SESSION 8A

IMPROVING WEED CONTROL DECISIONS

Chairman and Session Organiser	Mr J Clarke *ADAS Boxworth, Cambridge, UK*
Papers	8A-1 to 8A-4

Optimising herbicide use – the driving force behind the development of the Danish decision support system

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ABSTRACT

The development of the Danish decision support system (DDSS) was initiated in 1986 following a political decision calling for a 50% reduction in the use of pesticides. Since the introduction of the DDSS in 1991 it has been undergoing continual improvements in particular in respect to herbicide selection and dose optimisation. In the original version the selection of herbicide and dose was made only on input on weed species and growth stages. The present version also incorporates knowledge on the influence of climatic conditions around the time of spraying, the competitiveness of the crop cultivar and most recently a model optimising the composition and doses of herbicide mixtures has been included. In this paper the development of the DDSS since its introduction in 1991 is outlined. Furthermore the implementation and future development of the DDSS is discussed.

INTRODUCTION

In Denmark the public debate on the use of pesticides in agriculture and its possible effects on environment and human health has been going on since the early 1980'ies. The debate initiated a political action plan in 1986 stating that the agricultural use of pesticides had to be reduced by 50% before 1 January 1997 compared to the average use for 1981-85.

As a result of the political action plan it was decided to initiate the development of the computer assisted Danish decision support system (DDSS) for weed control later named 'PC Plant Protection'. The objective was to provide farmers with a decision support system that could minimise herbicide use in all major crops without adversely affecting profit margins. (Rydahl, 1995).

In the mid 1980'ies costs of weed control were marginal and only had little impact on profitability in most crops. The introduction of pesticide taxes (at present a 33.3% value added tax on herbicides) and the proposal within Agenda 2000 to reduce crop prices to world market levels has changed the situation. Today farmers also have to consider the costs of weed control when seeking ways to reduce the total costs. Besides an environmental pressure farmers are now also facing a cost pressure which has increased the demand for optimising herbicide use.

The DDSS works basically as a three-step model. Firstly the need to spray is assessed on the basis of an economic threshold for each weed species. For each crop the weed species have been grouped according to their competitiveness. For example in winter wheat the most competitive weed species like *Galium aparine* and *Alopecurus myosuroides* are considered necessary to control irrespectively of density. Medium competitive weed species, e.g., *Capsella bursa-pastoris* and *Lamium sp.* are only considered necessary to control if the density exceeds 2 plants/ m^2 while weakly competitive weed species like *Veronica persica* only will be considered at densities above 10 plants/m^2.

Secondly the level of control needed for each weed species identified as requiring control is determined. The level of control will depend on weed species and density. For example, the required level of control of *Galium aparine* ranges from 80% at a density of 0-1 plant/m^2 to 95% at densities above 150 plants/m^2. In contrast the level of control of *Capsella bursa-pastoris* ranges from 70% at a density of 2-10 plants/m^2 to 85% if the number of plants exceeds 150 per m^2, while the level of control of *Veronica persica* ranges from 65% at a density of 11-40 plants/m^2 to 75% at densities above 150 plants/m^2.

Lastly appropriate herbicides are selected and the dose required of each herbicide to achieve the intended level of control is calculated and listed according to costs of treatment or treatment frequency index (TFI). The term TFI was invented along with the political action plan as a measure of the intensity of pesticide application. Each pesticide has been assigned a standard dose and the TFI of a treatment is calculated as the applied dose divided by the standard dose. If more than one product is used the TFI of the treatment is the sum of the TFI of the individual products.

The first two steps of the DDSS are primarily based on expert knowledge rather than experimental data and the principles of the underlying models have not been changed significantly during the years. These models have been described in detail elsewhere (Baandrup & Ballegaard, 1989; Rydahl, 1995). In contrast the model used for selecting herbicides and calculating doses, i.e. optimising herbicide use has been undergoing continual improvements since the introduction of the DDSS in 1991. The purpose of this paper is to outline the development of this model with emphasis on the more recent additions and the implementation of DDSS in Denmark now and in the future.

OPTIMISING HERBICIDE DOSE

The original version

The backbone of the DDSS is the numerous herbicide efficacy data primarily originating from the official efficacy testing of new herbicides. In contrast to most other countries an official approval of an herbicide by the Danish Institute of Agricultural Sciences is based on data from experiments testing the herbicides not only at the dose recommended by the chemical companies but also at reduced doses. In competitive crops like cereals and oilseed rape herbicides are tested at four doses (2/1, 1/1, 1/2 and 1/4 of the recommended dose) while in less competitive crops like sugar beet and pea the 1/4 of the recommended dose is excluded.

Previous research has shown that the dose response curves of an herbicide on different weed species or on different growth stages of a weed species often can be assumed to be parallel, i.e. the dose response curves only differ in their horizontal location (Kudsk 1989). Hence, a basic assumption in the DDSS is that differences in the susceptibility of weed species or different growth stages of a weed species to a specific herbicide can be described as a parallel displacement of the dose response curves. Assuming parallel dose response curves means that the ratio of doses giving the same effect on different weed species is constant and independent of the response level considered.

Dose response curves were estimated for each combination of herbicide and weed species by combining the data from the field experiments with a prior knowledge of the slope of the dose response curve. The slope of the dose response curve was determined for each herbicide in semifield (=outdoor pot) experiments. Due to the variation in the field data some data are excluded and in general the estimated dose response curves tend to underestimate the potential of the herbicides.

The DDSS operates with four growth stages of annual weeds (0-2, 3-4, 5-6 and >6 true leaves). Based on semifield research done in the late 1980'ies with different herbicides and weed species at different growth stages estimates were produced describing the parallel displacement of the dose response curves. These values have been termed dose adjustment factors (Kudsk, 1989). Due to a limited number of data a common set of adjustment factors are used for all herbicides and annual weed species with a few exceptions such as *Galium aparine* and fluroxypyr and all wild oat herbicides. The predominant growth stage in the field trials at the time of treatment is used as the default growth stage for each herbicide. On perennial weeds growth stage has no influence on herbicide dose.

A more detailed description of the original model, the applied logistic dose response model and the underlying concept of parallel dose response curves have been given elsewhere (Kudsk, 1989; Baandrup & Ballegaard, 1989; Rydahl, 1995).

Adjusting herbicide doses according to climatic conditions

It is well documented that climatic conditions before, during and after application can influence herbicide performance markedly (Kudsk & Kristensen, 1992). In most studies only one climatic parameter was examined while keeping the others constant. Such studies allow for a ranking of importance of the climatic parameters, however it is difficult to transfer the results into farmer recommendations.

At our department we have advanced climate simulators at our disposal. In the climate simulators we can accurately simulate natural diurnal fluctuations in temperature and humidity. Nine climate scenarios were selected on the basis of a survey of the climatic conditions in Denmark during the two peak periods for herbicide application April-May and August-November (Kudsk & Kristensen, 1992; Mathiassen *et al.*, 1994) (Table 1). The climatic scenarios were based on the assumptions that (1) the diurnal variation in temperature could be described by a sin curve, (2) a constant vapour pressure throughout the day and (3) a relative air humidity of 100 when temperature was at minimum. Assuming constant vapour pressure means that air humidity at any time of the day can be calculated if the daily minimum and maximum temperatures are known, i.e. the only climatic information the farmer has to provide are the daily minimum and maximum temperatures. Large variations in daily temperatures will also result in large variations in relative air humidity.

Table 1. Climate scenarios used in the climate simulators.

Average daily temperature	Variation in daily temperatures		
	Low	Medium	High
5°C	4-6°C	2-8°C	0-10°C
	87-100% r.h.	66-100% r.h.	50-100% r.h.
12.5°C	10.5-14.5°C	8-17°C	5.5-19.5°C
	77-100% r.h.	55-100% r.h.	40-100% r.h.
20°C	16-24°C	14-26°C	12-28°C
	61-100% r.h.	48-100% r.h.	37-100% r.h.

The foliage-applied herbicides available on the Danish market were grouped according to chemical class, mode of action and formulation and one or two herbicides from each group were selected for the experiments. Some herbicides were examined at all nine climates whereas others were only examined at selected climates typically at the lowest and highest temperature regimes. Plants were grown outside in pots and transferred to the climate simulators one day before herbicide application and moved back outdoors five days after application. The reason for moving the plants out of the climate simulators after five days was, that weather conditions can only be reliably forecast five days ahead and hence any influence of climatic conditions beyond the first five days would be difficult to incorporate in a decision support system.

We only examined the influence of temperature and humidity in the post-spraying period although it has been shown that the climatic conditions in the pre-spraying period may also affect herbicide performance (Kudsk & Kristensen, 1992). We focussed on the post-spraying period because most herbicide applications in our country are made at the very early growth stages of weeds shortly after germination at which time the pre-spraying climatic conditions are not likely to have had a major influence on the growth of the weed plants. Secondly, the effects of variations in the pre-spraying climatic conditions are often indirect affecting the growth and physiological status of the plants and these effects can be difficult to simulate in semifield experiments. We did, however, do separate experiments examining the effect of soil moisture stress as this is known to have a profound influence on the effect of many herbicides (Kudsk & Kristensen, 1992).

Analysing the results of the experiments we found that often the dose response curves for an herbicide at different climates were not parallel (Mathiassen *et al.*, 1994). Consequently it was not possible to calculate dose adjustment factors covering the whole response level, as was the case with growth stages of weeds. Instead dose adjustment factors were calculated on the basis of the observed differences of the estimated doses in the 70 to 95% control range. Table 2 shows the range of dose adjustment factors used in the DDSS. Values above 1.0 indicate that the herbicide dose has to be increased and *vice versa*. An average daily temperature of 10-15°C and a daily minimum temperature of 5-10°C were used as the default climate. Adjustment of doses according to climatic conditions around the time of spraying was implemented in the DDSS in 1996.

Dose adjustment factors differ significantly between herbicides. For example the dose adjustment factors for bentazone vary from 0.6 to 1.4, i.e. more than a factor of two whereas the corresponding values for tribenuron are 0.8 to 1.0. No temperature related dose

Table 2. Dose adjustment factors used in the DDSS to adjust doses according to the prevailing climatic conditions.

Average daily temperature	Daily minimum temperature		
	<5°C	5-10°C	>10°C
<5°C	1.0-1.4		
5-10°C	1.0-1.3	0.9-1.2	
10-15°C	1.0-1.2	1.0	0.8-1.0
15-20°C		0.7-1.1	0.7-1.0
>20°C			0.5-1.1

adjustments are made for herbicides that are primarily soil active, e.g. pendimethalin and prosulfocarb.

In the present version of the DDSS users are only asked to provide information on temperatures on the day of application because this information is easily accessible. It is likely that the DDSS in the future will be available via the Internet and it would then be easy to link a five-day weather forecast to the system. Detailed studies on a few selected herbicides have shown that the first two to three days after application are more important to herbicide performance than the following days. Temperature does normally not change dramatically within a few days and it seems reasonable to assume that temperature on the day of application normally is a good indication of the temperature on the following day.

Soil moisture stress generally has a more pronounced influence on herbicide performance than temperature and the dose adjustment factors used in the DDSS vary from 1.0 to 6.0. Often moisture stress will result in dose recommendations exceeding the maximum registered dose. Soil moisture stress is only considered as an input parameter for weed plants with more than four leaves.

In general our studies have revealed less pronounced effects of climate on herbicide performance than previous studies and with most herbicides temperature and humidity generally have less influence on dose than the growth stage of the weeds. There appear to be several explanations for this. In our studies we compared herbicide performance at natural climates and maximum differences in temperature and humidity only prevail for a few hours. In most other studies temperature and humidity has been kept constant. Secondly using natural climates means that any increase in temperature, which may enhance herbicide activity, will be associated with a corresponding decrease in relative humidity that often will have an adverse effect on herbicide performance. Finally we only kept the plants at the various climates for five days whereas in previous studies plants were often kept at the various climates from spraying to harvest.

Adjusting herbicide dose according to crop cultivar

It is well documented that crop cultivars differ in their ability to suppress weeds and that herbicide doses can be reduced most in competitive cultivars (Christensen, 1994; Brain *et al.*, 1999). The effect of crop competition on herbicide performance cannot be described as a displacement of the dose response curve because the crop does not influence herbicide activity *per se* but reduces weed biomass. Hence in a competitive cultivar a lower dose is required to reduce weed biomass to a given level.

Christensen (1992) found that of the growth parameters routinely registered in the statutory variety testing of winter wheat and winter and spring barley straw length was most closely correlated to competitive ability. Since 1996 herbicide dose has been adjusted according to crop cultivar in winter wheat and winter and spring barley. In general, dose adjustments as a result of differences in competitiveness are small typically +/- 10% (Rydahl, pers. comm.).

Optimising herbicide mixtures

Most herbicides are very effective on a limited number of weed species that can be controlled with doses well below the recommended doses whereas on other weed species effective control can only be achieved with higher doses. Farmers are generally well aware of this and the use of herbicide mixtures to optimise weed control and minimise costs has become more the rule than the exception. In the original version of the DDSS only a few herbicide mixtures approved by the Danish Institute of Agricultural Sciences were included and they were handled as single herbicides, i.e. if reduced doses were recommended the doses of each herbicide was reduced equally. From an optimum point of view doses of each of the herbicides should be adjusted according to the weed flora in the field and both farmers and advisors have been asking for such a facility.

The latest addition to the DDSS is a module optimising the composition and doses of herbicide mixtures. The principles applied to optimise herbicide mixtures are those of the Additive Dose Model (ADM). ADM assumes additivity of doses and according to ADM one herbicide can be replaced, wholly or in part, by another herbicide at equivalent doses (Green & Streibig, 1993). If an herbicide mixture follows ADM and the required doses to produce a given effect of two herbicides applied alone are known, then it is easy to design mixtures of the two herbicides producing a similar effect.

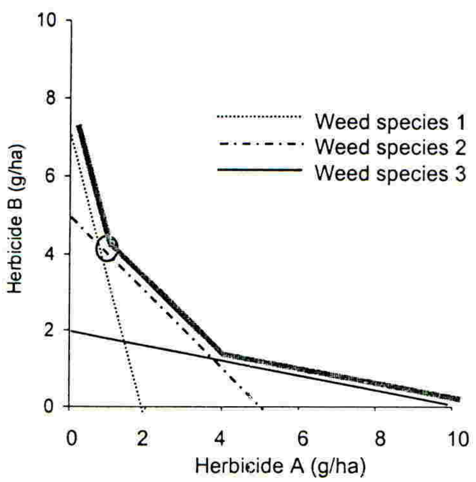

Figure 1. Graphical illustration of ADM for two herbicides and three weed species.

The principles of ADM can most simply be illustrated graphically (Figure 1). Any mixture along the isobole connecting the two points on the axes indicating the doses required of the two herbicides to obtain a given effect, e.g. 90% when applied alone will produce the same effect. For each herbicide mixture an isobole exists for each weed species as illustrated in Figure 1 for three weed species. Any mixture along the outer isobole, illustrated by the bold line in Figure 1, will produce at least 90% on all three weed species. The fact that the outer isobole is not a straight line means that there will be a point where the total use of herbicides expressed as g a.i./ha is at a minimum. The minimum of the outer isobole will be at one of the interceptions between the isoboles or the isoboles and the axes. The minimum can be found easily and in the example shown in Figure 1 the mixture resulting in the lowest possible use of active ingredient has been indicated with a circle.

From a farmers point of view it will be of more interest to minimise the costs of treatment or the TFI rather than the total use of active ingredient. This can be done easily by replacing the doses in g/ha with the costs expressed as DKK/ha or the TFI. In Figure 2 it can be seen that to minimise the costs of treatment another mixture to the one minimising the total use of active ingredient should be used whereas if TFI is the parameter to minimise the same mixture should be used. In this example costs of treatment were minimised by using a mixture consisting of 4.8 g Herbicide A/ha and 1.1 g Herbicide B/ha at a cost of ca. 32 DKK/ha. If TFI was to be minimised the mixture should consist of 0.8 g Herbicide A/ha and 4.2 g Herbicide B/ha at a cost of ca. 54 DKK/ha. The TFI of the two mixtures were 0.59 and 0.50. Using the principles of ADM makes it possible fully to exploit the strong points of the individual herbicides be it high activity on specific weeds or a low price.

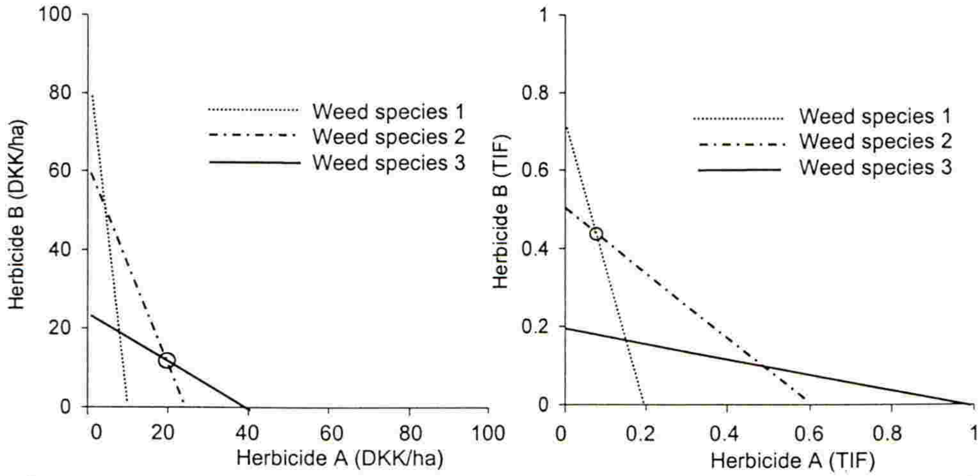

Figure 2. Graphical illustration of the same data as in Figure 1 but instead of g/ha the units on the axes are the Treatment Frequency Index (TIF) and DKK/ha. The calculations are based on a recommended dose of 10 g/ha (TFI=1) for both herbicides and a cost of 4 and 12 DKK/g of herbicide A and B, respectively.

The DDSS contains information on the dose response curve of any combination of herbicide and weed species and the dose required to produce a given effect can be calculated, i.e. the isoboles for any herbicide mixture can easily be established. If the herbicide mixtures follow

ADM it would be relatively simple to implement a facility which could optimise herbicide mixtures. In the recent years we have conducted numerous experiments to test the hypothesis that herbicide mixtures follow ADM. Our results have revealed that most herbicide mixtures either follow ADM or perform better than predicted by ADM (synergism) and with the exception of mixtures of the 'fop's' and 'dim's' and some broadleaf herbicides we have found very few examples of herbicide mixtures performing poorer than predicted by ADM (antagonism) (Kudsk & Mathiassen, 1995; Kudsk & Mathiassen, 1997).

Synergistic herbicide mixtures will produce a higher effect than predicted and hence they do not present a problem in relation to optimisation of herbicide mixtures. In contrast antagonistic herbicide mixtures will not produce the predicted effect and consequently these mixtures have been discarded. A model has been developed which can describe the divergence from ADM (Streibig *et al.*, 1998) and by implementing this model in the DDSS it would be possible to fully exploit the benefits of synergistic mixtures and further reduce the doses. Implementation of the model would however require a substantial input of data from semifield experiments which are currently not available.

In the literature ADM has primarily been used in studies with mixtures of herbicides with similar mode of action (Green & Streibig, 1993). Applying ADM on herbicide mixtures with dissimilar modes of action, which is most often the case with herbicide mixtures, will not produce straight line isoboles but simulation studies have demonstrated that deviations from a straight line are so small they can hardly be detected in a statistical analysis (Streibig, 1992).

The implementation of ADM in the DDSS and the results of the validation trials are presented elsewhere (Rydahl, 1999).

IMPLEMENTATION IN DANISH AGRICULTURE

The idea behind the development of the DDSS was to produce an on-farm decision support system and the full benefit of the system is only obtained if used on the farm by the farmer. In general farmers are recommended to use a two-step approach. The first step is to supply the information on weed flora and the expected growth stage at the time of treatment. The output will tell the farmer which herbicides he should have available at the time of spraying. The second step is to include information on the climatic conditions and the farmer will then get information on the dose to apply. The second step should be done immediately before spraying and that is why the DDSS should be used on the farm.

The DDSS is marketed by the Danish Agricultural Advisory Centre through the local advisors and has been sold to ca. 1,800 farmers. The fact that only ca. 2,000 out of ca. 50,000 farmers have purchased the DDSS was also reflected in a recent survey which revealed that although the use of reduced doses is very common only 15% of the farmers used the DDSS frequently and 64% of the farmers have never or only rarely used the system (Svendsen *et al.*, 1997). There are probably a number of reasons for the lack of use of the DDSS. Many farmers do not have access to a computer and often no motivation to use computers since the average age of Danish farmers is 52. Another reason may be that advisors have not recommended the system to farmers.

The development of the DDSS was initiated by the political debate on the use of pesticides in agriculture and the numerous validation trials carried out by the Danish Agricultural Advisory Centre have demonstrated reductions in herbicide doses of on average 50% compared to the recommended doses (Rydahl, 1995). The addition of the herbicide mixture module will result in further dose reductions (Rydahl, 1999). In the light of the political pressure to reduce pesticide use as well as the increasing need for farmers to reduce costs it is disappointing that so few farmers have acquired the DDSS. It is however important to remember that many farmers indirectly base their decisions of herbicide use on recommendations from the DDSS. Advisors will often consult the DDSS writing newsletters to the farmers and it is beyond question that the development of the DDSS has promoted the use of reduced herbicide doses.

The adjustment of the level of control according to the competitiveness of the weed species and the generally lower level of control than recommended by the herbicide producers are the main reasons for the success of the DDSS in reducing herbicide doses. The adjustment of the doses according to the prevailing conditions further adds to the potential of the DDSS. A survey of the validation trials revealed the following ranking of the parameters as to their influence on herbicide dose: growth stage>ADM>climate (except soil moisture stress)>crop cultivar (Rydahl, pers. comm.).

THE FUTURE DEVELOPMENT OF THE DDSS

Decision support systems will be playing an ever more important role in agriculture in the future not only in relation to pesticide use. In a recent report from the Bichel-Committee which have assessed the overall consequences of phasing out pesticides it was concluded that decision support systems are an important tool when it comes to implementing new research data and complying with the demand for a reduction in pesticide use (Anon, 1999).

Up to now focus has been on optimising the decision on herbicide dose. In the mid 1980'ies when the development of the DDSS was initiated nearly all fields were treated with herbicides and the attitude of farmers was that is was too risky not to apply herbicides. However since the mid 1970'ies a number of field trials had demonstrated that herbicide doses could be reduced substantially without yield loss (Kudsk, 1989). It was therefore much more likely that farmers would adopt an approach where reductions in herbicide use was achieved by reducing the doses rather than omitting herbicide application in fields with a low weed infestation. That is why the herbicide dose optimisation strategy has been driving force behind the development of the DDSS. Today the situation is more or less the same. Most fields are sprayed with herbicides and in conventional farming non-chemical weed control is only used when no herbicides are available (some minor crops) or as supplement to chemical weed control mainly to control survivors (e.g. sugar beet).

In the future Danish farmers are likely to face political demands for reductions in pesticide use that cannot simply be obtained by optimising the dose. Herbicides account for the major input of pesticides. Non-chemical weed control in row crops, in combination with band spraying of herbicides, has to be adopted by farmers to comply with the public demand for a significant reduction in herbicide use. Also it will become important to be able to identify fields where weed control is not cost effective. Precision weed control as an integrated part of precision farming is another important future development. Hence one could say that we are leaving the era of herbicide dose optimisation and entering the era of optimisation of weed control strategies. This will also be reflected in the future developments of the DDSS where more focus will be devoted to improving the decision making on the need for weed control.

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A biological framework for developing a weed management support system for weed control in winter wheat: Weed seed biology

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ABSTRACT

In order to predict the consequences of failure to control weeds in any single season, it is proposed that a knowledge of the population dynamics of the species concerned is essential. For annual species this may be represented by a seed cycle. The various processes within this cycle, viz. seed production, seed rain, seedbank and seedling recruitment, are subject to potential loss which ultimately will affect seed survival and population size. Available information on weed seed biology of selected grass and broad-leaved species is reviewed and notable gaps identified. It is concluded that whilst a wealth of literature is available, a number of areas require further investigation. In particular, with regard to reproductive output further information on the effects of inter and intra-specific competition, sub-lethal herbicide doses, nitrogen rates and genetic variation is required for individual species. So too, with regard to seedbank dynamics, information is notably lacking on post-dispersal predation, post-incorporation mortality, half-lives and seedling mortality post-emergence.

INTRODUCTION

Although the size of a seed population is ultimately dependent on seed supply, subsequent fate of that population will be influenced by post-dispersal predation and mortality, rate of incorporation into the soil seedbank, rate of seedling recruitment, mortality of seed within the seedbank and post-germination mortality. It is perceived that information is particularly lacking with regard to pre-dispersal losses, seedling mortality and the effects of agricultural practices on seed population dynamics. Such information is essential to optimise the use of herbicides and cultural methods of weed control within a weed management support system.

FACTORS TO BE INCLUDED

Flowering and seed rain

Few actual investigations of seed rain are published with an exception afforded by Leguizamón & Roberts (1982) which illustrates the short life cycle and early senescence of *Lamium* spp. compared with *Chenopodium album* and *Polygonum aviculare*, albeit the latter two species are less likely to occur in winter cereals. Species that senesce early in the crop, although likely to be less competitive, may become incorporated in the soil seedbank by natural agencies, but equally may suffer post-dispersal predation.

Moss (1983) investigated the periodicity of seed production by *Alopecurus myosuroides* for a number of locations over three years and observed that although in most situations 95% of seed had been shed by harvest, in some instances seedrain continued from late June until early September. Seed viability varied considerably throughout and ranged from 43-76%.

Pre- and post-dispersal losses

The combine harvester may have implications for re-distribution of seed within the field and hence patch dynamics. Movement of *Bromus sterilis* seed within the combine harvester resulted in seed being deposited at a modal distance three metres behind the combine, although some seed was discharged up to 20 metres forward of the point of intake (Howard *et al.*, 1991). Secondary movement following dispersal may result from the use of tillage equipment such that spring-tine or flexi-tine implements may move seeds greater distance than either straight tine or power harrow implements (Rew & Cussans, 1997). Likewise surface sown seeds were moved further than buried seeds and smaller seeds more than larger ones. Type of cultivation will influence not only horizontal movement, but also vertical distribution in the soil profile. The depth to which seeds are incorporated will affect the possibility of successful seedling emergence. The implications of burial depth on subsequent seedling emergence have been modelled by Grundy *et al.* (1996).

Considerable losses of seeds from the soil surface may occur post-harvest especially if drilling is delayed, such that losses in excess of 75% have been reported for *Avena fatua* (Wilson, 1972). As with *A.fatua* considerable numbers of *A.myosuroides* may suffer post-harvest mortality with as few as 30% of seed surviving on the soil surface until autumn (Moss, 1980). Likewise post-harvest losses of *B.sterilis* may exceed 40% (Froud-Williams, 1983). Possible causes of such losses have been conjectured as post-germination mortality, but the role of predation by invertebrates, rodents and birds may not be inconsiderable.

Seed production per plant

The reproductive capacity of weeds is indicative of their ability to contribute to the total weed population within an area and differs greatly between species, often differing by several orders of magnitude. It is of note that several endangered species have rather limited seed reproductive capacity whereas some of the more ubiquitous species are characterised by high fecundity e.g. *Matricaria* spp. *Papaver rhoeas, Capsella bursa-pastoris* and *C.album*, although some are notably depauperate e.g. *Veronica* spp. and *Myosotis arvensis*.

Estimates of seed production have often been conducted for isolated plants, free of inter- or intra-specific competition and hence such information should be treated with caution. Nonetheless, Wilson *et al.* (1988) investigated the role of crop competition on reproductive output of *Lamium purpureum, Viola arvensis* and *P.rhoeas* and demonstrated that the presence of winter wheat (206 plants m^{-2}) could reduce seed production by 96-99%. Similarly, Burghardt & Froud-Williams (1995) demonstrated that seed production by *B.sterilis* was appreciably reduced by both inter- and intra-specific competition, such that in the absence of a crop seed production was >400 per plant and in the presence of winter wheat <300 per plant. Furthermore, reproductive output differed considerably with source of provenance, such that for thirteen accessions of *B.sterilis* numbers of seeds per plant ranged from 1762-5303 with 60-179 seeds per panicle and a thousand seedweight of 3.08-14.87g (Burghardt & Froud-Williams, 1997). So too Christal *et al.* (1997) report a range of seed weights for *Stellaria media* ranging from 0.38-0.82mg based on progeny derived from twenty five populations grown in a spaced-plant trial. Likewise, the type of crop grown will also affect reproductive capacity (Chancellor & Peters, 1970) as will crop density and the amount of nitrogen applied (Wright 1993).

Periodicity of germination

The success of agrestal weeds is attributed partly to their persistence in the soil seedbank, itself a function of dormancy and potentially long life span. Thus in examining the fate of seed populations, two questions are particularly pertinent: when do they germinate and how long can they persist? Information on periodicty of germination is widely available for broad-leaved species from the detailed investigations conducted by H.A.Roberts and co-workers. So too, information is generally available for periodicity of grass-weeds. Species may show one of four patterns of seedling emergence viz. germination predominantly in autumn, germination in autumn and spring, germination restricted to spring or indifferent to season. Many of the broad-leaved species show a bimodal periodicity of germination in autumn and spring, with spring emergence confined to *P.aviculare* and *C.album*. The grass-weeds generally show pronounced autumn peaks of emergence as do the broad-leaved species *Galium aparine* and *Veronica hederifolia*. A knowledge of periodicity of emergence is of value in the timing of applications of herbicides (foliar and residual) and also for mechanical weed control.

Longevity

The comprehensive studies of Roberts and co-workers have shown seed decline of both population and individual species to be exponential. However, the rate of decline was influenced by the depth of burial, type and frequency of cultivation. For example, Roberts & Feast (1973) incorporated seeds of twenty species to a depth of 15cm. In the absence of cultivation the annual rate of decline of the entire population was 12% with a range of 6-21% for individual species. In contrast where soil was cultivated the annual rate of decline was 32% with a range of 20-26% for *Fumaria officinalis* and *P.rhoeas* and of 44-48% for *Veronica* spp. Using a natural population, Chancellor (1986) demonstrated that the rate of decline of various arable weed seeds beneath a long-term grass sward ranged from <1% per annum for *Fumaria officinalis* to >30% for *Chrysanthemum segetum* with corresponding half-lives of 1.5 & >20 years respectively. Unfortunately, information on the annual rate of decline of many agrestal species is not available from the published literature, but Wilson & Lawson (1992) indicate annual rates of decline for *V.hederifolia* (57%), *G. aparine* (66%), *P. rhoeas* (35%) and *Viola arvensis (*36%). Annual rates of decline for the grass-weeds *A. fatua, A. myosuroides* and *B. sterilis* appear somewhat greater with shorter longevity than that of broad-leaved species.

Despite the apparent size of the seedbank, comparatively few seeds contribute to annual seedling recruitment, often of the order of 2-6%. However, rates of decline greatly exceed losses that can be accounted for by successful seedling emergence, rendering calculation of half-lives impossible. This discrepancy between successful seedling emergence and seeds unaccounted for has been attributed to post-germination mortality.

Effects of agricultural practice

Effects of agricultural practices, in particular tillage, on individual weed species have been largely restricted to the annual grass-weeds *A.fatua* (Wilson 1981, 1985) *A.myosuroides* (Moss

1985) *B. sterilis* (Froud-Williams, 1983) and the broad-leaved species *G.aparine* (Wilson & Froud-Williams 1988, Wilson & Wright 1991). Comparatively less information is available concerning the effects of nitrogen and sub-lethal applications of herbicides on weed seed biology. Effects of nitrogen on the population dynamics of *B.sterilis, G.aparine* and *P.rhoeas* have been reported by Lintell Smith *et al.* (1991), McCloskey *et al.* (1998) and on *V.arvensis* by Grundy *et al.* (1995). The effect of sub-lethal herbicide applications on seed biology of *V.arvensis* has been investigated by Grundy *et al.* (1995) and of *Veronica persica* by Champion *et al.* (1998). A number of studies of reduced herbicide rate effects on seed production have been conducted in Scandinavia (Andersson 1996) but often for species not included in this review. However, use of sub-lethal rates of herbicides for *A. fatua* control resulted in reduced seed dormancy and viability of *A.fatua* compared to recommended rates (Peters 1990).

Attempts to ascribe specific attributes to individual weed species are potentially flawed in that species differ in phenotypic plasticity and genetic expression, such that phenological development, reproductive allocation, dormancy and persistence will be influenced by source of provenance and agronomic selection pressures. To date few studies of genetic variation amongst weed species are available (Peters 1986, 1991, Froud-Williams & Ferris-Kaan 1991, Burghardt & Froud-Williams 1997, Christal *et al.* 1997) but are clearly evident from the intra-specific variation in response to herbicides and occurrence of herbicide resistance.

CONCLUSIONS

Selection of species for consideration in a weed management support system needs to be based on three factors, economic importance, difficulty of control and frequency of occurrence. Hence species may be ranked in terms of relative importance for which there is a priority in terms of information required and also of endangered species for which information is required for conservation purposes. Detailed information on the autecology of nine selected species, viz. *A.myosuroides, Lolium multiflorum, Poa annua, S. media, Matricaria perforata, P.rhoeas, Sinapis arvensis, C.album and C.bursa-pastoris* is available within the 'Biological Flora of the British Isles' published in the *Journal of Ecology*. Notable exclusions are *Lamium* spp., *Veronica* spp., *Myosotis arvensis* and *Polygonum aviculare*.

For the most economically important species, *A.fatua, A.myosuroides, B.sterilis,* and *G.aparine,* detailed information on the population dynamics and seed cycle life histories are well documented. Equally for the majority of species identified in this review information concerning seed production, dormancy, longevity and periodicity of germination is also published. However, seed production is often based on estimates for isolated plants in non-arable environments. Information on reproductive output subject to inter-specific competition is less widely available. Losses of seed following seed rain pre-incorporation are also virtually unquantified except for the major grass-weeds and *G.aparine*. Reasons for such mortality are largely the subject of conjecture.

Studies of seed persistence are generally available but are often atypical in that they involve even-age populations, frequent or no-soil disturbance and calculation of half-life often not possible. By contrast periodicity of germination is well documented, but post-incorporation losses are poorly understood, including the causes of post-germination mortality. Hence there is a necessity for further research to investigate the processes regulating seedbank dynamics. In particular, priority should be given to post-dispersal losses including seedling mortality and half-life. As regards reproductive output the effects of sub-lethal herbicide applications and nitrogen rate require quantification as does the extent of genetic variation.

Nonetheless, sufficient data appears to exist to examine the impact of weed control strategies that do not achieve total control, or which have been deliberately omitted because control is not economically justifiable.

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A biological framework for developing a weed management support system for weed control in winter wheat: Weed competition and time of weed control

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ABSTRACT

There is a need to target weed control practices more precisely, both for economic and environmental reasons. The development of a Weed Management Support System for winter wheat provides a tool for the effective transfer of optimum advice on herbicides and weed control to farmers and their advisors. The proposed system defines the need for weed control and then selects the treatments to meet that need. In order to define the need for control, potential effects of the weeds on wheat yield and profitability have to be integrated with population dynamics data on the longer-term consequences of leaving weeds untreated. This paper concentrates on the competitive effects of weeds and on the effects of herbicide timing, using data for *Stellaria media* and *Alopecurus myosuroides* as examples. It describes key elements of a predictive approach to weed management, including; how to predict yield losses, how to incorporate risk into these estimates, reasons for allocating weeds to a limited number of competition classes and the effects of timing of control on yield loss.

INTRODUCTION

Herbicides are a major input into crop production in UK agriculture and there is real scope to minimise herbicide use and hence reduce costs by improving weed control decisions. There are two main reasons why there is a need to target weed control practices more precisely. Firstly, the profitability of arable crop production has declined dramatically in recent years and so there is a need to question all input costs, including herbicide use. Secondly, there is increasing national concern about the impact of agriculture on the environment and on biodiversity in particular. It is impossible for any one person to retain information on all aspects of weed control and a good, computer-based, weed management support system for winter wheat would provide a mechanism for the dissemination of the best advice for this, the major arable crop in the UK, to **all** farmers. Such a system would incorporate data on herbicide performance, weed biology and crop agronomy. The latter is particularly relevant to weeds, as many crop management decisions have an impact on them. In our view there are two main elements to a Weed Management Support System (WMSS); defining the need for control of the weed and, secondly meeting that need. Key pieces of information that must be included to assess the need for control are:

- predicted yield loss from the weed infestation present,
- numbers of seeds produced by untreated/surviving weeds and their longevity in soil,

- impact of time of weed control on herbicide performance and crop yield,
- effect of crop agronomy on weed infestation levels.

Having defined the need for control the WMSS will select herbicide products or other methods of weed control in winter wheat that are appropriate to control the species concerned, indicating herbicide doses and anticipated costs for alternative treatments. The user will be presented, where possible, with a series of options to be considered. This paper discusses information required for the biological elements of a WMSS to define the need for control. Seed biology aspects are being reviewed by Froud-Williams (1999) and this paper concentrates on the competitive effects of weeds and on timing of control, using *Stellaria media* (common chickweed) and *Alopecurus myosuroides* (black-grass) as examples.

IMPACT OF CULTURAL FACTORS

Cultural factors have an effect on the species and level of weeds and this in turn can affect the need for weed control. For example, it is well documented that minimum cultivations favour grass weeds and delayed drilling reduces levels of *A. myosuroides* in winter wheat. Verifiable data like this is of great value when using the WMSS in a strategic way to explore the advantages/disadvantages of specific cropping and cultural practices. Four cultural factors have been suggested for incorporation in a weed management system:

1. rotation,
2. cultivation type (plough v minimum tillage),
3. drilling date,
4. stubble management,

All these factors interact, influencing the number of weed seedlings present, their species and their dates of emergence which, in turn, impact on weed control decisions.

POPULATION DYNAMICS

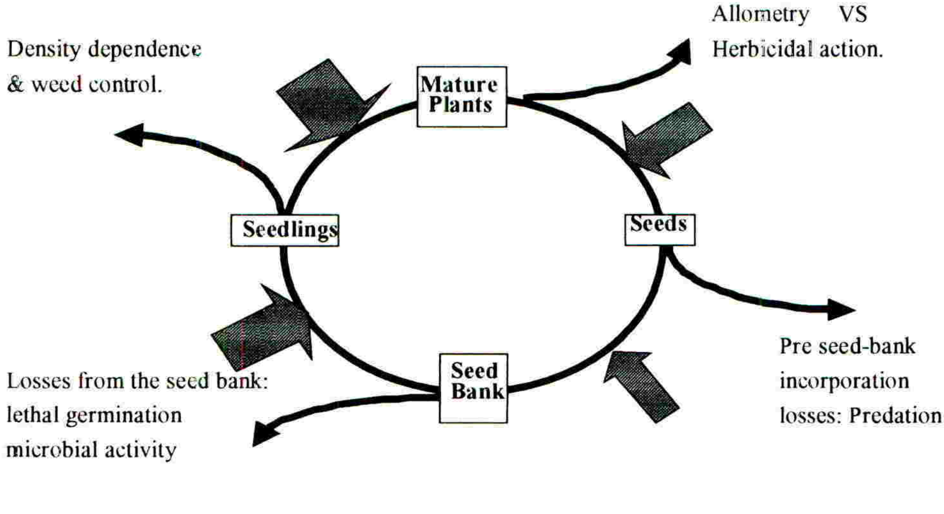

Figure 1. Diagram of a simple life cycle of an annual weed

There are a number of factors controlling the population dynamics of weeds. The key ones are identified in Fig. 1. Data, for example, on seed production by weeds, the fate of seeds in the soil and the % germination of buried seeds, can be used to gain some understanding of the possible longer-term consequences of particular weed control strategies. Current research projects and past literature will be used to create a data base of this information for key weed species. Froud-Williams (1999) in this session of the conference concentrates on seed biology and so this topic will not be discussed in detail here. However, the competitive effect of weeds on the crop, which forms the core of our paper, also impacts on the production of seeds by the weed. The more competitive the weed is, the more successful it will be and the greater will be its seed production and impact on the following crops.

WEED COMPETITION

An assessment of the potential yield loss that will occur if weeds are not controlled is essential for a WMSS that optimises the use of herbicides (or any other weed control technique). Such an assessment of the competitive effects of weeds also needs to consider other negative effects that the weeds may have, such as reduced grain quality and harvesting difficulties.

At its simplest, such an approach defines the competitive ability of different weed species and the farmer/advisor reaches a conclusion on weed control strategy based on the species present in the field and their relative abundance (on a very coarse basis: many, few, none). The work of Wilson & Wright (1990) in winter wheat forms a sound basis for producing a ranking of the competitive ability of different weed species and subsequent work in the UK (Ingle *et al.*, 1997) confirms the ranking of different species. This simple approach is already being used, if only subconsciously, by advisors but only to make choices between products and doses rather than asking the fundamental question 'does this level of infestation merit treatment?'

In practice it is our belief that it will not be possible to provide precise rankings for all weed species, but we will need to rank weeds in functional groups, so that a framework is created with a limited number of classes of weeds. These groups are selected because of their competitive threat to winter wheat. We propose to divide weeds into three groups (see below), but it may be necessary to sub-divide the third category into more and less-damaging species.

1. Critical: These are species for which good control is essential. Crop management and rotations may need to be changed to minimise problems associated with these species. Predictions of crop-weed competition to assess the need for control are unrealistic because they are so competitive and leave no room for mistakes.
2. Priority: This group of species represents the majority. If present in significant numbers high yield losses can result. However, they do not represent the same threat as the 'critical' species and, using relevant management, control can be optimised by prediction of crop-weed competition (provided sufficient safety-margins are observed).
3. Largely acceptable: These are the species where there is most potential for targeted weed management. They represent the lowest risk to crop yield, and because of their growth

habit (generally below crop canopy height) there is the most potential to use crop competition to enhance control measures or reduce herbicide doses.

This approach has the advantage that less common weeds, for which little information on competitive impact is likely to be available, can be grouped with similar but more common species. Allocations of common weeds to the three categories are presented in Table 1.

Table 1. Weed competition: proposed functional groups of weed species in winter wheat

Competition Group	Species
Critical:	Wild-oats (*Avena fatua, A. sterilis ssp. ludoviciana*)
	Cleavers (*Galium aparine*)
	Bromes (*Bromus sterilis, B. commutatus, B. hordeaceus*)
	Black-grass (*Alopecurus myosuroides*)
Priority:	Mayweeds (*Matricaria* spp.)
	Poppy (*Papaver rhoeas*)
	Volunteer oilseed rape (*Brassica napus*)
	Fat hen (*Chenopodium album*)
	Volunteer Italian rye-grass (*Lolium multiflorum*)
	Volunteer beans (*Vicia faba*)
	Meadow-grasses (*Poa annua*)
Largely Acceptable:	Chickweed (*Stellaria media*)
	Speedwells (*Veronica persica, V. hederifolia*)
	Red dead nettle (*Lamium purpureum*)
	Forget-me-not (*Myosotis arvensis*)
	Pansy (*Voila arvensis*)

Assessment of the consequences of not controlling the weeds is the core of threshold-based approaches to weed management, as discussed by Cussans *et al.,* (1986). A theoretical framework for estimating threshold weed levels was established at that time and some research has continued since. Threshold-based systems have been developed in several countries including Germany (Werner & Heitefuss, 1996) and Italy (Berti & Zanin, 1997).

The main problem with application of information from competition studies, especially in winter wheat is that, where large projects have looked at competition over several sites or years, it becomes clear that there is significant variability in the competitiveness observed (parameter instability) (Cussans & Courtney, 1994; Cussans *et al.*, 1996). Figure 2 demonstrates the variability in yield responses between 16 of our experiments investigating the yield effects of *A.myosuroides* in winter wheat. Some of the causes of this variability are explicable on the basis of simple observations (*e.g.* soil type, time of weed emergence), but some of the variability is due to processes that are not described by the simple models (*e.g.* soil moisture dynamics). This observation makes the inclusion of a description of risk important in future work on weed-crop competition so that predictions are applicable between sites and years.

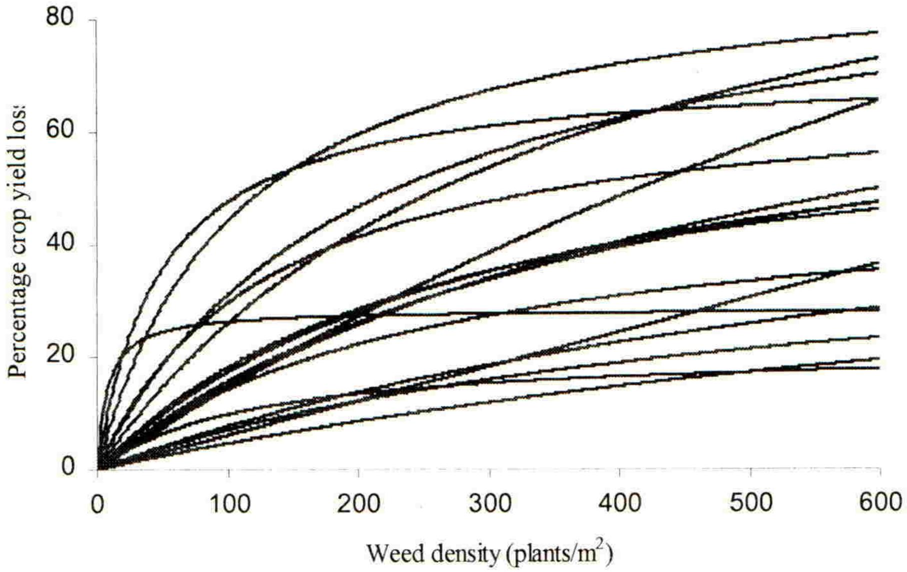

Figure 2. Variation in the yield loss from *A. myosuroides* in winter wheat at 16 sites over 3 years (1995-97)

A further problem to be resolved is how to assess weed levels so as to estimate future crop responses. This can be approached in various ways. At its simplest weeds can be categorised into high, medium and low infestation levels from superficial but rapid field walking. This could be refined more closely with more detailed assessments of critical areas of the field. It must be remembered that for the 'critical' and 'priority' species a simple presence/absence might be all that is required since they are so competitive. It is only low levels of weeds that will need more detailed assessment. Visual estimates of cover may provide a suitable technique and work is in progress to resolve this issue.

TIME OF WEED CONTROL

The second element of defining the need for control is an assessment of the consequences of different timings of treatment. There is often a dilemma between early and late treatment and the advantages and disadvantages of each vary with species. A WMSS has a strategic role in planning strategies prior to drilling, but such an approach will depend on historic perceptions of the weed problems in particular fields from previous years. The maximum benefit can come from the selection of post-emergence applications after making an assessment of weeds present. This requirement does highlight the benefits of the weed mapping proposed for spatially selective weed control (Lutman & Perry, 1999).

This section of the paper considers the impact of delayed weed control on yield responses of winter wheat. One of the key psychological requirements of a weed control management system that says on occasions 'do nothing', is the availability of treatments later in the year to recover a situation where weeds become more competitive than is acceptable to the user. Work on timing of control provides important information on this aspect of management.

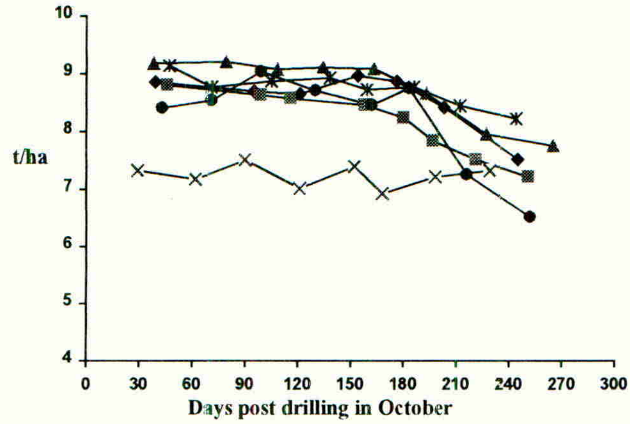

Figure 3. The effect of the time of control of chickweed (days post drilling) on winter wheat yield (t/ha) at Boxworth (B) and Drayton (D) in 1994-1996. The population density of chickweed plants/m^2 (pl/m2) and the SEM is given for each site.

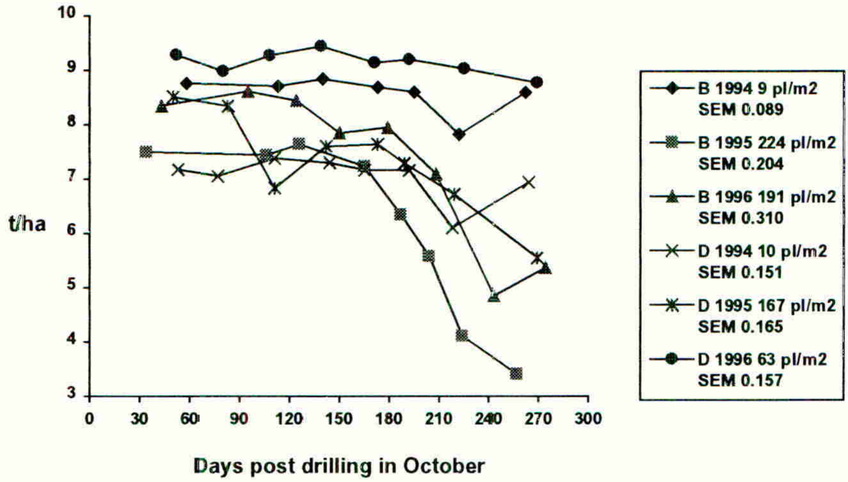

Figure 4. The effect of the time of control of black-grass (days post drilling) on winter wheat yield (t/ha) at Boxworth (B) and Drayton (D) in 1994-1996. The population density of black-grass plants/m^2 (pl/m2) and SEM is given for each site.

The classic design for a time of removal experiment was presented 30 years ago by Nieto *et al.* (1968). They identified the period of time over which maize and bean crops must remain weed free in order to preserve yield. There has been more recent work using this experimental approach, but this has been mainly in vegetable crops (*e.g.* Weaver, 1984; Bond & Burston, 1996). More recently, field trials with *S. media* and *A. myosuroides* have been set up in winter wheat to explore the consequences of delayed weed control. Treatments were targeted at four-week intervals over the growing season.

S. media was less competitive than *A. myosuroides* in these experiments, and for both species there was an effect of weed density. Sites with higher densities required earlier treatment and resulted in greater yield reductions (Figs. 3 & 4). In these experiments it was possible to leave spraying of both species until 150-180 days post drilling (mid-late March) without major yield losses. Consequently, in some situations decisions on the control of these species could be deferred or reconsidered in the spring. However, other aspects must also be considered when deciding on herbicide treatment such as: are there any environmental benefits from particular herbicide timings and, if weed control is left until the early spring, are there effective herbicides to control the weeds?

CONCLUSIONS

It is possible to explore the relationships between crop and weed competition, herbicide efficacy and timing of control, on crop yield (and weed seed production) (Brain *et al.*, 1999). Such work is based on the fusion of simple competition models (Kropff & Spitters, 1991) and herbicide dose response curves (Rydahl, 1995). It would be fair to say that currently these models are poorly parameterised for most weed species in winter wheat, and caution about variability in parameter values from site-to-site, and year-to-year needs to be exercised, as with yield loss relationships (Fig. 2) (Cussans *et al.*, 1996). So far these models, almost universally, have failed to take account of this variability or 'risk'. One approach to developing predictive methods is to incorporate our knowledge of the timing and extent of weed competitiveness into simple dynamic models (as opposed to static models) of weed-crop competition to predict the effect of timing of control. One such study is being undertaken by IACR-Rothamsted using growth and competition data gathered about weed and crop growth over a three-year trial programme.

As we enter the next millennium weed control practices will have to become more precisely targeted both for economic and environmental reasons. A good Weed Management Support System will provide a tool for the effective transfer of optimum advice on herbicides and weed control that includes an assessment of the need for control. It has the potential to offer alternative options to the user, taking into consideration changes in crop agronomy and longer term implications (via the seedbank). A considerable body of information on the competitive effects of weeds and on their population biology already exists for many key species and we can quantify the levels of variability in the data and their causes. Further development of methods of weed assessment to identify infestation levels is needed, but research on automated weed detection in relation to precision agriculture and the spatially selective treatment of weeds will, in the future, resolve this problem.

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Optimising mixtures of herbicides within a decision support system

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ABSTRACT

Since 1991 a Danish Decision Support System (DDSS) named PC-Plant Protection has been distributed in Denmark. This system offers decision support to identify and control 75 weed species in 11 crops. DSS models have also been implemented for pests and diseases. Presently, there are about 2,500 subscribers to the system.

The weed-model used in the DDSS until March 1999 is briefly discussed. A sub-model based on expert knowledge is used to quantify the need for weed control at a field level at the time of herbicide application. A logistic dose-response function quantifying about 500,000 combinations for different herbicide susceptibility due to: herbicide name, crop name, time of application, weed species, growth stages of weeds, temperatures, r.h. and water stress is used to calculate rates of single herbicides and tank-mixtures approved by Danish Institute of Agricultural Sciences. In March 1999 the Additive Dose Model (ADM) was integrated in the decision models of 8 cereal crops. Implications are discussed.

An ongoing political pressure in Denmark to reduce the total mass of pesticides used and the 'treatment frequency index' (TFI). TFI can be interpreted as a sum of the proportions of standard (maximum) rates used in a crop in one season. In 1996 a simple prototype integrating ADM into the DDSS for optimisation of treatment cost or TFI was constructed. This prototype was tested in 28 field experiments in cereals in 1996-98 with heavy weed infestations. Satisfactory weed control was achieved in all experiments. In spring barley the average rate was 35% of the normal rate and in winter wheat the average rate was 44% of the normal rate. Compared to the latest version of the DDSS without ADM this is a 27-29% reduction on TFI and 18-24% reduction on cost of treatment.

INTRODUCTION

Most selective herbicides will control only a limited spectrum of the weeds dominating a region. With increasing complexity in local weed infestations the relevance of using tank-mixtures increases too. Economic and other interests can also motivate the use of tank-mixtures. Commercial herbicides will often contain more than one active ingredient. A general disadvantage of such premixed herbicides is that the proportion of active ingredients is fixed. The herbicide composition cannot therefore be adjusted precisely to local conditions and inevitably, active ingredients are wasted.

In this paper, the development until March 1999 of weed model facilities of the DDSS are summarised, and implications from the integration of the ADM are described. A summary of the test results of an ADM-prototype in cereal crops is presented. The ADM was released with the updating of the DDSS from March 1999.

MATERIALS AND METHODS

The initial weed models in the DDSS were developed and tested in 1986-91. Based on a field report the version released in 1991 contains 3 steps (Baandrup, 1989):

1. evaluate the need for weed control;
2. specify the target efficacy level on the weed species present;
3. use a logistic and continuous dose/response function to calculate the rates needed to produce at least the target effect on all weeds present.

Steps 1 and 2 of the model were based on expert knowledge integrating aspects of yield loss caused by weeds, weed seed production and interference caused by weed biomass at harvest. Step 3 of the model calculates herbicide rates to meet the specified efficacy level. Differences in herbicide susceptibility due to differences between weed species and differences between different growth stages of weeds were integrated. With the annual updating of the DDSS during the 1990ies, additional crops and parameters were implemented in the dose-response calculations. At March 1999 the dose-response calculations for single herbicides and for approved tank mixtures were done using equation (1):

$$E_n = \frac{S_i}{1+exp(-2(a_n+b_h*log(d/(r_s*r_t*r_v))} \quad (1)$$

In graphical terms the dose-response curves produced using equation (1) are often referred to as 'S-shaped' curves, and the parameters used can be interpreted and documented in this way:

E_n relative efficacy of a herbicide on the fresh weight of weed species n

S_i competing ability of cereal variety i (Christensen, 1994).

a_n horizontal displacement of the dose-response curve of a given combination of an approved herbicide/tank-mixture, crop and time of year on weed n. Estimates from field studies used for efficacy approval (Jørgensen & Jensen, 1998; Josefsen & Kristensen, 1998). Practically, all new pesticides introduced in Denmark are being efficacy approved.

b_h steepness of dose-response curve around ED_{50}. Considered to be constant for a herbicide. Estimates based on semi-field experiments (not published).

d actual herbicide rate. For tank-mixtures, d is replaced by a tank-mixture 'proportion', and calculated proportions of the original tank-mixture rates are presented in the recommendations.

r_s correction-factor quantifying the influence on dose-response of weed growth stage. Estimates based on semi-field experiments (not published).

r_t correction-factor quantifying the influence of minimum- and maximum temperature and

RH on the day of herbicide application. Estimates based on experiments in climatic simulators (Kudsk & Kristensen, 1992).

r_v correction-factor quantifying the influence of water stress. Estimates based on experiments in climatic simulators (not published).

Principles for the model construction and a summary of the results from the validation of a more simple version of equation (1) has been described previously (Rydahl, 1995). In principle, additional non-interacting factors (Kudsk, 1989) can quite easily be integrated in equation (1).

The field conditions at the time of herbicide application in the experiments form the basis of the a_n estimates. From these, correction factors which quantify the influence of different growth stages of weeds and different climatic conditions are used to simulate dose-response functions of different scenarios. The version of the DDSS until March 1999 could simulate about 500,000 different scenarios including 75 weeds and 11 crops.

The rates calculated using equation (1) are used as input for the ADM (Kudsk & Mathiassen, 1995; Kudsk, 1999). This model facilitates calculation of herbicide mixtures in which the rates of mixture components have been optimised for an arbitrary constant, e.g. for chemical cost or for the TFI (Kudsk, 1999). The following principles were established before implementing the ADM in the cereal models of the DDSS:

- input herbicide rates are separated into 3 classes. When the dose-response parameters of a single herbicide/weed combination:
  1. if data are available to allow simulation of a reduced rate, this is used
  2. if data simulation indicate a higher rate, this is used
  3. if no data are available, a very large figure (100,000) is used
- only mixtures following the ADM are available. Synergistic effects and antagonistic mixtures have been ignored
- calculated mixtures including components with <5% of the max. rate have been ignored
- the user selects ADM optimisation for herbicide cost or for TFI, and the list of optional recommendations are sorted accordingly
- the ADM-mixtures may contain 2-4 components. The theoretical number of potential mixtures has been restricted based on practical experience
- mixtures of herbicides of common active ingredients have been ignored
- approved tank-mixtures are not used as components for ADM-mixtures
- generally, all 2-component ADM-mixtures of practical relevance will be accessible, 3-component ADM-mixtures are available when a herbicide is required to control specific weeds (such as *Galium aparine*) and 4-component ADM-mixtures could be selected in specific crops, e.g. sugar beet.

The principles of optimising herbicide rates using ADM are explained elsewhere (Kudsk, 1999). In 1996 a simple prototype capable of optimising 2-component ADM mixtures for herbicide cost and for TFI was constructed. Robustness and potential of this prototype have been tested in 28 field experiments in 1996-98. Based on field reports sent to DIAS, model recommendations were returned within 24 hours. The plot size were minimum 25 m^2, the sprayed volume 200 l/ha, spraying nozzles, pressure and speed adjusted according to local equipment and procedures. In comparison to the version of the DDSS used until March 1999 two different ADM-mixtures were tested. The mixture denoted as 'ADM-mixture I' was the mixture with the lowest value of TFI, and 'ADM-mixture II' was the mixture having the second lowest value of TFI.

RESULTS AND DISCUSSION

The herbicide rates used as input for calculating a 3-component ADM-mixture in a scenario of 3 herbicides and 3 weeds are shown in table 1. The calculated rates illustrate that none of the selected 3 herbicides can control all 3 species, and immediately a potential from establishing a 3-component mixture seems obvious.

Table 1. Input for ADM-calculations in the DDSS of 3 selected weeds and 3 selected weed species in spring barley.

	Metsulfuron methyl (met) 200 g/kg	Triasulfuron (tri) 200 g/kg	Fluroxypyr (flu) 180 g/l
Normal rate (gai/ha)	4	4	126
Cost (EURO/g)	1.09	0.88	0.30
Weed names	Herbicide rates used as input for ADM calculations		
Galium aparine	100,000.000	27.250	0.253
Chrysanthemum segetum	19.293	9.895	100,000.000
Polygonum lapathifolium	1.740	100,000.000	100,000.000

Using the rates of Table 1, the only possible 3-component ADM-mixture for the 3 herbicides and 3 weed species in Table 1 can be found from the equation system (2) - (4) solving into (5).

$$rate_{Met} = -\frac{100{,}000 rate_{Tri}}{27.250} - \frac{100{,}000 rate_{Flu}}{0.253} + 100{,}000 \quad (2)$$

$$rate_{Met} = -\frac{19.293 rate_{Tri}}{9.895} - \frac{19.293 rate_{Flu}}{100{,}000} + 19.293 \quad (3)$$

$$rate_{Met} = -\frac{1.740 rate_{Tri}}{100{,}000} - \frac{1.740 rate_{Flu}}{100{,}000} + 1.740 \quad (4)$$

$$(rate_{Met}, rate_{Tri}, rate_{Flu}) = (1{,}7398; 9{,}0026; 0{,}1694) = (0{,}35\frac{gai}{ha}; 1{,}8\frac{gai}{ha}; 30{,}6\frac{gai}{ha}) \quad (5)$$

Considering the efficacy of ADM-mixtures, some principles exist. Following the definition of ADM, the efficacy of the weed species defining the outer isobole (Kudsk, 1999) will be controlled exactly with the aimed efficacy levels specified by step 2 in the DDSS. Consequently, weed species not represented by the outer isobole will be controlled with efficacy levels higher than specified. Exact algorithms to calculate the efficacy on weeds not represented by the outer isobole have not yet been established, and the integration of this facility has been made by using a converging algorithm. The number of weeds controlled exactly with the efficacy level specified is determined by using (6):

$$N_{weeds} = N_{comps} - N_{\text{max-comp}} \quad (6)$$

where N_{weeds} *is* the number of weeds controlled exactly with the efficacy level specified, N_{comp} is the number of components in the mixture and $N_{\text{max-comp}}$ is the number of components in maximum rate. Compared to using single herbicides this illustrates the potential of the ADM to regulate herbicide efficacy more precisely.

The test results are summarised in Table 2. The experimental sites had very high weed infestations which is reflected by the relatively high yield increases. To evaluate the seasonal effect from weed control in cereals the total weed cover at harvest is often used. Levels below 10-15% in normally growing crops are considered to be acceptable. In the spring barley experiments the average annual total weed cover at harvest varied from 4.6% to 5.8%, and in winter wheat from 9.9-11.8%. The latter figures include one experiment having 63 weed plants per m^2 in the reference plot the early spring and 33-42% weed cover at harvest after all treatments. From a production risk point, these figures demonstrate a high level of robustness after the integration.

As illustrated in Table 2 'ADM-mixture I' was a bit cheaper and had slightly smaller TFI-values compared to the reference. The validation experiments were, however, conducted specifically to test the robustness of the ADM-integration. To evaluate the potential of the DDSS after integration of ADM also non-mixtures must be considered. If for instance, 1 gai/ha of tribenuron methyl can be used alone, it will be hard to even think of a competitive mixture. Therefore, Table 2 also shows average cost and TFI-values when the optimum treatment of plot 2, 3 and 6 in each experimental site was selected. These figures demonstrate a potential of the ADM-integration to reduce TFI by 27% in spring barley and 29% in winter wheat and a potential to reduce chemical cost by 18% in spring barley and 24% in winter wheat compared to the previous version of the DDSS. The previous version has demonstrated a potential to reduce TFI by about 50% compared to standard recommendations (Rydahl, 1995).

Table 2. Results from 28 validation experiments after integration of 2-component ADM-mixtures in the DDSS.

	Mean of 12 experiments in spring barley 1996-97, 263 weeds per m^2 in untreated plots				Mean of 16 experiments in winter wheat 1997-98, 205 plants per m^2 in untreated plots			
Plot: Treatment	Weed cover at harvest (%)	Yield and extra yield (t/ha)	TFI	Herb. cost (EURO /ha)	Weed cover at harvest (%)	Yield and extra yield (t/ha)	TFI	Herb. cost (EURO /ha)
1: Untreated	18.5	5.12	-	-	23.4	6.16	-	-
2: DDSS ex. ADM	4.6	0.46	0.43	8.91	10.3	0.78	0.62	17.70
3: ADM-mixture I	5.3	0.40	0.41	7.30	11.8	0.78	0.51	14.05
6: ADM-mixture II	5.8	0.46	0.47	9.05	9.9	0.67	0.69	18.24
LSD_{95} plot 2, 3, 6	n.s.	n.s.	-	-	n.s.	n.s.	-	-
ADM, TFI-opt., plot 2, 3, 6	-	-	0.35	6.48	-	-	0.44	-

In conclusion, highly infested fields of spring barley and winter wheat have been successfully controlled with a prototype integrating 2-component ADM-optimisation in the version of the DDSS used until March 1999. On average, 35% of the normal rates of herbicide was used in spring barley and 44% of the normal rates was used in winter wheat. No cases were found where the ADM-treatment differed significantly in yield or total weed cover at harvest compared to reference treatments. The release of the ADM in the DDSS from March 1999 also includes 3-component mixtures. Using this version, the field reports from the 12 validation experiments in spring barley were re-entered. It was seen that 3-component mixtures were not competitive in any of these cases.

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