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SID 5 Research Project Final Report

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Project identification

1. Defra Project code: AR0407
2. Project title: Modelling weed:crop dynamics and competition to improve long-term weed management
3. Contractor organisation(s): Plant and Invertebrate Ecology Division, Rothamsted Research, West Common, Harpenden, Herts., AL5 2JQ.
4. Total Defra project costs: £ 968,333
5. Project: start date .... 01 October 2001

   end date .... 01 October 2005

6. It is Defra's intention to publish this form.
Please confirm your agreement to do so..YES ☒ NO ☐

(a) When preparing SID 5s contractors should bear in mind that Defra intends that they be made public. They should be written in a clear and concise manner and represent a full account of the research project which someone not closely associated with the project can follow.

Defra recognises that in a small minority of cases there may be information, such as intellectual property or commercially confidential data, used in or generated by the research project, which should not be disclosed. In these cases, such information should be detailed in a separate annex (not to be published) so that the SID 5 can be placed in the public domain. Where it is impossible to complete the Final Report without including references to any sensitive or confidential data, the information should be included and section (b) completed. NB: only in exceptional circumstances will Defra expect contractors to give a "No" answer.

In all cases, reasons for withholding information must be fully in line with exemptions under the Environmental Information Regulations or the Freedom of Information Act 2000.

(b) If you have answered NO, please explain why the Final report should not be released into public domain

Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

Historically, research on weed biology and control had focussed on the aggressive species that threatened crop yields. However, it was becoming increasingly apparent, at the end of the last millennium, that the impact of farming on the wider diversity of arable farmed areas had become unacceptably high. This change in emphasis was formalised in Defra in the Government's sustainable food and farming strategy (Working with the Grain of Nature 2002). In terms of research into weed control, this orientation meant a shift away from studying noxious species towards underpinning potential reductions in the intensity of weed control. A Defra desk study on the impact of herbicides on weed abundance and diversity (PN0940) had already identified that some arable plant species had greater biodiversity value than others. The suite of weed projects starting in 2001 (this project together with AR0408 and AR0409) focussed on 7 key species for study: fat hen, annual meadow-grass, knotgrass, groundsel, charlock, common chickweed, and scentless mayweed. In addition in this project because of the shift of emphasis away from noxious species and towards the management of arable vegetation in general a wider study was undertaken characterising some 21 weed species and 3 crop species (for comparison).

The emphasis within this commission was on developing the tools that are needed to manage arable weeds in order to balance the sustainable production of crops with the support for wider biodiversity that healthy weed population can provide. The overall objective was "**To develop, and test, models of weed:crop competition and dynamics, and of weed ecological groupings, to improve decision making in long-term weed management.".** To that end the project included the development of ecological models for the description and prediction of both short-term weed:crop productivity and longer-term weed population dynamics. In addition the project undertook an extensive characterisation of a wide range of UK weed species both to support the modelling effort and to begin to develop functional groups for the prioritisation of management aimed at supporting biodiversity. An extensive series of evaluation trials were undertaken by a sub-contractor (ADAS) which were intended to demonstrate the effectiveness of our predictions of potential crop losses from moderate weed populations and of the longer-term consequences of reduced control of these populations.

1a) Development of models;

A great deal of development was undertaken to tailor the INTERCOM model of weed:crop productivity within season to UK winter wheat systems. The real potential of this technology for developing weed management strategies has been demonstrated with a series of experiments on weed:crop productivity in mixtures. This modelling approach provides a tool for the understanding the impact of weed mixtures on crop productivity and for predicting weed seed production under a range of conditions.

Using data gathered (mostly within the associated AR0409 project) long-term population models of the population dynamics of 7 key weed species identified were developed. These models were tested using the data from the ADAS evaluation trials (objective 3) and where the data were available were show to be very effective under these conditions. These long-term models of weed population dynamics need to be at the heart of any integrated weed control strategies and can be used to balance changes in the cost of production associated with changing agronomy with the potential benefits to be achieved through lower weed control costs over the long-term.

1b) Changes in crop canopy characteristics and competitiveness;

The potential for relatively small changes in within-season (non-herbicide) crop management to have very large implications for weed productivity and seed production. The relative impact of a range of factors was tested and one of the most significant was found to be the time of crop establishment (this information was fed back into objective 1a where time a model integrating the timing of agronomic practise on weed population dynamics was developed). While crop cultivar undoubtedly had an effect of weed suppression the size of it's impact was small relative to other changes in agronomy (It's important to note that this finding is probably only true for the intensive production systems being studied here.).

2) The ecophysiological basis of functional groups;

It's clear from this relatively small study that consideration of the plant functional traits as a tool for developing weed management strategies has a great deal of potential. From the study of 21 weed species undertaken here clear functional groups emerge that help to differential noxious weed species that contribute relatively little to wider biodiversity and must remain a focus for weed control from other groups of weed species that play different roles in supporting other trophic-groups of species with arable farmland.

3) Validation of predictions (ADAS sub-contract);

The data gathered in this series of field trials provides the vital evidence base that is needed to convince farmers and their advisors that reduced weed control can be tolerated under certain conditions without prejudicing the sustainability of crop production. There is a trade of between the level of weed that is left un-controlled and crop yield but it is clear that the existing approached are overly cautious and over use herbicide. These trials demonstrate that there is potential within the system to very dramatically increase weed productivity before crop yield is significantly compromised.

The work carried out within this project is already having an impact through the use of information and mathematical models generated here within the LINK project ‘Weed Manager (LK0916). However, as a consequence of these perceived negative impacts farmers may be reluctant to take up more environmentally beneficial weed management strategies without some form of financial support. One important potential use of the ecological and mathematical models developed within this project is to help to quantify the level of financial support that is required to balance the increased cost of production (and reduced crop yield) that would be caused by prescribed changes in weed management strategies.

Project Report to Defra

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also

seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:

- the scientific objectives as set out in the contract;
- the extent to which the objectives set out in the contract have been met;
- details of methods used and the results obtained, including statistical analysis (if appropriate);
- a discussion of the results and their reliability;
- the main implications of the findings;
- possible future work; and
- any action resulting from the research (e.g. IP, Knowledge Transfer).

1. Background

At the outset of this commission, research into weed management had been focussed strongly on improving understanding of the biology of the major aggressive weeds of arable cropping in the UK, in order to minimise their effects on crop production. However, it was becoming increasingly apparent, at the end of the last millennium, that the impact of farming on the wider diversity of arable farmed areas had become unacceptably high (Fuller *et al*, 1995; Preston *et al.,* 2002*;* Siriwardena *et al*, 1998). As a consequence Defra policy became oriented towards reductions of the impact of agriculture on arable ecosystems. This was formalised in the Government's sustainable food and farming strategy (e.g. see 'Working with the Grain of Nature 2002 (www.defra.gov.uk/wildlife-countryside/ewd/biostrat/index.htm)). In terms of research into weed control, this orientation meant a shift away from studying noxious species towards underpinning potential reductions in the intensity of weed control. A desk study on the impact of herbicides on weed abundance and diversity funded by Defra (PN0940) had already identified that some arable plant species had greater biodiversity value than others (see Marshall *et al* 2001, 2003). This project provided information on plant species that should be retained in fields, so as to provide resources for invertebrates and birds (see Fig 1.1). Seven of these desirable weeds acted as the core of this and the other two commissions (AR0408, AR0409). These were *Chenopodium album* (fat hen)*, Poa annua* (annual meadow-grass)*, Polygonum aviculare* (knotgrass), *Senecio vulgaris* (groundsel)*, Sinapis arvensis* (charlock)*, Stellaria media* (common chickweed)*,* and *Tripleurospermum inodorum* (scentless mayweed).

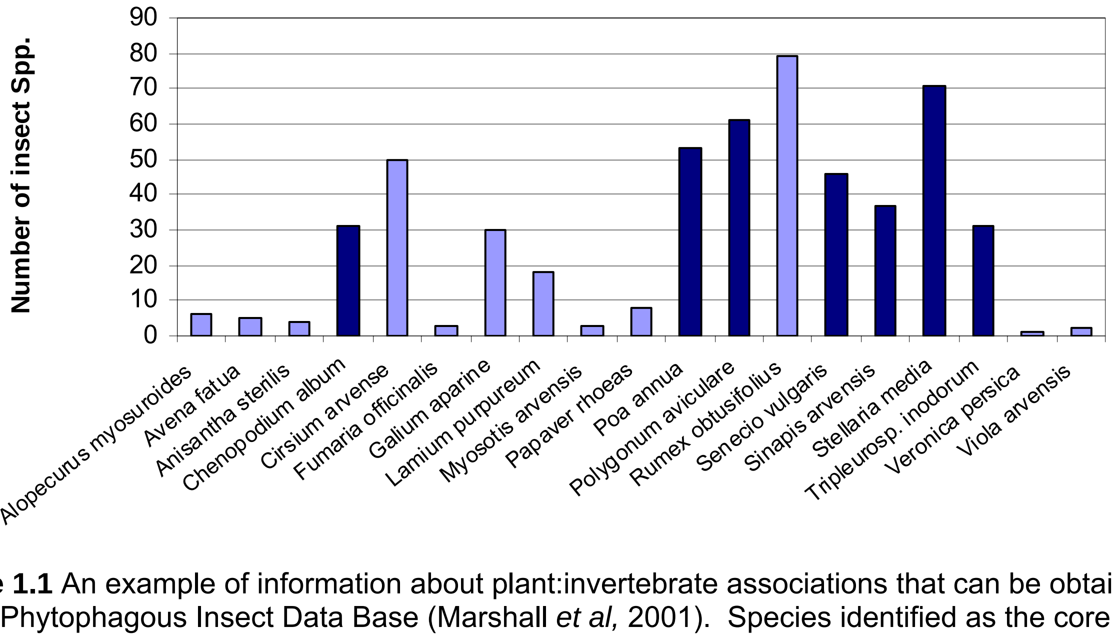

Figure 1.1 An example of information about plant:invertebrate associations that can be obtained from the Phytophagous Insect Data Base (Marshall *et al,* 2001). Species identified as the core of the AR0407,AR0408 and AR0409 projects are in darker shading.

It is now clear that wild plants play a vital role in the arable ecosystem, providing the 'services' of food and shelter to higher trophic organisms (invertebrates, birds and small mammals) within the ecosystem food webs. There is debate about the respective contribution of plants in fields compared to those off field (field margins & hedgerows) but the reports of the Farm Scale Evaluation of GM crops identifies links between within field plant abundance and numbers of invertebrates, and hence their contribution to food webs of arable ecosystems (e.g. Heard *et al.,* 2003, Hawes *et al.,* 2003).

For arable farmers to retain plants of biodiversity value in fields, a balance has to be struck between this objective and prevention of harvesting problems and yield loss arising from competition between the weeds and the crop (i.e. a balance between environmental and economic goals). However, overuse of herbicides, endeavouring to eliminate all weeds within fields, at current input and commodity prices, will reduce profitability. Consequently, for both economic and environmental reasons there is a need to refocus weed management towards a more targeted approach. Damaging weeds need to be controlled but less damaging and environmentally beneficial weeds can be left in the field to provide resources for vertebrates and invertebrates that are part of the arable ecosystem. Such a targeted approach requires appropriate linkage of weed control practice with a good understanding of the competitivity, biology and population dynamics of the weeds. Users need information on the biology of weeds to have confidence that a reduced weed control strategy in one year will not cause unmanageable problems in future years. This programme integrates the data from AR0408 and AR0409, to explore alternative ways of managing weeds.

The information from the project will feed into the SA LINK project (LK0916) Weed Management Support System (now Weed Manager), to enhance its value as a tool to encourage lower input weed management.

This project's aim was to meet the **Defra Objective in ROAME A to 'provide a better understanding of weed-crop competition and population dynamics.. to support rotational approaches to weed management that are both economically sustainable and reduce environmental impact'.** This will contribute towards meeting the government goal of enhancing biodiversity and reducing the environmental impact of farming.

A key component of the project was the comparative study of a wide range of weed species so that life-history and resource capture strategies could be compared and contrasted. Table 1.1 lists the species studied within the project. The work included a comparative study of resource capture by contrasting plant species (sections 3a and 4), modelling studies of comparative life-history strategies (section 3b), competitiveness a range of crop species and assessment of fecundity in contrasting crops (section 6). By gathering data for such a wide range of species and developing the models to describe both short-term resource capture in crops and longer-term population dynamics, the project (together with the companion projects AR0408 and AR0409) lays the foundations for the use of these tools in developing sustainable crop management for supporting biodiversity within cropped fields.

2. Scientific Aims and Objectives (from the project CSG7)

1. **Development of models;**

Extend existing mechanistic modelling approach to weed and crop growth to a wider range of UK weed and crop species. Develop a generic model framework for combining detail about crop:weed competition and other specific environmentally influenced processes, with longer-term descriptions of weed population dynamics.

2. **Changes in crop canopy characteristics and competitiveness;**

Assess the relative competitiveness of crop species. Compare the degree of variability in competitive ability between cultivars of winter wheat with the variation that is associated with other agronomic factors.

3. **The ecophysiological basis of functional groups;**

Measure key physiological parameters including phenology, gas exchange and biomass partitioning, for a wide range of UK weed species. Undertake multivariate analysis of the entire parameter/trait dataset to identify groupings of species .

4. **Validation of predictions (ADAS sub-contract);**

Undertake field experiments in key UK crop species to evaluate predictions of crop yield loss from weed populations. Use the data generated to make more precise model parameter estimates and refine future predictions. Follow the fate of field plots to study the longer-term implications of different weed management practices. Contrast the fate of the same weed populations in spring and winter sown crops.

TABLE: 1.1 Species studied in manipulative field experimentation. Species highlighted are the key species common to AR0407, AR0408 and AR0409.

Latin Name	Primary germination period	Common Name
Alopecurus myosuroides	Autumn	Black-grass
Anisantha sterilis	Autumn	Barren brome

Avena fatua	Autumn	Wild-oat
Poa annua	**Autumn**	**Annual meadow-grass**
Anagallis arvensis	Spring	Scarlet pimpernel
Capsella bursa-pastoris	Autumn	Shepherds purse
Chenopodium album	**Spring**	**Fat hen**
Fallopia convolvulus	Spring	Black bindweed
Galium aparine	Autumn	Cleavers
Geranium molle	Autumn	Dove's-foot cranesbill
Lamium purpureum	Autumn	Red dead-nettle
Lolium multiflorum	Autumn	Italian rye-grass
Myosotis arvensis	Autumn	Forget-me -knot
Papaver rhoeas	Autumn	Common poppy
Polygonum aviculare	**Spring**	**Knotgrass**
Senecio vulgaris	**Autumn**	**Groundsel**
Stellaria media	**Autumn**	**Common chickweed**
***Sinapis arvensis*.**	**Spring**	**Charlock**
Tripleurospermum inodorum	**Autumn**	**Scentless mayweed**
Veronica persica	Autumn	Common field-speedwell
Viola arvensis	Autumn	Field pansy

3. Development of models (objective 1);

a) Mechanistic modelling of weed and crop growth

A detailed mechanistic model of crop and weed growth in mixtures was developed in the 1990's by a group at Wageningen University in the Netherlands – INTERCOM (Kropff & van Laar, 1993). It was most appropriate to develop from this existing model but, as it originated from studies on sugar beet (a vegetative crop) and *C. album* some considerable modification and re-parameterisation was needed. A screening programme was carried out to provide the eco-physiological parameters for INTERCOM, for 21 weed and three crop species (Table 1.1). The experimental methodology used to derive the parameters is provided under **objective 3**. This section describes modifications that were made to the model and validation experiments carried out in the field in harvest years 2004 and 2005.

Methods

Two validation experiments were sown on 29/09/2003 and 29/09/2004 in the field at Rothamsted to test the predictions of the model using the parameters collected from the screening experiments. Three weed species (L*olium multiflorum*, *Veronica persica* and *Geranium molle*) with contrasting eco-physiology (see **objective 3**) were sown in 3 x 10m winter wheat plots as a single species or as weed mixtures, along with a weed free control, giving eight treatments in all. A randomised block design was used with four replicates. Emergence was recorded every 2-4 days after sowing. Weed and crop density was assessed on three 0.5 m^2 biomass samples harvested in January, March and April.

Results

i) Modifications to INTERCOM

1. Before canopy closure, INTERCOM models seedling growth using a simple function of thermal time. However, a previous study found that this approach was not sufficiently robust to model wild-oats emerging in the autumn and the spring (Weaver *et al.*, 1993). This was confirmed in a series of experiments on a range of weed species carried out as part of this commission and a new approach has, therefore, been developed combining the effects of temperature and light on seedling growth (Storkey, 2004).

2. The onset of shading in INTERCOM is defined as the point when the total canopy leaf area index (LAI) reaches 0.75. A review of previous data (Storkey, 2001) confirmed this to be accurate for the crop growing in rows. However, for the weeds which are randomly arranged in the canopy, a total LAI of 0.9 was found to be more appropriate.

3. Assimilation rate in INTERCOM is modelled using a function describing the response of photosynthesis to the environment, parameterised separately for each species in the system. Experiments carried out as part of this commission were used to develop a new approach that uses a generic function for all species to predict assimilation rate from knowledge of leaf traits (Storkey, 2005).

4. Winter wheat development and grain yield were modelled using routines developed in the model SIRIUS (Jamieson *et al.*, 1998). The onset of anthesis in the crop is determined by the leaf primordial number (which is a product of vernalisation and day length) and the rate of leaf production. After anthesis, all new biomass is allocated to the grain as well as 25% of the biomass present at anthesis.

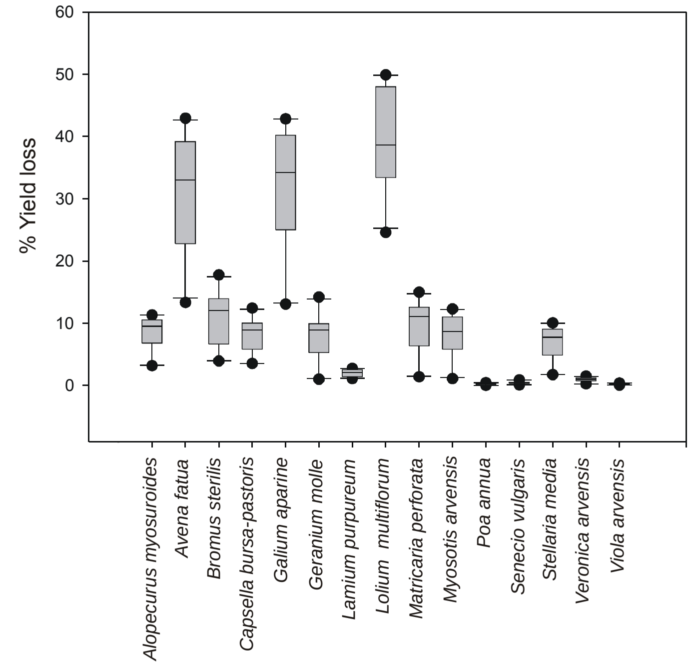

Figure 3.1. Relative competitiveness of autumn germinating weeds in winter wheat, as reflected in yield losses, predicted by INTERCOM for ten separate years. Sowing date: 30th September, crop density: 300 plants m^{-2}, crop emergence: 14 DAS, weed density: 10 plants m^{-2}, weed emergence: 14 DAS.

The modified version of INTERCOM was run to compare the predicted competitive ability (in winter wheat) of a range of autumn germinating weeds parameterised in the screening experiments. The model was run ten times using weather data from 1995-2004 recorded at Rothamsted Research (**Figure 3.1**). The relative competitiveness of the weeds appeared to be realistic, reflecting empirical results from the field (Wilson & Wright, 1990; Blair *et al.*, 1999). There was also significant variability in predicted weed competition between years, again reflecting known stochasticity in the field (Cussans *et al.*, 2005). As well as winter wheat, parameters have also been collected for two other crops, field beans (*Vicia faba*) and winter oilseed rape (*Brassica napus*).

ii) Model validatation

In 2003, the three weeds sown were *Lolium multiflorum*, *Veronica persica* and *Geranium molle*. There were also background populations present of *Alopecurus myosuroides*, *Bromus sterilis*, *Avena fatua* and *Poa annua*. In 2004, *V. persica* was replaced with *Stellaria media*.. However, *V. persica* was also present as a background population along with *A. myosuroides*, *Galium aparine*, *Matricaria perforata*, *P. annua* and *Viola arvensis*. INTERCOM (as modified within this project) successfully predicted the relative competitiveness of the different weed mixtures in the two years (**Figure 3.2**). However, there appeared to be a systematic under estimation of weed competition in general. It is likely that this is a result of competition for nitrogen which is not currently included in this version of INTERCOM. (Full details of the validation experiments and modifications to the model are included in a paper in preparation).

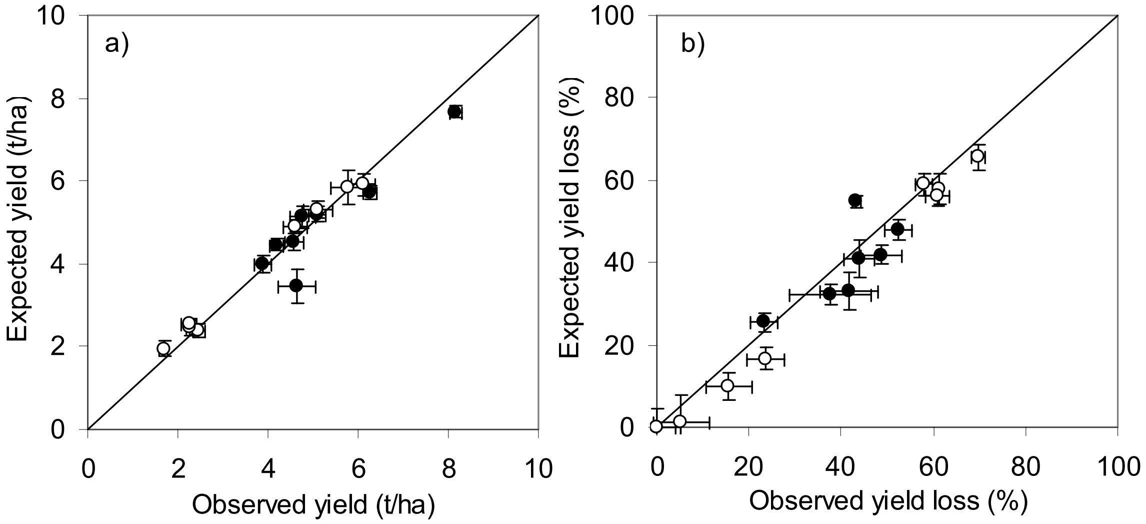

Figure 3.2. Mean predicted and observed wheat yield (a) and yield loss (b) from eight different sown weed populations in two years. (○) 2004, (●) 2005, Bars = standard error of the observed and expected mean of four replicates.

b) Longer-term descriptions of weed population dynamics.

The population dynamics modelling work undertaken as part of this project breaks down into three elements:

i In conjunction with the project AR0409 the existing model framework (Moss 1990) was parameterised for the 7 key weed species growing in a range of crops.

ii The implications of the variability in the parameter values observed was studied by developing a stochastic simulation based on the existing model framework.

iii The model framework was further developed to explicitly include the interaction between the timing of agronomic inputs and the inherent phenology of the plants and their invertebrate granivores.

i) <u>Parameterisation of existing model framework</u>

The simplistic life-history diagram for annual weed forms the basis of the ecological models of plant population dynamics that have been developed (Firbank & Watkinson, 1986; Moss, 1990; Freckleton & Watkinson, 1998; Munier-Jolain, Chauvel & Gasquez, 2002). In this project we have largely followed the structure described by Moss (1990) with a number of small exceptions. The aim of this part of the project was to integrate the observations of key biological process made by the three commissions (AR0407, AR0408, AR0409) into a longer-term population biology model for the key species.

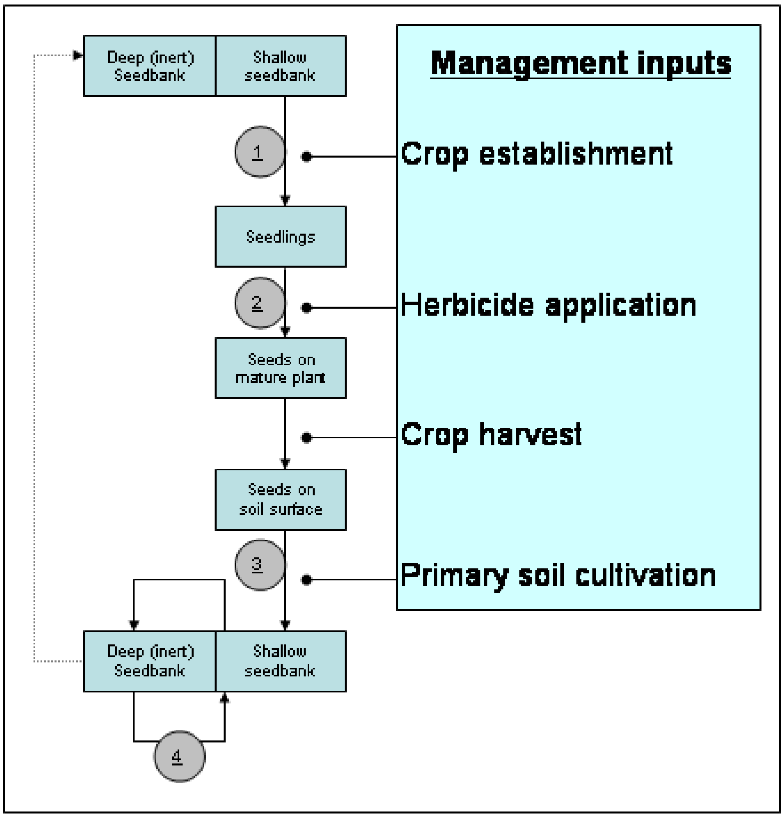

Figure 3.3: Life-history diagram for annual weeds. Key biological processes in the lifecycle are highlighted; 1. Recruitment of new individuals from the seedbank, 2. Competition with the crop and fecundity, 3. Seed losses due to predation and lethal germination and 4. Soil mixing due to cultivation.

Model structure and changes made to the existing population dynamics model (Moss 1990).

1) Recruitment of seedlings from the seedbank

At the time of crop establishment a proportion of seeds in the seedbank are stimulated to germinate and establish as seedlings for the following growing season. The total weed seedbank is divided into two functional components a deep seedbank and a shallow seedbank. In the initial model germination and recruitment of new individuals was predominantly from the shallow (surface) seedbank but was also possible from the deep seedbank, albeit at a very low frequency. To simplify the model after some initial sensitivity analysis a decision was made to make the deep seedbank effectively inert. No movement or germination of seeds can occur from the deep (inert) seedbank except through soil mixing due to cultivation. This represents an effective compromise between a model where a number of soil horizons are described and the soil mixing process is the focus of detailed mathematical description (Mead *et al* 2003) and a simpler model where the soil seedbank is a single block not split into horizons at all (Heard *et al* 2005 or Freckelton & Watkinson 1998). Discussion of the soil seedbank sampling carried out as part of the validation experiments (Section 6 Tables 6.3 & 6.4) illustrates how the vertical distribution of seeds in the soil seedbank plays a crucial role in determining the level of seedling recruitment.

$$Seedling\_Density(m^{-2}) = Shallow\_Seedbank\_Density(m^{-2}) * \mathrm{Recruiment}$$

Realistic levels of recruitment from the seedbank were the subject of an extensive review in the companion project AR0409.

2) Estimation of seed production.

Rather than use a two step calculation to estimate potential seed production from initial seedling density, a single non-linear function is used to estimate potential seed production from seedling density (as proposed in Moss, 1990). This change was made partly because a two step calculation represents an unnecessary complication and partly because of the nature of much of the data available better fits this simple model:

$$PotentialSeed\,\mathrm{Pr}\,oduction(m^{-2}) = \frac{S\max * Seedling\_Density(m^{-2})}{1.0 + (A\max / S\max) * Seedling\_Density(m^{-2})}$$

where Smax represent the maximum seed production of a solitary plant growing within the crop (in the absence of interspecific competition) and Amax represents an asymptotic (maximum) seed production per unit area at very high weed density within the crop.

It is important to note that these seed production parameters are both crop and weed specific. In other words for each weed species different parameter values are required for every crop species they occur in order to effectively describe the potential seed production.

The actual seed production in a crop is then calculated as;

$$Actual\_Seed\_\mathrm{Production}(m^{-2}) = Potential\_Seed\_\mathrm{Production} * herbicide\_efficacy$$

There are a number of points to note about this approach. Firstly, as stated previously the seed production parameters (Amax and Smax) are both crop and weed specific. Secondly, the form of the potential seed production calculation (a rectangular hyperbola) is the same as the well characterised seedling density vs yield loss relationship (Cousens,1985) and this agrees very much with all the data we have available (and implies a linear simple relationship between yield loss and weed seed production). The calculation of actual seed production in this way is a great simplification but was considered by us to be an acceptable compromise.

At the time of crop harvest all the seeds produced on the mature plant are assumed to drop to the soil surface and become available for seed predators. For a limited number of species (*Galium aparine* as an example) significant numbers of seeds are removed from the field as contamination of the harvested grain. This was considered for the key species under consideration but in none of the species was this seen to be an important issue in driving the population dynamics. It should be pointed out that when considering other issues such as population genetic structure or field-to-field spread the emigration of seeds may need to be considered.

Values for seed production in different crops was the subject of considerable experimental work both in this project and in the companion projects AR0408 and AR0409. In addition a literature review was undertaken as part of AR0409. The contribution made by this project to the growing dataset on weed seed production in contrasting crops is described in section 6 (Table 6.5).

3) Losses of seeds from the soil surface.

Because of the particular interest in separating individual seed loss processes in this project, the seed losses term of the initial model is separated into 1) Pre-dispersal seed predation from the adult plant, 2) Post-dispersal seed predation from the soil surface prior to their incorporation into the seed-bank by cultivation and 3) Lethal germination of seeds before incorporation into the seed-bank.

$$Seed\_losses(m^{-2}) = Seed\_\mathrm{Pr}\,oduction * (\mathrm{Pr}\,edation + lethal\_ger\min ation)$$

The proportional losses of seeds from the soil surface are assumed to be a sum of the proportion of seeds lost to predation and the proportion of seeds lost to lethal germination. It would be more rigorous to integrate these two processes over the entire period using a daily time-step. A more complex model was investigated but for the purposed of simplicity this has not been adopted.

Details of experimentation to quantify parameter values for these seed loss processes are given in the accompanying AR0409 report.

4) Seedbank mixing and annual seed mortality

Realistic values for the annual mortality of seeds in the seedbank are vital since models are very sensitive to this parameter. As well as undertaking an extensive review of the available data the companion project AR0409 has carried out some targeted experimentation to fill in gaps in the available data.

The process of soil mixing due to soil cultivation is described using two simple parameters; the proportion of seeds moved from the top to the bottom layers and the proportion of seeds moved from the bottom to the top. The approach closely follows Moss (1990).

Crop Rotation

The original model of Moss (1990) analysed the fate of *A. myosuroides* in a theoretical permaculture of winter wheat. Other models of individual weed species (Freckleton & Watkinson 1998) have simplified rotation by assuming that only one crop in a rotational sequence is important for the long-term population dynamics of the species. As part of this project we have demonstrated that in order to understand the complex dynamics of plant populations in real arable fields it is important to include the influence of crop rotational sequences. The description of multiple crops increases dramatically the workload required for parameterisation of the model. Simplification of a number of processes described by the model (as outlined above) reduces the number of parameters required for a single crop to just six but five of these parameters are crop specific.

Because the models developed describe in sufficient details key biological processes and how those processes are modified by agronomic decisions they provide a predictive framework for studying how changing control strategies (herbicidal and cultural) will effect populations of individual weed species. Figure 3.4 shows long-term predictions of *Stellaria media* population densities for a range of agronomic scenarios.

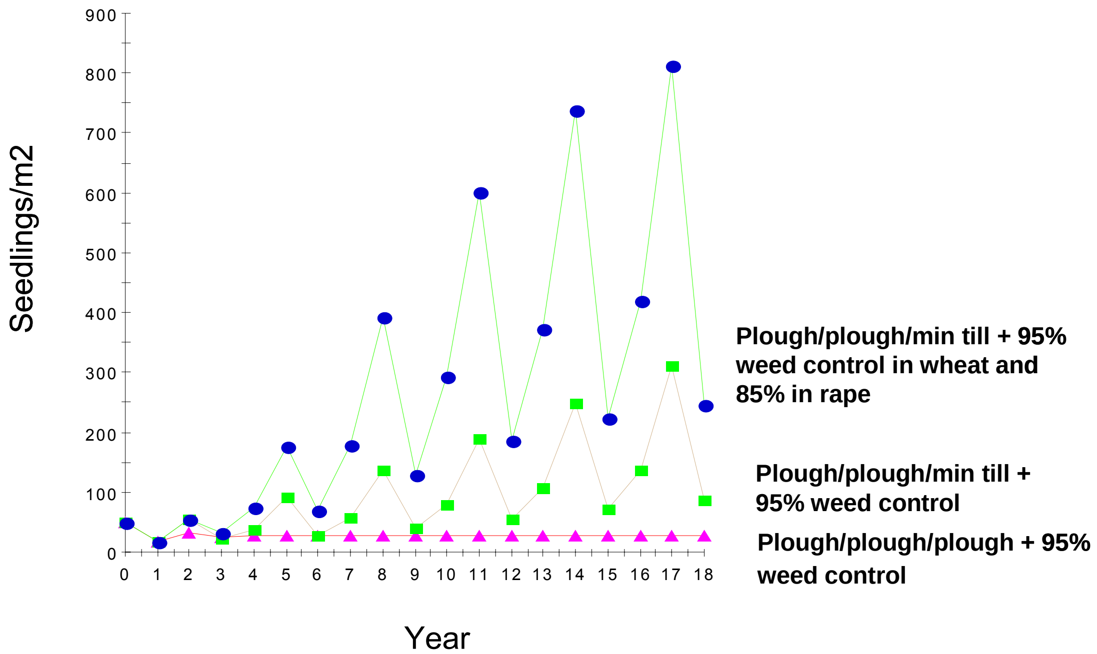

Figure 3.4 Effects of cultivation and weed control on *S. media* numbers in a wheat / wheat / oilseed rape rotation, demonstrating how replacing ploughing with minimum tillage, and poor control in one crop in the rotation, can result in substantial increases in weed populations

The key development of this approach, which is possible only when models have been effectively parameterised for a wide range of contrasting weed species, is to begin to predict community level properties for weeds in addition to the abundance of individual species. Figure 3.5 illustrates this approach we predict that the evenness of the weed community is increased as a result of increasing the diversity of crop species in the rotation.

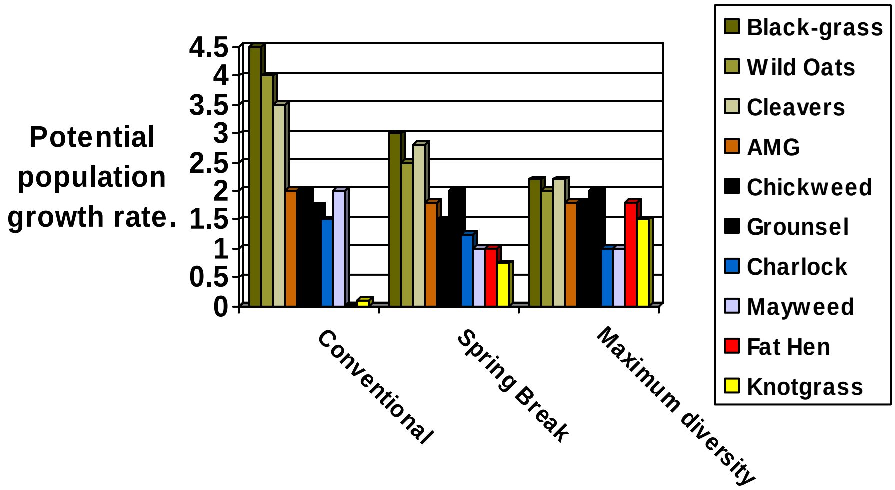

Figure 3.5: Predictions of the potential population growth rate of contrasting weed species under different rotational scenarios. Conventional refers to a 3 stage rotation Winter Wheat, Winter Wheat, Winter Oilseed Rape. Spring Break refers to a 3 stage rotation Winter Wheat, Winter Wheat, Spring Oilseed Rape. Maximum Diversity refers to a cropping strategy where crop diversity is increased: Winter Wheat, Winter Wheat, Spring Wheat, Spring Beans.

ii) Development of stochastic simulation for plant population dyanmics.

Studies within the project specifically aimed at understanding the implications of stochasticity in parameter values on long-term population dynamics has demonstrated the key importance of the nature of the variability in key parameter traits (such as fecundity and recruitment) as reflected in the 'shape' of the probability distribution function used to describe it. Some variability in key parameter values, for example, seedling recruitment and seed predation that is often thought of as stochastic (random) has been shown to be at least partly driven by the timing of agronomic events and modelled on that basis.

This part of the project started with an extensive dataset on three common which was available from previous Defra Funded research (CE0616). This allowed us to characterise the probability distributions for key biological parameters such as fecundity and recruitment. Data from other sources was used to characterise probability distributions for herbicide efficacy. Figure 3.6 shows the probability distribution characterised for fecundity (in this case in *S. media* and *A. myosuroides*). It should be noted that these probability distributions are far from uniform. They are characteristically skewed. This contrasts with the assumptions made in previous attempts to develop stochastic simulation models of plant-population dynamics (e.g. Squire *et al* 1997).

These non-uniform probability distributions have an important consequence for the likely variability in longer-term population growth rates that we would predict. In contrast to what would be predicted for a simple uniform probability distribution for these key biological parameters, the population growth rates that emerge are much more predictable. The same range of outcomes is observed but the extreme outcomes are predicted to be much rarer. Figure 3.7 illustrated the output from stochastic simulation of weed population dynamics (in this case *A. myopsuroides*).

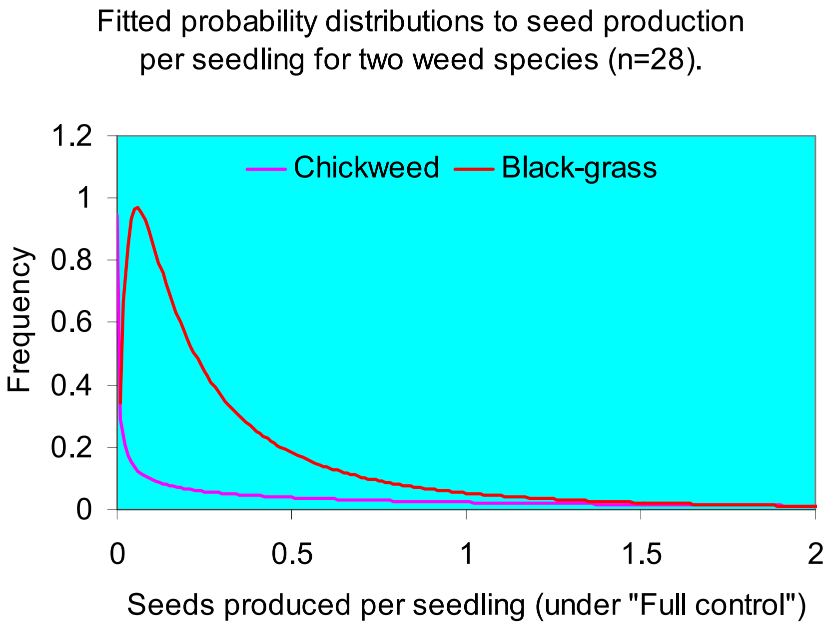

Figure 3.6: Probability distributions of plant fecundity levels observed in extensive datasets for *A. myosuroides* (black-grass) and *S. media* (chickweed) (Defra project CE0616).

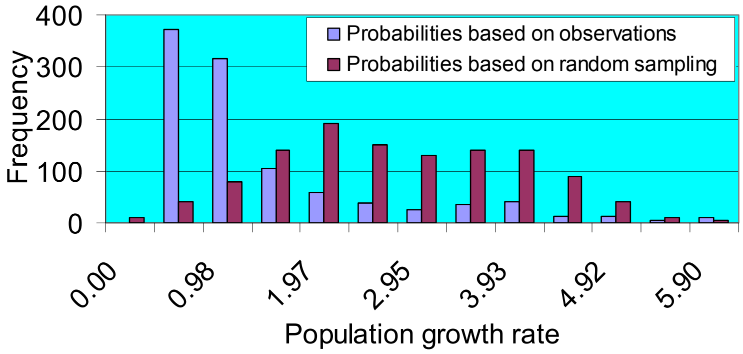

Figure 3.7: Predicted population growth rates for stochastic simulation of *A. myosuroides* population dynamics. Light coloured bars indicate the output where realistic probability distribution functions are used (from observed datasets) compared to the dark bars where a simple uniform distribution is assumed between the extreme parameter values contained in the dataset.

iii) Understanding the interaction between timing of agonomic events and the inherent phenology of the interacting species.

Data gathered as part of this project have highlighted the importance of the interactions between the timing of agronomic events and the inherent phenology of the species. These interactions have the potential to dramatically change the population dynamics of weed species and their potential value to other trophic groups such as granivores (carabids and birds for example). Comparing the way in which different species react to the timing of agronomic events such as sowing date, herbicide application and harvest date provides another tool to manipulate weed communities, in order to create a sustainable balance between crop production and the conservation of within-field biodiversity.

This project has integrated phenology and timing of agronomy information from a range of sources to create a simple model that allows us to study how the interactions between these two can modify weed population dynamics. Figure 3.8 shows an example of information about the inherent phenology of weed species that are needed. Figure 3.8 shows data from *C.album*, similar information has also been generated for the other 'key' weed species studies in these commissions. It should be noted that the seasonal timing of maximum fecundity in *C.album* is well within the known harvest window for common spring crops such as spring beans and spring wheat. New data has also been generated that allows us for the first time to quantify the seasonal patterns that are present in seed predation rates from the soil surface. Figure 3.9 shows data for *P.annua* but as part of the companion commission AR0409 work at Reading University has generated this information for the other 'key' species.

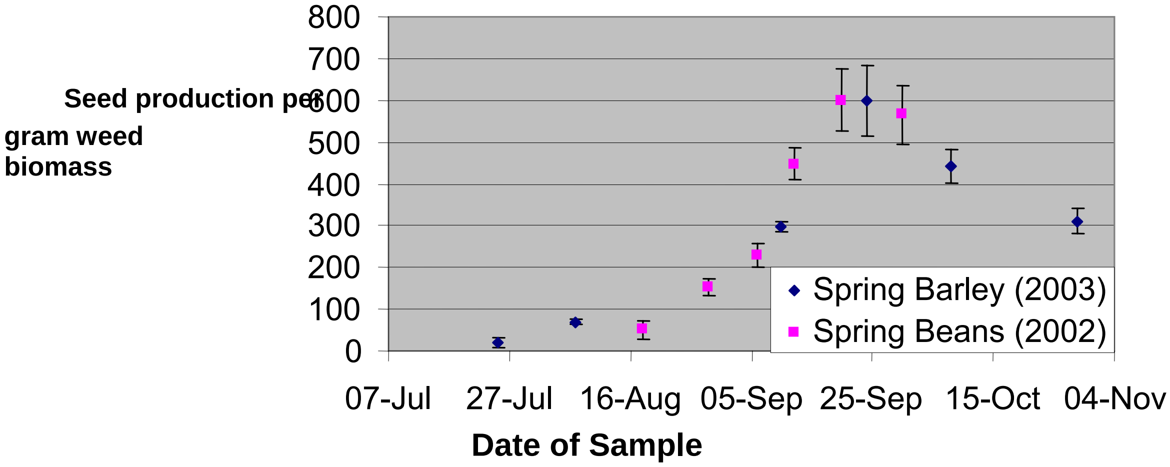

Figure 3.8: Phenology of fat hen seed production. Effective fecundity changes with date of observation.

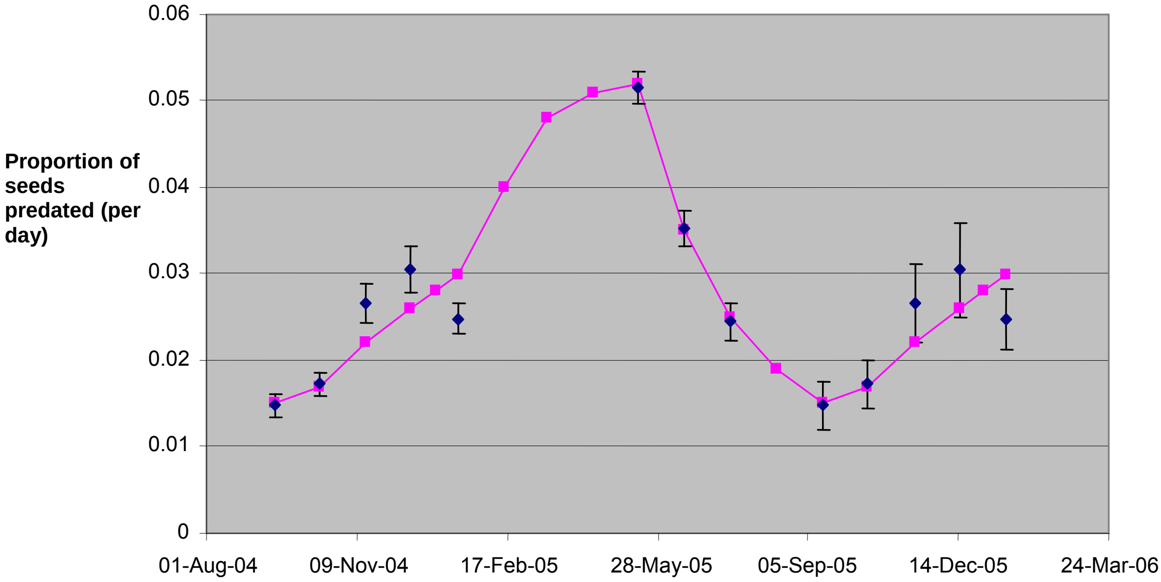

Figure 3.9: Phenology of weed seed losses: The rate of weed seed losses from the soil surface that are observed exhibits a distinct seasonal pattern. Data are for *Poa annua* seeds observed in four field trials. Refer to companion project report AR0409 for details.

A simple model has been developed that lets us integrate the sort of information shown in Figure 3.8 and Figure 3.9 on the inherent phenology of the weed species with information about the timing of agronomic events. The fixed parameter values for biological processes such as seedling recruitment, potential fecundity and weed seed predation are replaced with detailed functions describing the change of these properties over time. Figure 3.10 shows the output from this model, illustrating for two species the interaction between harvest date and the duration of the stubble following crop harvest (the period before primary cultivation incorporates seeds into the seedbank). Clearly the stubble duration is important; longer stubble durations promote increased seed predation. In *C.album* and to a much lesser extent in *P.annua* this work indicates that the timing of crop harvest can modify long-term population growth rates.

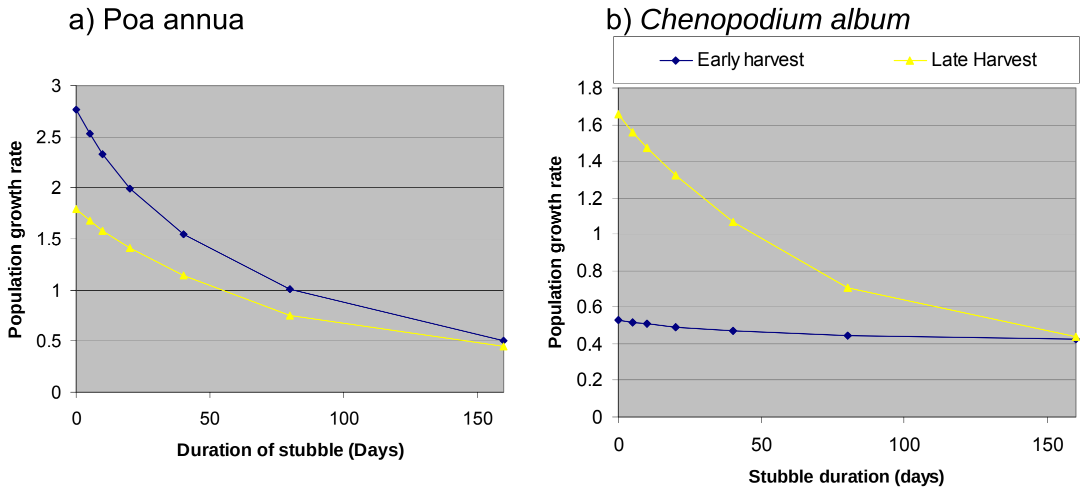

Figure 3.10: Predictions of plant population growth rate for a) *P.annua* and b) *C.album* under different scenarios. The timing of crop harvest (light coloured lines = late harvest; dark lines = early harvest) interacts with the duration of the stubble phase (the x axis).

The next step for this work is to include information about the timing of crop agronomy from historical farm records to explore the role that changing patterns in the timing of key agronomic events may have played a role in the decline of weed abundance within fields. Figure 3.11 illustrates the kind of data that are available to begin to test this hypothesis. In this example, prior to the 1990's there was a greater variability in the period between sowing and application of the first herbicide (and the average duration of this herbicide-free period was longer). This represented a potential opportunity for certain species to set seed before being affected by a herbicide.

Figure 3.11: Variability in timing of herbicide application in winter wheat crops on the Rothamsted farm for three historic periods. (data are from Rothamsted Farm records).

4) Changes in crop canopy characteristics and competitiveness (objective 2);

A number of the components of crop management can impact on the competitiveness of weeds. There is some debate about the relative contributions of such management tools as sowing date, crop density and cultivar choice, as well as the choice of crop, on weed competitiveness. If low input weed management approaches are to be adopted, what are the key management drivers determining the intrinsic competitiveness of weeds?

Methods

Two field experiments were undertaken at Rothamsted comparing the impact of winter wheat cultivars on weed suppression to the relative impact of a wide range of other agronomic inputs (crop species, sowing date, seed rate, fertiliser rate). In these experiments *A. myosuroides and G. aparine* were used as 'model' weed species to assess the extent of the potential impact of agronomic factors on weed population dynamics. Populations of constant seed density were sown at the time of crop establishment. In addition, in the last year of the project, an experiment comparing weed growth and seed production in winter and spring sown wheat crops was undertaken at Rothamsted to highlight this aspect of crop competitveness. In this experiment individual weed plants were first reared in small soil plugs in the glasshouse and then transplanted into the field 7 days after crop sowing of winter and spring wheat. Additionally, further plants were transplanted into the winter crop on the same date as they were introduced into the spring crop. This was done because of the unreliability of creating weed populations at the desired densities for all the species.

Results

A direct comparison between the impact of crop cultivar and other agronomic factors, such as sowing date, seed rate and fertiliser rate, on weed suppression has highlighted the limitation of adopting different crop cultivars, compared to other approaches. Although large and significant effects on weed growth and fecundity, and crop yield loss were observed for contrasting winter wheat cultivars, changes associated with other agronomic factors proved larger (Fig. 4.1). A change of 36% in crop yield and 20% in weed growth was observed between the least and most suppressive cultivars. This compared to changes of 90% and 67%, respectively, associated with changing cereal crop species. In terms of weed suppression the crop species were ranked as Winter Oats (most suppressive), Winter Wheat, Winter Barley (least competitive). For the crop cultivars studied the rank was Maris Widgeon (most suppressive), Consort, Mallaca (least).

For this experiment and others, there was a strikingly consistent relationship between crop yield loss and weed seed production across all the agronomic treatments, indicating that for this species at least our methodology for estimation of weed seed production using simple allometric scaling rules to link weed biomass, seed production and crop yield is very robust.

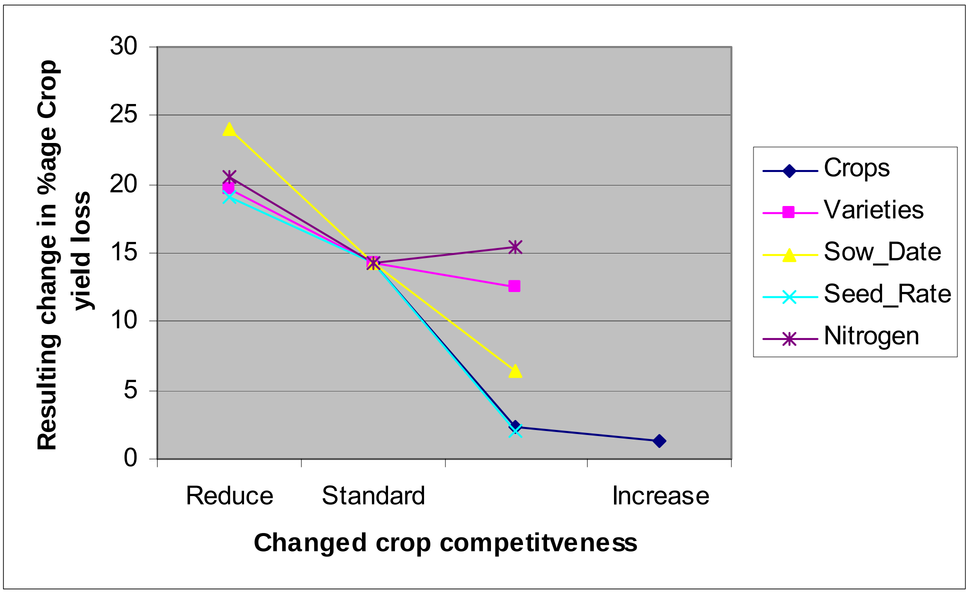

Figure 4.1 The relative impact of a wide range of agronomic factors (varieties, sowing date, seed rate, nitrogen rate, crop choice) on *A. myosuroides* growth and crop yield loss. ('reduce', 'standard' and 'increase' relate to lesser or greater suppression of weed growth).

When comparing weed growth in spring and autumn sown cereal crops, the relative impact of the two sowing times and the weed emergence dates varied considerably between the weed species studied (Fig. 4.2). It is interesting to compare the fate of the two aggressive grass weed species studied; *A. myosuroides* is dramatically effected by spring emergence (compared to autumn emergence) whereas *L. multiflorum* although highly suppressed when emerging late in the spring into an already established autumn sown crop does perform relatively well when emerging in a spring sown crop. These results seem to reflect the regeneration strategies of the species. While *A. myosuroides* is almost entirely an autumn emerging species *L. multiflorum* has a much broader time-window for germination. In the obligate spring-emerging species studies *(C. album)* a dramatic suppression of growth is observed when the plants emerge into an already established autumn sown crop. This conclusion is supported by studies in AR0408.

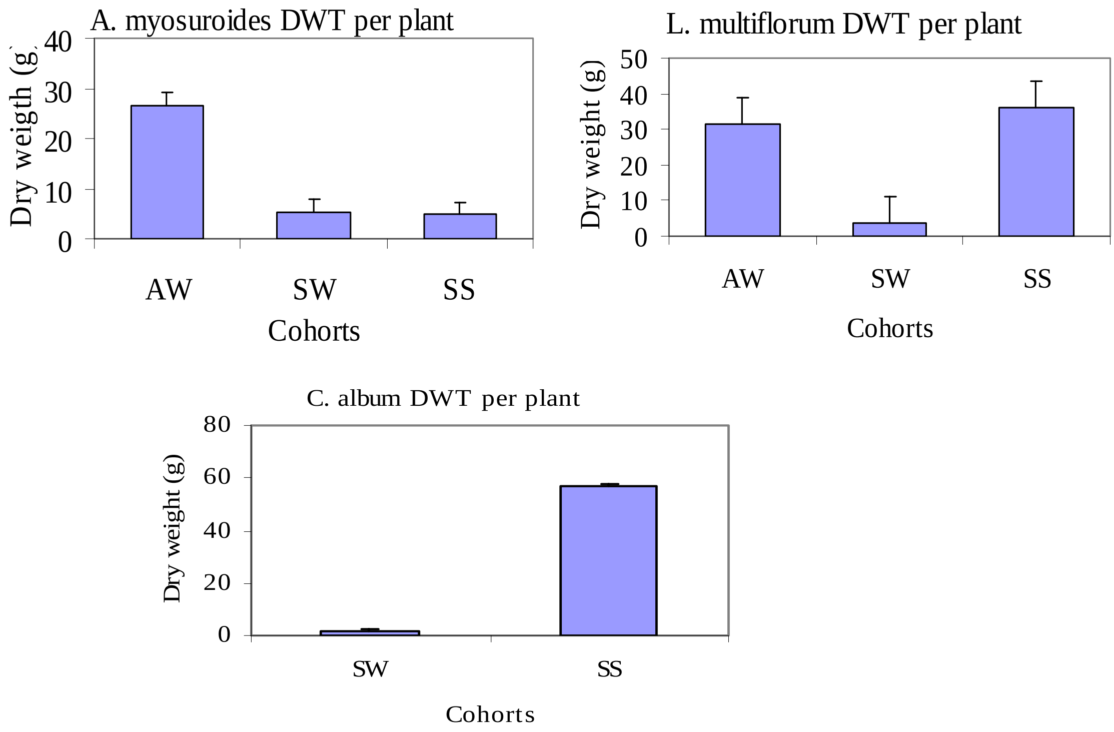

Figure 4.2 Comparison of the dry weight of *A. myosuroides* , *L. multiflorum* and *C. album* individuals in harvest (August) in spring and autumn cropping. AW = Autumn emerging in an autumn sown crop, SW = Spring emerging in an autumn sown crop and SS = Spring emerging in a spring sown crop.

Discussion

These results in terms of the potential contribution of crop cultivar to overall levels of weed suppression reflect other work in oilseed rape (Sim pers. comm.). They confirm that while the use of suppressive crop cultivars can contribute to an integrated approach to long-term weed control in isolation they are unlikely to provide a significant replacement for chemical control. It should be emphasised that this conclusion is only valid for higher input 'conventional' systems where the overall biomass and leaf productivity of the crop is intrinsically high. In lower input and organic systems the details of canopy architecture have been shown to be much more significant. In a wider context the results from this small number of experiments emphasise the extent to which within crop management can have a very dramatic effect on weed growth, aside from any influence that changed in herbicide practice might have. The results shown here highlight the role of the timing of crop establishment in determining the eventual fate of weed populations within crops. Changing the season of crop sowing (autumn to spring) clearly has a very dramatic effect (Figure 4.2) but even within the autumn sowing window changing sowing date by a few weeks can have a very dramatic effect (Figure 4.1).
The future challenge is to harness information about the influence that crop agronomy can have on weed populations to shape weed communities in order to contain aggressive weed species while sustaining populations of other potentially beneficial species.

5. The ecophysiological basis of functional groups (objective 3);

Traditionally, weed competition studies have focused on understanding the competitive effect of a single weed species in a crop. This had led to the development of crop - weed competition models incorporating a detailed knowledge of the ecophysiology of an individual weed species (*eg.* Kropff and Spitters 1991; Weaver *et al*. 1993; Cavero *et al*. 1999). This approach is used in section 3a. An alternative approach is to contrast a suite of ecophysiological parameters for a larger range of weed species to explain variations in their competitive ability (Regnier *et al*. 1988; Wilson and Wright 1990). Applying principles of comparative functional plant ecology to weed science in this way allows the benefits of these two approaches to be combined. This project has involved a broad-scale screening programme of a range of plant species for the characteristics that determine growth (Grime and Hunt

1975; Duarte *et al*. 1995). Multivariate, ordination analysis was then be used to identify species with similar ecological strategies and arrange them in functional groups (Grime *et al*. 1988). Comparative studies of functional ecology contribute to our understanding of weed:crop competition and identify contrasting ecological strategies within the weed flora that can be used to select for specific groups of species.

Methods

A number of experiments were done in the sand bed, hard standing area and field at Rothamsted to parameterise the eco-physiology of sixteen autumn germinating species and five species normally associated with spring drilled crops (Table 1.1)
The following parameters were measured for all the species and included in a trait / species matrix to identify functional groups: Seed mass, initial seedling green area (L_0), relative growth rate of green area in the autumn ($RGRL_a$) and the spring ($RGRL_s$), root weight ratio (root weight / total plant weight, *RWR*), mean specific leaf area (leaf area / leaf weight, *SLA*), maximum height, time of first flowering and time of leaf senescence. The sources of these data are described below.

Sand bed experiment
A sand bed experiment was designed to measure L_0 and seedling *RGRL.* Seeds of the 21 weed species and three crops (winter wheat, field beans and winter oilseed rape) were pre-germinated and sown into pots containing a mixture of loam and grit with additional slow release fertiliser. Twenty-five pots were sown up for each species and arranged in an outdoor sand bed in five replicate blocks, each block containing five pots of each species (Plate 5.1). The experiment was repeated twice in the autumn and twice in the spring. The sowing dates were 12/10/2001, 08/03/2002, 27/09/2002 and 24/04/2003. At approx. 7-d intervals for the autumn sowings and 4-d intervals for the spring sowings, five seedlings (one from each block) were sampled from each species to measure root, stem and leaf dry weight and leaf and stem green area.

Plate 5.1 Sand bed experiment to measure weed seedling relative growth rate.

Standing area experiment
A second pot experiment was sown in September 2003 to parameterise the response of the assimilation rates of the weed species to light and temperature. Twenty plants of each species were established and arranged in four replicate blocks in a hard standing area protected from frost (Plate 5.2). Assimilation rates were measured (using a CIRAS-2 Infra red gas analyser, PP Systems, Bedfordshire, UK) at four leaf temperatures, 5^{o}C, 10^{o}C, 15^{o}C and 20^{o}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, 2005a). Physiological differences in the rate of assimilation were small in comparison to 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 analysis to identify functional groups.

Plate 5.2 Experiment in the hard standing area to measure assimilation rate and root weight ratio (*RWR*)

Field experiments

Field experiments were sown at Rothamsted to measure biomass partitioning (including *SLA*), height and phenology (time to flowering and senescence). 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 x 3m) 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 $1m^2$ area was hand weeded to 50 plants m^{-2}. 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 27/09/2001, 17/10/2002, 29/09/2003 and 29/09/2004. 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 05/03/2002, 07/03/2003 and 03/03/2004 prior to a crop of spring wheat being drilled. At intervals of approximately four weeks, heights were recorded and five individual plants from each plot sampled and divided into stem, leaf and flowers to measure *SLA* and biomass partitioning.

Results

Two models to estimate the development of leaf area were fitted to the data, one using thermal time, (Equation 1) and the other effective day degrees, *EDD* (Equations 2 and 3). Units of *EDD* take account of both accumulated temperature and radiation, using a parameter, *f*, to measure the relative importance of the two variables in accounting for seedling growth (Scaife *et al.*, 1987).

$$\mathrm{Ln}(L) = \mathrm{Ln}\,(L_o) + RGRL \,.\, \Sigma\,(T - T_b) \qquad (1)$$

$$\mathrm{Ln}(L) = \mathrm{Ln}\,(L_o) + RGRL \,.\, \Sigma\, EDD \qquad (2)$$

$$EDD_i^{-1} = DD_i^{-1} + f \,.\, PAR_i^{-1} \qquad (3)$$

where: L is green area, L_o is initial green area at emergence, *RGRL* is the relative growth rate of total green area, T is daily mean temperature, T_b is the base temperature, *DD* is day degrees (°Cd) and *PAR* is accumulated photosynthetically active radiation (MJ) all on day i.

The use of *EDD* was found to provide a more robust model of the response of seedling growth rate to the environment (Figure 5.1) and the model was optimised for each species. Full details of the experimental method and results have been published in (Storkey, 2004). Four species failed to germinate in at least one of the original experiments and so are not included in this paper. However, the dataset was completed from later experiments.

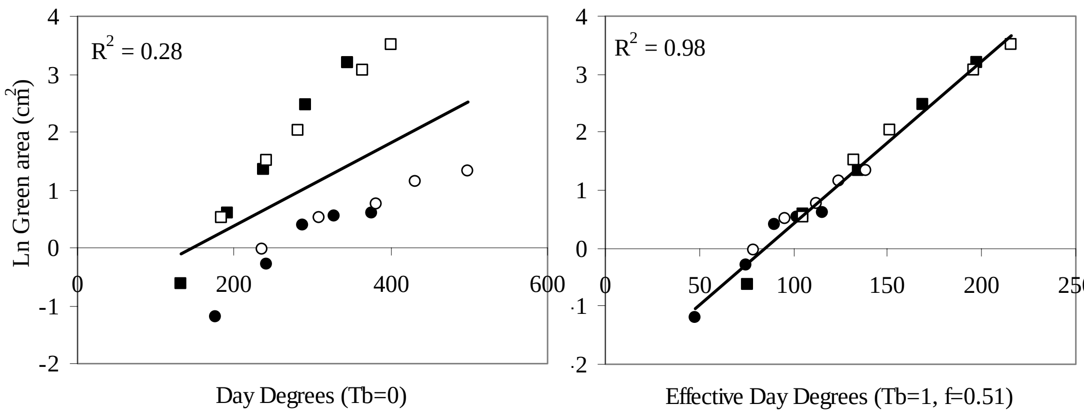

Figure 5.1: The development of leaf area in seedlings of black-grass using two models to describe environmental conditions; a) leaf area described by day degrees, b) leaf area growth described by effective day degrees (see text for definitions).

Analysis of the trait / species matrix
The combined results of the sand bed, standing area and field experiments were included in a matrix of 21 weed species and nine traits. In the context of sustainable weed management, species that were generally only found in spring crops were functionally distinct. The spring germinating species were, therefore, treated separately. The 16 autumn germinating species were included in a multivariate analysis to identify groups with a similar suite of eco-physiological traits. Regression analysis of these data identified a number of trade-offs between traits indicating contrasting strategies within the weeds studied (Fig. 5.2).

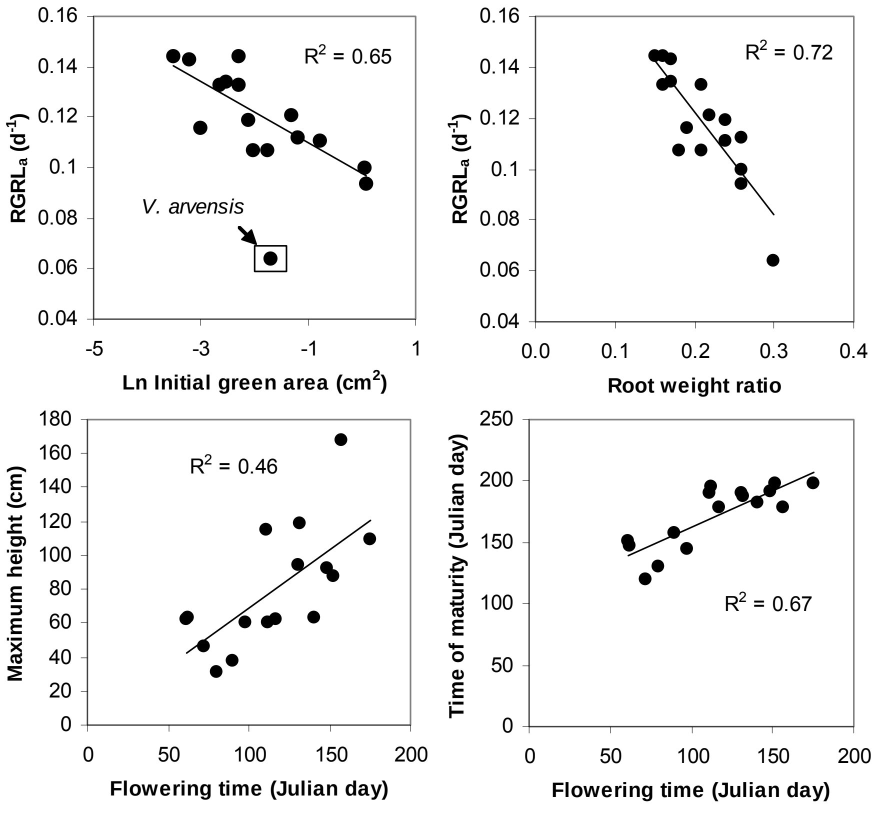

Figure 5.2 Significant correlations between traits used in the multivariate analysis of the autumn germinating weeds.

A principle components analysis was performed on the matrix using only the autumn germinating weeds after all the traits had been given an equal rating by converting to zero mean and unit standard deviation. A non-hierarchical cluster analysis was used to identify four functional groups based on alternative strategies for primary production (Fig. 5.3). Group 1 species are relatively tall and late maturing with a high *RWR*. This group includes the most competitive species. Group 2 species are also tall and late flowering but are characterised by having a lower initial green area and faster $RGRL_a$. Group 3 species are relatively short and early flowering while species in Group 4 are short and late flowering.

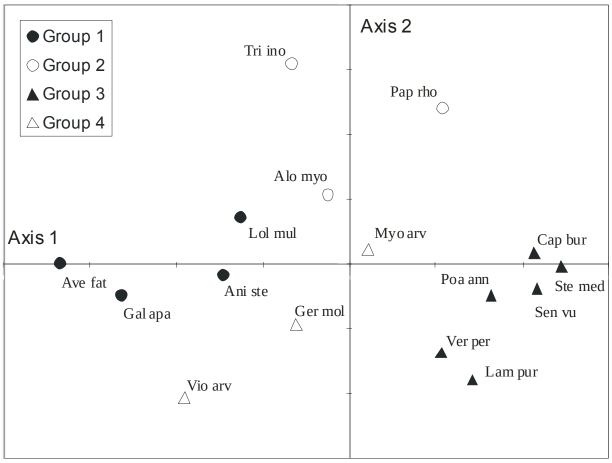

Figure 5.3. Principal components analysis on trait matrix of autumn germinating weeds.

Discussion

For the management of weeds within arable crops to be justified, as well as having a relatively low competitive ability, candidate weed groups must also be important for sustaining higher trophic levels. A previous study has identified weed species that combine a low competitive ability with high biodiversity value (Fig 1.1) (Marshall *et al.*, 2003). It is likely that this serendipity can be partly explained by the fact that traits that determine the pattern of primary productivity 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. This hypothesis was supported when the species included in the literature study were arranged in the functional groups identified as part of this commission. Two beneficial groups were identified (S1 and 3) that combined a relatively low competitive ability with a high importance for invertebrates and birds (Fig. 5.4). Full details of the results of the functional group analysis can be found in Storkey (2005b).

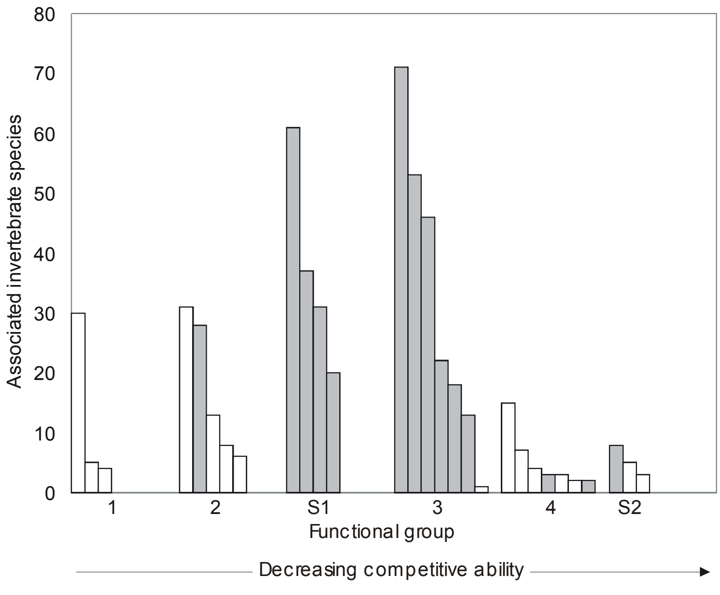

Figure 5.4 Contrasting value of functional groups to invertebrates and birds. Groups 1-4 as in Figure 4.4., Group S1 = ruderal spring germinating weeds, S2 = shade tolerant spring germinating weeds. Shaded bars = weed species present in diets of farmland birds.

6. Validation of predictions (ADAS sub-contract - Objective 4);

a) **Validation experiments.**
b) **Seed production assessments.**
c) **Measurements of weeds abundance in the seedbank.**
d) **Longer-term implications of reduced weed control.**

a) Validation experiments

A series of experiments were done to test our ability to predict crop yield losses based on simple indices of weed competitiveness. These competition indices were developed exclusively in winter wheat as part of a previous DEFRA contract (CE0616). A large part of the project was gather the information required to extend of this approach to spring sown and broad-leaved crops. The experimentation was carefully designed so that the balance between crop and weed productivity under different management scenarios could be assessed. The impact of control on weed productivity was recorded and in paired plots the impact of a lack of control in the same situation on crop yield measured.

Methods

A set of six identical field trials was established each year in both winter and spring sown crops at 3 ADAS sites, Boxworth (Cambridgeshire), Terrington (Norfolk) and High Mowthorpe (Yorkshire), over 4 field seasons (2001 to 2005). These trials tested crop yield loss predictions and weed control decisions made on the basis of initial weed seedling numbers. Fields were chosen with a known low level of aggressive weed species including grass-weeds and *G.aparine*.

Each field trial consisted of full control plots, untreated plots and 'managed' plots, in a fully randomised trial design with ten replicate blocks, plot size 3m x 12m. The full control plots were treated with a conventional herbicide programme for the weed species present and the untreated plots received no herbicides, except where aggressive grass-weeds were present, for which an appropriate graminicide was applied. Decisions whether to apply herbicides to the 'managed' plots were based on data from the autumn plant counts. If the weed species present resulted in more than a 5% yield loss to the crop (based on the data from the yield loss calculator in winter wheat (Lutman *et al,* 2003)) the plots were sprayed. For the winter sown crops an autumn crop and weed plant count was carried out using 5 x 0.1 m^2 quadrats per plot, followed by a spring crop and weed count using 10 x 0.1 m^2 quadrats per plot. For the spring sown crops only one crop and weed count was recorded in the late spring using 10 x 0.1 m^2 quadrats per plot. In the June of each year, for all crops, a full weed biomass was sampled from the field using one 0.5 m^2 quadrat per plot. The weeds and crop were then processed in the laboratory and dried in an oven at 80^oC for 48 hours and the dry weights (g) were recorded. All trial plots were combined to determine the final yield and treatments compared.

Results

A total of 21 validation field trials were completed in a combination of winter and spring wheat, oilseed rape and field bean crops. Two trials (winter beans and spring oilseed rape) were lost to pest damage in 2003 and were unable to be taken through to harvest. One further trial in spring wheat (2003) was taken through to harvest (providing valuable data for seed production species), but due to a difficult season the full control treatments were unable to be applied, resulting in no comparison plots.

Table 6.1 A summary of the 'managed' plots where decisions to spray or not to spray were correct or incorrect and the resulting yield loss compared to the full control. The percentage of plots that fall into 4 categories are described.

Crop Species	Number of trials	Percentage of decisions in each category			
		Un-sprayed		Sprayed	
		Correct	Incorrect	Correct	Incorrect
Winter wheat	6	15	45	15	25 CHECK THESE
Winter OSR	3	28	14	38	21
Winter Beans	2	30	65	5	0
Spring Wheat	4	47	53	0	0
Spring OSR	2	0	0	5	95
Spring Beans	5	24	44	22	10

Table 6.2 Crop yield loss (%age) in plots where errors in the management decisions were made.

Crop Species	Number of trials	Sprayed	Un-sprayed
Winter wheat	6	10.4	0.8
Winter OSR	3	11.8	-3.3
Winter Beans	2	8.9	-4.5
Spring Wheat	4	48.3	-
Spring OSR	2	-	4.8
Spring Beans	5	14.9	-3.1

Table 6.1 shows the percentage of the management decisions made that fall into four categories; No spray decisions that were correct and incorrect and spray decisions that were correct and incorrect. The benchmark for the decisions was a nominal 5% crop yield loss threshold. In terms of agronomic and economic sustainability over 70% of the decisions made in the 'managed' treatments for the winter crops were correct (no yield penalty was incurred as a result of inaccurate yield loss predictions in those situations), with the highest number of correct decisions in winter wheat (85%). In winter wheat where decisions proved wrong because crop yield loss was higher than predicted the average yield loss observed was 10.4% (5.4% above the nominal threshold) (Table 6.2).

Our lack of previous information about these weed species in spring crops meant that the decisions for these crops were more variable ranging from 53% to 100% correct decisions. However, where the decisions were correct in spring oilseed rape and all plots were sprayed with herbicide the mean yield loss was still above the 5% threshold at 40.7%. The highest number of correct decisions in the spring crops was in spring beans at 76% correct, with no yield loss compared to the full control. Where a correct decision has a mean yield loss with a negative value this indicates that the 'managed' treatments achieved a higher yield than the full control plots. Aggressive weed species, such *as G. aparine and A. myosuroides* were the major species responsible for the yield loss where the herbicide treatment had not effectively removed them. However in a spring wheat trial in 2002, the 'managed' plots were dominated by *S. arvensis*, resulting in a mean yield loss of 67% compared to the full control plots.

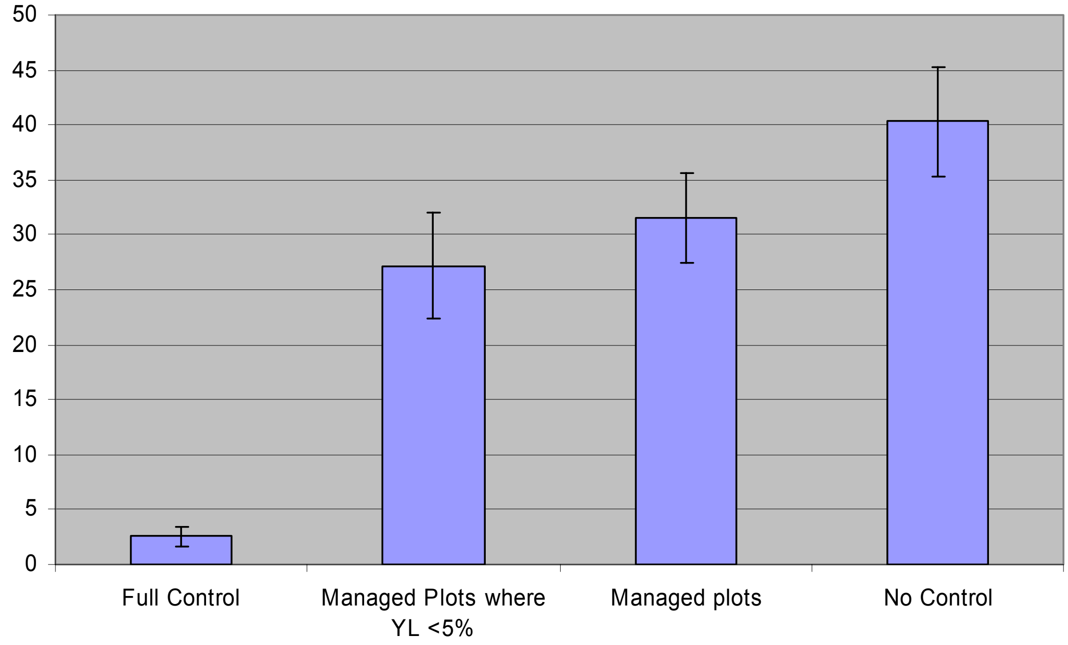

Figure 6.1: Total weed biomass recorded in mid-summer (June/July) in plots of winter wheat under contrasting management treatments.

Figure 6.1 shows the weed biomass at maturity (late July) achieved in the "managed" plots compared to full-control and no-control situations. A sub-set of plots where crop yield loss proved to be below the nominal 5% threshold used within the project are also identified. Where the plots were "managed" a considerable increase in weed biomass was observed for relatively little crop yield loss. Figure 6.2 shows the relative abundance of a range of weed species observed in spring and autumn sown crops.

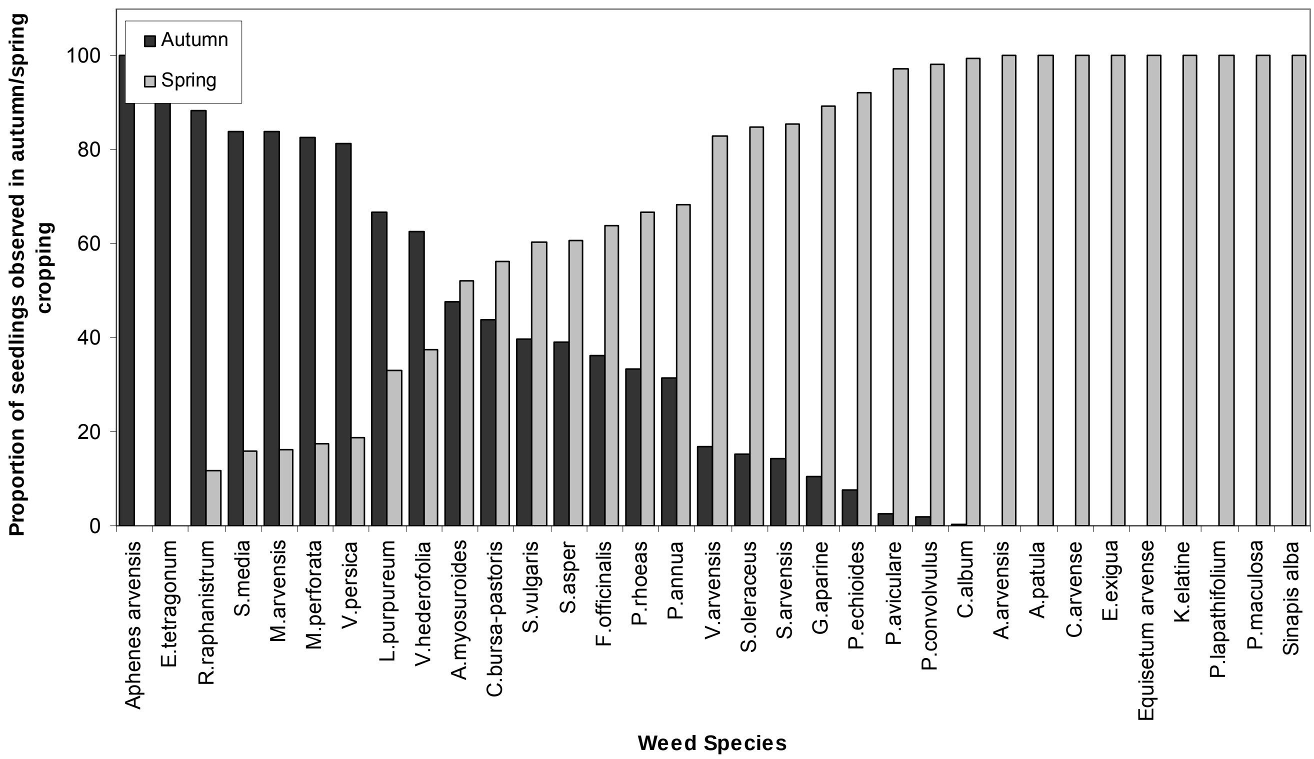

Figure 6.2: Characterisation of the recruitment strategy of a wide range of weed species observed in the validation trials. The x-axis indicates the proportion of the total abundance observed in spring compared to autumn sown crops.

Discussion

The decision whether to spray or not to spray the 'managed' plots was calculated using the yield loss calculator designed for a range of weed species in a winter wheat crop, as these were the only data of this kind available. It was therefore very difficult to accurately predict the yield loss from a number of weed species in both spring-sown and broad-leaved crops. Decisions were also made after the first weed plant counts (autumn for the winter-sown crops and spring for the spring-sown crops) were completed therefore no pre-emergence herbicides could be included. This resulted in higher yield losses in the spring crops and the winter oilseed rape, where levels of weed:crop competition were higher than had been predicted. Data have now been generated in a range of spring and broad-leaved crops that will be valuable for future yield loss predictions, however more detailed trials specifically investigating yield loss from a range of weeds in these crops is required. Another limiting factor in 'managing' areas to maintain the beneficial weed species is the choice of herbicides available. Most herbicides are broad spectrum and therefore the choice of products that will retain certain weed species is limited and information on their effectiveness is often scarce or unavailable for these target species (this issue is discussed further in project AR0408).

These results suggest that there is considerable scope in the system for increasing the productivity of weeds within crops without jeopardising the sustainability of crop production. There is clearly some direct penalty incurred from weed populations that remain uncontrolled in the crop but the near 10-fold increase in weed biomass observed in plots where crop yield loss was within 5% of the weed-free yield does indicate that a full herbicide programme is supra-optimal in situation where aggressive and pernicious weed are not present. This demonstration of the short-term direct implications of changing weed management needs to be closely linked with other work within the project which considers the longer term implications on weed population levels.

Data from these experiments have produced valuable information for the on-going modelling effort aimed at improving long-term predictions of weed populations under different cropping regimes. They provide much better estimates of the weed productivity achieved in a wide range of cropping and weed management scenarios.

b) Seed Production assessment

Having established the field trials outlines in **6.a)** we took the opportunity to add to our increasing knowledge of potential weed seed production. By measuring the seed production (Lutman 2002) of a range of species under such a range of growing conditions and crop species the aim was to test some of the principles established in AR0409, where much more detailed work on seed production was undertaken. Detailed protocols were developed for a very wide range of weed species with contrasting architecture and habit and these can provide the basis for future studies.

Methods

Plant samples were taken from the field trials at each of the 3 ADAS sites, from a range of winter and spring sown crops, between May and July in each of the 4 seasons. Each individual weed species was measured differently according to the nature of the plant and sampling times varied according to the flowering times of each species. All weeds sampled were natural populations identified at each site. For each individual species sampled, 20 plants were randomly collected from within untreated field trial plots. Samples were labelled individually and assessed in the lab. The total dry weight (g) per plant, the ratio of reproductive to vegetative dry weight (g) per plant and the number of seeds per plant were recorded. For each of the 20 plants the number of immature and ripened capsules or pods were counted, including any capsules that had already shed their seed. The plants were then dissected into a) reproductive parts (capsules or pods excluding any stalks) and b) non-reproductive parts (leaves, stem and any stalks). The reproductive and non-reproductive parts were then dried in an oven at 80^{o}C for 48 hours and the dry weights (g) were recorded. The average number of seeds per capsule was assessed by sampling a further 30 capsules or pods, from within the same field area as the main plant samples. The plant heads or capsules selected were mature heads that had not already senesced and shed their seed, but were not immature. Each capsule was assessed individually and the total number of seeds per capsule was counted. Species with high numbers of seeds per capsule, such as *Papaver rhoeas*, required a seed sub-sample for assessment. Data sets were compared using simple linear regression in Genstat (Payne et al., 2005) and averaged together for both winter and spring crops.

Results

Table 6.2: Seed production assessments made using validation trial plots. The data were used to derive overall 'scaling' or 'allometric' relationship between total biomass at maturity and seed production for each species.

Species	Number of sites	n	Seeds/g plant weight	SE	%VAF
Brassica napus (Volunteer OSR)	4	63	60.0	1.2	97.6
Fallopia convolvulus	7	133	93.6	9.4	42.7
Veronica hederifolia	1	19	138.2	13.8	84.6
Sinapis arvensis	3	65	138.5	10.1	74.4
Galium aparine	2	36	162.7	11.3	92.4
Lolium multiflorum	1	69	199.7	10.0	85.5
Polygonum aviculare	3	28	226.2	12.7	92.2
Fumaria officinalis	3	47	233.5	24.4	66.4
Viola arvensis	2	18	310.4	31.5	85
Sonchus arvensis	2	33	323.9	89.4	27.5
Chenopodium album	5	96	830.7	35.2	88.1
Veronica persica	3	59	838.6	32.3	92.1
Atriplex patula	2	40	934.1	48.3	90.5
Sonchuis asper	1	20	1097.9	77.6	91.3
Papaver rhoeas	9	147	1859.0	135.0	56.4
Senecio vulgaris	1	17	2570.0	157.0	94.3

Discussion

Data on the seed production of beneficial and common weed species in a range of arable crops was limited in the literature. Data have now been recorded for 16 weed species, some in contrasting crops, which improve the accuracy of the weed population dynamics models. These data have been collated with other species from the partner commission AR 0409 to form one large database and have been extremely valuable for the Decision Support System – Weed Manager, for the models and the weed encyclopaedia.

A more detailed analysis of these data suggests that some caution needs to be exercised when using biomass data to estimate weed seed return. For some weed species there is variability in the allometric parameter (seeds per gram) observed at different sites. In addition the timing of observation can have a profound effect on the apparent fecundity of some late maturing weed species (see Figure 3.8). These data provide a valuable insight into the variability in the allometric parameter that is possible between sites which provides the basis for any sensitivity analyses undertaken on longer-term weed population models.

c) Measurements of weeds abundance in the seedbank.

For a number of the trials sites the abundance of weeds seeds in the seedbank prior to the start of the experiments was assessed. This allowed us to take account of the seeds in the seedbank in our assessment of the longer-term impact of changes in weed management. Where the seedbank densities were known we were able to fully parameterise and test the longer-term weed population dynamics models discussed in section 3b.

Methods

For a single site each season the seed bank was assessed by taking 40 soil cores per plot, from a depth of 0-5cm (7cm diameter soil core) and 5-25cm (2.5cm diameter soil core), from the 4 replicate field blocks. A soil bulk density measurement was taken from each site. Soil samples were processed at ADAS Boxwort and when possible processed immediately. When it was not possible to process on the day of delivery they were stored in sealed plastic bags refrigerated at 5^oC until processing began (always within a week of delivery). Individual samples were laid out in large metal trays in the laboratory to air dry and soil particles were crumbled by hand to remove large lumps. Plastic seed trays, measuring 30cm x 25cm x 10cm, with no holes in the base, were filled to a depth of 2cm with a peat based compost providing a base layer of moisture. Individual trays per field plot were filled with 2000g of the crumbled field soil samples which were placed on top of the layer of compost. Two 'blank' trays per replicate block, containing just a layer of compost were placed on each pallet to check for contamination from external sources. All trays were labelled and placed on wooden pallets, in fully randomised blocks, in a polytunnel at ADAS Boxworth. The trays were then watered twice a week (or more frequently when required) using a hose and sprinkler system from above, between the December and June of the first season and then left dry between July and August. In the following September the dry soil surface was carefully broken up by hand and re-watered regularly until the following June when all assessments were completed, therefore the whole assessment for each individual seed bank covered an 18 month period. During the periods of watering weed emergence was recorded weekly, by identifying the species and number present and then removing those recorded seedlings from the trays. The seed bank was sampled from Boxworth in 2001 (Backside field) and 2004 (17 acres field), High Mowthorpe (Whether Plain south field) in 2002, Terrington (Hatchet field) in 2003.

Seed bank

Results

Table 6.3 shows the total number of species and the seedling population observed in the field trials as a percentage of the seedbank abundance. There is clearly tremendous variability in the percentage of the seedbank that became established as seedlings. Table 6.4 summarised the vertical distribution of the seeds found in the seedbank. It is important to note that where the seeds were more deeply buried (Boxworth and Terrington) the percentage of the total seedbank that establishes was very much reduced.

Table 6.3: The emergence of weeds from the soil seedbank observed in an autumn-sown crop.

Site	Total no. species in seed bank	Total no. species emerged	Percentage of total seed bank that emerge
Boxworth	18	6	0.22 %
High Mowthorpe	22	9	3.42 %
Terrington	29	16	0.09 %

Table 6.4: The distribution of seeds in the seedbank between shallow (0-5cm) and deep (5-25cm) horizons.

Site	% of total seed bank emerged 0-5 cm depth	% of total seed bank emerged 5-25 cm depth
Boxworth	9.7 %	90.3 %
High Mowthorpe	89.1 %	10.9 %
Terrington	13.6 %	86.4 %

Discussion

It is clear from the limited seedbank assessment undertaken as part of this project that the vertical distibution of seeds has a profound influence in the short term on the number of seedlings that emerge into the crop. In the longer term this will be reflected in the potential population growth rate. This re-enforces messages from previous studies on more aggressive weed species (Moss, 1990). This finding has repercussions both for the design of seedbank sampling and for the development of weed population models. When designing experiments that include monitoring of weed seedbanks the separation of the seedbank into simple vertical horizons that reflect the depth that weed seeds can emerge from is clearly very important. This finding also implies that the simplification of population models so that the seedbank is a simple single layer has considerable dangers.

d) Longer-term implications of reduced weed control.

In addition to the short term implications of reduced weed control on both crop yield and weed biomass these experiments continued into the following season to assess the longer term implications. Assessments of weed abundance were made both on the stubbles that followed the experiment and also following cultivation in the following autumn and spring. By combining the assessments of seedling numbers in the following crops with information about the weed seedbank we were able to validate our long-term weed population dynamics models for a limited number of species.

Methods

Weed abundance in following stubbles and crops.

For each of the experiments described in section (a) the fate of weed populations in the contrasting treatments was followed through into the following crop, by assessing weed numbers, using 10 x 0.1 m^2 quadrats per plot in the post-harvest stubble, before any cultivations were carried out. The fate of the weed populations on individual plots was also followed into the next year, to quantify the longer-term implications of weed control decisions; therefore each field trial ran for 2 years. At the end of the first year of the experiments (autumn of 2002), all 6 trial sites that were combined in the summer of 2002 were sown as a winter wheat crop. All plots were counted as described above. However, from the autumn of 2003 onwards these follow-on trials all remained fallow in the subsequent year, with a shallow cultivation in the autumn, followed by a plant emergence count and glyphosate spray, then a shallow cultivation in the following spring, plant emergence count and final glyphosate spray.

Validating long-term population dynamics models

Data were collated from these field trials for selected species from all aspects of the seed cycle. This included the number of seeds in the seed bank, autumn and spring plant emergence in the field in the first season and a value for seed production per g of plant biomass. From these data an estimate of the number of plants emerging in the following crop could be calculated, including a seed bank decline factor from the literature and not including seed predation. These data were then compared to the model estimates to check the accuracy and provide a validation of the models. As the weed seed cycle required seed bank data and only one site per season was sampled the number of complete weed seed cycles were limited. Seed production data could be transferred between sites where plants were sampled from the same crop.

Results

Weed abundance in following stubbles and crops

Figure 6.3 summarised the total weed abundance observed in the full-control and managed treatment plots in the different trials. The initial seedling numbers are little different between the treatments as would be expected. In the stubbles following the experiment the managed plots (where weed populations where crop yield loss was predicted to be less that 5% were tolerated) there is a very marked increase in the abundance. In the following crop season these differences while still appreciable had greatly decreased and at one site (Boxworth 2002) there was no significant difference between the treatments. Data for the latest series of field trials (2004) are still being collated. It has to be realised that the seedling number in the following crop is related both to the pre-existing seedbank, indicated by the 'initial weed counts' and by the seed rain in the test crop identified by the stubble counts.

Validating long-term population dynamics models

Due to the practical limitations on the seed bank sampling measurements a weed seed cycle could not be calculated for all species. However, it was possible to run the population dynamics model and compare the output with the field data for some species. For the species tested the ratio of the estimated:observed number of weed seedlings in the following crop was fairly constant. For example *P. rhoeas* had a ratio of 1.2 and 1.05 from 2 different seasons (2003/04 and 2004/05) at sites (Boxworth and High Mowthorpe). *S. media* and *V. persica* were both calculated in the season of 2003/04 at Boxworth and had ratios of 0.8 and 0.7 respectively.

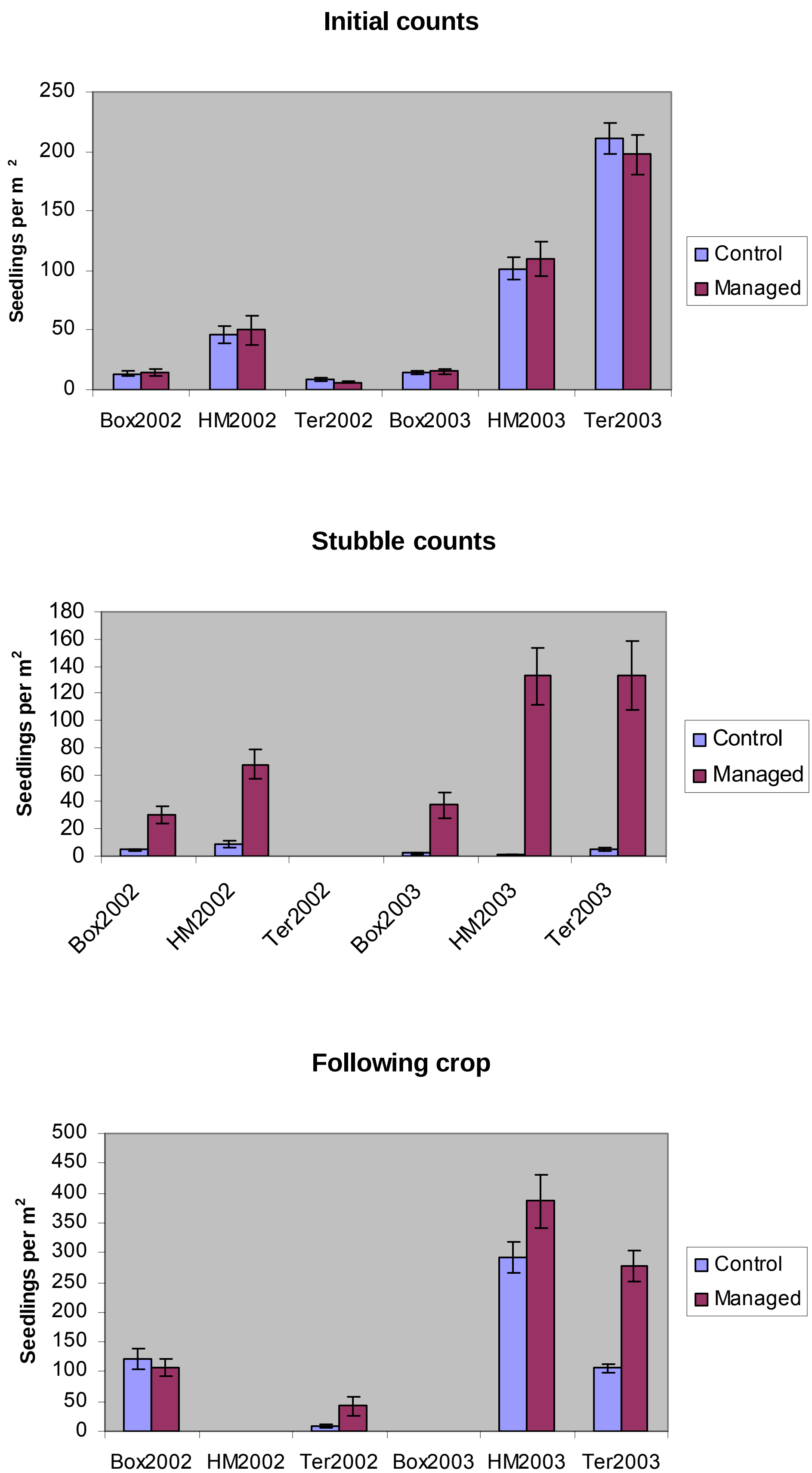

Figure 6.3: Weed abundance through the course of the field trials a) initial seedling number before the imposition of management treatments, b) weed seedling abundance on stubbles after crop harvest and c) weed seedling abundance in the following cropping season.

Discussion

The data generated by following the fate of the field plots from the seed bank assessment through 2 field seasons have validated the model predictions, as the numeric values from all stages of the seed cycle have been recorded. These data also aid us in beginning to understand the impact of maintaining a level of beneficial weed species in one crop and the weed infestation in the following crop. Cultivations and crop choice will play a major role in weed management over a whole rotation, therefore by understanding more about the weed biology, as we are from these data, maintaining beneficial species without reducing crop yield will become a more practical option.

Rather than focusing on any single aspect, the aim of these experiments was to study the complete picture; crop yield, weed abundance and productivity and the longer-term implications of changing management intensity.

7. Future priorities

This work within this commission has contributed greatly to the development of effective models for plant and community dynamics in arable farming systems that are the essential tools needed to balance the needs of 'weed' management with conservation of the arable plant flora as a resource for the wider arable ecosystem. In order to continue to develop sustainable (both from an agronomic/economic and ecological perspective) weed and crop management, we need to build on this body of work and address some key knowledge gaps:

- Proof of concept for functional weed management approaches. Drawing on modelling and functional groups approaches to create crop and weed management that selects against currently intractable weed species while sustaining populations of agronomically tolerable, and potentially ecologically beneficial, ones.
- Quantify the role of plant species and groups of plant species in supporting populations in higher trophic levels and explore extension of the plant functional group concept to include traits that explicitly influence interactions between plant species and other trophic groups.
- Basic plant population biology and competitiveness parameters for a range of weed species growing in crops other than winter wheat, and an expanded range of weed species in winter wheat.
- There is a specific need for better characterisation of processes involved in determining seedling recruitment and transient seed dormancy.
- Quantification of the effect of interaction between phenology of plants and invertebrates and the timing of agronomic practices.
- Define the trait matrix of rare arable weed flora; a logical extension of work defining ecophysiological functional groups of common weed species, is to look at a group of species in decline. Use this approach quantify the drivers that have resulted in the decline of these species over time and propose future weed and crop management strategies to halt this decline.
- Scaling experimental observations to whole fields and farms – including study of the relative contribution of plant communities in cropped and non-cropped areas to the wider arable ecosystem.
- To enable farmers and land managers to reduce herbicide use we need to demonstrate the robustness of the relationships between yield and weed number that we have proved in winter wheat. Development and dissemination of risk management tools to allow more accurate decisions to be made more widely is a vital component of future work. These frameworks could be used for other crops as information is generated. Information needs to be presented in a whole farm and rotational context.

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9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

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