially Collembola (Nakamura

1975, 1976; Edwards & Lofty, 1979; Bolger & Curry, 1980; Curry & Purvis, 1981; Purvis & Curry, 1984; House, 1989; House & del Alzugaray, 1989; Lübben, 1989; Humphreys & Mowat, 1994ab; Filser, 1995; Wardle, 1995; Scholte & Lootsma, 1998; Pinamonti & Sicher, 2001; Halaj & Wise, 2002). Applications of vermicomposts increased the number of trophic groups of soil arthropods (Gunadi *et al.*, 2002). Where catch crops of rye, radish or vetch were rotavated into the top 15 cm of soil, densities of 26 species of Collembola at up to 118,000 m^{-2} and mites at up to 89,000 m^{-2} were obtained (Axelsen & Kristensen, 2000). A tonne of manure contains 4.2 x 10^9 J of energy (Pimentel & Warneke, 1989), and so adding manure to the soil surface will increase the food energy for detritivores, which are often food-limited (Chen & Wise, 1997). Some members of the community of alternative prey that are enhanced by mulching/manuring feed directly on the mulch or manure, but others consume the fungi, yeasts, bacteria and other microbes that grow on it (Pimentel & Warneke, 1989). Some Acari (small enough to be eaten by generalist predators) proliferate by preying on the nematodes that are enhanced by the mulch/manure treatment (Larink, 1997). Thus, addition of these organic wastes to the system supports a complex community of organisms that proliferate in response to the detrital subsidy (and which would otherwise be at low density or absent), and this greatly increases the food available to generalist predators which can exploit detritivores (decomposers) as well as herbivores (Wise *et al.*, 1999; McNabb *et al.*, 2001). This practice also increases biodiversity; for example applications of cattle slurry supported 71 species of Acari, 24 species of Collembola, 16 species of Coleoptera and 27 species of Diptera (Curry, 1979; Bolger & Curry, 1980). However, it is important to also consider that cattle slurry can carry Ecoli 0157. Addition of spent mushroom compost to the soil surface boosted the number of alternative prey species from 40 species (control plots) to 51 species (compost plots) (Defra AR0301).

6.4.2 Effects on generalist predators

Organic materials added to the soil surface have been found to increase the abundance of carabid beetles (Pietraszko & De Clerq, 1982; Powell *et al.*, 1983; Purvis & Curry, 1984; Clark *et al.*, 1993; Brust, 1994a; Helenius & Tolonen, 1994; Humphreys & Mowat, 1994ab; Helenius *et al.*, 1995; Afun *et al.*, 1999; Halaj & Wise, 2002), staphylinid beetles (Pietraszko & De Clerq, 1982; Powell *et al.*, 1983; Clark *et al.*, 1993; Wardle, 1995; Rämert, 1996; Afun *et al.*, 1999), spiders (Edwards & Lofty, 1979; Riechert & Bishop, 1990; Clark *et al.*, 1993; Wardle, 1995; Riechert, 1998; Afun *et al.*, 1999; Rypstra *et al.*, 1999; Wise *et al.*, 1999; reviewed in Sunderland & Samu, 2000; Zahirovic *et al.*, 2001; Halaj & Wise, 2002) and other predators, such as Opiliones (Clark *et al.*, 1993; Wardle, 1995) and Acari (Chiang, 1970). Some species of carabid are unaffected by manure, but a proportion of the spring-breeding species (*Bembidion lampros*, *B. quadrimaculatum*, *B. femoratum*, *Loricera pilicornis*, *Harpalus rufipes* and *Clivina fossor*) are increased (Hance, 2002). Straw mulches were used in experimental vegetable gardens to retard weed growth and enhance survival of ground predators (Snyder & Wise, 1999, 2001), and they increased the abundance of staphylinid beetles (especially *Tachyporus* spp.) in broad bean (Heinze *et al.*, 2001). Straw refugia in fields increased spider eggsac production 18-87 fold and spider density 5-36 fold. Straw refugia also increased the abundance of ground beetles, rove beetles and harvestmen and boosted spider species richness by 60% (Halaj *et al.*, 2000). Grass hay mulch significantly increased spider density in vegetable plots (Riechert, 1998).

Mulches increased carabid abundance by 27 - 50% (Pietraszko & De Clerq, 1982; Helenius & Tolonen, 1994) and spider populations were enhanced twenty- to thirty-fold (Edwards &

Lofty, 1979; Riechert & Bishop, 1990; Wise *et al.*, 1999). Some lycosid spiders respond to the increased complexity of mulched litter layers in agroecosystems with reduced emigration rates compared to unmulched controls (Buddle & Rypstra, 2003). Against the general trend, Minarro & Dapena (2003) found that carabid abundance and diversity were less in straw mulch plots on the ground below apple trees than in plots that were tilled or treated with glyphosate. However, their study relied entirely on pitfall trapping (which is strongly affected by beetle activity – Sunderland *et al.*, 1995) and it is possible that beetle movement was more restricted in mulch plots than in tilled or herbicide-treated plots. Adding spent mushroom compost to the soil surface resulted in large significant increases in density of predators in each year of a three year study (Defra AR0301). There was evidence that these increases were achieved, at least in part, by enhanced predator reproduction in compost plots. Predator species richness was also boosted from 94 species in control plots to 118 species in compost plots (Defra AR0301).

6.4.3 Effects on pest abundance

Mulching cauliflower with grass-clippings increased predation on root fly *(Delia floralis* and *Delia radicum*) eggs (Hellqvist, 1996) resulting in increased yield compared with unmulched plots (although yields were significantly less than in insecticide-treated plots), but various mulches applied in sprout plots did not increase predation on *D. radicum* eggs compared to control areas (Humphreys & Mowat, 1994ab). In contrast, grass can actually encourage bean seed fly which casues damage on beans and peas. Straw and plastic mulches significantly reduced the abundance of cabbage root fly larvae (*Delia radicum*) in chinese cabbage, but yield was unaffected (Matthews-Gehringer & Hough-Goldstein, 1988). Damage to carrots caused by carrot fly (*Psila rosae*) was not significantly reduced by adding a 5 cm layer of mulch of chopped grass and clover to the soil surface, and the damage level was not clearly correlated with predator abundance (Rämert, 1996). Pest numbers and damage in vegetable allotments were reduced by addition of grass mulch. Riechert & Bishop (1990) proved that this effect was due to enhanced spider populations (in mulched plots where spiders were removed by hand there was no significant reduction of pests and damage). Soybean seedlings within 1 m of straw mulch predator refuges were significantly a third less damaged by pests than were control seedlings (Halaj *et al.*, 2000). In the USA, wheat straw mulch below potatoes significantly reduced abundance of Colorado potato beetle (*Leptinotarsa decemlineata*) and its damage. Predator abundance was enhanced and Brust (1994a) observed predators leaving the mulch, climbing potato plants and feeding on *L. decemlineata* larvae. Eggs and larvae of this pest were eaten by a succession of different species of generalist predators throughout the growing season. In a three year study of the effects of adding spent mushroom compost to the soil surface of winter wheat (Defra AR0301), aphid density was significantly lower in compost plots than in control plots in two out of three years (and in one year the action threshold for spraying aphicide was exceeded in control plots but not in compost plots). In Defra AR0301 it was shown that reduced aphid populations were not due to reduced settling of winged aphids into mulched plots (aphid reduction was probably due to increased predation), but reduced settling has been reported in other studies. Heimbach *et al.*, (2002) showed that straw mulch reduced the settling of alate aphids onto bean, brassicas and potatoes. Lövei & Bycroft (1992) found significantly fewer aphids (and significantly less plant damage) in cauliflower plots mulched with wheat straw compared to control plots. This may also have been due to reduced aphid settling, because natural enemy abundance did not vary between treatments (Lövei & Bycroft, 1992)

It has been suggested that cases of failure of enhanced abundance of predators to translate into improved biocontrol may be because the predators prefer alternative prey (such as detritivores) that are also enhanced by the mulch/manure (Humphreys & Mowat, 1994a; Rämert, 1996). This hypothesis has not yet been tested.

6.5 Summary & Conclusions

1. Since weeds cannot be tolerated in horticulture (except in a few crops, such as orchards), a combination of invertebrate refuges (at field margins and/or in strips running through the field) and surface applications of mulches and/or manures, has potential for maintaining farmland biodiversity and supporting valuable ecosystem services such as pollination and biocontrol.

2. An understorey of weeds or sown wildflowers under orchard trees is likely to boost biocontrol of pests on the trees themselves, but successful application of this approach will rely on developing optimal understorey species (that boost natural enemies rather than pests) and optimal understorey management practices (e.g. to avoid competition with the trees).

3. Invertebrate refuges, both at field margins and as strips running through fields, are clearly beneficial in terms of a) enhancing general farmland biodiversity, b) as overwintering sites for predators (tussock-forming grasses, such as *Dactylis glomerata*, are an especially valuable overwintering habitat), c) as invertebrate food sources for declining farmland birds, d) as food sources for pollinators, and e) as refuelling stations for flying predators which are thereby rendered more efficient biocontrol agents within crops.

4. Evidence that predators walk from edge and strip refuges directly into fields in the spring and, as a result, impact on pest populations in adjacent fields remains somewhat equivocal (some species definitely do, but it is possible that many other species do not, and there is even a danger that such habitats could attract natural enemies out of crops). However, edge and strip refuges are souces of flying natural enemies and so contribute to increasing regional abundance of these beneficials. It is likely that landscapes with a high proportion of refuge habitats will have large regional populations of beneficials, which will improve biological pest control in the area (rather than there being a direct one-to-one relationship between edge/strip refuges and adjacent fields).

5. Edge and strip refuges could, in theory, threaten adjacent crops by being a source of weeds, diseases and pests, and a barrier to the movement of beneficials. Although some examples of problems of this sort can be found (and management practices need to be developed to minimise such problems), currently available information would suggest that benefits of edge and strip refuges are likely to far outweigh disbenefits.

6. The mechanisms whereby surface mulches/manures enhance the abundance and diversity of natural enemies within the crop are largely understood, and there is ample evidence that this approach is effective in increasing natural enemies in arable crops, but experience in horticultural crops (especially in the UK) is very limited. In some cases the enhancement of natural enemies translated into pest reduction, and in other cases it did not. Failures may have been because predators preferred alternative prey (such as detritivores, that are also boosted by the mulch/manure treatment) to pest species, but this has not been investigated. With sufficient specific knowledge to optimise the system, the indications are that use of mulches/manures could also benefit the grower in other ways (e.g. disease control, weed suppression, improved soil conditions), and would put waste organic materials (that otherwise have to go into expensive landfill) to good use. However, it needs to be considered that some protocols exclude returning vegetable waste back onto fields for reasons of hygiene and disease control.

6.6 *References*

AEBISCHER NJ (1991) Twenty years of monitoring invertebrates and weeds in cereal fields in Sussex. In: *The Ecology of Temperate Cereal Fields* (eds LG Firbank, N Carter, JF Darbyshire & GR Potts), 305-331. Blackwell Scientific Publications, Oxford, UK.

AEBISCHER NJ & WARD RS (1997) The distribution of corn buntings *Miliaria calandra* in Sussex in relation to crop type and invertebrate abundance. In: *The ecology and conservation of corn buntings* Miliaria calandra (eds PF Donald & NJ Aebischer), 124-138. Joint Nature Conservation Committee, Peterborough, UK.

AFUN JVK, JOHNSON DE & RUSSELL-SMITH A (1999) The effects of weed residue management on pests, pest damage, predators and crop yield in upland rice in Cote d'Ivoire. *Biological Agriculture & Horticulture* **17**, 47-58.

ALDERWEIRELDT M (1989) Seasonal migration and the importance of edge zones for the survival of *Bathyphantes gracilis* (Blackwall 1841) (Araneae:Linyphiidae) on high input crop fields.*Mededelingen van de Fakulteit Landbouwwetenschappen Rijksuniversiteit Gent* **54/3a**, 835-844.

ALDERWEIRELDT M (1993) A five year survey of the invertebrate fauna of crop fields and their edges. Part 2. General characteristics of the spider taxocoenosis. *Bulletin et Annales de la Societé royale belge* **129**, 63-68.

ALFORD DV (1975) *Bumblebees*. Davis-Poynter, London, UK.

ALI AD & REAGAN TE (1985) Vegetation manipulation impact on predator and prey populations in Louisiana sugarcane ecosystems. *Journal of Economic Entomology* **78**, 1409-1414.

ALTIERI MA (1994) *Biodiversity and Pest Management in Agroecosystems*. Food Products Press, New York.

ALTIERI MA (1999) The ecological role of biodiversity in agroecosystems. *Agriculture, Ecosystems and Environment* **74**, 19-31.

ALTIERI MA & SCHMIDT LL (1986) Cover crops affect insect and spider populations in apple orchards. *California Agriculture*, January-February, 15-17.

ALTIERI MA & TODD JW (1981) Some influences of vegetational diversity on insect communities of Georgia soybean fields. *Protection Ecology* **3**, 333-338.

ANDERSEN A (1997) Densities of overwintering carabids and staphylinids (Col., Carabidae and Staphylinidae) in cereal and grass fields and their boundaries. *Journal of Applied Entomology* **121**, 77-80.

ANDREASEN C, STRYHN H & STREIBIG C (1996) Decline of flora in Danish arable fields. *Journal of Applied Ecology* **33**, 619-626.

ANON. (2001) The Countryside Stewardship Scheme PB 5096. MAFF Crown copyright, London.

ANON. (2002) The Countryside Stewardship Scheme PB 5726A. Defra, London.

ARANCON NQ, EDWARDS CA & LEE SS (2002) Management of plant parasitic nematode populations by use of vermicomposts. *2002 BCPC Conference – Pests & Diseases*, 705-710. British Crop Protection Council, Farnham, Surrey, UK

ASTERAKI EJ, HANKS CB & CLEMENTS RO (1995) The influence of different types of grassland field margin on carabid beetle (Coleoptera, Carabidae) communities. *Agriculture Ecosystems and Environment* **54**, 195-202.

AXELSEN JA & KRISTENSEN KT (2000) Collembola and mites in plots fertilised with different types of green manure. *Pedobiologia* **44**, 556-566.

BAGGEN LR & GURR GM (1998) The influence of food on *Copidosoma koehleri* (Hymenoptera: Encyrtidae), and the use of flowering plants as a habitat management tool to enhance biological control of potato moth, *Phthorimaea operculella* (Lepidoptera: Gelechiidae). *Biological Control* **11**, 9-17.

BAGGEN LR, GURR GM & MEATS A (1999) Flowers in tri-trophic systems: mechanisms allowing selective exploitation by insect natural enemies for conservation biological control. *Entomologia Experimentalis et Applicata* **91**, 155-161.

BAINES M, HAMBLER C, JOHNSON PJ, MACDONALD DW & SMITH H (1998) The effects of arable field margin management on the abundance and species richness of Araneae (spiders). *Ecography* **21**, 74-86.

BARKER AM & REYNOLDS CJM (1999) The value of planted grass field margins as a habitat for sawflies and other chick-food insects. *Aspects of Applied Biology* **54**, 109-116.

BARKER CJ (2000) Progress in the development and use of soil forming products from municipal solid waste. In: *Waste 2000* (ed. C McLardy), 611. The Waste Conference Ltd., University of Warwick Science Park, Coventry, UK.

BARONE M & FRANK T (2003) Habitat age increases reproduction and nutritional condition in a generalist arthropod predator. *Oecologia* **135**, 78-83.

BARTHEL J (1997) Einfluss von Nutzungsmuster und Habitatkonfiguration auf die Spinnenfauna der Krautschicht (Araneae) in einer süddeutschen Agrarlandschaft. *Agrarökologie* **25**, 1-175.

BAYRAM A & LUFF ML (1993)Winter abundance and diversity of lycosids (Lycosidae, Araneae) and other spiders in grass tussocks in a field margin. *Pedobiologia* **37**, 357-364.

BEARD RCW & MAUREMOOTOO JR (1994) The biodiversity of Coleoptera overwintering in arable field boundaries. *Brighton Crop Protection Conference – Pests & Diseases*, 943-944.

BEDFORD SE & USHER MB (1994) Distribution of arthropod species across the margins of farm woodlands. *Agriculture Ecosystems and Environment* **48**, 295-305.

BELL JR, GATES S, HAUGHTON AJ, MACDONALD DW, WHEATER CP & CULLEN WR (1999) Pseudoscorpions in field margins: effects of margin age, management and boundary habitats. *Journal of Arachnology* **27**, 236-240.

BELL JR, JOHNSON PJ, HAMBLER C, HAUGHTON AJ, SMITH H, FEBER RE, TATTERSALL FH, HART BH, MANLEY W & MACDONALD DW (2002a) Manipulating the abundance of *Lepthyphantes tenuis* (Araneae: Linyphiidae) by field margin management. *Agriculture, Ecosystems and Environment* **93**, 295-304.

BELL JR, HAUGHTON AJ, BOATMAN ND & WILCOX A (2002b) Do incremental increases of the herbicide glyphosate have indirect consequences for spider communities? *Journal of Arachnology* **30**, 288-297.

BENCE SR, STANDEN K & GRIFFITHS M (1999) Nest site selection by the harvest mouse (*Micromys minutes*) on arable farmland. *Aspects of Applied Biology* **54**, 197-202.

BENTON TG, VICKERY JA & WILSON JD (2003) Farmland biodiversity: is habitat heterogeneity the key ? *Trends in Ecology and Evolution* **18**, 182-188.

BEST RL, BEEGLE CC, OWENS JC, ORTZ M (1981) Population density, dispersion, and dispersal estimates for *Scarites substriatus, Pterostichus chalcites* and *Harpalus pennsylvanicus* (Carabidae) in an Iowa cornfield. *Environmental Entomology* **10**, 847-856.

BIGGER DS & CHANEY WE (1998) Effects of *Iberis umbellata* (Brassicaceae) on insect pests of cabbage and on potential biological control agents. *Environmental Entomology* **27**, 161-167.

BILDE T & TOFT S (1994) Prey preference and egg production of the carabid beetle *Agonum dorsale. Entomologia Experimentalis et Applicata* **73**, 151-156.

BILDE T & TOFT S (1997a) Consumption by carabid beetles of three cereal aphid species relative to other prey types. *Entomophaga* **42**, 21-32.

BILDE T & TOFT S (1997b) Limited predation capacity by generalist arthropod predators on the cereal aphid *Rhopalosiphum padi. Biological Agriculture and Horticulture* 15, 143-150.

BILDE T & TOFT S (1999) Prey consumption and fecundity of the carabid beetle *Calathus melanocephalus* on diets of three cereal aphids: high consumption rates of low-quality prey. *Pedobiologia* **43**, 422-429.

BILDE T & TOFT S (2001) The value of three cereal aphid species as food for a generalist predator. *Physiological Ecology* **26**, 58-68.

BISHOP L & RIECHERT SE (1990) Spider colonization of agroecosystems: mode and source. *Environmental Entomology* **19**,1738-1745.

BOATMAN ND (1998) The value of buffer zones for the conservation of biodiversity. *1998 Brighton Conference – Pests & Diseases*, 939-950. British Crop Protection Council, Farnham, Surrey, UK

BOATMAN ND (2001) Relationships between weeds, herbicides and birds. Defra Desk Study PN0940, 91-108.

BOIVIN G & HANCE T (2003) Ground beetle assemblages in cultivated organic soil and adjacent habitats: temporal dynamics of microspatial changes. *Pedobiologia* **47**, 193-202.

BOLGER T & CURRY JP (1980) Effects of cattle slurry on soil arthropods in grassland. *Pedobiologia* **20**, 246-253.

BOOIJ CJH, DEN NIJS LJMF & NOORLANDER J (1995) Spatio-temporal patterns of activity density of some carabid species in large scale arable fields. *Acta Jutlandica* **70**,175-184.

BROWN MW & GLENN DM (1999) Ground cover plants and selective insecticides as pest management tools in apple orchards. *Journal of Economic Entomology* **92**, 899-905.

BRUST GE (1990) Direct and indirect effects of four herbicides on the activity of carabid beetles (Coleoptera: Carabidae). *Pesticide Science* **30**, 309-320.

BRUST GE (1994a) Natural enemies in straw-mulch reduce Colorado potato beetle populations and damage in potato. *Biological Control* **4**,163-169.

BRUST GE (1994b) Carabids affect the ability of broadleaf weeds to compete. *Agriculture Ecosystems and Environment* **48**, 27-34.

BUDDLE CM & RYPSTRA AL (2003) Factors initiating emigration of two wolf spider species (Araneae: Lycosidae) in an agroecosystem. *Environmental Entomology* **32**, 88-95.

BUGG RL & WADDINGTON C (1994) Using cover crops to manage arthropod pests of orchards: a review. *Agriculture, Ecosystems and Environment* **50**, 11-28.

BUGG RL, EHLER LE & WILSON LT (1987) Effect of common knotweed (*Polygonum aviculare*) on abundance and efficiency of insect predators of crop pests. *Hilgardia* **55**, 1-52.

BUGG RL, WÄCKERS FL, BRUNSON KE, DUTCHER JD & PHATAK SC (1991) Cool-season cover crops relay intercropped with cantaloupe: influence on a generalist predator, *Geocoris punctipes* (Hemiptera: Lygaeidae). *Journal of Economic Entomology* **84**, 408-416.

BUJAKI G, KARPATI Z, KADAR F & TOTH F (1996) Comparison of the carabid fauna of a wheat field and its surrounding habitats. *Acta Jutlandica* **71**, 221-226.

BÜRKI HM & PFIFFNER L (2000) Die Bedeutung streifenförmiger, naturnaher Elemente als Überwinterungsquartier. *Agrarökologie* **37**, 165-179.

CARDINALE BJ, PALMER MA & COLLINS SL (2002) Species diversity enhances ecosystem functioning through interspecific facilitation. *Nature* **415**, 426-429.

CARDWELL C, HASSALL M & WHITE P (1994) Effects of headland management on carabid beetle communities in Breckland cereal fields. *Pedobiologia* **38**, 50-62.

CARRECK, NL, WILLIAMS IH & OAKLEY JN (1999) Enhancing farmland for insect pollinators using flower mixtures. *Aspects of Applied Biology* **54**, 101-108.

CHAMBERLAIN DE & FULLER RJ (2001) Contrasting patterns of change in the distribution and abundance of farmland birds in relation to farming system in lowland Britain. *Global Ecology and Biogeography* **10**, 399-409.

CHAMBERLAIN DE, FULLER RJ, BUNCE RGH, DUCKWORTH JC & SHRUBB M (2000) Changes in the abundance of farmland birds in relation to the timing of agricultural intensification in England and Wales. *Journal of Applied Ecology* **37**, 771-788.

CHAMBERS RJ, SUNDERLAND KD, STACEY DL & WYATT IJ (1982) A survey of cereal aphids and their natural enemies in winter wheat in 1980. *Annals of Applied Biology* **101**, 175-178.

CHAN MKY & CLOSE RC (1987) *Aphanomyces* root rot of peas 3. Control by the use of cruciferous amendments. *New Zealand Journal of Agricultural Research* **30**, 225-233.

CHANEY RL, RYAN JA, KUKIER U, BROWN SL, SIEBIELEC G, MALIK M & ANGLE JS (2001) Heavy metal aspects of compost use. In: *Compost Utilization in Horticultural Cropping Systems* (ed. PJ Stoffella & BA Kahn), 323-359. Lewis Publishers, Boca Raton, USA.

CHANEY WE (1998) Biological control of aphids in lettuce using in-field insectaries. In: *Enhancing Biological Control* (eds CH Pickett & RL Bugg), 73-83. University of California Press, Berkeley, California, USA.

CHAOUI H, EDWARDS CA, BRICKNER A, LEE SS & ARANCON NQ (2002) Suppression of plant diseases, *Pythium* (damping-off), *Rhizoctonia* (root rot) and *Verticillium* (wilt) by vermicomposts. *2002 BCPC Conference – Pests & Diseases*, 711-716. British Crop Protection Council, Farnham, Surrey, UKChen BR & Wise DH (1997) Responses of forest-floor fungivores to experimental food enhancement. *Pedobiologia* **41**, 316-326.

CHIANG HC (1970) Effects of manure applications and mite predation on corn rootworm populations in Minnesota. *Journal of Economic Entomology* **63**, 934-936.

CHIVERTON PA (1989) The creation of within-field overwintering sites for natural enemies of cereal aphids. *Proceedings of the Brighton Crop Protection Conference - Weeds 1989*, 1093-1096.

CHIVERTON PA (1994) Pitfall-trap catches of the carabid beetle *Pterostichus melanarius* in relation to gut contents and prey densities in insecticide treated and untreated spring barley. *Entomologia Experimentalis et Applicata* **36**, 23-30.

CHIVERTON PA (1999) Buffer zones of different floral composition – effects on the beneficial arthropod fauna. *Aspects of Applied Biology* **54**, 307-314.

CHIVERTON PA & SOTHERTON NW (1991) The effects on beneficial arthropods of the exclusion of herbicides from cereal crop edges. *Journal of Applied Ecology* **28**, 1027-1039.

CILGI T & JEPSON PC (1995) The risks posed by deltamethrin drift to hedgerow butterflies. *Environmental Pollution* **87**, 1-9.

CLARK MS, LUNA JM, STONE ND & YOUNGMAN RR (1993) Habitat preferences of generalist predators in reduced-tillage corn. *Journal of Entomological Science* **28**, 404-416.

COAKER TH & FINCH S (1973) The association of the cabbage root fly with its food and host plants. In: *Insect/Plant Relationships* (ed. HF Van Emden), 119-128. Blackwell, Oxford, UK.

COLLINS KL, BOATMAN ND, WILCOX A, HOLLAND JM & CHANEY K (2002) Influence of beetle banks on cereal aphid predation in winter wheat. *Agriculture Ecosystems and Environment* **93**, 337-350.

COLLINS KL, BOATMAN ND, WILCOX A & HOLLAND JM (2003a) Effects of different grass treatments used to create overwintering habitat for predatory arthropods on arable farmland. *Agriculture Ecosystems and Environment* **96**, 59-67.

COLLINS KL, BOATMAN ND, WILCOX A & HOLLAND JM (2003b) A 5-year comparison of overwintering polyphagous predator densities within a beetle bank and two conventional hedgebanks. *Annals of Applied Biology* **143**, 63-71.

COLUNGA-GARCIA M, GAGE SH & LANDIS DA (1997) Response of all assemblage of Coccinellidae (Coleoptera) to a diverse agricultural landscape. *Environmental Entomology* **26**, 797-804.

COOMBES DS & SOTHERTON NW (1986) The dispersal and distribution of polyphagous predatory Coleoptera in cereals. *Annals of Applied Biology* **108**, 461-474.

CORBET S (1995) Insects, plants and succession: advantages of long-term set-aside. *Agriculture, Ecosystems and Environment* **53**, 201-217.

CORBET S (2000) Conserving compartments in pollination webs. *Conservation Biology* **14**, 1229-1231.

CORBETT A (1998) The importance of movement in the response of natural enemies to habitat manipulation. In: *Enhancing Biological Control* (eds CH Pickett & RL Bugg), 25-48. University of California Press, Berkeley, California, USA.

COVENTRY E, NOBLE R, WHIPPS J & BANHAM H (2002a) Putting waste to a good use. *Grower* **137(21),** 16-17.

COVENTRY E, NOBLE R, WHIPPS J & BANHAM H (2002b) Waste not… and control white rot. *HDC News* **86**, 8-10.

COVENTRY E, NOBLE R, MEAD A & WHIPPS JM (2002c) Control of *Allium* white rot (*Sclerotium cepivorum*) with composted onion waste. *Soil Biology & Biochemistry* **34**, 1037-1045.

COWGILL SE, WRATTEN SD & SOTHERTON NW (1993a) The selective use of floral resources by the hoverfly *Episyrphus balteatus* (Diptera: Syrphidae) on farmland. *Annals of Applied Biology* **122**, 223-231.

COWGILL SE, WRATTEN SD & SOTHERTON NW (1993b) The effect of weeds on the numbers of hoverfly (Diptera: Syrphidae) adults and the distribution and composition of their eggs in winter wheat. *Annals of Applied Biology* **123**, 499-515.

CRAWFORD RL & EDWARDS JS (1986) Ballooning spiders as a component of arthropod fallout on snowfields of Mount Rainier, Washington, USA. *Arctic and Alpine Research* **18**, 429-437.

CRAWFORD RL, SUGG PM & EDWARDS JS (1995) Spider arrival and preliminary establishment on terrain depopulated by volcanic eruption at Mount St. Helens, Washington. *American Midland Naturalist* **133**, 60-75.

CRINER GK, ALLEN TG & SCHATZER RJ (2001) Compost economics: production and utilization in agriculture. In: *Compost Utilization in Horticultural Cropping Systems* (ed. PJ Stoffella & BA Kahn), 241-260. Lewis Publishers, Boca Raton, USA.

CROMAR HE, MURPHY SD & SWANTON CJ (1999) Influence of tillage and crop residue on postdispersal predation of weed seeds. *Weed Science* **47**, 184-194.

CURRY JP (1979) The arthropod fauna associated with cattle manure applied as a slurry to grassland. *Proceedings of the Royal Irish Academy B* **79**, 15-27.

CURRY JP & PURVIS G (1981) Studies on the influence of weeds and farmyard manure on the arthropod fauna of sugar beet. *Journal of Life Sciences of the Royal Dublin Society* **3**, 397-408.

DEAN DA & STERLING WL (1985) Size and phenology of ballooning spiders at two locations in Eastern Texas. *Journal of Arachnology* **13**,111-120.

DENG X, ZHENG ZQ, ZHANG NX & JIA XF (1988) Methods of increasing winter survival of *Metaseiulus occidentalis* (Acari: Phytoseiidae) in north west China. *Chinese Journal of Biological Control* **4**, 97-101.

DENNIS P (1991) The temporal and spatial distribution of arthropod predators of the aphids *Rhopalosiphum padi* W. and *Sitobion avenae* (F) in cereals next to field-margin habitats. *Norwegian Journal of Agricultural Science* **5**,79-88.

DENNIS P & FRY LA (1992) Field margins: can they enhance natural enemy population densities and general arthropod diversity on farmland ? *Agriculture Ecosystems and Environment* **40**, 95-115.

DENNIS P, THOMAS MB & SOTHERTON NW (1994) Structural features of field boundaries which influence the overwintering densities of beneficial arthropod predators. *Journal of Applied Ecology* **31**, 361-370.

DENYS C & TSCHARNTKE T (2002) Plant-insect communities and predator-prey ratios in field margin strips, adjacent crop fields, and fallows. *Oecologia* **130**, 315-324.

DESENDER K (1982) Ecological and faunal studies on Coleoptera in agricultural land. II. Hibernation of Carabidae in agro-ecosystems. *Pedobiologia* **23**, 295-303.

DESENDER K & ALDERWEIRELDT M (1988) Population dynamics of adult and larval carabid beetles in a maize field and its boundary. *Journal of Applied Entomology* **106**,13-19.

DESENDER K, ALDERWEIRELDT M & POLLET M (1989) Field edges and their importance for polyphagous predatory arthropods. *Mededelingen van de Fakulteit Landbouwwetenschappen Rijksuniversiteit Gent* **54/3a**, 823-833.

DESENDER K, MAELFAIT JP, D'HULSTER M & VANHERCKE L (1981) Ecological and faunal studies on Coleoptera in agricultural land. I. Seasonal occurrence of Carabidae in the grassy edge of a pasture. *Pedobiologia* **22**, 379-384.

DE SNOO GR (1996) Enhancement of non-target insects: indications about dimensions of unsprayed crop edges. *Acta Jutlandica* **71**, 209-219.

DE SNOO GR & DE LEEUW J (1996) Non-target insects in unsprayed cereal edges and aphid dispersal to the adjacent crop. *Journal of Applied Entomology* **120**, 501-504.

DE SNOO GR, VAN DER POLL RJ & BERTELS J (1998) Butterflies in sprayed and unsprayed field margins. *Journal of Applied Entomology* **122**, 157-161.

DEWAR AM, MAY MJ, WOIWOD IP, HAYLOCK LA, CHAMPION GT, GARNER BH, SANDS RJN, QI AM & PIDGEON JD (2003) A novel approach to the use of genetically modified herbicide tolerant crops for environmental benefit. *Proceedings of the Royal Society of London, B* **270**, 335-340.

DINTER A (1997) Density and activity density fluctuations of *Oedothorax apicatus* (Blackwall) in winter wheat in northern Germany. *Acta Jutlandica* **72**, 87-99.

DRAMSTAD W & FRY G (1995) Foraging activity of bumblebees (*Bombus*) in relation to flower resources on arable land. *Agriculture, Ecosystems and Environment* **53**, 123-135.

DUELLI P & OBRIST MK (2003) Regional biodiversity in an agricultural landscape: the contribution of semi-natural habitat islands. *Basic and Applied Ecology* **4**, 129-138.

DUFFIELD SJ & AEBISCHER NJ (1994) The effect of spatial scale of treatment with dimethoate on invertebrate population recovery in winter wheat. *Journal of Applied Ecology* **31**, 263-281.

DUFFIELD SJ, JEPSON PC, WRATTEN SD & SOTHERTON NW (1996) Spatial changes in invertebrate predation rate in winter wheat following treatment with dimethoate. *Entomologia Experimentalis et Applicata* **78**, 9-17.

DOVER JW (1997) Conservation headlands: effects on butterfly distribution and behaviour. *Agriculture, Ecosystems and Environment* **63**, 31-49.

DOVER JW (1999) Butterflies and field margins. *Aspects of Applied Biology* **54**, 117-124.

DOVER J, SOTHERTON N & GOBBETT K (1990) Reduced pesticide inputs on cereal field margins: the effects on butterfly abundance. *Ecological Entomology* **15**, 17-24.

DOWNIE IS, COULSON JC & BUTTERFIELD JEL (1996) Distribution and dynamics of surface-dwelling spiders across a pasture-plantation ecotone. *Ecography* **1**, 29-40.

DRÈS M & MALLET J (2002) Host races in plant-feeding insects and their importance in sympatric speciation. *Philosophical Transactions of the Royal Society of London B* **357**, 471-492.

EASTMAN, BR, KANE PN, EDWARDS CA, TRYTEK L, GUNADI B, STERMER AL & MOBLEY JR (2001) The effectiveness of vermiculture in human pathogen reduction for USEPA biosolids stabilization. *Compost Science & Utilization* **9**, 38-49.

EDWARDS CA & LOFTY JR (1979) The effects of straw residues and their disposal on the soil fauna In: *Straw Decay and its Effect on Disposal and Utilisation* (ed E Grossbard, 37-44. John Wiley & Sons, Chichester, UK.

EIGENBRODE SD & PIMENTEL D (1988) Effects of manure and chemical fertilizers on insect pest populations on collards. *Agriculture, Ecosystems and Environment* **20**, 109-125.

EPSTEIN E (2001) Human pathogens: hazards, controls, and precautions in compost. In: *Compost Utilization in Horticultural Cropping Systems* (ed. PJ Stoffella & BA Kahn), 361-380. LEWIS PUBLISHERS, BOCA RATON, USA.

ESTEVEZ B, DOMON G & LUCAS E (2000) Contribution de l'écologie du paysage à la diversification des agroésystèmes à des fins de phytoprotection. *Phytoprotection* **81**, 1-14.

FEBER RE, SMITH H & MACDONALD DW (1996) The effects on butterfly abundance of the management of uncropped edges of arable fields. *Journal of Applied Ecology* **33**, 1191-1205.

FEBER RE, SMITH H & MACDONALD DW (1999) The importance of spatially variable field margin management for two butterfly species. *Aspects of Applied Biology* **54**, 155-162.

FEBER RE, JOHNSON PJ, SMITH H, BAINES M & MACDONALD DW (1995) The effects of arable field margin management on the abundance of beneficial arthropods. BCPC Symposium Proceedings No.**63***, Integrated Crop Protection: Towards Sustainability* ? pp. 163-170.

FERNÁNDEZ GARCÍA A, GRIFFITHS GJK & THOMAS CFG (2000) Density, distribution and dispersal of the carabid beetle *Nebria brevicollis* in two adjacent cereal fields. *Annals of Applied Biology* **137**, 1-9.

FILSER J (1995) The effect of green manure on the distribution of Collembola in a permanent row crop. *Biology and Fertility of Soils* **19**, 303-308.

FITZGERALD JD & SOLOMON MG (2003) Can flowering plants enhance numbers of beneficial arthropods in UK apple and pear orchards ? *Biocontrol Science & Technology*, under review.

FRAMPTON GK, CILGI T, FRY GLA & WRATTEN SD (1995) Effects of grassy banks on the dispersal of some carabid beetles (Coleoptera Carabidae) on farmland. *Biological Conservation* **71**, 347-355.

FRANK T (1996) Species diversity and activity densities of epigeic and flower visiting arthropods in sown weed strips and adjacent fields. *Bulletin SROP/WPRS* **19(3)**, 101-105.

FRANK T (1997) Species diversity of ground beetles (Carabidae) in sown weed strips and adjacent fields In: *Entomological Research in Organic Agriculture*, 297-307. AB Academic Publishers.

FRANK T (1998a) The role of different slug species in damage to oilseed rape bordering on sown wildflower strips. *Annals of Applied Biology* **133**, 483-493.

FRANK T (1998b) Slug damage and numbers of the slug pests, *Arion lusitanicus* and *Deroceras reticulatum*, in oilseed rape grown beside sown wildflower strips. *Agriculture Ecosystems and Environment* **67**, 67-78.

FRANK T (1999) Density of adult hoverflies (Dipt., Syrphidae) in sown weed strips and adjacent fields. *Journal of Applied Entomology* **123**, 351-355.

FRANK T (2000) Auswirkungen auf Prädatoren und Parasitoide. *Agrarökologie* **37**, 113-126.

FRANK T (2003) Influence of slug herbivory on the vegetation development in an experimental wildflower strip. *Basic and Applied Ecology* **4**, 139-147.

FRANK T & BARONE M (1999) Short-term field study on weeds reducing slug feeding on oilseed rape. *Journal of Plant Diseases and Protection* **106**, 534-538.

FRANK T & FRIEDLI J (1999) Laboratory food choice trials to explore the potential of common weeds to reduce slug feeding on oilseed rape. *Biological Agriculture and Horticulture* **17**, 19-29.

FRANK T & NENTWIG W (1995) Ground dwelling spiders (Araneae) in sown weed strips and adjacent fields. *Acta Oecologica* **16**, 179-193.

FREEMAN JA (1946) The distribution of spiders and mites up to 300 feet in the air. *Journal of Animal Ecology* **15**, 69-74.

FRENCH BW & ELLIOTT NC (1999) Spatial and temporal distribution of ground beetle (Coleoptera: Carabidae) assemblages in riparian strips and adjacent wheat fields. *Environmental Entomology* **28**, 597-607.

FRY GLA (1995) Landscape ecological principles and sustainable agriculture. *BCPC Symposium Proceedings Crop Protection: Towards Sustainability ?*, **63,** 247-254. British Crop Protection Council, Farnham, Surrey, UK.

FULLER RJ, GREGORY RD, GIBBONS DW, MARCHANT JH, WILSON JD, BAILLIE SR *et al.* (1995) Population declines and range contractions among lowland farmland birds in Britain. *Conservation Biology* **9**, 1425-1441.

FUSSELL M & CORBET SA (1992) Flower usage by bumble-bees: a basis for forage plant management. *Journal of Applied Ecology* **29**, 451-465.

FYE RE (1983) Cover crop manipulation for building pear psylla (Homoptera, Psyllidae) predator populations in pear orchards. *Journal of Economic Entomology* **76**, 306-310.

GLÜCK E & INGRISCH S (1990) The effect of biodynamic and conventional agriculture management on Erigoninae and Lycosidae spiders. *Journal of Applied Entomology* **110**,136-148.

GOLDSCHMIDT H & TOFT S (1997) Variable degrees of granivory and phtyophagy in insectivorous carabid beetles. *Pedobiologia* **41**, 521-525.

GREENSTONE MH, MORGAN CE & HULTSCH AN (1987) Ballooning spiders in Missouri, USA, and New South Wales, Australia: family and mass distributions. *Journal of Arachnology* **15**, 163-170.

GROSSBARD E (1979) *Straw Decay and its Effect on Disposal and Utilisation*. John Wiley & Sons, Chichester, UK.

GUNADI B, EDWARDS CA & ARANCON NQ (2002) Changes in trophic structure of soil arthropods after the application of vermicomposts. *European Journal of Soil Biology* **38**, 161-165.

GURR GM, VAN EMDEN HF & WRATTEN SD (1998) Habitat manipulation and natural enemy efficiency: implications for the control of pests. In*: Conservation Biological Control* (ed, P Barbosa), 155-183. Academic Press, San Diego, USA.

GURR GM, WRATTEN SD & LUNA JM (2003) Multi-function agricultural biodiversity: pest management and other benefits. *Basic and Applied Ecology* **4**, 107-116.

HALAJ J & WISE DH (2002) Impact of a detrital subsidy on trophic cascades in a terrestrial grazing food web. *Ecology* **83**, 3141-3151.

HALAJ J, CADY AB & UETZ GW (2000) Modular habitat refugia enhance generalist predators and lower plant damage in soybean. *Environmental Entomology* **29**, 383-393.

HALLEY JM, THOMAS CFG & JEPSON PC (1996) A model for the spatial dynamics of linyphiid spiders in farmland. *Journal of Applied Ecology* **33**, 471-492.

HANCE T (2002) Impact of cultivation and crop husbandry practices. In: *The Agroecology of Carabid Beetles* (ed. JM Holland), 231-249. Intercept, Andover, UK.

HANKS G, HOLMES S. & RAHN C (2002) Grow quality lilies in wood-fibre and green compost based mixes ! *HDC News* **88**, 14-16.

HARWOOD RWJ, WRATTEN SD & NOWAKOWSKI M (1992) The effect of managed field margins on hoverfly (Diptera: Syrphidae) distribution and within-field abundance. *1992 BCPC Conference – Pests & Diseases*, 1033-1037. British Crop Protection Council, Farnham, Surrey, UK.

HARWOOD RWJ, WRATTEN SD, NOWAKOWSKI M & MARSHALL EPJ (1994) Wild flower strips and winter/summer populations of beneficial invertebrates in farmland. *IOBC/WPRS Bulletin* **17**, 211-219.

HASSALL M, HAWTHORNE A, MAUDSLEY M, WHITE P & CARDWELL C (1992) Effects of headland management on invertebrate communities in cereal fields. *Agriculture Ecosystems and Environment* **40**,155-178.

HAUGHTON AJ, BELL JR, GATES S, JOHNSON PJ & MACDONALD DW (1999a) Methods of increasing invertebrate abundance within field margins. *Aspects of Applied Biology* **54**, 163-170.

HAUGHTON AJ, WILCOX A, CHANEY K & BOATMAN ND (1999b) The effects of different rates of glyphosate on non-target invertebrates in field margins. *Aspects of Applied Biology* **54**, 185-190.

HAUGHTON AJ, BELL JR, BOATMAN ND, & WILCOX A (1999c) The effects of different rates of the herbicide glyphosate on spiders in arable field margins. *Journal of Arachnology* **27**, 249-254.

HAUGHTON AJ, BELL JR, WILCOX A & BOATMAN ND (2001a) The effect of the herbicide glyphosate on non-target spiders: Part 1. Direct effects on *Lepthyphantes tenuis* under laboratory conditions. *Pest Management Science* **57**, 1033-1036.

HAUGHTON AJ, BELL JR, BOATMAN ND & WILCOX A (2001b) The effect of the herbicide glyphosate on non-target spiders: Part II. Indirect effects on *Lepthyphantes tenuis* in field margins. *Pest Management Science* **57**, 1037-1042.

HAUSAMMANN A (1996) The effects of weed strip-management on pests and beneficial arthropods in winter wheat fields. *Journal of Plant Diseases and Protection* **103**, 70-81.

HAWTHORNE A (1995) Validation of the use of pitfall traps to study carabid populations in cereal field headlands. *Acta Jutlandica* **70**, 61-75.

HAWTHORNE A & HASSALL M (1995) The effect of cereal headland treatments on carabid communities. *Acta Jutlandica* **70**,185-198.

HAWTHORNE AJ, HASSALL M & SOTHERTON NW (1998) Effects of cereal headland treatments on the abundance and movements of three species of carabid beetles. *Applied Soil Ecology* **9**, 417-422.

HE Z, YANG X, KAHN BA, STOFFELLA PJ & CALVERT DV (2001) Plant nutrition benefits of phosphorus, calcium, magnesium, and micronutrients from compost utilization. In: *Compost Utilization in Horticultural Cropping Systems* (ed. PJ Stoffella & BA Kahn), 307-320. Lewis Publishers, Boca Raton, USA.

HEIDGER C & NENTWIG W (1989) Augmentation of beneficial arthropods by strip-management. 3. Artificial introduction of a spider species which preys on wheat pest insects. *Entomophaga* **34**, 511-522.

HEIMBACH U, EGGERS C & THIEME T (2002) Weniger Blattlause durch Mulchen ? *Gesunde Pflanzen* **54**, 119-125.

HEINZE M, EGGERS C & HEIMBACH U (2001) Untersuchungen zum Einfluss verschiedener Mulchsaatsysteme auf Staphylinidae in Ackerbohnen – Bestanden. *Mitteilungen der Deutschen Gesellschaft Allgemeine und Angewandte Entomologie* **13**, 257-260.

HELENIUS J & TOLONEN T (1994) Enhancement of generalist aphid predators in cereals: Effect of green manuring on recruitment of ground beetles. *IOBC/WPRS Bulletin* **17**, 201-210.

HELENIUS J, HOLOPAINEN J, MUHOJOKI M, POKKI P, TOLONEN T & VENÄLÄINEN A (1995) Effect of undersowing and green manuring on abundance of ground beetles (Coleoptera, Carabidae) in cereals. *Acta Zoologica Fennica* **196**, 156-159.

HELLQVIST S (1996) Mulching with grass-clippings in cauliflower: effects on yield and brassica root flies (*Delia* spp.). *International Journal of Pest Management* **42**, 39-46.

HICKMAN JM & WRATTEN SD (1996) Use of *Phacelia tanacetifolia* strips to enhance biological control of aphids by hoverfly larvae in cereal fields. *Journal of Economic Entomology* **89**, 832-840.

HOITINK HAJ, KRAUSE MS & HAN DY (2001) Spectrum and mechanisms of plant disease control with composts. In: *Compost Utilization in Horticultural Cropping Systems* (ed. PJ Stoffella & BA Kahn), 263-273. Lewis Publishers, Boca Raton, USA.

HOLLAND JM (1994) Progress towards integrated arable farming research in western Europe. *Pesticide Outlook* **6**, 17-23.

HOLLAND JM & LUFF ML (2000) The effects of agricultural practices on Carabidae in temperate agroecosystems. *Integrated Pest Management Reviews* **5**, 109-129.

HOLLAND JM, WINDER L, PERRY JN (1999a) Arthropod prey of farmland birds: their spatial distribution within a sprayed field with and without buffer zones. *Aspects of Applied Biology* **54**, 53-60.

HOLLAND JM, PERRY JN & WINDER L (1999b) The within-field spatial and temporal distribution of arthropods in winter wheat. *Bulletin of Entomological Research* **89**, 499-513.

HOLLAND JM, BEGBIE M, BIRKETT T, REYNOLDS CJM & THOMAS CFG (2001) The influence of hedgerows on coleopteran distributions: results from a multi-field sampling study. In "*Hedgerows of the world: their ecological functions in different landscapes*" (eds C Barr & S Petit), 177-186. IALE, UK

HOLLAND JM, BEGBIE M, BIRKETT T, REYNOLDS CJM & THOMAS CFG (2002) The distribution of carabid beetles across the arable landscape: results from a 70 ha sampling study. In: *How to protect or what we know about Carabid Beetles* (eds J Szyszko, PJ den Boer & T Bauer), 117-131. Warsaw Agricultural University Press, Warsaw, Poland.Holland J, Birkett T, Begbie M, Southway S & Thomas CFG (2003) The spatial dynamics of predatory arthropods and the importance of crop and adjacent margin habitats. *IOBC/WPRS Bulletin* **26(4),** 65-70.

HOLLIDAY NJ & HAGLEY EAC (1984) The effect of sod type on the occurrence of ground beetles (Coleoptera: Carabidae) in a pest management apple orchard. *Canadian Entomologist* **116** 165-171.

HOOKS CRR & JOHNSON MW (2003) Impact of agricultural diversification on the insect community of cruciferous crops. *Crop Protection* **22**, 223-238.

HOUSE GJ (1989) No-tillage and legume cover cropping in corn agroecosystems: Effects on soil arthropods. *Acta Phytopathologica et Entomoliga Hungarica* **24**, 99-104.

HOUSE GJ & ALL JN (1981) Carabid beetles in soybean agroecosystems. *Environmental Entomology* **10**, 194-196.

HOUSE GJ & DEL ALZUGARAY MR (1989) Influence of cover cropping and no tillage practices on community composition of soil arthropods in a North Carolina agroecosystem. *Environmental Entomology* **18**, 302-307.

HUMPHREYS IC & MOWAT DJ (1994a) Effects of organic treatment on beetle predators of the cabbage root fly and on alternative prey species. *IOBC/WPRS Bulletin* **17(8),** 115-123.

HUMPHREYS IC & MOWAT DJ (1994b) Effects of some organic treatments on predators (Coleoptera: Carabidae) of cabbage root fly, *Delia radicum* (L.) (Diptera: Anthomyiidae), and on alternative prey species. *Pedobiologia* **38**, 513-518.

HURST C & DOBERSKI J (2003) Wild flower seed predation by *Pterostichus madidus* (Carabidae: Coleoptera). *Annals of Applied Biology* **142**, 251-254.

HUUSELA-VEISTOLA E (1998) Effects of perennial grass strips on spiders (Araneae) in cereal fields and impact on pesticide side-effects. *Journal of Applied Entomology* **122**, 575-583.

HUUSELA-VEISTOLA E & KURPPA S (1996) Effects of pesticides and use of perennial strips on the vegetation-living insects in a cereal field. *Bulletin IOBC/WPRS* **19(3)**, 90-100.

HUXEL GR & MCCANN K (1998) Food web stability: the influence of trophic flows across habitats. *American Naturalist* **152**, 460-469.

HUXEL GR, MCCANN K & POLIS GA (2002) Effects of partitioning allochthonous and autochthonous resources on food web stability. *Ecological Research* **17**, 419-432.

IDINGER J, KROMP B & STEINBERGER KH (1996) Ground photoeclector evaluation of the numbers of carabid beetles and spiders found in and around cereal fields treated with either inorganic or compost fertilizers. *Acta Jutlandica* **71**, 255-267.

IDRIS, AB & GRAFIUS E (1995) Wildflowers as nectar sources for *Diadegma insulare* (Hymenoptera: Ichneumonidae), a parasitoid of diamondback moth (Lepidoptera: Yponomeutidae). *Environmental Entomology* **24**, 1726-1735.

JENSEN TS, DYRING L, KRISTENSEN B, NIELSEN BO & RASMUSSEN ER (1989) Spring dispersal and summer habitat distribution of *Agonum dorsale* (Coleoptera Carabidae). *Pedobiologia* **33**,155-165.

JEPSON PC (ed) (1989) *Pesticides and Non-target Invertebrates*. Intercept, Wimborne, Dorset, UK.

JEPSON PC & THACKER JRM (1990) Analysis of the spatial component of pesticide side-effects on non-target invertebrate populations and its relevance to hazard analysis. *Functional Ecology* **4**, 349-355.

JERVIS MA & KIDD NAC (1996) Phytophagy. In: *Insect Natural Enemies* (eds M Jervis & N Kidd), 375-394. Chapman & Hall, London, UK.

JMHASLY P & NENTWIG W (1995) Habitat management in winter wheat and evaluation of subsequent spider predation on insect pests. *Acta Oecologica* **16**, 389-403.

JOHNSON NE & CAMERON RS (1969) Phytophagous ground beetles. *Annals of the Entomological Society of America* **63**, 909-914.

JORGENSEN HB & TOFT S (1997a) Food preference, diet dependent fecundity and larval development in *Harpalus rufipes* (Coleoptera: Carabidae). *Pedobiologia* **41**, 307-315.

JORGENSEN HB & TOFT S (1997b) Role of granivory and insectivory in the life cycle of the carabid beetle *Amara similata. Ecological Entomology* **22**, 7-15.

JOYCE KA, HOLLAND JM & DONCASTER CP (1999) Influences of hedgerow intersections and gaps on the movement of carabid beetles. *Bulletin of Entomological Research* **89**, 523-531.

KAJAK A & LUKASIEWICZ J (1994) Do semi-natural patches enrich crop fields with predatory epigean arthropods. *Agriculture Ecosystems and Environment* **49**, 149-161.

KAREIVA P (1990) Population dynamics in spatially complex environments: theory and data. *Philosophical Transactions of the Royal Society of London* **330**, 175-190.

KELLS AR, HOLLAND JM & GOULSON D (2001) The value of uncropped field margins for foraging bumblebees. *Journal of Insect Conservation* **5**, 283-291.

KEMP JC & BARRETT GW (1989) Spatial patterning: impact of uncultivated corridors on arthropod populations within soybean agroecosystems. *Ecology* **70**, 114-128.

KEINEGGER M & KROMP B (2001) The effect of strips of flowers on selected groups of beneficial insects in adjacent broccoli plots. *Mitteilungen der Deutschen Gesellschaft für Allgemeine und Angewandte Entomologie* **13**, 583-586.

KISS J, KÁDÁR F, KOZMA E & TÓTH I (1993) Importance of various habitats in agricultural landscape related to integrated pest management: a preliminary study. *Landscape and Urban Planning* **27**,191-198.

KLIMES LSE & SECHTEROVA E (1989) Epigaeic arthropods across an arable land and grassland interface. *Acta Entomologica Bohemoslovica* **86**, 459-475.

KLINGER K (1987) Auswirkungen eingesäter Randstreifen an einem Winterweizen-Feld auf die Raubarthropodenfauna und den Getreideblattlausbefall. *Journal of Applied Entomology* **104**, 47-58.

KOLLMANN J & BASSIN S (2001) Effects of management on seed predation in wildflower strips in northern Switzerland. *Agriculture, Ecosystems and Environment* **83**, 285-296.

KREBS JR, WILSON JD, BRADBURY RB & SIRIWARDENA GM (1999) The second silent spring ? *Nature* **400**, 611-612.

KROMP B (1999) Carabid beetles in sustainable agriculture: a review on pest control efficacy, cultivation impacts and enhancement. *Agriculture, Ecosystems and Environment* **74**, 187-228.

KROMP B & STEINBERGER KH (1992) Grassy field margins and arthropod diversity: a case study on ground beetles and spiders in eastern Austria (Coleoptera: Carabidae; Arachnida: Aranei, Opiliones*). Agriculture, Ecosystems and Environment* **40**, 71-93.

KROMP B & NITZLADER M (1995) Dispersal of ground beetles in a rye field in Vienna, Eastern Austria. *Acta Jutlandica* **70**, 269-277.

LAGERLÖF J & WALLIN H (1993) The abundance of arthropods along two field margins with different types of vegetation composition: an experimental study. *Agriculture Ecosystems and Environment* **43**,141-154.

LAGERLÖF J, STARK J & SVENSSON B (1992) Margins of agricultural fields as habitats for pollinating insects. *Agriculture Ecosystems and Environment* **40**, 117-124.

LANDIS DA, WRATTEN SD & GURR GM (2000) Habitat management to conserve natural enemies of arthropod pests in agriculture. *Annual Review of Entomology* **45**, 173-199.

LARINK O (1997) Springtails and mites: important knots in the food web of soils. In: *Fauna in Soil Ecosystems* (ed. G Benckiser), 225-264. Marcel Dekker, New York, USA.

LEAKE AR (2002) Biodiversity in different farming systems. *The BCPC Conference – Pests & Diseases 2002*, British Crop Protection Council, Farnham, Surrey, UK, **2**, 949-956.

LEE HC (1997) Organic and inorganic aspects of fertliser use strategies in cereals. *Aspects of Applied Biology* **50**, 95-101.

LEE JC, MENALLED FD & LANDIS DA (2001) Refuge habitats modify impact of insecticide disturbance on carabid beetle communities. *Journal of Applied Ecology* **38**, 472-483.

LEMKE A & POEHLING HM (1998) Effects of sown weed strips in cereal fields on the abundance of spiders (Arachnida: Araneae) and cereal aphids (Homoptera: Aphididae). *Bulletin IOBC/WPRS* **21(8)**, 29-37.

LEMKE A & POEHLING HM (2002) Sown weed strips in cereal fields: overwintering site and "source" habitat for *Oedothorax apicatus* (Blackwall) and *Erigone atra* (Blackwall) (Araneae: Erigonidae). *Agriculture, Ecosystems and Environment* **90**, 67-80.

LETHMAYER C (2000) Herbivore – Förderung von Schädlingen. *Agrarökologie* **37**, 127-135.

LETHMAYER C, NENTWIG W & FRANK T (1997) Effects of weed strips on the occurrence of noxious coleopteran species (Nitidulidae, Chrysomelidae, Curculionidae). *Zeitschrift fur Pflanzenkrankheiten und Pflanzenschutz* **104**, 75-92.

LEUIS K (1967) Influence of wild flowers on parasitism of Tent Caterpillar and Codling Moth. *Canadian Entomologist* **99** 444-446.

LIANG W & HUANG M (1994) Influence of citrus orchard ground cover plants on arthropod communities in China: a review. *Agriculture, Ecosystems and Environment* **50**, 29-37.

LIEBMAN M, MOHLER CL & STAVER CP (2001*) Ecological Management of Agricultural Weeds*, Cambridge University Press, Cambridge, UK.

LONGLEY M & SOTHERTON NW (1997) Factors determining the effects of pesticides upon butterflies inhabiting arable farmland. *Agriculture Ecosystems and Environment* **61**, 1-12.

LONGLEY M, CILGI T, JEPSON PC & SOTHERTON NW (1997) Measurements of pesticide spray drift deposition into field boundaries and hedgerows. I. Summer applications. *Environmental Toxicology and Chemistry* **16**, 165-172.

LOOTSMA M & SCHOLTE K (1997) Effect of soil moisture content on the suppression of *Rhizoctonia* stem canker of potato by the nematode *Aphelenchus avenae* and the springtail *Folsomia fimetaria. Plant Pathology* **46**, 209-215.

LOOTSMA M & SCHOLTE K (1998) Effect of soil pH and amendments with dried fodder rape on mycophagous soil animals and *Rhizoctonia* stem canker of potato. *Pedobiologia* **42**, 215-222.

LOREAU M (2000) Biodiversity and ecosystem functioning: recent theoretical advances. *Oikos* **91**, 3-17.

LOSEY JE & DENNO RF (1999) Factors facilitating synergistic predation: the central role of synchrony. *Ecological Applications* **9**, 378-386.

LÖVEI GL & BYCROFT B (1992) The effect of mulch on the incidence of insect pests, natural enemies and plant damage in organically grown cauliflowers. *Proceedings of the 45th New Zealand Plant Protection Conference 1992*, 62-63.

LÖVEI GL & SUNDERLAND KD (1996) Ecology and behaviour of ground beetles (Coleoptera: Carabidae). *Annual Review of Entomology* **41**, 231-256.

LÖVEI GL, MACLEOD A & HICKMAN JM (1998) Dispersal and effects of barriers on the movement of the New Zealand hover fly *Melanostoma fasciatum* (Dipt., Syrphidae) on cultivated land. *Journal of Applied Entomology* **122**, 115-120.

LÖVEI GL, HODGSON DJ, MACLEOD A & WRATTEN SD (1993a) Attractiveness of some novel crops for flower-visiting hoverflies (Diptera: Syrphidae) comparisons from two continents. In: *Pest Control and Sustainable Agriculture* (eds S Corey, D Dall, & W Milne), 368-370. CSIRO, Canberra, Australia.

LÖVEI GL, HICKMAN JM, MCDOUGALL D & WRATTEN SD (1993b) Field penetration of beneficial insects from habitat islands: hoverfly dispersal from flowering crop strips. *Proceedings of the 46th New Zealand Plant Protection Conference*, 325-328.

LÖVEI GL, MCDOUGALL D, BRAMLEY G, HODGSON DJ & WRATTEN SD (1992) Floral resources for natural enemies: the effect of *Phacelia tanacetifolia* (Hydrophyllaceae) on within-field distribution of hoverflies (Diptera: Syrphidae). *Proceedings of the 45th New Zealand Plant Protection Conference*, 60-61.

LÜBBEN B (1989) Influence of sewage sludge and heavy metals on the abundance of Collembola on two agricultural soils. In*: Third International Seminar on Apterygota, Siena, Italy* (ed. R Dallai), 419-429.

LUCZAK J (1995) Plant-dwelling spiders of the ecotone between forest islands and surrounding crop fields in an agricultural landscape of the Masurian Lakeland. *Ekologia Polska* **43**, 79-102.

LUFF ML (1980) The biology of the ground beetle *Harpalus rufipes* in a strawberry field in Northumberland. *Annals of Applied Biology* **94**, 153-164.

LUND RD & TURPIN FT (1977) Carabid damage to weed seeds found in Indiana cornfields. *Environmental Entomology* **6**, 695-698.

LYS JA (1994) The positive influence of strip-management on ground beetles in a cereal field: increase, migration and overwintering. In: *Carabid Beetles: Ecology and Evolution* (eds K Desender, M Dufrene, M Loreau, ML Luff & JP Maelfait), 451-455. Kluwer Aademic Publishers, Dordrecht, The Netherlands.

LYS JA & NENTWIG W (1991) Surface activity of carabid beetles inhabiting cereal fields. *Pedobiologia* **35**,129-138.

LYS JA & NENTWIG W (1992) Augmentation of beneficial arthropods by strip-management. 4. Surface activity movements and activity density of abundant carabid beetles in a cereal field. *Oecologia* **92**, 373-382.

LYS JA & NENTWIG W (1994) Improvement of the overwintering sites for Carabidae, Staphylinidae and Araneae by strip-management in a cereal field. *Pedobiologia* **38**, 238-242.

LYS JA, ZIMMERMANN M & NENTWIG W (1994) Increase in activity density and species number of carabid beetles in cereals as a result of strip-management. *Entomologia Experimentalis et Applicata* **73**, 1-9

MACLEOD A (1999) Attraction and retention of *Episyrphus balteatus* DeGeer (Diptera: Syrphidae) at an arable field margin with rich and poor floral resources. *Agriculture, Ecosystems and Environment* **73**, 237-244.

MAELFAIT JP & DE KEER R (1990) The border zone of an intensively grazed pasture as a corridor for spiders (Araneae). *Biological Conservation* **54**, 223-238.

MADER HJ, SCHELL C & KORNACKER P (1990) Linear barriers to arthropod movements in the landscape. *Biological Conservation* **54**, 209-222.

MAFF (1998) *The countryside stewardship scheme*. MAFF Publications, London, UK.

MAFF (1999) *Arable stewardship*. MAFF Publications, London, UK.

MARINO PC & LANDIS DA (1996) Effect of landscape structure on parasitoid diversity and parasitism in agroecosystems. *Ecological Applications* **6**, 276-284.

MARINO PC, GROSS KL & LANDIS DA (1997) Weed seed loss due to predation in Michigan maize fields. *Agriculture, Ecosystems and Environment* **66**, 189-196.

MARSHALL EJP, BROWN VK, BOATMAN ND, LUTMAN PJW, SQUIRE GR & WARD LK (2003) The role of weeds in supporting biological diversity within crop fields. *Weed Research* **43**, 77-89.

MARSHALL EJP & MOONEN AC (2002) Field margins in northern Europe: their functions and interactions with agriculture. *Agriculture Ecosystems and Environment* **89**, 5-21.

MARSHALL J, BAUDRY J, BUREL F, JOENJE W, GEROWITT B, PAOLETTI M, THOMAS G, KLEIJN D, LE COEUR D & MOONEN C (2002) Field boundary habitats for wildlife, crop, and environmental protection. In: *Landscape Ecology in Agroecosystems Management* (ed. L Ryszkowski), 219-246. CRC Press, Boca Raton, USA.

MATTHEWS-GEHRINGER D & HOUGH-GOLDSTEIN J (1988) Physical barriers and cultural practices in cabbage maggot (Diptera: Anthomyiidae) management on broccoli and chinese cabbage. *Journal of Economic Entomology* **81**, 354-360.

MAUREMOOTOO JR, WRATTEN SD, WORNER SP & FRY GLA (1995) Permeability of hedgerows to predatory carabid beetles. *Agriculture Ecosystems and Environment* **52**, 141-148.

MCLACHLAN ARG & WRATTEN SD (2003) Abundance and species richness of field-margin and pasture spiders (Araneae) in Canterbury, New Zealand. *New Zealand Journal of Zoology* **30**, 57-67.

MCLAUGHLIN A & MINEAU P (1995) The impact of agricultural practices on biodiversity. *Agriculture, Ecosystems and Environment* **55**, 201-212.

MCNABB DM, HALAJ J & WISE DH (2001) Inferring trophic positions of generalist predators and their linkage to the detrital food web in agroecosystems: a stable isotope analysis. *Pedobiologia* **45**, 289-297.

MENALLED FD, LEE JC & LANDIS DA (2001) Herbaceous filter strips in agroecosystems: Implications for ground beetle (Coleoptera: Carabidae) conservation and invertebrate weed seed predation. *Great Lakes Entomologist* **34**, 77-91.

MENALLED FD, MARINO PC, GAGE SH & LANDIS DA (1999) Does agricultural landscape structure affect parasitism and parasitoid diversity ? *Ecological Applications* **9**, 634-641.

MENALLED FD, MARINO PC, RENNER KA & LANDIS DA (2000) Post-dispersal weed seed predation in Michigan crop fields as a function of agricultural landscape structure. *Agriculture Ecoststems and Environment* **77**, 193-202.

MENSAH RK (1999) Habitat diversity: implications for the conservation and use of predatory insects of *Helicoverpa* spp. in cotton systems in Australia. *International Journal of Pest Management* **45**, 91-100.

MILLER NJ, KIFT NB, REYNOLDS KA, GREATOREX EC, LYNN J & TATCHELL GM (2003) Genetic diversity and rate of increase in the cabbage aphid, *Brevicoryne brassicae* (L.): No evidence for specialised host races. *Bulletin of Entomological Research*, under revision.

MINARRO M & DAPENA E (2003) Effects of groundcover management on ground beetles (Coleoptera: Carabidae) in an apple orchard. *Applied Soil Ecology* **23**, 111-117.

MONSRUD C & TOFT S (1999) The aggregative numerical response of polyphagous predators to aphids in cereal fields: attraction to what *? Annals of Applied Biology* **134**, 265-270.

MOREBY SJ (1997) The effects of herbicide use within cereal headlands on the availability of food for arable birds. *The BCPC Conference – Weeds 1997*, British Crop Protection Council, Farnham, Surrey, UK, 1197-1202.

MOREBY SJ & SOUTHWAY SE (1999) Influence of autumn applied herbicides on summer and autumn food available to birds in winter wheat fields in southern England. *Agriculture, Ecosystems and Environment* **72**, 285-297.

MOREBY SJ, SOUTHWAY S & BOATMAN ND (1999) The importance of the crop edge compared to the mid-field, in providing invertebrate food for farmland birds. *Aspects of Applied Biology* **54**, 217-222.

MORRIS AJ, BRADBURY RB & WILSON JD (2002) Indirect effects of pesticides on breeding yellowhammers *Emberiza citrinella*. *The BCPC Conference – Pests & Diseases 2002*, British Crop Protection Council, Farnham, Surrey, UK, **2**, 965-970.

MUEHLCHEN AM, RAND RE & PARKE JL (1990) Evaluation of crucifer green manures for controlling *Aphanomyces* root rot of peas. *Plant Disease* **74**, 651-654.

MURPHY DD (1983) Nectar sources as constraints on the distribution of egg masses by the checkerspot butterfly *Euphydryas chalcedona* (Lepidoptera: Nymphalidae). *Environmental Entomology* **12**, 463-466.

MURPHY DD, LAUNER AE & EHRLICH PR (1983) The role of adult feeding in egg production and population dynamics of the checkerspot butterfly *Euphydryas editha*. *Oecologia* **56**, 257-263.

MURRAY KA, WILCOX A & STOATE C (2002) A simultaneous assessment of farmland habitat use by breeding skylarks and yellowhammers. *Aspects of Applied Biology* **67**, 121-127.

NAKAMURA Y (1975) Decomposition of organic materials and soil fauna in pasture. 3. Disappearance of cow dung and the associated macrofaunal succession. *Pedobiologia* **15**, 210-221.

NAKAMURA Y (1976) Decomposition of organic materials and soil fauna in pasture. 4. Disappearance of cow dung and succession of the associated soil micro-arthropods. *Pedobiologia* **16**, 243-257.

NAKANO S & MUAKAMI M (2001) Reciprocal subsidies: dynamic interdependence between terrestrial and aquatic food webs. *Proceedings of the National Academy of Sciences, USA* **98**, 166-170.

NAKANO S, MIYASAKA H & KUHARA M (1999) Terrestrial-aquatic linkages: riparian arthropod inputs alter trophic cascades in a stream food web. *Ecology* **80**, 2435-2441.

NENTWIG W (1989) Augmentation of beneficial arthropods by strip-management. II. Successional strips in a winter wheat field. *Journal of Plant Disease Protection* **96**, 89-99.

NENTWIG W, FRANK T & LETHMAYER C (1998) Sown weed strips: artificial ecological compensation areas as an important tool in conservation biological control. In: *Conservation Biological Control* (ed, P Barbosa), 133-153. Academic Press, San Diego, USA.

NENTWIG W (1998) Weedy plant species and their beneficial arthropods: potential for manipulation in field crops. In: *Enhancing Biological Control* (eds CH Pickett & RL Bugg), 49-71. University of California Press, Berkeley, California, USA.

NIELSEN SA & TOFT S (2000) Responses of a detoxification enzyme to diet quality in the wolf spider, *Pardosa prativaga*. *Proceedings of the 19th European Colloquium of Arachnology*, 65-70. Aarhus University Press, Aarhus, Denmark.

NOBLE R, WHIPPS JM & COVENTRY E (2000) An alternative to landfill: composting onion and other vegetable wastes to control pests and diseases and avoid pollution. In: *Waste*

2000 (ed. C McLardy), 355-360. The Waste Conference Ltd., University of Warwick Science Park, Coventry, UK.

NYFFELER M & BENZ G (1980) The role of spiders as insect predators in cereal fields near Zürich (Switzerland). *Proceedings of the 8th International Arachnological Congress*, Vienna, pp. 127-131.

NYFFELER M & BREENE RG (1992) Dominant insectivorous polyphagous predators in winter wheat: high colonization power, spatial dispersion patterns and probable importance of the soil surface spiders. *Dtsch Ent Z NF* **39**,177-188.

OKA IN & PIMENTEL D (1976) Herbicide (2,4-D) increases insect and pathogen pests on corn. *Science* **193**, 239-240.

OSBORNE JL & WILLIAMS IH (1996) Bumblebees as pollinators of crops and wild-flowers. In: *Bumblebees for pleasure and profit* (ed. A Matheson), 24-32. IBRA, Cardiff, UK.

OSBORNE J, WILLIAMS I & CORBET SA (1991) Bees, pollination and habitat change in the European Community. *Bee World* **72**, 99-116.

ÖSTMAN Ö, EKBOM B & BENGTSSON J (2001a) Landscape heterogeneity and farming practice influence biological control. *Basic and Applied Ecology* **2**, 365-371.

ÖSTMAN Ö, EKBOM B, BENGTSSON J & WEIBULL AC (2001b) Landscape complexity and farming practice influence the condition of polyphagous carabid beetles. *Ecological Applications* **11**, 480-488.

OUYANG Y, GRAFTON CARDWELL EE & BUGG RL (1992) Effects of various pollens on development, survivorship, and reproduction of *Euseius tularensis* (Acari, Phytoseiidae). *Environmental Entomology* **21**, 1371-1376.

OZORES-HAMPTON M, OBREZA TA & STOFFELLA PJ (2001) Weed control in vegetable crops with composted organic mulches. In: *Compost Utilization in Horticultural Cropping Systems* (ed. PJ Stoffella & BA Kahn), 275-286. Lewis Publishers, Boca Raton, USA.

PAOLETTI MG (2001) Biodiversity in agroecosystems and bioindicators of environmental health. In: *Structure and Function in Agroecosystems Design and Management – Advances in Agroecology* (eds M Shiyomi & H Koizumi), 11-44. CRC Press, Boca Raton, Florida, USA.

PARKER WE (2002) What impact is ICM having on pest and disease management in field vegetables ? *The BCPC Conference – Pests & Diseases 2002*, British Crop Protection Council, Farnham, Surrey, UK, **2**, 463-470.

PERRIN RM (1975) The role of the perennial stinging nettle *Urtica dioica* as a reservoir of beneficial natural enemies. *Annals of Applied Biology* **81**, 289-297.

PETERSEN MK, EKBOM B & RAVN HP (1996) Temperature dependent winter survival of *Bembidion lampros* and *Tachyporus hypnorum. Journal of Insect Physiology* **42**, 997-1005.

PIETRASZKO R & DE CLERCQ R (1982) Influence of organic matter on epigeic arthropods. *Mededelingen van de Fakulteit Landbouwwetenschappen Rijksuniversiteit Gent* **47/2,** 721-728.

PFIFFNER L & LUKA H (2000) Overwintering of arthropods in soils of arable fields and adjacent semi-natural habitats. *Agriculture, Ecosystems and Environment* **78**, 215-222.

PFIFFNER L & LUKA H (2003) Effects of low-input farming systems on carabids and epigeal spiders – a paired farm approach. *Basic and Applied Ecology* **4**, 117-127.

PIMENTEL D & WARNEKE A (1989) Ecological effects of manure, sewage sludge, and other organic wastes on arthropod populations. *Agricultural Zoology Reviews* **3**, 1-30.

PINAMONTI F & SICHER L (2001) Compost utilization in fruit production systems. In: *Compost Utilization in Horticultural Cropping Systems* (ed. PJ Stoffella & BA Kahn), 177-200. Lewis Publishers, Boca Raton, USA.

POLIS GA, HURD SD (1995) Extraordinary high spider densities on islands: flow of energy from the marine to terrestrial food webs and the absence of predation. *Proceedings of the National Academy of Sciences, USA* **92**, 4382-4386.

POLIS GA, HURD SD (1996) Allochthonous input across habitats, subsidized consumers, and apparent trophic cascades: examples from the ocean-land interface. In: *Food Webs: Integration of Patterns and Dynamics* (eds GA Polis & KO Winemiller), 275-285. Chapman & Hall, London, UK.

POLIS GA, ANDERSON WB & HOLT RD (1997) Toward an integration of landscape and food web ecology: the dynamics of spatially subsidized food webs. *Annual Review of Ecology and Systematics* **28**, 289-316.

POLIS GA, HOLT RD, MENGE BA & WINEMILLER KO (1996) Time, space and life history: influences on food webs. In: *Food Webs: Integration of Patterns and Dynamics* (eds GA Polis & KO Winemiller), 435-460. Chapman & Hall, London, UK.

POLLARD E (1968) Hedges III. The effect of removal of the bottom flora of a hawthorn hedgerow on the Carabidae of the hedge bottom. *Journal of Applied Ecology* **5**, 125-139.

POTTER A & COLVIN J (2000) Waste producers: forces for change. In: *Waste 2000* (ed. C McLardy), 443-452. The Waste Conference Ltd., University of Warwick Science Park, Coventry, UK.

POTTS, G.R. (1986) *The Partridge: Pesticides, Predation and Conservation*. Collins, London, UK.

POVEY FD, SMITH H & WATT TA (1993) Predation of annual grass weed seeds in arable field margins. *Annals of Applied Biology* **122**, 323-328.

POWELL W (1986) Enhancing parasite activity in crops. In: *Insect Parasitoids* (eds J Waage & D Greathead), 319-340. Academic Press, London, UK.

POWELL W, BARDNER R & BATER J (1983) Encouragement of aphid predators. *Report of Rothamsted Experimental Station, UK, for1983*, 94.

POWELL W, DEAN GJ & DEWAR A (1985) The influence of weeds on polyphagous arthropod predators in winter wheat. *Crop Protection* **5**, 182-189.

POWELL W, DEAN GJ & WILDING N (1986) The influence of weeds on aphid-specific natural enemies in winter wheat. *Crop Protection* **4**, 298-312.

PURVIS G & CURRY JP (1984) The influence of weeds and farmyard manure on the activity of Carabidae and other ground-dwelling arthropods in a sugar beet crop. *Journal of Applied Ecology* **21**, 271-283.

RAATIKAINEN M & HUHTA V (1968) On the spider fauna of Finnish oat fields. *Annales Zoologici Fennici* **5**, 254-261

RADWAN Z & LÖVEI GL (1982) Distribution and bionomics of ladybird beetles (Col., Coccinellidae) living in an apple orchard near Budapest, Hungary. *Zeitschrift für angewandte Entomologie* **94**, 169-175.

RÄMERT B (1996) The influence of intercropping and mulches on the occurrence of polyphagous predators in carrot fields in relation to carrot fly (*Psila rosae* (F.)) (Dipt., Psilidae) damage. *Journal of Applied Entomology* **120**, 39-46.

RANDS MRW (1985) Pesticide use on cereals and the survival of grey partridge chicks: a field experiment. *Journal of Applied Ecology* **22**, 49-54.

RASKIN R (1993) Der Einfluss des Ackerrandstreifenprogramms auf die Entwicklung der Syrphiden- und Carabiden-Fauna auf Agrarflächen. *Mitteilungen der Deutschen Gesellschaft für allgemeine und angewandte Entomologie* **8**, 391-396.

REDDERSEN J (1995) Feeding biology of fungivorous insects from Danish cereal fields. *Pedobiologia* **39**, 370-384

RIECHERT SE (1998) The role of spiders and their conservation in the agroecosystem. In: *Enhancing Biological Control* (eds CH Pickett & RL Bugg), 211-237. University of California Press, Berkeley, California, USA.

RIECHERT SE & BISHOP L (1990) Pest control by an assemblage of generalist predators: Spiders in garden test systems. *Ecology* **71**, 1441-1450.

RIEDEL W (1991) Overwintering and spring dispersal of *Bembidion lampros* (Coleoptera:Carabidae) from established hibernation sites in a winter wheat field in Denmark. In: *Behaviour and Impact of Aphidophaga* (eds L Polgár, RJ Chambers, AFG Dixon & I Hodek), 235-241. SPB Academic Publishing, The Hague, The Netherlands.

RIEDEL W (1995) Spatial distribution of hibernating polyphagous predators within field boundaries. *Acta Jutlandica* **70**, 221-226.

RIEDEL W & STEENBERG T (1998) Adult polyphagous coleopterans overwintering in cereal boundaries: winter mortality and susceptibility to the entomopathogenic fungus *Beauveria bassiana*. *BioControl* **43**,175-188.

RIEUX R, SIMON S & DEFRANCE H (1999) Role of hedgerows and ground cover management on arthropod populations in pear orchards. *Agriculture, Ecosystems and Environment* **73**, 119-127.

ROBINSON RA & SUTHERLAND WJ (2002) Post-war changes in arable farming and biodiversity in Great Britain. *Journal of Applied Ecology* **39**, 157-176.

RODENHOUSE NL, BARRETT GW, ZIMMERMAN DM & KEMP JC (1992) Effects of uncultivated corridors on arthropod abundances and crop yields in soybean agroecosystems.*Agriculture Ecosystems and Environment* **38**,179-191.

ROE NE (2001) Compost effects on crop growth and yield in commercial vegetable cropping systems. In: *Compost Utilization in Horticultural Cropping Systems* (ed. PJ Stoffella & BA Kahn), 123-134. Lewis Publishers, Boca Raton, USA.

RYPSTRA AL, CARTER PE, BALFOUR RA & MARSHALL SD (1999) Architectural features of agricultural habitats and their impact on the spider inhabitants. *Journal of Arachnology* **27**, 371-377.

SALVETER R (1998) The influence of sown herb strips and spontaneous weeds on the larval stages of aphidophagous hoverflies (Dipt., Syrphidae). *Journal of Applied Entomology* **122**, 103-114.

SAMU F, MATTHEWS GA, LAKE D & VOLLRATH F (1992) Spider webs are efficient collectors of agrochemical spray. *Pesticide Science* **36**, 47-53.

SCHNEIDER F (1969) Bionomics and physiology of aphidophagous Syrphidae. *Annual Review of Entomology* **14**, 103-124.

SCHNEIDER-ORELLI O (1945) Bienenweide und Schädlingsbekämpfung. *Schweiz. Bienenztg*. **9**, 423-429.

SCHOLTE K & LOOTSMA M (1998) Effect of farmyard manure and green manure crops on populations of mycophagous soil fauna and Rhizoctonia stem canker of potato. *Pedobiologia* **42**, 223-231.

SENGONCA C, KRANZ J & BLAESER P (2002) Attractiveness of three weed species to polyphagous predators and their influence on aphid populations in adjacent lettuce cultivations. *Journal of Pest Science* **75**, 161-165.

SETTLE WH, ARIAWAN H, ASTUTI ET, CAHYANA W, HAKIM AL, HINDAYANA D, LESTARI AS, PAJARNINGSIH & SARTANTO (1996) Managing tropical rice pests through conservation of generalist natural enemies and alternative prey. *Ecology* **77**, 1975-1988.

SIGSGAARD L (2000) Early season natural biological control of insect pests in rice by spiders – and some factors in the management of the cropping system that may affect this control.

Proceedings of the 19th European Colloquium of Arachnology, 57-64. Aarhus University Press, Aarhus, Denmark.
SIKORA LJ & SZMIDT RAK (2001) Nitrogen sources, mineralization rates, and nitrogen nutrition benefits to plants from composts. In: *Compost Utilization in Horticultural Cropping Systems* (ed. PJ Stoffella & BA Kahn), 287-305. Lewis Publishers, Boca Raton, USA.
SIRIWARDENA GM, BAILLIE SR, BUCKLAND ST, FEWSTER RM, MARCHANT JH & WILSON JD (1998) Trends in the abundance of farmland birds: a quantitative comparison of smoothed bird census indices. *Journal of Applied Ecology* **35**, 24-43.

SLATER RA, FREDERICKSON J & GILBERT EJ (2001) *The State of Composting 1999*. The Composting Association, Wellingborough, UK.

SMART, LE, STEVENSON JH & WALTERS JHH (1989) Development of field trial methodology to assess short-term effects of pesticides on beneficial arthropods in arable crops. *Crop Protection* **8**, 169-180.

SMITH D & PAPACEK DF (1991) Stidies of the predatory mite *Amblyseius victoriensis* (Acarina: Phytoseiidae) in citrus orchards in south-east Queensland: control of *Tegolophus australis* and *Phylocoptruta oleivora* (Acarina: Eriophyidae), effects of pesticides, alternative host plants and augmentative release. *Experimental and Applied Acarology* **12**, 195-217.

SMITH H, FIRBANK LG & MACDONALD DW (1999) Uncropped edges of arable fields managed for biodiversity do not increase weed occurrence in adjacent crops. *Biological Conservation* **89**, 107-111.

SNYDER WE & WISE DH (1999) Predator interference and the establishment of generalist predator populations for biocontrol. *Biological Control* **15**, 283-292.

SNYDER WE & WISE DH (2001) Contrasting trophic cascades generated by a community of generalist predators. *Ecology* **82**, 1571-1583.
SOLOMON M, FITZGERALD J & JOLLY R (1999) Artificial refuges and flowering plants to enhance predator populations in orchards. *Bulletin IOBC/WPRS* **22(7)**, 31-37.
SOTHERTON NW (1984) The distribution and abundance of predatory arthropods overwintering on farmland. *Annals of Applied Biology* **105**, 423-429.
SOTHERTON NW (1995) Beetle banks – helping nature to control pests. *Pesticide Outlook* **6**, 13-17.
SOTHERTON NW (1985) The distribution and abundance of predatory arthropods overwintering in field boundaries. *Annals of Applied Biology* **106**,17-21.
SPEIGHT MR (1983) The potential of ecosystem management for pest control. *Agriculture, Ecosystems and Environment* **10**, 183-199.
SPEIGHT MR & LAWTON JH (1976) The influence of weed-cover on the mortality imposed on artificial prey by predatory ground beetles in cereal fields. *Oecologia* **23**, 211-223.
SPILLETT SM (2000) IPPC – thoroughly modern regulation. In: *Waste 2000* (ed. C McLardy), 3-8. The Waste Conference Ltd., University of Warwick Science Park, Coventry, UK.
STEFFAN-DEWENTER I, MÜNZENBERG U & TSCHARNTKE T (2001) Pollination, seed set and seed predation on a landscape scale. *Proceedings of the Royal Society of London B* **268**, 1685-1690.
STEPHENS MJ, FRANCE CM, WRATTEN SD & FRAMPTON C (1998) Enhancing biological control of leafrollers (Lepidoptera: Tortricidae) by sowing buckwheat (*Fagopyrum esculentum*) in an orchard. *Biocontrol Science and Technology* **8**, 547-558.

STOATE C (2002) Increasing the Government's Farmland Bird Index through conservation management at the farm scale: a ten-year demonstration. *The BCPC Conference – Pests & Diseases 2002*, British Crop Protection Council, Farnham, Surrey, UK, **2**, 971-976.

STOATE C, MOREBY SJ & SZCZUR J (1998) Breeding ecology of farmland yellowhammers *Emberiza citrinella. Bird Study* **45**, 109-121.

STRONG DR, MORIN JL & CONNORS PG (1996) Top down from underground ? The under-appreciated influence of subterranean food webs on aboveground ecology. In: *Food Webs: Integration of Patterns and Dynamics* (eds GA Polis & KO Winemiller), 170-178. Chapman & Hall, London, UK.

SUNDERLAND KD (1987) Spiders and cereal aphids in Europe. *Bulletin SROP/WPRS* **1987/X/I**, 82-102.

SUNDERLAND KD (1991) The ecology of spiders in cereals. *Proceedings of the 6th International Symposium on Pests and Diseases of Small Grain Cereals*. Board of Plant Protection Halle, Halle/Saale, Germany, **1**, 269-280.

SUNDERLAND KD (1992) Effects of pesticides on the population ecology of polyphagous predators. *Aspects of Applied Biology* **31**, 19-28.

SUNDERLAND KD & SAMU F (2000) Effects of agricultural diversification on the abundance, distribution, and pest control potential of spiders: a review. *Entomologia Experimentalis et Applicata* **95**, 1-13.

SUNDERLAND KD, DESNOO GR, DINTER A, HANCE T, HELENIUS J, JEPSON P, KROMP B, LYS JA, SAMU F, SOTHERTON NW, TOFT S & ULBER B (1995) Density estimation for invertebrate predators in agroecosystems. *Acta Jutlandica* **70**, 133-162.

SUTTLE KB (2003) Pollinators as mediators of top-down effects on plants. *Ecology Letters* **6**, 688-694.

TAMAKI G & HALFHILL JE (1968) Bands on peach trees as shelters for predators of the green peach aphid. *Journal of Economic Entomology* **61**, 707-711.

TEW TE, TODD IA & MACDONALD DW (1994) Field margins and small mammals. In: *Field margins: integrating agriculture and conservation* (ed. ND Boatman), 85-94. BCPC Monograph **58**, British Crop Protection Council, Farnham, Surrey, UK.

THIES C & TSCHARNTKE T (1999) Landscape structure and biological control in agroecosystems. *Science* **285**, 893-895.

THOMAS CFG (1996) Modelling aerial dispersal of linyphiid spiders. *Aspects of Applied Biology* **46**, 217-222.

THOMAS CFG & MARSHALL EJP (1999) Arthropod abundance and diversity in differently vegetated margins of arable fields. *Agriculture Ecosystems and Environment* **72**,131-144.

THOMAS CFG, GREEN F & MARSHALL EJP (1997) Distribution, dispersal and population size of the ground beetles, *Pterostichus melanarius* (Illiger) and *Harpalus rufipes* (Degeer) (Coleoptera, Carabidae), in field margin habitats. *Entomological Research in Organic Agriculture* **15**, 337-352.

THOMAS CFG, HOL EHA & EVERTS JW (1990) Modelling the diffusion component of dispersal during recovery of a population of linyphiid spiders from exposure to an insecticide. *Functional Ecology* **4**, 357-368.

THOMAS CFG, PARKINSON L & MARSHALL EJP (1998) Isolating the components of activity-density for the carabid beetle *Pterostichus melanarius* in farmland. *Oecologia* **116**, 103-112.

THOMAS CFG, HOLLAND JM & BROWN NJ (2002) The spatial distribution of carabid beetles in agricultural landscapes. In: *The Agroecology of Carabid Beetles* (ed. JM Holland), 305-344. Intercept, Andover, UK.

THOMAS CFG, COOKE H, BAULY J & MARSHALL EJP (1994) Invertebrate colonisation of overwintering sites in different field boundary habitats. *Aspects of Applied Biology* **40**, 229-232.

THOMAS CFG, PARKINSON L, GRIFFITHS GJK, FERNANDEZ GARCIA A & MARSHALL EJP (2001) Aggregation and temporal stability of carabid beetle distributions in field and hedgerow habitats. *Journal of Applied Ecology* **38**, 100-116.

THOMAS CFG, BRAIN P & JEPSON PC (2003) Aerial activity of linyphiid spiders: modelling dispersal distances from meteorology and behaviour. *Journal of Applied Ecology* **40**, in press.

THOMAS JA (1995) The conservation of declining butterfly populations in Britain and Europe: priorities, problems and successes. *Biological Journal of the Linnaean Society* **56**, 55-72.

THOMAS MB, WRATTEN SD & SOTHERTON NW (1991) Creation of "Island" habitats in farmland to manipulate populations of beneficial arthropods: predator densities and emigration. *Journal of Applied Ecology* **28**, 906-917.

THOMAS MB,WRATTEN SD & SOTHERTON NW (1992a) Creation of "Island" habitats in farmland to manipulate populations of beneficial arthropods: predator densities and species composition. *Journal of Applied Ecology* **29**, 524-531.

THOMAS MB, MITCHELL HJ & WRATTEN SD (1992b) Abiotic and biotic factors influencing the winter distribution of predatory insects. *Oecologia* **89**, 78-84.

Thomas SR, Goulson D & Holland JM (2000) Spatial and temporal distributions of predatory Carabidae in a winter wheat field. *Aspects of Applied Biology* **62**, 55-60.

THOMAS SR, NOORDHUIS R, HOLLAND JM & GOULSON D (2002) Botanical diversity of beetle banks: effects of age and comparison with conventional arable field margins in southern UK. *Agriculture, Ecosystems and Environment* **93**, 403-412.

THORUP-KRISTENSEN K (1994) Effect of nitrogen catch crop species on the nitrogen nutrition of succeeding crops. *Fertilizer Research* **37**, 227-234.

THORUP-KRISTENSEN K & NIELSEN NE (1998) Modelling and measuring the effect of nitrogen catch crops on nitrogen supply for succeeding crops. *Plant and Soil* **203**, 79-89.

TOFT S (1995a) Two functions of gossamer dispersal in spiders ? *Acta Jutlandica* **70**, 257-268.

TOFT S (1995b) Value of the aphid *Rhopalosiphum padi* as food for cereal spiders. *Journal of Applied Ecology* **32**, 552-560.

TOFT S (1996) Indicators of prey quality for arthropod predators. *Acta Jutlandica* **71**, 107-116.

TOFT S (1997) Acquired food aversion of a wolf spider to three cereal aphids: intra- and interspecific effects. *Entomophaga* **42**, 63-69.

TOFT S & LÖVEI GL (2000) The epigeic spider fauna of single-row hedges in a Danish agricultural landscape. *Proceedings of the 19th European Colloquium of Arachnology*, 237-242. Aarhus University Press, Aarhus, Denmark.

TOFT S & NIELSEN SA (1997) Influence of diet quality on the respiratory metabolism of a wolf spider *Pardosa prativaga. Proceedings of the 16th European Colloquium on Arachnology*, 301-307.

TOOLEY J & BRUST GE (2002) Weed seed predation by carabid beetles. In: *The Agroecology of Carabid Beetles* (ed. JM Holland), 215-229. Intercept, Andover, UK.

TOOLEY JA, FROUD-WILLIAMS RJ, BOATMAN ND & HOLLAND JM (1999) Weed seed predation in arable field margins by carabid beetles (Carabidae: Coleoptera). *Aspects of Applied Biology* **54**, 211-216.

TOPPING CJ (1997) Predicting the effect of landscape heterogeneity on the distribution of spiders in agroecosystems using a population dynamics driven landscape-scale simulation model. *Biological and Agricultural Horticulture* **15**, 325-336.

TOPPING CJ (1999) An individual-based model for dispersive spiders in agroecosystems: simulations of the effects of landscape structure. *Journal of Arachnology* **27**, 378-386.

TOPPING CJ & SUNDERLAND KD (1994a) The potential influence of set-aside on populations of *Lepthyphantes tenuis* (Araneae: Linyphiidae) in the agroecosystem. *Aspects of Applied Biology* **40**, 225-228.

TOPPING CJ & SUNDERLAND KD (1994b) A spatial population dynamics model for *Lepthyphantes tenuis* (Araneae: Linyphiidae) with some simulations of the spatial and temporal effects of farming operations and land-use. *Agriculture Ecosystems and Environment* **48**, 203-217.

TÓTH F & KISS J (1997) Occurrence of *Pardosa* (Araneae Lycosidae) species in winter wheat and in the field margin. *Proceedings of the16th European Colloquium of Arachnology, Siedlce*, pp. 309-315.

TRUMPER EV & HOLT J (1998) Modelling pest population resurgence due to recolonization of fields following an insecticide application. *Journal of Applied Ecology* **35**, 273-285.

VAN EMDEN HF (1963) Observations on the effect of flowers on the activity of parasitic Hymenoptera. *Entomologist's Monthly Magazine* **98**, 265-270.

VAN EMDEN HF (1965a) The effect of uncultivated land on the distribution of cabbage aphid (*Brevicoryne brassicae*) on an adjacent crop. *Journal of Applied Ecology* **2**, 171-196.

VAN EMDEN HF (1965b) The role of uncultivated land in the biology of crop pests and beneficial insects. *Scientific Horticulture* **17**, 121-136.

VAN EMDEN HF (1981) Wild plants in the ecology of insect pests. In: Pests, Pathogens and Vegetation (ed. JM Thresh), 251-261. Pitman, London, UK.

VAN EMDEN HF (1990) Plant diversity and natural enemy efficiency in agroecosystems. In: *Critical Issues in Biocontrol* (eds M Mackauer, LE Ehler & J Roland), 63-80. Intercept, Andover, UK.

VANGSGAARD C (1996) Spatial distribution and dispersal of spiders in a Danish barley field. *Revue Suisse de Zoologie, hors Serie* 671-682.

VARCHOLA JM & DUNN JP (2001) Influence of hedgerow and grassy field borders on ground beetle (Coleoptera: Carabidae) activity in fields of corn. *Agriculture, Ecosystems and Environment* **83**, 153-163.

VIA S (1991) Specialized host plant performance of pea aphid clones is not altered by experience. *Ecology* **72**, 1420-1427.

VIA S (1999) Reproductive isolation between sympatric races of pea aphids. I. Gene flow restriction and habitat choice. *Evolution* **53**, 1446-1457.

VIA S, BOUCK AC & SKILLMAN S (2000) Reproductive isolation between divergent races of pea aphids on two hosts. II. Selection against migrants and hybrids in the parental environments. *Evolution* **54**, 1626-1637.

VOGT H & WEIGEL A (1999) Is it possible to enhance the biological control of aphids in an apple orchard with flowering strips ? *Bulletin IOBC/WPRS* **22(7),** 39-46.

WAINHOUSE D & COAKER TH (1981) The distribution of carrot fly (*Psila rosae*) in relation to the flora of field boundaries. In: *Pests Pathogens and Vegetation* (ed. JM Thresh), 263-272. Pitman, London.

WALKER JM (2001) US Environmental Protection Agency regulations governing compost production and use. In: *Compost Utilization in Horticultural Cropping Systems* (ed. PJ Stoffella & BA Kahn), 381-399. Lewis Publishers, Boca Raton, USA.

WALLIN H (1985) Spatial and temporal distribution of some abundant carabid beetles (Coleoptera: Carabidae) in cereal fields and adjacent habitats. *Pedobiologia* **28**,19-34.

WALLIN H (1986) Habitat choice of some field-inhabiting carabid beetles (Coleoptera: Carabidae) studied by recapture of marked individuals. *Ecological Entomology* **11**, 457-466.

WALLIN H (1989) Habitat selection, reproduction, and survival of two small carabid species on arable land: a comparison between *Trechus secalis* and *Bembidion lampros. Holarctic Ecology* **12**,193-200.

WARD LK & SPALDING DF (1993) Phytophagous British insects and mites and their food-plant families – total numbers and polyphagy. *Biological Journal of the Linnean Society* **49**, 257-276.

WARDLE DA (1995) Impacts of disturbance on detritus food webs in agro-ecosystems of contrasting tillage and weed management practices. *Advances in Ecological Research* **26**, 105-185.

WEIBULL AC, ÖSTMAN O & GRANQVIST A (2003) Species richness in agroecosystems: the effect of landscape, habitat and farm management. *Biodiversity and Conservation* **12**, 1335-1355.

WELLING M (1990) Dispersal of ground beetles (Col., Carabidae) in arable land. *Mededelingen van de Fakulteit Landbouwwetenschappen Rijksuniversiteit Gent* **55(2b),** 483-491.

WELLING M & KOKTA C (1988) Untersuchungen zur Entomofauna vin Feldrainen und Feldrändern in Hinblick auf Nützlingsförderung und Artenschutz. *Mitteilungen der Deutschen Gesellschaft für allgemeine und angewandte Entomologie* **6**, 373-377.

WESTERMAN PR, HOFMAN A, VET LEM & VAN DER WERF W (2003) Relative importance of vertebrates and invertebrates in epigeic weed seed predation in organic cereal fields. *Agriculture, Ecosystems and Environment* **95**, 417-425.

WHITE AJ, WRATTEN SD, BERRY NA & WEIGMANN U (1995) Habitat manipulation to enhance biological control of *Brassica* pests by hover flies (Diptera: Syrphidae). *Journal of Economic Entomology* **88**, 1171-1176.

WHITE PCL & HASSALL M (1994) Effects of management on spider communities of headlands in cereal fields. *Pedobiologia* **38**,169-184.

WIEDEMEIER P & DUELLI P (2000) Ökologische Ausgleichsflächen als Winterbiotope für bodenaktive Nützlinge im Intensivkulturland. *Agrarökologie* **37**, 181-198.

WIKLUND C & KARLSSON B (1984) Egg size variation in satyrid butterflies: adaptive vs. historical, "bauplan" and mechanistic explanations. *Oikos* **43**, 391-400.

WILBY A & THOMAS, MB (2002) Natural enemy diversity and pest control: patterns of pest emergence with agricultural intensification. *Ecology Letters* **5**, 353-360.

WILLIAMS PH (1982) The distribution and decline of British bumblebees (*Bombus* Latr.). *Journal of Apicultural Research* **21**, 236-245.

WILLIAMS PH (1986) Environmental change and the distributions of British bumblebees (*Bombus* Latr.). *Bee World* **67**, 50-61.

WILSON JD, MORRIS AJ, ARROYO BE, CLARK SC & BRADBURY RB (1999) A review of the abundance and diversity of invertebrate and plant foods of granivorous birds in northern Europe in relation to agricultural change. *Agriculture Ecosystems and Environment* **75**, 13-30.

WILSON PJ & AEBISCHER NJ (1995) The distribution of dicotyledonous arable weeds in relation to distance from the field edge. *Journal of Applied Ecology* **32**, 295-310.

WINDER L, MERRINGTON G & GREEN I (1999) The tritrophic transfer of Zn from the agricultural use of sewage sludge. *The Science of the Total Environment* **229**, 73-81.

WINSTONE L, MARSHALL EJP & ARNOLD GM (1997) Movement patterns of *Pterostichus cupreus* and *Nebria brevicollis* in habitat patches with different vegeation structures. *Acta Jutlandica* **72**, 39-46.

WISE DH, SNYDER WE, TUNTIBUNPAKUL P & HALAJ J (1999). Spiders in decomposition food webs of agroecosystems: theory and evidence. *Journal of Arachnology* **27**, 363-370.

WISSINGER SA (1997) Cyclic colonization in predictably ephemeral habitats: a template for biological control in annual crop systems. *Biological Control* **10**, 4-15.

WRATTEN SD (1988) The role of field boundaries as reservoirs of beneficial insects. In: *Environmental Management in Agriculture: European Perspectives* (ed. JR Park), 144-150. Belhaven Press, London, UK.

WRATTEN SD & THOMAS MB (1990) Environmental manipulation for the encouragement of natural enemies of pests. *Organic and Low Input Agriculture*: BCPC Monograph **45**, 87-92.

WRATTEN SD & VAN EMDEN HF (1995) Habitat management for enhanced activity of natural enemies of insect pests In: *Ecology of Integrated Farming Systems* (eds DM Glen, MP Greaves & HM Anderson), 117-145. John Wiley & Sons, Chichester, UK.

WRATTEN SD, VAN EMDEN HF & THOMAS MB (1998) Within-field and border refugia for the enhancement of natural enemies. In: *Enhancing Biological Control* (eds CH Pickett & RL Bugg), 375-403. University of California Press, Berkeley, California, USA.

WRATTEN SD, BOWIE MH, HICKMAN JM, EVANS AM, SEDCOLE JR & TYLIANAKIS JM (2003) Field boundaries as barriers to movement of hoverflies (Diptera: Syrphidae) in cultivated land. *Oecologia* **134**, 605-611.

WYSS E (1995) The effects of weed strips on aphids and aphidophagous predators in an apple orchard. *Entomologia Experimentalis et Applicata* **75**, 43-49.

WYSS E, NIGGLI U & NENTWIG W (1995) The impact of spiders on aphid populations in a strip-managed apple orchard. *Journal of Applied Entomology* **119**, 473-478.

ZAHIROVIC S, HEIMBACH U & SOMMER R (2001) Einfluss verschiedener Mulchsaatsysteme auf Spinnen in Ackerbohnen-Beständen. *Mitteilungen der Deutschen Gesellschaft Allgemeine und Angewandte Entomologie* **13**, 261-264.

ZANGGER, A (1994) The positive influence of strip-management on carabid beetles in a cereal field: accessibility of food and reproduction in *Poecilus cupreus*. In: *Carabid Beetles: Ecology and Evolution* (eds K Desender, M Dufrene, M Loreau, ML Luff & JP Maelfait), 469-472. Kluwer Aademic Publishers, Dordrecht, The Netherlands.

ZANGGER A, LYS JA & NENTWIG W (1994) Increasing the availability of food and the reproduction of *Poecilus cupreus* in a cereal field by strip-management. *Entomologia Experimentalis et Applicata* **71**, 111-120.

ZHAO JZ, AYERS GS, GRAFIUS EJ & STEHR FW (1992) Effects of neighboring nectar-producing plants on populations of pest Lepidoptera and their parasitoids in broccoli plantings. *The Great Lakes Entomologist* **25**, 253-258.

CHAPTER 7

THE WEED SEEDBANK OF HORTICULTURAL SYSTEMS

7.1 What is the weed seedbank?

The number of selective products for chemical weed control is declining and, in addition to the environmental pressure for reduced pesticide inputs, there is greater emphasis on rationalising the use of the products available. To achieve this, it is necessary to explore ways of optimising the timing of application and rates of herbicide inputs as well as improving the efficiency of non-chemical methods. Understanding weed population dynamics is vital in developing such weed management systems in a way that is both sustainable and sympathetic to habitat biodiversity. The soil weed seedbank is a critical aspect of weed population dynamics, and thus must be an integral component of any weed management strategy.

The seedbank is often referred to as the memory of past weed management strategies and is the source of future potential weed populations. The soil seedbank provides a habitat for weed seeds to disperse themselves both in time and space and hence an avoidance tactic to prevent all seeds of a given species germinating during unfavourable conditions. The buffering capacity provided by this environment gives weeds a great resilience to short-term changes in weed control regimes and ensures the propagation of a species.

In the regularly disturbed habitats of field vegetable systems, the most successful weed species tend to be those which mimic most closely the annual cycle of the crop, so that the seedbank tends to be dominated by annual weeds with emergence and maturation times similar to that of the crop itself. In less disturbed horticultural habitats such as orchards, then perennial weeds may be more of a problem and so the seedbank reflects this. In some aspects of horticulture, such as container grown nursery stock, seedbanks are less important. Nevertheless, wind blown species such as Hairy bitter-cress can quickly colonise and shed seed in pots, which may then provide a source of introduction of new weeds when relocated. However, it is generally true that in all horticultural situations, failure to control weeds in even one season can cause dramatic explosions in seedbank density, which may then take years of careful management to reverse. The main issued addressed in this chapter are:

- How the seedbank and its management can contribute towards creating greater floral diversity and encouraging biodiversity
- How the wide range of crop sowing times relative to weed emergence in horticultural systems will determine both the onset and severity of weed competition and the weed species spectrum in a given crop at a given time of year.
- How the seedbank has changed in the last 50 years with agricultural intensification and the possible mechanisms for that change

7.2 The importance of weed seed(bank)s for biodiversity

The weed seedbank impacts directly on biodiversity in two major ways by providing;

1. the source of future weed populations, hence contributing directly towards floral diversity.
2. a direct source of food to both birds and invertebrates.

Understanding the dynamics of the weed seedbank and hence the mechanisms that determine both future weed populations and weed seed availability, are important in the successful management of weed populations towards biodiversity in horticultural systems. Many processes contribute towards the population dynamics of weed species of which the seedbank is just one component. The factors that influence the size and species composition of the seedbank alone are many and complex, as summarised in Fig 7.1. For the purpose of this study, a short summary of the key factors are presented.

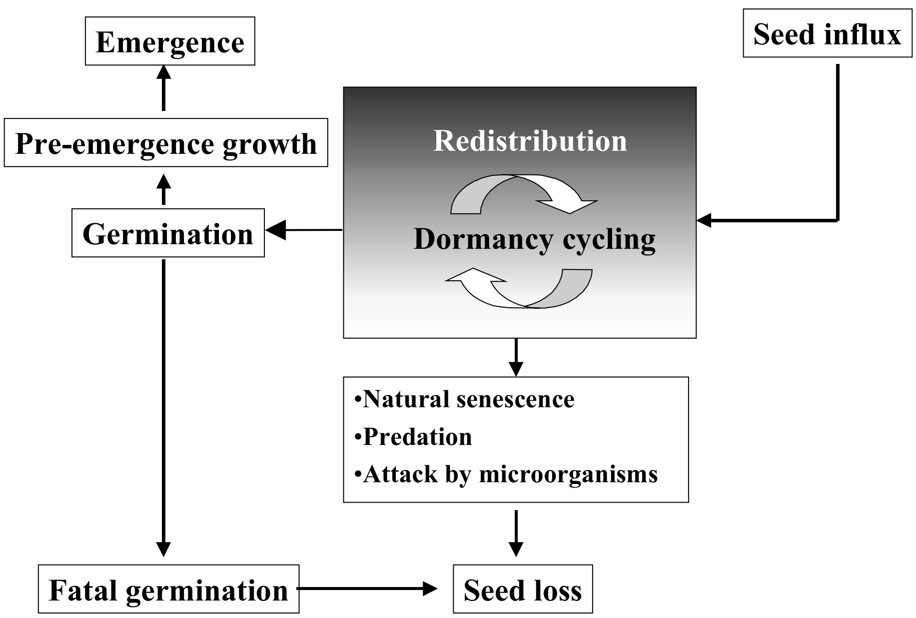
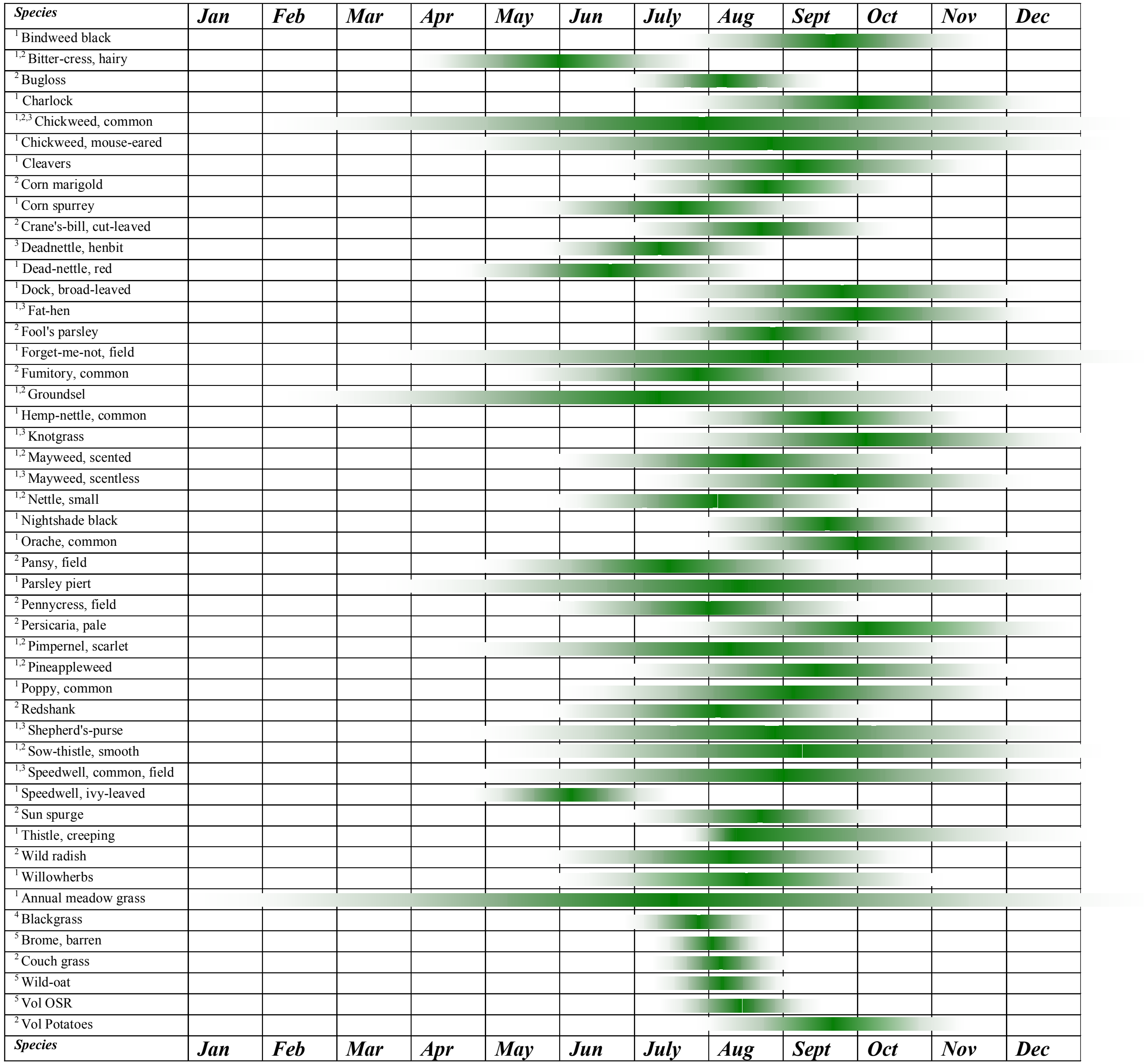


Fig 7.1. Simplified diagram of the dynamics of the weed seedbank. Reproduced from the 9th edition of the Weed Management Handbook, 9th edition, Blackwell Science Limited, Naylor 2002)

7.2.1 Inputs to the horticultural weed seedbank

The seedbank is regularly replenished. The major periods of influx generally depend on the seed dispersal time of the dominant weed species within the local population (although the seeds of some non-local species may be imported over relatively long distances by for example wind, animals and human activity). Some species that are capable of all-year-round emergence, such as common chickweed, have the potential to continually shed seed all year round. In contrast species with more restricted emergence, like Knotgrass and Black nightshade, will have a similarly defined period of seed shedding (Fig 7.2a). Seed production for each species is difficult to derive experimentally as weeds are notoriously "plastic" in their response to environmental constraints such as competition (Froud-Williams, 1999). However recent studies are beginning to provide some insight to the relationship between seed production and plant weight for a number of key weed species (Lutman, 2002; Grundy, 2003). Crops can also contribute to the seedbank and become weeds themselves, for example oilseed rape. During harvesting of the crop, small but significant numbers of the seed yield can be lost during harvesting and returned to the soil. A recent study in Canada has reported average seed losses of 5.9% of the total crop yield for oilseed rape, which can produce a substantial increase in the seedbank of the volunteer oilseed rape populations for a number of years (Gulden & Shirtliffe, 2003). The timing of weed seed shedding relative to the time of crop harvest has great bearing on the weed species contribution to the seedbank each year (Figs 7.2 b through to m). Thus, continual cropping of a single crop in the same field can encourage a build up of weeds of a certain life-cycle.

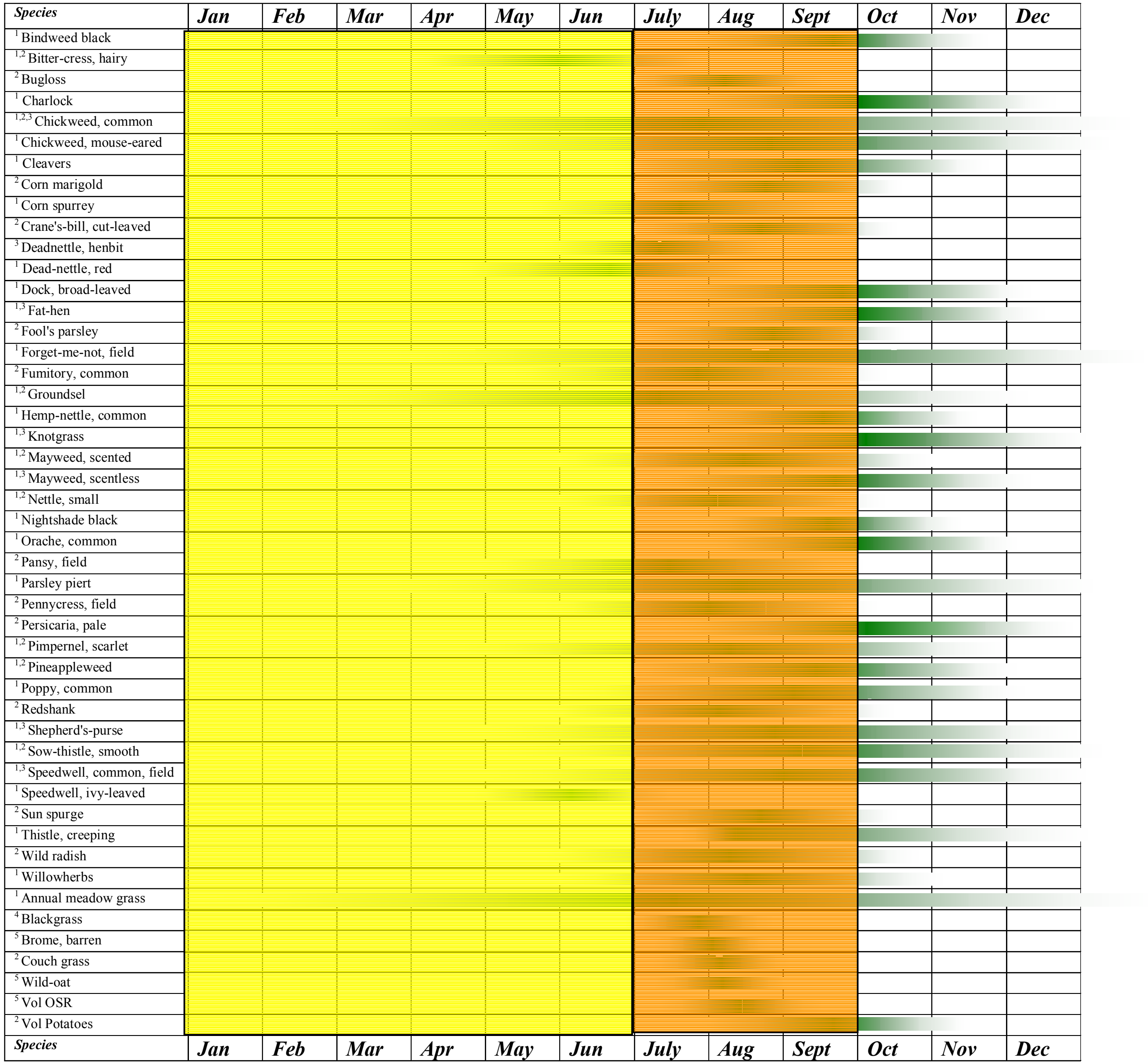
Fig 7.2a Seed shedding times for key weed species typical of horticultural systems

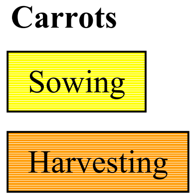


Sources of seed shedding times:
[1] Grime *et al* (1988)
[2] Bond, W (pers. com.)
[3] Leguizamon & Roberts (1982)
[4] Moss, SR (pers. com.)
[5] Lutman, PJW (pers. com.)

Note for several species, shedding times

Fig 7.2b Seed shedding times for key weed species typical of horticultural systems relative to typical sowing and harvesting times for carrots (sowing and harvesting times from Nickersons-Zwaan 2003/2004)

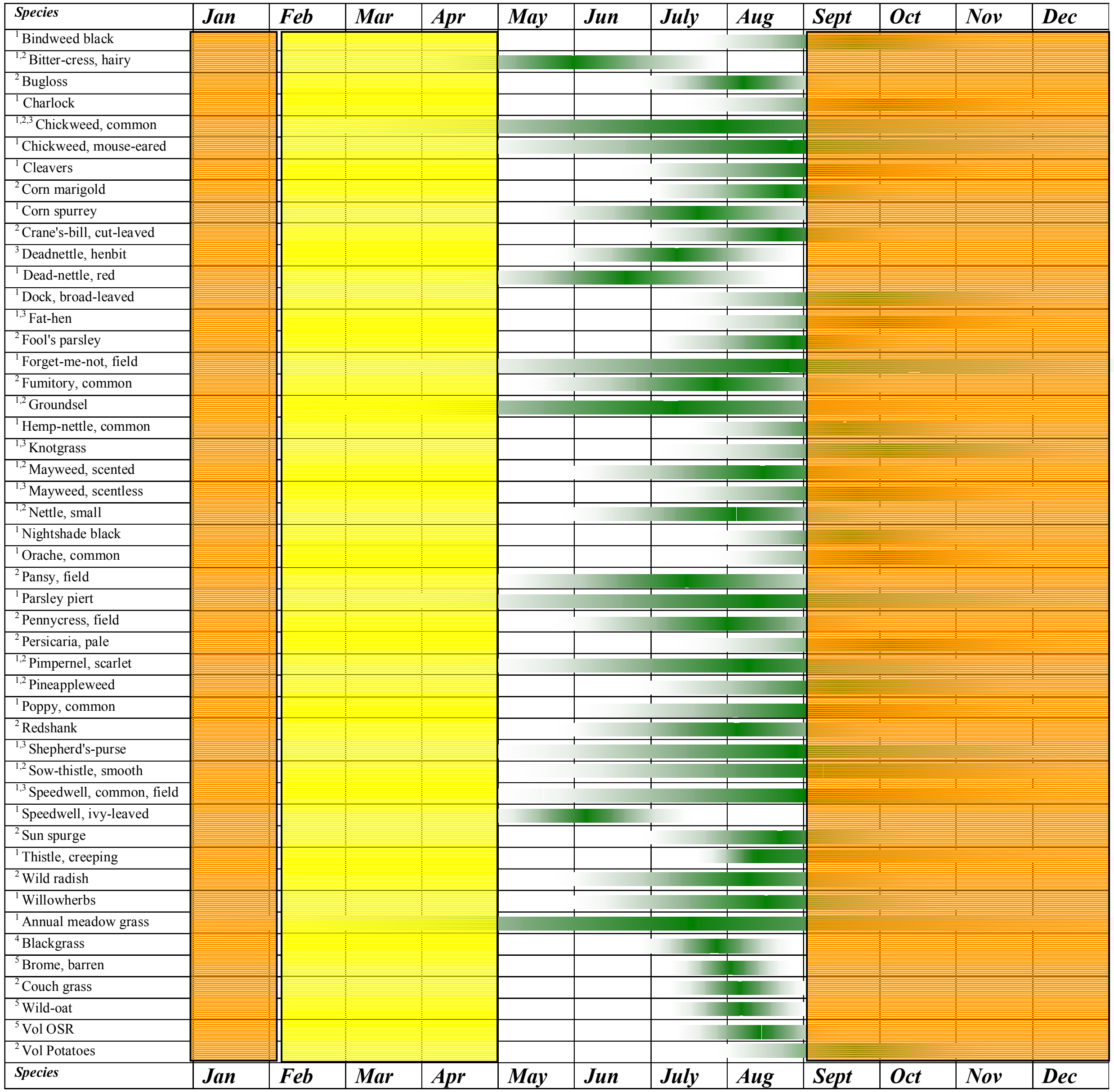


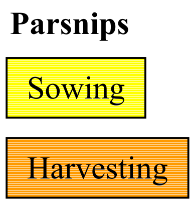


Sources of seed shedding times:
[1] Grime *et al* (1988)
[2] Bond, W (pers. com.)
[3] Leguizamon & Roberts (1982)
[4] Moss, SR (pers. com.)
[5] Lutman, PJW (pers. com.)

Note for several species, shedding times

Fig 7.2c Seed shedding times for key weed species typical of horticultural systems relative to typical sowing and harvesting times for parsnips (sowing and harvesting times from Nickersons-Zwaan 2003/2004)

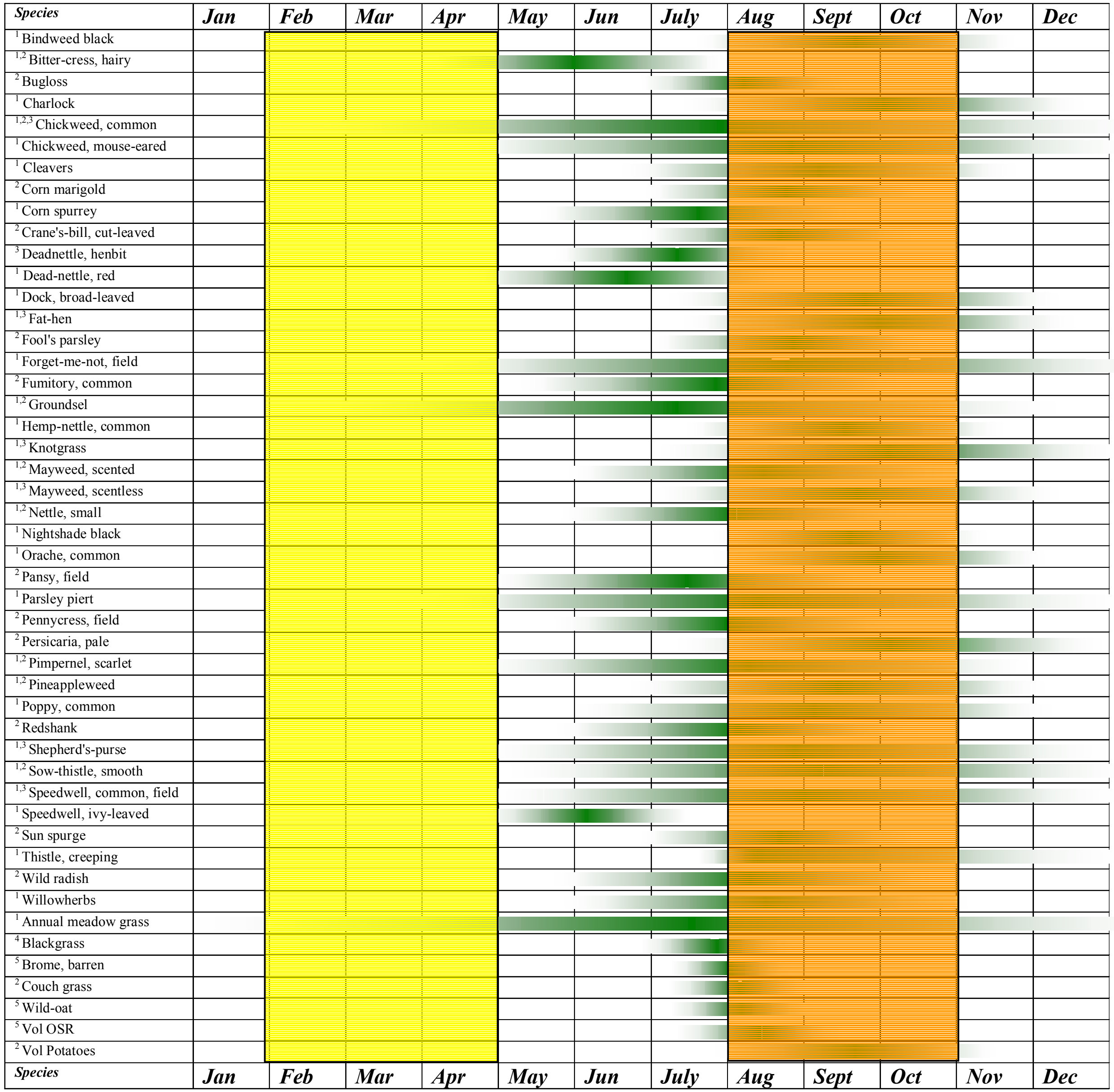


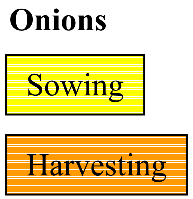


Sources of seed shedding times:
[1] Grime *et al* (1988)
[2] Bond, W (pers. com.)
[3] Leguizamon & Roberts (1982)
[4] Moss, SR (pers. com.)
[5] Lutman, PJW (pers. com.)

Note for several species, shedding times

Fig 7.2d Seed shedding times for key weed species typical of horticultural systems relative to typical sowing and harvesting times for bulb onions (sowing and harvesting times from Nickersons-Zwaan 2003/2004)

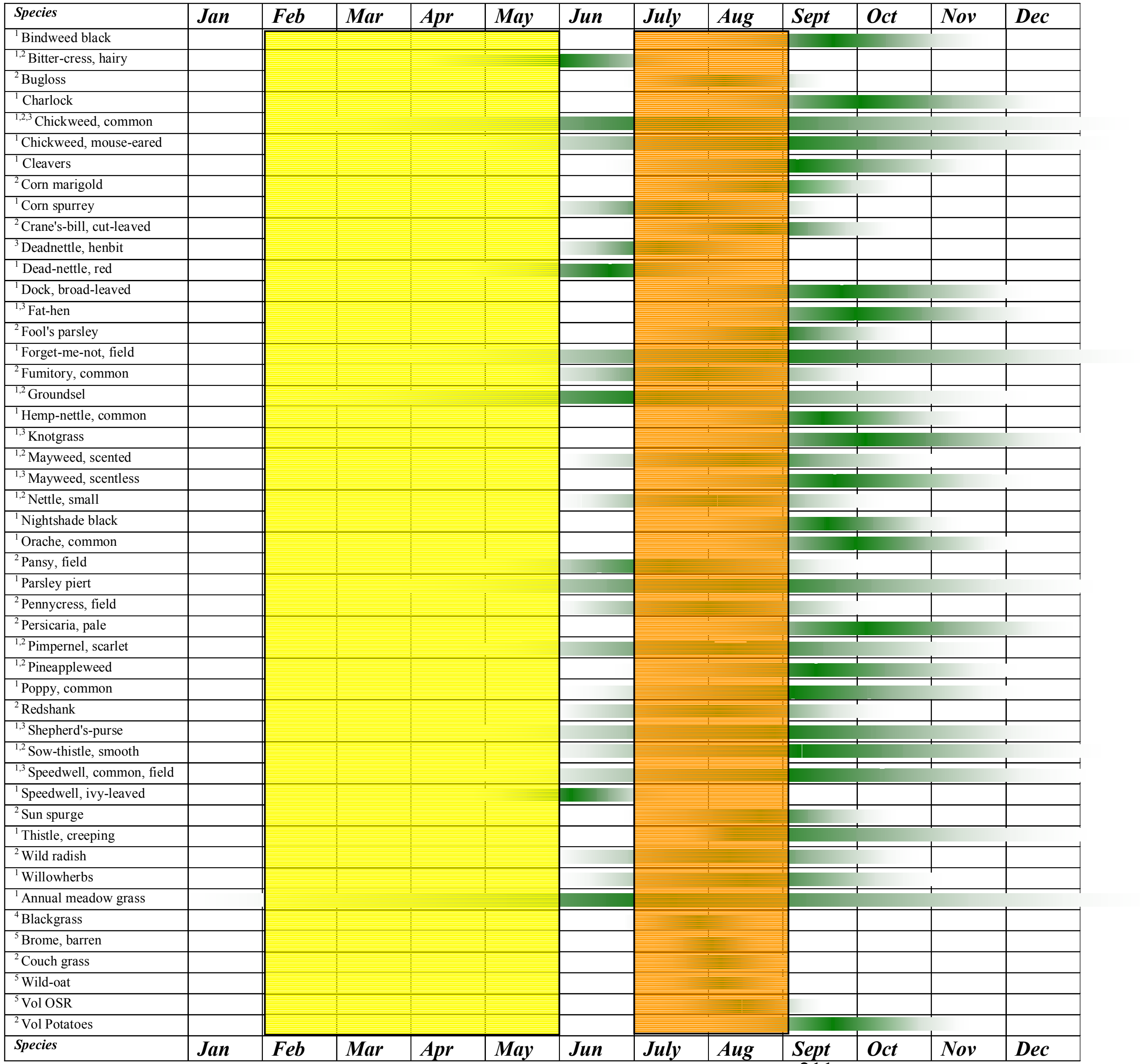




Sources of seed shedding times:
[1] Grime *et al* (1988)
[2] Bond, W (pers. com.)
[3] Leguizamon & Roberts (1982)
[4] Moss, SR (pers. com.)
[5] Lutman, PJW (pers. com.)

Note for several species, shedding times

Fig 7.2e Seed shedding times for key weed species typical of horticultural systems relative to typical sowing and harvesting times for early salad onions (sowing and harvesting times from Nickersons-Zwaan 2003/2004)



Onions (salad -early)

Sowing

Harvesting

Sources of seed shedding times:
[1] Grime *et al* (1988)
[2] Bond, W (pers. com.)
[3] Leguizamon & Roberts (1982)
[4] Moss, SR (pers. com.)
[5] Lutman, PJW (pers. com.)

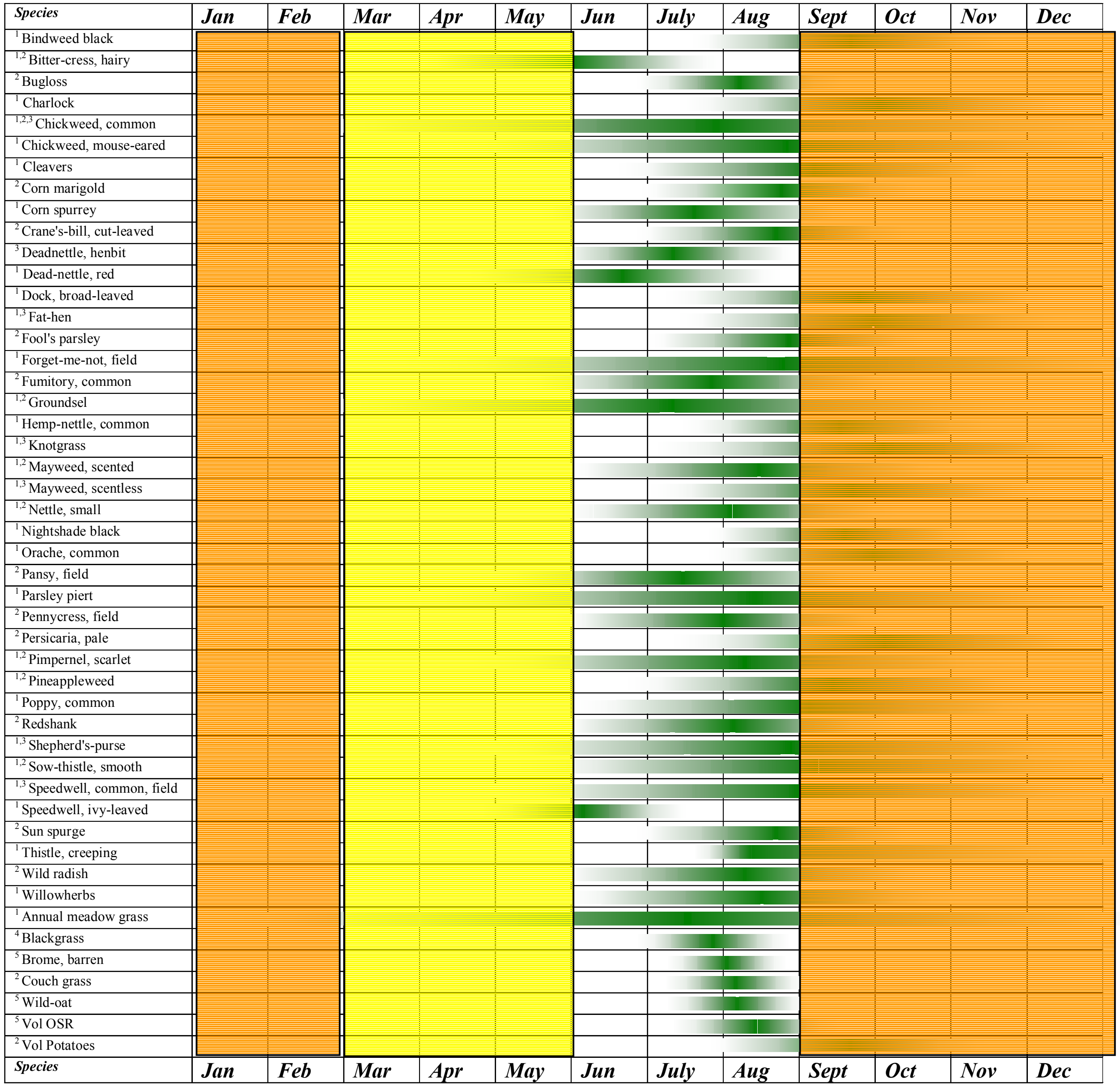
Note for several species, shedding times

Fig 7.2f Seed shedding times for key weed species typical of horticultural systems relative to typical sowing and harvesting times for overwinter salad onions (sowing and harvesting times from Nickersons-Zwaan 2003/2004

Sources of seed shedding times:
[1] Grime *et al* (1988)
[2] Bond, W (pers. com.)
[3] Leguizamon & Roberts (1982)
[4] Moss, SR (pers. com.)
[5] Lutman, PJW (pers. com.)

Note for several species, shedding times

Fig 7.2g Seed shedding times for key weed species typical of horticultural systems relative to typical sowing and harvesting times for leeks(sowing and harvesting times from Nickersons-Zwaan 2003/2004)



Leeks

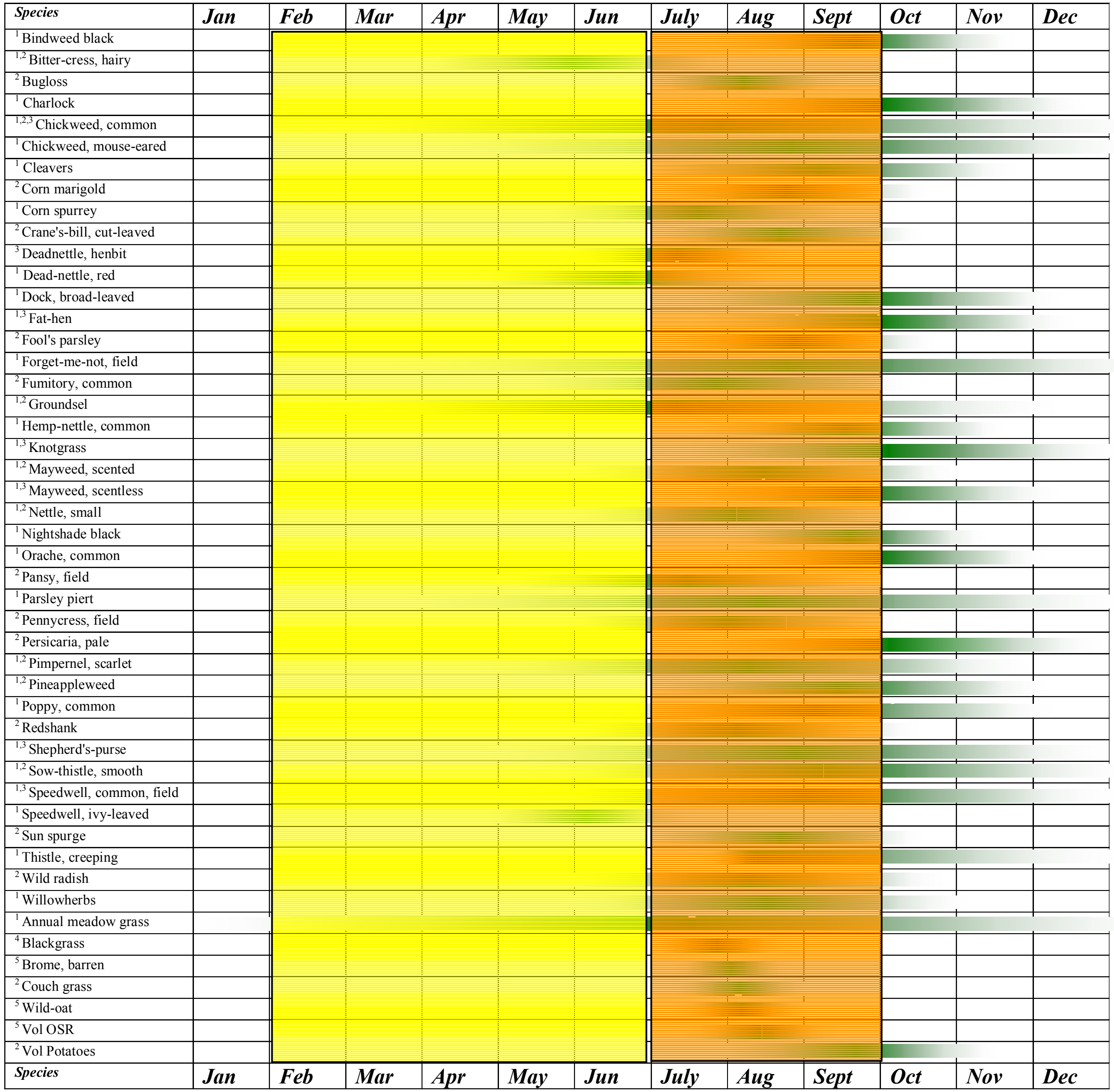
Sowing/transplanting

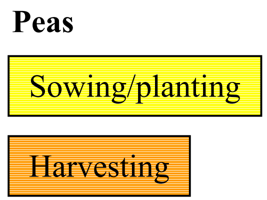
Harvesting

Sources of seed shedding times:
[1] Grime *et al* (1988)
[2] Bond, W (pers. com.)
[3] Leguizamon & Roberts (1982)
[4] Moss, SR (pers. com.)
[5] Lutman, PJW (pers. com.)

Note for several species, shedding times

Fig 7.2h Seed shedding times for key weed species typical of horticultural systems relative to typical sowing and harvesting times for peas (sowing and harvesting times from Nickersons-Zwaan 2003/2004)





Sources of seed shedding times:
[1] Grime *et al* (1988)
[2] Bond, W (pers. com.)
[3] Leguizamon & Roberts (1982)
[4] Moss, SR (pers. com.)
[5] Lutman, PJW (pers. com.)

Note for several species, shedding times

Fig 7.2i Seed shedding times for key weed species typical of horticultural systems relative to typical sowing and harvesting times for dwarf beans (sowing and harvesting times from Nickersons-Zwaan 2003/2004)

Dwarf bean

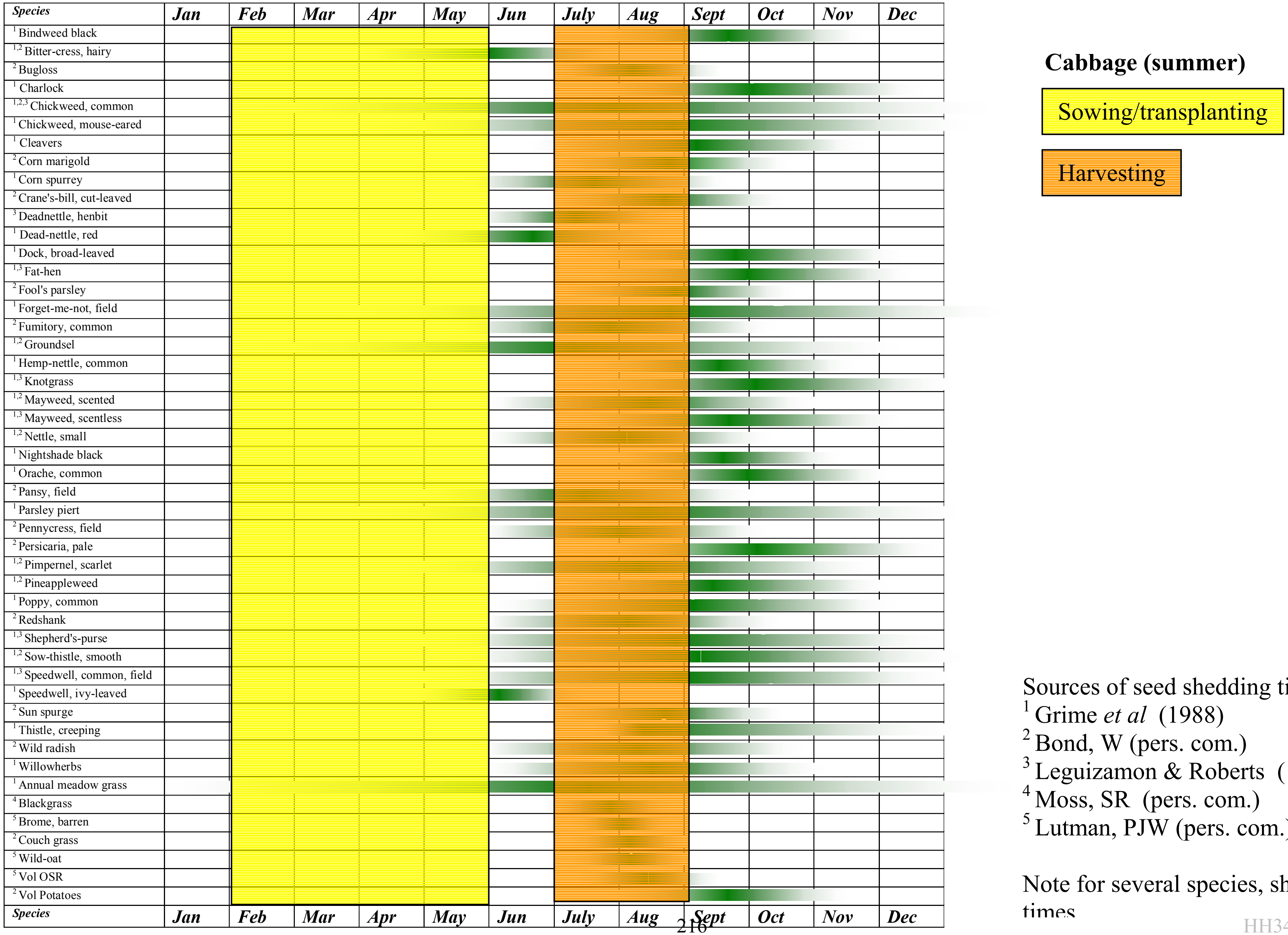
Sowing

Harvesting

Sources of seed shedding times:
[1] Grime *et al* (1988)
[2] Bond, W (pers. com.)
[3] Leguizamon & Roberts (1982)
[4] Moss, SR (pers. com.)
[5] Lutman, PJW (pers. com.)

Note for several species, shedding times

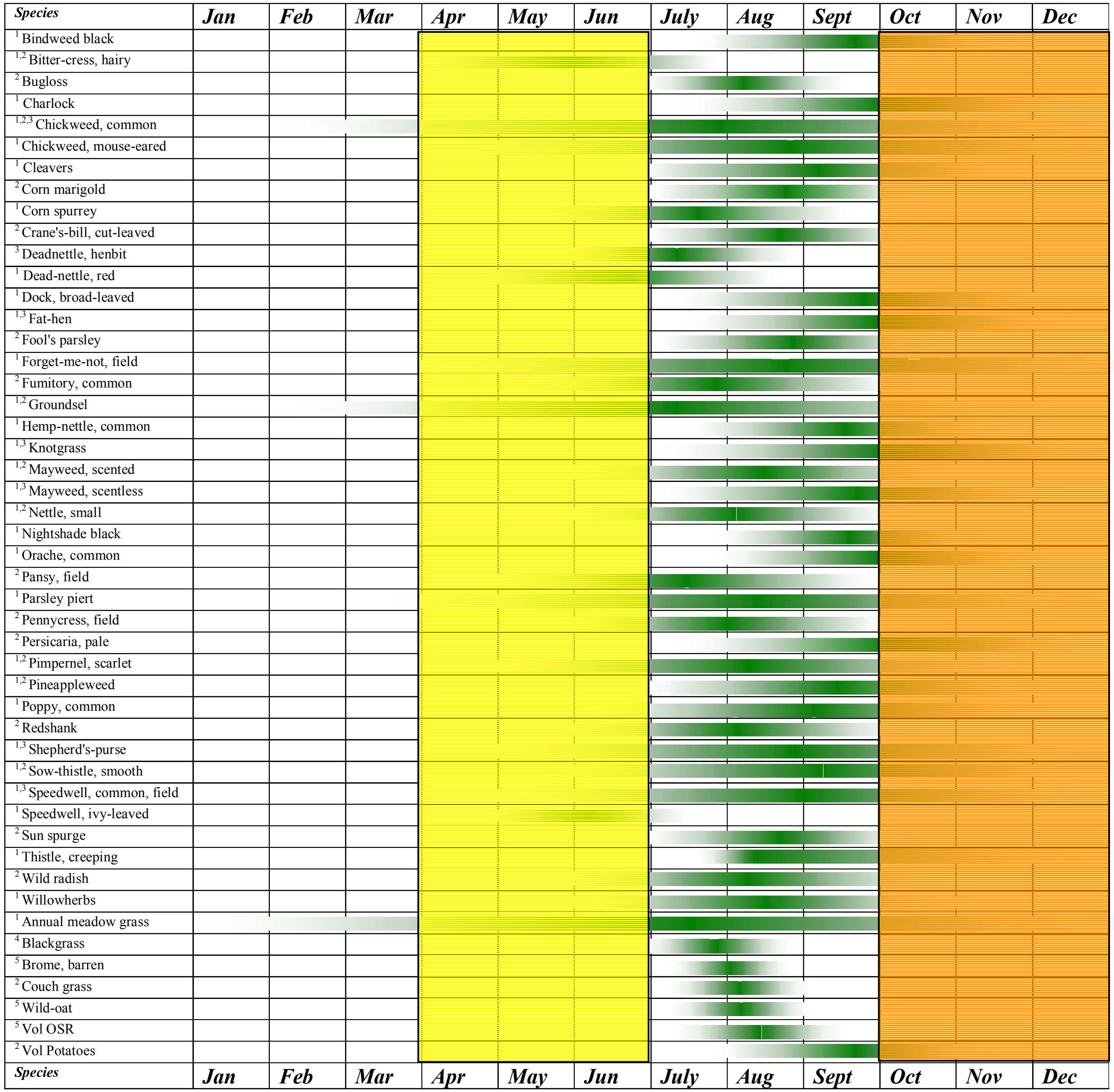
Fig 7.2j Seed shedding times for key weed species typical of horticultural systems relative to typical sowing and harvesting times for summer cabbage (sowing and harvesting times from Nickersons-Zwaan 2003/2004)



Sources of seed shedding times:
[1] Grime *et al* (1988)
[2] Bond, W (pers. com.)
[3] Leguizamon & Roberts (1982)
[4] Moss, SR (pers. com.)
[5] Lutman, PJW (pers. com.)

Note for several species, shedding times

Fig 7.2k Seed shedding times for key weed species typical of horticultural systems relative to typical sowing and harvesting times for winter cabbage (sowing and harvesting times from Nickersons-Zwaan 2003/2004)



Cabbage (winter)

Sowing/transplanting

Harvesting

Sources of seed shedding times:
[1] Grime *et al* (1988)
[2] Bond, W (pers. com.)
[3] Leguizamon & Roberts (1982)
[4] Moss, SR (pers. com.)
[5] Lutman, PJW (pers. com.)

Note for several species, shedding times

Fig 7.21 Seed shedding times for key weed species typical of horticultural systems relative to typical sowing and harvesting times for summer + autumn cabbage (sowing and harvesting times from Nickersons-Zwaan 2003/2004)

Species	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
[1] Bindweed black												
[1,2] Bitter-cress, hairy												
[2] Bugloss												
[1] Charlock												
[1,2,3] Chickweed, common												
[1] Chickweed, mouse-eared												
[1] Cleavers												
[2] Corn marigold												
[1] Corn spurrey												
[2] Crane's-bill, cut-leaved												
[3] Deadnettle, henbit												
[1] Dead-nettle, red												
[1] Dock, broad-leaved												
[1,3] Fat-hen												
[2] Fool's parsley												
[1] Forget-me-not, field												
[2] Fumitory, common												
[1,2] Groundsel												
[1] Hemp-nettle, common												
[1,3] Knotgrass												
[1,2] Mayweed, scented												
[1,3] Mayweed, scentless												
[1,2] Nettle, small												
[1] Nightshade black												
[1] Orache, common												
[2] Pansy, field												
[1] Parsley piert												
[2] Pennycress, field												
[2] Persicaria, pale												
[1,2] Pimpernel, scarlet												
[1,2] Pineappleweed												
[1] Poppy, common												
[2] Redshank												
[1,3] Shepherd's-purse												
[1,2] Sow-thistle, smooth												
[1,3] Speedwell, common, field												
[1] Speedwell, ivy-leaved												
[2] Sun spurge												
[1] Thistle, creeping												
[2] Wild radish												
[1] Willowherbs												
[1] Annual meadow grass												
[4] Blackgrass												
[5] Brome, barren												
[2] Couch grass												
[5] Wild-oat												
[5] Vol OSR												
[2] Vol Potatoes												
Species	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**

Cauliflower (summer + autumn)

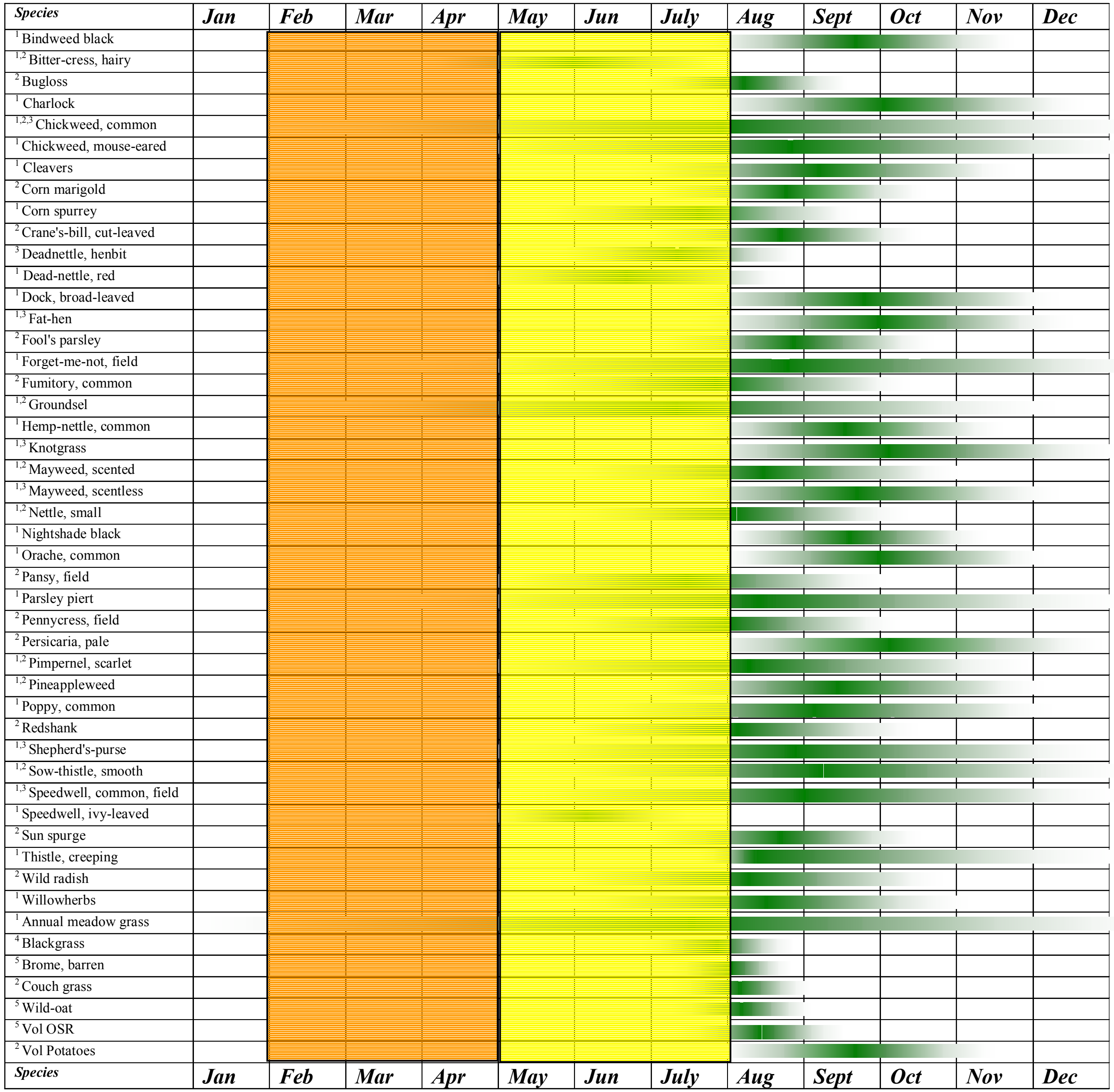
Sowing/transplanting

Harvesting

Sources of seed shedding times:
[1] Grime *et al* (1988)
[2] Bond, W (pers. com.)
[3] Leguizamon & Roberts (1982)
[4] Moss, SR (pers. com.)
[5] Lutman, PJW (pers. com.)

Note for several species, shedding times

Fig 7.2m Seed shedding times for key weed species typical of horticultural systems relative to typical sowing and harvesting times for winter cauliflower (sowing and harvesting times from Nickersons-Zwaan 2003/2004)



Cauliflower (winter)

Sowing/transplanting

Harvesting

Sources of seed shedding times:
[1] Grime *et al* (1988)
[2] Bond, W (pers. com.)
[3] Leguizamon & Roberts (1982)
[4] Moss, SR (pers. com.)
[5] Lutman, PJW (pers. com.)

Note for several species, shedding times

7.2.2 Losses from the seedbank including weed seed predation

Once seeds have entered the seedbank there are several sources of subsequent seed loss including predation (by birds, small mammals and invertebrates) attack by pathogens and micro-organisms, natural physiological ageing and germination (Fig 7.1). Germination (including fatal germination (Mohler & Galford, 1997; Grundy *et al.*, 2003)), is known to be a major source of loss of seeds from the seedbank (Forcella, 2003) but it is difficult to separate losses due to ageing, attack by micro-organisms and fatal germination since all result in deterioration of the seed

Seed predation may significantly reduce seed numbers in the seedbank, but it is an area largely unquantified in weed biology and therefore often underestimated in dynamic seedbank/weed population models (Watson *et al*., 2003). It is likely that species composition, density, habitat, microhabitat and season all interact to modify seed numbers lost to predation. In general, for many species deeper burial increases the longevity of seeds in the soil. This is partly because seeds left at the surface are more accessible to predation than those buried. In a study in Sweden, losses up to 92%, 84% and 83% observed for black-bindweed, fat-hen and Field pennycress respectively were thought to be attributed to predation alone (Andersson, 1998).

As a rule-of-thumb, in the absence of any appreciable additions of weed seeds, when a mixed-age population of viable seeds is subjected to a consistent cultivation regime it tend to decline exponentially (Roberts 1962; Roberts & Dawkins 1967). However, this represents a generalised response and there can be considerable species to species variability. A study made at Long Ashton Research Station and Rothamsted Research in the UK on arable land showed a rapid decline in seed numbers within the first few days of incorporation, probably due to predation and disease. Thereafter three broad-leaved species Cleavers, Common chickweed and Common poppy were classified as having the three different strategies of exponential, gradual and long-term persistence respectively (Miller *et al.*, 1998). Often, it is the smaller-seeded species that tend to form persistent seedbanks and a relationship between seed weight and variance in linear dimensions has been proposed as an indicator of persistence (Thompson *et al.*, 1993). Compact seeds were found to be persistent whilst those above a critical variance in their dimensions were short-lived. Although this relationship offers a guide to the relative persistence of seeds in the seedbank, is an empirical simplification of a number of interacting factors. The persistence of small seeds is partly because small round seeds become incorporated into the soil with greater ease than larger shaped seeds. However, the lack of nutritional reward and the difficulty in finding the less conspicuous smaller seeds may also offer some protection to these smaller seeds. Some of these ecological arguments for the evolution of seed size and its relationship with predation and persistence are more fully developed in Fenner (2000).

Different approaches have been used to characterise seedbanks in terms of seed persistence as summarised by Thompson *et al.*, (1997). Unfortunately, the models used in many studies to give an estimate of seed persistence for a given species, generally fail to satisfactorily describe the variation in survivorship from one year to the next. This is because in practice annual differences in predation pressure and weather all contribute to the variation in survivorship. In the Long Ashton/Rothamsted study, seed decline also seemed to differ between soil type (Lutman *et al.*, 2002). Hence, whilst models give an indication of patterns of loss over time, we still do not know enough of the biological interactions between the factors involved on a site-specific basis to accurately quantify and predict seed loss and the proportion that can be attributed to seed predation.

7.3 The relative timing of crop and weed emergence

Autumn sowing, typical of many arable crops, is generally associated with autumn germinating winter annual species. This is because the disturbance of the seedbank during seedbed preparation and crop sowing, will tend to trigger a flush of weed emergence in species that have low dormancy at that specific time of year. In contrast drilling in the spring, typical of the majority of field vegetable crops, allows summer annuals to flourish. Similarly, drilling date can also have more subtle implications for the weed species likely to emerge in a given crop. A long-term study in Sweden in spring-sown cereals clearly demonstrated that the composition of the weed flora varied depending on crop sowing date (Milberg *et al*, 2001). Importantly this study illustrated the importance of date of disturbance of the seedbank relative to the underlying annual dormancy cycles. In horticulture, the wide range of possible crop the sowing/transplanting times also means that a similarly wide spectrum of crop/weed scenarios may result.

7.3.1 Weed seed dormancy

In relatively short-term studies it is often difficult to identify the factors that are important in determining the patterns of emergence for different weed species. However, it is well known that when results from longer-term studies are averaged over time, they demonstrate that some weed species follow characteristic, and potentially predictable, patterns of annual emergence (Lawson *et al.*, 1974). This is because many of the common weed species of horticultural systems posses non-deep physiological dormancy and therefore able to cycle between the non-dormant state through conditional dormancy back to state of full dormancy (secondary dormancy) (Baskin & Baskin, 1998). This cyclic dormancy is one of the most important features of weed seedbank dynamics and provides a mechanism by which weed seeds can extend their longevity in the soil. Dormancy defines the emergence periodicity of a species. The periodicity tables for common agricultural weeds are derived from data averaged from long-term emergence studies (Fig 7.3). They provide a general guide to the average underlying dormancy cycles and emergence flushes of weed species (Roberts & Feast, 1970; Roberts & Potter, 1980; Roberts, 1982). Two basic categories of dormancy breaking and germination ecology are evident in horticultural weeds;

1. those species with seeds requiring warm temperatures during the summer months to break dormancy, for example red deadnettle and ivy-leaved speedwell (Roberts & Neilson, 1982).
2. those requiring winter chilling to break dormancy, for example fat-hen and knotgrass (Courtney, 1968; Roberts & Benjamin, 1979)

In general the dormancy breaking process takes place during the season unfavourable to the growth and successful reproduction of that species. For example, a weed species at risk of severe winters will tend to have a long chilling period to release dormancy and subsequently a slow response germination rate at low temperatures to avoid the risk of frost. However, some species show intermediate behaviour (eg shepherd's purse) or are able to germinate virtually all year round (eg chickweed or annual meadow grass) (Roberts & Feast, 1970). In spring sown field vegetable crops that dominate horticultural production, the majority of weeds are those requiring winter chilling and hence having spring emergence. This is in contrast to many of the autumn-germinating grass weeds that dominate autumn-sown arable crops.

Traditional physiological methods of studying dormancy are confounded by the difficulty of separating the germination and dormancy processes. However, advances made in seed science in recent years are improving our understanding of the physiology of these cycles in the weed seedbank. Temperature and water potential appear to be the two primary factors determining dormancy cycles and recent models based on thermal time have proved to be increasingly successful in predicting the timing of loss and induction of dormancy (Bowmeester & Karssen 1993; Christensen *et al*., 1998; Batlla & Benech-Arnold, 2003). These models have however been less successful in predicting actual numbers because of the population variability in dormancy (Vleeshouwers & Bouwmeester, 2001). As stated by Vleeshouwers & Kropff (2000), ultimately the most important progress towards the development of dormancy models "might be expected from research at the molecular physiological level". Examples of these contemporary methods and opportunities for understanding dormancy are described by Chao (2002).

Fig 7.3. Germination periods of some common annual weeds (reproduced from the 9th edition of the Weed Management Handbook, Blackwell Science Limited, Naylor 2002)

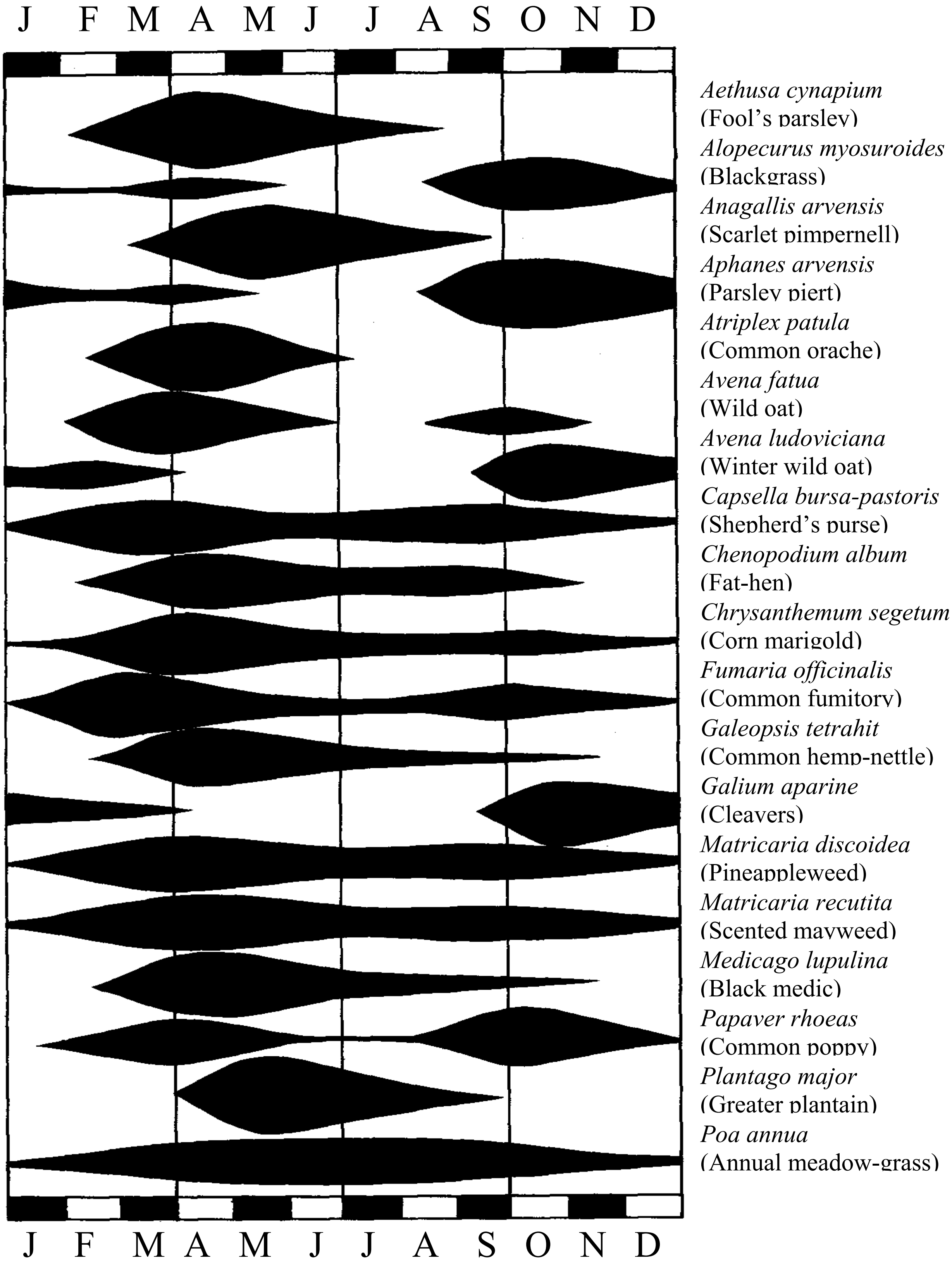
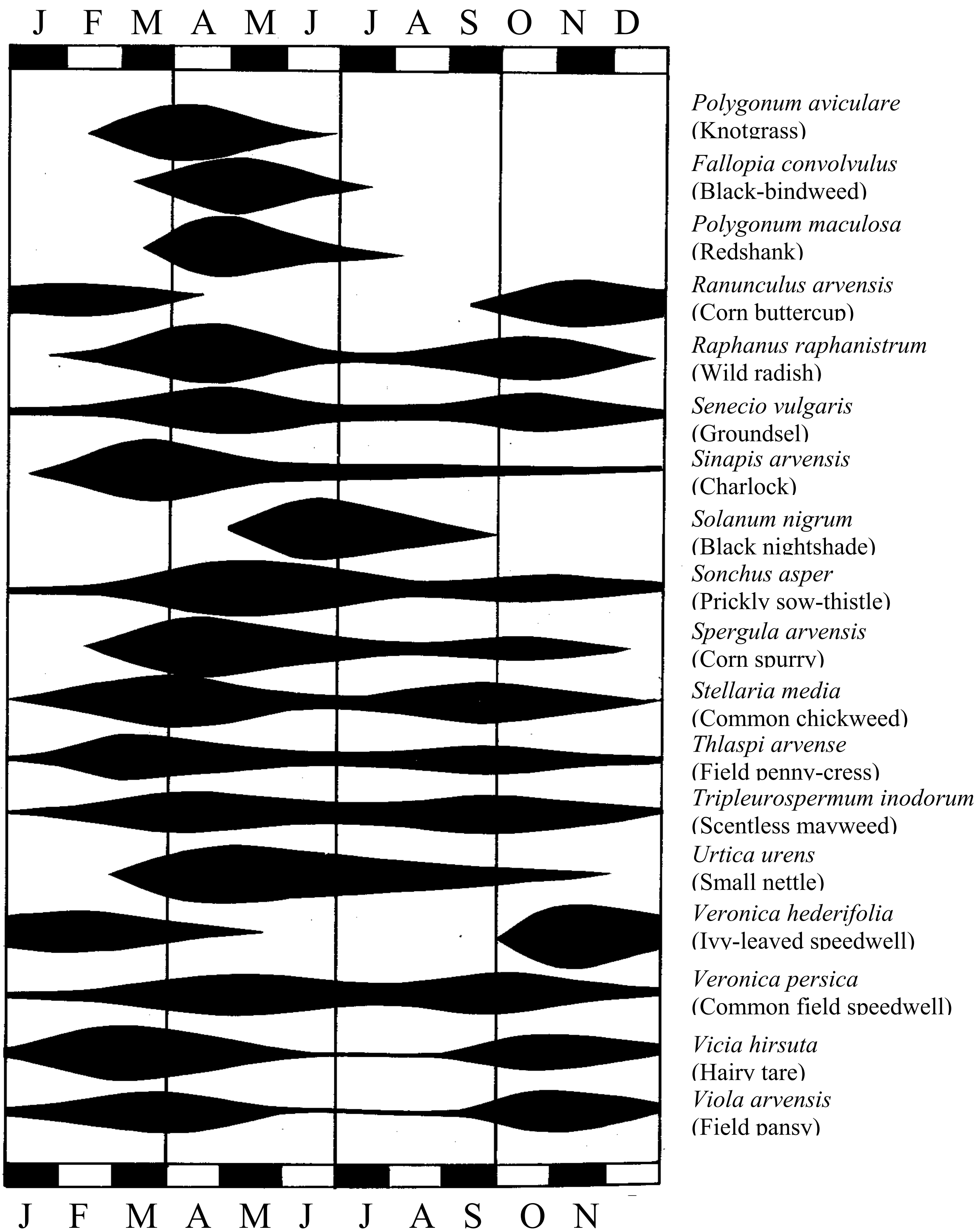


Fig 7.3. cont…. Germination periods of some common annual weeds (reproduced from the 9th edition of the Weed Management Handbook, Blackwell Science Limited, Naylor 2002)



7.3.2 Germination & Emergence

Vertical gradients exist in soil microclimate, such as water availability, temperature and light. In addition, unlike crop seeds, weed seeds are typically variable in their vertical distribution in the soil profile. Many weed seeds are thought to be able to perceive and respond to these gradients such that germination is prevented at depths from which the seedlings cannot emerge. Therefore, one of the major factors influencing the success of weed seed germination and subsequent emergence is the seed's position within the soil profile (Mohler & Galford, 1997; Grundy *et al* 1999).

In well-prepared horticultural seedbeds, soil moisture and temperature are likely to be the major determinants of seed germination patterns and so these two driving factors can be used as the basis of seed germination models. Hydrothermal time is a combination of thermal time above a base temperature and hydrotime above a base water potential (Gummersson 1986). and this concept, and variations based on it, have been used to successfully predict the germination (and subsequent emergence) of crop species such as carrot in variable field conditions (Rowse & Finch-Savage, 2003). However, there are only a small number of examples where these modelling concepts, originally developed to predict germination of commercial crop seed, have been applied to describe the behaviour of weed species. So far the germination time courses of fat-hen and chickweed have been successfully described in this way (Grundy *et al.*, 2000; Roman *et al.*, 1999).

Studies have looked at the post-germination/pre-emergence phase and identified that whilst germination makes the greatest contribution towards the exact timing of an emergence event, the pre-emergence growth phase can have a major affect on the number of seedlings emerging due to post-germination death. The period of pre-emergence growth will also influence the spread of the flush of emergence because of the variations in the time required for seedlings from different burial depths to reach the surface (Finch-Savage *et al.,* 1998). Although pre-emergence growth has been studied for a few weed species (Vleeshouwers 1997; Grundy *et al.,* 2003;) most research has focused on cultivated species which may ultimately help us to understand the behaviour of weeds.

7.3.3 Identifying the onset of competition to optimise the timing of weed management

Crucially it is the relative emergence time of the crops and weeds determines the extent of crop/weed competition during subsequent growth and hence determines the optimum or critical timing for successful weed removal (see also Chapter 2). This establishment phase is particularly important for many horticultural field vegetables where some crop species are innately slow to establish enabling weeds to have a potential competitive head start. The relative emergence timing of crops and weeds is critical in the absence of the herbicides where physical methods are required that often exploit differences in growth stage of the crop and weed (Sattin *et al.* 1998). However, the timing and temporal spread of a flush of weed emergence is also important when using single post-emergence applications of herbicide (Myers *et al.,* 2002), which are extremely dependent on precise timing to maximise their effect and to avoid subsequent applications. Despite the importance of this phase in weed management, the consequences of any given seedbed husbandry, sowing practice or even ambient weather condition on the relative timing of the crop and weeds is not known or well understood. Descriptive simulation models for germination and seedling emergence in response to seedbed conditions are being developed largely for crops in France (Durr *et al.*,

2001) and the UK (Finch-Savage *et al.*, 1998; Whalley *et al.*, 1999; Rowse & Finch-Savage, 2003), but they could also be used for the weed seeds that germinate and grow in the same seedbeds (Colbach *et al.* 2002ab). Any improvements that can be achieved in optimising the timing of weed removal (either chemically or physically) will clearly have positive implications for growers, consumers and the environment.

7.3.4 Shifts in the time of weed emergence with climate change

An understanding of weed emergence and growth relative to weather conditions may help predict likely behaviour in atypical years and how the weed flora and weed management may change with climate. One example is the 2000/2001 UK season, which was notably difficult for both crop establishment and weed control due to an abnormally wet autumn followed by a cool wet spring and very dry early summer. A survey of agronomists and agrochemical advisors regarding the impact of this weather pattern on subsequent weed management (as reported by Strachan & Clarke in the BCPC 38thAnnual Review of Weed Control 2001) noted that these atypical weather conditions caused problems with the correct timing of pre-emergence herbicides in cereals and reduced their residual activity due to leaching. Therefore there was a need for greater reliance on post-emergence sprays, which were frequently required at increased rates to counteract delays in spraying and the fact that many weeds were larger by the time spraying was possible. The poor crop establishment caused by unusually dry seedbeds for crops sown in the late spring/early summer months, lead to poorly competitive cereal crops that gave greater opportunity for weeds to establish. The weed management problems were partly caused by a combination of poor conditions for good herbicide efficacy and lack of information available to allow farmers/growers to assess the risk of the situation deteriorating and the potential knock-on effects on crop and weed management.

In the long-term, subtle changes in our climate may lead to equally challenging weed control issues for growers in the future. For example, the length of the growing season may directly alter the timing and magnitude of weed emergence. Importantly, the ability to time farm operations (physical and chemical) in relation to weather could prove to be just as critical for weed management (Harris & Hossell, 2001). Suggestions have also been made that there will be greater variability in temperature and precipitation (Watkinson & Freckleton, 2001). Wetter winters and an earlier start to the spring growing season could provide weed management problems because of difficulties with field access for machinery at the time when control is needed. Better foresight of how the relative establishment of crop and weeds may respond to these climatic changes would be of benefit in planning appropriate control strategies and research (Grundy, 2002).

7.4 Reasons for change in the weed seedbank since 1950

7.4.1 Tools for modifying the species composition of the seedbank and subsequent above-ground weed flora.

There are many possible ways in which the seedbank may be influenced within an agricultural system by manipulating any one of the component processes (as summarized in Fig 7.1). Similarly, the dynamic nature of the seedbank means that over the last 50 years it has undergone changes in both density and species content in response to long-term general trends in agricultural practice. The most influential changes have been in the type and timing of cultivation, stubble management, time of crop drilling, choice and diversity crop of rotation and the introduction of herbicides. Albeit on a less dramatic scale, methods such as solarization, mulching, soil sterilization, steaming, residual herbicides and the use of dormancy breaking stimulants have also contributed. In the future, new technologies such as and the introduction of genetically-modified crops may also play their part in modifying the seedbank. All these methods, either used alone or in combination, can be used towards encouraging the establishment of certain "desirable" weed flora from the seedbank or for suppressing/depleting species from the seedbank that are becoming problematic. In this capacity, knowledge of the ecology of the weed seedbank has certainly been highlighted in numerous studies as "increasingly applicable towards improving the way we manage weeds" (Ghersa & Martinez-Ghersa, 2000) Thus, manipulating the weed seedbank may be used as part of a strategy to manage the long-term diversity of the weed flora and ultimately biodiversity. The effect of some of these methods are described in more detail below.

7.4.1.1 Herbicides

Until effective alternatives have been developed, chemical weed control will remain the standard for horticultural growers for the foreseeable future. Some of the implications of herbicide strategies on the above-ground weed flora are described elsewhere in this study in chapter 4. However, this section specifically concerns itself with the observations from studies that have monitored long-term the changes in the seedbank that have resulted from different herbicide regimes.

In a 16-year study (begun in 1963) the number of viable seeds in the top 15 cm of the soil were monitored on cropped plots which were either treated with herbicide or untreated (Roberts & Neilson, 1981). Carrots were amongst the mono-crops studied and the dominant weed species at the start of the study included annual meadow grass, parsley piert, chickweed and field pansy. Efforts were made to remove weeds on all plots before they reached maturity, however the seedbank was still replenished. Notably, of the mono-crops that were grown (i.e. carrots, spring barley, spring wheat and maize), it was on the carrots plots where the most appreciable increase in weed seeds was observed in the absence of herbicide (linuron), compared with the control plots that received no herbicide. Previous studies have shown that cultural means alone are difficult to prevent seed return in vegetable rotations (Roberts, 1968), and the increase in the seedbank on the carrot plots in the 16-year study was largely attributable to a major increase in Annual meadow grass (and to a lesser extend chickweed, shepherd's purse). These species all tended to dominate the vegetable rotation probably because they are all difficult to remove from among the carrot crop and are also comparatively short-lived species capable of all year round emergence and rapid seed shedding between cultivations (Roberts & Neilson, 1981). Other more recent studies have confirmed that a standard rate herbicide regimes generally lead to a reduction in the size of the weed seedbank over time whilst more seeds are generally found with regimes using reduced herbicide rates (Jones *et al.*,1997; Fykse & Waernhus, 1999; Hoffman *et al* 1999, Squire *et al.,* 2000).

Although there have been examples where reduced rates of herbicides have been successful with seedbank populations remaining relatively constant (Marshall & Arnold, 1994), herbicide application rates based on thresholds have been shown to be generally less successful at maintaining stable seedbank populations (Lawson *et al.*, 1992). At this time, the variability in the effectiveness of decision support models based on the seedbank or weed seedlings that are used for reducing herbicide application rates, demonstrate our lack of understanding of the complex interactions between "weed seedbank, weed emergence treatment effectiveness, weed-crop interference and environmental conditions" (Hoffman *et al.,* 1999). Herbicides have been shown not only to influence the quantity but also the quality of the seedbank and above-ground flora as described elsewhere in this study (Chapter 4)

7.4.1.2 Tillage; conventional vs. "conservation"

Position of seeds within the soil profile and frequency of disturbance are two ways in which rate of decline due to germination can be directly modified. Cultivation influences the rate of decline chiefly through increased germination potential. However, regardless of frequency, cultivation will only modify the magnitude of a flush of weed germination and emergence. The species content of this flush of emergence itself will ultimately depend the species-specific underlying dormancy cycles of the weed species present (Fig 7.3).

Different tillage systems have been shown to modify seedbank floristic diversity and distribution (Vanesse & Leroux, 2000). Studies have shown that reduced tillage (or conservation tillage as it is sometimes termed) is generally accompanied with an increase in the numbers of weed seeds found in the seedbank (Cardina *et al*., 1998; Tørresen, 1998) and these seeds tend to be located in the upper part of the soil profile (Moss, 1988; Hoffman *et al.*, 1998; Tørresen *et al.*, 2003). Apart from the benefits of reduced soil erosion and pesticide leaching, a number of other environmental benefits are associated with non-inversion tillage, such as increased availability of weed seeds for beneficial insects (Cromar *et al.*, 1999) and maintenance of earthworm populations (Hutcheon & Iles, 1996). Recruitment to the above-ground weed flora in reduced tillage regimes also tends to be biased towards the seeds in these shallower layers of the soil profile (Sissons *et al.*, 2000). Hence, the seedbanks of reduced tillage fields usually bear a much less resemblance to the above ground-flora than those of conventionally cultivated fields (Froud-Williams *et al.*, 1983)

In the above-ground flora, it is the annual grass weeds, wind-dispersed and perennial species that benefit from these reduced tillage regimes (Froud-Williams *et al,.* 1983; Turley *et al.,* 1996; Tuesca *et al.*, 2001), since they have either short-term or no seedbank, or they rely on vegetative propagation (McCloskey *et al.,* 1996; Tørresen & Skuterud, 2002). In contrast it is the annual broad-leaved weeds that benefit from conventional tillage, probably because this allows them to exploit the advantage offered by their persistent seedbank strategy (McCloskey *et al.,* 1996). The decline of weed seeds from the seedbank also tends to be more rapid with conventional as opposed to reduced tillage (Froud-Williams *et al.,* 1983). In the absence of seed return, soil seedbank densities will tend to decrease exponentially over time, but decline is more rapid under cultivation. In studies at HRI Wellesbourne, seasonal annual loss was found to be almost 60% when cultivated on a monthly basis throughout the year, 36% with four cultivations annually and as little as 22% with no cultivation at all (Roberts, 1981). Mulugeta & Stoltenberg (1997) also observed that greater soil disturbance resulted in a 16-fold increase in seedbank depletion of fat-hen compared with zero tillage, largely attributed to the greater emergence encouraged by the soil disturbance in the conventionally cultivated treatments.

7.4.1.3 Rotations

The specific effects of crop rotations on subsequent weed and weed seedbank populations are perhaps less-well documented than the effects of tillage or herbicides. Continuous crops tend to have the most dominance in the seedbank since weed species are promoted that mimic the life cycle of the crop and escape the repeated use of the same weeding regime (Chancellor, 1979; Cardina *et al.*, 1998). Therefore, rotations including spring-sown crops will tend to have an increased number of spring germinating species in the seedbank (Squire *et al.*, 2000). Similarly, rotations that have had either sunflower or oilseed rape have been shown to reduce the dominance of grass weeds in the seedbank; probably because of effective use grass-weed herbicides in these crops (Belo & Dias, 1998). Conversely, by increasing crop diversity within a rotation the life cycle and seed production from all groups of weeds can be equally disrupted (Cardina *et al.,* 1998; Kegode *et al.*, 1999), and hence dominance of a particular species (or group of species) in the seedbank minimised. Population-projection models have illustrated that ultimately certain crop rotations have the capacity to even bring about the elimination of a species (Jordan *et al.,* 1995).

7.4.1.4 Stubble management in preceeding crops (including arable)

Management of stubble after crop harvest is very important in weed management and can have important consequences for the following crop. A UK study demonstrated that control of volunteer oilseed rape was greatly improved if seeds shed at harvest were left on the soil surface for at least two weeks prior to incorporation (Pekrun & Lutman, 1998). Leaving the seeds on the soil surface prevented the seeds becoming light sensitive and so the persistence of these seeds was reduced. However, the effects of stubble management will vary with weed species.

In addition to the implications for the seedbank, and hence weed management in future crops, a number of studies have shown that stubbles left during the winter months support high wintering densities of many species of granivorous bird. For example, in a recent UK study linnets and reed bunting were rarely found on fields where weed seeds important in their diets fell bellow 250 seed m^{-2} (Moorcroft *et al.*, 2002) (see Chapter 5). For horticultural field crops, the possibilities for leaving plant material over winter from the previous crop need further investigation. This practice may not be acceptable for certain crop rotations for reasons of field hygiene (see also Chapter 6 section 6.4). Stubbles could provide a green bridge to undesirable pests or diseases (such as from diseased oilseed rape stubble as described by Maude *et al*, 1986 and Humpherson-Jones, 1983) or there may be possible residue effects on the crops drilled or transplanted in the following spring or nutrient imbalances. Addition of organic materials have also been reported to sometimes influence the severity of soil borne diseases that effect both crops and weeds (Leibman & Davis, 2000). This may result in conflicts that need to be quantified between management prescriptions for weed control, bird populations and biodiversity and finally the healthy establishment of the following crop. For example, for some herbicides there is a requirement for ploughing before sowing the following crop. Some soils (e.g. silts) are ploughed in autumn so that the weathering by frosts produces a suitable spring seedbed.

7.4.1.5 Modifying weed seed dormancy

A number of seedbank management techniques act directly on the germinability of the weed seeds by either stimulating or suppressing germination (Dyer, 1995.) Synthetic gibberellins have been used to enhance germination in species such as Black nightshade but with variable success in the field (Bond & Baker, 1990). A novel method to selectively deplete the seedbank has been the application of dormancy-breaking compounds such as smoked water. The method has been demonstrated in Australia with native and introduced weed species, however as yet it is not understood how compounds in the smoke affect the seeds. Light pulses are also used, particularly to encourage germination of fat-hen.

Mulches act by modifying the microclimate experienced by the seeds whilst in the cases of living mulches some plant residues can also have an inhibitory effect on germination. Polyethylene mulches have commonly used in horticulture to improve the early establishment of crops for a number of years but the cost of using them has been seen to be inhibitory for some vegetable crops. Recent advances in lifting and storage technology allowing reuse of the mulches and even the introduction of biodegradable mulches, are increasing its attractiveness to growers. Used specifically as a pre-planting mulch in vegetables systems, it has been found that weed establishment and growth were greatly reduced for a period of several weeks (Davies *et al.*, 1993). The mechanisms involved in the suppression of weed emergence following the use of pre-planting mulches are likely to be complex, but it is possible that a dormancy of the seeds may be induced (Grundy *et al.,* 1996). Indeed, the success of many of these novel methods for managing the seedbank and subsequent weed flora would be enhanced by a greater understanding of the annual dormancy cycle of buried weed seeds (Murdoch & Carmona, 1993).

7.4.2 Surveys

The status of what are termed “non-target” arable weed species in the seedbank have been previously collated by Squire (2001) as part of PN 0940. These species are considered non-target because they are either rare and therefore included with Biodiversity Action Pans (BAP’s) or they are common species that can sometimes be tolerated within arable crops below a certain population density. Many of these common non-target weed species in arable crops such as fat-hen, chickweed, knotgrass and annual meadow grass are common weeds of horticulture (Chapter 1, Table 1.2). However, in horticulture the term non-target is inappropriate as all these species, even at low levels of infestation, are troublesome and likely to cause some yield penalty, quality penalty or harvesting difficulty.

Although Squire (2001), has summarised many of the studies made of arable seedbanks (for example, Roberts & Chancellor 1986), few surveys have been made specifically in horticultural holdings. The exception to this would be the study made by Roberts (1958), where fields previously in a cereal rotation were sampled after being in vegetables for 2 years. Roberts & Stokes (1966) also concentrated their survey on fields, very few of which had been in vegetable (or mainly vegetable) rotations for less than 10 years; many had been in vegetable or rotation more than 60 years prior to the survey which was made between 1958 and 1962. Finally, Roberts & Neilson (1982) who survey 89 vegetable fields of England between 1968 and 1972.

Table 7.1. Presence of species (✓) in the seedbank 1955 to 1977. Species present in the seedbank but not in the list of species highlighted in this desk study are highlighted in blue.

Common name	Latin name	Roberts (1958)	Roberts & Stokes (1966)	Roberts & Neilson (1982)	Roberts & Chancellor (1986)
		1955	1958-1962	1968-75	1972-1977
BROAD-LEAVED WEEDS					
Annual mercury	*Maercurialis annua*		✓		
Black-bindweed	*Fallopia convovulus*	✓	✓	✓	✓
Bitter-cress, hairy	*Cardamine hirsuta*				
Bugloss	*Anchusa arvensis*				
Charlock	*Sinapis arvensis*		< 4 fields		✓
Chickweed, common	*Stellaria media*	✓	✓	✓	✓
Cleavers	*Galium aparine*	Seedlings only	< 4 fields		
Clover, red	*Trifolium pratense*	✓			
Clover, white	*Trifolium repens*		✓		✓
Corn marigold	*Chrysanthemum segetum*				
Corn spurrey	*Spergula arvensis*	✓	✓	✓	
Crane's-bill, cut-leaved	*Geranium dissectum*				
Cudweed, marsh	*Gnaphalium uliginosum*		✓	✓	
Deadnettle, henbit	*Lamium amplexicaule*		✓		
Dead-nettle, red	*Lamium purpureum*		✓		
Dock, broad-leaved	*Rumex obtusifolius*		✓ (*Rumex* spp.)		
Dock, curled	*Rumex crispus*	✓			✓
Fat-hen	*Chenopodium album*	✓	✓	✓	✓
Fool's parsley	*Aethusa cynapium*		< 4 fields		✓
Forget-me-not, field	*Myosotis arvensis*	Seedlings only	< 4 fields		✓
Fumitory, common	*Fumaria officinalis*	✓	✓		
Goosefoot, red	*Chenopodium rubrum*				
Goosefoot, many-seeded	*Chenopodium polyspermum*		✓		
Groundsel	*Senecio vulgaris*	✓	✓	✓	✓
Hairy Tare	*Vicia hirsuta*	✓	✓(*Vicia* spp.)		
Hemp-nettle, common	*Galeopsis tetrahit*				
Knotgrass	*Polygonum aviculare*	✓	✓	✓	✓
Mayweed, scented	*Matricaria recutita*	✓	✓	✓	
Mayweed, scentless	*Tripleurospermum inodorum*	✓	✓	✓	
Medick, black	*Medicago lupulina*	✓	✓		
Mouse-ear, sticky	*Cerastium glomeratum*	✓	✓		
Mouse-ear, common	*Cerastium fontanum*				✓
Nettle, small	*Urtica urens*	Seedlings only	✓	✓	
Nettle, common	*Urtica dioica*				✓
Nightshade black	*Solanum nigrum*		✓		
Orache, common	*Atriplex patula*	✓	✓		✓
Pansy, field	*Viola arvensis*	✓	✓	✓	✓
Parsley piert	*Aphanes arvensis*	✓	✓		✓
Pennycress, field	*Thlaspi arvense*	✓	< 4 fields		
Persicaria, pale	*Persicaria lapathifolia*		< 4 fields		
Pimpernel, scarlet	*Anagalis arvensis*	✓	✓	✓	✓
Pineappleweed	*Matricaria matricariodes*		✓	✓	✓
Plantain, greater	*Plantago major*	✓	✓	✓	✓
Poppy,long-headed	*Papaver dubium*	✓		✓	
Poppy, common	*Papaver rhoeas*	✓	✓ (*Papaver* spp.)	✓	✓
Redshank	*Persicaria maculosa*		✓	✓	✓
Rush, toad	*Juncus bufonius*		✓	✓	✓
Sandwort, slender	*Arenaria leptoclados*			✓	
Shepherd's-purse	*Capsella bursa-pastoris*	✓	✓	✓	✓
Sow-thistle, smooth	*Sonchus oleraceus*		✓		

Sow-thistle, prickly	*Sonchus asper*	✓	✓		✓
Speedwell, wall	*Veronica arvensis*	✓	✓	✓	✓
Speedwell, thyme-leaved	*Veronica serpyllifolia*				✓
Speedwell, common, field	*Veronica persica*	✓	✓	✓	✓
Speedwell, ivy-leaved	*Veronica hederifolia*	✓	✓		
Spurge, sun	*Euphorbia helioscopia*		✓		
Spurge, dwarf	*Euphorbia exigua*				✓
Swine-cress, lesser	*Coronopus didymus*		✓		
Thale cress	*Arabidopsis thaliana*	✓			
Thistle, creeping	*Cirsium arvense*				
Venus's-looking-glass	*Legouisa hybrida*				✓
Wild radish	*Raphanus raphanistrum*	✓	< 4 fields		
Willowherbs	*Epilobium spp*		✓		
GRASSES					
Bent, creeping	*Agrostis stolonifera*				✓
Bent, black	*Agrostis giganteaa*				✓
Blackgrass	*Alopecurus myosuroides*				✓
Brome, barren	*Anisantha sterilis*	Seedlings only			
Couch grass	*Elytrigia repens*				✓
Meadow grass, annual	*Poa annua*	✓	✓	✓	✓
Meadow-grass, rough	*Poa trivialis*				✓
Wild-oat	*Avena fatua*				✓
VOLUNTEERS					
Vol OSR	*Brassica napus*				
Vol Potatoes	*Solanum tuberosum*				
Median density (seeds m^{-2}) in the top 15cm		**10,700**	**10,200**	**4,120**	**4,360**
No. spp recorded		**34**	**47**	**23**	**35**

An early study made in 1953 the Horticultural Advisory Officers of the National Agricultural Advisory Service noted that chickweed, fat-hen, small nettle and annual meadow grass were the most common and problematic weeds (Roberts, 1954). Shepherd's purse and field speedwell were less frequent and not considered a major problematic weeds at this time. Roberts (1958) recorded an average of 229 million/ac (approx. 56, 600 seeds m^{-2}) in the top 15 cm of the soil of an arable (mainly cereals) field at Wellesbourne in 1953. After only one year of vegetable cropping this declined to 38% and by 1955, after two years of vegetable cropping, this was further reduced 19% (approx 10, 700 seeds m^{-2}), however individual species responded differently. Whilst this provides a baseline it should be noted that only one field was sampled.

Then study made between 1958 and 1962, was from a much more intensive sample was used totalling 58 fields throughout England (Roberts & Stokes, 1966). A median value of 10, 200 seeds m^{-2} (similar to that of the samples taken in 1955, Roberts (1958)) was recorded, however there was considerable variability between fields. Again, annual meadow grass, small nettle, chickweed, groundsel, shepherd's purse, fat-hen and field speedwell accounted for 80% of the seeds that were recorded. It was noted that changing from a predominantly cereal rotation to vegetable dominated rotation tended to favour species that have short life-cycles capable of exploiting the generally more frequent cultivations associated with vegetable cropping. Roberts & Stokes (1966) also noted that the majority of fields sampled between 1958 and 1962 had not used herbicides to control weeds. They stated "the increasingly widespread adoption of chemical methods of weed control can thus be expected to have an appreciable influence on the character of the populations of viable weed seeds present in vegetable fields".

A decade later following the more wide spread use of herbicides seed numbers in vegetable fields had declined to a median of 4120 seed m^{-2} (Roberts & Neilson, 1982). By this time vegetables were becoming increasingly grown within cereal rotations. They noted that whilst there was "little change in the overall relative importance of the most frequently occurring species", it was probable that the widespread use of herbicides had been a major factor in the decline of the seedbank.

Roberts & Chancellor (1986) carried out another extensive survey of 64 fields between 1972 and 1977, but this time of mainly arable fields in which potatoes were sometime included within the rotation. This more recent study found a median value of 4,360 seed m^{-2}, which was comparable with the density found in the study of vegetable fields made by Roberts & Neilson (1982). However, since the early 1970's, there have essentially been no further surveys made specifically of vegetable fields

Moreover, even those surveys that have been made on arable soils have been "sporadic and largely uncoordinated" (Squire, 2001). Even within a specific field, the sampling strategy can make a significant difference because distribution of weeds both above-ground and in the seedbank can vary greatly; some species tending to more associated with the field margin and others more associated within the cop (Marshall, 1989). Therefore, it is only possible to extrapolate that some of the general observations and trends in arable soils over the last 50 years are likely to be similar for horticultural soils.

Some of the most striking changes in the arable flora since the early 1960's have been documented by Sutcliffe & Kay (2000). Whilst many of the rarer species found in the 1960's are also present 30 years later, their abundance has declined significantly. In their 1997 survey of 156 arable fields, they noted that for example scentless mayweed and field speedwell (both common weeds of field vegetable crops) had declined significantly between 1906s and 1997. Importantly, the seedbank has also shown a general decline (Robinson & Sutherland, 2002) and this supports the trend in field vegetable fields observed by Roberts & Neilson (1982) in the early 1970s (Table 7.1). It was suggested by Sutcliffe & Kay (2000) that for many of the rarer species, seedbank numbers may now be at "critically low levels". A number of measures have been suggested to help conserve and promote these species such as field margins, using very specific herbicides to target only the most aggressive weeds and leaving stubbles as long as possible. However, many of these schemes may not be so appropriate to horticulture (see Chapters 2 & 3).

7.4.3 Changes in the seedbank with relaxing weed management

Because of the complex interactions of the seedbank management tools described in section 7.4.1 above, it remains difficult to explain why some weed management regimes appear to suppress or increase certain weed species, or indeed to explain the case-to-case inconsistencies. At present, because of the relatively short-term nature of many existing studies and the buffering capacity of the seedbank itself, it is difficult to know whether changes in the seedbank resulting from transition to less intensive management, are oscillations or true long-term changes in direction (Albrech & Sommer, 1998). However, reduced rates of herbicide or complete cessation of herbicide applications will in general lead to an increase in weed numbers in the seedbank (Schmidt *et al*, 1995; Barberi *et al.,* 1998; Bond *et al.,* 1998; Squire *et al.,* 2000). Rotations including a large proportion of spring sown crops can also lead to an increase in species richness; possibly through amplification of species already in the seedbank at very low levels (Hebden *et al.*, 1998). However the TALISMAN experiments showed that a relaxing of weed management will also tend to amplify the more dominant weeds (Squire *et al.*, 2000). In a 3-year-study of the seedbanks of an organic, integrated and conventional system, it was the most difficult to control weeds such as fat-hen, chickweed and mayweed that increased most significantly over time (Albrecht & Sommer 1998). Barberi *et al.,* (1998) also noted that it was some of the most troublesome weeds in a continuous crop of maize that also had the highest relative abundance indices in the organic and reduced input systems. The fear that the adoption of herbicide-free weed management will equate to more injurious weeds, has been one of the major constraints to the uptake of organic methods (Bond *et al.*, 1998; Bond & Grundy 2001).

7.5 Restoration of vegetation from the seedbank for biodiversity purposes.

Several studies have examined the success of establishing desirable a diverse weed populations using both the natural seedbank or sown mixes (Lawson *et al*, 1994). These areas have been specifically created within a range of field scenarios including set-aside schemes, as field margins or as eco-strips within fields to help deliver biodiversity benefits. These areas have been proposed as a way of enhancing biodiversity however there are a range of approaches to their management (Vickery *et al*., 2002). There are some examples where non-rotational set-aside has been found after a number of years to favour both rare arable weeds and species diversity (Albrecht, 2003), however the successional behaviour of these areas and hence their successful establishment vary greatly. Development of desirable communities from the natural seedbank and seed rain can (for example for strips, boundaries or margins) be an unreliable process and sowing of species–rich mixes are often required. This has been seen in grassland establishment on previous arable soils (Pywell *et al.,* 2002). This is because the early successional stages of vegetation development on agricultural land (including both arable and horticultural) tends to be dominated by perennial weeds such as dock (Turley *et al.,* 1998; Van der Putten *et al.,* 2000) and wind-borne such as the sow thistles species can also benefit (Albrecht & Sommer, 1998; Davies *et al.*, 1998). A selective and appropriate programme of herbicides could potentially be used, not only to manage weeds within a cropping system, but also to manipulate the species composition and dominance of the weed flora over time. There are examples of where pre-emergence herbicides combined with light cultivation (i.e. a stale seedbed) have been suggested as preparation to sowing and successful establishment of conservation wildflower mixes (Pywell *et al.,* 1998). Selective pre-emergence herbicides could possibly be used in this way to "steer" the direction of secondary succession and allow desirable species to establish rather than certain undesirable species from the existing seedbank. However, it is generally true to say that without such specific introduction and/or management for rarer species, the more aggressive common arable weeds both already present in the seedbank and wind-blown, will tend to suppress their expression in the above-ground flora (Davies *et al.*, 1998; Turley *et al.,* 1998).

7.6 The role of seedbank modelling

7.6.1 Models to help optimise the timing and intensity of weed management

As a supplement or alternative to herbicides, many non-chemical weed control options directed at the seedbank such as the use of mulches and cultivations, fail to produce reliable results simply because of haphazard timing relative to the underlying dormancy cycles. Therefore, a better understanding of the germination behaviour of weed species in relation to cultural and meteorological events would undoubtedly present a number of opportunities for improvement of these methods. During the 1990's, there has been a shift in emphasis towards quantifying and modelling the seedbank, thus potentially enabling its use as a predictive resource. Many authors have argued that partitioning of the processes of emergence in the field (i.e. dormancy breaking, germination and pre-emergence growth), may offer improved insight into the underlying biology and thus provide more robust predictive models. For example, a wide range of different weed seedbank distributions and compositions could be modelled using a range of different tillage operations. This information could be used to maximise the stimulation of emergence when using a stale seedbed or to target specific problematic species, or even populations within a species, through exploiting dissimilarities in emergence characteristics.

The relative emergence times of the crop and weed are particularly important factors in determining the critical timing of weed removal as has been illustrated in a number of competition studies. Using the seedbank to help predict the timing of emergence is becoming increasingly possible using a combination of long-term databases and relatively simple laboratory-derived models based on temperature and moisture thresholds. However, several of the critical constraints and requirements to improve weed emergence models are well argued by Forcella *et al.* (2000). These include the need for better integration of the component models that drive emergence and continuous integrated information on the microclimate of the soil profile. In addition, detailed forecasts are still limited to a maximum of about a week in advance. Hence, it is currently unrealistic to suggest that predictive models could use actual, as opposed to average, weather predictions to predict weed emergence several weeks in advance. Long-term seasonal averages, and most importantly *their distribution,* would still be adequate for long-term planning for weed management (e.g. assigning risk to seasons at the extremes of the distribution). Despite some of the current limitations for using information about the timing of emergence for weed management, there are examples of forecasting computer software in the United States (Archer *et al.*, 2000) that are able to give at least informed guidance on likely outcomes.

7.6.2 Dynamic seedbank models for identifying long-term changes

Dynamic seedbank models that incorporate all the stages summarised in Fig.7.1 may be used to predict the broader long-term outcome of weed management strategies such as identifying shifts in weed flora, composition and spatial position (Rasmussen & Holst, 2003). As yet, our understanding of the interactions of many of the biological processes involved in seedbank dynamics has a long way to go (Grundy, 2003). One of the greatest benefits likely to be gained from the development of dynamic seedbank models are as a learning tool to help us to discover new ways of long-term modification the seedbank to our advantage and to understand the complexity of the processes involved (Watkinson & Freckleton, 2001; Rasmussen *et al.,* 2002). These dynamic models should incorporate both dominant species and those that are more rare and have specific beneficial properties for biodiversity so that greater insight can be gained into the development and maintenance of balanced communities.

Whilst scientifically or educationally valuable, overly-complex and over-parameterised models would be unlikely to provide the format required in practice by growers; simple robust versions would need to be developed. In the long-term, in combination with bioeconomic models for weed management (Buhler *et al.*, 1996) and incorporating measures of biodiversity value (such as in the WWMS, Collings *et al.*, 2003) robust dynamic models (and eventually decision support systems) could contribute significantly to making the most effective and environmentally desirable use of the increasingly limited weed control resources in horticulture. (Knott, 2002)

7.7 Summary & Conclusions

1. The weed seedbank impacts on biodiversity directly as a source of food for both birds and invertebrates, but also as the source of future weed populations which may themselves contribute towards floristic diversity.

2. Understanding weed population dynamics is vital to the development of sustainable weed management systems that are sympathetic to biodiversity. The soil weed seedbank is a critical aspect of weed population dynamics and therefore an integral part of any weed management strategy.

3. Few surveys have been specifically made of the weed seedbanks of horticultural holdings. The most recent were made in the early to mid 1970s. It was noted that changing from arable to vegetable dominated rotation tended to favour weed species capable of short-life cycles and exploiting the generally more frequent cultivations of vegetable cropping systems. It was proposed that the decline in the size of the seedbank from the previous survey in the early 1960s was probably partly due to the widespread introduction of herbicides. This general decline in the seedbank has also been noted in other arable studies with many rare species low at critically low levels.

4. There is little information on seedbanks of non-field vegetable horticultural systems that is relevant to the UK and could be reported in this study.

5. The weed seedbank may be modified in many ways by agricultural practice. The most influential are timing and intensity of cultivation, stubble management, time of crop drilling, choice and diversity of crop rotation and choice of herbicides.

    - Standard herbicide regimes tend to result in a reduction in the size of the seedbank, whilst regimes using reduced rates or no herbicide have more weed seeds.
    - Reduced tillage is generally accompanied by an increase in the weed seedbank, particularly in the upper part of the soil profile. This can increase availability of seeds for invertebrates and birds, however it is usually the annual grass weeds, wind-dispersed species and perennial weeds that benefit from reduced tillage rather than the annual broad-leaved species.
    - Continuous crops tend to show dominance of weed species in the seedbank and hence increasing the diversity of the crop rotation will minimise the dominance of certain weed species in both the seedbank above ground- flora.

6. In horticulture, the wide range of possible crop sowing and transplanting times results in a similarly wide spectrum of crop/weed combinations compared with arable systems. However, field vegetables, which dominate horticultural production, are mainly spring sown and thus associated with spring germinating weed species. Many of these species have been highlighted as important in their beneficial associations with birds and invertebrates.

7. To establish a desirable and diverse weed flora from the natural seedbank and seed rain can be unreliable without specifically introducing rare species and specifically managing for them. The more aggressive arable weeds and successional vegetation

development towards perennial species, will otherwise tend to suppress their expression above-ground. The germination ecology and management requirements for many of these rare weed species are poorly understood.

8. The timing of weed seed shedding relative to crop harvest has a significant effect on the weed species able to contribute towards the seedbank each year. There is a need to improve our understanding and quantification of weed seed production in a range of different cropping situations and environmental conditions.

9. Seed predation may account for a significant reduction in seed numbers from the seedbank. Currently, we know little of the precise biological interactions between specific weed species and seed predators. This makes it difficult to predict with any accuracy the relative proportion of seed loss attributed to predation in different cropping and environmental scenarios.

10. The success of many novel methods of managing the weed seedbank would be enhanced by a greater understanding of the annual dormancy cycle of buried weed seeds. It is fair to say that a physiological understanding of weed seed dormancy remains an enigma of weed science.

11. The relative emergence time of crop and weeds are crucial to good crop establishment and optimising weed removal timing. For example, many non-chemical means of weed removal rely on exploiting growth stage differences between the crop and weed, whilst the optimum timing of post-emergence herbicides will depend on the spread of a flush of weed emergence relative to the crop.

12. At present the soil surface (i.e. the interface between the soil weed seedbank and the above-ground environment) zone has widespread influence on the success of weed management and supporting biodiversity yet it represents an extremely variable and poorly understood/quantified area of weed population dynamics.

13. Weed emergence from the seedbank, growth and fecundity relative to prevailing weather conditions may help predict weed behaviour in atypical years. Better foresight of how crops and weed populations may respond to potential long-term climatic changes in the UK would be helpful to planning appropriate future management strategies where farm operation (both physical and chemical) could prove critical.

14. Models may provide a tool to predict the long-term outcome of weed management strategies and shifts in the weed flora (both composition and spatial). Therefore they should include not only common weed species but also those that are rare or have specific beneficial properties.

15. Variability in the success and accuracy of decision support systems reflects a lack of understanding of the complex interactions within the seedbank and in weed biology in general. There are a number of constraints to reliable model development, however better integration of the component processes has been highlighted as critical to their success. These models could help to make the most effective use of a declining weed control resource in horticulture.

7.8 References

ALBRECHT H & SOMMER H (1998) Development of the arable weed seed bank after the change from conventional to integrated and organic farming. *Aspects of Applied Biology 51, Weed Seedbanks: determination, dynamics and manipulation*. 279-288.

ALBRECHT H (2003) Development of the daspore pool in soil during six years set-aside. *Aspects of Applied Biology 69, Seedbanks: determination, dynamics and management*. 101-106.

ANDERSSON L (1998). Post-dispersal seed removal in some agricultural weeds. *Aspects of Applied Biology 51, Weed Seedbanks: determination, dynamics and manipulation*. 279-288.

ARCHER D, EKLUND J, FORCELLA F, & GUNSOLUS (2000) WeedCast 2.0: Forcasting weed emergence and growth in crop environments. http://www.morris.ars.usda.gov

BARBERI P, MACCHIA M, COZZANI A & BONARI E (1998). Structure of weed seedbank communities under different management systems for continuous maize crop. *Aspects of Applied Biology 51, Weed Seedbanks: determination, dynamics and manipulation*. 289-296.

BASKIN CC & BASKIN JM (1998) *Seeds: Ecology, biogeography, and evolution of dormancy and germination*. Academic Press, San Diego, USA

BATLLA D & BENECH-ARNOLD RL (20030. A quantitative analysis of dormancy loss dynamics in *P. aviculare* L. seeds: Development of a thermal time model based on changes in seed population and thermal parameters. *Seed Science Research* **13:** 55-68.

BELO AF & DIAS LS (1998). Changes in grass-weed seedbanks in relation to arable crops and rotations. *Aspects of Applied Biology 51, Weed Seedbanks: determination, dynamics and manipulation*. 221-228.

BOND W & BAKER JP (1990). Responses of dry-stored seed of *Solanum nigrum* L. to germination stimulant Ac 94377. *Annals Of Applied Biology (tests Of Agrochemicals And Cultivars 11)* **116**: 84-85.

BOND W, BURSTON S, MOORE HC, BEVAN JR & LENNARTSSON MEK (1998). Changes in the weed seedbank following different weed control treatments in transplanted bulb onions grown organically and conventionally. *Aspects of Applied Biolgoy 51, Weed Seedbanks: determination, dynamics and manipulation*. 273-278.

BOND W & GRUNDY AC (2001) Non-chemical weed control management in organic farming systems. *Weed Research* **41**, 383-405

BOUWMEESTER HJ & KARSSEN CM (1993). Seasonal periodicity in germination of seeds of *Chenopodium album* L. *Annals of Botany* **72**, 463-473.

BUHLER DD, KING RP, SWINTON SM, GUNSOLUS JL & FORCELLA F (1996) Field evaluation of a bioeconomic model for weed management in corn (*Zea mays*). *Weed Science* **44,** 915-923

CARDINA J, WEBSTER TM & HERMS CP (1998). Long-term tillage and rotation effects on soil seedbank characteristics. *Aspects of Applied Biology 51; Weed Seedbanks: determination, dynamics and manipulation*. 213-220.

CHANCELLOR RJ (1979). The long-term effects of herbicides on weed populations. In: *Annals of Applied Biology 91*, Proceedings of a review of long term effects of herbicides. 141-144.

CHAO WS (2002) Contemporary methods to investigate seed and bud dormancy. *Weed Science* **50**, 215-226.

COLBACH N, CHAUVEL B, DÜRR C, RICHARD (2002a) Effect of environmental conditions on blackgrass (Alopecurus myosuroides Huds.) germination with time. I. Effect of temperature, storage conditions and light. *Weed Research,* 42, 210-221

COLBACH N, DÜRR C, CHAUVEL B, RICHARD (2002b). Effect of environmental conditions on blackgrass (Alopecurus myosuroides Huds.) germination with time. II. Effect moisture conditions and storage length. *Weed Reseach, 42,* 222-230.

COLLINGS LV, GINSBURG D, CLARKE JH, MILNE AE, PARSON DJ, WILKINSON DJ, BENJAMIN LR, MAYES A, LUTMAN PJ, DAVIES DHK (2003) WMSS: Improving the precision and prediction of weed management strategies in winter dominant rotations. *Proceedings BCPC International Congress Crop Science and Technology,* (in press).

CHRISTENSEN BAUER M, MAYER SE & ALLEN PS (1998). A simulation model to predict seed dormancy loss in the field for *Bromus tectorum* L. *Journal of Experimental Botany* **49**, 1235-1244.

COURTNEY AD (1968). Seed dormancy and filed emergence in *P. aviculare. Journal of Applied Ecology* **5**: 675-684.

CROMAR HE, MURPHY SD, SWANTON CJ (1999). Influence of tillage and crop residue on postdispersal predation of weed seeds. *Weed Science* **47**, 184-194.

DAVIES DHK, CHRISTAL A, FISHER NM, LAWSON HM & MCN WRIGHT G (1998). Soil seedbank changes under non-rotational set-aside management and the relationship with vegetation development. *Aspects of Applied Biology 51, Weed Seedbanks: determination, dynamics and manipulation*. 255-264

DAVIES DHK, DRYSDALE A, MCKINLAY RG & DENT JB (1993). Novel approaches to mulches for weed control in vegetables. In: *Proceedings of Crop Protection in Northern Britain*: 271-276.

DURR C, AUBERTOT J-N, RICHARD G, DUBRULLE P, DUVAL Y, BOIFFIN J (2001) SIMPLE: a model for SIMulation of PLant Emergence predicting the effects of soil tillage and sowing operations. *Soil Science Society of America Journal,* **65**, 414-42

DYER WE (1995). Exploiting Weed Seed Dormancy and Germination Requirements through Agronomic Practices. *Weed Science* **43**, 498-503.

FENNER M (2000). *Seeds: The ecology of regeneration in plant communities*. 2nd edition. CABI Publishing, Wallingford, UK

FINCH-SAVAGE WE, STECKEL JRA & PHELPS K (1998) Germination and post-germination growth to carrot seedling emergence: predictive threshold models and sources of variation between sowing occasions. *New Phytologist* **139**, 505-516

FORCELLA F (1998) Real-time assessment of seed dormancy and seedling growth for weed management. *Seed Science Research* **8,** 201-209

FORCELLA F, BENECH-ARNOLD RL, SANCHEZ R & GHERSA CM (2000) Modelling seedling emergence. *Field Crops Research* **67**, 123-139.

FORCELLA F (2003). Debiting the seedbank: priorities and predictions. *Aspects of Applied Biology 69, Seedbanks: determination, dynamics and management*. 151-162

FROUD-WILLIAMS, R.J., CHANCELLOR, R.J. & DRENNAN, D.S.H. (1983) Influence of cultivation regime on buried weed seeds in arable cropping systems. *Journal of Applied Ecology*, **20**, 199-208.

FROUD-WILLIAMS RJ (1999) A biological framework for developing a weed management support system for weed control in winter wheat: weed seed biology. In *Proceedings 1999 Brighton Crop Protection Conference - Weeds.* 747-752.

FYKSE H & WAERNHUS K (1999) Weed development in cereals under different growth conditions and control intensities. *Acta Agriculturae Scandinavica Section B Soil and Plant Science* **49**, 134-142

GHERSA CM & MARTINEZ-GHERSA MA (2000). Ecological correlates of weed seed size and persistence in the soil under different tilling systems: implications for weed management. *Field Crops Research* **67**, 141-148.
GRIME JP, HODGSON JG & HUNT R. (1988) *Comparative Plant Ecology: a functional approach to common British species.* Unwin Hyman Ltd., London, UK.
GRUNDY AC, BOND W & BURSTON S (1996) The effect of short-term covering of the soil surface with black polyethylene mulch on the subsequent patterns of weed seedling emergence and the extent of seed loss from the weed seedbank. In: *Proceedings X Colloque International sur la Biologie des Mauvaises Herbes,* Dijon, France, 395-401.
GRUNDY AC MEAD A & BURSTON S (1999) Modelling the effect of cultivation on seed movement with application to the prediction of weed seedling emergence. *Journal of Applied Ecology* **36**:663-678
GRUNDY AC, PHELPS K, READER RJ & BURSTON S (2000). Modelling the germination of *Stellaria media* using the concept of hydrothermal time. *New Phytologist* **148**, 433-444.
GRUNDY AC (2002). Extreme weather and weeds: can we realistically predict weed emergence and how useful would that information be? *BCPC 39th annual review of weed control*. 32-35.
GRUNDY AC (2003). Predicting weed emergence: a review of approaches and future challenges. *Weed Research* **43**, 1-11.
GRUNDY AC (2003). To quantify weed seed persistence, production and dormancy in vegetable crops. *Defra final report for Project HH 2011SFV*
GRUNDY AC, MEAD A & BURSTON S (2003) Modelling the emergence responses of weed seeds to burial depth: interactions with seed density, weight and shape. *Journal of Applied Ecology* **40**. 757-770
GULDEN, R. H. AND S. J. SHIRTLIFFE (2003). Harvest losses of canola (*Brassica napus*) cause large seedbank inputs. *Weed Science* **51**, 83-86.
GUMMERSON RJ (1986) The effect of constant temperatures and osmotic potential on the germination of sugar beet. *Journal of Experimental Botany* **37**, 729-41.
HARRIS D & HOSSELL JE (2001) Weed management constraints under climatic change. In: *Proceedings 2001 Brighton Crop Protection Conference – Weeds*, Brighton, UK, 91-96.
HEBDEN PM, RODGER SJ, MCN WRIGHT G & SQUIRE G (1998). Effects of rotation and cropping system on dynamics of seedbank species. *Aspects of Applied Biology 51, Weed Seedbanks: determination, dynamics and manipulation*. 243-248.
HOFFMAN ML, OWEN MDK &BUHLER DD (1998). Effects of crop and weed management on density and vertical distribution of weed seeds in soil. *Agronomy Journal* **90**, 793-799
HOFFMAN ML, BUHLER DD & OWEN MDK (1999) Weed population and crop yield responses to recommendations from a weed control decision aid. *Agronomy Journal* **91**: 386-392.
HUMPHERSON-JONES FM (1983) Pathogenicity studies on isolates of *Leptosphaeria maculans* from brassica seed production crops in south-eat England. *Annals of Applied Biology* **103,** 7-44.
HUTCHEON JA & ILES DR (1996). Influence of crop management systems and rotation on earthworm populations 1990-1994. *Aspects of Applied Biology 47, Rotations and cropping systems 229-236.*
JONES NE, CLARKE JH & BURN AJ (1997). The effects of herbicide input level and rotation on winter seed availability for birds. *Proceedings Brighton Crop Protection Conference – Weeds*, 1161-1166.
JORDAN N, MORTENSEN DA, PRENZLOW DM & COX KC (1995). Simulation Analysis of Crop-Rotation Effects on Weed Seedbanks. *American Journal of Botany* **82**, 390-398.

KEGODE GO, FORCELLA F & CLAY S(1999). Influence of crop rotation, tillage, and management inputs on weed seed production. *Weed Science* **47**, 175-183.

KNOTT C (2002). Weed control in vegetable crops. In: *Weed Management Handbook* (ed REL Naylor) 9th edition, Blackwell Science, Oxford, UK

LAWSON HM, WRIGHT GM, *et al* (1992). The effects of reduced herbicide strategies on the weed flora in cereals in Scotland: and interim report. *IXe Colloque international sur la biologie des mauvaises herbes, 16-18 September 1992, Dijon, France. Paris, France, Anpp*: 269-278

LAWSON HM, WAISTER PD & STEPHENS RJ (1974) Patterns of emergence of several important arable weed species. *British Crop Protection Council Monograph* **9**, 121-135. The British Crop Protection Council, Farnham, UK.

LEGUIZAMON ES & ROBERTS HA (1982). Seed production by an arable community. *Weed Research* **22**, 35-39.

LIEBMAN M & DAVIS SA (2000). Integration of soil, crop and weed management in low-external- input farming systems. *Weed Research* **40**, 27-47.

LUTMAN PJW (2002). Estimation of seed production by *Stellaria media, Sinapis arvensis* and *Tripleurospermum inodorum*. *Weed Research*, **42**, 359-369.

LUTMAN PJW, CUSSANS GW *ET AL.* (2002). The persistence of seeds of 16 weed species over six years in two arable fields. *Weed Research* **42**, 231-241

MARSHALL EJP (1989). Distribution Patterns of Plants Associated with Arable Field Edges. *Journal of Applied Ecology* **26**, 247 258

MARSHALL EJP & ARNOLD GM (1994). Weed Seed Banks in Arable Fields under Contrasting Pesticide Regimes. *Annals of Applied Biology* **125**, 349-360.

MAUDE RB, BAMBRIDGE JM & SPENCER A (1986) Diseases of brassicas – biology, resistance and control. In: *36th Annual Report for 1985 National Vegetable Research Station*, Wellesbourne, Warwick: 56-60.

MCCLOSKEY M, FIRBANK LG, WATKINSON AR & WEBB DJ (1996) The dynamics of experimental arable weed communities under different management practices. *Journal of Vegetation Science*. **7**: 799-808

MILBERG P, HALLGREN E & PALMER MW (2001). Timing of disturbance and vegetation development: How sowing date affects the weed flora in spring-sown crops. *Journal of Vegetation Science*, **12**, 93 98.

MILLER ACE, LUTMAN PJW, WRIGHT KJ & MCN WRIGHT G (1998). A preliminary report on patterns of seedbank decline and the relationship between seedbank and seedling emergence for seven arable weed species in winter wheat. *Aspects of Applied Biology 51; Weed Seedbanks: determination, dynamics and manipulation*. 59-67

MOHLER CL & GALFORD AE (1997) Weed seedling emergence and seed survival: separating the effects of seed position and soil modification by tillage. *Weed Research,* **37**: 147-155.

MOORCROFT D, WHITTINGHAM MJ, BRADBURY RB & WILSON JD (2002). The selection of stubble fields by wintering granivorous birds reflects vegetation cover and food abundance. *Journal of Applied Ecology,* **39**, 535-547

MOSS SR (1988). Influence of cultivations on the vertical distribution of weed seeds in the soil. In: *Proceedings of the 8thUntrnational Symposium on Weed Biology, Ecology and Systematics,* 71-80.

MULUGETA D & STOLTENBERG DE (1997). Increased weed emergence and seed bank depletion by soil disturbance in a no-tillage system. *Weed Science,* **45**, 234-241.

MURDOCH AJ & CARMONA R (1993) The implications of the annual dormancy cycle of buried weed seeds for novel methods of weed control. In*: Proceedings 1993 Brighton Crop Protection Conference – Weeds,* Brighton, UK, 329-334.

MYERS MW, CURRAN WS, MORTENSEN DA, VANGESSEL MJ & MAJEK BA (2002) Effects of soil disturbance and geographic location on weed species emergence. In: *Proceedings of 12th EWRS Symposium, Papendal, Arnhem, The Netherlands*, 364-365.

NAYLOR REL (2002) *Weed Management Handbook* (ed REL Naylor) 9th edition. British Crop Protection Council, published by Blackwell Science Ltd., Oxford, UK

NICKERSON-ZWAAN (2003) Vegetable seeds 2003-04.

PEKRUN C & LUTMAN PJW (1998). The infuence of post-harvest cultivation on the persistence of volunteer oilseed rape. *Aspects of Applied Biology 51; Weed Seedbanks: determination, dynamics and manipulation*. 113-118.

PYWELL RF, NOWAKOWSKI M, WALKER KJ, BARRATT D & SPARKS TH (1998). Preliminary studies of the effects of pre-emergence herbicides on the establishment of injurious weeds and wildflower mixes. *Aspects of Applied Biology 51, Weed seedbanks: Determination, Dynamics & Manipulation.* 173-178.

PYWELL RF, BULLOCK JM, HOPKINS A , WALKER KJ, SPARKS TH, BURKE MJW & PEEL S (2002). Restoration of species-rich grassland on arable land: assessing the limiting processes using a multi-site experiment. *Journal of Applied Ecology,* **39**, 294-309.

RASMUSSEN IA, HOLST N, PETERSEN L & RASMUSSEN K (2002) Computer model for simulating the long-term dynamics of annual weeds under different cultivation practices. In: *Proceedings 5th EWRS Workshop on Physical Weed Control*, Pisa, Italy, 6-13.

RASMUSSEN IA & HOLST N (2003) Computer model for simulating the long-term dynamics of annula weeds: from seedlings to seeds. *Aspects of Applied Biology 69, Seedbanks: determination, dynamics and management*. 277-284

ROBERTS HA (1954). Weeds of vegetable crops and their control. *NAAS quarterly Review* **24:**139-145

ROBERTS HA (1958). Studies on the weeds of vegetable crops. I initial effects of cropping on the weed seeds in the soil. *Journal of Ecology* **46**, 759-768.

ROBERTS HA (1962). Studies on the effects of vegetable crops. II Effects of six years of cropping on the weed seeds in the soil. *Journal of Ecology*, **50**, 803-813

ROBERTS HA (1968). The changing population of viable weed seeds in an arable soil. *Weed Research*, **8**, 253-256

ROBERTS HA (1982). Seasonal patterns of weed emergence. *Aspects of Applied Biology 1. Broad-leaved weeds and their control in cereals*. 153-154.

ROBERTS HA & CHANCELLOR RJ (1986). Seed banks of some arable soils in the English midlands. *Weed Research*, **26**, 251-257

ROBERTS HA & DAWKINS PA (1967). Effect of cultivation on the numbers of viable weed seeds in soil. *Weed Research*, **7**, 290-301.

ROBERTS HA & FEAST PM (1970) Seasonal distribution of emergence in some annual weeds. *Experimental Horticulture,* **21**, 36-41.

ROBERTS HA & NEILSON JE (1981). Changes in the soil seed bank of four long-term crop/herbicide experiments. *Journal of Applied Ecology* **18**, 661-668.

ROBERTS HA & NEILSON JE (1982) Role of temperature in the seasonal dormancy of seeds of *Veronica hederifolia. New Phytologist*, **90**, 745-749.

ROBERTS HA & NEILSON JE (1982) Seed banks of soils under vegetable cropping in England. *Weed Research*, **22,** 13-16

ROBERTS HA & POTTER ME (1980) Emergence patterns of weed seedlings in relation to cultivation and rainfall. *Weed Research* **20,** 377-386.

ROBERTS HA & STOKES GF (1966). Studies on the effects of vegetable crops. VI Seed populations of soil under commercial cropping. *Journal of Applied Ecology*, **3**, 181-190.

ROBERTS E H & BENJAMIN S K (1979) The interaction of light, nitrate and alternating temperature on the germination of *Chenopodium album*, *Capsella bursa pastoris* and *Poa annua* before and after chilling. *Seed Science & Technology* **7**: 379-392.

ROBINSON RA & SUTHERLAND WJ (2002) Post-war changes in arable farming and biodiversity in Great Britain. *Journal of Applied Ecology*, **39**,157-176.

ROMAN ER, THOMAS AG, MURPHY SD & SWANTON CJ (1999) Modelling germination and seedling elongation of common lambsquarters (*Chenopodium album). Weed Science* **47**, 149-155.

ROWSE HR & FINCH-SAVAGE WE (2003) Hydrothermal threshold models can describe the germination response of carrot (*Daucus carota*) and onion (*Allium cepa*) seed populations across both sub- and supra-optimal temperatures. *New Phytologist* **158**: 101-10

SATTIN M, BERTI A. & ZANIN G. (1998) Influence of weed time of emergence and removal on crop yield loss. *FAO Report of "Expert Consultation on Weed Ecology and Management",* Rome, pp. 55-64

SCHMIDT W, WALDHARDT R & MROTZEK R (1995). *Extensification in arable systems: Effects on flora, vegetation and soil seed bank:* Results of the INTEX-project (University of Goettingen). *Tuexenia* **15**: 415 435.

SISSONS MJD, VAN ACKER RC, DERKSON DA & THOMAS AG (2000). Depth of seedling recruitment of five weed species measured in situ in conventional- and zero-tillage fields. *Weed Science* **48**, 327-332.

SQUIRE GR, RODGER S & WRIGHT G (2000). Community-scale seedbank response to less intense rotation and reduced herbicide input at three sites. *Annals of Applied Biology* **136**, 47 57.

SQUIRE GR (2001) Non-target weed species in the seedbank. In: *The impact of herbicides on weed abundance and biodiversity: A report for the UK Pesticide Safety Directorate PN0940* (eds EJP Marshall, V Brown, ND Boatman, PJW Lutman & G Squire). pp 134. IACR Long Ashton Research Station, UK

STRACHAN P & CLARKE J (2001) A review of the impact of the weather in 2000/01 on weeds and weed control. *38th Annual Review of Weed Control 2001.*

SUTCLIFFE OL & KAY QON (2000). Changes in the arable flora of central southern England since the 1960s. *Biological Conservation*, **93**: 1-8

THOMPSON K, BAND SR & HODGSON JG (1993). Seed size and shape predict persistence in soil. *Functional Ecology* **7**, 236-241.

THOMPSON, K, BAKKER J & BEKKER R (1997). *The soil seed banks of NorthWest Europe:methodology, density and longevity*. Cambridge University Press, Cambridge, UK.

TØRRESEN KS (1998). Emergence and longevity of weed seeds in soil with different tillage treatments. *Aspects of Applied Biology 51; Weed Seedbanks: determination, dynamics and manipulation*. 197-204.

TØRRESEN, K. S. & R. SKUTERUD (2002). Plant protection in spring cereal production with reduced tillage. IV. Changes in the weed flora and weed seedbank. *Crop Protection* **21**: 179-193.

TØRRESEN, K. S., R. SKUTERUD, TANDSAETHER HJ & HAGEMO MB (2003). Long-term experiments with reduced tillage in spring cereals. I. Effects on weed flora, weed seedbank and grain yield. *Crop Protection* **22**: 185-200.

TUESCA D, E PURICELLI & PAPA JC (2001). A long-term study of weed flora shifts in different tillage systems. *Weed Research* **41**, 369-382.

TURLEY DB, BACON ETG, SHEPHERD CE, PETERS NCB, POTYKA I, GLEN DM, DAMPNEY PMR & JOHNSON PN (1996). Straw incorporation – rotational ploughing for grass weed control. *Aspects of Applied Biology 47, Rotations and cropping systems* 257-264.

TURLEY DB, WRIGHT G & HEBDEN P (1998). Changes in the weed seedbank during long-term set-aside. *Aspects of Applied Biology 51; Weed Seedbanks: determination, dynamics and manipulation*. 265-272.

VAN DER PUTTEN WH, MORTIMER SR, HEDLUND K, VAN DIJK C, BROWN VK, LEPS J, RODRIGUEZ-BARRUECO C, ROY J, LEN TAD, GORMSEN D, KORTHALS GW, LAVOREL S, REGINA IS, SMILAUER P (2000). Plant species diversity as a driver of early succession in abandoned fields: A multi sire approach. *Oecologia* **124**: 91-99.

VANASSE A & LEROUX GD (2000). Floristic diversity, size, and vertical distribution of the weed seedbank in ridge and conventional tillage systems. *Weed Science* **48**, 454-460.

VICKERY J, CARTER N & FULLER RJ (2002). The potential value of managed cereal field margins as foraging habitats for farmland birds in the UK. *Agriculture Ecosystems & Environmen*t, **89**, 41-52.

VLEESHOUWERS LM (1997) Modelling the effect of temperature, soil penetration resistance, burial depth and seed weight on pre-emergence growth of weeds. *Annals of Botany* **79,** 553-563.

VLEESHOUWERS LM & KROPFF MJ (2000) Modelling field emergence patterns in arable weeds. *New Phytologist* **148**, 445-457.

VLEESHOUWERS LM & BOUWMEESTER HJ (2001) A simulation model for seasonal changes in dormancy and germination of weed seeds. *Seed Science Research* **11**, 77-92.

WATKINSON AR & FRECKLETON RP (2001) Climatic change and weed population dynamics. In: *Proceedings 2001 Brighton Crop Protection Conference – Weeds*, Brighton, UK, 83-90.

WATSON SJ, MAUCHLINE AL, BROWN VK & FROUD-WILLIAMS RJ (2003) Post-dispersal losses of *Stellaria media* and *Polygonum aviculare* seeds in spring barley (*Hordeum vulgare*). *Aspects of Applied Biology 69, Seedbanks: determination, dynamics and management*. 203-208.

WHALLEY WR, FINCH-SAVAGE WE, COPE RE, ROWSE HR & BIRD NRA (1999) The response of carrot (*Daucus carota* L.) and onion (*Allium cepa* L.) seedlings to mechanical impedance and water stress at sub-optimal temperatures. *Plant Cell and Environment* **22**, 229-242.

CHAPTER 8

REVIEW OF STEWARDSHIP AND CROP ASSURANCE SCHEMES AND THEIR IMPACT ON BIODIVERSITY IN HORTICULTURAL SYSTEMS.

8.1 Overview

There is a range of schemes that impact directly or indirectly on biodiversity in horticultural systems. In broad terms they can be split into:

1. **Crop based product assurance schemes** that are crop production oriented, based around integrated crop management (ICM) production systems of specific horticultural crops Table 8 and deal at a local crop level with issues of environmental stewardship and crop safety. E.g. recommendations of best practice for pesticide application. Organic production schemes are included for completeness, although it is recognised their standards are different and they operate under a separate legal framework.
2. **Agri-environment schemes** which are not horticulture specific and are directed at the enhancement and protection of the agricultural landscape and rural environment. Some schemes are sponsored by directly by government (e.g. Country Stewardship Scheme - CSS) others are voluntary schemes that are administered and audited through a variety of organisation organisations (e.g. VI The Voluntary Initiative; LEAF Linking Environment & Farming: FWAG, Farming & Wildlife Advisory Group)

In practice the schemes are often cross-linked in a variety of ways often at a local farmer/ producer level or through the policies of the major buyers/retailers who market the major part of horticultural production in the UK.

8.2 Crop based product assurance schemes

Product assurance schemes are industry wide initiatives that address important issues concerning the production of 'produce' - fruit, salads and vegetables. Broadly their stated aim can be summarised as:

- To promote safe and environmentally responsible production of fruit, salads and vegetables through the use of integrated crop management (ICM) and maintain consumer confidence in the safety and integrity of produce.

The current schemes are listed in Table 8.1. APS protocols are in the public domain, (www.assuredproduce.co.uk), Tesco Natures Choice protocols are not; however Tesco states that it accepts the standards of APS as equivalent to the Natures Choice scheme. APS also has recently secured equivalence to EUREPGAP. Therefore for this review they are grouped together under APS.

Table 8.1 Product Assurance Schemes

Scheme	General details
Assured Produce Scheme (APS)	Adopted by all major UK retailers for fruits, vegetables and salads
Natures Choice	Specific to Tesco (this is additional to ASP for Tesco)
EUREPGAP	International standard of Good Agricultural practice
Organic production schemes	Operated under the UK Register of Organic Food Standards (UKROFS) banner to at least EC standards by differing certifying bodies (at least 10)

APS covers the production of over 40 different crop types of fruit vegetables and salads and includes herbs, hops and mushrooms but it does not cover ornamentals, flower bulbs and nursery stock production. The proportion of the UK horticulture & potatoes land area (approx. 360,000ha) covered by APS, or its equivalent, is approximately 75%.

The basis of the APS system is a generic crop production protocol supplemented by crop specific protocols. APS crop specific protocols routinely refer to the generic protocol for advice on conservation and protection of biodiversity even for major crops like potatoes. Chapter 13 in the generic protocol is entitled 'Conservation Issues' and is attached as annex.

The section directly relevant is italicised below:

*It is **strongly recommended** that each member have a plan for the management of wildlife and conservation of the environment on their own property that is compatible with sustainable commercial agricultural production and minimised environmental impact. A key aim should be the enhancement of environmental biodiversity on the farm through positive conservation management.*

Key elements could be to:

- *Conduct a baseline audit to understand existing animal and plant diversity on the farm. Conservation organisations such as FWAG can help conduct surveys to measure biodiversity and identify areas of concern.*
- *Take action to avoid damage and deterioration of habitats.*
- *Create an action plan to enhance habitats and increase biodiversity on the farm.*

Consideration should be given to the conversion of unproductive sites such as low lying wet areas, woodlands, headland strip or areas of impoverished soil, to conservation areas for the encouragement of natural flora and fauna wherever possible.

However other aspects of the APS protocols are relevant to biodiversity issues in the planning, auditing and production of crops. These include:

- site selection and history, including rotations,
- soil management, mapping, erosion, drainage,
- potential fertiliser and pesticide losses to ground water, risks from organic manures
- water extraction and usage
- pesticide usage, best practice, training and restrictions, storage & disposal
- waste recycling & management

Essentially, to qualify and maintain accreditation under APS a producer has to have a full audit trail and traceability for all relevant aspects of the generic and crop specific protocols.

If we take site selection and history as an example best practice involves starting with a field audit. An example of a typical field audit is attached in annex 2. It includes reference to weed populations, soil types, environmental issues such as hedgerows, etc. Therefore large quantities of information are potentially available under the umbrella of APS although collecting and collating the information that is widely dispersed amongst a variety of organisations and individuals, and in a variety of formats, would be daunting.

The footprint of organic horticultural production covered by the different organic certifying bodies in the UK is relatively small and no herbicides are allowed (5.4% total fruit area, 4.5% total vegetable area either organic or in conversion; no separate figures for other horticultural sectors: Defra organic statistics for 2003). However a significant proportion of the organic horticultural sector are growing a very diverse range of crops within a relatively small farmed area and as a matter of policy aim to have a positive effect on local biodiversity.

8.3 UK Agri-environment schemes

8.3.1 Voluntary schemes

The main voluntary scheme that involves registration of horticultural crops is LEAF (Linking Environment &Farming). LEAF is run as a charity and encourages farmers to adopt Integrated Farm Management (IFM) in a sustainable system of agriculture. LEAF provides farmers with a self-assessment audit of their farm to set targets to improve their business while enhancing the environment. In horticultural production it could be regarded as a bolt-on to the existing crop-based assurance schemes. They publish figures for the crop areas registered for certification under LEAF. The figures published in April 2003 are in Table 8.2. The proportion of the total area of individual crop registered is remarkably variable with lettuce quite high at 26% with potatoes, top fruit, strawberries and vining peas particularly low.

Table 8.2 LEAF Registered Hectares (2003) **(**crops from consolidated list)

Crop	Area registered ha	As a percentage of UK total area
Potatoes	1545	0.9%
Onions bulb/salad	722	6.0%
Carrots parsnip	1071	7.1%
Lettuce	1581	26.3%
Cauliflower	90	0.7%
Vining peas	115	0.3%
Top fruit	13	0.1%
Strawberries	77	1.9%

FWAG Farming & Wildlife Advisory Group is a company limited by guarantee who concentrate on conservation advice in a farming context and who often provide the advice and guidance for farmers and growers to enter into government and retailer sponsored schemes. Horticulture is not normally separated from whole farm activities in conservation and biodiversity. From their web-site two of the three on-farm examples demonstrating good practice in farmland biodiversity are involved in intensive vegetable production.

In 2000 the Government invited farming representatives to present a package of measures to achieve the environmental benefits sought by Government as an alternative to a proposed tax on the pesticides used in agriculture and horticulture. This was accepted in 2001 and has become known as the Voluntary Initiative. Therefore in reality this scheme lies between the true voluntary and government sponsored schemes. The overall objective is to reduce the environmental effects of pesticide use and improve the biodiversity of arable farmland. The initiative consists of three key activities; Research, Training and Communication & Stewardship.

One of the key elements of the VI is for growers to formally consider the environmental impact of their farming activities and take steps to manage and reduce it. This process includes developing a crop protection management plan (CPMP). No distinction is made between horticultural and other farming activities, although obviously pesticides are used very intensively in many horticultural situations.

Under the VI area targets have been set.

end 2003 - 200,000ha will be covered by CPMPs..

end 2006 (end of VI) - 30% of all sprayed land should be under a CPMP.

LEAF has been involved in developing a proforma CPMP and it is available (http://www.voluntaryinitiative.org.uk/Content/CPMPs.asp) for farmers to tailor to their own needs and circumstances. It is also supported by APS. The proforma specifically deals with on-farm issues such as ecological value, mapping key environmental features and wildlife habitats and has individual sections on biodiversity assessment, and conservation. In some respects it is a more sophisticated and formal version of the field audit data gathered as part of the APS scheme. Clearly the timescale is such that there has been insufficient time interval to monitor the success of the VI in its effect on farmland biodiversity.

8.3.3 Government sponsored schemes

The stated purpose of a CPMP is to put the environment at the centre of crop protection activities and to identify environmental risks to water insects plants and animals.

Agri-environment support schemes set up within the UK are administered on a country basis. Their aims and objectives are to support farmers financially to cover the costs of managing land in more environmentally beneficial ways. Within England, schemes are grouped within the recent English Rural Development Programme (ERDP), though a number of schemes have been running for many years. For example, the Environmentally Sensitive Areas (ESAs) were initiated in 1987 and were amongst the first schemes to be developed within the European Union (EU). The current schemes are listed in Table 8.3.

Table 8.3. Agri-environment schemes in England. * = pre-ERDP

	Year started	Uptake (year)
Countryside Stewardship Scheme*	1991	13745 agreements on 343132 ha (2002)
Energy Crops Scheme		
Environmentally Sensitive Areas*	1987	10915 agreements on 532000 ha (2000)
Farm Woodland Premium Scheme*		
Hill Farm Allowance Scheme		
Organic Farming Scheme*		
Woodland Grant Scheme		
Processing and Marketing Grant		
Rural Enterprise Scheme		
Vocational Training Scheme		

In relation to the impact of agri-environment schemes on biodiversity, reports from Europe indicate that effects vary between the taxa studied. The most recent review will be published in the Journal of Applied Ecology shortly (Kleijn & Sutherland, *in press*). Assessments of schemes have been concentrated in the UK and The Netherlands. Whilst many are scientifically weak in design, taxa have shown increases, decreases and no measurable change in relation to the introduction of schemes. None of the reviews are specifically aimed at assessing impacts within horticultural areas or specific crops, so data in this area are lacking.

Nevertheless, it is possible to examine the uptake of schemes in England in areas where horticultural crops are concentrated. A comparison of counties with significant horticultural industries with more arable counties is made in Table 8.2. Whilst no account is taken of amount of horticulture or total farm area, there is little indication that there is less interest in agri-environment schemes in counties with a significant horticultural industry. Thus, opportunities to combine biodiversity mitigation with production, using agri-environmental support mechanisms, would seem feasible.

Table 8.4. Uptake of Countryside Stewardship to 2002, measured by agreement area (ha) and length of arable boundary (km), in counties with significant horticulture and counties with only minor horticultural interest.

Horticultural areas			Arable areas		
County	Area (ha)	Margins (km)	County	Area	Margins (km)
Norfolk	8535	3712	Hampshire	5393	1745
Suffolk	3872	640	Oxfordshire	3826	837
Lincolnshire	6242	1512	Gloucestershire	4163	430
Humberside	2685	1028	Wiltshire	6437	1291

8.4 Linkages between schemes

APS and similar schemes operates primarily through crop specific protocols, although other schemes VI (The Voluntary Initiative), FWAG (Farming & Wildlife Advisory Group), LEAF (Linking Environment & Farming) and CSS (Countryside Stewardship Scheme) operate primarily at a farm level. Horticulture, especially vegetable production, is very spatially dynamic. Individual farms and growers are rarely dedicated to purely horticultural production, most often operating a rotation with a range of arable crops, or animals in some instance. Also a significant proportion of horticultural production is on short-term rented land (although the exact proportion is difficult to estimate), with crops now routinely transported large distances from production field to packhouse. Teasing out specific effects and impacts that can be directly related to the horticultural element of farming operations is likely to be difficult. In addition, the situation is further complicated by that fact that some growers may supply more than one retailer.

Retailers who insist their suppliers are accredited under APS also promote linkages to environmental enhancement groups like LEAF or FWAG.

- **Sainsbury** has joined with FWAG to develop and launch a Farm Biodiversity Action Plan (BAP) for its supplier base to integrate wildlife conservation by managing areas of land that attract and support native species of wildlife and give specific examples of farms where this policy is in operation
- **Waitrose** asks its growers to carry out an independent assessment of environmental factors through LEAF, FWAG and RSPB
- **Tesco** monitors the effects of the Natures Choice scheme on farmland (Wildlife Choice). Under the Wildlife Choice scheme each grower has to establish special wildlife habitats and management plans to improve biodiversity.
- **M&S** has completed a supply chain review of biodiversity impacts and is developing partnerships with suppliers through LEAF.

Again most of this monitoring appears to be at the farm level rather than specifically targeted at the horticultural sectors and is often anecdotal in nature with little provision of hard data. Most often the indicator species are birds although plants and mammals are occasionally mentioned.

In addition to the APS and similar schemes, several retailers have developed global prohibited pesticide lists although some of them are already prohibited in the UK.

- **M&S** has prohibited or restricted the use of 60 pesticides and is aiming to prohibit 19 further active ingredients
- **Co-op** has a list of 50 pesticides that are prohibited or restricted. And its stated aim is for zero residues in all its food
- **Waitrose** is working with its suppliers to eliminate the use of several pesticides.

8.5 UK Biodiversity Action Plans (BAPs) – how do they relate to horticulture

In 1994 the UK Government published Biodiversity: The UK Action Plan which was subsequently followed by reports setting up Habitat Action Plans and Species Action Plans. As an example a UK BAP exists to get 15,000 hectares of land surrounding mainly cereal fields into environmental management to enhance the biodiversity of farmland, under the term 'cereal field margins' by 2010. This is probably the closest that any of the national BAPs get to intensive horticulture. Detailed information is provided at www.ukbap.org.uk. The Website is informative but unsurprisingly does not separate horticulture from agriculture. However it does provide a summary of knowledge gaps and research ideas and (www.ukbap.org.uk/Library/Crosscuttingdatabase.xls). Most of the proposed research does not specifically target agriculture, but where it does, pasture/livestock are the primary targets. Intensive crop production is rarely mentioned which again, in effect, leaves horticulture out of this particular research/knowledge network. It might be expected that an extremely biodiverse industry like horticulture might figure more prominently than it does when considering contributions and issues relating to biodiversity policy. Perhaps horticulture should aim to make much more of the fact that as an industry it could potentially play a significant and valuable part in protection of the UK's biodiversity.

8.6 Benefits/Impacts

Intuitively, better targeting of inputs, careful field margin management, better use of crop rotation, pesticide reduction, should bring environmental benefits and can make economic sense, but direct environmental benefits may not automatically follow. Recent research work on the environmental benefits of ICM based systems has rarely been horticulture specific and data are almost completely lacking. Although environmental benefits have been ascribed to ICM systems, this has principally been researched and developed in the arable sector.

Morris & Winter (2000) have assessed the Farm Biodiversity Action Plans (BAPs) sponsored by Sainsbury plc (section 8.4). Of the holdings assessed some 23 % of the land area was classed as horticultural land use as opposed to the average 2% horticultural land use for England as a whole, indicating that the horticulture sector took an above average interest in biodiversity issues. However the sample disproportionately represents horticulture, arable and egg producers due to the involvement of the retailer and their promotion of Farm BAPs to their suppliers. The majority of growers with Farm BAPs were found to have received conservation advice in some form compared to less than 10% of farmers and growers overall (Winter *et al*., 1996). However it was concluded that monitoring methods need development (and funding) and that measurable outputs from the Farm BAPs are not available or not collated. Therefore it was not possible to robustly estimate any impacts on target species.

8.7 Summary & Conclusions

1. Horticulture is making a positive effort to minimise environmental impacts through voluntary and government led schemes.

2. Standards of environmental protection in horticulture are likely at least as high as in farming as a whole.

3. Horticulture is spatially dynamic and it is difficult to separate horticulture activities from whole farm schemes for protection of biodiversity.

4. Robust horticulture specific data are hard to find.

5. Few measurable indicators are available; need to develop more effective monitorin.

6. Horticulture, by its nature, occupies a very diverse range of niches in farming operations; in itself this is likely to make positive contributions to biodiversity

7. Horticulture could (should) make much more of its diverse role as a guardian of biodiversity in agricultural production

8.8 References

KLEIJN, D. & SUTHERLAND, W.J. (In press) How effective are agri-environment schemes in conserving and promoting biodiversity? *Journal of Applied Ecology*.

MORRIS C. & WINTER M. (2000) *Assessment of farm Biodiversity Action Plans*; report to the Farming & Wildlife Advisory Group (FWAG); Cheltenham & Gloucester College of Higher Education, Countryside and Community Research Unit

WINTER M GASSON R CURRY N SELMAN P & SHORT C (1996) *Socio-Economic Evaluation of Free Conservation Advice Provided to Farmers by ADAS and FWAG*. Report to MAFF Cheltenham : Countryside & Community Press.

HM GOVERNMENT (1994) *Biodiversity: The UK Action Plan* HMSO London

Annex 1: Assured Produce Scheme - Generic Protocol

Chapter 13 Conservation Issues

ENVIRONMENTAL AWARENESS

13.1.1 Benefits

A number of environmental benefits have been identified in recent ICM research projects, although this research has principally been developed in the arable sector the benefits can be relevant to fresh produce crops:

From these findings substantial agronomic and environment benefits have been identified. The idea of integrating beneficial natural processes into modern farming practice so that farming makes more efficient use of inputs (such as fertilisers, seeds, energy and pesticides) makes good commercial sense. In addition, better targeting of inputs, careful field margin management and the better use of traditional practices, such as crop rotation will bring environmental benefits.

Whilst pesticide reduction can make economic sense, direct environmental benefits may not automatically follow. Precise application to avoid off-crop impacts has obvious benefits. Similarly a 'threshold' approach to pesticide use (i.e. not using pesticides if pest and weed populations are below the levels that cause economic damage) can provide food supplies within the crop which can help to sustain beneficial insects, thereby improving biological control and biodiversity.

Encouragingly, however, there appear to be few long-term direct effects on non-target insect and spider populations when pesticides are used in accordance with current commercial practice - even at full manufacturers' recommended rates.

Environmental enhancement requires positive action. The most significant benefits are from an awareness and sensitive treatment of vulnerable areas, maintaining and enhancing their status and condition and creating new habitats.

A number of environmental benefits have been identified from the work and include:

- Where there is a balanced crop rotation ICM has resulted in a more diversified farm mosaic - encouraging biodiversity and more varied landscape.
- Where habitats have been created and hedges/field boundaries managed to encourage beneficial invertebrates, the effects on pest populations have not yet been quantified and hence the impact on the crop and a wider range of invertebrates is not yet fully known, although available food sources for some bird species are increased.
- In non-cropped areas careful management increases plant biodiversity.
- The importance of hedges and field margins to wildlife has been confirmed. Over 90% of farmland biodiversity is found in hedgerows and field margins.
- Increases have been recorded in the numbers of bird species that show a strong preference for integrated direct-drilled stubbles over conventional ploughed fields.

- Minimal tillage shows many benefits over ploughing, including reduced soil erosion, run-off of pesticides and leaching of nutrients. It also improves soil structure, earthworm populations and water infiltration on some soil types.

The measurement of environmental effects however is a complex and long-term process - some can take years before any appreciable effects can be seen from changes in farming practice. Decisions need to be made on a crop by crop and field by field basis.

Outside advice

To increase environmental awareness, it is **strongly recommended** that outside advice on environmental improvement is sought, where necessary from appropriate organisations such as FWAG and LEAF.

ENVIRONMENTAL ENHANCEMENT

13.2.1 Environmental Management

Sound environmental management is not only the maintenance and enhancement of wildlife and habitats, but also the management of the soil, air and water. It is the positive management of these factors that leads to a better use of resources with a consequent reduction in waste and lessens the risk of pollution. All reasonable pro-active efforts should be made to conserve the environment.

All legislation relevant to the conservation of the environment should also be observed, by following the guidance given in Defra's "Environmental Matters" series of Codes of Good Agricultural Practice for the protection of water, air and soil (see Appendix A).

Members may find it useful to refer to specialist booklets and information sources on specific subjects e.g. 'Controlling Soil Erosion' an advisory booklet from Defra (see Appendix A).

In the light of consumer concern, members should understand and assess the impact that their growing activity has on the environment, and consider how they can enhance the environment for the benefit of the local community and flora and fauna.

It is **strongly recommended** that each member have a plan for the management of wildlife and conservation of the environment on their own property that is compatible with sustainable commercial agricultural production and minimised environmental impact. A key aim should be the enhancement of environmental biodiversity on the farm through positive conservation management.

Key elements could be to:

- Conduct a baseline audit to understand existing animal and plant diversity on the farm. Conservation organisations such as FWAG can help conduct surveys to measure biodiversity and identify areas of concern.
- Take action to avoid damage and deterioration of habitats.

- Create an action plan to enhance habitats and increase biodiversity on the farm.

Consideration should be given to the conversion of unproductive sites such as low lying wet areas, woodlands, headland strip or areas of impoverished soil, to conservation areas for the encouragement of natural flora and fauna wherever possible.

Annex 2: Typical field audit when planning field vegetable cropping

FIELD AUDIT

EXPLANATORY NOTES

Aim

To ensure good field selection

Reasons

- Stabilise pool entries
- Improve consistency
- Ensure sustainable production
- Quality assurance (Before the onset of costs)
- Management of risks
- To collect basic field information
- To encourage the thought process of field selection

It is not an objective to use only perfect fields and only have expensive ideal options, but to ensure we are aware of all the options and have thought about and managed the risks.

Field data

Straightforward details of identification, location and other specific details.

The estimated drilled area is very important in order to ensure accurate planning of tonnages.

Production period and harvest date restrictions clearly need to be flagged up early to ensure that we can plan for a reasonable spread of production from the onset and we do not have push and pull too much around.

Soil Type

Suitability of soil type as we know is exceedingly important part of the production of root crops.

What we are looking for is the soil type of the field and if it changes and to what. The changes in soil type will indicate possible changes required for field management and the variability of the finished crop. As long, as the changes in soil types are manageable and will not cause major restrictions and problems with the consistency of the final product it should be acceptable for use.

The soil audit is for the mineralised carrot production programmes that we are working on. This is still very much development work but never the less an excellent method of soil testing for nutrients because of its detailed micronutrient and soil balancing analysis.

General Field Features

This is looking at features which may effect quality i.e. breakages, carrot fly spraying restrictions etc.

Environmental features may include ditches, waterways, woodland and NSA sites.

Rotation

This is to ensure compliance with protocols, responsible production and assessment of possible production risks.

I am particularly interested in possible relationships between previous cropping and quality.

Irrigation

To ensure that there is enough water and equipment available to grow the intended crop.

To assist the monitoring system and level required.

Cropping History

This is to highlight any specific risks and possible problems, which may need assessing. Further action as to ascertain the suitability of fields may need to be taken such as Elisa testing for Cavity Spot

Volunteers can also be of particular interest in trying to assess relationship between different crop performances.

FIELD AUDIT

Field Name ____________________________ Area (ha) _______________________

Location ______________________________ Est. Drilled Area (ha _____________

Crop ________________________________ Variety to be used ______________

Latest Harvest date______________________ Production Period________________

<u>Soil Type</u>

Please state what two soil types make up the majority of the field:

Mostly1.____________________ Least 2.____________________________

To be soil audited Y/N By Fresh Growers Y/N

For each of the following please circle the fields content:

Gravel	Low	Med	High
Stone	Low	Med	High
Flint	Low	Med	High
Clods	Low	Med	High

Other Please Specify ____

<u>General Field Features</u>

Wet holes	Y/N	Severe Slopes	Y/N
Poor shape	Y/N	Close to Houses	Y/N

Access (Please circle)	Good	Average	Poor
Loading Area (please circle)	Good	Average	Poor

Environmental Features ____

Other please specify ____

<u>Rotation</u>

Last six years 1_______________ 2_________________ 3__________________

4_______________ 5 _________________ 6 __________________

Year last in Carrots ___________________

Year last in Potatoes ___________________

Irrigation

Available Volume__________________________ Restrictions________________

Available Period __________________________ Restrictions________________

Equipment Type ____________________ Capacity/acre________________

Application cycle Number of days _________

Cropping History

Has the field had any of the following diseases in the past?

Cavity spot	Violet root rot	Scab	White rot
Fusarium	Rhizoctonia	Sclerotinia	

For the following please state anything that you think might be a problem:

Weeds Please specify ____

Volunteers Please specify____

Pests Please specify____

Other Known Problems ____

CHAPTER 9

RISK ANALYSIS FOR NON-TARGET PLANTS IN HORTICULTURE

9.1. Background to Risk Analysis

In an earlier report (PN0940) examining the impact of herbicides on weed abundance and diversity, the authors looked generally at the arable landscape. Chapter 10 of that report considered risk assessment for non-target plants within crops and gave a resumé of the formal risk analysis methods associated with the regulatory procedure. Rather than re-iterate what was presented there we simply refer the reader to pages 109-112 of that report, noting that, at least in the case of vegetable crops grown in a standard arable rotation, the same general criteria would apply.

Several points from that review are worth emphasising:

- Acceptable levels of risk would be higher in target areas (i.e. the crop itself) because of the need to control weeds;
- There is a strong drive within the scientific community to move towards a 'tiered approach' to regulation of plant protection products;
- Such an approach would require significant development work, particularly with regard to the consequences of sub-lethal effects;
- There is a greater emphasis on probabilistic methods to determine risk.

The various quantitative methods that have been developed are important in determining safety levels, etc., and they represent the best estimates that can be offered in relation to risks and impacts with respect to particular weed species. In PN0940 the authors state that "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". Elsewhere in this document important weed species are identified which have significance for particular horticultural crops. The point is also made that for edible horticultural crops the tolerance of weed species in the crop is essentially zero, as contamination may well render them unsaleable. This must obviously be qualified by the fact that horticultural crops only occupy a small proportion of the cultivated land in the United Kingdom, so that a formal risk analysis would need 'weighting' with respect to its contribution to the overall impact on biodiversity.

Whilst it is important that this type of risk assessment is undertaken there is a danger that these forms of risk analysis miss some of the more strategic and immediate questions. Furthermore, the formidable variety of horticultural crops and the complications associated with herbicide approvals in the case of minor crops suggest that the limitations of data already associated with arable crops may well make formal risk assessments somewhat dubious. For these reasons we have chosen to look rather more broadly at the risks associated with pesticides at different levels.

The final paragraph of Chapter 10 of PN0940 suggests that there are strong suggestions of a causal link between herbicide use and the decline in farmland biodiversity. Their proposal is that a radical re-appraisal of crop management may be required, emphasising a potential change in herbicide practice. Causality is a complex and contentious area. It has become particularly important in the subject of statistics where the conventional experimentation is not always possible for ethical or practical reasons, and where the complexity of interacting processes make simple inference impossible (e.g. medicine, ecology).

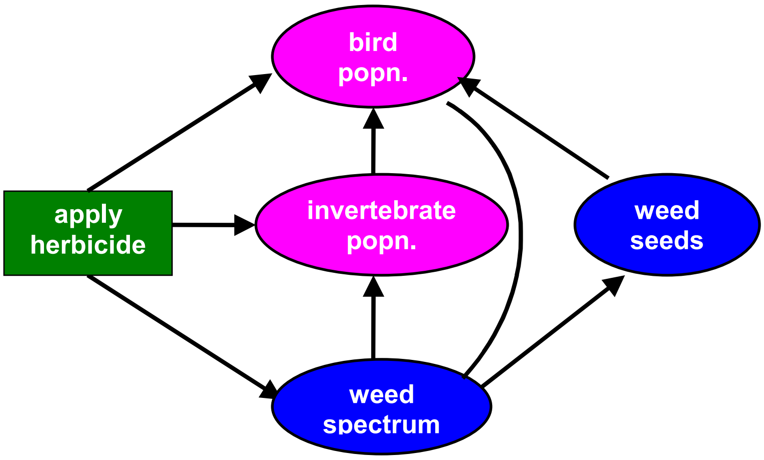
9.2 Graphical Modelling

The use of graphical modelling has also become popular, and is proving useful as a universal tool for discussion and elicitation of influence and causation. In what follows we use influence diagrams to examine some potential impacts of pesticides on non-target crops. These models are preliminary, and are intended primarily as guidelines to demonstrate how one might proceed. However, they provide extremely important tools for policy development

1. Because they offer a relatively simple visual description of sometimes complex processes, thereby allowing all parties to discuss the influence and impact of various factors with one another;
2. For the very same reason they give some opportunity for conflict resolution;
3. They also offer the potential for scenario modelling by examining (and potentially modifying) the 'edges' between variables.

Where quantitative data are available and the various edges can be quantified, algorithms exist to enable formal analyses of the process, incorporating sensitivity analyses. In ecological modelling some of the processes may not be easily quantified, but the graphical models enable researchers to think clearly about the interactions, and at least be aware of their complexity so that proper 'conditioning' of processes or variables can be undertaken.

Figure 9.1: Birds and invertebrates



As an example consider Figure 9.1, which shows a simple influence diagram relating the use of herbicides to bird populations. The application of pesticide will have an obvious effect on the weed spectrum, which, in turn, will impact on weed seed production and the invertebrate population as well as the bird population directly through habitat. Both weed seeds and the invertebrate population will also have direct effects on the bird population, and, indeed, the population mix in terms of food availability. And, of course, the herbicide itself may have direct effects on both the invertebrate population and the bird population by way of toxic or other effects. Thus the association between herbicide application and bird population is not a simple one, and any association (frequently measured by the simple correlation coefficient) is a naïve, empirical one that is unlikely to be consistent between samples. Any realistic attempt to discover a causal relationship between herbicide application and bird population numbers would need to consider all these interactions

In Chapter 5 of his book *Decision Analysis* Smith (1989) points out the benefits of structured diagrams, usually called Influence Diagrams, in describing the structure of a problem and the decisions that bear on it. An influence diagram is a schematic representation of a decision problem; they are more compact than Decision Trees and are reasonably straightforward to understand. They are a very useful way of thinking of the basic structure of a problem, and form a useful framework by which the decision maker can discuss the problem with the client, and the visual nature of the method is helpful in obviating omissions from the description of the problem structure.

Influence diagrams are more compact than decision trees in that they look at the relationships between decision 'spaces' and uncertain quantities rather than considering all possible outcomes. More formally, an influence diagram is a directed graph with nodes classified in one of three ways:

(a) *chance nodes* represented by an oval;
(b) *decision nodes* represented by a rectangle;
(c) *value nodes* represented by a hexagon.

Note that this is the convention adopted in the graphs presented here; the actual shapes of the nodes may vary in other applications though the symbols tend to have similar shapes.

9.3 Some examples of risk scenarios

In this section we consider some simple examples of potential risk scenarios, starting with the sorts of decisions a grower might make under possible incentive schemes for pesticide reduction. We then look at the potential impact of two processes that are essentially under way (global warming and pesticide withdrawal) with regard to their impact (influence) on other factors. Finally, we focus on an end-point or value node – that of changes in weed spectra to see what potential factors may impact on it.

9.3.1 Individual growers' decisions

Figure 9.2a sets out a possible scenario for a grower and shows some of the connections associated with pesticide reduction / biodiversity, etc. At this stage we are not intending to quantify anything, simply to understand the influences at work. It is best to start with the 'incentive scheme' node which could be considered as a chance node or a decision node (though the decision is not that of the grower, but of the regulator). To differentiate it and highlight its ambiguity we give this node a different shape and colour. Incentive schemes may influence the grower's decision in two ways – it may influence them to grow a particular crop (which might not be profitable under normal circumstances), and it should influence them to reduce pesticides. The scheme itself is likely to be associated with a value node to increase bio-diversity. Another of the grower's value nodes will be the maximisation of yield and quality, which contributes to the maximisation of income.

Note how the reduction of pesticides is likely to increase weed pressure, which has the potential outcome of crop rejection (this is a decision outwith the remit of the grower, and may essentially be considered as a chance node). A separate decision has been coded for herbicide application which links into weed suppression and crop rejection, though this could possibly be considered as a reflection of the herbicide reduction link – see Figure 9.2b. The balance between herbicide reduction and its consequences (including a possibly higher risk of crop rejection through contamination) and the incentives for increasing bio-diversity become important considerations for 'tuning' incentive schemes. From an economic perspective the grower may only be interested in the maximisation of their income, though some growers will have different utility functions, and a balance between income and bio-diversity may be their goal.

Fig. 9.2a: Individual growers' decisions

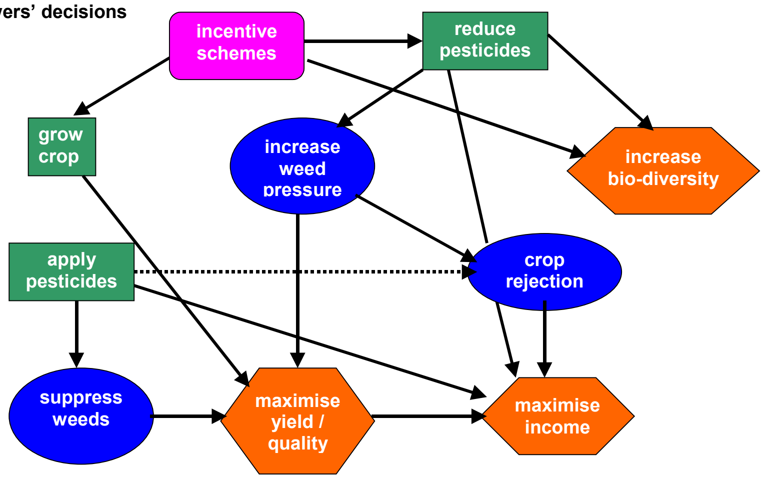
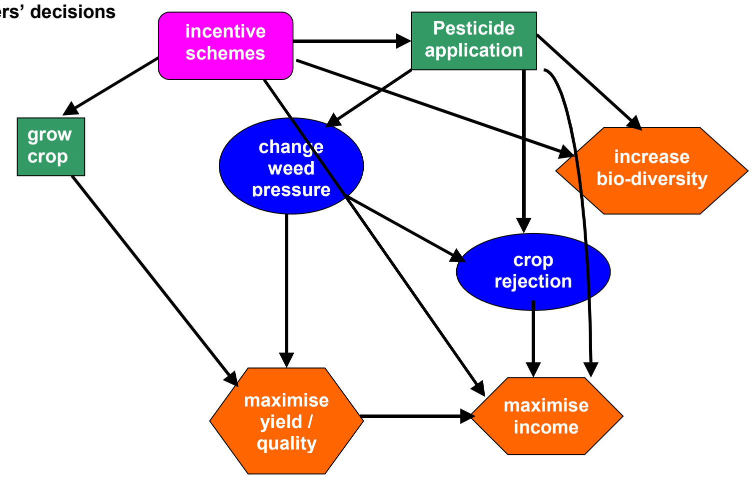


Fig. 9.2b: Individual growers' decisions

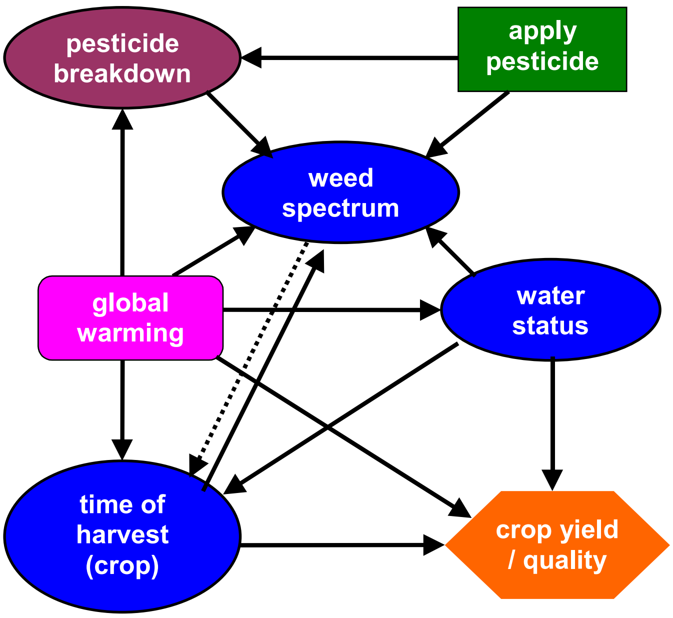


9.3.2 Impact of global warming

Again global warming is a chance node inasmuch as the predictions for it are variable, and any quantitative model would need to consider the spectrum of predictions; however, we have changed it here to demonstrate its focus within this particular system. A preliminary influence diagram for global warming is given in Figure 9.3. The most obvious effects of global warming will be on timing of harvest, water status and herbicide breakdown. It will also have a direct effect on the weed spectrum because of the temperature tolerance of different weeds and their own advancement through the warming process. Of course herbicide application itself and its changing rate of breakdown forms another complex that affects the weed spectrum, whilst water status will also have an impact on weed composition. It is possible to think of the interaction of weed spectrum and crop harvest operating in both directions. In terms of the value node yield and quality will be directly affected by global warming though much of the impact may be mediated via water status and time of harvesting, with weed spectrum possibly affecting crop quality.

Unless drought-tolerant crops are introduced it would seem likely that another consequence of global warming (or, at least, the water status induced by it) will be a greater reliance on irrigation. This diagram could be easily extended therefore by a decision node for irrigation that could increase the complexity through interactions with pesticide, crop timing and crop yield and quality. Figure 9.3 illustrates quite well how complex even a small diagram can become, and it also demonstrates how any quantitative modelling will need to take account of these interactions.

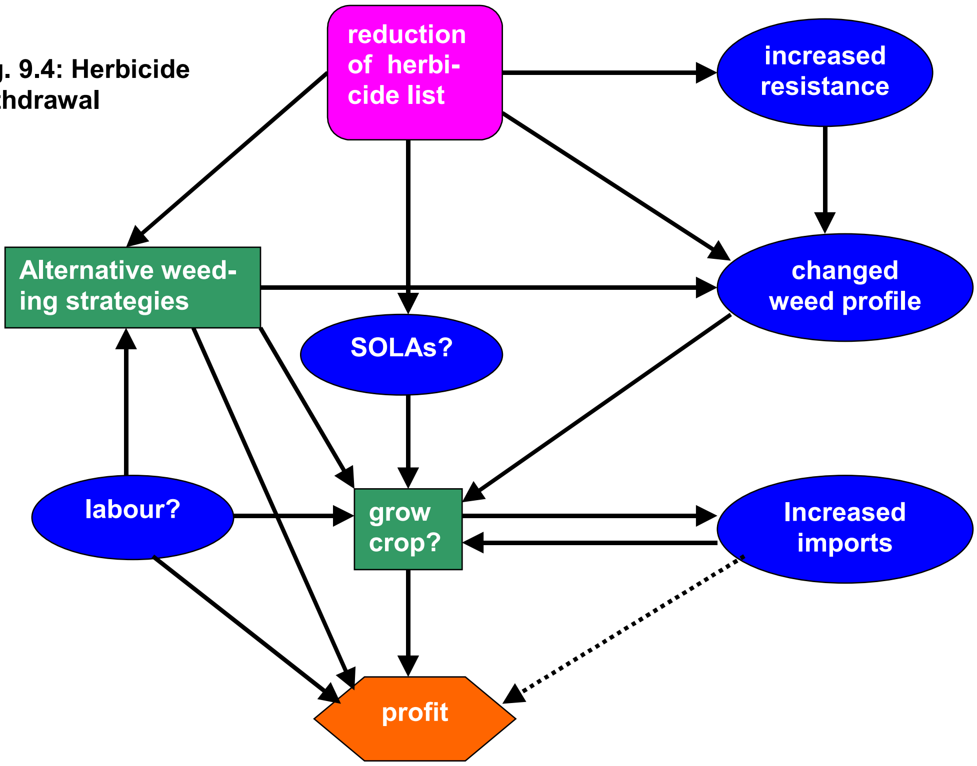
Figure 9.3: Impact of global warming



9.3.3 Herbicide withdrawal

Some possible consequences of herbicide withdrawal are shown in Figure 9.4. Strictly, withdrawal of herbicides or reduction of the herbicide list is essentially a decision. Immediate effects would be a change in the weed profile assuming some weeds could be less effectively eliminated, but also a possible change through increased resistance to remaining agents. These factors would certainly affect any decision about whether to grow the crop. Another line of argument affecting that decision would be whether SOLAs were available to moderate the withdrawal. Another decision would be the alternative weeding strategies that might be adopted, but this could be affected by the availability of labour, and these decisions and consequences will affect the decision on whether to grow. So the decision to grow is contingent on several different primary factors, and another one that could be added is the chance node associated with increased imports. Here the arrows go both ways as there is a level of interdependence between the decision and the chance event. In this illustration we have simply drawn all the 'loose' ends into the value node of profit, but this could obviously be thought of in different ways.

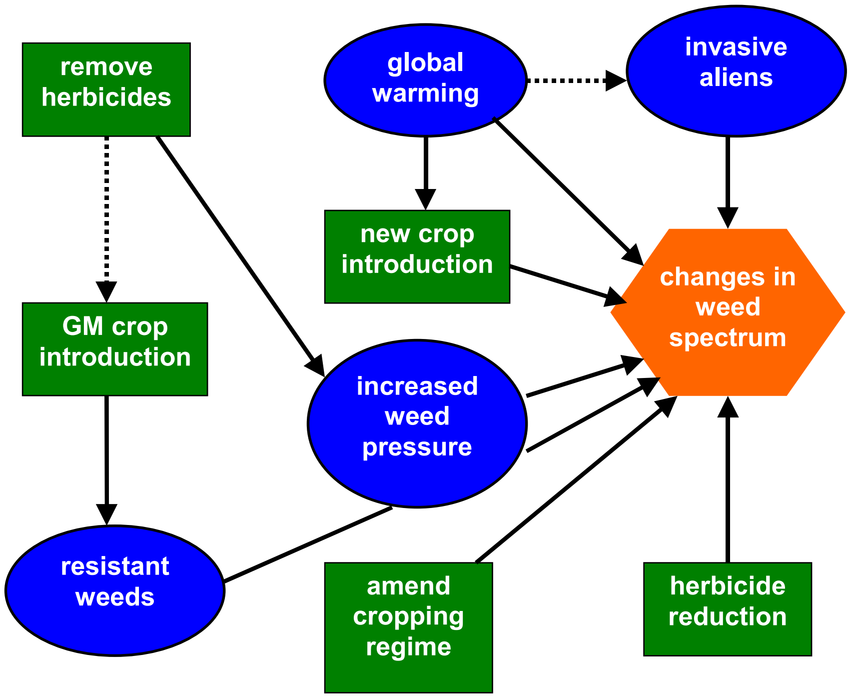
Fig. 9.4: Herbicide withdrawal



9.3.4 Changes in weed spectrum

In this diagram (Figure 9.5) we consider some of the chance factors (or consequences) and decision that will effect changes in the weed spectrum. At a different level we have already considered global warming, and we enter that here together with a potential consequence, that of invasive aliens, i.e. new species that may become pests because of a changing climate. Other chance factors could be increased weed pressure (a consequence of other decisions) and resistant weeds. This scenario is in some ways more strategic than the others in that there are more decision nodes than before. The decision to reduce herbicides is likely to impact directly on the weed spectrum, whereas a decision to remove them from the available list would have repercussions on weed pressure and resistance and could also affect a grower's decision as to whether to use a herbicide tolerant crop (contingent, of course, on approval at some stage!). The decision to introduce new or novel crops has been set as a decision contingent on global warming (to distinguish it from GM), while amendment of the cropping regime may be a change prompted by economic or technological changes.

Figure 9.5: Changes in weed spectrum



9.4 Next steps

What has been presented here is an alternative way of considering risk, and it can be seen that embedding the risk concept within the context of decision-making allows a much broader approach to be taken to the problem. In particular it allows policy-based decisions to be considered along with strategic decisions of an individual. In effect we are suggesting that this method may prove a useful first step in considering the risk process with respect to weeds and biodiversity.

The diagrams we have presented are simple prototypes, and arise out of some of the observations in preceding chapters. All of them are probably too simplistic, and one of the first steps to be taken would be to broadcast them and seek wider opinions through workshops, seminars and brain-storming sessions so that a broader consensus can be built up. Note the earlier comment that these diagrams are intended as visualisations of complex problems. It is obviously useful to try and break them into smaller problems, but the reductionist approach that has held in much of science until now is not entirely appropriate. With complex, inter-connected systems a missing link can skew any analysis dramatically, so it is very important to try and think through all possible linkages and make any influence diagram as self-contained as possible. These models can obviously be considered on different scales; for example, the individual growers' decision in 9.3.1 is at a completely different level to the essentially policy-based decision set out in 9.3.3. An aspect of the problem of biodiversity that has not been considered is the spatial one. The sorts of quantitative models considered in the GM / organic debate about pollen contamination, and similar allee models in ecology would be important when considering the spatial mozaic of crops, though this is more likely to apply with arable crops, but may have some relevance for horticultural crops that have a high density locally.

There is quite an extensive theory associated with influence diagrams, and certain rules have to be obeyed for an influence diagram to be converted into extensive form that enables a decision tree to be evaluated (see Smith, 1989 for details). Of course, it may be (in fact it is very likely) that not all arrows (or edges) can be quantified, but that immediately demonstrates an advantage of this approach in highlighting where information is required. There do exist other techniques such as sensitivity analysis that enable some ordination of the impacts or sensitivity of certain decisions or information: outcomes may be extremely insensitive to perturbation of some factors but very sensitive to others. The study of highly-ordered stochastic systems has become a significant topic in applied statistics and influence diagrams (or Bayes' networks as they are also called) form the foundation for this type of analysis.

Unlike conventional risk analysis as presented in other reports, what is proposed here is a much more extensive examination of risk taking into account all the factors bearing on a particular problem. The significance of drawing attention to all the interactions is that the solution of an influence diagram relies on the concept of conditional probability which is rarely fully considered in an ecological context.

9.5 Summary & Conclusions

1. Influence diagrams provide a useful tool for initially describing complex problems in a risk context.

2. Unlike conventional risk scenarios they do not tend to be constrained by formal quantitative arguments.

3. They provide an important framework for understanding the interactions between decisions and chance events, and enable a problem to be properly formulated.

4. Without necessarily being quantified the context enables policy-makers to see what factors may be affected and how by taking certain policy-decisions.

5. In the context of herbicides and biodiversity they should enable decisions to be taken about important research directions, e.g. where important data are not available.

CHAPTER 10

KNOWLEDGE GAPS & RESEARCH NEEDS

10.1 General Conclusions

This desk study has confirmed that achieving a balance between production and biodiversity in horticulture presents a number of interesting and complicated challenges compared with arable systems. As with much of agriculture, there is a lack of baseline survey data by which any positive management towards increasing biodiversity can be measured. This is particularly true for horticulture where we can only extrapolate from the collation and interpretation of the similarly disjointed and uncoordinated collection of surveys made in arable crops.

There has been a decline of more than 38% in the horticultural crop area since 1977 (excluding potatoes), compared with a 100% increase in wheat. The area of potatoes grown is the largest in the 'horticulture' sector, but in 2000 this was 5.3% of the wheat area. Despite the relatively small environmental "footprint" of horticulture, the combination of soil types, wide range of crops and crop architectures, diverse weed species and spring cropping provide a number of opportunities to complement and enhance strategies already in place in cereal crops. However, horticultural crops are much higher value than winter wheat and the purchasers of horticultural crops put stringent quality requirements on growers. These quality requirements are such that growers cannot risk leaving weeds as it may result in complete crop rejection and thus huge loss of income. The same is not true for cereals where there may simply be a modest reduction in price. Therefore, whilst there are different production systems for all horticultural crops there is a common aim throughout: from the aspects of quality, yield and harvesting, weeds within the crop area are simply not tolerated and all weed species are targets for control. This intolerance of the majority of horticultural crops to weeds, make the relaxation of weed management and use of thresholds within the crop even less attractive than in arable systems.

Hedges, field margin refuges, mulches and over winter stubbles would appear to be the most practically achievable way of enhancing biodiversity within horticultural systems. However, it will be necessary to examine whether these approaches will deliver all the desired biodiveristy benefits or whether there are certain organisms/groups of organisms that will not respond measure also being located within the field centres. Importantly, any such strategies that actually take land out of production could not be entered into without appropriate compensation to growers. This is because many of the horticultural crops, particularly vegetables, are grown on valuable high-grade land. In contrast to cereals, there is currently no EU area aid payment for horticulture (although this will change). If growers were compensated for loss of production and management of land for environmental benefits, there would need to be a benchmark against which improvement could be measured.

Managing such areas would need to be carefully tailored so that the biodiversity encouraged was beneficial (e.g. source of pollinators and biocontrol of pests) and did not conflict with the management of crop itself. For example, by introducing the "wrong combination of flora" that actually attracts or harbours potentially threatening crop pests. As in arable crops, most of these interactions between weeds in horticultural systems and the associated bird and invertebrate populations are poorly understood. A better understanding (and quantification) of the establishment, ecology and population dynamics of these flora and their trophic interactions may help towards developing suitable management prescriptions adjacent to specific horticultural crops. Knowledge of the specific biology and ecology of many of these beneficial or rare arable weed species are also lacking which hinders their establishment and management.

Many of the common horticultural weeds have already been identified within arable systems as being beneficial in encouraging biodiversity. However, whilst simply reducing herbicides or doses alone could encourage some of the common beneficial species, it is unlikely to improve populations of the rare arable weed species. Without selectively sowing desirable species followed by a combination of appropriate chemical and cultural management, succession will generally lead to the establishment of less beneficial annual and perennial species and more grasses.

Ironically, whilst it is generally accepted that the widespread use of herbicides has contributed to the depletion of biodiversity in the last 50 years, in horticulture, the loss of products may in itself remove a tool to help us manage for biodiversity in the future. The decline of herbicides in horticulture is a result of the EU pesticide review and the economic disincentive to the agrochemical industry to develop new products. The reliance on a small number of largely broad-spectrum products in horticulture provides little scope for selective management for specific weed species, either within the crop (in the few examples where they can be tolerated) or even the designated sacrificial margins.

Importantly, the reliance on a small (and still decreasing) number of products also compromises efforts to prevent the development of herbicide resistance, which should underpin all good chemical weed management programmes. The worst-case scenario resulting from the loss of products could be that certain horticultural crops could no longer be grown in the UK. There are no easy answers to reversing this decline in products. Articles written as long ago as the late 1950s already expressed concern that "*the large number of different crops involved, each of which poses a separate problem, and the fact that the acreage of many of the individual crops is relatively small, so that the potential market for any specific product is not great enough to encourage industry to undertake the costly research necessary for its development*" (Roberts, 1960). In most horticultural crops the cost of alternative non-chemical methods are often more expensive and can themselves have negative and still largely unquantified impacts on biodiversity. Therefore, the development of more cost effective, reliable and novel methods of non-chemical control will be an important complementary method of weed management in horticulture in the future. However, non-chemical methods alone are unlikely to be able replace the continuing need for herbicides to meet market demands and we can expect very few new herbicides for horticulture in the future. New products being developed for cereals and other major crops may have potential for use in horticulture, but exploring these possibilities needs facilitating and sufficient support.

The remit of this study has raised a wide range of complex issues and research needs relating to the impact of herbicides and weeds on biodiversity in horticulture. It has also highlighted many of the concerns (such as loss of herbicides) constraints (such as crop quality demands) and knowledge gaps for the future of sustainable weed management in horticulture. For simplicity, the following section collates and briefly summarises the key topics covered in each of the study chapters. Ultimately the integration of properly researched tactical management approaches is essential to prevent the development of impractical or conflicting strategies in horticulture:

10.2 Crop/ weed interactions:

1. There are **no recorded weed surveys in horticultural** crops, therefore we have no baseline information to measure whether weed biodiversity has declined or not.

2. Much **information on the weed flora could potentially be gained from efficacy trials data** submitted to the Pesticide Safety Directorate Defra for herbicide product Approval, where comparisons are made with plots untreated with herbicides

3. The weed spectrum in a field is linked to soil type and within a crop it is dependent on time of sowing. Horticultural crops may only occupy a small area in comparison with cereals but the wide range of crops (vegetables and flowers) are sown/planted mainly in spring on lighter soils and **the weed spectrum is more diverse than winter sown cereals.** This may offer opportunities for biodiversity.

4. Where horticultural crops are grown in a rotation that includes cereals they may **inherit cereal weeds**. Thus any biodiversity schemes for leaving weeds within the wheat crop will have a knock-on effect in horticultural crops in the rotation.

5. Weeds affect quality, yield and harvestability – **quality is the most important factor.** Consequently, unless quality and harvesting are also taken into account, the concept of critical periods to determine the timing of weed control in relation to potential yield loss has only limited application in horticulture.

6. There has been little research world wide on **weed economic thresholds** in horticultural crops and none in the UK. The UK research on winter-sown cereals cannot be directly extrapolated to crops with different morphology and time of sowing. However, the sensitivity of the crop to weeds, its high value (compared to cereals) and the effect of only a few weeds on quality in some crops are likely to make thresholds for most horticultural crops impractical.

7. Factors which may affect the **weed flora composition in the future** are: changes in cropping, increase of species uncontrolled by the few available herbicides, herbicide resistance, climate change and GM herbicide-tolerant crop volunteers.

10.3 Current crop areas and weed management

1. There has been a **decline of more than 38% in the horticultural crop (excluding potatoes) area since 1977**, compared with a 100% increase in wheat. Under the current CAP regime wheat is supported with area aid but horticultural crops are not. In comparison with arable crops, horticultural crops leave a very small 'footprint'. In 2000 the total area of arable crops excluding potatoes, was 4,097,514 ha (GB), the potato area 161,502 ha (UK), and the total area of other horticultural field crops (UK) was only 181,662 ha.

2. There are different production systems for all horticultural crops but there is a common aim: from the aspects of quality, yield and harvesting, weeds are not tolerated. Thus **all weed species are targets for control**.

3. It is possible to control weeds by **non-chemical methods**, however organic production remains small and the costs of alternative weed control methods are higher than for weed control with herbicides and hand labour has now become expensive and scarce. Non-chemical methods are also aimed at controlling all weeds and repeated cultivations may, in addition, have adverse and as yet unquantified effects on biodiversity

4. There are few **options for the grower to manipulate weed populations** and species within most horticultural crops. Changing seed rates, manipulation of row widths, time of sowing or planting and choice of variety may be available for cereals, but not usually for many horticultural crops.

5. If certain weeds identified as beneficial for bird food (e.g. chickweed) are left to flourish within horticultural crops the practicality of achieving this in vegetables would be difficult, either with herbicides, or non-chemical means **without the risk of potential contamination of harvested produce** and in some cases cause crop rejection. Similarly, if strips within a field were left untreated and weedy, this crop area could not be harvested because of contaminant risk.

6. Areas specially "set-aside" on the farm and linked to **margins along field edges and water-courses could be the most suitable means of achieving environmental benefits.** Crops where there may be possibilities are top fruit and cane and bush fruit, and some growers are already addressing this and beneficial flora could even be sown with the grass in alleys, but this has not been tested yet. Field margin biodiversity areas could perhaps combined with existing buffer zones and horticultural crops grown in arable rotations could link field margins with those in adjacent arable crops.

7. If more areas were to be taken out of production and managed for biodiversity **compensation would be needed**.

10.4 Herbicides in horticulture

1. There are few options for the grower to avoid weed competition and virtually all **horticultural crops are dependent on a diminishing number of herbicides**. In 2000 the total herbicide treated area of wheat was over 7.3 million ha and far exceeded the herbicide input for horticulture.

2. Pesticide Usage Surveys show that in the last 20 years the percentage area of perennial crops treated with herbicides has not changed, but in 1972, 104% of the vegetable area was treated with herbicides; by 1999, this had increased to 341%, (3 to 4 passes) Possible reasons are: repeat low dose programmes are used in some crops (onions, carrots) but the **total amount of herbicide has not increased**

3. There will be several **important herbicide losses in 2007** as a result of lack of support in the EC Review. Of the top ten most popular herbicides for vegetables, three will be lost.

4. Crops identified as having **important gaps for weed control** (HDC GAP Analysis, URL http://www.hdc.org.uk) after 2007 are carrots, celery, herbs, dwarf French beans, vining peas.

5. Lack of herbicides for weed control mean some fruit and vegetables will become **uneconomic to grow** and will be imported.

6. Strategies based on **reduced doses of herbicides could leave the more aggressive weed species** classed as moderately susceptible, or moderately resistant, on the label. These species are likely to have a greater effect on many vegetable crops than on cereals. These species are often undesirable species (cleavers) rather than "beneficial" weeds. Reduction of herbicide use or doses is very unlikely to improve the populations of rare species.

7. There may be possibilities for getting new herbicides for horticulture **by exploring new products currently being developed for use in cereals**. However, there would need to be sufficient support to facilitate these opportunities.

10.5 Relationship between weeds and birds in horticulture

1. Common **farmland birds have shown significant population declines** over the past 30 years. The reasons for the declines are associated with changes in agriculture, notably the move to winter cropping, silage cutting in grassland and intensification of management, including the use of herbicides.

2. The **life history stages of birds** that have been affected by agricultural change are **nesting** (habitat loss and change in habitat quality), **nestling survival** (reduced amounts of weeds and insects) and **adult survival over winter** (reduced food availability).

3. There is very **limited data on the utilisation of horticultural crops by birds** for nesting or foraging. Crops of peas, field beans and potatoes are important habitats for some ground nesting birds, notably yellow wagtail and skylark.

4. As horticulture is only a very small part of the agricultural acreage (7%), the **environmental "footprint" of the industry might be assumed to be small**. However, the indirect benefits of the industry to birds, especially the growth of **spring crops and the provision of stubbles**, may mean that the industry benefits birds far greater than previously supposed. Such crop stubbles can be important for providing seeds for adult birds over winter, though reduced weed control may be required in the preceding crop to achieve sufficient seeding. A number of **horticultural crops are shorter and more open** than winter cereals. Thus they may provide **suitable nesting habitat** for a number of bird species, especially for second broods in mid-summer.

5. A number of **weeds are important components of the diet** of farmland birds. These include the Polygonaceae, some Chenopodiaceae, Carophyllaceae and annual meadow grass. However, the imperative to control weeds in most of horticulture is such that **few such crops provide seeds and insects for birds during the crop growth period**. Perennial crops have greater opportunity to provide food, if they support an associated perennial ground flora. Nevertheless, most horticultural fields do not provide direct food resources for birds.

6. Mitigating the current approaches to weed control in horticultural crops is most likely to be best achieved by **creating habitat at field edges**. There is little opportunity to reduce weed control within fields, as the risk of crop rejection is high if there is contamination or quality is compromised. Margin strips of diverse perennial herbaceous vegetation, or in some circumstances allowing the annual weed flora to develop, or **creating specific winter bird food mixtures**, appear to be the most practical and beneficial prescriptions.

10.6 Relationship between weeds and invertebrates in horticulture

1. Since weeds cannot be tolerated in horticulture (except in a few crops, such as orchards), a combination of **invertebrate refuges** (at field margins and/or in strips running through the field) and surface applications of mulches and/or manures, has potential for maintaining farmland biodiversity and supporting valuable ecosystem services such as pollination and biocontrol.

2. An understorey of weeds or sown wildflowers under orchard trees is likely to boost biocontrol of pests on the trees themselves, but successful application of this approach will rely on **developing optimal understorey species** (that boost natural enemies rather than pests) and optimal understorey management practices (e.g. to avoid competition with the trees).

3. Evidence that predators walk from edge and strip refuges directly into fields in the spring and, as a result, impact on pest populations in adjacent fields remains vague. However, **edge and strip refuges are sources of flying natural enemies and so contribute to increasing regional abundance of these beneficials**. It is likely that landscapes with a high proportion of refuge habitats will have large regional populations of beneficials, which will improve biological pest control in the area

4. The spatial **location of horticultural crops is dynamic, whilst edge/strip refuge habitats are more static** (often including perennial plant species). Therefore it is necessary to determine which plant species and edge/strip management practices are **generally suitable for both horticulture and agriculture** (i.e. that have the maximum number of benefits and the minimum number of disbenefits). This is because edge and strip refuges could, in theory, threaten adjacent crops by being a source of weeds, diseases and pests, and a barrier to the movement of beneficials. Currently available information would suggest that **benefits of edge and strip refuges are likely to far outweigh disbenefits**.

5. **Edge/strip refuge habitats, and orchard understoreys, are potential sinks** as well as sources of some natural enemies during the main growing season of crops. It is poorly understood whether periodic partial disruption of the habitat (e.g. by mowing some sections) would force natural enemies from the refuge into the crop, and whether this would enhance the biological control of crop pests.

6. The mechanisms whereby **surface mulches/manures enhance the abundance and diversity of natural enemies** within the crop are largely understood, and there is ample evidence that this approach is effective in increasing natural enemies in arable crops, but experience in horticultural crops (especially in the UK) is very limited. With sufficient specific knowledge to optimise the system, the **indications are that use of mulches/manures could also benefit the grower in other ways** (e.g. disease control, weed suppression, improved soil conditions), and would put waste organic materials (that otherwise have to go into expensive landfill) to good use. However, some retailers will not allow any waste and organic material back on fields and there are many crops where treated sewage sludge is certainly not allowed. Clearly, these restrictions within production protocols would need to be taken into account.

10.7 The weed seedbank of horticultural systems

1. Understanding weed population dynamics is vital to the development of sustainable weed management systems that are sympathetic to biodiversity. The soil **weed seedbank is a critical aspect of weed population dynamics.** Weed seed production and seed persistence are central to the longevity of weed populations.

2. Seed predation may account for a significant reduction in seed numbers from the seedbank. Currently, **we know little of the precise biological interactions between specific weed species and seed predators.** This makes it difficult to predict with any accuracy the relative proportion of seed loss attributed to predation in different cropping and environmental scenarios.

3. The **surface zone of the soil profile** where weed seeds collect on shedding is particularly important for both biodiveristy (as a source of food) and weed management, but its ecology remains poorly understood and unquantified.

4. The **relative emergence time of crop and weeds are crucial** to good crop establishment and optimising weed removal timing. For example, the improved efficacy of many non-chemical means of weed removal rely on exploiting growth stage differences between the crop and weed, whilst the optimum timing of post-emergence herbicides will depend on the spread of a flush of weed emergence relative to the crop. Relative crop and weed establishment times should be considered within existing crop sowing programmes that are designed to ensure continuity of supply.

5. Weed emergence from the seedbank, growth and fecundity relative to prevailing weather conditions may help predict weed behaviour in atypical years. Better foresight of **how crops and weed populations may respond to potential long-term climatic changes in the UK would be helpful to planning appropriate future management strategies** where farm operation (both physical and chemical) could prove critical.

6. The success of many novel methods of managing the weed seedbank would be enhanced by a **greater understanding of the annual dormancy cycle** of buried weed seeds. It is fair to say that a physiological understanding of weed seed dormancy remains an enigma of weed science.

7. **Few surveys have been specifically made of the weed seedbanks of horticultural holdings.** Changing from arable to vegetable dominated rotation tends to favour weed species capable of short-life cycles to exploit the generally more frequent cultivations of vegetable cropping systems. The decline in the size of the seedbank noted in the 1970 seedbank survey was probably partly due to the widespread introduction of herbicides. There is little information on seedbanks of non-field vegetable horticultural systems that is relevant to the UK and could be reported in this study. Continuous crops tend to show dominance of weed species in the seedbank and hence increasing the diversity of the crop rotation will minimise the dominance of certain weed species in both the seedbank above ground- flora.

8. To **establish a desirable and diverse weed flora from the natural seedbank** and seed rain can be unreliable without specifically introducing rare species and specifically managing for them. The more aggressive arable weeds and sucessional vegetation development towards perennial species, will otherwise tend to suppress their expression above-ground. The germination ecology and management requirements for many of these **rare weed species are poorly understood.**

10.8 Review of stewardship and crop assurance schemes and their impact on biodiversity in horticultural systems.

1. Horticulture is making a **positive effort to minimise environmental impacts** through voluntary and government led schemes.

2. Standards of environmental protection in horticulture are likely at least as high as in farming as a whole.

3. Horticulture is spatially dynamic and **it is difficult to separate horticulture activities from whole farm scheme**s for protection of biodiversity.

4. Robust **horticulture specific data are hard to find**.

5. **Few measurable indicators are available** and there is a need to develop more effective monitoring.

6. Horticulture, by its nature, occupies a very diverse range of niches in farming operations; in itself this is **likely to make positive contributions to biodiversity**

7. **Horticulture could(should) make much more of its diverse role** as a guardian of biodiversity in agricultural production

10.9 Risk

1. Influence diagrams provide a useful tool for initially describing complex problems in a risk context.

2. Unlike conventional risk scenarios they do not tend to be constrained by formal quantitative arguments.

3. They provide an important framework for understanding the interactions between decisions and chance events, and enable a problem to be properly formulated.

4. Without necessarily being quantified the context enables policy-makers to see what factors may be affected and how by taking certain policy-decisions.

5. In the context of herbicides and biodiversity they should enable decisions to be taken about important research directions, e.g. where important data are not available.

10.10 Knowledge Gaps and Research Needs

There is a general lack of information in regard to the interactions between birds and invertebrates and horticultural crops against a backdrop of weed management challenges in the future. As a results a number of specific research gaps that have been identified from the review above. Given the complexity of horticulture a priority list of 20 brief research gaps is given below which fall within four broad themes; namely 1) baseline monitoring, 2) practical measures for encouraging biodiversity, 3) underpinning weed biology and ecology and 4) improving long-term sustainable weed management strategies for horticulture:

Baseline monitoring:

1. Survey current weed flora of horticultural systems to provide baseline data.
2. Field survey bird utilisation of all horticultural crops for nesting and foraging through the year and also evaluate and extract data of bird occurrence in horticulture from BBS and CBC datasets
3. Survey cropping patterns that precede different horticultural crops
4. Identify weed species that contribute to winter seed supply in different crop stubbles.
5. Develop measurable indicators of biodiversity for horticulture.

Practical measures for encouraging biodiversity:

6. Evaluate crop management factors that favour particular birds, particularly crop structure, mulching and timing of operations
7. Can partial disruption of refuge habitat force natural enemies into the crop and enhance biological control?
8. Evaluation of annual and perennial margin strips and wildflower seed mixtures for a range of horticultural crops.
9. Investigate the effectiveness of selected surface mulches/manures for increasing natural enemy abundance and biological pest control within horticultural crops whilst respecting hygiene and harvesting protocols.
10. Determine optimal understorey species and management practices for use in orchards.
11. Is there scope for increasing weed tolerance levels (species and abundance)?

Underpinning weed biology and ecology:

12. Understand the relative time of emergence of crops and weeds within the changing seedbed environment to improve weed control strategies that rely on crop/weed growth-stage differentials to be effective.
13. Improve our understanding of weed seed dormancy (e.g. to improve our ability to predict weed survival and emergence through a rotation and target control techniques more effectively).
14. Understand the germination ecology and management requirements for desirable and rare arable weeds for the establishment and maintenance of beneficial margins.
15. Improve estimates of critical stages in weed population dynamics (e.g. seed production, seed predation and seed persistence).

Improving long-term sustainable weed management strategies for horticulture:

16. Integrate models of weed biology and ecology to help predict the long-term outcome of weed management strategies and shifts in the weed flora. These should also include weed species identified as rare or having specific beneficial properties.
17. How will horticultural crops and weed populations respond to long-term climate change so we can plan for future sustainable weed management?
18. Are there opportunities for using influence diagrams as a framework for understanding complex interactions and risks associated with the future of weed management and biodiversity in horticulture?
19. Improve the reliability and cost-effectiveness of existing non-chemical and novel weed management techniques to complement and integrate with herbicides
20. Prioritise future weed management needs on crops where gaps for herbicide weed control will exist after 2007 and examine whether new products developed for cereals and other major crops have potential use for horticulture.

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