Economic factors influencing control and management decisions for annual grasses in crops and pastures

John Moore, Agriculture Western Australia, Albany, Western Australia 6330, Australia.

Introduction

The most significant economic factor of decision aids for weed control is adoption. And the most widely adopted decision aids are those that are simple to use. These include weed by herbicide charts/bulletins, herbicide labels and the personal adviser (who may be a consultant, distributor, government adviser, spray contractor, or neighbour etc.). I suspect these sources account for over 90% of the decisions on 'what goes in the tank'. There is also a number of response curves or surfaces fitted to data sets and computer models available, yet very few appear to be used at the farm level. Do we just produce these for our own edification or to influence the personal advisers above? In answering, I think most model authors have the intention of having their models widely applied but this is rarely their fate.

In my experience, when the returns from weed control approach the costs of control, farmers become interested in the economics of control. When this occurs they will accept more complex decision aids and the level of computer ownership means that more complex models can be presented in very simple and acceptable formats. For example, Pannell's (1990a) model for determining the optimum rate of Hoegrass® (diclofop-methyl) for 2–3 leaf annual ryegrass (*Lolium rigidum* Gaudin.) control in wheat (*Triticum aestivum* L.) is included in the HerbiGuide® computer program in a simple format. The user inputs five numbers (weed density, yield potential, wheat price, application costs and fixed costs) and is given the optimal rate of Hoegrass, expected profit and the sensitivity of the profit on herbicide rate as a graph. This is a simple, effective decision tool which was designed to appeal to users by packaging it with the other weed and pest control information.

Part of the problem of the weed control decision is its dimensionality. People handle one, two and three dimensional problems with relative ease, but have great difficulty with more dimensions. Decision aids like the spray charts tackle this problem by presenting a two dimensional weeds by herbicides table and cover the crop dimension by printing it on the back as a separate table and a multitude of other dimensions as comments or notes attached to various columns and rows. Advisers integrate the multi-dimensional problem into a one dimensional 'solution', or perhaps a two dimensional list of 'best bet alternatives'. Computers programs also take the multi-dimensional input and convert it to a one or two dimensional output.

The economic factors influencing the control decision depend on the model being applied and these factors may be different to the set of factors that determined whether that particular model is appropriate. For example, the Pannell model above has delineated five important factors for the ryegrass in wheat situation. Other factors have determined whether wheat was grown, a pre-emergence herbicide was not used, the appropriate growth stage for application, and Hoegrass as the appropriate herbicide etc. Thus to determine the important economic factors I shall firstly scan through the models available, outline what the farmer needs or wants, then return to the factors of influence. The emphasis will be on annual ryegrass, wild oats (*Avena* spp.) and crop oriented applications, with some comment on pastures to finish.

The available crop models with emphasis on wild oats and annual ryegrass

I have categorized the models into eight groups to help deal with the range and number available.

i. Herbicides for specific situations

- Agriculture Department spray guides and information notes
- Pesticide information and registration status
- CRIS – On line chemical registration information system (available from the National Registration Authority, Canberra)
- Pesticide and pest information
- Peskem – Computer program (available from the University of Queensland Gatton College, Gatton Queensland)
- Pesticide, pest and price information plus some analysis, current research data and storage of users experience. Includes Pannell's (1990a) model.
- HerbiGuide – Computer program (available from HerbiGuide, Box 44, Albany, Western Australia).

ii. Economics of specific weeds or situations

- Pannell and Gill (1994). Mixtures of wild oats (*Avena fatua*) and annual ryegrass in wheat, competition and optimal economic control. A statistical model was used in order to examine optimal economic control practices at different weed densities.
- Pannell (1990a). Model of wheat yield response to application of diclofop-methyl to control annual ryegrass. A general model of crop yield response to herbicide application is proposed. The model includes three components; the effect of herbicide rates on weed density, the effect of surviving weed density on crop yield and the effect of herbicide directly on the crop. The model was used to estimate the response of wheat yield to application of diclofop-methyl at 0-0.9 kg a.i. ha^{-1} to control annual ryegrass in Australia. It was found that the competitiveness of ryegrass plants surviving treatment was reduced by the treatment and that the proportion of yield loss at a given ryegrass density was not independent of the absolute weed-free yield. The response function was used to calculate economic thresholds and optimal herbicide rates.
- Cousens *et al.* (1986). Modelling the economics of controlling wild oats in winter wheat.
- Blackshaw (1986). Leatherjackets (*Tipula* spp.) and viola (*Viola arvensis* Murray) in barley (*Hordeum vulgare* L.).
- Murdoch (1988). Long-term profit from weed control. Economic and biological sub-models to develop long-term strategies for the control of wild oats in spring barley.
- Martin *et al.* (1987). Prediction of wheat yield loss due to competition by wild oats. Yield loss parameters need to be related to genetic and environmental variables.
- Auld and Tisdell (1986). Economic threshold/critical density models in weed control. Basic economic threshold model of wild oats in wheat. The influence of reinvasion, time-intervals, spillovers and uncertainties. The impact of yield improvement, carryover effects, control costs and price effects, including quality.
- Gorddard *et al.* (1995). An optimal control model for integrated weed management under herbicide resistance. The optimal strategy includes a declining herbicide dosage as resistance develops, with compensatory increases in the level of non-chemical control.

iii. More general economic weed models or multiple crop/weeds

- Pannell (1990b). An economic response model of herbicide application for weed control. Determinants, other than

resistance and risk, of optimal herbicide usage. A theoretical response model based on biological relationships is used to derive equations for the optimal herbicide rate, the threshold weed density for herbicide application and the threshold crop yield.
- Streibig *et al.* (1989). Estimation of thresholds for weed control in Australian cereals. A non-linear regression model of crop yield related to weed densities was fitted to nine weeds of Victoria.
- Berti and Zanin (1994). Mixed weeds.
- Forcella (1987). Herbicide-resistant crops: yield penalties and weed thresholds for oilseed rape (*Brassica napus* L.).

iv. Biological models
- Pollard (1982). Sterile brome (*Bromus sterilis* L.).
- Marshall and Arnold (1994). Weed seed banks.
- Weiner (1982). Neighbourhood model.
- Auld and Coote (1990). INVADE: towards the simulation of plant spread.
- Zwerger and Hurle (1989). For weed species with a high population growth rate, infestation was determined mainly by seed production, plant survival and rate of emergence. For those with a low growth rate, seed survival in soil was critical.
- Cousens *et al.* (1987). The use of biologically realistic equations to describe the effects of weed density and relative time of emergence on crop yield. A model, based on a rectangular hyperbola to describe the relationship between population density and relative time of seedling emergence of wild oats and yield of barley and wheat.
- Wilson *et al.* (1984). Exercises in modelling populations of wild oats to aid strategic planning for the long term control of this weed in cereals. Containment is best achieved by moderate control annually rather than efficient control in alternate years.
- Wilson and Cussans (1983). Population models in strategic planning for control of wild oats. Looks at interaction with cultivation and burning.

v. Competition
- Medd *et al.* (1985). The influence of wheat density and spatial arrangement on annual ryegrass competition. Geometrical arrangement of the crop had no effect on competition by ryegrass. The effect of ryegrass was substantially reduced by increasing wheat sowing density. A reciprocal yield model (1/Y = 0.0092 + 0.0037 weed density/crop density) predicted yield reduction.
- Mutsaers (1989). Dynamic equation for plant interaction and application to yield-density-time relations. A model of plant interactions was developed in which space was determined in terms of the actual and potential amount of growth factors absorbed per unit time.
- Aldrich (1987). Factors affecting competition such as crop, weed, time of emergence, season and relative competitiveness.
- Tollenaar (1992). Looks at one sided and two sided models of competition for wheat and wild oats to take account of neighbourhood effects.
- Beyschlag *et al.* (1990). Light competition and canopy structure and concludes structure is the important feature determining growth in competition.
- Cudney *et al.* (1991). Model for light to explain wild oat in wheat competition under no nitrogen or moisture competition.
- Breay (1989). Wild oats and sugar beet (*Beta vulgaris* L.). The effects of competition on crop yield were highly significant on sandy loam but not on peat soil.
- Weaver *et al.* (1994). Influence of light competition and time of emergence of wild oats on wheat.

vi. Integrated weed management
- Sells (1995). Uses stochastic dynamic programming to follow the sets of chronological events.
- Dunan *et al.* (1994). Uses a simulation model to show that competitive ability of wild oats and barley can be used to reduce herbicide usage by using higher seeding rates and more competitive varieties.
- Pandey and Medd (1991) and Pandey and Medd (1992). Use stochastic multiperiod models to show the effects of future benefits from current decisions.
- Requesens and Baez (1990). A conceptual demographic model with an analysis of the bibliography concerning the effects of physical, biological and cultural factors on the demographic processes for wild oats.

vii. Whole enterprise models
- Pannell (1994). The value of information in herbicide decision making for weed control in Australian wheat crops. The expected value of information can reach 15% of expected gross margin. The value of information about yield prospects is higher than that for weed density. The value of information is markedly affected by the degree of risk aversion and the type of decision rule adopted. Use of information reduces the expected level of herbicide usage.
- King *et al.* (1986). Maize (*Zea mays* L.).
- Doyle *et al.* (1986). Blackgrass (*Alopecurus myosuroides* Huds.).
- Mishoe *et al.* (1984). Soybean (*Glycine max* (L.) Merr.).
- Sells (1995). Stochastic dynamic programming to account for uncertain herbicide performance.
- PADRANK computer program (available from Agriculture Western Australia).
- Dorr and Pannell (1992). Economics of improved spatial distribution of herbicide for weed control in crops. The optimum herbicide rate was insensitive to spatial variability. The costs of the spatial variation of herbicide application were estimated to be as high as 25% of net returns. Profit was more sensitive to variance in herbicide rate within the path of the spray boom (due to factors such as nozzle design, wind and boom roll) than to variance due to over- or under-lap of the boom.

viii. Whole farm models
- MIDAS linear programming computer model.
- Nevo *et al.* (1994). Expert system.

Developing models that are likely to be used

When building a model that is intended to be used by decision makers, I try to mimic the path that the user is likely to follow during this process. For the purposes of this paper I have assumed the decision maker is a profit maximizing rationalist farmer. For a starting point I have chosen the break of the season, so we can walk through a typical decision making cycle and look at the data or analytical deficiencies.

March inputs

What is the paddock history? Are summer weeds present? What are the grass weeds, and their resistance status? What broadleaf weeds are present? What was the previous crop? What is the intended crop and its potential yield? Prices of pesticides and produce. Cost of operations e.g. spraying, cultivating, planting etc.

March outputs

Expected returns for various crops e.g. PADRANK.

April/May (Break of season) inputs

Species, density, growth stage and stress status of weeds. Soil type and erodibility? Future expected trafficability. Planned paddock use next season.

April/May outputs

Rate and type of herbicide. Degree of cultivation. Planting rate or variety of crop e.g. triazine tolerant canola (*Brassica rapa* L.).

June/July inputs

Crop emergence date, size and density. Weed size and density. Trafficability and expected future trafficability. Planned paddock use next season.

June/July output

Rate and type of herbicide. Method of application. Pasture manipulation.

August/September inputs
Weed size and density. Grain contamination dockage schedules. Planned paddock use next season.

August/September outputs
Rate and type of herbicide. Spray-topping.

November/December inputs
Weed size and density. Grain contamination dockage schedules. Planned paddock use next season.

November/December outputs
Rate and type of herbicide. Crop-topping.

Once this essential set of decisions has been formulated, it is a little easier to fill in the detail. Firstly, the decision making process is a chronological event and as new information becomes available during the year it impacts on future decisions. For example, in 1993 heavy rainfall during winter made spraying difficult and consequently many farmers decided to control wild radish (*Raphanus raphanistrum* L.) in spring. Thus, unexpected market or seasonal changes must be catered for in the decision model. At the same time, strategic information should be incorporated. If a farmer enters a heavy annual ryegrass infestation for a paddock destined for wheat at April/May then some of his options are: pre-plant herbicide – trifluralin, triasulfuron or chlorsulfuron; cultural ± herbicide – tickle cultivate, work back, plant and accept a delay in planting, wait for large emergence, then spray and direct drill to avoid disturbance that would encourage further germinations; post-emergence herbicide – diclofop-methyl; cultural – separate ryegrass seed from grain after harvest. Other possible decisions could be to delay cropping for a year to enable ryegrass to be manipulated in the pasture by spray-topping, or plant an alternate crop, such as a legume, where alternative and cheaper controls may be available e.g. simazine or sethoxydim.

The dominant factors and operations for grass control are the price and yield of the crop because this determines the list of alternatives considered. In the table below I have outlined my impression of the importance of the various factors for use in models at the farm level. The variance is a multiplier e.g. for crop species the value of 10 indicates that the most competitive crop is about 10 times more competitive than the least competitive crop (Table 1).

Also important is the level of decision making. For example the price of wheat, lupins and nitrogen may determine whether lupins are grown, whether they are sprayed to control grasses carrying take-all (a root disease of the following wheat crop) and whether they are harvested, crop topped or ploughed in as manure. A similar situation occurs for weed control in pastures prior to a crop. Thus in two of our major rotations, lupins:cereal and pasture:crop it is economic losses associated in the following year that are the main driving force in the current year weed control decision making process.

These interactions are difficult to define and even more difficult to accurately quantify. The good results are published with gay abandon and the rest are filed. e.g. In 1985 yield response to grass removal was around 10%, in 1988 the response was 10% and in 1992 was 50–100%.

Work by Wallace in Western Australia has shown that controlling grasses in the year before crop reduces take-all, increases soil nitrogen and improves yields of the following wheat crop. This resulted in gross margins for wheat on pasture manipulated areas being almost double those on untreated areas ($230–310 ha^{-1} vs. $429–499 ha^{-1}). These are good reasons for taking a multi-year perspective for decision aids for annual ryegrass control in pasture and crops. Her data also show that in the year following ryegrass control, the density is reduced but returns to untreated levels in the next season.

Table 1. Author's subjective ranking of factors affecting grass control.

Factor	Variance	Importance
Crop species competitiveness	10	High
Crop variety competitiveness	2	Low–Medium
Planting rate	4	Low–Medium
Potential yield	4	Medium
Grain price	3	High
Weed species competitiveness	20	High
Weed density	50	Moderate
Cultural type	100	High
Cultural cost	20	Medium
Herbicide type	100	High
Herbicide price	10	Medium
Efficacy	10	Low–Variable
Phytotoxicity	10	Low–High
Weather conditions	100	Low–High
Application cost	8	Moderate
Fixed costs	10–100	Low

What should be crystallizing by now is that there is a hierarchy of models that need to be applied. Each one restricts the options to a subset of the previous. For example, the climate model says wheat rather than bananas grow in the wheat belt almost regardless of the price of produce. The soil model restricts wheat to the non-saline soils. The regional varieties model or book restricts the choice of varieties. Then the weeds and herbicides may restrict the variety.

The economic factors and their influence depends on the level of decision making. I have split the levels of decision making into six levels as shown below.

i. Global level
Residues. Consumer health and environmental considerations. Market preference for 'organic produce'. Exportability – weed, pest, toxin or pesticide contamination. e.g. dodder, ergot.

ii. National level
Registration, consumer and producer health and environmental considerations.

iii. State level
Quarantine. Noxious weeds.

iv. Farm level
Climate – temperature, light, average rainfall and distribution, frost, break of season. Weed demography, invasiveness and infestation size. Tenancy. Grain, produce and stock prices. Rotation. Equipment available. Annual rainfall. Dockage levels for contamination. Weed by disease by pest interactions. Weed by nitrogen interactions. Weed effects in break crops. Yield by delay in seeding relationship. Expected emergence patterns. Farmer risk category.

v. Paddock level
Crop type/variety and competitiveness. Planting rate by weed effect relationship. Yield potential and reliability. Weed type and competitiveness. Weed density and distribution. Herbicide price. Nitrogen status. Stress status. Application cost. Cultural or other weed control method costs. Soil type and erodibility. Weed seed banks. Emergence pattern. Future use of paddock. Resistance status. Seed cleaning price. Mixture compatibilities.

vi. Day level
Weather conditions and trafficability. Availability of product. Growth stages of crop and weed. History – frost, stress, nutrition. Cultural effectiveness. Herbicide effectiveness. Water quality.

By and large, the factors in lower levels are averaged for models in high levels and the factors in high levels are taken as given or constants for lower level models. Obviously, a multi-level model could be constructed, however its complexity is likely to preclude it from widespread use. What user wants to consider residues and gross margins when all they want to know is "can I spray atrazine in the rain?"

The economic factors that have most influence on grass control will depend on the situation. At present, on the south coast of Western Australia, I consider farmers would order them tentatively as follows for cropping: 1) Gross margin of crop, 2) Disease carryover effect, 3) Soil erodibility, 3) Grass species, 4) Grass density, 5) Herbicide resistance, 6) Cost of control, 7) Profitability of control and 8) Convenience.

Research suggestion

Formulate the current knowledge base into more applicable and adoptable models.

Spatial variability

Spatial variability is becoming more important with herbicide resistance and increased swathing. Many grass seeds are harvested with the crop and concentrated in a band in the swath or windrow behind the harvester. This leads to dense infestations over 10–20% of the paddock. Do you apply a rate determined by the small area of heavy infestation, the larger area of low density or some average between the two? Is it worthwhile changing harvesting systems to avoid the bands of heavy weed infestation? Thornton *et al.* (1990) have considered the effects of weed distribution on thresholds for control and concluded that it has a substantial effect on the calculation of economic thresholds for control. Brain and Cousens (1990) support this for high weed densities but qualify it by saying the error of the yield estimate "at densities where practical decisions are being made is minimal". Both authors agree that more research is required on weed distributions within paddocks is required. This will help determine the type and precision of equipment required for optimally controlling naturally patchy weed infestations. The interesting aspect of this work is that if the weedy area is sufficiently small, then even at very high densities it is not worth spraying the paddock.

From a harvesting techniques point of view it may be more profitable to concentrate the weed seed at harvest into very narrow bands of very high density which would be ignored rather than spreading the weed seed more evenly over the paddock which would then require rational control. Concentrating weed seed during the harvest operation opens up a number of alternate control scenarios such as catching mechanically, mutilating, or chemically treating seed as it leaves the harvester or spraying or mechanically treating strips in the paddock. Auld and Tisdell (1987) have also published locally on this topic.

Research suggestions

- Case studies of the typical spacial variability of the major weeds.
- Decision aids for patch spraying.
- Development of 'on the go' variable rate sprayers and weed density detectors.
- The influence of weed density on dose response functions of the major preplant and post-emergent herbicides.

The pasture phase

The 'weeds' in a pasture are considerably more difficult to define than they are in a crop. For example, capeweed (*Arctotheca calendula* (L.) Levyns) and grasses are the species most controlled by farmers but they are usually the greatest producers of feed in most pastures. In fact Arnold *et al.* (1985) quote average capeweed contents of pasture in Western Australia of 37% and 50% for high and low rainfall areas respectively.

The economics of weed control in pasture is usually further complicated by returns coming in future years rather than the year of application. A good example of this is pasture manipulation or spray-topping preceding a crop where the expected return is from increased crop profit which will offset losses in pasture production.

The particular weeds and their density in a pasture are usually a reflection of the particular grazing enterprise. Thus any weed control strategy must integrate the stock management for any reasonable economic analysis to be conducted. There are many cases where the lack of profit optimization at the enterprise level leads to a weed problem. I present Ramshaw's (1980) chart as an example of twelve weeds that he considers is due to inappropriate enterprise management. I hasten to add that even in profit maximizing situations, weeds may still occur and it will be profitable to treat them. For example, under high stocking rate regimes, the thistles, docks (*Rumex* spp.) and capeweed disappear from pastures but silvergrass (*Vulpia* spp.) encroaches. This is easily controlled with \$2.50 ha^{-1} worth of simazine and still makes this enterprise very profitable. Without this input, the system is likely to crash from lack of nitrogen as silvergrass displaces clover over time.

Research in Western Australia has shown that dock infested ryegrass / clover pastures are actually more productive than the two species mix when the proportion of dock is less than 30% in winter. This is because dock captures rainfall events before the annuals germinate and after they senesce and also act as a biological haystack carrying unused production from spring over summer as rootstocks to return it as rapid edible leaf growth at the break of the season when annual feed is scarce.

Research suggestions

- Integrated weed management where weed control is a normal and inseparable part of the set of grazing enterprises for the farm or economic unit.
- Basic ecology of plants that make up the pasture system without regard for their weed status.
- Find a more desirable broadleaf pasture species to displace the current 'weeds'.

Additional Reading

Abadi-Ghadim, A.K., Pannell, D.J. and Ghadim, A.A.K. (1991). Economic tradeoff between pasture production and crop weed control. *Agricultural Systems* 36, 1-15.

Arnold, G.W., Noy-Meir, I. and Galbraith, K.A. (1982). A process based model of herbage consumption by grazing sheep: Technical Memorandum, CSIRO Division of Land Resources Management, No. 82-10, 8 pp.

Bourdot, G.W. and Saville, D.J. (1988). The economics of herbicide use in cereal crops in New Zealand. *New Zealand Journal of Experimental Agriculture* 16, 201-7.

Cousens, R.D., Johnson, M.P., Weaver, S.E., Martin, T.D. and Blair, A.M. (1992). Comparative rates of emergence and leaf appearance in wild oats (*Avena fatua*), winter barley (*Hordeum sativum*) and winter wheat (*Triticum aestivum*). *Journal of Agricultural Science* 118, 149-56.

Cudney, D.W., Jordan, L.S., Corbett, C.J. and Bendixen, W.E. (1989). Developmental rates of wild oats (*Avena fatua*) and wheat (*Triticum aestivum*). *Weed Science* 37, 521-4.

Gill, G.S. and Diggle, A.J. (1993). Herbicide resistance in annual ryegrass in the cropping belt of Western Australia – a case for integrated weed management: Integrated weed management for sustainable agriculture, Hisar, India, 18-20, p. 19.

Martin, M.P.L.D. and Field, R.J. (1987). Competition between vegetative plants of wild oat (A*vena fatua* L.) and wheat (*Triticum aestivum* L.). *Weed Research* 27, 119-24.

Mortimer, A.M., Sutton, J.J., Putwain, P.D. and Gould, P. (1990). The dynamics of mixtures of arable weed species: Symposium on integrated weed management in cereals, Helsinki, Finland, p. 1.

Noy-Meir, I., Arnold, G.W. and Galbraith, K.A. (1982). A compartment model of pasture yield and composition: Technical Memorandum. CSIRO Division of Land Resources Management, No. 82-9, 10 pp.

Roberts, M., Cartledge, D.R. and Stern, W.R. (1984). Pasture meter calibration on swards of subterranean clover, annual ryegrass and mixtures of both. *Journal of the Australian Institute of Agricultural Science* 50, 187-9.

Ryel, R.J., Barnes, P.W., Beyschlag, W., Caldwell, M.M. and Flint, S.D. (1990). Plant competition for light analyzed with a multispecies canopy model: I. Model development and influence of enhanced UV-B conditions on photosynthesis in mixed wheat and wild oat canopies. *Oecologia* 83, 304-10.

Seefeldt, S.S., Jensen, J.E. and Fuerst, E.P. (1995). Log-logistic analysis of herbicide dose-response relationships. *Weed Technology* 9, 218-27.

Zanin, G. Berti, A. and Giannini, M. (1992). Economics of herbicide use on arable crops in north-central Italy. *Crop Protection* 11, 174-9.

References

Aldrich, R.J. (1987). Predicting crop yield reductions from weeds. *Weed Technology* 1, 199-206.

Arnold, G.W., Ozanne, P.G., Galbraith, K.A. and Dandridge, F. (1985). The capeweed content of pastures in southwest Western Australia. *The Australian Journal of Agricultural Research* 25, 117-23.

Auld, B.A. and Coote, B.G. (1990). INVADE: towards the simulation of plant spread: *Agriculture, Ecosystems and Environment* 30, 121-8.

Auld, B.A. and Tisdell, C.A. (1986). Economic threshold / critical density models in weed control: Proceedings, EWRS symposium on economic weed control, pp. 261-8.

Auld, B.A. and Tisdell, C.A. (1987). Economic thresholds and response to uncertainty in weed control. *Agricultural Systems* 25, 219-27.

Berti, A. and Zanin, G. (1994). Density equivalent: a method for forecasting yield loss caused by mixed weed populations. *Weed Research* 34, 327-32.

Beyschlag, W., Barnes, P.W., Ryel, R., Caldwell, M.M. and Flint, S.D. (1990). Plant competition for light analysed with a multispecies canopy model: II. Influence of photosynthetic characteristics on mixtures of wheat and wild oats. *Oecologia* 83, 374-80.

Blackshaw, R.P. (1986). Resolving economic decisions for the simultaneous control of two pests, diseases or weeds. *Crop Protection* 5, 93-9.

Brain, P. and Cousens, R. (1990). The effect of weed distribution on predictions of yield loss. *Journal of Applied Ecology* 27, 735-42.

Breay, T. (1989). The competitive effect of wild oats and cereal cover crops in sugar beet: *British Sugar Beet Review* 57, 24-6.

Cousens, R., Brain, P., O'Donovan, J.T. and O'Sullivan, P.A. (1987). The use of biologically realistic equations to describe the effects of weed density and relative time of emergence on crop yield. *Weed Science* 35, 720-5.

Cousens, R., Doyle, C.J., Wilson, B.J. and Cussans, G.W. (1986). Modelling the economics of controlling *Avena fatua* in winter wheat. *Pesticide Science* 17, 1-12.

Cudney, D.W., Jordan, L.S. and Hall, A.E. (1991). Effect of wild oat (*Avena fatua*) infestations on light interception and growth rate of wheat (*Triticum aestivum*). *Weed Science* 39, 175-9.

Dorr, G.J. and Pannell, D.J. (1992). Economics of improved spatial distribution of herbicide for weed control in crops. *Crop Protection* 11, 385-91.

Doyle, C.J., Cousens, R. and Moss, S.R. (1986). A model of the economics of controlling *Alopecurus myosuroides* Huds. in winter wheat. *Crop Protection* 5, 143-50.

Dunan, C.M., Moore, F.D. and Westra, P. (1994). A plant process-economic model for wild oats management decisions in irrigated barley. *Agricultural Systems* 45, 355-68.

Forcella, F. (1987). Herbicide-resistant crops: yield penalties and weed thresholds for oilseed rape (*Brassica napus* L.). *Weed Research* 27, 31-4.

Gorddard, R.J., Pannell, D.J. and Hertzler, G. (1995). An optimal control model for integrated weed management under herbicide resistance. *Australian Journal of Agricultural Economics* 39, 71-87.

King, R.P., Lybecker, D.W., Schweizer, E.E. and Zimdahl, R.L. (1986). Bioeconomic modelling to stimulate weed control strategies for continuous corn (*Zea mays*). *Weed Science* 34, 972-9.

Marshall, E.J.P. and Arnold, G.M. (1994). Weed seed banks in arable fields under contrasting pesticide regimes. *Annals of Applied Biology* 124, 349-60.

Martin, R.J., Cullis, B.R. and McNamara, D.W. (1987). Prediction of wheat yield loss due to competition by wild oats (*Avena* spp.). *Australian Journal of Agricultural Research* 38, 487-99.

Medd, R.W., Auld, B.A., Kemp, D.R. and Murison, R.D. (1985). The influence of wheat density and spatial arrangement on annual ryegrass, *Lolium rigidum* Gaudin, competition. *Australian Journal of Agricultural Research* 36, 361-71.

Mishoe, J.W., Jones, J.W., Swaney, P.D. and Wilkerson, G.P. (1984). Using crop and pest models for management applications. *Agricultural Systems* 15, 153-70.

Murdoch, A.J. (1988). Long-term profit from weed control. *Aspects of Applied Biology* 18, 91-8.

Mutsaers, H.J.W. (1989). A dynamic equation for plant interaction and application to yield-density, time relations. *Annals of Botany* 64, 521-31.

Nevo, A., Oad, R. and Podmore, T.H. (1994). An integrated expert system for optimal crop planning. *Agricultural Systems* 45, 73-92.

Pandey, S. and Medd, R.W. (1991). A stochastic dynamic programming framework for weed control decision making: an application to *Avena fatua* L. *Agricultural Economics* 6, 115-28.

Pandey, S. and Medd, R.W. (1992). A multiperiod economic model for control of wild oats (*Avena fatua*): Proceedings of the 1st International Weed Control Congress, Melbourne, pp. 375-7.

Pannell, D.J. (1990a). Model of wheat yield response to application of diclofop-methyl to control ryegrass (*Lolium rigidum*). *Crop Protection* 9, 422-8.

Pannell, D.J. (1990b). An economic response model of herbicide application for weed control. *Australian Journal of Agricultural Economics* 34, 223-41.

Pannell, D.J. (1994). The value of information in herbicide decision making for weed control in Australian wheat crops. *Journal of Agricultural and Resource Economics* 19, 366-81.

Pannell, D.J. and Gill, G.S. (1994). Mixtures of wild oats (*Avena fatua*) and ryegrass (*Lolium rigidum*) in wheat: competition and optimal economic control. *Crop Protection* 13, 371-5.

Pollard, F. (1982). A computer model for predicting changes in a population of *Bromus sterilis* in continuous winter cereals. Proceedings of the 1982 British Crop Protection Conference – Weeds, Brighton, England, p. 973-9.

Ramshaw, D.G. (1980). What makes a pasture weedy. Department of Agriculture, Tasmania, Farmnotes 27 / 80.

Requesens, E.C. and Baez, A. (1990). Fundamentals for the integrated management of *Avena fatua* L. *Malezas* 18, 35-6.

Sells, J.E. (1995). Optimizing weed management using stochastic dynamic programming to take account of uncertain herbicide performance. *Agricultural Systems* 48, 271-96.

Streibig, J.C., Combellack, J.H., Pritchard, G.H. and Richardson, R.G. (1989). Estimation of thresholds for weed control in Australian cereals. *Weed Research* 29, 117-26.

Thornton, P.K., Fawcett, R.H., Dent, J.B. and Perkins, T.J. (1990). Spatial weed distribution and economic thresholds for weed control. *Crop Protection*, 9, 337-42.

Tollenaar, H. (1992). Reinterpretation and evaluation of some descriptive models for weed-crop interference in terms of one-sided and two-sided competition. *Oikos* 65, 256-64.

Weaver, S.E., Kropff, M.J. and Cousens, R. (1994). A simulation model of competition between winter wheat and *Avena fatua* for light. *Annals of Applied Biology* 124, 315-31.

Weiner, J. (1982). A neighbourhood model of annual-plant interference. *Ecology* 63, 1237-41.

Wilson, B.J., Cousens, R. and Cussans, G.W. (1984). Exercises in modelling populations of *Avena fatua* L. to aid strategic planning for the long term control of this weed in cereals. Comptes rendus du 7eme colloque international sur l'ecologie, la biologie et la systematique des mauvaises herbes, pp. 287-94.

Wilson, B.J. and Cussans, G.W. (1983). Population models in strategic planning for control of *Avena fatua*. 10th International Congress of Plant Protection, Brighton, England, pp. 20-5.

Zwerger, P. and Hurle, K. (1989). Studies on the relative importance of individual population dynamics parameters for the development of weed infestation. *Zeitschrift fur Pflanzenkrankheiten und Pflanzenschutz* 96, 346-52.

Zanin, G. Berti, A. and Giannini, M. (1992). Economics of herbicide use on arable crops in north-central Italy. *Crop Protection* 11, 174-9.

Developments in grass weed management in a mixed farming situation

B.J. Butler, NSW Agriculture, PO Box 129, Cowra, New South Wales 2794, Australia.

Introduction

Over the past thirty years farmers in central and southern slope regions of New South Wales have made significant changes to their farming practices. Many of these have been facilitated by the availability of a range of herbicides, in particular those that control grasses. Coupled with the introduction of broadleaf crops into the crop rotation, herbicide availability has produced cost effective methods of reducing the impact of grass weeds on the yield and quality of products. In fact, the problem of grass weeds has been significantly reduced through the improved options farmers now have in using grass control herbicides during the broadleaf crop phase.

However, the reliability of these widely adopted techniques is now under threat by the development of herbicide resistance. Herbicide resistant annual ryegrass (*Lolium rigidum* Gaudin) is becoming more widely reported but at this stage is surfacing on less than 15% of properties. Resistant wild oats (*Avena* spp.) are less common and are reported to occur on <2% of properties.

Farmers affected by herbicide resistant wild oats and/or ryegrass are using a range of approaches which rely greatly on herbicide crop associations. Some herbicides still give a percentage of control, and when used in conjunction with seed reduction strategies, can result in low weed densities. It is anticipated that seed reduction strategies such as chemical fallowing, spray-topping/winter cleaning, mowing and heavy grazing will become more important.

Ryegrass

Whilst annual ryegrass remains a major threat to crop yields, particularly as resistance develops, it is a very valuable pasture species for livestock and soil development. Ryegrass plays a useful role in suppressing less desirable grasses like vulpia (*Vulpia* spp.) and broadleaf weeds. In the past, farmers have been happy to have ryegrass in some pastures in the knowledge that it could be readily controlled in crops which follow. As this situation changes the role of ryegrass as a source of forage will need to be reassessed.

Vulpia

Vulpia is endemic on most properties and is a problem as a source of cereal diseases, and for its effect on pasture quality and animal performance due to seed contamination. Control of this species during the pasture phase has met with minor success and the benefits are only temporary. The cost of spraying large areas of pasture is unacceptable to most farmers and the reduction in carrying capacity during winter/early spring can be a major problem.

Production of broadleaf crops using herbicides such as trifluralin at high rates and simazine have provided excellent opportunities for vulpia control, resulting in the weed not being a significant problem in subsequent cereal crops.

Wild oats

Wild oats are a significant problem to much fewer farmers than ryegrass with an estimated 25 to 35% having a moderate to major problem. Less than 2% of these farms have resistant wild oats. The problem has become less due to the use of broadleaf crops in the rotation where a wide range of herbicide options result in excellent control.

Limited survey work in the Cowra district indicates that less than 20% of wheat crops are sprayed with herbicides which specifically control wild oats, whilst over 80% of canola crops are sprayed with herbicides effective on wild oats.

The future

As herbicide resistance becomes more widespread, a number of management options will need to be integrated into the current system. These are not yet widely used or evaluated in this area and farmers will be seeking information on their potential value.

These are:

- In-crop spray-topping
- Seed collection at harvest
- No-till seeding
- More competitive crops/systems
- Nutrient manipulation – deep banding
- Burial – mouldboard ploughing
- Herbicide resistant crops/varieties
- New herbicide use patterns – simazine in cereals.

The adoption of no-till/stubble retention systems will raise many questions on weed management. Trifluralin is widely used in broadleaf crops and is still providing reliable control of ryegrass where resistance to aryloxyphenoxypropionates and cyclohexanediones is present. It is valuable for vulpia and wild oat control, but its effectiveness under no-till and stubble retention systems will be reduced. Evaluation of techniques that could improve effectiveness is required.

Under these new cropping systems, use patterns for commonly used herbicides will need to be reassessed in line with the changed dynamics of weed germination and growth.

Conclusion

Crop production on the central and southern slope regions of New South Wales has changed dramatically due to the availability of herbicides. To a large extent herbicides have replaced cultivation. However, in the future, if a situation arises where herbicides can no longer be relied upon to control weeds, will a return to the dependence on cultivation be possible/practical and acceptable to the community?

If not, what strategies can be implemented as alternatives to both cultivation and herbicide application?

It is expected that greater emphasis on seed reduction strategies, especially during the pasture phase using non-selective herbicides and non-herbicide techniques, will become more important in the future. The use of herbicides can be reduced by applying highly effective control measures using herbicides as part of a weed control strategy during the pasture and cropping phase. This will not only reduce the problems associated with herbicide resistance, but provide more reliable control of cereal diseases.

It is critical that resources be allocated to investigate the above issues to ensure the development of more sustainable farming systems. In seeking these answers, investigators should work closely with farmers and farm groups and advisory officers from the public and private sector.