WHAT IS THE APPROPRIATE PARADIGM FOR MANAGING AND MODELLING WEED PROBLEMS: THE CASE FOR A LONGER TERM POPULATION MANAGEMENT

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Abstract There are a number of theoretical concerns with applying short-term, or static, approaches to weed management decision-making. An alternative is to adopt a population management approach where the carryover effects of decisions are taken into account. The focus of such an approach is to manage weed populations through time rather than minimise the yield effect of weeds in a single season. Rather than viewing weeds as an annual production problem, the weed seed bank can be considered a renewable resource stock and the management goal is to deplete this resource stock through time. The principles of natural resource economics illustrate that including the carryover effects of weed control will, for a given size of a seed bank, result in a greater level of weed control and a higher economic benefit than if control decisions were based solely on the current period effects. A dynamic economic model was developed of a continuous Australian cropping system to test these principles. The results suggest that a paradigm shift from short-term weed management to longer-term population management is warranted if appropriate integrated weed management strategies are to be developed.

INTRODUCTION

Weed control, particularly in cropping systems, is struggling with a paradox. On the one hand growers have resigned to live with weeds. This attitude implies a sense of inevitability that weeds can't be beaten, so control is focussed predominantly on conserving crop yield using herbicides. Moreover, there is a belief that striving for high efficacy has been counter productive – not only have populations failed to be contained, but burgeoning problems of herbicide resistance have resulted. On the other hand, growers are concerned at the cost of weed control and are seeking more efficient technology to moderate costs, hence the paradox

Here we contend that growers have become over-dependent on herbicides for weed control, and through neglect for other control options many problems have arisen. These include herbicide resistance, negative externalities from inappropriate herbicide use, diversification of weed floras and, above all, the persistence of weed populations which causes the need for recurring expenditure on control. Moreover, weed control decision-making and economic considerations adopted in weed management have failed to evolve appropriately or address this paradox.

This paper considers alternative economic approaches for modelling weed management, with a view to advancing systems towards more efficient management. It is hypothesised that weed control strategies that consider varying levels of weed control, carryover effects from a control decision and deploy control tactics are economically superior to myopic alternatives.

MODELLING APPROACHES / FRAMEWORKS

Economic models can be defined as being static (i.e. single season or year), dynamic (i.e. multiple seasons or years), deterministic (i.e. no uncertainty) or stochastic (i.e. includes uncertainty). In increasing order of complexity an individual model may be static and deterministic, static and stochastic, dynamic and deterministic, or dynamic and stochastic. Given the range of models and weed problems, it is pertinent to ask, what is an appropriate framework for modelling weed management? This will depend upon the particular weed management problem, and the questions being asked. Outlined below are the main distinguishing features of static and dynamic models. Although stochastic effects are important in weed management, the effects of including random variables are not addressed in any detail in this paper.

Static models The presence of weeds in a crop or pasture results in short term damage in relation to reduced yield, and in some cases reduced quality from product contamination. The actual yield loss is a function of the initial weed population (x) and the number of weeds killed, which is dependent upon the level of weed control (u). Consequently, yield (Y) is a function of weed-free yield (Y_w) and yield loss (Y_L) from weed density (i.e. $Y_L = f(x,u)$).

The yield loss is a proportional function, i.e. $0 \leq f(x,u) \leq 1$. Therefore:

$$Y = Y_w\left[1 - f(x,u)\right] \tag{1}$$

The goal of a grower is to maximise the returns from a crop or pasture. The profit function for this static deterministic problem is given in equation (2), where π is profit, P_y is crop price, P_u is the weed control cost, $g(x,u)$ is a function of the level of weed control, and C is the variable costs (excluding weed control).

$$\pi = P_y Y - P_u g(x,u) - C \tag{2}$$

The problem facing a grower is to determine how much to expend on weed control, i.e. the value of u, to maximises profit. This is usually solved numerically using budgeting or a mathematical programming algorithm, however, simple calculus can be used to demonstrate the general principles. The optimal level of control can be found by the following first-order condition, where the partial derivative of the profit function with respect u is set to zero.

$$\frac{\partial \pi}{\partial u} = P_y\left(\frac{\partial Y}{\partial u}\right) - P_u\left(\frac{\partial g}{\partial u}\right) = 0 \tag{3}$$

Equation (3) requires that for the optimal level of weed control, u^*, the revenue from a marginal change in weed reduction in the current period (i.e. $P_y(\partial Y/\partial u)$) equals the marginal cost of control (i.e. $P_u(\partial g/\partial u)$).

The simple economic threshold (ET) is probably the most common and recognised static model in weed management and has become entrenched within weed science as the defacto decision-making paradigm. The ET is defined as the weed density from where the financial benefits from controlling a weed exceed the costs of control. It is a binary decision making concept, where the choice is either to spray or not spray, with a single fixed herbicide dose. Despite its promotion as a vital component of integrated weed management (IWM), the ET has largely not been adopted by farmers. Czapar *et al*. (1997) reported that only 9% of corn and soybean farmers in Illinios used ET as a basis for weed management, whereas 45% of farmers based control decisions on the previous years weed problem. The major reasons for not using ET were concerns about weeds interfering with harvest (64%), landlord perception (38%), weed seed production (38%) and field appearance (36%). Czapar *et al*. (1997) concluded that weed thresholds that addressed long-term costs and benefits of weed control decisions might be more acceptable to farmers.

The myopic single-period basis to ET has been strongly criticised (Cousens 1987, Swinton and King 1994 and Wallinga and van Oijen 1997). In reality, decisions relating to weed control have carryover effects: weeds that escape control this season may reproduce and replenish the seed bank resulting in a greater weed burden in following seasons; herbicides may persist as residues and delay the planting of or affect future crops; buildup of certain species or residues may preclude the growing of particular crops in a rotation, or force a shift to grow less profitable crops.

The economic optimum threshold (EOT), which incorporates the weed population dynamics, was developed in response to the need to consider future changes in weed populations. A number of studies (Cousens *et al*. 1986, Doyle *et al*. 1986 and Bauer and Mortensen 1992) have determined the EOT to be significantly lower than the ET.

It has been argued that the use of a fixed herbicide dose associated with an ET may not be economically efficient in many circumstances (Pannell 1990). Since there is a curvilinear relationship between weed density and crop yield, an economic framework that allows for varying levels of control may be more appropriate. Such an approach addresses the 'how much' question of weed control, whereas the ET and EOT address a different question of 'when' should control be undertaken. Pannell (1990) presented a number of arguments for permitting flexibility in determining herbicide doses. These included the facts that: herbicide efficacy is affected by environmental conditions; the optimal dose may depend on factors such as commodity prices and crop yield; there are possibly herbicide resistance implications for different dose rates; and that farmers differ in their risk attitudes and may prefer different rates to hedge against uncertainty. There are additional realistic arguments to further extend the model frameworks to include other control options, or combinations of weed control methods, adding to the demand for more complex frameworks.

Dynamic models Dynamic models are so named as they trace the effects of decisions over time. Thus some of the main shortcomings (inability to capture carryover effects) of static (short term) frameworks can be overcome by adapting the concepts into a dynamic context.

From an economic perspective a weed can be viewed as a renewable resource with the seed bank representing the stock of this resource. The size of the seed resource stock changes through time due to depletion by weed management and new seed stocks being created via the process of self renewal through seed production. The change in the seed bank from one period to the next is described by equation (4) where *SB* is the density of seeds in the soil (seed bank), *S* is seedling recruitment, *M* is the seed loss due to predation and natural mortality and *N* is new seed added to the seed bank either from reproduction or importation through natural spread or operations such as harvesting and sowing.

$$SB_{t+1} = SB_t - S_t - M_t + N_t \tag{4}$$

The seed bank can be indirectly regulated by changing weed control inputs that target the mortality or vigour of plants (e.g. cultivation, herbicides), or directly through targeting reproduction and seed rain processes (e.g. selective spray-topping, crop-topping, seed catching, windrowing) or through losses via seed mortality (e.g. cultivation, stubble burning, predation).

In a dynamic setting the objective of the farmer is to determine the level of depletion of the seed bank from weed control in each season or year that maximises profit over a period of *T* years. The objective function can be formally stated as:

$$\max J = \sum_{t=0}^{T} \pi\left(x_t, u_t\right) \tag{5}$$

subject to

$$x_{t+1} - x_t = h\left(x_t, u_t\right) \tag{6}$$

where *J* is the net present value (NPV) of cumulative profits over the planning horizon *T*, π is a measure of annual farm profit, *x* is the state variable (i.e. weed seed bank), *u* is the weed control variable, and *h* is the rate of change in the state variable. Note that π in equation (5) is identical to its calculation in equation (2). Equation (6) is called a state equation and represents the change in the state variable from one period to the next. Equation (4) represents an example of a state equation.

The optimal annual levels of the control variable, u^*, that maximise the objective function *J* can be determined using optimal control theory. The first step is to define the Hamiltonian function:

$$H_t = \pi\left(x_t, u_t\right) + \lambda_{t+1} h\left(x_t, u_t\right) \tag{7}$$

The Hamiltonian function, *H*, is the net profit obtained from an existing level of the state variable (i.e. $\pi(.)$) plus the value of any change in the stock of the state variable valued at the shadow price, λ_{t+1}. The dynamic maximisation problem presented in equation (7) differs to the static maximisation in equation (2) in that the future income effects from current period decisions are explicitly included in the current period return. The determination of the optimal level of annual control, u^*, is obtained from solution of a number of necessary first-order conditions which won't be dealt in any detail here. One of these conditions is the maximum condition, which is calculated by setting the partial derivative of *H* with respect to *u* to zero.

$$\frac{\partial H(.)}{\partial u_t} = \frac{\partial \pi(.)}{\partial u_t} + \lambda_{t+1} \frac{\partial h(.)}{\partial u_t} = 0 \tag{8}$$

The first term of equation (8), $\partial p(.)/\partial u_t$, has the same interpretation as the static first-order condition in equation (3), i.e. the marginal benefit from control in the current period must equal the marginal cost. However, in the dynamic context there is a second term to be accounted for in determining the optimal u_t, $\lambda_{t+1}(\partial h(.)/\partial u_t)$, which reflects the influence of *u* on the change of the state variable. Therefore, this condition clearly states that in a weed control problem, any increase in the seed bank will have a negative impact on future revenue.

Adoption of a dynamic economic model that includes the carryover effects of weed management will result in a greater optimal level of annual control than if a static model (i.e. equations 2 and 3) was used to determine u^*. The cumulative economic benefits from implementing the decision rules from a dynamic model over a time horizon of *T* years will be greater than a strategy of each year implementing optimal static decision rules over the same period.

CASE STUDIES

Wild oats (*Avena* spp.) and wild radish (*Raphanus raphanistrum*) are important weeds of winter grain crops in southern Australia. Both weeds compete vigorously with crops and can produce large numbers of seed. An important difference is seed longevity as wild radish seeds can remain viable in the soil for up to 20 years depending on depth of burial (Holm *et al.* 1997), while wild oats seeds has been shown to have a half-life of about six months (Martin and Felton 1993). Given the stark difference in seed bank longevity, the two weeds provide a valuable case study for testing alternative weed management paradigms.

Population dynamics models were developed to determine the impact of control options upon the seed bank. The models used the following equation to trace changes in the seed bank over a generation:

$$SB_{t+1} = SB_t g(1 - mm)(1 - hm)(1 - dm) \\ r(1 - sm) + SB_t (1 - g)(1 - sd) \quad (9)$$

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

Three scenarios were developed to represent alternative management paradigms; simple ET, EOT and a dynamic IWM strategy. For wild radish, the weed control options developed were:

Option 1: No control (NC)

Option 2: Post-emergent herbicide (PE)

Option 3: PE + an autumn tickle (AT)

Option 4: PE + a competitive cultivar (CC)

Option 5: PE + selective spray-topping (SST)

Table 1. Selected population dynamics parameter values for wild radish weed control options.

	Control Option						
	NC	PE	AT	CC	SST	SST+AT	LG
Germination (%)	10	10	30	10	10	30	5
Seed decay (%)	15	15	15	15	15	15	15
Seedling mortality							
- pre-sow (cohort 1)	98	98	98	98	98	98	0
- post-em herbicide (cohort 1 and 2)	0	95	95	95	95	95	0
Density dependant mortality							
- α	2.7×10^{-5}	2.7×10^{-5}	2.7×10^{-5}	1.0×10^{-4}	2.7×10^{-5}	2.7×10^{-5}	0.02
- β	39.88	39.88	39.88	39.88	39.88	39.88	55.00
Seed production							
- γ (cohorts 1 and 2)	545.8	36.5	36.5	36.5	36.5	36.5	20.0
- γ (cohort 3)	35.0	35.0	35.0	35.0	35.0	35.0	20.0
- ρ (cohorts 1 and 2)	0.035	4.3×10^{-10}	4.3×10^{-10}	4.3×10^{-10}	4.3×10^{-10}	4.3×10^{-10}	0.01
-ρ (cohort 3)	0.035	0.035	0.035	0.035	0.035	0.035	0.01
Seed rain loss (%)	30	30	30	30	85	85	30

Table 2. Optimal wild radish and wild oats decision rules for the alternative scenarios.

	Wild radish		Wild oats	
	Seeds (m^{-2})	Decision rule	Seeds (m^{-2})	Decision rule
ET	53	PE	39	PE
EOT	1	PE	6	PE
IWM	0	NC	0	NC
	1	CC	6	PE
	52	SST	92	SST+
	6325	PG	7690	F

Option 6: PE + SST + AT (SST+AT)

Option 7: PE + SST + AT + CC (SST+AT+CC)

Option 8: PE + SST + CC (SST+CC)

Option 9: Pasture and livestock grazing (PG)

The IWM scenario was allowed to have combinations of all these scenarios, while the ET and EOT were confined to options 1 and 2. The wild oat control options were:

Option 1: Winter fallow (F)

Option 2: No control (NC)

Option 3: Post-emergent herbicide (PE)

Option 4: Selective spray-topping only (SST-)

Option 5: PE + selective spray-topping (SST+)

The wild oats ET and EOT scenarios consisted of options 2 and 3, while the IWM scenario was allowed to consist of any of the control options.

The population dynamics parameter values for each wild radish option are given in Table 1. Further details on the wild oats model and parameter values can be found in Jones and Medd (1999). Other parameter values used in this analysis were a weed-free yield of 4 t ha^{-1}, crop price of \$135 t^{-1}, a return from grazing of \$119 ha^{-1}, and crop variable costs of \$276.44 ha^{-1}. For wild radish, post-emergent herbicide costs (including application) were \$17.97 ha^{-1} and selective spray-topping costs (including application) were \$8.97 ha^{-1}.

Density dependant mortality was estimated using equation (10), where D_i is the density of mature plants of the ith cohort, S_i is seedling density of the ith cohort, W is crop density and α and β are estimated parameters.

$$D_i = S_i \Big/ \left[1 + \alpha\left(\sum_{i=1}^{n} S_i + \beta W\right)\right] \tag{10}$$

The fecundity equation is as follows, where N_i is seed production from the ith cohort and γ and ρ are estimated parameters.

$$N_i = \gamma D_i \big/ (1 + \rho D_i) \tag{11}$$

Parameter values for α, β, γ and ρ for wild radish were obtained from G. Madafiglio (personal communication 1999). The yield loss function used in the model is the rectangular hyperbola proposed by Cousens (1985).

$$Y_L = I \sum_{i=1}^{n} D \Big/ \left[1 + \sum_{i=1}^{n} D(I/A)\right] \tag{12}$$

The yield loss function parameters for wild radish were I=1.15 and A=100 (G. Madafiglio, personal communication 1999).

The simple ET for both wild oats and wild radish was estimated using a budgeting model. A dynamic optimisation model was developed to determine the EOT and optimal IWM decision rules. The objective function of the dynamic optimisation model was the maximisation of NPV over 20 years. The dynamic optimisation model was solved using equation (9) as the state equation.

RESULTS

The ET for wild radish was determined to be 53 seeds m^{-2} and for wild oats was 39 seeds m^{-2} (Table 2). The EOT was calculated at 1 seed m^{-2} for wild radish and 6 seeds m^{-2} for wild oats. The optimal IWM decision rules for both wild radish and wild oats was dependent upon the initial size of the seed bank and are given in Table 2. These results show an increasing level of control is warranted as seed density increases, until crop production is no longer profitable and a substitution to pasture and grazing livestock or a winter fallow is preferable.

Assuming initial populations of 2000 seeds m^{-2} for wild radish and 1000 seeds m^{-2} for wild oats, the effect of implementing the different decision rules for each of the scenarios upon the seed bank is illustrated in Figures 1 and 2. This indicates that for wild radish the ET and EOT paradigms had only a minimal effect on reducing the seed bank. The ET and EOT scenarios had an identical effect on the wild radish seed bank as the critical threshold density for each of these frameworks was not approached. Adoption of the IWM scenario for wild radish resulted in a significant seed bank decline.

For wild oats all scenarios resulted in a decline in the seed bank, however, the IWM scenario resulted in the most rapid decline and smallest seed bank over the time horizon studied.

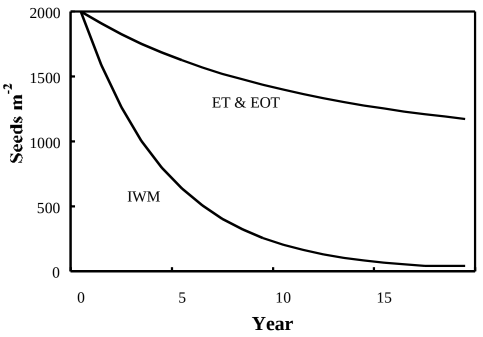

Figure 1. Effects on wild radish seed bank from the alternative paradigms

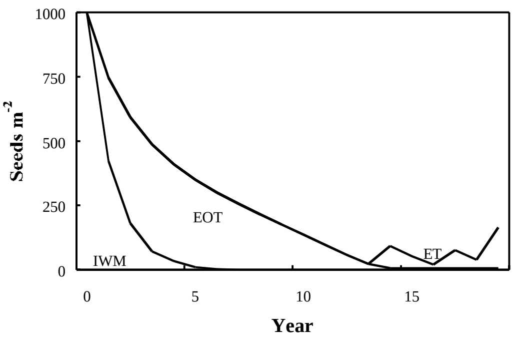

Figure 2. Effects on wild oats seed bank from the alternative paradigms

The economic performance of the IWM strategy was superior to ET and EOT for both wild radish and wild oats. For wild radish the NPVs calculated over the 20 years were $2,744 for IWM, and $1,486 for both ET and EOT. For wild oats the calculated NPVs were $3,938 for IWM, $3,552 for EOT and $3,498 for ET.

DISCUSSION

These case studies indicate that the adoption of a dynamic framework resulted in a significantly lower weed population and greater economic returns over time compared to a static framework such as the ET. There was a substantial difference in the rate of change in weed population between the two dynamic approaches, with the IWM paradigm being superior in both weed cases.

In the context of the current paradox, it is probable that weed problems are persisting, and costs escalating primarily because weeds are being managed in a static framework. Little consideration or weight is given to the effects of decisions on future consequences because managers are besotted with minimising costs of control, or damage from competition. Management of weeds under a static short term paradigm can maintain populations, whereas it is evident from the case studies that populations can be depleted over time under a dynamic (multi-period or long term) paradigm. Thus, the management objectives of growers have a powerful influence on whether or not weed populations are depleted or renewed.

The principle reason for the difference is that as the size of the seed bank increases there is a negative effect on future revenue, and vice versa. Modelling carryover effects, flexible doses and integrated control tactics in concert provides the key to long term sustainable management of weeds.

From the case studies presented, the setting of objectives to minimise costs or maximise returns in the current crop clearly does not optimise returns over the long term. Moreover, the case studies illustrate that unless weed control combines several methods of attack into integrated strategies, there is little scope for escaping the current paradox, with the result that weed populations will be maintained, or compounded, costs will continue to rise and herbicide resistance is likely to further escalate.

The paradox exists, we contend, because weeds are viewed as a short-term production problem, rather than a resource to be managed. By adopting a long term investment strategy to managing the resource our results show that weed populations can be minimised and greater economic benefits realised. These concepts are analogous to managing nitrogen fertiliser inputs in a cropping system (with little carryover implications) versus soil amelioration with lime.

Based on the theoretical findings of the case studies we accept the hypothesis that weed control strategies that simultaneously consider varying levels of weed control, carryover effects from a control decision and which deploy control tactics are economically superior to myopic alternatives. The hypothesis remains to be field or farm tested. How the findings hold up against real world uncertainty from variable climatic and commodity price influences has also to be tested. What is clear, however, is that progress in advancing more efficient and sustainable weed management systems can be made from the marriage of weed ecology with economics.

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