

A functional group approach to the management of UK arable weeds to support biological diversity

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Summary

Weeds have an important role in maintaining farmland biodiversity. This needs to be balanced with their potential negative impact on crop yield and quality. Mechanistic models of crop–weed competition are an important tool in striking this balance. A range of common UK annual weeds were screened for the eco-physiological traits required by the models. Using multivariate techniques, a number of functional groups with a similar pattern of productivity and competition were identified, based on trade-offs between traits. A scheme was developed to assign species outside of the data set to one of the groups, based on life cycle, seed mass, maximum height and time of first flowering. As

well as having a similar competitive ability, species within a group also appeared to have a similar ecosystem function, in terms of supporting higher trophic groups. Two beneficial groups of species were identified that combined a relatively low competitive ability with a high importance for invertebrates and birds. The identification of functional groups in the UK arable flora is a useful tool for assessing a weed community in the context of reconciling biodiversity provision with crop production. Preserving beneficial plant functional types within the crop would complement non-cropped wildlife refuges, such as field margins.

Keywords: biodiversity, competition, mechanistic models, plant ecological strategy scheme, traits.

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Introduction

The post-war decline in populations of organisms associated with arable habitats in the UK is well documented (Krebs *et al.*, 1999; Robinson & Sutherland, 2002). Particular concerns have been raised over the reduced abundance of annual plants adapted to arable fields (Sutcliffe & Kay, 2000; Wilson & King, 2003) and farmland bird species (Siriwardena *et al.*, 1998). These declines are widely believed to be a result of the intensification of crop production (including the increased use of pesticides, fertilisers and more competitive cultivars) and changes in cropping patterns from spring-sown to autumn-sown crops (Chamberlain *et al.*, 2000; Robinson & Sutherland, 2002). Recent attempts to reverse the decline in farmland biodiversity have been focussed on establishing wildlife refuges on non-cropped land (Critchley *et al.*, 2004). This approach will tend to

select against less competitive annual plants, which rely on regular disturbance to persist. There is evidence that these species, adapted to the cultivated body of the field, perform an important ecological function in terms of supporting biodiversity of invertebrates and birds (Hawes *et al.*, 2003; Marshall *et al.*, 2003).

The importance of the annual, dicotyledonous flora in maintaining biodiversity has been recognized in the promotion of cultivated conservation headlands (Sotherton, 1992). However, this will lead to spatially fragmented, concentrated areas of resource, representing a small percentage of the total area of the farm. An alternative or complementary strategy would be to manage sustainable, but economically acceptable populations of weed species within the cropped body of the field. Such an approach will involve balancing the competitive effect of the weeds on the crop with the potential benefit to higher trophic groups. Mechanistic

models that predict the productivity and competition of weeds in response to environmental variables will be an important tool in striking this balance (Bastiaans *et al.*, 2000).

Mechanistic competition models rely on the input of a large number of eco-physiological parameters for each species in the system. Because the emphasis in the past has been on the judicious control of pernicious weeds, efforts to parameterize the models have traditionally been focussed on a few economically important species (Kropff & Spitters, 1992; Weaver *et al.*, 1994; Caverso *et al.*, 1999; Lindquist & Mortensen, 1999; Deen *et al.*, 2003). The additional objective of encouraging farmland biodiversity has highlighted the paucity of information on the eco-physiology of a large number of common but less competitive species. This presents the problem of how to assess naturally occurring weed populations in terms of their competition with the crop and resource provision for higher trophic groups.

This paper investigates the novel approach of defining a small number of weed functional groups on the basis of the eco-physiological traits that determine their pattern of primary productivity in space and time. While this trait space will be a continuum, the approach assumes members of a group will occupy discrete areas as a result of differences in plant strategy. It is also predicted that species with a similar eco-physiological profile will have a similar function in terms of competition with the crop and eco-system service. A weed community could, therefore, be assessed on the basis of the functional groups that are represented.

Plant functional groups have previously been identified in the context of adaptation to contrasting habitats characterized by the degree of competition, stress and disturbance (the C–S–R plant ecological strategy scheme, Grime, 2001). This approach has been further extended to define the plant traits that determine the distribution of plant types across continents (Diaz *et al.*, 2004). According to this scheme, the majority of arable weeds are characterized by a ruderal growth habit and regeneration strategy (high relative growth rate, small seed and short stature). However, within ruderal weeds, there remains large variation in the traits that determine their competitive impact on the crop and their biodiversity value. It should be possible, therefore, to further divide the weed flora into functional groups at a finer scale.

UK arable weeds have previously been studied in the context of a number of functional traits. These include the ability to persist in habitats with contrasting management (Critchley *et al.*, 2004), competitiveness with the crop (Wilson & Wright, 1990; Blair *et al.*, 1999), the response to nitrogen fertiliser (Blackshaw *et al.*, 2003; Moss *et al.*, 2004) and the ability to invade

the field body from the margins (Marshall, 1989). This paper takes a more fundamental approach by grouping species on the basis of the eco-physiological parameters required by a competition model, INTERCOM (Kropff & Spitters, 1992), that determine their pattern of resource capture and competitive ability. It was considered likely that some of these traits will also be important in other aspects of plant function, such as their value to higher trophic groups. Therefore, relevant data on the associations of invertebrates and birds with arable plants were also examined.

Materials and methods

A series of screening experiments were carried out in pots and the field at Rothamsted Research (Hertfordshire, UK) between October 2000 and August 2005 to provide the eco-physiological parameters required by INTERCOM for a range of 21 weed species. These studies were also used to populate a species/trait matrix for identifying functional groups within the UK arable weed flora. For each of the species, values for the following eco-physiological traits were included in the matrix: initial green area at emergence (L_0), relative growth rate of green area in the autumn (RGRL_a) and the spring (RGRL_s), mean root weight ratio (root weight/total plant weight, RWR), mean specific leaf area (leaf area/leaf weight, SLA), maximum height and seed mass. The timing of first flowering and maximum biomass production were also included.

A range of 21 common annual weeds of UK cereal crops were chosen for the study. This included 16 species commonly found in autumn drilled crops: *Alopecurus myosuroides* Huds., *Anisantha sterilis* L., *Avena fatua* L., *Capsella bursa-pastoris* L., *Galium aparine* L., *Geranium molle* L., *Lamium purpureum* L., *Lolium multiflorum* Lam., *Myosotis arvensis* L., *Papaver rhoeas* L., *Poa annua* L., *Senecio vulgaris* L., *Stellaria media* L., *Tripleurospermum inodorum* L., *Veronica persica* Poir. and *Viola arvensis* Murray. In addition, five species normally only associated with spring drilled crops were also included: *Anagallis arvensis* L., *Chenopodium album* L., *Fallopia convolvulus* (L.) Á. Löve, *Polygonum aviculare* L. and *Sinapis arvensis* L. The sources of the data included in the species/trait matrix are described below.

Pot experiments

A pot experiment was carried out to parameterize a simple model of weed seedling relative growth rate. Seedlings were sown in pots placed in an outdoor sand bed and sampled sequentially every 4–7 days to measure the increase in green area (L). The experiment was

repeated twice in the autumn and twice in the spring. A model that combines the effect of temperature and light on growth was fitted to all the data for each species. Full details of the experiment, sampling regime and analysis were described in Storkey (2004). For the purposes of this study, the model was used to estimate the typical relative growth rate of green area during the establishment period of weeds emerging in autumn (RGRL_a) and spring (RGRL_s) drilled crops. The mean relative growth rates (d⁻¹) over the months of October and April were calculated from the model fitted to meteorological data measured at Rothamsted for 10 years between 1994 and 2004. The mean of all years was taken as the value for RGRL_a and RGRL_s. Seed mass was measured on an air dried sample of 100 seeds of each species.

A second pot experiment was sown in September 2003 to parameterize the response of the assimilation rates of the weed species to light and temperature. Twenty plants of each species (one per 4-L pot) were established and arranged in four replicate blocks in an outdoor enclosure protected from frost. Assimilation rates were measured (using a CIRAS-2 Infra red gas analyser, PP Systems, Bedfordshire, UK) at four leaf temperatures, 5, 10, 15 and 20°C, between November and March for the two lower temperatures and April and May for the higher temperatures. After each reading, the plants were sampled to measure SLA and leaf nitrogen content. Full details of the experiment, sampling regime and results of the assimilation measurements were described in Storkey (2005). Physiological differences in the rate of assimilation were small in comparison with the effect of leaf morphology, particularly SLA. Differences in SLA between the species were measured in the field experiment described below; assimilation rates were, therefore, not included in the trait set used in the present analysis.

Plants sampled between November and March were also used to parameterize the RWR of the weed species up to flowering. For each species, four plants were sampled and the above-ground material separated. The roots were then washed out and above and below-ground material dried overnight at 80°C. The RWR of the spring-germinating species was measured on plants sown in February 2005. For each species, two values of RWR had now been measured, one for seedlings from the growth rate experiment and one for mature plants from the assimilation rate experiment described in this section. The mean of these two values was taken for each species and included in the trait matrix.

Field experiments

Field experiments were conducted at Rothamsted to measure the following traits of the 21 weed species; SLA,

time to first flowering, maximum height and timing of maximum biomass production. The 21 species were divided into autumn and obligate spring emerging weeds. All the autumn emerging weeds, apart from *P. rhoeas* and *T. inodorum*, were broadcast by hand into small experimental plots (3 × 3 m) prior to a crop of winter wheat (cv. 'Consort') being drilled. *P. rhoeas* and *T. inodorum* were broadcast onto the surface post drilling. Target densities of the weeds were chosen to provide ample plant numbers for sampling, while avoiding intra-specific competition between the weeds. Where weed densities were very high, a 1-m² area was hand weeded to 50 plants per m². Apart from the exclusion of herbicides, the wheat crop was managed according to standard farm practice. The experiment was a randomised block design including three replicate plots of each species and was repeated over four seasons, the sowing dates were 27 September 2001, 17 October 2002, 29 September 2003 and 29 September 2004. For the spring emerging weeds, *A. arvensis*, *C. album*, *F. convolvulus*, *P. aviculare* and *S. arvensis*, the same experimental design was used, but the weeds were sown in three years on 5 March 2002, 7 March 2003 and 3 March 2004 prior to a crop of spring wheat (cv. 'Chablis') being drilled.

At intervals of approximately 4 weeks, five plants were sampled from each plot and all of the leaf material removed. Leaf area was measured using a Delta-T WinDias leaf area meter (Cambridgeshire, UK) and dried at 80°C overnight to enable SLA (m²g⁻¹) to be calculated. Total above-ground biomass was measured to record the timing of maximum biomass production. At each sample date, the height of each weed species was also measured. The time of first flowering was recorded from regular field visits. Not all of the weed species established successfully in each year, but at least 2 years data are available for all species. SLA was found to be of a very plastic trait (Storkey, 2005) and so a mean value from all sample dates across all three seasons was used in the trait matrix. A logistic curve was fitted to the height data plotted against photothermal time, using the statistical package Genstat (Payne *et al.*, 1987), to estimate maximum height from the pooled data from all four seasons. The mean time to first flowering from all the experiments and the timing of maximum biomass production were included in the trait matrix as Julian days.

Analysis of trait matrix

The complete trait matrix consisted of 21 species and nine traits (Table 1). In the context of sustainable weed management, species that are only generally found in spring sown crops are functionally distinct. The obligate

Table 1 Trait matrix of 16 autumn-germinating and five spring-germinating weeds

Autumn species	Seed mass (mg)	Initial green area (cm ²)	RGRL _a (d ⁻¹)	RGRL _s (d ⁻¹)	SLA (m ² g ⁻¹)	RWR	Maximum height (cm)	Flowering (Julian day)	Maturity (Julian day)
Group 1									
<i>A. sterilis</i>	8.11	0.46	0.111	0.098	0.026	0.24	94	131	190
<i>A. fatua</i>	19.72	1.09	0.094	0.093	0.023	0.26	168	157	178
<i>G. aparine</i>	13.06	1.06	0.100	0.079	0.021	0.26	92	149	192
<i>L. multiflorum</i>	2.95	0.27	0.121	0.129	0.024	0.22	119	132	187
Group 2									
<i>A. myosuroides</i>	2.19	0.10	0.133	0.125	0.026	0.21	115	111	190
<i>P. rhoeas</i>	0.11	0.03	0.144	0.149	0.033	0.15	88	152	198
<i>T. inodorum</i>	0.27	0.04	0.143	0.133	0.016	0.17	109	175	198
Group 3									
<i>C. bursa-pastoris</i>	0.09	0.07	0.133	0.113	0.032	0.16	60	98	144
<i>L. purpureum</i>	0.73	0.17	0.107	0.099	0.028	0.21	31	80	130
<i>P. annua</i>	0.45	0.05	0.116	0.105	0.028	0.19	38	90	157
<i>S. vulgaris</i>	0.23	0.08	0.134	0.111	0.020	0.17	46	72	120
<i>S. media</i>	0.54	0.10	0.144	0.117	0.032	0.16	62	61	160*
<i>V. persica</i>	0.57	0.12	0.119	0.105	0.028	0.24	63	62	147
Group 4									
<i>G. molle</i>	1.23	0.30	0.112	0.079	0.029	0.26	62	117	178
<i>M. arvensis</i>	0.27	0.13	0.107	0.100	0.032	0.18	63	141	182
<i>V. arvensis</i>	0.67	0.18	0.064	0.07	0.026	0.30	60	112	195
Group 5									
<i>C. album</i>	0.79	0.07	0.097	0.123	0.026	0.11	60	152	197
<i>F. convolvulus</i>	5.06	0.25	0.099	0.104	0.025	0.14	64	152	197
<i>P. aviculare</i>	1.93	0.11	0.106	0.105	0.024	0.11	58	152	209
<i>S. arvensis</i>	2.33	0.70	0.108	0.112	0.022	0.12	97	121	181
Group 6									
<i>A. arvensis</i>	0.81	0.10	0.075	0.056	0.029	0.27	8	152	209

*Estimated value.

spring-germinating species were, therefore treated separately. It can be argued that *S. arvensis* is often also found in autumn drilled crops, but for the purposes of this study it was treated as predominantly spring germinating. The 16 species that are common in autumn sown crops were included in a multivariate analysis to identify groups with a similar suite of eco-physiological traits. Traits were included in the analysis that are relevant to the competitive ability of the weeds in an autumn crop: initial green area, RGRL_a, mean SLA (from the field experiments), mean RWR, maximum height, time to first flowering and timing of maximum biomass production. All of the traits were given an equal rating by converting to zero mean and unit standard deviation. A principal components analysis was performed on the transformed matrix using Genstat and four groups defined using a non-hierarchical cluster analysis. The number of groups was selected using the analysis suggested by Krzanowski and Lai (1988).

Results

Although there were not enough spring weeds included in the study to perform a formal multivariate analysis, the eco-physiology of *A. arvensis* appears to be suffi-

ciently different from the remaining four species to justify assigning it to a separate group. In contrast to the other spring-germinating weeds, it is characterized by a short stature, high RWR and low relative growth rate (Table 1), all of which are characteristics of a more shade tolerant species. The remaining spring weeds generally have a high relative growth rate in the spring (although relatively low in the autumn) and a low RWR, which are all characteristic of a more ruderal habit.

Within the trait data set of the remaining 16 predominantly autumn-germinating species, there were a number of significant correlations (Table 2, Fig. 1), indicating potential trade-offs between traits. A high relative growth rate during establishment was associated with a small initial green area and low RWR. Species with a delayed flowering time were able to invest more in vegetative growth and generally achieved a greater maximum height. Later flowering was also associated with later maturity, measured as the time of maximum biomass production. These relationships suggests the existence of distinct strategies within the autumn-germinating annual weed flora and determined the position of the species in the trait space determined by the principal components analysis (Fig. 2). Four emergent functional groups were identified within the

Table 2 Correlation matrix of traits used in multivariate analysis of 16 autumn-germinating weeds. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

	Flowering	Height	RGRL _a	RWR	SLA	Seed	Maturity
Height	0.68**						
RGRL _a	-0.12	-0.02					
RWR	0.13	0.23	-0.85***				
SLA	-0.35	-0.40	0.09	-0.25			
Seed	0.31	0.61**	-0.47	0.69**	-0.39		
Maturity	0.82***	0.60**	-0.21	0.32	-0.16	0.35	
L_0	0.24	0.43	-0.63**	0.75***	-0.25	0.90***	0.203

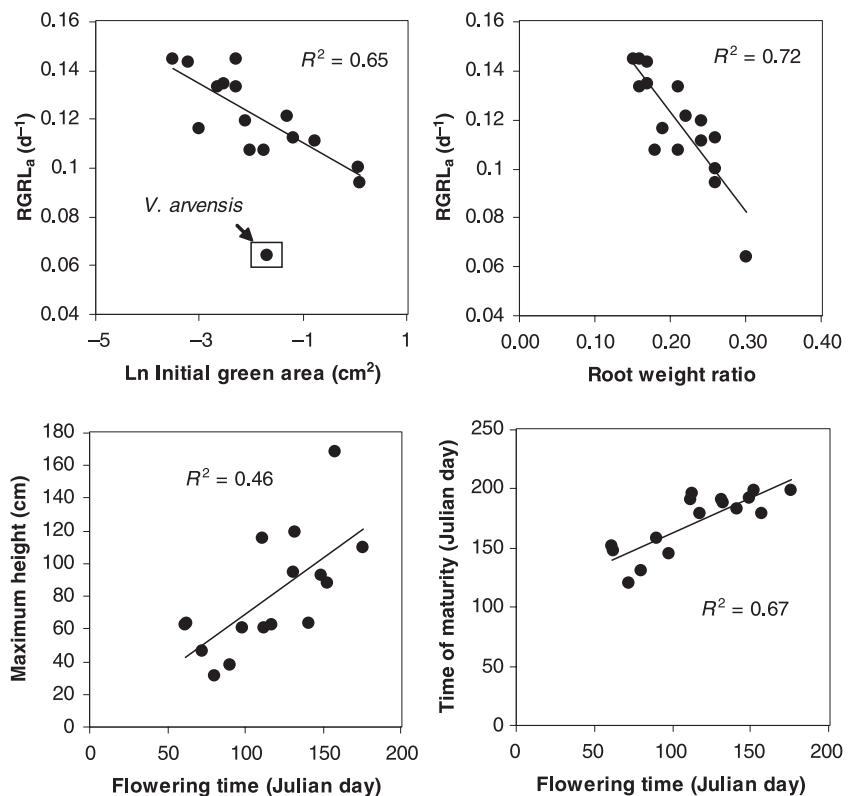


Fig. 1 Significant correlations between traits used in the multivariate analysis of the autumn-germinating weeds.

autumn-germinating species using the cluster analysis. The separation of group 3 from the remaining species appears to be particularly distinct.

If seed mass is used as a surrogate for initial green area (there was a strong correlation between the two ($P < 0.001$), Table 2), species can be assigned to a functional group on the basis of three easily measured botanical traits; maximum height, time of first flowering and seed mass (Fig. 3). Group 1 (*A. sterilis*, *A. fatua*, *L. multiflorum* and *G. aparine*) have a relatively large seed, extend above the crop canopy and are late maturing. This group includes the most competitive species. Group 2 (*A. myosuroides*, *P. rhoeas* and *T. inodorum*) are also tall and late flowering but are characterized by having a smaller seed mass. Group 3 (*C. bursa-pastoris*, *L. purpureum*, *S. vulgaris*, *P. annua*, *S. media* and *V. persica*) were relatively short and early flowering, while group 4 (*G. molle*, *M. arvensis* and *V. arvensis*) are

short and late flowering. The approach of defining plant strategy on the basis of life history and botanical traits, for which information is widely available in the literature, also provides a framework for assigning species outside this study to a functional group (Fig. 4).

The division of functional groups was based on mean trait values for each species. However, despite the same seed stock being used for each experiment, variability in trait values was observed within a species between years, as a response to different growing conditions. This was particularly true for flowering time. As a result, although group 3 was characterized on the basis of the mean trait values as early flowering, there was some overlap with other groups. However, this variability tended to be systematic and, within any one year, all of the species in group 3 flowered earlier than any of the other species. Fig. 3 illustrates the degree of variability in the observed values for all the species in a group for

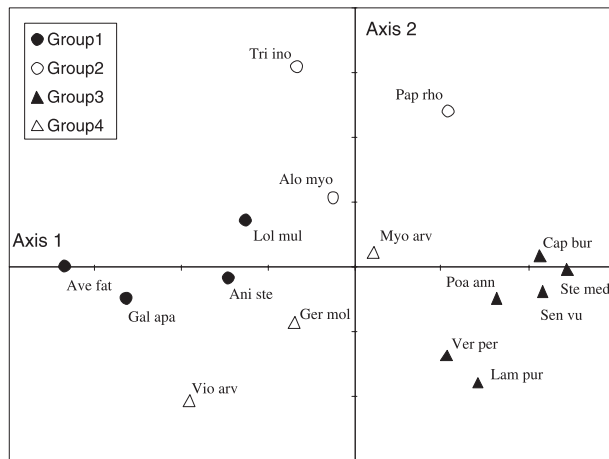


Fig. 2 Principal components analysis on trait matrix of autumn-germinating weeds: Alo myo, *Alopecurus myosuroides*; Ani ste, *Anisantha sterilis*; Ave fat, *Avena fatua*; Cap bur, *Capsella bursa-pastoris*; Gal apa, *Galium aparine*; Ger mol, *Geranium molle*; Lam pur, *Lamium purpureum*; Lol mul, *Lolium multiflorum*; Myo arv, *Myosotis arvensis*; Pap rho, *Papaver rhoeas*; Poa ann, *Poa annua*; Sen vul, *Senecio vulgaris*; Ste med, *Stellaria media*; Tri ino, *Tripleurospermum inodorum*; Ver per, *Veronica persica*; Vio arv, *Viola arvensis*.

maximum height, seed mass and flowering time. In addition, traits such as RWR and SLA will vary with growth stage. For the purposes of this analysis, mean values including seedlings and mature plants were used as an indication of broad differences in strategy between species.

Discussion

This study has developed a scheme for defining functional groups on the basis of the traits that determine their pattern of resource capture. Underlying these groups are a number of trade-offs between traits that result from evolutionary pressures (Westoby, 1998). The trade-off between seed size and seedling growth rate is particularly well established in the literature (Fenner, 1983; Shipley & Peters, 1990; Westoby *et al.*, 1992; Seibert & Pearce, 1993) and has been demonstrated for the predominantly autumn-germinating species in this study.

Because of variability in a particular trait between populations of the same species (Hawes *et al.*, 2005) and as a result of morphological plasticity, it should be emphasized that the defining of functional groups at a species level will always be a generalisation. In addition, the growth pattern of the weeds in this study has only been measured in a winter wheat canopy. The applicability of the functional groups in other crops, therefore, requires further study. Despite these limitations, the trait based approach provides a useful framework for asses-

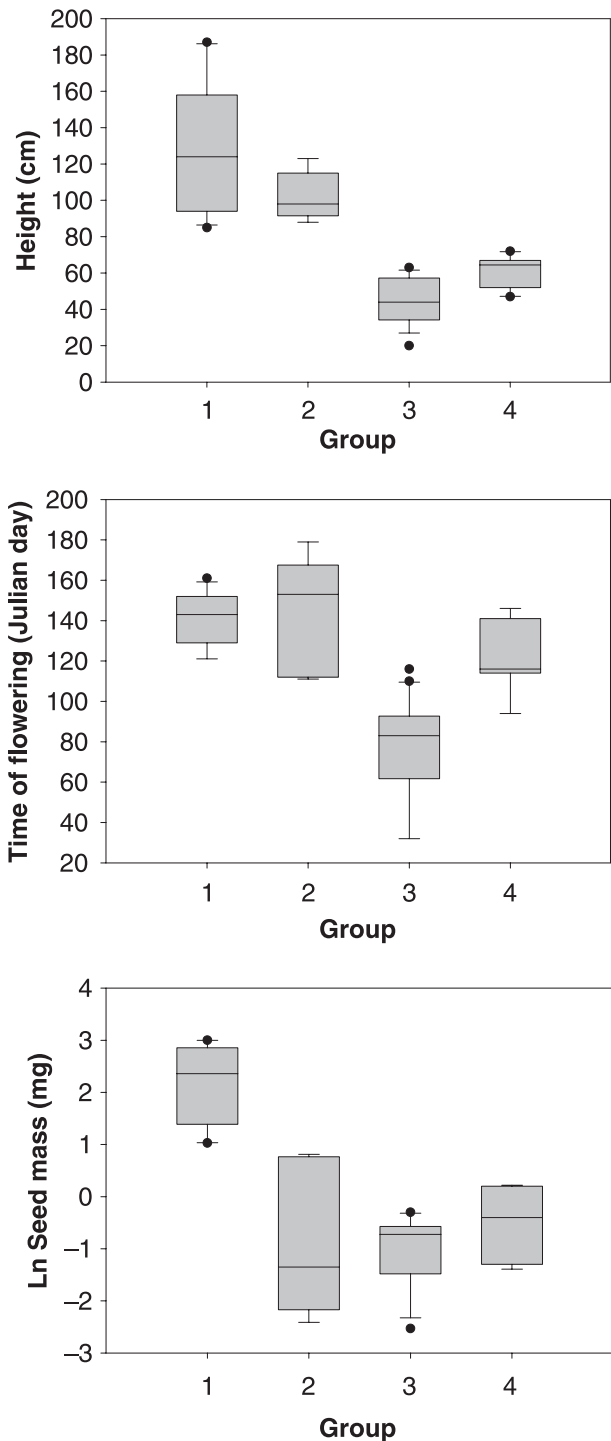


Fig. 3 Box and whisker plots illustrating variation within and between functional groups in plant traits used to define plant strategy. Plots are derived from the entire data set for all the species in each group, showing the range of observed values. The boundaries of each box represent the 25th and 75th percentile with the line indicating the median. Whiskers represent the 10th and 90th percentile with outliers indicated by ●.

sing a weed community in terms of the balance between its potential competitive impact on a crop (Wilson & Wright, 1990) and its value to higher trophic groups

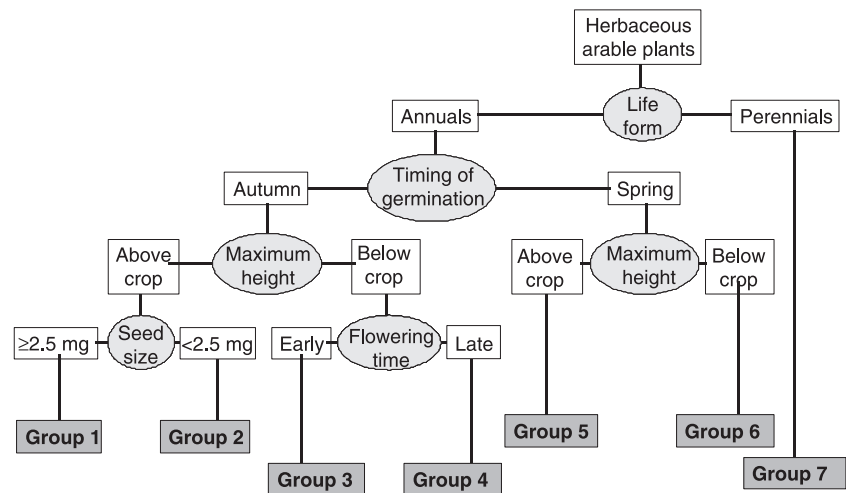


Fig. 4 Scheme for assigning herbaceous arable plants to functional groups.

(Marshall *et al.*, 2003). In this context, the functional groups developed here could be used as criteria for defining a beneficial weed community as described below.

The traits chosen for the multivariate analysis were largely determined by the parameters required by simulation models of crop–weed competition. Species within a functional group were, therefore, broadly similar in terms of their competitive ability in winter wheat (Wilson & Wright, 1990; Blair *et al.*, 1999), Table 3. For the management of weeds within arable crops to be justified, however, as well as having a relatively low competitive ability, candidate weed groups must also be important for sustaining higher trophic levels. A previous literature study has identified weed species that combine a low competitive ability with high biodiversity value (Marshall *et al.*, 2003). It is likely that this serendipity can be partly explained by the fact that traits that determine the pattern of productivity and competition are also important in the potential value of plants to herbivores. As well as varying in their competitive ability, therefore, it is likely that the functional groups identified in this study will also differ in their potential value to invertebrates and birds. To test this hypothesis, the species included in the literature study were arranged in functional groups using the scheme illustrated in Fig. 4 (Table 3).

There were trends in the relative value of the different groups to invertebrates and birds. Among the annual weeds, groups 3 and 5 emerge as having the most potential biodiversity value with groups 1, 4 and 6 having relatively little. While general trends between the groups in their relative importance to invertebrates and birds have been identified, it would be useful to investigate the guilds of organisms that are associated with each group, to try and identify the specific eco-physiological traits that underlie these associations. If the two criteria of competitive ability and importance

for biodiversity are applied to the groups developed in this study, groups 1, 2 and 7 must be effectively controlled in the body of the field because of their high competitive ability and groups 4 and 6 appear to have little biodiversity value. This leaves groups 3 and 5 that could potentially deliver biodiversity benefit if populations were allowed to persist in the body of the field.

The grouping of species in this study was primarily intended as a tool for assessing naturally occurring weed communities in terms of the service they provide to the eco-system and their effect on crop yield. The groups were not primarily defined on the basis of their response to management, for example, cultivation (McCloskey *et al.*, 1996) or a specific herbicide (Sherrott, 2001). However, appropriate management filters may be available that exploit the unique characteristics of the groups. For example, selective herbicides are available for autumn cereals that have the potential to remove all of the species in group 1 while leaving all of the species in group 3 (Simpson *et al.*, 2004). Populations of the early flowering species in group 3 may also be selected for by delaying their control until the spring, as they are able to complete most of their life cycle before herbicide application. It has been shown that the critical period of weed control for *S. media* occurs in late March (Blair *et al.*, 1999); delayed control, therefore, need not result in a yield penalty. Finally, the inclusion of spring sown crops will also be an important tool for controlling the competitive autumn weeds in group 1 and encouraging the spring ruderals in group 5.

Management recommendations already exist for controlling competitive weeds in conservation headlands while leaving beneficial species (Sotherton, 1992; Sherr-ott, 2001). However, the application of these techniques to the body of the field has not been found to result in significantly more weeds in following stubbles (Critchley *et al.*, 2001). This may have been a result of growers

Weed species	Value for Invertebrates	Importance for seed-eating birds	Competitive index
Group 1			
<i>Anisantha sterilis</i>	—	—	(5)
<i>Avena fatua</i>	—	—	5
<i>Galium aparine</i>	***	—	2
Group 2			
<i>Alopecurus myosuroides</i>	—		13
<i>Galeopsis tetrahit</i>	**	—	
<i>Papaver rhoeas</i>	*		13
<i>Sonchus oleraceus</i>	***	*	50
<i>Tripleurospermum inodorum</i>	***		13
Group 3			
<i>Capsella bursa-pastoris</i>	**	*	50
<i>Cerastium fontanum</i>	**	**	(25)
<i>Lamium purpureum</i>	**	—	63
<i>Poa annua</i>	***	**	50
<i>Senecio vulgaris</i>	***	**	83
<i>Stellaria media</i>	***	***	25
<i>Veronica persica</i>	—		63
Group 4			
<i>Aethusia cynapium</i>	—		
<i>Fumaria officinalis</i>	—	*	63
<i>Geranium dissectum</i>	—		63
<i>Matricaria recutita</i>	**	—	13
<i>Myosotis arvensis</i>	—	—	25
<i>Solanum nigrum</i>	*		
<i>Viola arvensis</i>	—	**	250
Group 5			
<i>Chenopodium album</i>	***	***	25
<i>Fallopia convolvulus</i>		***	17
<i>Persicaria maculosa</i>	**	***	(25)
<i>Polygonum aviculare</i>	***	***	50
<i>Sinapis arvensis</i>	***	**	13
Group 6			
<i>Anagallis arvensis</i>	—		100
<i>Euphorbia helioscopia</i>	*	—	
<i>Spergula arvensis</i>	*	*	
Group 7			
<i>Cirsium arvense</i>	***	*	17
<i>Rumex obtusifolius</i>	***	**	

Species have been grouped according to the scheme illustrated in Fig. 4. The value for invertebrates is based on the number of insect species associated with a particular weed (0–5 species = –; 6–10 = *; 11–25 = **; 26+ = ***). Value for seed feeding birds (not important = –; important for 1 or 2 species = *; important for 3–8 species = **, important for >8 species = ***). The competitive index is the weed density (m^{-2}) that gives a 5% yield loss in winter wheat (figures in parenthesis are expert opinion).

being naturally averse to tolerating weeds in the field and being over-cautious in their approach to weed control. In contrast to conservation headlands, therefore, more robust tools are required to support decisions about ‘what’ and ‘how much’ weed to leave. The development of these tools will be particularly important for enhancing the value of agri-environment schemes that are designed to benefit boundary-avoiding bird species. For example, allowing weeds to persist to maturity in a crop would provide greater resource for

seed-eating birds in a following over-winter stubble, as opposed to one following a ‘clean’ crop. Low in-field weed populations would also complement the provision of undrilled patches [‘skylark (*Alauda arvensis* L.) scrapes’] by combining resource availability and accessibility (Morris *et al.*, 2005). This study has provided a framework for deciding on the weed types that may be appropriate targets for weed management approaches of this kind. Because these species adapted to the cultivated body of the field are distinct from the flora found in the

Table 3 Competitive ability and importance for biodiversity of 32 common UK arable weeds (adapted from Marshall *et al.*, 2003)

field margins, sustaining their populations would increase the overall functional diversity of the farm ecosystem. However, additional tools are required to identify the appropriate threshold level of these weeds that is economically acceptable but also ecologically significant.

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