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Economics of factor-adjusted herbicide doses: Best-Efficacy Targeting or Best Fixed Doses vs 'blind' upper or lower label doses

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ABSTRACT
Herbicide labels recommend sufficiently large doses to achieve high efficacy of weed control under a range of environmental conditions. While users may not apply doses greater than recommended they may apply less, but do so without quantitative guidance. This paper explores long-run biological and economic outcomes of fixed label doses and strategies keyed to density of weeds in "best fixed-dose" (**BFD**) and "best efficacy-targeting" (**BET**) modes. Analysis based on 59 experiments in wheat fields across southern Australia, from 1986 to 1995, indicate the latter strategies are superior to maximum label rates in terms of (a) mean net present values of current and future benefits and costs of weed management, expressed as Hamiltonians keyed to weed seed banks, (b) mean current gross margins, and (c) lower overall herbicide use. **BFD** have further practical advantages in simplicity and lower information requirements for the user, **BET** in tailoring applications to specific field environments.

INTRODUCTION
Herbicide labels recommend doses sufficiently high to achieve high rates of weed kill under a range of conditions, but recommend non-use when weeds are stressed by cold, drought or other cause. And, while users may not apply doses greater than recommended, they may be free to apply less, but do so without quantitative guidance. "Follow the label" is not just a rule of thumb, but a legal requirement that must not be ignored. However, following the label when a range of choice in doses is offered leaves the question open to uneven guesswork for many users. This is especially so across mainland Australia, the USA, Canada and Europe, where legislation allows farmers to use doses lower than those on the label, except when a label explicitly prohibits this. Our aim is to lead toward reducing the guesswork by exploring how to develop decision-support tools, or decision rules, for economically optimising herbicide doses, for minimising weed impacts in future seasons as well as controlling weeds in the current season, while reducing overall herbicide use.

Herbicide performance is influenced by complex interactions of environmental conditions (weather and soil, both before and after application) (Caseley, 1990; Kudsk & Kristensen, 1992; Minkey & Moore, 1996, 1998; Lundkvist, 1997) and plant factors (species, stage of development, competitive ability of the crop, etc.) (Rioux *et al*., 1974; Lemerle and Verbeek, 1995). Particular factors of importance may include moisture stress (Boydston, 1990; Dastgheib *et al*., 1990; Dickson *et al*., 1990;

Lemerle and Verbeek, 1995), nitrogen deficiency (Dickson *et al*., 1990), temperature, light, wind, humidity and rainfall (Caseley, 1990; Coupland,1983, 1984; Devine, 1989; Doran & Anderson, 1976; Jensen & Kudsk, 1988; Madafiglio *et al.* 2000; McMullan, 1994; Merritt, 1984; Muzik, 1975; Nalewaja & Woznica, 1985; Wicks *et al*., 1993). As a general principle, a lower rate of herbicide may kill most of the target weeds under favourable conditions. Under less favourable conditions, a higher rate will be required; and with unfavourable conditions, even the highest rates of herbicide may have little or no effect on weeds.

Numerous studies have evaluated the use of herbicides at doses below label recommendations with the goal of reducing production costs or environmental effects of weed management (Bussan *et al*., 2000). While in the cases of some individual trials, weed control and crop yields were the same when herbicides were applied at full or reduced rates, there was less consistent weed control over years and locations with reduced rates than with full label rates (Buhler *et al*. 1994; Devlin *et al*. 1991; Fernandez-Quintanilla, 1998; Griffin *et al*. 1992; Krausz *et al*. 1993; Mirkamali,1993; Mulder and Doll 1993; O'Sullivan and Bouw 1993; Prostko and Meade 1993; Rabaey and Harvey 1994; Steckel *et al*. 1990; Zhang et al., 2000; Zoschke 1994). Weed escapes in reduced-rate weed management systems may decrease crop yield and increase weed seed production (Bussan *et al*., 2000; Cook and Clarke, 1997; DeFelice *et al*. 1989; Jones and Medd, 2000; Richards *et al*. 1997; Skorda *et al.* 1993; Steckel *et al*.1990).

Jensen & Kudsk (1989) first introduced the concept of '**factor-adjusted doses'** to accommodate the prevailing environmental conditions, with the observation that dose-response curves for percent weed kill make parallel shifts according to influencing factors. Moreover, to facilitate implementation of a political plan in Denmark to reduce agricultural use of pesticides, a decision support system was conceived. The program "PC Plant Protection" (formerly named Danish Decision Support System, DDSS) aims to minimise herbicide use while maintaining farmers' profits. Originally the selection of herbicide and dose was based on weed species and growth stage, but now incorporates knowledge of weather conditions around the time of application, and competitiveness of crop cultivar to optimise the composition and doses of herbicide mixtures (Christensen, 1998; Kudsk,1999; Rydahl, 1999).

In Western Australia, Minkey and Moore (1996, 1998) have developed a factor-adjustment model that determines doses to achieve efficacy targets given the environmental conditions in the field at the time of spraying. The *Herbirate* model of Minkey and Moore (1998) recommends doses aimed to achieve 90% efficacy given environmental information supplied by the user on the day of application.

Labels often recommend the upper dose for heavy weed densities or stress conditions. Our analysis examines such conditions in the case of a post-emergent grass weed herbicide in wheat and goes further to quantify the economics of herbicide strategies for dealing with a variety of better growth conditions and lower weed densities. In this study, we take into account the economic penalties associated with allowing the weed seed bank to be re-charged for future seasons by inadequate weed control in the current season, as well as the short run costs and benefits of controlling weeds. The present analysis quantifies the extent to which high weed densities call for the highest herbicide efficacy, and low weed densities allow lower efficacies to be targeted.

Limiting weed seed production is a key goal of weed management programs (Jones and Medd, 2000). It is not surprising that the adoption of reduced-rate systems has been hindered by the increased risk of weeds surviving to maturity and producing seeds (Bussan *et al*. (2000). Our paper combines the paradigm of minimising weed seedbanks with new findings on environmentally modified herbicide performance to show how economic guidelines may be developed for quanitative decisions on dose.

METHODS

Because post-emergence herbicide decisions must be made early in the season, before the remainder of the season's weather has been received, and well before the time of crop ripening and harvest, they may be based on weed densities and growing conditions but not upon estimates of weed-free yields. Though not observable at the time of decision, the economic outcomes of herbicide decisions do depend on crop yield potentials and losses due to weeds (Martin *et al*., 1990; Pannell, 1990), not only in the present season but also in future seasons due to weed seed carryover (Jones & Medd, 2000). Therefore, this study is analogous to a numerical simulation study using sequences of weather in a model exploring N-fertiliser decisions for dryland wheat in Oregon (Nordblom *et al.* 1985). The economic outcomes of standard and best "blind" doses are compared with outcomes of strategies taking into account environmental factors observable (or calculable) at the time of application decisions.

Central to the present study are the efficacy/dose equations of Medd *et al.* (in press), which follow up the pioneering work on 'Factor-Adjusted Doses" in Denmark by Jensen and Kudsk (1988) and Kudsk (1989, 1999), and the development of *Herbirate* in Western Australia by Minkey and Moore (1998). Based on 59 commercial dose response experiments on a selective post emergence grass herbicide on a grass weed in wheat under a wide variety of growth conditions from across southern Australia from 1986 to 1995, Medd *et al.* (in press) found three environmental variables and two decision variables had the greatest significance in predicting efficacy. The key environmental variables proved to be the maximum temperature on the day of spraying (TMAX), the sum of minimum temperatures on the seven previous days (PRE7), and soil moisture deficit for the 10 days prior to spraying (SMPRE10). The decision variables are herbicide dose (DOSE) and spray water volume (SVOL). Given the values of the above variables in a particular year, Eq.1 yields an estimate of the percentage of weeds killed (efficacy) based on Eq.2 (Table 1).

The parameter b2 of Eq.2 comes into play only in the absence of the recommended oil in the tank mix of water and herbicide (Medd *et al.*, in press). When the oil is used, the value of this parameter switches to zero; for the purposes of this paper, we assume oil is used. Also, for the purposes of the present discussion, we hold SVOL constant at 100 litres ha^{-1}, a spray water volume in the range recommended on the product label. These assumptions have the effect of limiting the decision space under analysis.

(1) $$E = \frac{100}{1 + \exp(-F)}$$

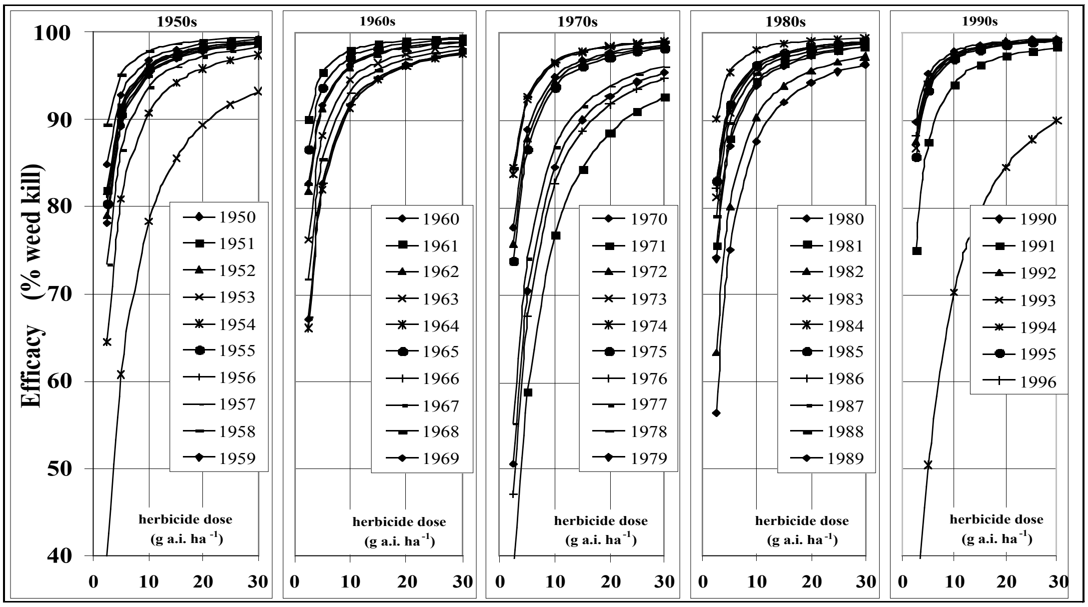
(2) $$F = b_1 + b_2 + b_3 \ln(DOSE) + b_4 TMAX + b_5 PRE7 - b_6 SMPRE10 + b_7 SVOL - b_8 TMAX \times SVOL$$

Table 1: Herbicide efficacy parameters		
Parameter	Solution	Standard Error
b_1	-11.13	3.38
b_2	-1.32	0.25
b_3	1.22	0.12
b_4	0.59	0.20
b_5	0.049	0.01
b_6	0.055	0.03
b_7	0.081	0.029
b_8	0.0044	0.0018
Source: Medd *et al* (in press)		

Under this formulation, wide year-to-year variations in dose response are calculated, given the weather records from the two contrasting case study locations used in this study, Condobolin and Wagga Wagga (Table 2). The case of Wagga Wagga is illustrated in Figure 1 in which simulated dose response curves, based on Eq.1 and Eq.2 and the environmental conditions for each year from 1950 to 1996, are plotted.

Table 2: Summary of environmental variables for contrasting rain-fed wheat farming districts in New South Wales, Australia					
Condobolin (Lat 33.03S, Long 147.11E), 40 seasons (1957-96)					
	PRE7 (°C)	**TMAX (°C)**	**SMRE10 (mm)**	**weed-freeYield (t ha^{-1})**	**annual rainfall (mm)**
Mean	26.57	14.82	3.68	2.62	250.0
CV (%)	62.8	20.5	125.9	41.4	38.1
Variance-Covariance Matrix:					
PRE7	278.04	-20.55	-21.99	3.68	
TMAX		9.23	3.87	-0.57	
SMPRE10			21.40	-2.37	
WFY				1.18	
Wagga Wagga (Lat 35.07S, Long 147.24E), 47 seasons (1950-96)					
Mean	26.10	12.78	1.72	3.62	372.6
CV (%)	46.6	18.1	198.7	35.2	30.6
Variance-Covariance Matrix:					
PRE7	147.67	-3.01	-16.70	5.17	
TMAX		5.33	1.20	-0.78	
SMPRE10			11.73	-2.39	
WFY				1.63	

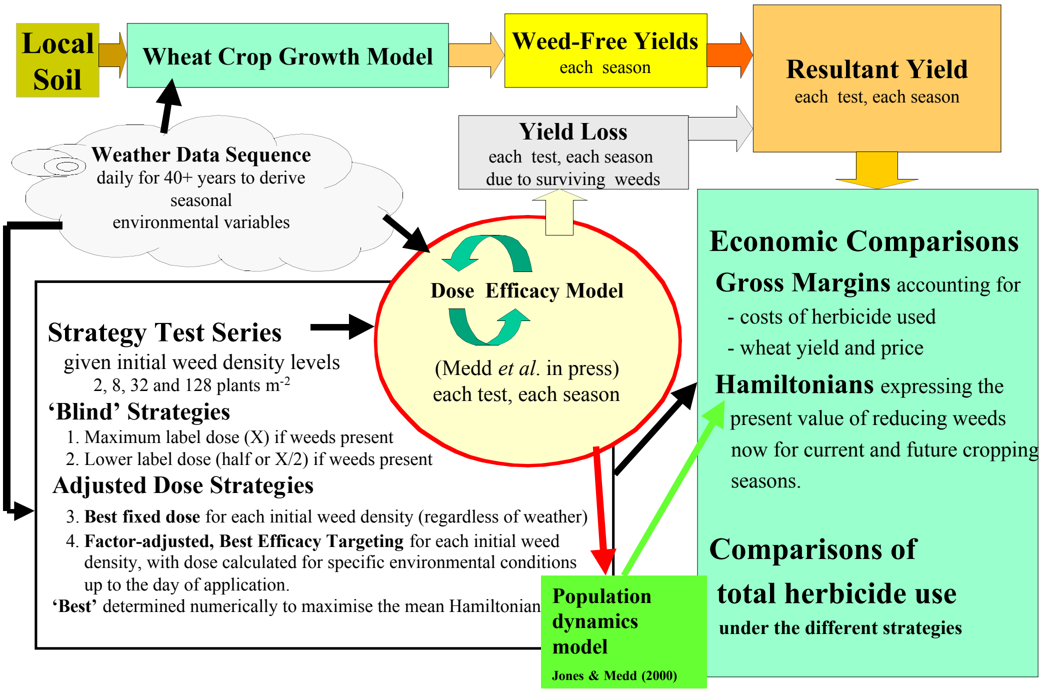
Figure 1. Simulated herbicide dose response with Wagga Wagga weather, 1950-96



all with SVOL = 100 litres ha^{-1}

A schematic chart of our simulation model is given in Figure 2.

Figure 2. Strategy Test Flow Chart: economics of 'blind' vs adjusted dose strategies



Mention is necessary of the means used for deriving values for the three environmental variables, TMAX, PRE7, SMPRE10, and 'weed-free yields" for each season in runs of the simulation model for each of the two locations. Intermediate determinations had first to be developed for each season's sowing and herbicide application dates. Daily rainfall, evaporation, and minimum and maximum temperature records were available for both locations: a 40-year sequence for Condobolin and 47 years at Wagga Wagga. We assumed sowing dates were five days following the accumulation of 25mm rainfall after May 1st each season.

Our estimates of "weed-free yield" are derived by Cornish and Murray's (1989) equation relating potential wheat yields to the season's rainfall and sowing date (Eq.3).

(3) $$Y = 4.21 + 0.0095R - 0.028A$$

where R = crop season total rainfall (mm)
A = number of days elapsed from 31 December to sowing date

Herbicide application dates were determined for our model according to the accumulation of at least 460 'degree days' following the sowing date, sufficient for weeds to reach two-leaf growth stage, and a break in rainfall of five days, sufficient for equipment to operate in the field. Based on application dates particular to each season, the three environmental variables could be based on the weather record. Among these, SMPRE10 was the least straightforward, requiring further intermediate calculations.

As described in Medd *et al*. (in press), crop water requirements (mm) were estimated for each site using FAO's *CropWat* for Windows (www.fao.org/ag/agl/aglw/wcrop.htm), version 4.2. Rainfall monthly totals and evaporation monthly averages were entered into the *CropWat* program along with soil class, crop type and sowing date. This provided an indication of possible crop and weed water stress for the period from crop sowing to date of herbicide efficacy assessment. Specifically, it allowed derivation of values for the moisture stress variable SMPRE10 such that a value of '0' indicates no moisture stress, and positive values indicate mm of moisture deficit: the higher the value the greater the level of water stress.

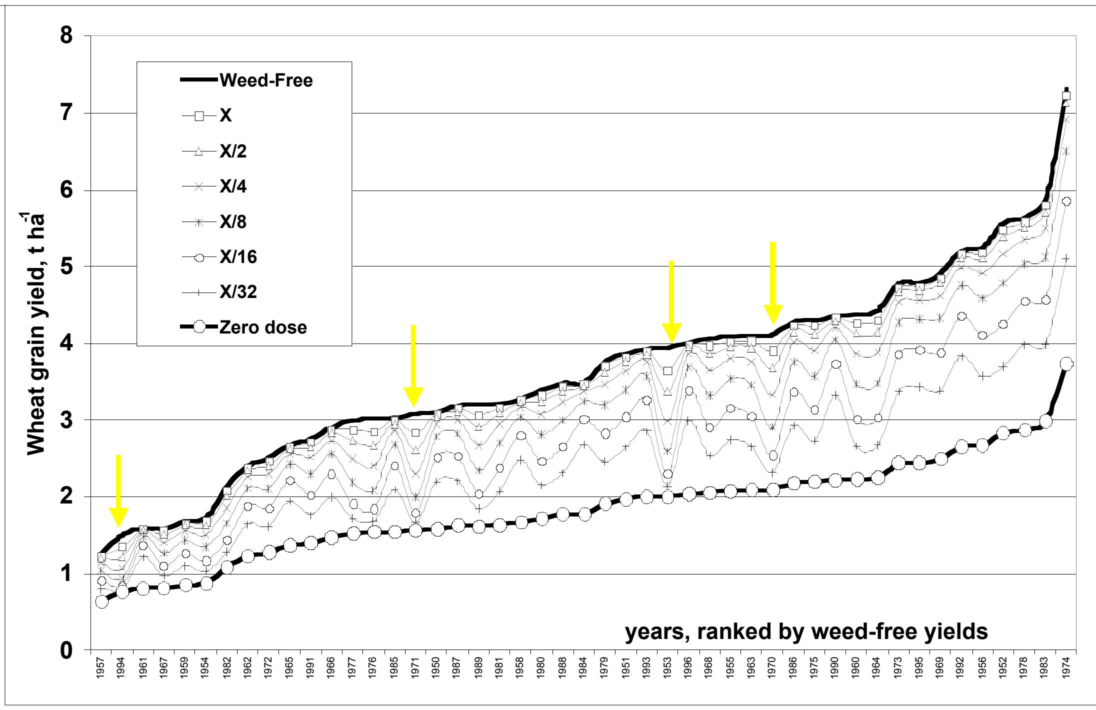
Following Cousens (1985) and Pannell (1990) we take the proportion of crop yield lost due to weeds to be a hyperbolic function of weed density, with the greatest marginal losses due to the first weeds and lower marginal losses where weeds are added to a large existing number. Following Jones and Medd (2000), the final yield harvested is a function of "weed-free yield" (Eq.3), crop density, and the effects of weeds, represented by the density of mature weeds in the crop. We assume the relationships as shown in Eq.4.

(4) $$G = Y\left[1 - \left(\frac{D}{\phi C + \rho D}\right)\right]$$

where G = final grain yield harvested ($t\ ha^{-1}$)
Y = weed-free yield potential (from Eq.3)
D = Weed density (mature plants m^{-2})
$\phi = 1.16$
$\rho = 1.22$
C = crop density (plants m^{-2}) = 90

The combined effects of weather and herbicide dose were simulated for individual seasons at Wagga Wagga, assuming initial weed density of 128 plants m^{-1}, to produce the wheat yields in Figure 3. The effects of the large year-to-year differences in efficacy functions seen in Figure 1 are apparent also in Figure 3 in which individual years are ranked across the horizontal axis from lowest to highest weed-free yields.

Figure 3. Simulated wheat yield at Wagga Wagga, 1950-96, weed-free and with 128 weed plants m^{-2} under the affects of full-label dose (X) and fractional doses



In Figure 3, the 'zero dose' series was simulated with a dose of 0.01g ha^{-1} as our dose response function (Eq.1 & 2) does not permit a dose value of zero. The envelope between the 'weed-free' yield curve and the 'zero dose' curve is widest for large initial weed densities (as with the 128 plants m^{-2} in Figure 3) and becomes narrower as densities are lowered (not shown here). Examples of seasons having stress conditions that depress simulated herbicide efficacy are indicated with the arrows in Figure 3.

Economic objectives and intermediate outcomes

We aim to test herbicide dose strategies by comparing multiple scenarios from our economic simulation model (Figure 2) in the cases of two study locations in southern New South Wales, Australia. Both 'blind' and adjusted dose strategies were examined using 40 seasons of weather data for Condobolin and 47 seasons for Wagga Wagga. The 'blind' strategies involved using the upper or lower label dose when the target weed is present, regardless of weed density or weed growth conditions. The 'adjusted dose' strategies take two forms. The first aims for the best long and short-run economic result by adjusting the dose according to weed density regardless of weather; this we call the 'best fixed dose' (**BFD**) for a weed density. The second aims to optimise long and short-run economic results by choosing the 'best efficacy target' (**BET**) for each weed density and adjusting the dose each season to achieve such targets.

The economic model calculates a single period gross margin (**GM**) for each season under a given strategy. The equation used to calculate **GM** is as follows:

(5) $$\text{GM} = P_y Y(SB, X) - P_X X - C_1 - C_2$$

where P_y is the wheat price (\$164 t^{-1})
Y is wheat yield
P_u is the unit cost of the herbicide used (\$1.65 g^{-1})
SB is the weed seed bank (seeds m^{-2})
X is the rate of herbicide applied (g ha^{-1})
C_1 is the cost of application (\$2.22 ha^{-1})
C_2 is other variable costs (\$166.24)

The model incorporates a weed seed bank model developed by Jones and Medd (2000) which explicitly accounts for the carryover of seed already in the ground and any seed added in the current season by surviving weeds. This model calculates the change in the weed seed bank for a given application of herbicide ie

(6) $$\Delta SB = g(SB, X)$$

where ΔSB is the change in the weed seed bank from one period to the next.

Central to the present analysis is the accounting of future costs from allowing weeds to escape control and produce new seeds by using a dynamic optimisation model developed by Jones and Cacho (2000). Optimal control theory can be used to determine the level of control that maximises returns over the longer term. An important component of a dynamic problem is the costate variable, denoted by λ. The means through which the costate variable enters the optimal control problem is the **Hamiltonian** function (**H**):

(7) $$H_t = GM_t + \beta\lambda_{t+1}\, g(SB, X_t)$$

where β is a discount factor, λ_{t+1} is the costate variable, and t represents the time period. GM_t is the gross margin, as defined in Eq.5.

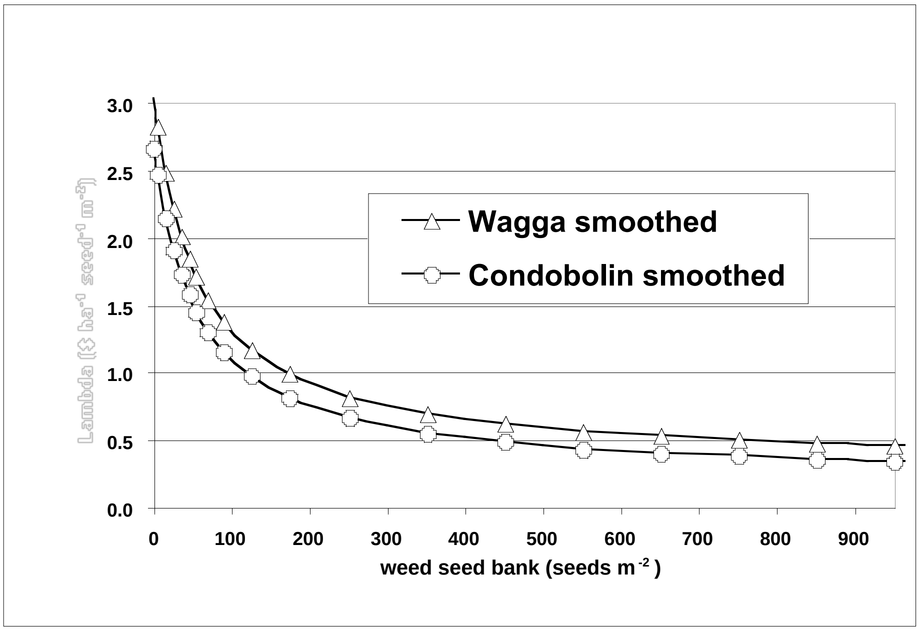
The **Hamiltonian** function represents the net profit obtained from the existing level of weed density and herbicide control (ie ***GM***) plus the value of any change in weed seed bank in the following period valued at the shadow price given by the costate variable, λ_{t+1}. The costate variable represents the shadow price of a unit of the stock of the seed bank.

In the last term of Eq.7, the $g(SB_t,X_t)$ function indicates the rate of change in the weed seed bank corresponding to herbicide dose X. When the function is multiplied by the costate variable, λ_{t+1}, it is converted to a monetary value and represents the rate of change of the economic value of the seed bank corresponding to herbicide dose X. In effect this term can be viewed as the future profit effect of weed population changes.

An increase in the number of seeds deposited to the seed bank will increase the weed population and reduces profits, up to the maximum weed population possible. Hence $\lambda_t \leq 0$. Due to the beneficial effect of the current weed control on future profits, a higher level of optimal weed control is derived from the **H** function than when only the **GM** is considered.

The optimal control model was solved for a range of weed seed banks from zero to 1000 seeds m^{-2} for both Wagga Wagga and Condobolin. This determined the costate variable, λ, for changes to the seed bank over this range (Figure 4). This illustrates the principle that at low seed bank levels there is a high future cost for each **additional** seed added to the seed bank, whereas at high seed banks the future cost of each additional seed is low. This is equivalent to the concept that if you already have a lot of weeds one more weed is not likely to increase damage. Note that λ is plotted in Figure 4 using positive values, hence the **H** is solved using the equation
H = **GM** - $\beta\lambda g(SB,X)$. A discount rate of 7 percent is used.

Figure 4: The costate variable (λ_{t+1}) values for various weed seed banks



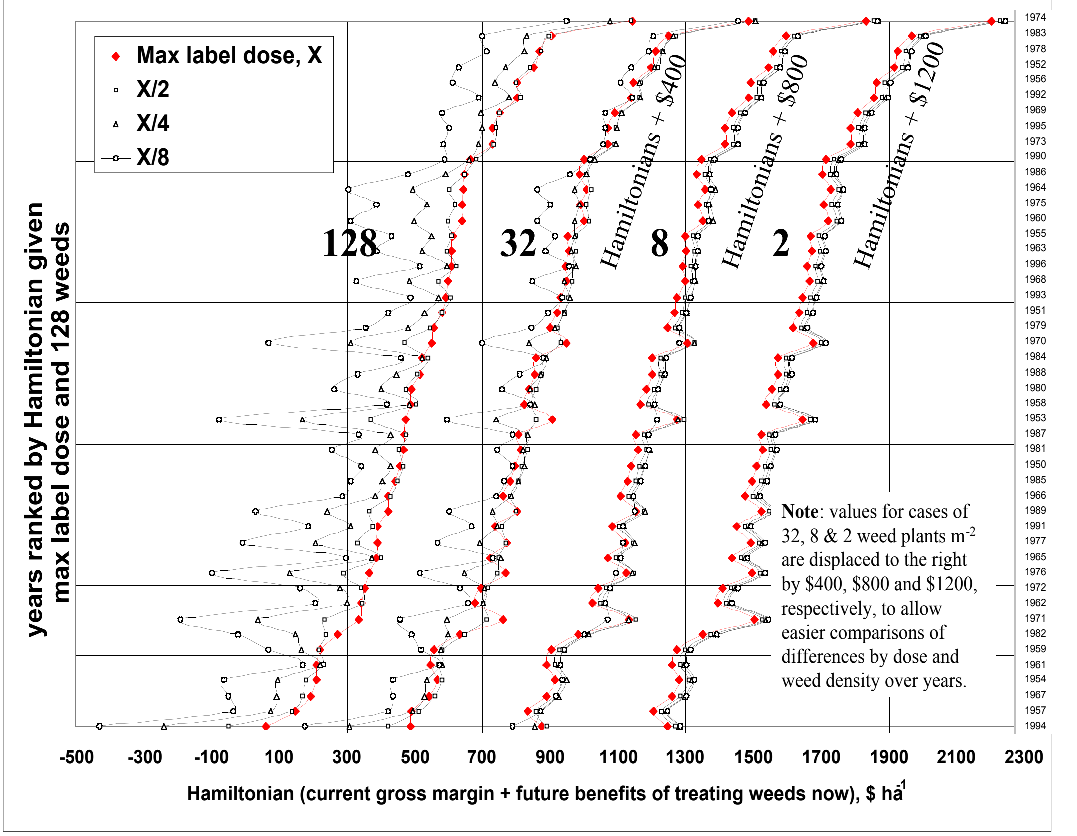
With this costate variable information along with the changes in the seed bank from a given initial weed density, the model in Figure 2 calculates both the **GM** and **H** values each season for each dose rate and or efficacy targeting strategy.

Effects of fixed doses on the Hamiltonian given different initial weed densities
With high initial weed densities, such as 128 plants m^{-2}, any shortfall in weed control has large consequences for current yields and, therefore, gross margins, as well as in terms of recharging the weed seedbank. The combined effects are expressed in the **Hamiltonian** value, as illustrated in Figure 5, for Wagga Wagga. The interpretation for 128 plants m^{-2} is that the highest **Hamiltonians** are consistently available only with the maximum label dose (**X**). The lower label dose, at **X/2**, yields **Hamiltonian** values sometimes slightly better, but often considerably worse than the full label dose. The sub-label doses **X/4** and **X/8** produce disastrous results due to weeds escaping control.

In the case of an initial weed density at 32 plants m^{-2}, the sub-label doses again most frequently showed inferior **Hamiltonian** values. Very frequently the simulated **X/2** dose produced results similar to or slightly better than the full label dose. However, under stress conditions, typified by 1953, 1970, 1971 and 1994 at Wagga Wagga, the full upper label dose was required to maximise the **Hamiltonian** (Figure 5).

In the cases of 8 and 2 plants m^{-2}, the **X/2** dose consistently produces higher **Hamiltonian** values than the full label dose. In the case of 2 plants m^{-2}, the **X/4** dose is frequently better than the **X/2** dose.

FIGURE 5. Simulated Hamiltonians with maximum label (X) and fractional herbicide doses given weed densities of 128, 32, 8 and 2 plants m^{2} and Wagga Wagga weather, 1950-96



In light of such weather-induced variance in efficacy at a location, and such shifts in the economics of herbicide doses with weed density, the context of the main questions examined in the present study becomes clearer. Now obvious is the question of which dose level best economically suits a particular weed density. A more subtle question arises with the possibility of predicting the efficacy response curve on the day of spraying. Will it pay to target a particular efficacy level for each weed density and calculate the dose required to achieve this target for conditions in each particular paddock and season?

Herbicide strategies

Both the initial weed density (WD) and weather conditions are expected to be important determinants of the optimal dose rate and herbicide strategy. Three questions were addressed using economic model:

1. what is the optimal dose rate for a given weed density using **GM** and **H** frameworks?
2. given that it is possible to predict the efficacy response curve on the day of spraying, is a 'best efficacy targeting strategy (**BET)** economically superior to a 'best fixed dose strategy' (**BFDS)** for managing weed populations?
3. How do **BETS** and **BFDS** compare economically with blind max-label and half-lable approaches?

Answers to these questions were approached numerically. For each initial weed density (128, 32, 8 and 2 plants m^{-2}), a series of simulation runs (47 seasons in a run for Wagga Wagga and 40 for Condobolin) were completed at 1g increments for dose ranges up to 30g ha^{-1}. Statistics were calculated for each simulation, including mean **GM** and mean **H**.

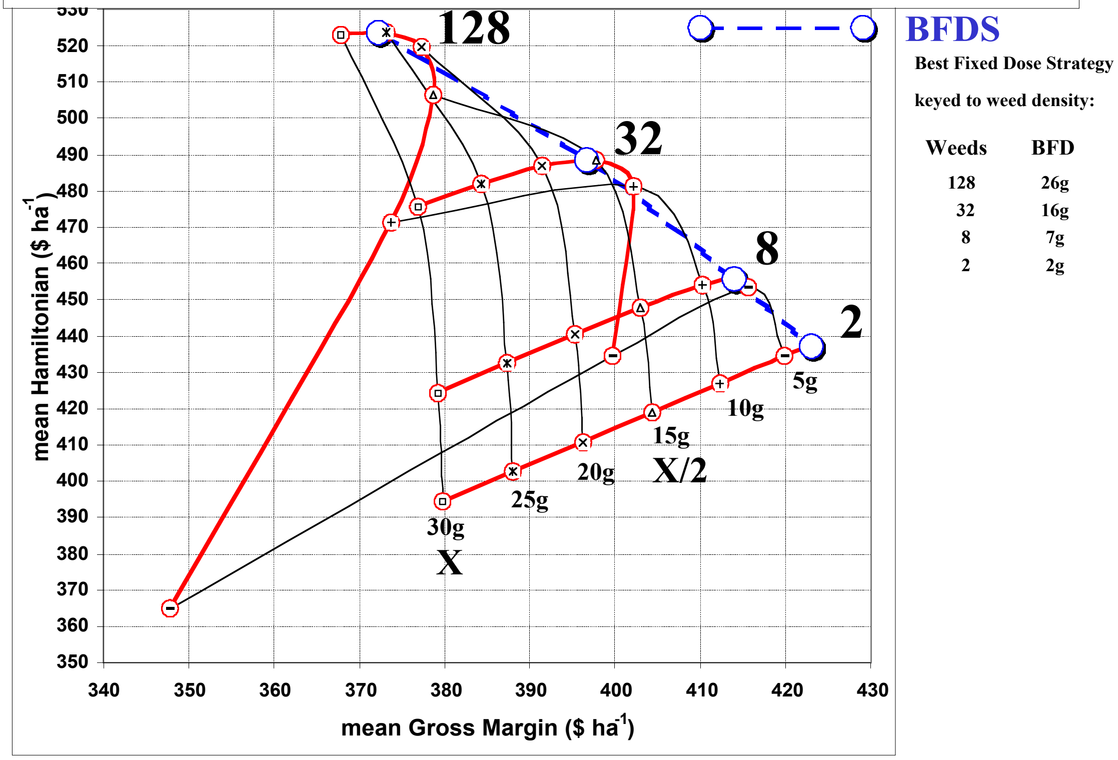
For each initial weed density, a series of simulation runs were conducted with efficacy targets incremented at 1% levels up to 99%, with a final increment to 99.5%. In the case of the **BETS** scenario, different doses were calculated automatically in the model according to each season's weather in terms of TMAX, PRE7 and SMPRE10. In addition to mean **GM** and mean **H**, the mean dose was calculated for each efficacy and weed density combination.

This approach to numerical analysis of the questions allows clear graphical interpretations of the results in terms of long and short-run economic considerations. Current **GM**s represent the short-term concerns of herbicide cost versus immediate crop losses due to surviving weeds. Long-term considerations are represented by the **H** which adds to the gross margin an accounting for future weed damage averted. This allows exploring the conditions in which there may be important trade-offs between short and long-term considerations; ie when it can be worth sacrificing some current income to take care of a weed problem now that is likely to cost far more if left to the future.

STRATEGY RESULTS (temporal trade-off curves and 'best' strategies)
Results for the cases of fixed doses of the 'blind' and adjusted kind are given in Figure 6 for Wagga Wagga. Consider first the simplest case of applying the maximum label dose (**X** = 30g ha^{-1}) regardless of weed density. This produces a mean **Hamiltonian** result close to that of the 'best' fixed dose (BFD) for 128 plants m^{-2}, but a lower mean gross margin. At lower simulated weed densities, the max label dose performs less well in these economic dimensions than lower fixed doses. The reader can see the effects of other fixed 'blind' doses (25g, 20g, 15g, 10g and 5g ha^{-1}) across weed densities in Figure 6.

The 'temporal trade-off curves' in Figure 6 are particularly worth noticing. Over a range of doses for 128 plants m^{-2} (from 5g to 10g and 15g ha^{-1}), both short and long-run economic results are improved. Between 15g and 26g ha^{-1}, however, there is a tradeoff range in which short term benefits are lost to gain longer-term benefits. At doses above 26g ha^{-1} the simulation points to losses in both short and long-term benefits. These sorts of tradeoff ranges are also prominent in the case of 32 plants ha^{-1} (Figure 6).

Figure 6. Simulated long & short-run economic results with fixed herbicide doses at Wagga Wagga under weed densities of 128, 32, 8 and 2 plants m^{-2}

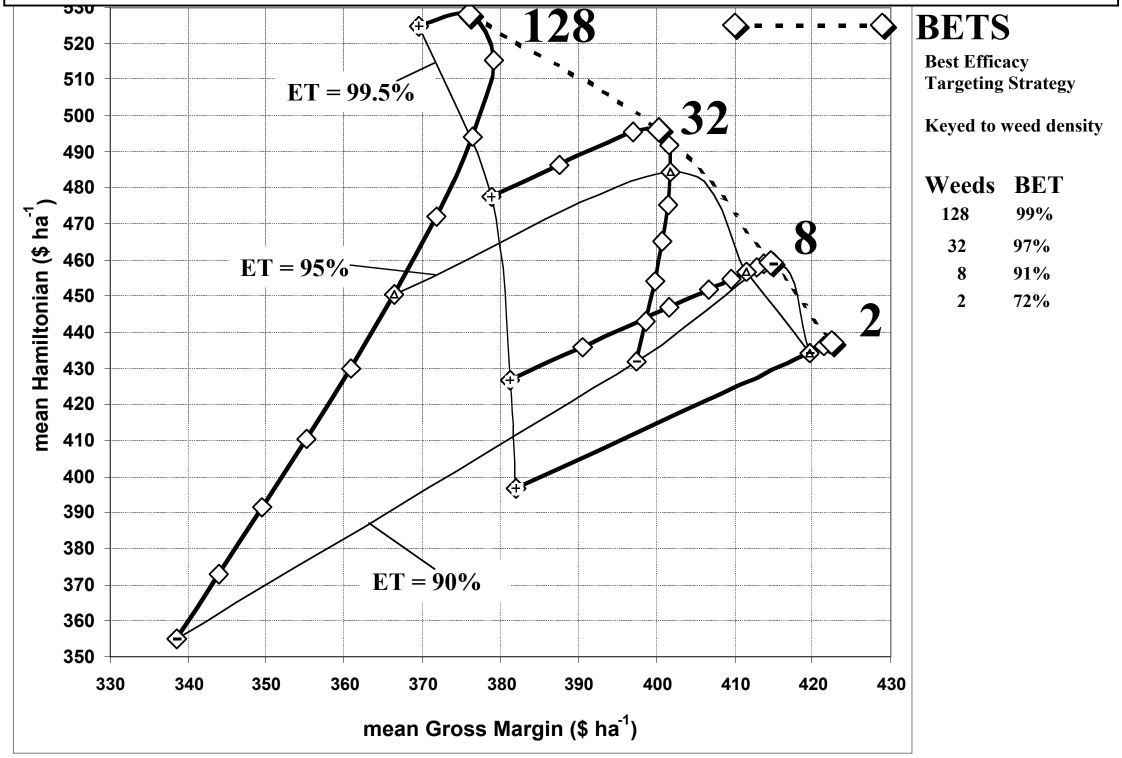


The lower label dose (**X/2** = 15g ha^{-1}) performs best economically with a weed density of 32 plants m^{-2}, but is dominated by other options at densities above and below this. At high weed densities (e.g., 128 plants m^{-2}), the **X/2** dose is too low on average. Although it looks good from the short-run perspective of mean current gross margins through savings in herbicide costs, it frequently allows too many weeds to survive (recall Figures 1, 3 and 5), incurring a penalty in terms of the long-run mean **Hamiltonian** (Figure 6).

Sub-label doses in the simulation (7g ha^{-1} for 8 plants m^{-2}, and 2g for 2 plants) are part of the 'best fixed dose strategy' (**BFDS**), adjusted or keyed to weed densities (Figure 6). This is a true strategy in the sense of defining actions for specific conditions, doses for weed densities in this case. While weather affects the outcomes of this strategy, weather is disregarded in application of its decision rules.

A strategy which does take into account weather, prior to and on the day of herbicide spraying, as well as accounting for weed density, is what we call a 'best efficacy targeting strategy' (**BETS**). Analysis of simulation runs for Wagga Wagga at the same four weed densities permitted identification of the 'best efficacy target' for each. It was a matter of selecting the 'efficacy target' that produces the highest mean Hamiltonian value for each density (Figure 7). Analogous to the case of **BFDS**, the highest weed densities call for the highest 'efficacy targets'. The contrast from fixed dose strategies here is that doses will be adjusted up or down in aiming for a given 'efficacy target' under varying weather conditions encountered from one season to the next.

Figure 7. Simulated long & short-run economic results with efficacy targeting (ET) at Wagga Wagga under weed densities of 128, 32, 8 and 2 plants m^{-2}



This season-to-season tracking, with variable doses to achieve 'efficacy targets', is illustrated in Table 3. **BETS** results are shown for several weed densities here in addition to the 128, 32, 8 and 2 plants m^{-2} to enhance the **BETS** concept that 'best' economic doses are a function of both weed density and weather. In Table 3, the years 1953, 1970, 1971 and 1994 stand out as ones in which the highest doses would be called for. In our analysis, we have set an upper limit in line with the maximum label dose, 30 g a.i. ha^{-1}. The seasons in which this dose appears are ones in which the 'efficacy target' for the given weed density is not fully attainable within the label limit. This would be apparent in Figure 1 if horizontal lines were struck across the chart at the **BETS** efficacy levels heading Table 3, and the required dose levels for each season were read from the horizontal axis.

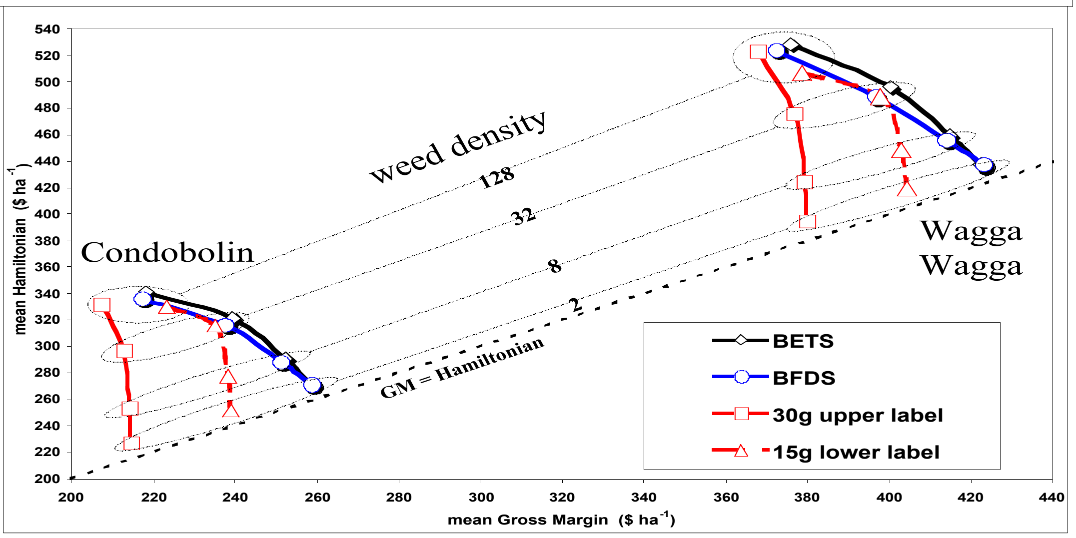
SUMMARY

All the economic analysis we have illustrated so far has focussed on the case of WaggaWagga. Here, in Figure 8, we summarise the main economic results for both the Condobolin and Wagga Wagga locations. The lower rainfall at Condobolin (recall Table 2) is associated with the lower mean weed-free wheat yields there compared to Wagga Wagga; 2.62 versus 3.62 t ha^{-1}. This key difference is reflected in both dimensions of Figure 8, **'mean Gross Margin'** and mean **Hamiltonian**.

Table 3. Herbicide doses calculated for 'best efficacy target strategy' (BETS) keyed to weed densities, with season-specific weather at Wagga Wagga, 1950-96, subject to max dose limit of 30 g a.i. ha^{-1}

	---- weed density, plants m^{-2} ----							
	128	96	64	32	8	4	2	1
BETS:	99%	99%	98%	97%	91%	84%	72%	61%
1950	17.3	17.3	10.2	7.5	3.1	1.9	1.1	0.8
1951	20.3	20.3	12.0	8.8	3.7	2.2	1.3	0.9
1952	23.4	23.4	13.8	10.1	4.2	2.6	1.5	1.0
1953	30.0	30.0	30.0	30.0	15.5	9.5	5.6	3.8
1954	30.0	30.0	23.8	17.4	7.3	4.5	2.6	1.8
1955	22.0	22.0	13.0	9.5	4.0	2.4	1.4	1.0
1956	20.9	20.9	12.3	9.0	3.8	2.3	1.4	0.9
1957	29.5	29.5	17.4	12.8	5.3	3.3	1.9	1.3
1958	12.8	12.8	7.5	5.5	2.3	1.4	0.8	0.6
1959	24.3	24.3	14.3	10.5	4.4	2.7	1.6	1.1
1960	30.0	30.0	21.8	16.0	6.7	4.1	2.4	1.6
1961	12.1	12.1	7.1	5.2	2.2	1.3	0.8	0.5
1962	20.4	20.4	12.0	8.8	3.7	2.3	1.3	0.9
1963	26.4	26.4	15.6	11.4	4.8	2.9	1.7	1.2
1964	30.0	30.0	22.5	16.5	6.9	4.2	2.5	1.7
1965	15.6	15.6	9.2	6.7	2.8	1.7	1.0	0.7
1966	19.7	19.7	11.6	8.5	3.6	2.2	1.3	0.9
1967	30.0	30.0	21.6	15.8	6.6	4.0	2.4	1.6
1968	30.0	30.0	18.5	13.5	5.7	3.5	2.0	1.4
1969	19.6	19.6	11.5	8.5	3.5	2.2	1.3	0.9
1970	30.0	30.0	30.0	26.9	11.2	6.9	4.0	2.8
1971	30.0	30.0	30.0	30.0	16.5	10.1	5.9	4.1
1972	26.9	26.9	15.9	11.6	4.9	3.0	1.7	1.2
1973	17.6	17.6	10.4	7.6	3.2	1.9	1.1	0.8
1974	18.4	18.4	10.8	7.9	3.3	2.0	1.2	0.8
1975	29.0	29.0	17.1	12.5	5.2	3.2	1.9	1.3
1976	30.0	30.0	30.0	29.8	12.5	7.6	4.5	3.1
1977	30.0	30.0	30.0	23.3	9.8	6.0	3.5	2.4
1978	17.6	17.6	10.4	7.6	3.2	1.9	1.1	0.8
1979	24.8	24.8	14.6	10.7	4.5	2.7	1.6	1.1
1980	28.7	28.7	16.9	12.4	5.2	3.2	1.9	1.3
1981	27.1	27.1	16.0	11.7	4.9	3.0	1.8	1.2
1982	30.0	30.0	24.8	18.1	7.6	4.6	2.7	1.9
1983	21.2	21.2	12.5	9.2	3.8	2.3	1.4	0.9
1984	12.0	12.0	7.1	5.2	2.2	1.3	0.8	0.5
1985	19.3	19.3	11.4	8.3	3.5	2.1	1.2	0.9
1986	20.1	20.1	11.9	8.7	3.6	2.2	1.3	0.9
1987	19.2	19.2	11.4	8.3	3.5	2.1	1.2	0.9
1988	23.4	23.4	13.8	10.1	4.2	2.6	1.5	1.0
1989	30.0	30.0	30.0	22.5	9.4	5.7	3.4	2.3
1990	12.4	12.4	7.3	5.3	2.2	1.4	0.8	0.6
1991	27.6	27.6	16.3	11.9	5.0	3.1	1.8	1.2
1992	14.5	14.5	8.6	6.3	2.6	1.6	0.9	0.6
1993	15.3	15.3	9.0	6.6	2.8	1.7	1.0	0.7
1994	30.0	30.0	30.0	30.0	21.2	13.0	7.6	5.2
1995	16.3	16.3	9.6	7.1	3.0	1.8	1.1	0.7
1996	13.9	13.9	8.2	6.0	2.5	1.5	0.9	0.6
MEAN	22.97	22.97	15.96	12.51	5.56	3.40	1.99	1.37
STDEV	6.23	6.23	7.35	7.19	4.01	2.45	1.44	0.99

Figure 8. Long & short-run economic comparisons of upper and lower label doses and 'best' strategies keyed to weed density, for Condobolin and Wagga Wagga, with weeds at four densities: 128, 32, 8 and 2 plants m^{-2}



The dotted diagonal lines in Figure 8, point to results for the different weed densities in the two locations. Results for the case of 2 plants m^{-2} are closest to the 'GM = Hamiltonian' diagonal because the future economic benefits of treating this level of weeds now, while positive, are not large. With increasing weed densities there are stronger incentives (in future benefits) to carry out treatment. The results shown for Wagga Wagga in Figure 8 are drawn from the analysis behind Figures (for 'blind' upper and lower label doses, and a 'Best Fixed Dose Strategy', **BFDS**) and Figure 7 (for derivation of a 'Best Efficacy Targeting Strategy', **BETS**). The analogous results for Condobolin are also summarised in Figure 8.

While the absolute values of results for the two case study locations stand in sharp contrast, the relative values of the different herbicide strategies are fully consistent, Figure 8. Simulations for both locations indicate the superiority of BETS over all others in terms of maximizing mean **Hamiltonians** at each weed density. But this is followed closely by **BFDS**, which are also superior to the 'blind dose' strategies at every weed density. At 128 weed plants m^{-2}, the upper label dose gives better economic results than the lower label dose, but at 32 plants m^{-2} and below, this lower 'blind' dose dominates the upper 'blind' dose.

We may also summarise results of the different strategies in terms of mean herbicide use by the different strategies (Figure 9). The 'blind' applications of upper label (30g) and lower label (15g) doses regardless of weed density or weather are indicated as horizontal lines in Figure 9. The **BFDS** doses, low for low weed densities and highest for high densities, differ between the two locations above 2 plants m^{-2}, with slightly

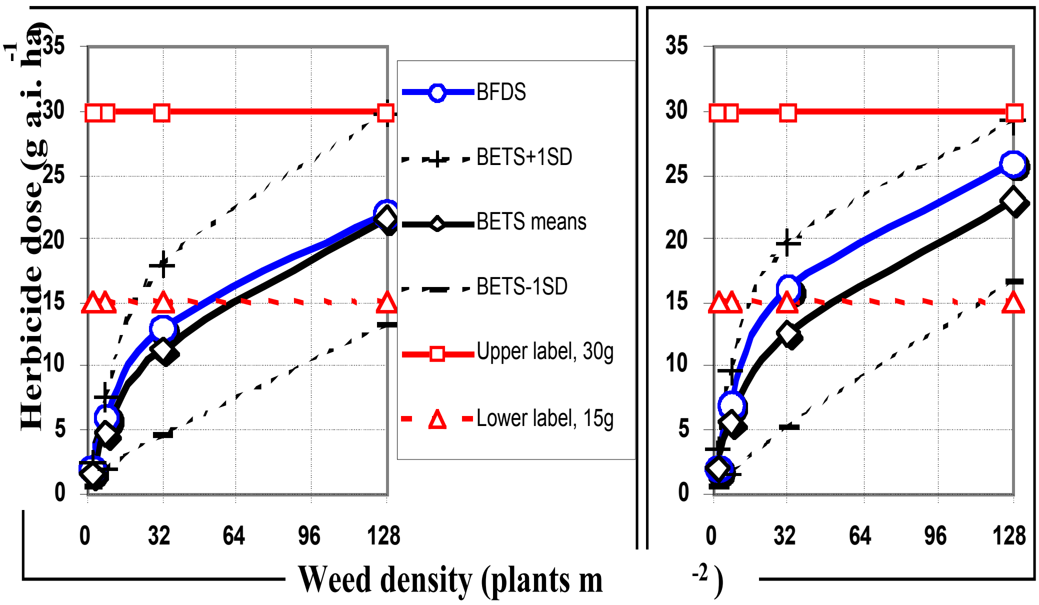
Figure 9. Herbicide use by weed density and strategy

Condobolin

Weed Density	BFDS	BETS means	SD
128	22	21.6	8.3
32	13	11.3	6.7
8	6	4.7	2.8
2	2	1.5	0.9

Wagga Wagga

Weed Density	BFDS	BETS means	SD
128	26	23.0	6.2
32	16	12.5	7.2
8	7	5.6	4.0
2	2	2.0	1.4



higher doses called for at Wagga Wagga where greater potential yield losses due to weeds are at stake. The same could be said of mean doses in the case of **BETS**, noting also that these are consistently lower than BFDS doses. It must also be remembered, of course, that **BETS** doses vary with the weather from season-to-season. This is indicated in Figure 9 by the 'BETS+SD' and 'BETS-SD' curves showing the standard deviations above and below the means at each weed density.

These findings show most clearly the value of quantitative guidance for the user to know when high doses are required and when lower doses will serve well. In light of these results, though only simulated for two locations in Australia, it is clear why very uneven results were reported by others examining the performance of reduced herbicide rates (recall references earlier in this paper). In our simulation analysis, we have controlled or accounted for the key sources of variation affecting the economic outcomes in the short and long run: differences in weed density and season-to-season differences in weather.

Given a weed density, our simulation model was designed to show the biological and economic outcomes for each season's environmental conditions and to summarise these over multiple seasons at two contrasting locations. There were large year-to-year variations in potential (weed-free) wheat yields, with coefficients of variation (CV) of 41% and 35% for Condobolin and Wagga Wagga, respectively. Such levels of variation are not unusual at the field-level in rain-fed farming (Nordblom *et al.* 1985).

The biological outcomes simulated for each season include density of remaining weeds, change in the weed seed-bank, actual yields (after losses due to remaining weeds), efficacy, and herbicide dose. The economic outcomes calculated at the end of each season are the **Gross Margin** for the current season and the **Hamiltonian** representing current and future benefits. The Hamiltonian takes the current season's gross margin into account along with the likely reductions in future costs due to more complete control of weeds in the current season.

The model provides a way to adjust the herbicide dose according to the season's environmental conditions (PRE7, TMAX and SMPRE10) in the paddock in order to achieve a desired efficacy. A fixed level of efficacy (say, 95%) across low and high weed densities would allow greater numbers of weeds to survive at the high densities. Thus, the idea pursued here: to define the best economic level of efficacy for each weed density. In the case of efficacy targeting, doses were adjusted from season-to-season by the model. For each weed density, we define the "best efficacy-target" as that with the highest mean **Hamiltonian** value over the multi-year run of seasons. We call the application of such "best efficacy-targets", according to weed densities, the "best efficacy-targeting strategy" (**BETS**).

In contrast, the fixed-dose strategies all result in efficacy variations from season to season. To find the "best" fixed dose for a weed density, the entire sequence of seasons was run with each of a range of doses. For a given weed density, we call the fixed dose with the highest mean Hamiltonian value over the run of seasons the "best fixed-dose". We call the application of such "best fixed doses" according to weed densities the "best fixed-dose strategy" (**BFDS**).

In addition to the two adjustable strategies described above, we considered the economic outcomes associated with using the upper label dose (30g/ha) and the half-dose (15g/ha) whenever weeds are sprayed, regardless of weed density. These two "strategies" have the advantage of simplicity. One question that has been answered is whether and by how much they can be bettered by strategies that are keyed to weed density. Another question is in regard to total herbicide use. Our analysis permitted an explicit view of the trade-offs between economics, current and future, and total herbicide use in managing weeds and weed seed-banks over time.

If what is wanted is a simple set of rules that only require estimates of weed density for good long run economic results, these can be expressed concisely. Taking the present case as an example, with 100 litres of spray water ha^{-1}, the associated **BFDS** could be listed by weed density and production zone. Such information would fit easily on a herbicide label.

But a finer resolution of the economic decision space will be wanted by some users; especially where farms are large and environmental conditions and weed densities are monitored closely. Where small differences in current cost or future benefits per hectare are multiplied by thousands of hectares, the greater weight of consequences can focus decisions. It can also create a desire for answers tailored to the conditions and costs faced in a particular paddock on a particular farm. This is where the idea of **BETS** can come into its own.

While a comparable **BETS** decision support tool will not fit on the herbicide label, it could easily be made available at the internet website of a manufacturer. Limitations to a manufacturer's liability could be made clear to users whenever they access such a model. On the same limited-liability terms from the manufacturer, decision support models could also be made available through agricultural service providers. The benefits from using this kind of quantitative tool are expected to include (a) the avoidance of under-dosing for required effectiveness given the environmental conditions and weed density, (b) the avoidance of over-dosing, and (c) enhanced awareness of when conditions are unsuitable for effective herbicide treatments.

Considering the economic penalties expected from allowing a substantial number of weeds to compete with the crop and set seeds for subsequent seasons, the present analysis has quantified the extent to which high weed densities call for the highest efficacy levels, and low weed densities the lower efficacies. In addition to the long-run economic benefits, adjustable dose strategies, can result in lower overall herbicide use than constant (upper or half) label doses. Because this has been a major concern in Denmark (Jensen & Kudsk, 1989) and elsewhere, particularly in Europe, we think the findings and especially the methods of the current study will be of interest beyond Australia as well.

CONCLUSIONS

This paper has quantified and demonstrated a new paradigm in the economics of weed control: that the overarching aim must be to manage and reduce weed seedbanks for the longer term, not merely to kill weeds in the current crop for short-term yield loss reduction.

Strategies of “best fixed-dose for weed density” (**BFDS**) were found to produce economic results nearly as good as “best efficacy-targeting” (**BETS**) in long run simulations, but with the important practical advantages of simplicity and lower information requirements

The modelling framework developed for this analysis can be used for other locations to test the extent to which **BFDS** and **BETS** “rules of thumb” would change. The initial indication from our analysis of two contrasting wheat districts is encouraging. Though quite different in climates, the rules for them were similar: for any given weed density, the “best fixed-dose” at the drier Condobolin location was never more than a few grams per hectare below that for Wagga Wagga.

If a robust **BFDS** could be identified with such a simulation model and field-tested for each major wheat district, this sort of information would be of considerable use to growers. The potential application to precision farming is also obvious. If one knows where the weed patches are, and how dense they are there, one has a basis now for applying just the amount of herbicide to economically manage weed populations as part of an integrated weed management program, a way to avoid applying too little or more herbicide than is required for the situation.

Considering the amount of weather and soil information required for **BETS** to determine appropriate herbicide doses each season to ‘chase’ efficacy targets, the question of cost and benefit of this information naturally arises. It is likely this type of tailored decision support information will be of interest chiefly in the cases of expensive selective herbicides and to managers of larger farms, such as found widely in Western Australia and New South Wales, the Great Plains of the US and Canada, and the steppes of Central Asia.

Because other herbicides also exhibit differences in efficacy according to environmental conditions, they too should be amenable to the new economic decision-support paradigms represented by **BET** and **BFD** strategies.

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