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The Economics of Weed Control Strategies: A Dynamic Programming Analysis of Wild Oats Control

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ABSTRACT

Wild oats (Avena fatua and A. ludoviciana) is a weed of cereal crops which, as a consequence of its impact upon cereal yields and persistence, leads to significant economic losses in the grain growing regions of Australia. In this study, a dynamic programming model is developed to examine the impact of a range of management strategies for the control of wild oats in wheat. This analysis draws upon earlier work on this topic by Pandey and Medd (1990, 1991). The strategies evaluated include conventional herbicide control to reduce weed densities, selective spray-topping to reduce seed set of the weed, and summer crop and winter fallow rotational options which provide a break in the cereal cycle and allow accelerated control of wild oat populations. It is hypothesised that those strategies which involve measures that directly reduce seed production and minimise wild oats seed bank populations will yield the greatest economic benefit. The dynamic programming model provides a means of determining the optimal combination of strategies over time for various initial values of the seed bank. The methodology outlined in this study is provided as an economic framework for evaluating weed control problems in annual cropping systems.

INTRODUCTION

Background to the wild oat problem

Wild oats (*Avena fatua* and *A. ludoviciana*) are among the most important weeds of winter cereal and pulse crop production worldwide. The main effect of wild oats is to reduce the yield of crops through direct competition for water and nutrients. Other negative impacts arise from crops being contaminated with wild oat seed, incurring a cost for seed cleaning and handling or from being downgraded with significant price dockages. Wild oats are alternate hosts to several important cereal diseases and have also developed resistance to herbicides.

In Australia, Medd and Pandey (1990) estimated for the 1987/88 season that the annual cost of wild oats was approximately $42 million. This consisted of almost $30 million expenditure on herbicides and herbicide application, and over $13 million due to reduced grain production. This was a conservative estimation of the problem and was incomplete since it did not estimate the cost of contamination, disease hosting or of managing herbicide

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resistance (which at that time was unknown). Although the current cost of wild oats is unknown, there is no indication that the problem has abated and wild oats remain as arguably the most important weed of winter grain production in Australia.

The main features for the continuing weediness of wild oats in winter cereals are its asynchronous germination, similar growth period to cereals such as wheat, the shedding of seed prior to harvest and the ability of the seed to remain dormant in the soil. It is now clear from a number of unrelated studies, detailed below, that the key to reducing wild oat populations is the prevention of seed production. By regulating seed inputs, seed stocks are rapidly depleted since their half life has been shown to be about six months (Martin and Felton 1993). Given that suitable technology now exists to control seed inputs, several questions arise as to the economics of alternative control strategies and to broader issues of population management in a long term context. These are addressed in the paper using wild oats as an example.

A selective review of the literature

Research on wild oats control has focused on two main directions; the application of herbicides and the use of fallow and rotations.

A number of studies have attempted to identify the economic optimal strategies for controlling wild oats with herbicides. Cousens, Doyle, Wilson and Cussans (1986) used an economic simulation model to measure the benefits of applying the herbicide difenzoquat in different cultural regimes. They found that the highest long-term benefits were obtained when a herbicide was applied every time wild oats exceeded a density of between 2 and 3 seedlings m^{-2}. They concluded that when wild oat populations are lowered (2 to 3 seedlings m^{-2}) there was scope for a reduction in herbicide use rather than spraying indiscriminately at the full dose every year. They noted, however, that such a strategy involves risks as there is evidence that the variability of herbicide performance increases as dose is decreased.

Pandey and Medd (1990) assessed the potential benefits to use herbicides to kill wild oats seed (seed kill strategy) as a complementary tactic to traditional measures which target the current infestation (plant kill strategy). The study determined that a seed kill technology, combined with an existing plant kill tactic, was an economically viable option whereas seed kill alone was not economically attractive. At the time of their study there was no existing seed kill strategy to promote, however, the authors concluded that directing research resources to develop seed kill technology was justifiable.

The issue of post-emergence herbicide (diclofop-methyl) dose response in wild oats was further developed by Pandey and Medd (1991). The aim of their study was to compare a stochastic multiperiod simulation framework to a single period approach for deriving optimal herbicide decision rules taking into account the multiperiod effects of current weed control decisions, stochastic influences and farmers attitude to risk. The study determined that the optimal herbicide dose decreased with increases in the seed bank. The authors concluded that a dynamically optimal solution maintained a lower steady state weed population and higher economic returns compared with a single period solution.

Recent work by Medd, Nicol and Cook (1995) has demonstrated that wild oat populations can be dramatically reduced in the wheat phase of a rotation by the integrated use of seed kill tactics. This involves the late application by spray-topping of flamprop-methyl when wild oats have commenced elongation at growth stage 31 (Zadoks *et al.* 1974) specifically to reduce wild oat seed production. It is an additional management option and does not substitute for the need to undertake yield conservation measures of pre or early postemergence application of herbicides.

A number of studies have suggested that an economically attractive alternative to continuous winter cereal cropping and the reliance on herbicides for the control of wild oats is the use of winter fallow and summer crops in rotation with winter cereals. The majority of the studies reported here were set in predominantly summer rainfall regions of northern NSW and/or southern Queensland. Philpotts (1975) proposed the prevention of wild oat seeding by clean winter fallowing and was able to demonstrate from experiments that wild oat seed numbers were dramatically reduced after clean winter fallows and summer crops. Uncontrolled areas resulted in seed densities of almost 6000 seeds m^{-2} while after 2 summer crops the number of wild oats plants was less than 1 plant m^{-2}. According to Philpotts there was no evidence of any additional benefit in term of seed numbers from the third year without wheat.

A study by Wilson, Cartledge and Watkins (1977) supported Philpotts' findings, determining that the density of wild oats in second and third winter crops was successively higher than in the first winter crop after summer fallow and/or summer crops grown on winter fallow. Using gross margin analysis Wilson (1979) determined that there were economic advantages over continuous wheat from a rotation where summer crops were grown after a clean winter fallow. The typical rotation used was two years of wheat, long fallow (i.e fallow through summer and winter), two years of summer crop (sorghum) and a long fallow back to a winter crop. Wilson noted that the continuous wheat system became more profitable in areas where sorghum was a less reliable crop (i.e. due to a lack of summer soil moisture).

Martin and Felton (1993) found that the rotation of wheat with sorghum was a more effective means of controlling wild oats and caused a decline in the seed bank, compared with the use of selective herbicides in the wheat phase. They found that annual use of tri-allate or flamprop-methyl for yield conservation in wheat did not prevent a substantial build up of the wild oat seed reservoir after 4 successive crops. However, the rotation with sorghum, which allowed 2 winters for control of wild oats either by cultivation or with herbicide, resulted in an exponential decline in wild oat seed numbers in the soil.

Fisher and Lee (1980) determined that an economically optimal policy to manage wild oat populations and the disease crown rot involved a rotation of wheat followed by an 18 month fallow. They determined that when initial wild oat populations was greater than 1000 plants m^{-2} it became profitable to forgo all cropping for 18 months, then plant sorghum, followed by a 12 month fallow and then the wheat/18 month fallow rotation was established.

In a US study by Taylor and Burt (1984) various herbicide and fallow strategies were considered for wild oats control. They found the optimal policy to be heavily dependant upon the density of wild oat seeds in the soil and whether the land was previously cropped or fallow. They determined thresholds for the application of postemergent herbicide which ranged from 6 to 13 plants ft^{-2}, depending upon soil moisture and wheat price.

Objectives of the paper

Previous research on the control of wild oats has been partial, either focusing upon herbicide treatments alone in winter cereals or upon rotations involving summer crops and clean winter fallow with winter cereals. There has been no comprehensive economic analysis which considers the integration of wild oats control options and determines an optimal set of decision rules under Australian conditions. The purpose of this paper is to undertake such an analysis.

The primary objective of the paper is to determine the sequence of wild oat control strategies that maximises net returns over the long term. The strategies evaluated include a range of plant kill and seed kill tactics in wheat, and rotations involving summer crops, wheat and winter fallow. The study area is the Tamworth region of northern NSW. The primary hypothesis is that a prophylactic management of wild oat populations which involves an integration of control options will result in higher economic returns than a therapeutic treatment of wild oats (i.e. routine application of herbicides in wheat to improve yield in the current year). This is done by comparing the outcomes of 2 prophylactic scenarios involving seed kill and summer crop rotations with a therapeutic scenario. A secondary hypothesis is that the strategy which minimises the size of the seed bank will result in the greatest long term economic benefits.

Prophylactic management strategies which result in a minimal seed bank may also provide environmental and human health benefits from a lower long term usage of herbicides. Although cumulative herbicide applications associated with the optimal strategies for each scenario are measured, these benefits are not quantified in this study.

A FRAMEWORK FOR WILD OAT POPULATION DYNAMICS

The purpose of this section is to, first, present the theoretical framework for evaluating the population dynamics of wild oats and, second, to demonstrate the effectiveness of the various herbicide control options upon the wild oats seed bank.

Seed bank dynamics with herbicide control

A simulation model was developed to trace the effects of the various herbicide control strategies upon the size of the seed bank during the wheat phase of production. The work by Medd, Nicol and Cook (1995) demonstrated that seed kill strategies, either alone or in conjunction with plant kill tactics, can reduce the production of wild oats seed. The following control options were developed from research and their impacts upon the seed bank over a 10 year time horizon were assessed.

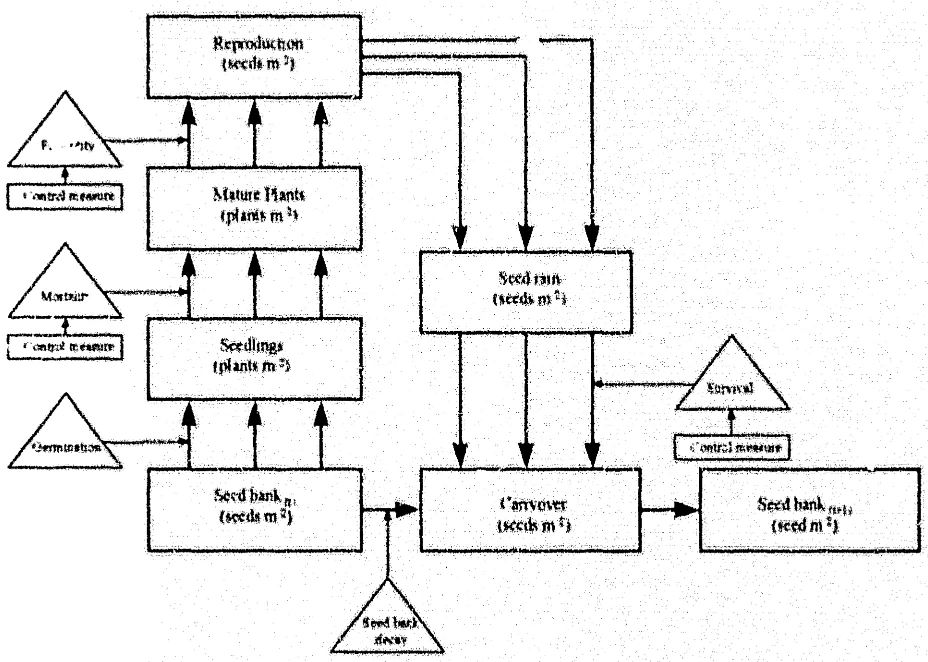
- No annual control.
- Plant kill control only, applied annually.
- Seed kill control only, applied annually.
- Plant kill plus seed kill control, applied annually.

In a single generation a proportion of viable seeds germinate resulting in seedlings. Some seedlings survive and mature, reproduce, die and deposit seed to the seed bank. This process of the seed dynamics is generally described by the following equation.

$$SB_{t+1} = SB_t - R_t - M_t + NS_t \tag{1}$$

where SB_{t+1} is the size of the seed bank at the start of the period t+1, SB_t is the starting stock of the seed bank, R is the loss due to recruitment, M is the loss due to mortality and NS is new seed added to the seed bank. The annual population of wild oats germination can be divided into a number of cohorts[1], with each cohort experiencing differences in mortality and fecundity given the divergent seasonal and crop competitiveness conditions throughout a season. A graphical description of the population dynamics described by equation (1) is given in Figure 1. Different cohorts are represented by the arrow streams.

Figure 1: Population dynamics of an annual life cycle of wild oats



The simple seed bank dynamics processes described above are developed in greater detail and presented in equations (2) to (7).

$$
\begin{aligned}
S_t &= \delta SB_t && (2)\\
W_t &= (1-\gamma)S_t && (3)\\
RS_t &= \exp(\alpha * \log W_t(\lambda + \varepsilon * \log W_t)^{-1}) && (4)\\
NS_t &= \theta RS_t && (5)\\
CY_t &= (1-\psi)((1-\delta)SB_t) && (6)\\
SB_{t+1} &= NS_t + CY_t && (7)
\end{aligned}
$$

where S is seedlings; δ is the annual germination of wild oats seed; W is the density of mature plants; γ is the mortality of seedlings; RS is reproduced seed resulting from the reproduction of wild oats; α, λ and ε are constants in the fecundity equation which will

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[1] A cohort is defined as one age generation of the total plant population.

differ for plant and seed kill tactics; *NS* is new seed which enters the seed bank; θ is the survival rate of new seed; *CY* is the carryover of the seed bank from one stage to the next; ψ is the death rate of dormant seed.

The values for δ, γ, θ, ψ are derived from Medd (unpublished research data) and are given in Table 1. These are mean values and are expected to vary with seasonal conditions. It is expected that in any season 50% of the seed bank will germinate with the remaining seed being dormant in the soil. Some mortality of the dormant seeds occur such that 25 percent is carried over and becomes available for germination in the following year. The annual germination of wild oats is assumed to take the form of 3 cohorts (Table 1).

Table 1: Plant mortality and seed rain survival values assumed for cohorts and management options and germination, seed decay rate and cohort values

	No control (%)	Plant kill (%)	Seed kill (%)	Plant & seed kill (%)	Winter fallow (%)
Plant mortality - cohort 1 (γ)	85	85	85	85	100
Plant mortality - cohort 2 (γ)	15	75	15	75	100
Plant mortality - cohort 3 (γ)	75	75	50	75	100
Seed rain survival - 1 (θ)	60	50	20	20	0
Seed rain survival - 2 (θ)	60	50	20	20	0
Seed rain survival - 3 (θ)	60	50	20	20	0
		Non specific to control option (%)			
Germination (δ)			50		
Dormant seed death rate (ψ)			75		
Weed population - cohort 1			30		
Weed population - cohort 2			60		
Weed population - cohort 3			10		

Equation (4) represents the fecundity equations estimated by Medd, Nicol and Cook (1995) for determining the reproduction of the wild oat population. The constants in this equation will differ depending upon the control option and the cohort. The coefficients for this equation for plant kill and seed kill are given in Table 2[2].

Table 2: Constant values for fecundity equations for plant kill and seed kill options

	α	λ	ε
Plant kill - cohort 1	8.60	0.74	0.88
Plant kill - cohort 2	7.60	1.20	0.80
Plant kill - cohort 3	6.80	2.00	0.67
Seed kill - all cohorts	7.42	2.04	0.66

Impacts of control options on the seed bank from alternative herbicide strategies

The simulation model was solved for the 4 control options for initial seed bank densities of 1000, 2000 and 3000 seeds m^{-2} and the results reported in Figures 2, 3 and 4. In practice there is a significant range in wild oat seed densities not only between regions but also at an

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[2] The no control option uses the plant kill coefficients and the combined plant and seed kill option uses the seed kill coefficients.

individual farm and paddock level. Therefore, the results of the studied options must be reported for a range of initial seed bank densities for a complete analysis. The initial seed bank range evaluated represents the seed densities that can be expected in wheat crops infested with wild oats.

Regardless of the initial seed bank density, the no control option resulted in an increase in the seed bank to over 4500 seeds m^{-2} by year 10. The plant kill option also resulted in increases in the seed bank, to just over 3000 seeds m^{-2} by year 10. The seed kill option resulted in a decline in the seed bank to close to zero seeds m^{-2} by year 10 for all initial seed bank values. Likewise, the combined plant and seed kill control option resulted in a zero seed bank by year 6.

These results illustrate that reliance on the traditional plant kill approach to manage wild oats is ineffective in controlling seed populations in continuous wheat systems. On the other hand both the seed kill control option and seed kill combined with plant kill appear to have considerable potential as management strategies to control wild oat populations in the long term.

The significance of these results, however, is limited as they rely on the underlying assumption of a continuous wheat rotation. This form of production is unsustainable in most regions and hence wheat is commonly rotated with other crops, pastures and fallow. This provides the opportunity for an integrated weed management system rather than reliance solely upon monoculture and the therapeutic use of herbicides. Consequently, the performance of control strategies such as seed kill and seed kill combined with plant kill must be evaluated in the context of a rotational system rather than under the assumption of a wheat monoculture.

Figure 2: Seed bank dynamics over 10 years for 1000 seeds m^{-2}

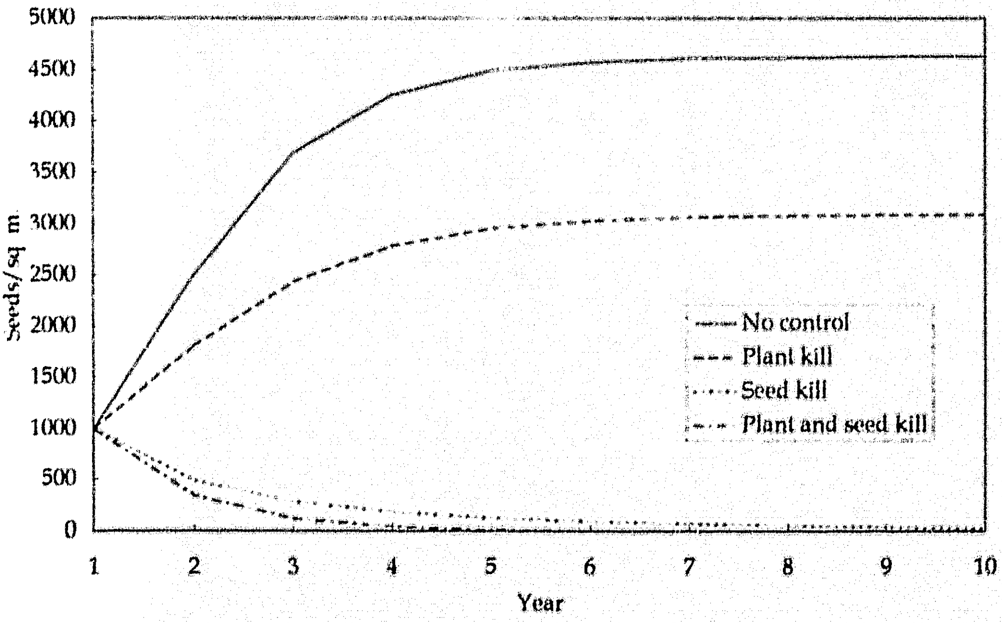


Figure 3: Seed bank dynamics over 10 years for 2000 seeds m^{-2}

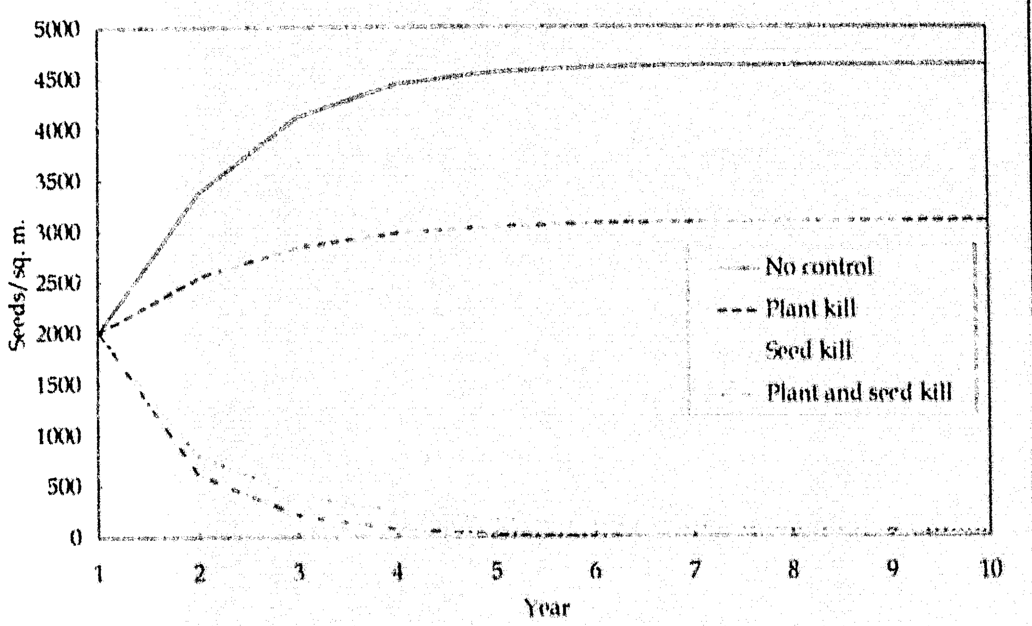
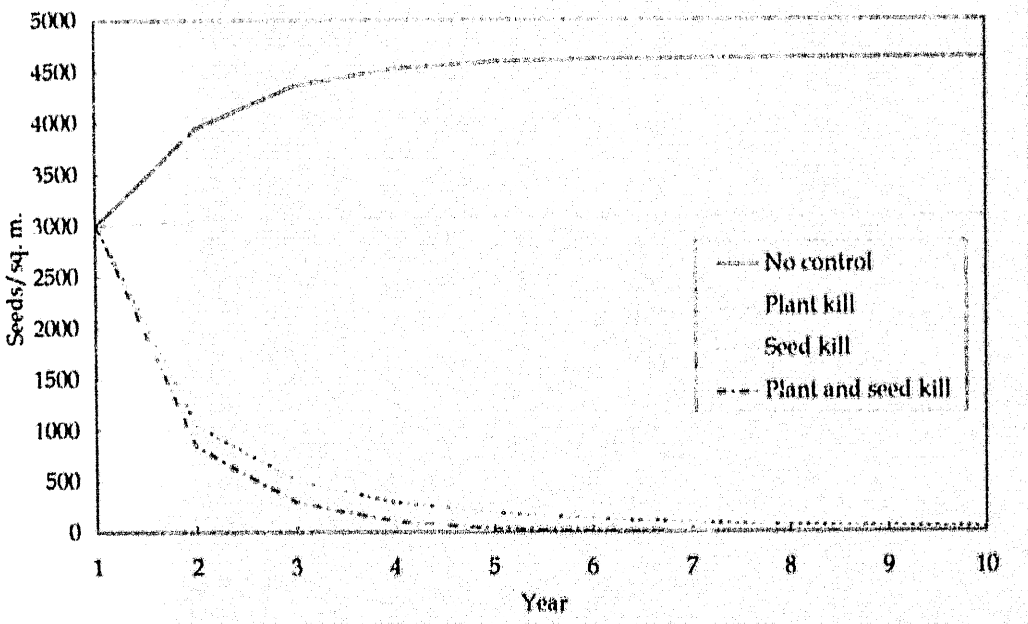


Figure 4: Seed bank dynamics over 10 years for for 3000 seeds m^{-2}



A DYNAMIC PPROGRAMMING MODEL OF WILD OATS CONTROL

The solution procedure

Although the foregoing analysis demonstrates the impact upon the seed bank from the various control options, the model is unable to determine the economically optimal control option for managing wild oats. The simulation model was solved under a fixed annual policy of applying either of the control options whereas in reality it is possible that the marginal benefits of control are exceeded by the marginal costs as seed densities decline to a certain level. Such a scenario may help explain why there is a degree of tolerance by farmers for some level of weed infestation. Various combinations of the control options over the time horizon may be applied by a decision maker e.g. seed kill followed by plant kill. In addition to the herbicide treatments presented there are a range of non-chemical control options, such as the summer cropping and winter fallow options. For these reasons a comprehensive economic analysis is required which takes into account the marginal costs and marginal benefits through time and considers a broader range of chemical and non-chemical control options.

An economic analysis of controlling a weed population must take into account the intertemporal aspects of population dynamics and the control options. Methodologies suited to this task include dynamic programming, multiperiod linear programming and simulation.

The simulation model used in the previous section could be adapted to a monte-carlo model, whereby a large number of wild oat control sequences are randomly selected, evaluated and ranked according to economic performance. However, this is an inefficient procedure for this problem as an extremely large number of plans would need to be considered and there is no guarantee that a globally optimal solution was reached. Consequently, an optimisation framework is preferred.

Of the optimisation techniques considered, multiperiod linear programming and dynamic programming, the latter was chosen because it is an efficient solution technique for intertemporal problems (Kennedy 1986) and the framework allows for the possibility of a stochastic specification without adding considerably to the computational burden. There has not been an extensive use of dynamic programming in weeds research, however, applications of dynamic programming apart from the wild oat studies discussed earlier include the identification of optimal resistance strategies in situations of ryegrass resistance to diclofop-methyl in Western Australia (Gorddard 1991), and optimal herbicide rates for the control of hardheads (*Acroptilon repens*) in Victoria (Kennedy 1987).

Model description

Finite stage dynamic programming is a mathematical optimisation technique for solving multistage decision problems (Bellman 1957). Such decision problems involve a sequence of decisions extending over a given period of time, called the planning horizon. The goal of a dynamic programming model is to maximise (or minimise) a specified objective function, such as the present value of net revenues. The planning horizon is divided into a number of time intervals, called stages. The dynamic programming problem consists of a sequence of decisions to be made in each stage of the planning horizon. Any decision made in a stage will result in a change in the state of the decision system at the next stage, expressed by the state transformation function, and results in a return at each decision stage, given by the stage return function. The state variable is particularly important to dynamic programming problems and is needed to quantify the condition of the system at the time the decision is made.

The successful application of dynamic programming requires the appropriate specification of stages, decision alternatives, state variables, state transformation functions and stage return functions. These are described in detail for the wild oats problem as follows.

Stage

The stage for the model is defined to be 1 year, since planting decisions must be made annually. The planning horizon consists of 15 stages, or years.

Decision alternatives

The relevant decisions for wild oats control in the study area are to (a) grow wheat without applying a herbicide (no control); (b) grow wheat with a pre-emergence or post-emergence herbicide (plant kill); (c) grow wheat with a late application of herbicide to prevent wild oats seed set (seed kill); (d) grow wheat with both plant kill and seed kill herbicide strategies; (e) grow a summer crop such as sorghum; and (d) clean winter fallow the land.

A number of restrictions are placed on the decision variables. These are as follows:

- Winter fallow is restricted to a maximum of 1 year duration. It is possible to allow land to remain fallow for periods longer than this and achieve greater reductions in wild oat seed populations, however, this practice can lead to greater susceptibility of the land to soil erosion and is not recommended.
- Wheat is restricted to a maximum of 3 years of continuous crops in a rotation due to the effects of soil borne diseases such as crown rot (*Fusarium graminarearum* Group 1) and take-all (*Guammanomyces graminis* var. *tritici*). The effect of these diseases is to reduce yields in wheat after the first crop following fallow. With successive wheat crops fungal spores build up in the soil and can only be significantly reduced by including a non-host crop in the rotation, such as sorghum, or by winter fallowing.
- Successive sorghum crops are restricted in the model as there are herbicide residue and possible resistance problems associated with repeated applications of Atrazine®. The effect of Atrazine® residues in the soil is to significantly reduce the yield of sensitive winter crops.
- Due to sowing and harvesting time conflicts, sorghum must follow a winter fallow when grown after wheat.
- If wheat follows sorghum it can only be grown after a winter fallow. The reason for this restriction is that there is rarely adequate soil moisture after harvesting sorghum to grow a winter cereal.
- Rotational restrictions ensure that first year wheat can only follow fallow, second year wheat can only follow first year wheat, and third year wheat can only follow second year wheat. Fallow can follow any previous decision. A more detailed description of each of the discrete decision alternatives is given in Table 3.

Apart from the benefits from wild oats control and providing a break in the disease cycle, winter fallow can provide increases in wheat yield in the first year due to higher levels of soil moisture and nutrients (accumulated through mineralisation). There are yield penalties of 20% and 40% from the weed free wheat yield following fallow for second and third wheat crops respectively (I. Collett, pers. comm.) due to the combined effects of disease and the yield benefits from fallow.

Table 3: Decision variables and rotational rules

Decision	Description	Follow decision variable
1	Winter fallow	2,3,4,5,6,7,8,9,10,11,12,13,14
2	Sorghum	1
3	Wheat year 1 - no control	1
4	Wheat year 1 - plant kill	1
5	Wheat year 1 - seed kill	1
6	Wheat year 1 - plant and seed kill	1
7	Wheat year 2 - no control	3,4,5,6
8	Wheat year 2 - plant kill	3,4,5,6
9	Wheat year 2 - seed kill	3,4,5,6
10	Wheat year 2 - plant and seed kill	3,4,5,6
11	Wheat year 3 - no control	7,8,9,10
12	Wheat year 3 - plant kill	7,8,9,10
13	Wheat year 3 - seed kill	7,8,9,10
14	Wheat year 3 - plant and seed kill	7,8,9,10

State variables

Two state variables are included in the model; seed bank density and land use. The seed bank state variable describes the wild oats population dynamics with the stock of seeds in the soil (seeds m^{-2}) the primary variable. This state variable is represented by 5001 discrete values from 0 to 5000 seeds m^{-2}. The land use state variable reflects whether the land was previously fallow, cropped to sorghum or cropped to wheat. This state variable is a necessary inclusion to account for the rotational constraints discussed above. The land use variable assumes a discrete value between 1 and 14 to represent previous land use.

Stage return function

The stage return is measured as the gross margin of the decision for the seed bank and land use state value combination and is given by

$$\pi = PR_t Y_t - C(k_t) \tag{8}$$

where π is the stage return, PR_t is the commodity price, Y_t is yield, $C(k_t)$ is the cost of producing the decision k in the current stage. $C(k_t)$ is a function of both the variable cost of production and the cost of the weed control.

Wheat yield loss from wild oats is a function of the density of mature wild oat plants. The yield (Y) of a weedy crop (Cousens *et al* 1986) is given by equation (9).

$$Y = Y^{max} \chi(W) \tag{9}$$

where Y^{max} is the yield in the absence of weeds, W is the weed density (plants m^{-2}) and $\chi(W)$ is a yield loss function. W is determined from equation (3). It has been argued by Cousens (1985) that the yield loss function is a hyperbola of the following form.

$$\chi(W) = 1 - W/(\phi^{-1} + \rho W^{-1}) \tag{10}$$

where ϕ is the proportional yield reduction per unit weed density at low levels of infestation and ρ is a constant which determines the way in which proportional yield loss changes with weed density. For this study the values of these parameters are $\phi = 104.4$ and $\rho = 1.22$ (Martin, Cullis and McNamara 1987).

The rates and cost of the herbicide treatments, active ingredients plus application costs, are given in Table 4. Wheat and sorghum prices were calculated as five year averages over the period 1990-91 to 1994-95 (ABARE 1995). Variable costs for wheat and sorghum and sorghum yield were derived from Patrick (1996) and Scott (1996) while wheat yields were obtained from I. Collett (pers. comm.).

Table 4: Data used in the dynamic programming model

Wheat price ($ t^{-1})	133.00
Sorghum price ($ t^{-1})	139.00
Weed free wheat yield - first year following fallow (t ha^{-1})	3.5
Weed free wheat yield - second year following fallow (t ha^{-1})	2.8
Weed free wheat yield - third year following fallow (t ha^{-1})	2.1
Sorghum yield (t ha^{-1})	3.75
Phytotoxicity - plant kill (%)	1.00
Phytotoxicity - plant kill (%)	2.00
Wheat variable cost ($ ha^{-1})	118.38
Sorghum variable cost ($ ha^{-1})	154.04
Winter fallow variable cost ($ ha^{-1})	31.08
Herbicide rate plant kill - tri-allate (L ha^{-1})	2.00
Herbicide rate seed kill - flamprop-methyl (L ha^{-1})	2.25
Herbicide cost - plant kill ($ ha^{-1})	25.40
Herbicide cost - seed kill ($ ha^{-1})	19.31

Phytotoxicity[3] of between 0 and 10 percent can occur with the application of herbicides in winter cereals. For the purpose of this analysis, phytotoxicity of 1 percent and 2 percent are assumed for plant kill and seed kill treatments respectively (Table 4). The combined plant and seed kill treatment is thus 3 percent. These are mean values and can vary depending upon the season and wheat cultivar sown.

State transformation function

The seed bank state variable is defined by the transformation function given in equation (7) which is itself derived from equations (2) to (6).

The land use is a deterministic state variable assuming a value of 1,2,3,...,14 indicating fallow, sorghum, wheat year 1 with no control,..., wheat year 3 with plant and seed kill (Table 3). Its transition from stage to stage is dependant upon the decision in the previous stage and is given by the following transformation function.

$$L_{t+1} = k_t \qquad k_t = 1,2,\ldots,14 \qquad (11)$$

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[3] Phytotoxicity is a side-effect from the application of a herbicide whereby there is some yield damage imposed upon the crop.

[illegible]

Recursive equation

The objective of the model is to maximise the net present value (NPV) of net returns from a hectare of land, subject to the constraints imposed by the state variables. The recursive equation of the wild oat dynamic programming model is given by the following equation.

$$V_t(SB_t,L_t) = \max_{k} [\pi(SB_t,L_t) + \beta V_{t+1}(SB_{t+1},L_{t+1})] \tag{12}$$

where

$V_t(.)$ = the maximum present value of net returns from year t to the end of the planning horizon (T=15)

SB_t = the size of the seed bank (seeds m^{-2})

L_t = the previous land use

k = the decision variable

$\pi(.)$ = the immediate returns associated with the k-th decision alternative

β = the discount factor (0.909 = 1/1+0.1)

It is assumed that the terminal value equals zero, i.e. at t=15, $V_{t+1}(.) = 0$.

DYNAMIC PROGRAMMING MODEL RESULTS

Analysis of alternative control scenarios

The solution of the recursive equation provides the optimal policy and NPV of returns for all combinations of states and stages. The results of the model were determined for initial seed bank densities of 1000, 2000 and 3000 seeds m^{-2} to reflect the ranges of weed invasion.

Three separate control strategies were then evaluated, referred to as scenarios 1, 2 and 3 respectively. The first is a therapeutic scenario, where weed control is by the routine application of herbicides in wheat to improve yield in the current year, while the latter scenarios are the prophylactic control options (i.e. integrated weed control strategies to reduce seed populations) . These are discussed as follows:

- Scenario 1: No access to either seed kill control or sorghum. This confines the control of wild oats in wheat to the traditional practices of pre-emergence and post-emergence herbicides and fallow.
- Scenario 2: Access to both seed kill control and sorghum.
- Scenario 3: No access to sorghum. Here the decision maker is confined to a wheat-fallow rotational system but with access to both plant kill and seed kill control options. This scenario is included to reflect the fact that not all farms in the study region can, or wish to, participate in summer cropping. Reasons for this include unsuitable soil types, lack of management skills, and the highly variable net returns from sorghum being a deterrent to its production by risk averse farmers.

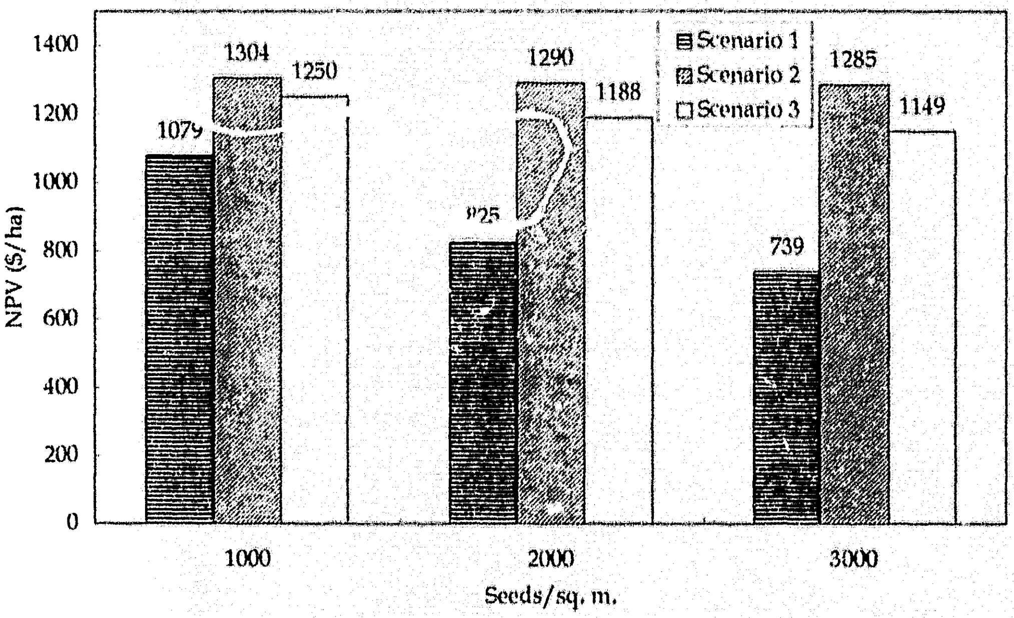
The starting point of the recursive equation assumes that the previous land use (year 0) was wheat, hence the first decision that can be chosen is winter fallow. This is a realistic condition given the seed densities being evaluated.

Net present value

The NPVs for scenarios 2 and 3 were consistently greater than for scenario 1 for all initial seed bank sizes considered (Figure 5). The difference in NPV between scenario 1 and the latter 2 scenarios varied between 16 and 74 percent, depending upon the initial seed bank and the scenario. This result suggests that the two prophylactic scenarios are economically superior to a therapeutic control of wild oats, thus leading to an acceptance of the primary null hypothesis.

The NPV of scenario 2 was consistently greater (between 4 and 12 percent depending upon initial seed bank) than scenario 3. The principal reason for this difference was the higher returns associated with a sorghum rotation when compared to wheat which was infested with wild oats early in the planning horizon.

Figure 5: NPV of optimal policies for various control scenarios and initial seed banks



Seed bank density and optimal rotation policy

For the 3 initial seed bank densities considered, scenario 1 had a consistently greater seed population over the planning horizon than scenarios 2 and 3 (Figures 6, 7 and 8). Scenario 3 had a marginally lower seed bank size than scenarios 2. Given that this scenario was determined to have a lower NPV than scenario 2 the secondary hypothesis was rejected.

For scenario 1 the optimal policy was a fallow-wheat-wheat rotation, with a plant kill treatment in the wheat phase of the rotation for all seed densities (Table 5). The exception to this rule was in years 12, 14 and 15 of the 1000 seeds m^{-2} case where the seed bank was low enough not to warrant weed control. There was a gradual decline in the seed bank over the planning horizon which was predominantly attributable to the clean winter fallow. Increases in the seed bank occurred during the years when wild oats in wheat were controlled by plant kill. Despite the decline in the seed bank, seed densities remained unacceptably high in most cases (except for the 1000 seeds m^{-2} scenario from year 8) which would lead to a significant yield impact from wild oat infestations.

Table 5: Optimal decisions for the scenario 1

	Initial Seed bank (seeds m^{-2})		
Year	1000	2000	3000
1	fallow	fallow	fallow
2	wheat (plant kill)	wheat (plant kill)	wheat (plant kill)
3	wheat (plant kill)	wheat (plant kill)	wheat (plant kill)
4	fallow	fallow	fallow
5	wheat (plant kill)	wheat (plant kill)	wheat (plant kill)
6	wheat (plant kill)	wheat (plant kill)	wheat (plant kill)
7	fallow	fallow	fallow
8	wheat (plant kill)	wheat (plant kill)	wheat (plant kill)
9	wheat (plant kill)	wheat (plant kill)	wheat (plant kill)
10	fallow	fallow	fallow
11	wheat (plant kill)	wheat (plant kill)	wheat (plant kill)
12	wheat (no control)	wheat (plant kill)	wheat (plant kill)
13	fallow	fallow	fallow
14	wheat (no control)	wheat (plant kill)	wheat (plant kill)
15	wheat (no control)	wheat (plant kill)	wheat (plant kill)

For scenario 2 the optimal rotation policy differed depending on the size of the initial seed bank (Table 6). At a density of 1000 seeds m^{-2} the optimal policy was fallow-sorghum followed by fallow-wheat-wheat with a plant kill treatment in the first wheat crop. After this the seed bank was low enough that no further weed control was economic. At initial densities of 2000 and 3000 seeds m^{-2} the optimal policy was fallow-sorghum-fallow-sorghum followed by the fallow-wheat-wheat rotation without weed control. The seed bank dynamics for the optimal policies indicate that, regardless of the size of the initial seed bank, seed density can be reduced to close to zero by year 6. At the higher seed densities the use of sequences of fallow and sorghum in a rotation is effective in reducing the population of wild oats.

Table 6: Optimal decisions for scenario 2

	Initial Seed bank (seeds m^{-2})		
Year	1000	2000	3000
1	fallow	fallow	fallow
2	sorghum	sorghum	sorghum
3	fallow	fallow	fallow
4	wheat (plant kill)	sorghum	sorghum
5	wheat (no control)	fallow	fallow
6	fallow	wheat (no control)	wheat (no control)
7	wheat (no control)	wheat (no control)	wheat (no control)
8	wheat (no control)	fallow	fallow
9	fallow	wheat (no control)	wheat (no control)
10	wheat (no control)	wheat (no control)	wheat (no control)
11	wheat (no control)	fallow	fallow
12	fallow	wheat (no control)	wheat (no control)
13	wheat (no control)	wheat (no control)	wheat (no control)
14	wheat (no control)	fallow	fallow
15	wheat (no control)	sorghum	sorghum

The use of sorghum as a wild oats control measure was generally replaced by wheat with a combined plant and seed kill in scenario 3 (Table 7). At an initial seed density of 1000 seeds m^{-2}, wheat with combined plant and seed kill followed the first fallow and was then succeeded by wheat with plant kill. The fallow-wheat-wheat rotation with no weed control was then established. For the 2000 and 3000 seeds m^{-2} cases, the first 2 wheat crops following fallow were treated with a combined plant and seed kill control. The fallow-wheat-wheat rotation with no weed control was then adopted. The wild oats population was significantly reduced over the time horizon under this scenario, with the seed bank close to zero by year 5.

Table 7: Optimal decisions for scenario 3

	Initial Seed bank (seeds m^{-2})		
Year	1000	2000	3000
1	fallow	fallow	fallow
2	wheat (plant and seed kill)	wheat (plant and seed kill)	wheat (plant and seed kill)
3	wheat (plant kill)	wheat (plant and seed kill)	wheat (plant and seed kill)
4	fallow	fallow	fallow
5	wheat (no control)	wheat (no control)	wheat (no control)
6	wheat (no control)	wheat (no control)	wheat (no control)
7	fallow	fallow	fallow
8	wheat (no control)	wheat (no control)	wheat (no control)
9	wheat (no control)	wheat (no control)	wheat (no control)
10	fallow	fallow	fallow
11	wheat (no control)	wheat (no control)	wheat (no control)
12	wheat (no control)	wheat (no control)	wheat (no control)
13	fallow	fallow	fallow
14	wheat (no control)	wheat (no control)	wheat (no control)
15	wheat (no control)	wheat (no control)	wheat (no control)

Herbicide applications

The cumulative application of herbicides (active ingredient L ha^{-1}) are presented in Figure 9. Under scenario 1, quite high applications of tri-allate are made over the planning horizon (14 to 20 L ha^{-1}). The cumulative application of herbicides is dramatically reduced under both scenario 2 (5.6 to 7.2 L ha^{-1} of Atrazine® and tri-allate) and scenario 3 (6.25 to 8.5 L ha^{-1} of tri-allate and flamprop-methyl). Therefore, a range of unquantified social benefits can be attributed to the optimal weed control policies which are additional to those measured in this study.

Figure 6: Derived seed bank dynamics for 1000 seeds m^{-2}

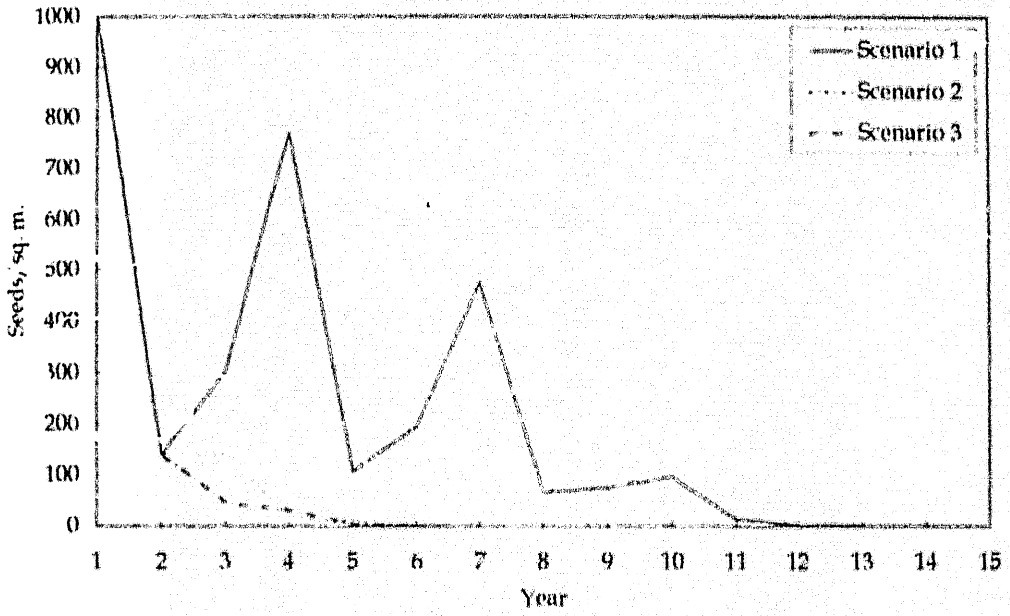


Figure 7: Derived seed bank dynamics for 2000 seeds m^{-2}

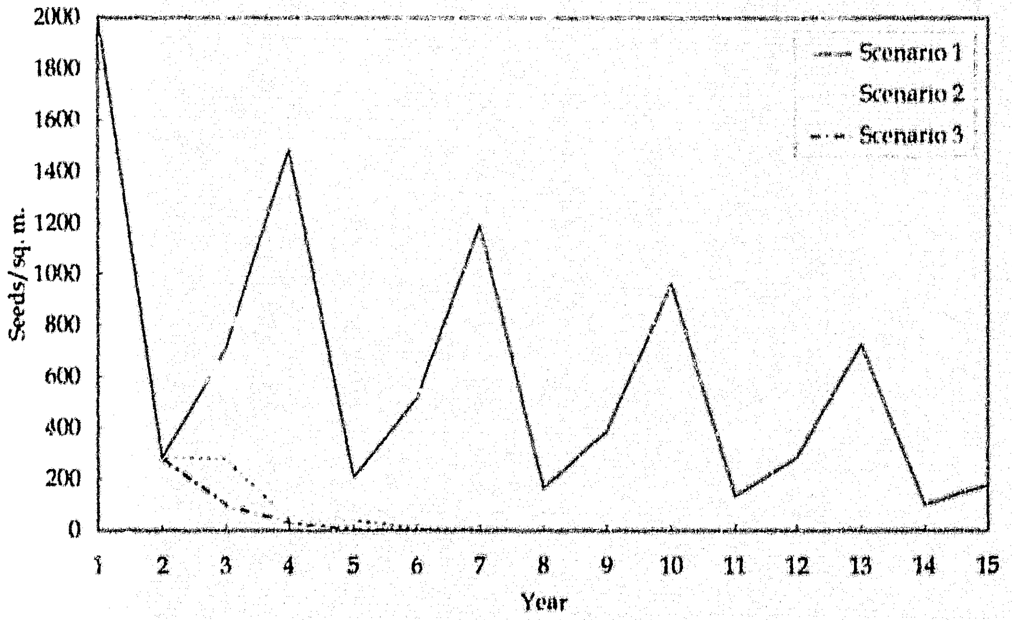


Figure 8: Derived seed bank dynamics for 3000 seeds m^{-2}

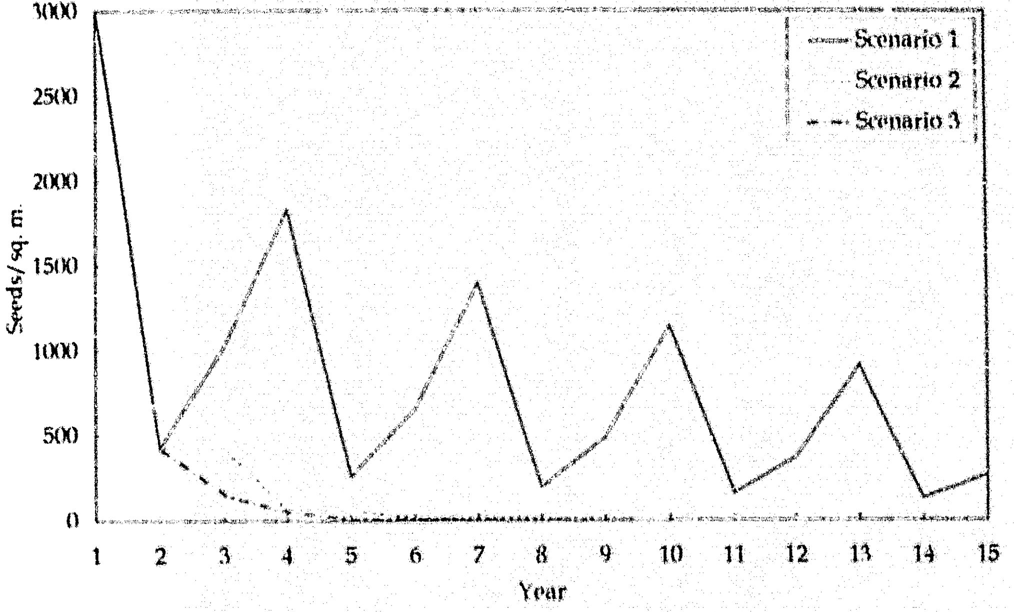
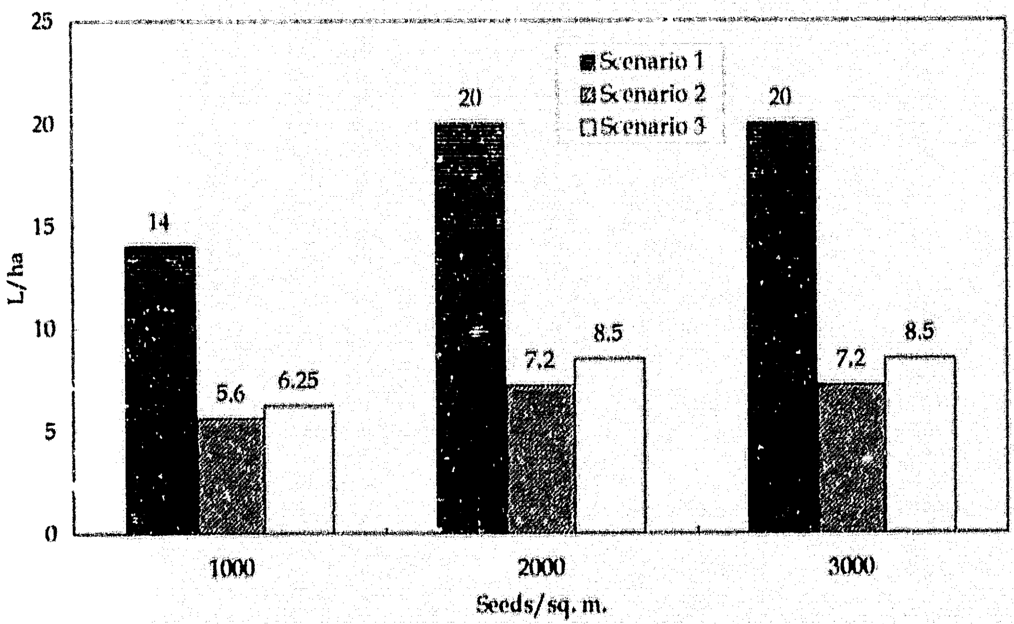


Figure 9: Cumulative herbicide applications of optimal policies for various control scenarios and initial seed banks



Sensitivity analysis

Sensitivity analysis was applied to a number of parameters which were considered a priori to have an impact upon the results. These were the discount rate, the weed free wheat yield, commodity prices, and wild oat plant mortality and seed rain survival rates. The fecundity equations estimated by Medd, Nicol and Cook (1995) were an important determinant of the seed bank dynamics, however, there was no information to guide how these parameters may change. Thus no sensitivity analysis was applied to these functions. The sensitivity analysis is reported for the 2000 seeds m^{-2} initial seed bank density for the 3 scenarios. For brevity in reporting only the one initial seed density was considered. It is the authors opinion that this provides an adequate reflection of the sensitivity of the 3 seed bank densities to the changed parameters.

Discount rates

If the economy continues with the current trend of low inflation and lowering interest rates it is probable that the appropriate discount rate will be less that used in the analysis. Consequently, the discount rate was reduced from 10 to 5 percent to test the sensitivity of the results to this parameter. There was no change to the optimum rotation policy or seed bank for any of the 3 scenarios. The NPV increased, as expected, to \$1181 ha^{-1} for scenario 1, \$1819 ha^{-1} for scenario 2 and \$1714 ha^{-1} for scenario 3.

Weed free wheat yield

The weed free wheat yield used in the analysis is a mean value, however, the probability distribution associated with this parameter for the study region is expected to be non-normal and skewed to the right for a range of climatic and management reasons. A weed free yield of 4 t ha^{-1} was used to test the sensitivity of the results to higher wheat yields. For scenarios 1 and 3 there was no change to either the optimum rotation policy or the seed bank. For scenario 2 the sorghum and fallow in years 3 and 4 of the base results were substituted for 2 years of wheat with plant kill. This was then followed by the fallow-wheat-wheat sequence with no weed control. There was no change to the seed bank for this scenario. The NPVs were \$1054 ha^{-1}, \$1499 ha^{-1} and \$1461 ha^{-1} for scenarios 1, 2 and 3 respectively.

Wheat and sorghum price

Five year average commodity prices were used in the study, however, current wheat and sorghum prices are considerably higher than the averages used. The model was resolved using the current prices of \$175 t^{-1} for wheat and \$160 t^{-1} given in Patrick (1996) and Scott (1996) to test the robustness of the results to alternative prices. The outcome of this sensitivity testing was the same as for higher wheat yield. There were no changes to the rotation and seed bank for scenarios 1 and 2, and the changed optimum rotation for scenario 3 was the same as for the wheat yield of 4 t ha^{-1} sensitivity test. The NPVs were \$1332 ha^{-1}, \$1833 ha^{-1} and \$1792 ha^{-1} for the 3 scenarios.

Plant mortality

The plant mortality of wild oat seedlings is heavily dependant upon seasonal conditions. There was little information, however, to provide a useful guide as to how plant mortality may vary so a 10 percent reduction in the mortality rate for each cohort and control option was imposed. For scenario 1 the effect of this change was significant. The optimum rotation policy remained the same, however, the final seed bank in year 15 increased from 425 seeds m^{-2} in the base results to 2370 seeds m^{-2}. The NPV for scenario 1 was almost halved to \$467 ha^{-1} due to the higher mature weed densities and the resultant negative impact upon yield

For scenario 2 the impact of this changed parameter was negligible given the selection of sorghum in the rotation as a weed control measure. For scenario 3, the only change to the optimum rotation was to substitute wheat with no control in year 4 for wheat with plant kill. The seed bank was marginally higher for this change and the NPV was reduced to \$1129 ha^{-1}.

Seed rain survival
Seed rain survival is also dependant upon seasonal conditions and, as with plant mortality, due to a lack of information to provide an alternative guide the survival rates of seed rain were increased by 10 percent. As with the sensitivity analysis of plant mortality, the major impact of this parameter change was experienced by scenario 1. The seed bank in year 15 was 1901 seeds m^{-2} and the NPV was reduced to \$679 ha^{-1}. There was no impact upon scenario 2 as wheat production did not take place in the rotation until the wild oat seed bank was driven to zero. For scenario 3 the optimum rotation was unchanged but the seed bank was marginally higher than for the base results. The NPV was reduced to \$1176 ha^{-1}.

SUMMARY AND CONCLUSIONS

The primary objective of this paper was to estimate the economic benefits associated with an integrated weed management approach for wild oats in northern NSW involving chemical and non-chemical controls. The paper presented a framework for assessing the population dynamics of wild oats and used a simulation model to trace through time the impact upon the seed bank of various control options. This indicated that options involving a seed kill technology generally resulted in rapid declines in the seed bank. The results of the simulation model for the traditional reliance of plant kill technology showed a continued increase in the seed bank density in a continuous wheat system. This demonstrated the ineffectiveness of this approach alone to manage seed populations.

A dynamic programming model was developed to economically assess a range of control options over a 15 year time horizon. The options included a number of herbicide technologies along with rotational options of winter fallow and sorghum. The results of the dynamic programming model suggest it is economic to reduce wild oat infestations by adopting an integrated management approach by utilising fallow and summer cropping where possible. In farming systems where summer cropping is not considered an option, seed bank populations can be reduced with fallow and combined plant and seed kill herbicide treatments, however, the returns from this system were slightly less than rotations involving sorghum. The results of the study support the findings of Pandey and Medd (1990), that seed kill alone is not a viable tactic, as the dynamic programming model never selected seed kill by itself.

The primary hypothesis, that a prophylactic management of populations will result in higher economic returns than a therapeutic treatment of weed problems was accepted. Control options that targeted seed production (scenarios 2 and 3) gave higher economic returns over the 15 year time horizon than the traditional therapeutic control system of fallow and plant kill (scenario 1). The secondary hypothesis, that the treatment which results in the lowest seed bank yields the greatest economic benefits, was not accepted. For each initial seed bank density the wheat only rotations in scenario 3 resulted in both lower seed bank values and NPVs than for scenario 2.

Two general conclusions that can be drawn from this analysis. First, winter fallowing and summer crops such as sorghum are economic and effective weed control measures when wild oat seed bank densities are high. Second, in farming systems where summer cropping is not possible the use of seed kill with traditional weed control measures such as plant kill and winter fallow can dramatically reduce the wild oats seed bank and lift economic returns over the long term.

Sensitivity analysis was applied to the discount rate, weed free wheat yield, commodity prices, wild oat plant mortality and seed rain survival. The results of these tests indicate that the general results and conclusions drawn, particularly with respect to the performance of the prophylactic controls, are robust to these parameter changes.

This paper is an advancement on earlier work in that it adopts an integrated weed management framework and considers both herbicide and non-herbicide strategies aimed at killing wild oat seed. The work by Pandey and Medd (1990) did not consider non-herbicide options for controlling wild oat seed production, while the fallow/rotation studies only considered plant kill herbicide strategies for comparison. Moreover, this study was able to include the results of more recent research which gives the efficacy of the seed kill technology (Medd, Nicol and Cook 1995) which was not available to Pandey and Medd (1990, 1991).

Areas for further work include consideration of additional decision alternatives, such as lucerne and pastures, and adaptation of the model for southern cropping systems where summer cropping is not a viable alternative. An important extension of the model is the inclusion of stochastic state variables, particularly climate[4] and commodity prices. The latter extension is a priority area for application to general weed control problems in the cropping regions of southern Australia.

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