What are the future benefits of a change in the weed seedbank?

Randall E. Jones[1,3], Oscar J. Cacho[2,3] and Richard W. Medd[1,3]
[1] NSW Agriculture, Forest Road, Orange, New South Wales 2800, Australia
[2] Faculty of Economics, Business and Law, University of New England, Armidale, NSW 2351, Australia
[3] Cooperative Research Centre for Australian Weed Management

Summary An economic framework that is appropriate for measuring the long-term economic benefits from weed control technologies is presented. The key concept is the treatment of the weed seedbank as a renewable resource stock, with any changes in the stock of the seedbank resource having future economic implications. A reduction in the seedbank in any period will result in future economic benefits, and conversely any increase in the seedbank will lead to future economic costs. A population dynamics model was linked to a numerical optimal control model and solved for a 20-year period to determine optimal weed management strategies for two weeds; wild oats (*Avena* spp.) and wild radish (*Raphanus raphanistrum*). Two weed control options were assessed; a traditional post-emergence herbicide representing a 'plant kill' approach to weed management, and a late season selective spray-topping herbicide treatment representing a 'seed kill' approach to weed management. An important contribution of this approach is the economic value placed on each seed entering the seedbank and how this value is affected by weed species, weed population management approach, and the initial size of the seedbank.

Keywords Population dynamics, IWM, optimal control model, renewable resource, economic benefits.

INTRODUCTION

It is well understood that increases in the plant density of a weed leads to economic costs due to yield losses and lower crop returns. This is the principle justification for a range of weed control measures aimed at preserving yield and increasing crop returns. Less well understood is the concept that new weed seeds added to the seedbank from uncontrolled weeds also incur an economic cost. This economic cost per seed results from potential yield losses and/or increased control costs in later seasons due to the carryover of the weed seedbank.

It is important to account for the carryover effects of a weed control technology to properly measure the economic benefits and costs from a change in future weed populations (Jones and Medd 2000). This can be achieved using an economic framework that treats the weed seedbank as a renewable resource, the stock of which changes due to management practices.

Traditional herbicide treatments at the post-emergence stage of the life-cycle represent a 'plant kill' approach to weed management. The goal of such technologies is to maintain and conserve crop yield. In contrast, the goal of 'seed kill' technologies is to minimise seed input so as to achieve a reduction in the weed seedbank over time. Such technologies are an important component of a population management approach to weed control.

The objectives of this paper are as follows:

- Present an economic framework for assessing the long-term benefits of weed control technologies.
- Estimate the economic value of any change in the weed seedbank.
- Determine the economic value of 'seed kill' approaches to weed population management.

MATERIALS AND METHODS

A dynamic economic framework When the weed seedbank is treated as a resource stock the weed management problem is how much of the weed stock should be depleted in the current period and how much should be allowed to be carried forward to the future, either from new seed input or from carryover of non-germinated seeds. The greater the stock of weed seeds now, the greater will be the stock of seeds and economic impact in the future.

A simple two-period diagrammatical concept can be used to present the optimal allocation of a weed seedbank resource stock through time (Figure 1).

Although restriction to two periods may appear an unrealistic representation of the problem, the diagram illustrates the fundamental economic concepts. The framework can be extended to additional time periods using algebra. The horizontal axis represents the level of weed control (u) in the current year (t_0), which can be achieved by varying dose of a post-emergence herbicide or aggregating complementary weed control technologies onto an integrated weed management (IWM) strategy. The curves *MB* and *MC* represent the marginal benefits and marginal costs of control in t_0 given a specific initial weed seedbank. The single year optimum level of control is u_0. Weed control in t_0 will reduce the starting seedbank in the next year (t_1). Therefore, weed control in the current year will have a positive effect upon revenue in year t_1. The curve *MFB* represents the marginal future benefit from control in year t_0 due to the reduction in the future seedbank from what it otherwise would have been. Combining *MB* and *MFB* determines the total marginal benefit (*TMB*) from control in year t_0, and the optimal inter-temporal level of control, u_1, is determined by the intersection of *TMB* and *MC*. This illustrates that the optimal level of weed control is greater when the seed carryover effects from weed management are economically valued.

The optimal control model A numerical optimal control (NOC) model was developed to determine optimal weed management decision rules and their effect upon the resource stock (i.e. the weed seedbank). The NOC model analysis had two objectives. First, to compare the optimal herbicide decision rules and long-term effects upon the weed seedbank and economic returns from the adoption of either static (i.e. single year) or inter-temporal (i.e. multiple years) decision-making frameworks for a post-emergence (PE) herbicide. This is a traditional 'plant kill' approach to weed management. Second, to derive optimal herbicide decision rules and economic benefits from adopting a 'seed kill' technology in addition to the 'plant kill' technology. The 'seed kill' technology was represented by a selective spray-topping herbicide (SST). The following scenarios were designed to evaluate these objectives.

STATIC: PE herbicide only from a static model
PE: PE herbicide only
PE+SST: PE herbicide plus a SST herbicide

The decision variable for each scenario was the optimal dose of a PE herbicide for a given seedbank. Herbicide dose is used as a proxy for the desired level of weed control and is allowed to range beyond the recommended dose. However, the results from this analysis do not lead to a recommendation for increasing or decreasing herbicide doses from the registered rate but signify the need for higher levels of weed control intervention. The variable *u* is used in the NOC model to represent the PE herbicide dose decision so as to maintain consistency with the use of the variable in Figure 1 where it represents the optimal level of weed control.

The rationale for the STATIC and PE scenarios is to show the impact upon the optimal decision rules from adopting static or inter-temporal decision making frameworks. The NOC model parameters were identical for both scenarios except for STATIC the model was solved for a single year instead of the 20-year simulation. The economic potential of a 'seed kill' technology was obtained by comparing the outcomes for the scenarios PE and PE+SST. The analysis applied the scenarios to the problem of separately managing wild oats and wild radish populations.

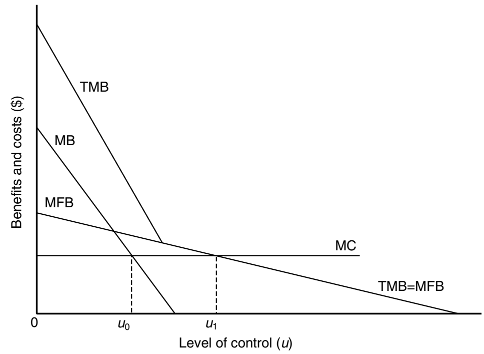

Figure 1. Optimal inter-temporal level of weed control when marginal costs (MC), marginal benefits (MB), marginal future benefits (MFB) and marginal total benefits (TMB) are considered.

For the NOC model the dynamic weed problem is stated as:

$$(1)\ \max PV = \max_{u_t} \left\{ \sum_{t=0}^{T} \beta^t \pi(SB_t, u_t) \right\}$$

subject to:

$$(2)\ \Delta SB_t = SB_{t+1} - SB_t = f(SB_t, u_t)$$

$$(3)\ SB_0 = SB(0)$$

where *SB* is the value of the weed seedbank resource (i.e. the state variable), *u* is the PE herbicide dose rate (representing the level of weed control), *PV* is the present value of financial returns, π is the net profits, β is the discount factor (i.e. 1/1+*dr*), *dr* is the discount rate (5%), ΔSB_t is the change in the weed seedbank and *SB*(0) is the initial weed seedbank in year t_0. The first step in solving this problem is to define the Hamiltonian (*H*) function:

$$(4)\ H_t = \pi(SB_t, u_t) + \beta\lambda_{t+1} f(SB_t, u_t)$$

The Hamiltonian is the net profit obtained from an existing level of the state and control variables plus the value of any change in the stock of the state variable valued at the costate variable (λ_{t+1}). The Hamiltonian can be simplified as follows:

$$(5)\ H_t = \pi_t + L_t$$

where $L_t = \beta\lambda_{t+1}\Delta SB_t$, the future benefit from weed control. The value of λ associated with weed seedbanks is always negative. This is due to the interaction between λ and ΔSB_t, and consequently the value of *H*. The variable ΔSB_t can take either positive (i.e. seedbank increasing) or negative (i.e. seedbank decreasing) values. If we accept the principle that $\lambda_{t+1} < 0$ then the following conditions will apply:

- If $\Delta SB_t < 0$ then $L_t > 0$ and H_t is increased.
- If $\Delta SB_t > 0$ then $L_t < 0$ and H_t is decreased.

These rules state that if the seedbank declines as a result of a decision then there is some future benefit from that decision as L_t is positive. If the seedbank increases there is some future cost as L_t will be negative.

Equation (2) is known as the equation of motion and is represented by a population dynamics model (Jones and Medd 1999, 2000). The population dynamics model was developed to determine the impact of control options upon the seedbank and used the following general equation to trace changes in the seedbank over a generation.

$$(6)\quad SB_{t+1} = SB_t g(1-mm)(1-hm)(1-dm)r(1-sm) + SB_t(1-g)(1-sd)$$

where g is germination, mm is mortality from cultivation, hm is herbicide induced mortality, dm is density-dependant mortality, r is production of seeds, sm is mortality of new seeds and sd is decay of non-germinated seeds in the soil.

Mortality from a PE herbicide was based upon a logit dose response function estimated by Pandey (unpublished).

$$(7)\quad hm = \frac{\exp\left[a_1 + a_2 \log(u)\right]}{1 + \exp\left[a_1 + a_2 \log(u)\right]}$$

The PE dose is assumed to be diclofop-methyl for wild oats and bromoxynil for wild radish. No data was available to estimate a dose response function for bromoxynil in wild radish, so parameter values were chosen to derive a function that fitted field experience. The dose response coefficients used along with the recommended label (u_{label}) rates are given in Table 1.

The SST herbicides chosen were flamprop-m-methyl for wild oats and flumetsulam for wild radish. These two herbicides were selected as they are registered for this purpose and there are herbicide resistance benefits as they are from different chemical groups than the selected PE herbicides. The registered rates of the SST herbicides are 2.25 L ha^{-1} for flamprop-m-methyl and 25 g ha^{-1} for flumetsulam. The seed rain mortality from the SST herbicides was assumed to be 95%.

The net profit component of the Hamiltonian function was calculated as follows,

$$(8)\quad \pi = P_y(Y_{WF}\, Y_L) - VC - P_u u - P_{SST}$$

where P_y is crop price (\$180 ha^{-1}), Y_{WF} is the weed-free yield (4 t ha^{-1}), VC is the crop variable cost (\$304 ha^{-1}), P_u is the herbicide input costs (\$18.75 L^{-1} for diclofop-methyl; \$14.80 L^{-1} for bromoxynil) and P_{SST} is the cost of the SST herbicide (\$28.38 ha^{-1} for flamprop-m-methyl; \$17.75 ha^{-1} for flumetsulam). The yield loss function (Y_L) is based upon Cousens (1985) and the function and parameter values are given in Jones and Medd (1999, 2000). The value of P_{SST} is set to zero for STATIC and PE as these scenarios do not include a SST herbicide. In the case of STATIC, $H_t = \pi$ as L_t was set to zero.

RESULTS

The PE scenario resulted in higher optimal doses (u^*) than the STATIC scenario (Tables 2 and 3). The divergence in the optimal dose rates between these two scenarios was consistent for all wild oats and wild radish seedbanks considered.

For scenario PE+SST, the inclusion of an additional weed control technology in the form of a SST herbicide reduced the optimal PE herbicide dose rates compared to those obtained for PE. These results indicate the choice of weed control technologies included in an IWM strategy can have an impact upon the optimal level of usage of each technology.

The λ values represent the economic value of a marginal change in the weed seedbank calculated at various seedbank levels. For example, at a wild oats seedbank of 100 seeds m^{-2} the PE scenario indicates that an additional seed added to the seedbank will result in a future additional cost of \$1.48 seed^{-1}. The results indicate that as the weed seedbank declines the negative values of λ increase.

The effect of the relationship between π and L in determining the value of H is illustrated in Figure 2 for wild oats and wild radish seedbanks of 1000 seeds m^{-2}. The value of L is negative over some of the dose rate range (1.8 L ha^{-1} for wild oats and 2 L ha^{-1} for wild radish), and increases with the dose rate but at a diminishing rate. The value of π increases with dose until a maximum is reached, which coincides with the optimum according to STATIC (4.0 L ha^{-1} for wild oats and 1.8 L ha^{-1} for wild radish). The function H also increases with the dose rate, but achieves an optimum

Table 1. Selected herbicide dose parameter values.

	Units	Wild oats	Wild radish
a_1		1.462	2.5
a_2		1.496	1.5
u_{label}	L ha^{-1}	1.5	1.0

Table 2. Optimal control variable (u^*) and costate variable (λ) values for selected wild oats seedbanks from NOC model.

	STATIC	PE		PE+SST	
SB seeds m^{-2}	u^* L ha^{-1}	u^* L ha^{-1}	λ \$ seed^{-1}	u^* L ha^{-1}	λ \$ seed^{-1}
0	0.00	0.00		0.00	
50	1.12	1.85	-1.54	1.31	-1.19
100	1.55	2.75	-1.48	1.77	-0.90
500	3.03	5.49	-0.78	3.29	-0.42
1000	3.97	6.54	-0.46	4.20	-0.30
5000	7.04	8.53	-0.13	7.23	-0.16

(6.5 L ha^{-1} for wild oats and 2.3 L ha^{-1} for wild radish) at a significantly higher dose than for π. This is due to the influence of the increasing L. Beyond this point the reduction in π from increasing dose exceeds the gains from an increasing L, and consequently H declines.

DISCUSSION

The results of the analysis from the NOC model showed that there are significant differences between static and inter-temporal decision making frameworks for the management of wild oats and wild radish. The inclusion of the future economic benefits from weed control indicates the need for a higher level of control than if only the current period benefits were considered.

The model showed that a weed seed added to the seedbank has a greater marginal impact when there are few weed seeds present. When the seedbank is large an additional weed seed will have a negligible effect upon future economic returns, as the damage from existing weed populations is already significant. Importantly, the lower λ values for PE+SST suggest that the costs of seed input can be mitigated to some extent by the adoption of 'seed kill' technologies.

The model resulted in the significantly higher optimal dose rates for all scenarios than is registered for the two herbicide-weed case studies. These results do not lead to a recommendation for high PE herbicide doses for these two weeds. What the results do suggest is that the optimal level of weed control for a given seedbank is significantly higher than that which can be obtained from just the use of these PE herbicides at the registered rate. Consequently, it can be concluded that the optimal inter-temporal levels of weed control are unlikely to be achieved solely through the application of traditional PE herbicides. This implies that an IWM approach, with particular emphasis upon 'seed kill' technologies, is necessary in this case study to achieve long-term benefits from weed population management.

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Table 3. Optimal control variable (u^*) and costate variable (λ) values for selected wild radish seedbanks from NOC model.

	STATIC	PE		PE+SST	
SB seeds m^{-2}	u^* L ha^{-1}	u^* L ha^{-1}	λ \$ $seed^{-1}$	u^* L ha^{-1}	λ \$ $seed^{-1}$
0	0.00	0.00		0.00	
50	0.47	1.38	-1.09	0.54	-0.72
100	0.67	1.51	-0.63	0.73	-0.48
500	1.35	1.98	-0.18	1.40	-0.19
1000	1.80	2.32	-0.11	1.84	-0.13
5000	3.41	3.72	-0.04	3.43	-0.05

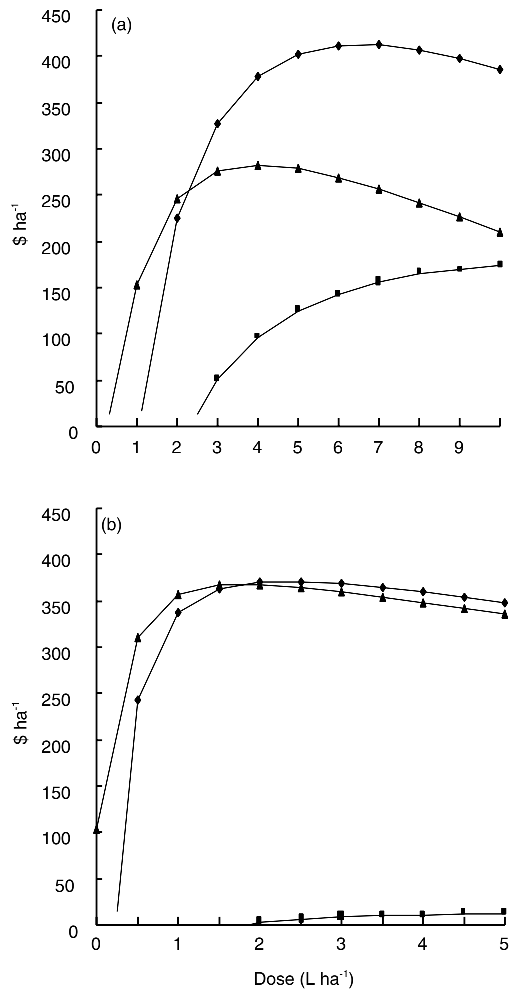

Figure 2. Derivation of the Hamiltonian (H) (♦), future economic benefit (L) (■) and net profit (π) (▲) of wild oats (a) and wild radish (b) from the NOC model where SB_t = 1000 seeds m^{-2}.