# The role of weeds in supporting biological diversity within crop fields

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## Summary

Weeds are major constraints on crop production, yet as part of the primary producers within farming systems, they may be important components of the agroecosystem. Using published literature, the role of weeds in arable systems for other above-ground trophic levels are examined. In the UK, there is evidence that weed flora have changed over the past century, with some species declining in abundance, whereas others have increased. There is also some evidence for a decline in the size of arable weed seedbanks. Some of these changes reflect improved agricultural efficiency, changes to more winter-sown crops in arable rotations and the use of more broad-spectrum herbicide combinations. Interrogation of a database of records of phytophagous insects associated with plant species in the UK reveals that many arable weed species support a high diversity of insect species. Reductions in abundances of host plants may affect associated insects and other taxa. A number of insect groups and farmland birds have shown marked population declines over the past 30 years. Correlational studies indicate that many of these declines are associated with changes in agricultural practices. Certainly reductions in food availability in winter and for nestling birds in spring are implicated in the declines of several bird species, notably the grey partridge, *Perdix perdix*. Thus weeds have a role within agroecosystems in supporting biodiversity more generally. An understanding of weed competitivity and the importance of weeds for insects and birds may allow the identification of the most important weed species. This may form the first step in balancing the needs for weed control with the requirements for biodiversity and more sustainable production methods.

**Keywords:** biodiversity, birds, fauna, insects, trophic interactions, weeds, weed community, crop, fields.

## Introduction

Weeds are an important constraint on yield in most crops across the world. As a result, considerable research has been aimed at developing weed control and understanding weed biology. At present, more money is spent by growers on weed control than other crop inputs, perhaps reflecting that research effort. The global pesticide market was valued at $29 billion in 2000 (CPA, 2002), divided approximately between herbicides 48%, insecticides 27%, fungicides 19% and other products 6%. Improved crop management techniques, including herbicides, have resulted in good control of weeds and have facilitated different cropping patterns and steadily increasing crop yields. Perhaps, unsurprisingly, there have been coincident changes in the flora of intensively managed arable farmland (Marshall, 2001; Marshall *et al.*, 2001). In association with the advances in agriculture, there is also evidence of changes in other taxa (Stoate *et al.*, 2002). In the UK, previously common species of fauna associated with farmland have shown marked reductions in range and population size

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over the past 30 years, most notably among birds (Fuller *et al*., 1995). A range of cornfield weed species, such as *Ranunculus arvensis* L. and *Scandix pecten-veneris* L., have declined markedly this century (Sutcliffe & Kay, 2000), to the extent that some are now extinct in the UK. These annual flowers, previously regarded as weeds, are dependent on the arable ecosystem, which is characterized by regular soil cultivation (Wilson, 1993).

Most countries are signatories to the Rio Convention on the Conservation of Biodiversity. The reasons for the conservation of biodiversity are moral, aesthetic, social and economic. Increasingly, it is argued that biological diversity within ecosystems, including agroecosystems, provides a range of biological functions, such as nutrient cycling and pest control (Altieri, 1999). Thus, biodiversity has a functional component. For example, there are some indications that more diverse agricultural systems may enhance natural control of crop pests (Estevez *et al*., 2000). Nevertheless, most ecological research on biodiversity is made outside the arable habitat. There is, therefore, a need for basic research in arable systems to understand the links between biodiversity, ecosystem function and sustainability.

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

Most countries now have action plans for the conservation of biological diversity. An emerging paradigm is the conservation of species and communities within the farmed landscape as a whole, as noted in Canada (Mineau & McLaughlin, 1996). In the UK, for example, there are almost no true wilderness areas and more than 75% of the land surface is farmed in one way or another. With such fragmentation of natural habitats and predominance of agriculture, there may be a need to develop practical means of maintaining diversity in the wider landscape. Further, should climate change occur, the farmed landscape may need to provide opportunities for species to disperse between habitats as environmental suitabilities change. In this paper, evidence is sought for changes in weed floras and for information on the importance of weeds for other taxa and biodiversity in general. As an example of intensive agricultural management data are examined for the UK, however supporting information from elsewhere is also reviewed. The hypothesis is proposed that (a) weeds are important for farmland diversity and (b) changes in agricultural management have reduced the diversity of weed flora, with subsequent impacts on other non-target taxa. A review of the available published information has been used to evaluate the roles of weeds, changes in weed flora, associated taxa and changes in weed management.

## Changes in weed communities

Classic studies were reported in the early twentieth century (Brenchley, 1911, 1912, 1913), which attempted to identify the associations of weeds in arable land with soil types and crops. The strict association of weeds with soil types was limited, with many species of weeds being of general occurrence. Some species are nevertheless most often found on certain soils. These data give a picture of the arable weed flora 90 years ago. The last large-scale survey of arable weeds in the UK was conducted by technical staff of Schering Agriculture (now Bayer CropScience GmbH) in 1988 (Whitehead & Wright, 1989). Weeds in winter wheat and winter barley were recorded, representing a 4% sample of UK fields. The commonest broad-leaved and grass weeds are given in Table 1 (Whitehead & Wright, 1989).

Certain species were more prevalent in the East, notably *Alopecurus myosuroides* Huds., whereas others, notably *Fumaria officinalis* L., were commoner in the West. An earlier survey examined weed incidence in central southern England (Froud-Williams & Chancellor, 1982; Chancellor & Froud-Williams, 1984). A similar area was surveyed in the 1960s and again in 1977 and 1997 (Sutcliffe & Kay, 2000). This study has shown a variety of responses among the weed flora. Some species have become more common, others have remained stable, whereas others have become rarer. Species that were less common in the 1960s have tended to become rarer. A suite of species has become commoner, including *A. myosuroides*, *Anisantha sterilis* (L.) Nevski, *Galium aparine* L. and *Sisymbrium officinale* (L.) Scop. (Table 2).

It is not easy to predict the size and content of likely weed communities, given the generalist occurrence of so many species and the variation that is a natural feature of weed assemblages. Field-to-field variation in weeds is commonly found, even within an individual farm (Marshall & Arnold,

**Table 1** The main broad-leaved and grass weeds in winter cereals (percentage fields infested out of a total of 2359 fields assessed) in Great Britain (total) from four sales regions (Schering Ltd)

| Species | Percentage of fields with species present | | | | | |
|---|---|---|---|---|---|---|
| | Total | *Rank* | Scotland/N. East | Anglia | Southern | Western |
| Broad-leaved weeds | | | | | | |
| *Stellaria media* | 94 | *1* | 98 | 92 | 90 | 96 |
| *Veronica persica* | 72 | *3* | 79 | 76 | 69 | 59 |
| *Matricaria* spp. | 67 | *4* | 72 | 68 | 63 | 63 |
| *Galium aparine* | 58 | *5* | 59 | 60 | 55 | 58 |
| *Lamium purpureum* | 47 | *6* | 59 | 36 | 47 | 39 |
| *Viola arvensis* | 45 | *7* | 37 | 45 | 49 | 54 |
| *Sinapis arvensis* | 36 | *10* | 27 | 41 | 38 | 42 |
| *Veronica hederifolia* | 30 | *11* | 28 | 33 | 33 | 26 |
| *Capsella bursa-pastoris* | 23 | *12=* | 26 | 21 | 20 | 24 |
| Volunteer oilseed rape | 23 | *12=* | 36 | 22 | 10 | 16 |
| *Papaver rhoeas* | 18 | *15* | 13 | 27 | 20 | 11 |
| *Fumaria officinalis* | 17 | *16* | 21 | 7 | 17 | 20 |
| *Chenopodium album* | 13 | *18=* | 17 | 11 | 10 | 13 |
| *Aphanes arvensis* | 12 | *20* | 6 | 13 | 17 | 14 |
| *Geranium* spp. | 11 | *21* | 9 | 11 | 11 | 14 |
| Grass weeds | | | | | | |
| *Poa annua* | 79 | *2* | 82 | 66 | 78 | 88 |
| *Avena* spp. | 42 | *8* | 35 | 51 | 45 | 40 |
| *Alopecurus myosuroides* | 38 | *9* | 25 | 70 | 35 | 26 |
| *Elytrigia repens* | 21 | *14* | 23 | 21 | 19 | 20 |
| *Lolium* spp. | 14 | *17* | 15 | 7 | 15 | 19 |
| *Anisantha sterilis* | 13 | *18=* | 15 | 12 | 12 | 10 |
| *Poa trivialis* | 7 | *22=* | 8 | 3 | 12 | 2 |
| Volunteer cereals | 7 | *22=* | 7 | 7 | 9 | 5 |

N. East = Northumberland, Durham, Yorkshire; Anglia = East Anglia and the English midlands; Southern = south and south-west Britain; Western = Wales and its borders, Cheshire, Lancashire (from Whitehead & Wright, 1989).

1994). Nevertheless it is clear that some broad changes have occurred over the past 75 years in arable plant communities in the UK.

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

Reviewing changes in biodiversity in arable land, Robinson & Sutherland (2002) note that there is evidence of declining seedbanks in arable land in Britain (Fig. 1). A similar trend has been reported in Denmark (Jensen & Kjellsson, 1995). Viable seed density in the soil declined by 50% in Danish arable fields between 1964 and 1989.

Elsewhere in Europe, studies of weed communities of organic arable fields in Sweden indicated that a number of rare species might be supported by such systems (Rydberg & Milberg, 2000). There was also a tendency for conventional fields to support more nitrophilous weed species. A comparison of organic vs. an integrated arable system in Germany indicated that the abundance and diversity of weed flora increased on the organic system (Gruber *et al*., 2000), although no rare species were recorded. No-plough tillage increased weed abundance, notably grass species. A significantly more diverse flora was found in organic compared with conventional fields in Denmark by Hald (1999b) and

**Table 2** Changes in occurrence of selected weed species in 100 fields in central southern England (from Sutcliffe & Kay, 2000)

| Species | Increase (+), decline (–) or stable | Occurrence in 1960s | Occurrence in 1997 |
|---|---|---|---|
| *Aethusa cynapium* | + | 44 | 74 |
| *Alopecurus myosuroides* | + | 13 | 76 |
| *Anagallis arvensis* ssp. *foemina* | – | 7 | 3 |
| *Anisantha sterilis* | + | 0 | 77 |
| *Anthemis arvensis* | – (Post 1977) | 6 | 0 |
| *Avena fatua* | + | 18 | 54 |
| *Capsella bursa-pastoris* | + (Post 1977) | 19 | 61 |
| *Centaurea cyanus* | – | 2 | 0 |
| *Chenopodium album* | + | 24 | 53 |
| *Convolvulus arvensis* | + | 52 | 71 |
| *Cirsium arvense* | + | 25 | 62 |
| *Cirsium vulgare* | + | 1 | 52 |
| *Elytrigia repens* | + | 42 | 67 |
| *Euphorbia exigua* | Stable | 39 | 31 |
| *Fallopia convolvulus* | Stable | 72 | 71 |
| *Galeopsis angustifolia* | – | 11 | 1 |
| *Galium aparine* | + | 21 | 88 |
| *Geranium dissectum* | + | 10 | 59 |
| *Kickxia spuria* | Stable | 18 | 18 |
| *Papaver rhoeas* | + (Post 1977) | 43 | 74 |
| *Polygonum aviculare* | Stable | 86 | 80 |
| *Silene noctiflora* | – | 21 | 4 |
| *Sisymbrium officinale* | + | 0 | 31 |
| *Spergula arvensis* | – | 5 | 0 |
| *Tripleurospermum inodorum* | – | 60 | 49 |
| *Veronica persica* | – | 84 | 75 |

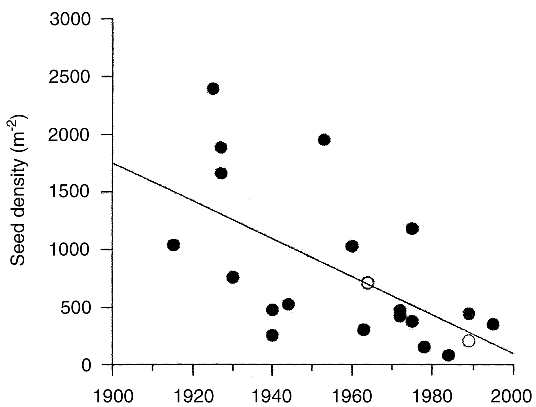


**Fig. 1** Published estimates of seed density in arable soils. Points represent densities of dicotyledonous seed in the top 1 cm of soil in arable fields in Britain (filled symbols, from sources in Robinson, 1997) and Denmark (open symbols, Jensen & Kjellsson, 1995). Studies are included only if they sampled the entire seedbank between September and November and the fields had been part of a cereal-based rotation for at least 5 years; results from adjacent fields and years have been averaged. Slope of regression through British data: 17 seeds $m^{-2}$ $year^{-1}$, $R^2 = 0.35$ (from Robinson & Sutherland, 2002).

in Sweden by Rydberg & Milberg (2000). However, organic production will not automatically preserve and encourage a diverse field weed flora under current economic pressures (van Elsen, 2000).

## Changes in farming systems

Changes in farming systems in Europe have been recently reviewed by Stoate *et al.* (2002) and the impacts on farmland birds have been explored by Chamberlain *et al.* (2000). In arable land increases in autumn-sown arable crops, oilseed rape (Table 3), fertilizer and pesticide use have been reported. The move from spring to winter sown cropping has had a marked impact on the weed flora by favouring autumn-germinating species (Chancellor, 1985; Hald, 1999a). Other changes in grassland and arable management that may have affected the weed flora were outlined by Marshall & Hopkins (1990). Mechanization, increases in field size, agrochemical development and moves from hay cutting to silage are all likely to have impacted on plant species composition in farmland. In the UK, the specialization of farm enterprise has resulted in declines in numbers of mixed farms that have both stock and arable cropping.

Concentrating on arable cropping, a study of the patterns of herbicide usage in the UK has shown that over the past 30 years there have been significant changes (Marshall *et al.*, 2001). These reflect herbicide development, although most products remain available to farmers, at least until removal under current EU review processes. By evaluating the list of susceptibilities on herbicide product labels, it is possible to assess the

**Table 3** Areas of major arable crops sown in England, Wales and Scotland (GB) between 1974 and 1998 (MAFF Pesticide Usage surveys)

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

Areas = $x \times 1000$ ha.
Figures in parentheses are percentage of total arable crops.

spectrum of weeds that has been controlled over time with changing herbicide use patterns. These have resulted in an increase in the number of broad-leaved species that are being controlled (Table 4) (Marshall *et al.*, 2001). This is mainly apparent for the most prominent UK crop, winter wheat, but is also evident for spring barley. The changes in herbicide use in oilseed rape and field beans have had little or no effect on species' susceptibility, but these are used on a much smaller area than the cereal crops. The main differences in the cereal crops are increased sensitivity of *Veronica* spp., *Lamium* spp. and weeds in the Polygonaceae. This increased sensitivity started with the introduction of ioxynil + bromoxynil in the early 1980s and was continued when the herbicides metsulfuron and diflufenican were introduced at the end of the 1980s. Thus, the greater selection against a wider range of weeds has been in place since the 1980s and is not a new phenomenon.

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

An appreciation of the impact of intensive production on environmental, nature and landscape values in the Netherlands (ten Berge *et al.*, 2000) is leading to the consideration of modified production systems. While the trend of the past century has been the simplification of production systems, there is a contrary view that more diverse systems are more sustainable in terms of resource conservation. There may be opportunities to exploit complimentarity in resource capture by species in more diverse production systems (Vandermeer *et al.*, 1998).

## Links between weeds and other taxa

Plants are key components of terrestrial ecosystems, providing the primary production upon which food chains are built. Different plant parts may then provide a range of resources for associated fauna. Leaves and stems may be browsed, whereas pollen and nectar provide resources for pollinating insects. In addition to providing food for herbivores, plants have other functions, e.g. by provision of cover, reproduction sites and

**Table 4** Numbers of weeds species noted as susceptible on herbicide product labels for four arable crops in the UK

| Winter wheat | | Barley | | Field beans | | Oilseed rape | |
|---|---|---|---|---|---|---|---|
| Herbicide | Number of species | Herbicide | Number of species | Herbicide | Number of species | Herbicide | Number of species |
| Mecoprop | 34 | Dicamba + MCPA + mecoprop | 21 | Simazine | 38 | TCA | 5 |
| MCPA | 25 | MCPA | 24 | Fluazifop | 9 | Propyzamide | 16 |
| Chlorotoluron | 19 | Metsulfuron | 31 | Cycloxydim | 6 | Clopyralid | 14 |
| Isoproturon | 18 | Ioxynil + bromoxynil | 25 | Bentazone | 23 | Graminicides | 9 |
| Metsulfuron | 31 | Ioxynil + bromoxynil + mecoprop | 33 | | | Benazolin + clopyralid | 12 |
| Isoproturon + diflufenican | 35 | | | | | Metazachlor | 18 |
| Ioxynil + bromoxynil | 25 | | | | | | |
| Fluroxypyr | 10 | | | | | | |
| Graminicides | 10 | | | | | | |
| Ioxynil + bromoxynil + mecoprop | 33 | | | | | | |

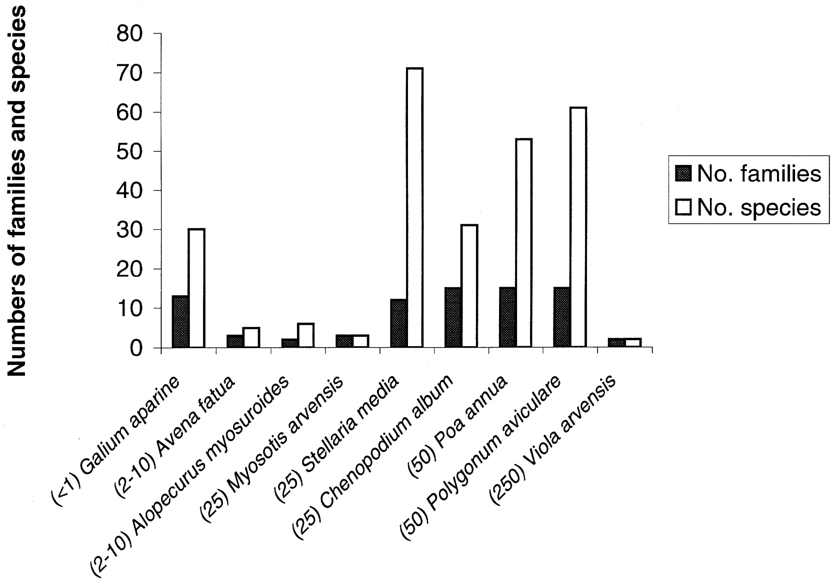


**Fig. 2** Numbers of families and species of phytophagous insects recorded on selected weed species in the Plant-Insect Database (numbers in brackets: $n$ = number of weeds $m^{-2}$ needed to give 5% wheat yield loss).

structure within habitats. Plants may also provide environmental heterogeneity in space and time. In agriculture and horticulture, weeds may play some and perhaps all of these roles, providing diversity, ecosystem functions and supporting many other species. Nevertheless, information in the literature on these roles is not comprehensive. The following sections review information on insects and birds.

### *Insects*

In assessing the importance of different weed species to invertebrates, it is essential to have information on host plant relationships that is reliable and relevant. In reality, this can only be obtained by targeted work in the field on single weed species. Unfortunately, such studies are seldom undertaken, although work on arable weed communities has provided insight into the potential of this approach (Brown *et al.*, 1987; Brown & Hyman, 1995). Literature records seldom differentiate between occasional occurrences of insects on plants and common and abundant occurrences or, indeed, the habitat in which the species is found. Undoubtedly, in the UK, the Phytophagous Insect Data Base (PIDB) developed by the Centre for Ecology and Hydrology (CEH), UK, is of outstanding value in terms of a collation of host plant records and is a unique resource (Ward, 1988; Ward & Spalding, 1993).

The PIDB holds information on linkages between insects and plants compiled from the literature, from museum collections and from unpublished sources. The linkages are based on feeding records, but do not include nectar or pollen feeders. The PIDB is extensive (45 000 linkages or more), however it suffers from the disadvantages already cited. These apart, its interrogation was highly appropriate to determine the relative potential importance of different weed species for phytophagous insects.

The following relationships were assessed for the insect fauna associated with a range of 30 individual weed species (Marshall *et al.*, 2001):

- number of families of insects;
- number of species of insects (generalist or specialist);
- number of insect species dependent on the weed species for completion of life history (mainly host-specific species);
- number of pest species.

Numbers of phytophagous insects recorded vary markedly between weed species, with some, such as *Veronica persica* Poiret, with very few records, whereas *Stellaria media* (L) Vill. has over 70 species records (Fig. 2; Table 5). A number of insect species are dependent on particular weeds to complete their life cycle. For these insects, weeds are particularly important. Even among weeds that are routinely targeted for control in cereal crops (Fig. 2), it is clear that some weeds support few insects, whereas others support a diversity of invertebrates. The PIDB does not give a measure of abundance. Consequently, for assessing the value of species in terms of resources for birds and small mammals, the data have to be viewed with some caution. However, it does provide taxonomic and functional categories of insect species (e.g. insects feeding externally or internally in plant tissues, flower or seed feeders, etc.), which are of clear relevance to the known preferred diet of farmland bird species.

**Table 5** Numbers of phytophagous insects associated with selected weed species, derived for the Plant-Insect Database

| Weed species | Insect families | Insect species | Host-specific species | Pest species |
|---|---|---|---|---|
| *Aethusa cynapium* | 4 | 4 | 0 | 0 |
| *Alopecurus myosuroides* | 2 | 6 | 0 | 2 |
| *Anagallis arvensis* | 3 | 3 | 0 | 0 |
| *Avena fatua* | 3 | 5 | 1 | 0 |
| *Anisantha sterilis* | 4 | 4 | 2 | 0 |
| *Capsella bursa-pastoris* | 5 | 13 | 2 | 3 |
| *Cerastium fontanum* | 13 | 22 | 1 | 0 |
| *Chenopodium album* | 15 | 31 | 2 | 3 |
| *Cirsium arvense* | 19 | 50 | 5 (1) | 4 |
| *Euphorbia helioscopia* | 4 | 5 | 0 | 1 |
| *Fumaria officinalis* | 1 | 3 | 0 | 0 |
| *Galeopsis tetrahit* | 6 | 13 | 1 | 0 |
| *Galium aparine* | 13 | 30 | 4 | 4 |
| *Geranium dissectum* | 2 | 2 | 0 | 0 |
| *Lamium purpureum* | 8 | 18 | 2 (1) | 1 |
| *Matricaria recutita* | 9 | 15 | 1 (1) | 1 |
| *Myosotis arvensis* | 3 | 3 | 0 | 0 |
| *Papaver rhoeas* | 7 | 8 | 0 | 2 |
| *Persicaria maculosa* | 9 | 20 | 1 | 1 |
| *Poa annua* | 15 | 53 | 7 (3) | 4 |
| *Polygonum aviculare* | 15 | 61 | 4 (2) | 3 |
| *Rumex obtusifolius* | 15 | 79 | 4 | 1 |
| *Senecio vulgaris* | 10 | 46 | 4 | 3 |
| *Sinapis arvensis* | 13 | 37 | 3 | 13 |
| *Solanum nigrum* | 3 | 7 | 0 (1) | 2 |
| *Sonchus oleraceus* | 14 | 28 | 1 (1) | 1 |
| *Spergula arvensis* | 4 | 8 | 0 | 1 |
| *Stellaria media* | 12 | 71 | 4 | 3 |
| *Tripleurospermum inodorum* | 15 | 31 | 3 (2) | 4 |
| *Veronica persica* | 1 | 1 | 0 | 0 |
| *Viola arvensis* | 2 | 2 | 0 | 0 |

Data are numbers of insect families, species, host-specific insect species and pest species recorded on particular weeds (number in parentheses = number of Red List insect species).

### *Birds*

It is now well established that many species of farmland birds are undergoing long-term population declines and range contractions in the UK (Fuller *et al.*, 1995; Siriwardena *et al.*, 1998). Baillie *et al.* (2001) provide recent data on population declines. Among farmland birds, *Perdix perdix* L. (grey partridge), *Streptopelia turtur* L. (turtle dove), *Alauda arvensis* L. (skylark), *Turdus philomelos* C.L. Brehm (song thrush), *Muscicapa striata* Pallas (spotted flycatcher), *Sturnus vulgaris* L. (starling), *Passer domesticus* L. (house sparrow), *Passer montanus* L. (tree sparrow), *Carduelis cannabina* L. (linnet), *Pyrrhula pyrrhula* L. (bullfinch), *Emberiza citrinella* L. (yellowhammer), *Emberiza schoeniclus* L. (reed bunting) and *Miliaria calandra* L. (corn bunting) have declined by over 50% between 1968 and 1998, based on Common Bird Census (CBC) data from the British Trust for Ornithology. Several species have experienced major declines over the 10 years 1988–98, including *P. montanus* (63% decline), *M. striata* (55%), *S. turtur* (42%), *E. citrinella* (40%) and *S. vulgaris* (30%). The causes of these declines are not fully understood in most cases, although there is strong evidence that concurrent changes in agricultural practices are largely responsible. Potential mechanisms are reviewed by Fuller (2000), and include pesticides, however only for one species, *P. perdix*, has a relationship between pesticide use and population decline been conclusively demonstrated (Campbell *et al.*, 1997; Burn, 2000).

Seeds are particularly important for granivorous bird species during the winter, although some depend on them all year. Chicks of most farmland bird species, even those that are granivorous as adults, require invertebrate food, although there are some exceptions, e.g. *C. cannabina*, *S. turtur*. Arable plants form a major part of the diet of many farmland birds. However, weed species vary considerably in terms of their relative importance in bird diet. Weed species have been categorized in terms of their importance to birds as seeds. Representative common weed species were

**Table 6** The importance of families and genera of common weed species in farmland bird diet (Marshall *et al.*, 2001)

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

classified as important or present in the diet of each bird species using data derived from previous reviews (Wilson *et al.*, 1996; Buxton *et al.*, 1998). The level of taxonomic specification for plants varied, so information was compiled at family, genus and species level depending on the information available. *Stellaria media* and species of Polygonaceae and Chenopodiaceae are of particular importance for farmland birds (Table 6).

Weeds are also important as host plants for arthropods that are eaten by birds, but there is insufficient information to classify their relative importance. Indeed, for many arthropods, vegetation density and structure may be more important than botanical composition. Some farmland birds feed mainly or entirely on invertebrates throughout their lives, but many species, including a large proportion of those that are currently in decline, feed largely on seeds and other plant material as adults, but require invertebrate food to nourish their growing chicks. Wilson *et al.* (1996) give a detailed account of the diet of species of farmland birds. The same authors (Wilson *et al.*, 1999) also reviewed the abundance and diversity of invertebrate (and plant) foods of 26 granivorous bird species of northern Europe. Invertebrate taxa which they found to be important components of the diet of a wide range of bird species included spiders and mites (Arachnida), especially spiders (Araneae); beetles (Coleoptera), especially ground beetles (Carabidae); and weevils (Curculionidae); grasshoppers, crickets, bush crickets, etc. (Orthoptera); flies (Diptera), especially crane flies and their larvae (leatherjackets) (Tipulidae); bugs (Hemiptera), especially aphids (Aphididae); ants, bees, wasps and sawflies (Hymenoptera), especially ants (Formicidae); and butterflies, moths and their larvae (Lepidoptera). Three groups were identified as showing evidence of association with declining bird species: ground beetles (Carabidae); grasshoppers, bush-crickets and crickets (Orthoptera); and larvae of butterflies and moths (Lepidoptera).

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

## Interactions between crop management, weeds and biodiversity

### *Crop management and weeds*

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

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

A long-term study of crop rotation and weed control in the USA has shown the relative importance of these factors in maize, soybean and barley (Doucet *et al.*, 1999). Overall, weed management explained 37.9% of total variation in weed assemblages, whereas rotation only accounted for 5.5%. Nevertheless, crop rotation is an important component of integrated weed management. Similarly, studies on conventional vs. no-tillage soil management in Canada, have confirmed the selective effects on weed communities of herbicides and soil preparation (Swanton *et al.*, 1999). Several herbicides applied as desiccants in the late stages of crop growth can affect weed seed viability and inhibit germination (Bennett & Shaw, 2000).

### *Crop management and insects*

A comparison of herbicide-treated and untreated plots in the headlands of winter cereal fields in southern England (Moreby & Southway, 1999) has clearly demonstrated that untreated plots had greater weed density and diversity and significantly higher numbers of many invertebrate taxa, notably those that are important in the diet of farmland birds. The Heteroptera, Auchenorrhynca and Coleoptera were particularly reduced on herbicide-treated plots. An example of a species for which herbicide effects have been demonstrated is the knotgrass beetle, *Gastrophysa polygoni* (L.). This beetle feeds on *Polygonum aviculare* L. and *F. convolvulus* and appears to have poor dispersal. Sotherton (1982) found that larvae feeding on host plants or egg cases sprayed with 2–4 D herbicide suffered significantly higher mortalities than larvae that fed on untreated material. Treatment of spring barley with 2–4 D + mecoprop significantly reduced mean densities of the food plants and egg batches on sprayed areas compared with unsprayed areas. In addition, in fields that were treated with a herbicide mixture containing dicamba and dichlorprop, which were more effective against the host plants, knotgrass beetles were completely absent.

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

Impacts on insects appear to be mostly indirect effects, mediated by the removal or reduction of weeds with the crop. Direct effects of herbicides on insect species are rare, however Ahn *et al.* (2001) demonstrated effects of glufosinate-ammonium at concentrations used in orchards on different life history stages of several predatory arthropods.

### *Crop management and birds*

Fuller (2000), reviewing relationships between agricultural changes and bird populations, suggested that although the loss of hedgerows since the 1940s had been substantial, it did not appear to have been a principal driver of recent (i.e. post 1970) declines in farmland bird populations. Factors resulting from agricultural intensification on arable farms identified by Fuller (2000), which have implications for birds, include increased mechanization, increased use of inorganic fertilizers and less farmyard manure, reduction in spring sowing of cereals, simplification of rotations and decline in mixed ley farming, and changes in cropping patterns, in addition to increases in pesticide use. Detailed examination of the changes in farming practice in the UK and its relation to changes in farmland bird species indicates a plausible link between intensification of production and bird population declines (Chamberlain *et al.*, 2000). There is an apparent time lag between bird declines and intensification of production. However, as many components of crop management intensification are interdependent, it is not possible to easily identify effects of specific factors, such as herbicides. Moreover, it may be a suite of factors affecting bird populations and ranges.

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

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

## Balancing biodiversity and crop production

Production systems are essential for food and non-food products. Nevertheless, threats to plants from impacts of weed management within production systems may impact on biological diversity. Those impacts, mediated directly or indirectly through the elimination of plants or effects on reproductive potential, may affect ecosystem function by affecting soil processes, nutrient cycling and trophic interactions via fauna, flora, microflora and fungi. Trophic effects on invertebrates and birds from the control of weeds are now clearly in evidence. Several initiatives, notably for integrated crop management, indicate there are implications for biological diversity within fields from different approaches to weed control (Clements *et al.*, 1994; Mayor & Dessaint, 1998). The protection of the farmers' investment and avoidance of risk have been the driving forces for efficient weed control in the past. However, a new paradigm is to match crop production with conservation of biological resources (Paoletti *et al.*, 1992) and the development of more sustainable systems. Others see one of the tasks of modified production systems as the provision of biodiversity (van Elsen, 2000). Current data indicate that some weeds need to be maintained within crops for birds and insects. A balance is required between the methods of production, the demand for products and the environmental impacts that occur.

Studies of weed seedbanks illustrate the dynamic nature of weed populations and the ability of weeds to produce high seed return, if control is relaxed. This offers some possibility of relaxing weed control either rotationally or in limited areas of crops, as with conservation headlands. Nevertheless, the major constraint is that the most fecund and often the most competitive weed species respond best to simple relaxation of management. Therefore, relaxed weed control would need to be managed carefully to allow the less common and less competitive species to increase, while controlling the competitive species. This may indicate a new approach to weed management, with the explicit aim of maintaining specific weed assemblages. These might be more traditional assemblages that were common 100 years ago, or assemblages tailored to maintaining beneficial invertebrate species, or for biodiversity more generally.

The aim must be to strike a balance between adequate weed control, including the prevention of weed seed build-up, and the requirement for some plants to support biological diversity. For some, clean crops and zero tolerance of weeds is the approach, with noncrop areas supporting biodiversity. This may be suitable for large countries, such as the USA. However, in western Europe, where the landscape is almost entirely agricultural, different approaches are required. These approaches need to be based on integrated weed management, although modifications to crop management in selected areas of fields, such as conservation headlands and uncropped wildlife strips (Marshall & Moonen, 2002), may provide sufficient resources for some species of concern. Some data are available on the importance of different weed species for beneficial and pest invertebrates, bird species and on the relative competitive effects of the weeds (Marshall *et al.*, 2001). Using competitive ability of weed species, the number of insect species associated with particular weeds and the importance of weed seeds in the diet of farmland birds, we suggest a pragmatic approach to evaluating the importance of weed species for biodiversity. As an example, the evaluation of several weeds is presented in Table 7. Clearly, certain weeds, such as *Poa annua* L. and *P. aviculare*, are more important for biodiversity in arable systems than others, such as *A. myosuroides* and *V. persica*. On the basis of this approach, the challenge will be to select species and populations that may be tolerated to achieve a sustainable ecological balance. An understanding of the selection pressures applied by management, including the use of herbicides, and their effects on diversity will also be needed, as well as more comprehensive and quantitative data on the interactions between flora and fauna at the appropriate spatial scales within crops.

**Table 7** The importance of a representative list of common weed species for invertebrates and birds and their economic importance in terms of crop yield loss

| Weed species | Value for invertebrates[1] | No. Red Data Book species | No. pest species | Importance for seed-eating birds[2] | Competitive index[3] |
|---|---|---|---|---|---|
| *Aethusa cynapium* | – | 0 | 0 | | |
| *Alopecurus myosuroides* | – | 0 | 2 | a | 12.5 |
| *Anagallis arvensis* | – | 0 | 0 | a | 100.0 |
| *Anisantha sterilis* | – | 0 | 0 | – | (5.0) |
| *Avena fatua* | – | 0 | 0 | – | 5.0 |
| *Capsella bursa-pastoris* | ** | 0 | 3 | * | 50.0 |
| *Centaurea cyanus* | c | c | c | b** | |
| *Cerastium fontanum* | ** | 0 | 0 | ** | (25.0) |
| *Chenopodium album*† | *** | 0 | 4 | *** | 25.0 |
| *Chrysanthemum segetum* | c | c | c | a | |
| *Cirsium arvense*‡ | *** | 1 | 4 | * | 17.0 |
| *Euphorbia helioscopia* | * | 0 | 1 | – | |
| *Fallopia convolvulus* | c | c | c | *** | 17.0 |
| *Fumaria officinalis* | – | 0 | 0 | * | 62.5 |
| *Galeopsis tetrahit* | ** | 0 | 0 | – | |
| *Galium aparine* | *** | 0 | 4 | – | 1.7 |
| *Geranium dissectum* | – | 0 | 0 | | 62.5 |
| *Lamium purpureum* | ** | 1 | 1 | – | 62.5 |
| *Matricaria recutita* | ** | 1 | 1 | – | 12.5 |
| *Myosotis arvensis* | – | 0 | 0 | – | 25.0 |
| *Papaver rhoeas* | * | 0 | 2 | a | 12.5 |
| *Persicaria maculosa*† | ** | 0 | 1 | *** | (25.0) |
| *Poa annua*† | *** | 3 | 4 | ** | 50.0 |
| *Polygonum aviculare*† | *** | 2 | 3 | *** | 50.0 |
| *Rumex obtusifolius*‡ | *** | 0 | 1 | ** | |
| *Senecio vulgaris*† | *** | 0 | 3 | ** | 83.0 |
| *Sinapis arvensis*† | *** | 0 | 13 | ** | 12.5 |
| *Solanum nigrum* | * | 1 | 2 | a | |
| *Sonchus oleraceus*† | *** | 1 | 1 | * | 50.0 |
| *Spergula arvensis* | * | 0 | 1 | * | |
| *Stellaria media*† | *** | 0 | 3 | *** | 25.0 |
| *Tripleurospermum inodorum*† | *** | 2 | 4 | a | 12.5 |
| *Veronica persica* | – | 0 | 0 | | 62.5 |
| *Viola arvensis* | – | 0 | 0 | ** | 250.0 |

[1]The estimated relative importance of selected plant species for invertebrates (based on the available datasets). Insect criteria is based on the number of insect species associated with particular weeds (0–5 species = –; 6–10 = *; 11–25 = **; 26+ = ***). [2]The importance of the plant genus for seed-feeding birds where *** = important for >8 bird species; ** = important for 3–8 species and * = 1 or 2 species; – = not important). [3]Weed density ($m^{-2}$) that gives 5% crop yield loss in wheat (figures in parentheses are expert opinion).
†Arable species that are important for in-field biodiversity.
‡Grassland/arable species important for biodiversity.
a = No information at genus or species level.
b = Because of the rarity of cornflower, it is highly likely that references in the literature refer to other members of this genus, e.g. black knapweed *C. nigra*, greater knapweed *C. scabiosa*.
c = No invertebrate data.

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