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A herbicide dose strategy able to account for environmental variation allows lower overall herbicide use without compromising long run economic benefits

Thomas L. Nordblom^{1,3}, Randall E. Jones² and Richard W. Medd²

Cooperative Research Centre for Australian Weed Management (Weeds CRC)

¹ Farrer Centre, School of Agriculture, Charles Sturt University, Wagga Wagga, NSW 2678

² NSW Agriculture, Orange, NSW 2800, ³ NSW Agriculture, Wagga Wagga, NSW 2650

Summary This paper approaches biological and economic risks in association with strategic and tactical decisions on herbicide dose. Underlying sources of the risks investigated are weed seed bank density and the season-to-season variations in weather. In a simulation model these affect the interplay of dryland wheat crops, a selective post-emergence herbicide and wild oats for different economic and biological outcomes. For fixed and factor-adjusted herbicide dose strategies, our simulation model shows how weather variations result in measurable risks, expressed as cumulative probability distributions of herbicide efficacy, crop yields, changes in weed seed banks in the short and long runs, and economic benefits. Where it is possible to accurately determine the weed densities and weather factors for each spray application, a 'best efficacy-targeting strategy' (*BETS*) is defined. Simulated results with *BETS*, run with a long sequence of weather, are better than or equal to best fixed doses for any given weed density in terms of crop yields, weed seed bank reduction and long-run economic benefits. Compared to a strategy of continuous maximum doses, *BETS* allows for lower over-all herbicide use: 23% less with 128 weeds m⁻², 58% less with 32 weeds, and 80% less with 8 weeds.

Keywords tactics, environment, weather, *Avena* spp., wild oats, weed density, seedbank, weed population control, wheat, simulation, Hamiltonian

INTRODUCTION

Herbicide labels recommend doses sufficient to achieve acceptable efficacy under a broad range of application conditions. However, in order to reduce production costs or environmental effects of weed management there is increased interest in using herbicides at dose rates below label recommendations.

Experimental evidence indicates equivalent weed control and crop yields in some cases when herbicides were applied at full (1X) or reduced rates (<X), whereas in others there was less consistent weed control over years and locations with reduced rates (Bussan *et al.* 2000). Besides dose, herbicide performance is influenced by complex interactions of environmental conditions, especially moisture stress, nitrogen deficiency, temperature, light, wind, humidity and

rainfall (Medd *et al.* 2001). Some labels offer a choice in dose yet frequently provide only general and subjective guidelines, hence decision making is almost blind with respect to environmental influences on efficacy, adding to risk.

Thus, the adoption of reduced rate systems is hindered by the increased risk of lower efficacy, reduced yields and of weeds surviving to maturity and producing seeds. Weed escapes have the potential to decrease crop yield and increase weed seed production in the current season as well as increase the economic burden of weeds in subsequent seasons. Depleting seedbanks is a key goal of weed management programs that aim for population control (Jones and Medd 2000).

The objective of this paper is to consider risks arising from short-term variations in the weather and biological environment which affect herbicide efficacy, yields, seedbanks and economic outcomes. We consider what a decision-maker might do about these risks in terms of strategic and tactical decision making. In particular, the analysis focuses on a simulation of results for a selective post-emergence grass herbicide used against wild oats (*Avena* spp.) in wheat (Medd *et al.* 2001).

Even when assuming that the prices of a herbicide and crop are constant, a grower still faces risks of using more or less herbicide than that which gives the best balance for present and future seasons. In light of the risks of weed seedbank blowouts, and the future costs these can entail, blind or fixed cut-backs in herbicide doses are compared with factor-adjusted doses.

METHODS

A schematic chart of the bioeconomic simulation framework for comparing risks under different herbicide dose strategies is illustrated in Figure 1. This framework explicitly accounts for the effects of weather on herbicide performance, which is linked with water balance, wheat yield, yield loss and weed seedbank dynamics models. Following Medd *et al.* (2001), variability in herbicide efficacy (*E*) is taken to be a function (f_a) of herbicide dose given the environment, $E = f_a(\text{DOSE}|\text{ENVIR})$, for a selective post-emergence grass herbicide, clodinafop-propargyl, to control wild oats in wheat in a rain fed system at Wagga Wagga (Table 1).

The key variables in the relationship are the sum of minimum temperatures over the seven days prior to spraying (*PRE7*), maximum temperature on the day of spraying (*TMAX*), soil moisture deficit at day 10 prior to spraying (*SMPRE10*) and spray water volume, which is held constant herein at 100 L ha⁻¹.

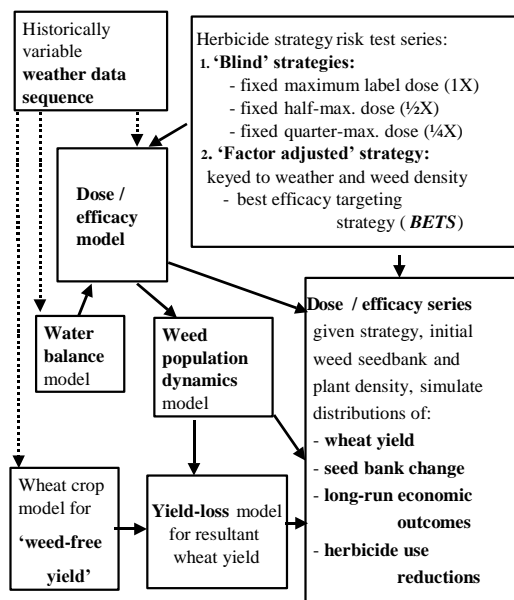


Figure 1. Schematic chart of the simulation framework.

Table 1. Environmental variable summary (*ENVIR*)¹ for Wagga Wagga, for the years 1950 – 1996.

	<i>PRE7</i> (°C)	<i>TMAX</i> (°C)	<i>SMPRE10</i> (mm)
Mean	26.1	12.78	1.72
CV (%)	46.6	18.1	198.7

¹ *ENVIR* data from Nordblom *et al.* (in press).

Where the key environmental values are given for a spray date, the dose required to deliver a desired efficacy level may be calculated with the inverse function (f_b): $DOSE = f_b(E|ENVIR)$.

Weed-free wheat yield (*WFY*), calculated only at harvest after Cornish and Murray (1989), plays no role in our post-emergence herbicide decisions but is used in assessing the economic outcomes thereof. Mean *WFY* calculated for the 1950-1996 period was 3.62 t ha⁻¹ with CV = 35%. Wheat yield loss due to weed competition is predicted by $G = WFY [1 - (ID / (1 + ID/A))]$ where G = final grain yield harvested (t ha⁻¹), D = weed density (mature plants m⁻²), I = percent yield loss per unit weed density as weed density approaches zero ($I = 1.044$), $A =$

maximum yield loss of a weedy crop relative to the yield of a weed free crop ($A = 0.8196$) (Jones and Medd 2000).

Residual weeds surviving herbicide treatment, due to low dose, unfavourable weather or misses at spraying, are expected to impose costs in future years by adding to the seedbank. The greater the weed density, the greater this risk of residual weeds and seedbank recharge. Nevertheless, in terms of avoiding future costs, the value of reducing the seedbank by one seed m⁻² is greater in the case of low-density weeds than is the case with higher density weeds (Jones and Cacho 2000). This is expressed by the costate variable (λ), which is a function of the change in seedbank given the initial seedbank, in the Hamiltonian function: $H_t = GM_t + \beta \lambda_{t+1} g(SB_t, DOSE_t)$, where β is a discount factor $1/(1+r)$, r is the discount rate (7%), t represents the time period, and g is the change in seedbank being a function of current weed seedbank SB_t and herbicide $DOSE$. GM_t is the current year gross margin. The term λ , always negative, can be viewed as the 'future profit effect' of marginal changes in the weed seedbank. Best efficacy targets, in terms of highest mean H , for each of several weed densities at Wagga Wagga, were found by numerical simulation; results shown in Figure 2 (Nordblom *et al.* in press).

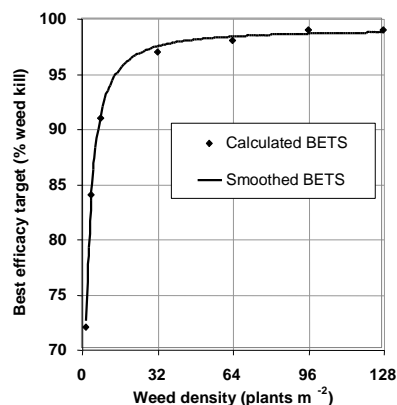


Figure 2. Best Efficacy Targeting Strategy (*BETS*)

It is this *BETS* strategy for using tactical dose calculations sensitive to current weather and weed density that we compare with 'blind' or fixed doses used regardless of weather or weed density, viz: 1X, ½X and ¼X (in this case 30, 15 and 7.5 g a.i. ha⁻¹, respectively). The highest dose that may be selected by *BETS* is taken to be the same as 1X (30 g ha⁻¹).

Changes in weed seed bank dynamics were predicted by $SB_{t+1} = SB_t - SR_t - MT_t + N_t$ 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, SR_t is the loss due to

seedling recruitment, MT_t is the loss due to seed predation, export and mortality, and N_t is new seed added to the seed bank through reproduction and importation (Jones and Medd 2000). Annual flux (R) in the seedbank is assessed as $R = SB_{t+1}/SB_t$, hence population decline is signified by $R < 1$, population increase by $R > 1$ and neutral change when $R = 1$.

Our test scenarios of *BETS* against fixed doses of 1X, $\frac{1}{2}$ X and $\frac{1}{4}$ X include three initial weed densities (8, 32 and 128 weed plants m^{-2}) chosen to span a range of potential economic losses and best economic dose levels. Each of the various strategies result in comparable probability distributions of herbicide dose and efficacy, wheat yields, wild oat seedbanks, and economic consequences (H).

RESULTS

Over the course of seasons, lower than maximum doses were frequently selected by *BETS* when environmental conditions for attaining efficacy targets were favourable (Figure 3a). For example, the 1X dose was predicted in less than 10% of seasons when specifying 97% efficacy. In contrast, fixed doses resulted in wide distributions of efficacies among seasons (Figure 3b), with lower doses having greater risk of reduced efficacy. For instance, there is only 10% probability of achieving less than 95% efficacy with 1X, 30% probability with $\frac{1}{2}$ X and 80% probability with $\frac{1}{4}$ X.

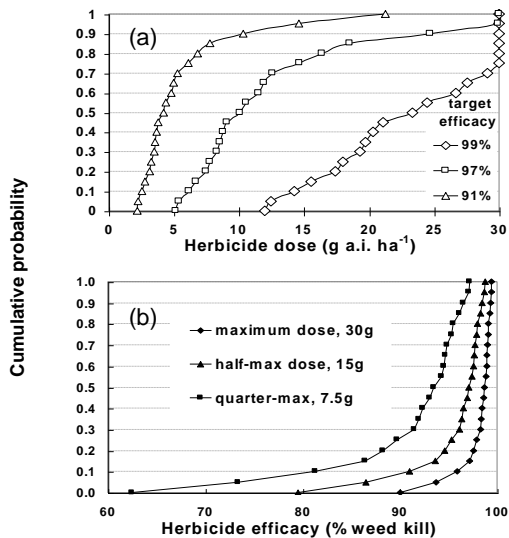


Figure 3. Cumulative probability distributions of (a) factor-adjusted dose given *BETS* targets of 99%, 97% and 91% , and (b) efficacy for 1X, $\frac{1}{2}$ X and $\frac{1}{4}$ X doses.

Simulated wheat crop yields with *BETS* did not appear to be compromised, being as high in any season and as with the 1X dose (Figure 4). For example, there was 50% or better probability of achieving 3.5 or more t ha^{-1} yield, irrespective of herbicide strategy or weed density (results for lower densities not shown). Likewise, simulated seedbank suppression is as thorough with *BETS* as with the 1X dose (Figure 5). Only in the case $\frac{1}{4}$ X was there less than 90% probability of seedbanks being depleted through population decline ($R < 1$).

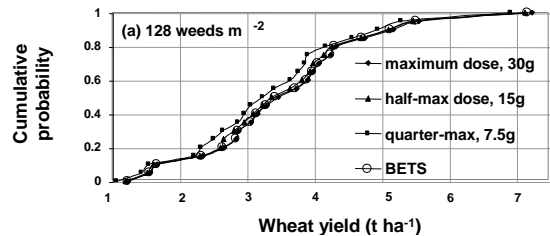


Figure 4. Simulated yield distributions for *BETS* and three fixed herbicide doses for 128 wild oats m^{-2} .

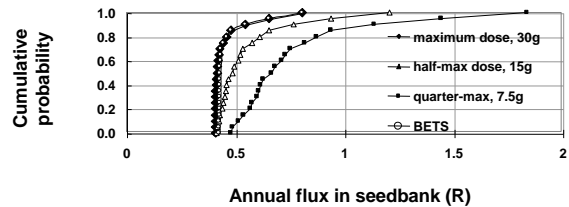


Figure 5. Simulated distributions of relative change in seedbank for herbicide strategies for an initial seedbank of 481 seeds m^{-2} , corresponding to 128 plants m^{-2} .

As in the case of wheat yield, there is no economic penalty in terms of (H) from using *BETS* (Figure 6). The cumulative probability distribution for *BETS* lay consistently to the right of the fixed dose strategies, indicating that this strategy is economically superior.

Comparisons of over-all use of herbicide at fixed maximum dose indicate large possible reductions are offered by *BETS*; 23% less with 128 weeds, 58% less with 32, and 80% less with 8 weed plants m^{-2} (Figure 7).

DISCUSSION

While *BETS* is in the tradition of earlier factor-adjusting programs (eg. Kudsk 1985, 1989, Minkey and Moore 1998), it is unique in taking the economic as well as the biological consequences into account. Weed density and the environmental factors affecting efficacy are of crucial importance in the evaluation of dose strategies.

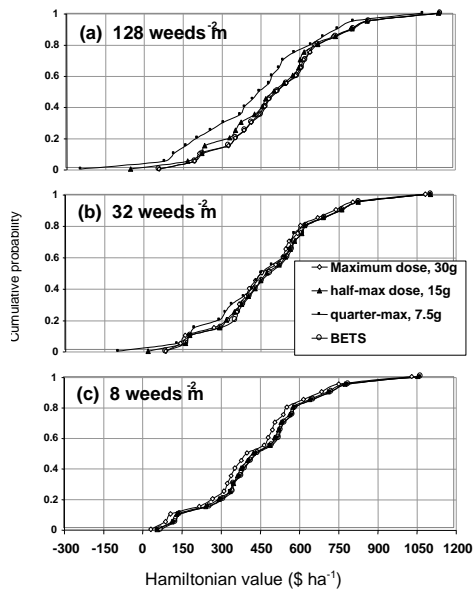


Figure 6. Cumulative probability distributions of H for *BETS* and three fixed herbicide doses under three weed densities.

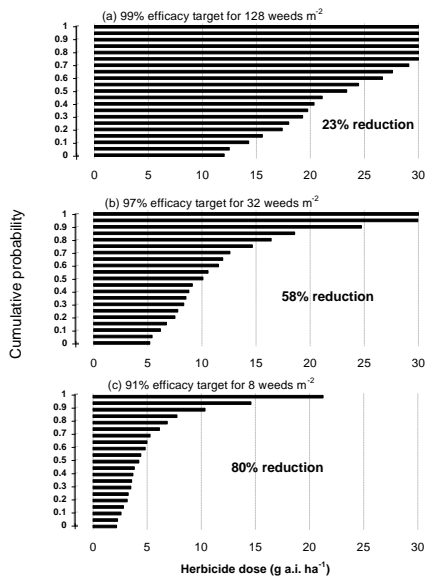


Figure 7. Simulated reductions in herbicide use with *BETS* in comparison with maximum label doses in the cases of 128, 32 and 8 weeds m^{-2} .

Our simulation results suggest that by accounting for environmental variation, as with *BETS*, it may be possible to reduce herbicide use without compromising

crop yields, weed seedbank suppression or economic benefits.

By strategically changing efficacy targets according to weed density, then tactically altering the dose to reach the targeted efficacy level given current weather conditions, *BETS* minimises the risks of applying too much or too little for the prevailing conditions. Other herbicide-weed-crop combinations should be amenable to the same sort of analysis provided sufficient response data are available for estimation of the efficacy-dose relationships for environmental variables observable on or before the date of spraying. It is likely this type of tailored decision support information will be of interest in the cases of expensive herbicides or those where dose related externalities are apparent.

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