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Economic evaluation of a weed-activated sprayer for herbicide application to patchy weed populations

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Spatial distribution of weeds in a crop is patchy. Traditional boom sprayers waste herbicide by applying it to areas where weed density is already low. A new technology, Weed Activated Spray Process (WASP), uses sensors to detect the presence of weeds and control spray nozzles accordingly. The economic benefits of this technology to extensive crop farmers in Western Australia are investigated using a model based on the economics of information. Existing technology is likely to reduce profits because the weed density at which it switches off spraying is too high. Even if sensitivity to low densities could be improved, likely benefits of pre-crop usage would still be very low or negative.

1. Introduction

Expenditure on chemical herbicides by Australian farmers has grown rapidly over the past twenty years, so that now they constitute the highest or second highest input cost for most extensive crop farmers. Concern over the level of use of herbicides in agriculture and their costs to farmers, consumers and the environment (e.g., Combellack 1989; Hoar *et al.* 1986; Kovach *et al.* 1992; Nielsen and Lee 1987; Pimentel 1983) has led to the development of a number of new herbicide application technologies, including rope-wick applicators (Cooke and Smith 1985; Keeley *et al.* 1984; Moomaw and Martin 1990) and roller applicators (Mayeux and Crane 1984; Messersmith and Lym 1985; Schneider *et al.* 1982; Welker and Peterson 1989). This article reports on an investigation of the potential economic value of one such technology, known as a Weed Activated Spray Process (WASP) (Felton *et al.* 1987, 1991).

The use of information about *temporal* variation in weed density to adjust weed management practices has been shown to generate economic benefits (Pannell 1994; Swinton and King 1994; Thornton *et al.* 1990). The

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benefits of WASP arise from use of information about the *spatial* variability of weeds (e.g., Wiles, Wilkerson and Gold 1992). The nature and biological implications of this spatial variability have been widely studied (e.g., Auld and Tisdell 1988; Brain and Cousens 1990; Hughes 1989; Wiles *et al.* 1992a, 1992c), with some attention also to the related issue of spatial distribution of applied herbicides (e.g., Dorr and Pannell 1992). WASP employs an electronic eye to detect the presence or absence of green matter beneath the spray nozzle of a boom sprayer, allowing reductions in herbicide usage by automatically preventing the application of herbicides to areas of a paddock which have an insufficient density of weeds to warrant the expense. Because it cannot distinguish between green matter of different plant species and treat them differently, WASP is only of use when desirable crop or pasture plants are not present.

Although the aim of the WASP technology is to reduce herbicide usage, a full evaluation of its benefits should not be based solely on the reduction achieved. The economic benefits are affected by a number of complexities, including the following:

1. The benefits of the technology depend on the spatial distribution of weeds. The more patchy the distribution, the greater the potential for the WASP.
2. The benefits of reducing herbicide usage are partly offset by the costs of increased weed competition in patches where the weed density is greater than zero, but too low to activate the spray nozzle.
3. For various reasons, including inherent limitations of the technology, the information provided to the spray nozzle by the weed detector is imperfect. Some areas of the paddock will be sprayed despite a low weed density, while some patches with many weeds will be missed.
4. The impact of spraying or not spraying a weed is felt over subsequent years due to the level of carry over of weed seeds.
5. From a social perspective, the benefits depend on the external costs of herbicide usage (to consumers, the environment and, possibly, other farmers).

Although there have been various evaluations of WASP or WASP-like technology in the past, each has considered only a sub-set of the relevant issues (e.g., Ahrens 1994; Audsley 1993; Thompson, Stafford and Miller 1991). In particular, the nature of the problem as a valuation of information (Wiles, Wilkerson and Gold 1992) has not been captured in previous studies. The only exception is Oriade *et al.* (1996) but their evaluation was for a hypothetical technology for differential spraying of large patches (hectares in size). They concluded that 'site-specific management' seems to hold promise for weeds and that the patchiness of weeds plays a key role in determining its potential value.

In this article we focus on the potential on-farm benefits and costs of the WASP technology when used for weed control immediately prior to cropping. We capture all of the complexities outlined above except externalities. This omission is justified on the basis that (a) the herbicides in question are of very low persistence and so external benefits would be very minor relative to direct financial benefits and costs, and (b) whether or not there are external costs, it is valuable to consider the private benefits and costs to farmers, since these will be the prime determinants of adoption of the technology.

We develop a framework based on Bayesian decision theory (Anderson, Dillon and Hardaker 1977) to estimate the value of the information collected and used in real time by a WASP sprayer. The framework allows for the savings and costs (both direct and indirect) of the technology, as well as the imperfect nature of the information it uses. Given the uncertainty about a number of aspects of the performance of the technology, the analysis takes the form of a wide-ranging sensitivity analysis to identify which factors are most likely to influence the decision about whether the WASP technology is economically viable for a farmer.

The next section provides further information about the WASP technology. Following this, the modelling framework is presented and assumptions employed in the quantitative model are given. Results from the sensitivity analysis are presented and discussed before conclusions from the study are outlined.

2. The WASP technology

The WASP sprayer discriminates between green vegetation and background matter through the difference in light reflectance. It operates on the basis that green plant matter has a different absorption of red and near-infra-red light compared to other background such as soils of dry crop residues (Felton *et al.* 1987). The WASP technology is fitted to a conventional boom sprayer. Each nozzle of the boom sprayer is fitted with its own sensor which has a field of view the same width as that covered by the spray from the nozzle. The user is able to specify the minimum proportion of this field of view which must be taken up by green matter before the spray nozzle is activated. With current commercially available technology this threshold field of view cannot be set lower than 3 per cent.

There is no mechanism in WASP to control the dosage that is sprayed onto each patch of weeds, so a patch with a weed density just above the threshold is sprayed with the same dosage as a more heavily infested patch. The ‘threshold’ in the last sentence refers to the weed density above which spraying by the WASP is triggered. It does not necessarily coincide with the economic threshold, defined as the weed density above which application of a fixed recommended herbicide dose is economically justified (Pannell 1990). The limitations of the economic threshold approach to herbicide decision-making have been widely canvassed (e.g., Cousens 1987; Pannell 1988) but given the nature of WASP, the economic threshold is helpful to evaluate the economic impacts of the actual threshold used by the WASP. In addition, in some results presented later (tables 4, 5 and 6), we assume that the WASP's threshold is able to be adjusted to the economic threshold for the specific situation.

In the remainder of the article, the term 'economic threshold' will be used exclusively to refer to a weed density above which spraying would be economically justified. In the first set of results presented, the actual threshold used by WASP does not correspond to the economic threshold but rather to a fixed value determined by the current limitations of the technology.

Pannell (1990) showed that the optimal herbicide dose is positively related to weed density, so although WASP improves the selectivity of herbicide use relative to a conventional sprayer, there remains a degree of mismatch between density and dosage. Furthermore, like any technology, the system is liable to occasional mistakes, spraying bare ground or failing to spray dense patches. We lack evidence on the frequency of these mistakes and so have assessed their significance using sensitivity analysis.

There have been a number of field evaluations of WASP in Australia, focusing on savings in herbicides. For example, Felton *et al.* (1991) measured a 90 per cent reduction in herbicide use over 2 681 hectares on 33 farms in New South Wales and Queensland. WASP reduced herbicide use on summer weeds by 67 to 87 per cent in a trial in Western Australia (Martin 1992). In the United States, Ahrens (1994) measured reductions in spray volume of 47 to 88 per cent using WASP in two North Dakota fallow sites.

The purchase cost of WASP technology is currently substantial, estimated as A\$38 000 for a complete modification to an average-sized boom sprayer in Western Australia. We assume a disposal value of A\$20 000 after a productive life (T) of 10 or 20 years and a real discount rate (r) of 7.5 or 15 per cent. Denoting $A(T, r)$ as the sprayer's annuity cost as a function of T and r, $A(10, 7.5) =$ A\$6 900; $A(10, 15) =$ A\$8 600; $A(20, 7.5) =$ A\$4 200; and $A(20, 15) =$ A\$6 300.

3. The model: overall framework

Consider a field in which weed density prior to spraying, ψ, is spatially distributed within the field according to the density function $f(\psi)$. Suppose that it is possible to subdivide the field into n smaller regions or patches in which the assumption of a spatially uniform weed distribution is reasonable. In patch *i*, representing a proportion $pr(i)$ of the total area, initial weed density is ψ_i. If herbicide is applied, a proportion *k* is killed, where in general $k < 1$. Weed density after spraying, *W*, is given by:

$$W = \psi(1 - hk), \tag{1}$$

where *h* is a binary variable taking values 1 if herbicide is applied or zero if not. Crop yield is reduced by competition with those weeds which survive or avoid herbicide application. Let $D(W)$ represent proportional yield loss. Empirical evidence (Cousens 1985) indicates that $d^2D/dW^2 > 0$, and that a suitable functional form is:

$$D(W) = 1 - a/[1 + a/(bW)] \tag{2}$$

where parameter *a* can be interpreted as the asymptotic yield loss as $W \to \infty$. Crops typically give some positive yield even at very high weed densities, so *a* is normally less than one. The parameter *b* is the proportional yield loss per weed as $W \to 0$. There has been debate over the appropriate form for this function and the economic implications of different forms (e.g., Swinton 1991; Pannell 1991), but the evidence supporting this particular form for virtually all weed situations appears compelling.

Crop yield in the absence of weeds would be Y_0, assumed for convenience to be spatially uniform. In patch *i*, final crop yield after allowing for weed competition, *Y*, is given by:

$$Y_i = Y_0[1 - D(W_i)] \tag{3}$$

Average crop production per unit area for the field is

$$Y = \Sigma_{i=1..n} Y_0[1 - D(\psi_i\{1 - h_i k\})]pr(i) \tag{4}$$

Profit for patch *i* is:

$$\pi_i = P_y Y_0[1 - D(\psi_i\{1 - h_i k\})] - h_i P_h - P_f, \tag{5}$$

where P_y is output price, P_h is herbicide cost per unit area and P_f is other production costs, assumed to be fixed. Average profit per unit area for the field is:

$$\pi = \Sigma_{i=1..n}\{P_y Y_0[1 - D(\psi_i\{1 - h_i k\})] - h_i P_h - P_f\}pr(i). \tag{6}$$

Using a similar model, Pannell (1990) showed that as initial weed density falls, the benefits of applying a fixed herbicide dose also fall. There exists an economic threshold weed density (τ), below which the costs of purchasing and applying the herbicide outweigh the benefits. If the threshold is known, information about how the weed density varies over space or, more usually, over time can be used to increase the expected net profit from the crop.

Information of this type about spatial variability is the source of the benefits from the WASP technology. The problem investigated here is whether these benefits are likely to be sufficient to warrant the expense of purchasing the technology. If π_w represents a stream of annual profits when WASP technology is used during the evaluation period, π_T represents a stream of profits using traditional spray application technology, C_W represents a stream of purchase and operating costs of the WASP technology and NPV signifies the net present value, the problem is whether:

$$\mathrm{NPV}(\pi_W - \pi_T) > \mathrm{NPV}(-C_W) \tag{7}$$

Because WASP is purchased as an add-on to a traditional boom sprayer, the cost of the boom sprayer is not included in equation 7; it must be borne whether or not WASP is purchased.

3.1 The value of information about weed density

The field can be divided into patches where the weed density exceeds the economic threshold for spraying ($\psi > \tau$) and patches where it does not. When WASP technology is used, the field can also be divided into patches where herbicide is applied ($h = 1$) and patches where it is not ($h = 0$). In practice, these two divisions of the field will not coincide exactly. Reasons for this may include: failure of the operator to set the sprayer's threshold at the true economic threshold; a divergence between the field of view of a sensor and the piece of ground sprayed by the corresponding nozzle; wind moving herbicide droplets before reaching their target; and intrinsic limitations of the technology in sensing weeds. This means that patches can be categorised into groups where, relative to traditional spray application technology, the use of WASP technology (a) makes no difference to profit; (b) increases profit; and (c) decreases profit. Table 1 shows how these categories apply to the different types of patch. It is clear from table 1 that the level of profit improvement provided by the WASP depends on the

Table 1 Impact of WASP technology on profit relative to traditional spray application technology

	$h = 1$	$h = 0$
$\psi > \tau$	0	$-$
$\psi < \tau$	0	$+$

Notes:
$h = 1$ means spray; $h = 0$ means do not spray; ψ is the initial weed density; τ is the economic threshold weed density.
($+$ = profit improved; $-$ = profit reduced; 0 = profit unchanged)

accuracy of the technology in detecting patches with sufficiently low weed density to not spray. We now outline how this accuracy is represented in the framework.

Let π_0 signify the profit obtained if no herbicide is applied and π_1 signify the profit obtained if herbicide is applied, calculated using equation 5 with h set to 0 and 1, respectively. The benefits of applying a fixed herbicide dose to a patch is $\beta = (\pi_1 - \pi_0)$. β is positively related to the weed density in the patch ($\mathrm{d}\beta/\mathrm{d}\psi > 0$) and approaches zero as the weed density approaches the threshold density. Also, if $\psi < \tau$, then $\beta < 0$ so that non-application of herbicide is preferred to application. Assume that we rank the patches by β so that the first m patches have $\beta < 0$. Let $\rho_c = \mathrm{prob}(h = 0|\psi < \tau)$, the probability that the WASP correctly switches off a nozzle in a patch where $\psi < \tau$. Similarly let $\rho_e = \mathrm{prob}(h = 0|\psi > \tau)$, the probability that the WASP erroneously switches off a nozzle in a patch where $\psi > \tau$. Depending on the cause of any errors made by the sprayer, it is possible that these probabilities are related to the weed density, ψ. For example, it is possible that ρ_e would be lower in patches with higher weed densities. However, for convenience and the lack of any quantitative information, we will assume that the probabilities are constant throughout the field. In summary, the net annual benefits across a field of using the WASP technology ($\pi_W - \pi_T$) in a given year are given by:

$$\pi_W - \pi_T = \Sigma_{i=1..m}[-\beta_i \rho_c pr(i)] + \Sigma_{i=m+1..n}[-\beta_i \rho_e pr(i)] \tag{8}$$

The two terms in equation 8 correspond to two categories into which the treated land is divided: the areas where $\psi < \tau$ and where $\psi > \tau$. Equation 8 calculates the impact of switching off spray in a proportion of each these areas. In the first case, switching off is a benefit, while in the second it is an error and results in a cost.

Equation 8 is equivalent to:

$$\pi_W - \pi_T = \Sigma_{i=1..n}[\beta_i (h_i - 1) pr(i)]. \tag{9}$$

If $h_i = 1, (\pi_W - \pi_T) = 0$. If $h_i = 0$ and $\beta_i > (<) 0, (\pi_W - \pi_T)_i < (>) 0$.

It is also possible that, in some circumstances, the strategy of not spraying a paddock at all will be more profitable than use of a traditional boom sprayer: $\pi_0 > \pi_T$. In this case, the net annual benefits across a field from using the WASP technology ($\pi_W - \pi_0$) in a given year are given by:

$$\pi_W - \pi_0 = \Sigma_{i=1..m}[\beta_i (1 - \rho_c) pr(i)] + \Sigma_{i=m+1..n}[\beta_i (1 - \rho_e) pr(i)] \tag{10}$$

or equivalently by:

$$\pi_W - \pi_0 = \Sigma_{i=1..n}[\beta_i h_i pr(i)]. \tag{11}$$

If $h_i = 0, (\pi_W - \pi_0)_i = 0$. If $h_i = 1$ and $\beta_i > (<) 0, (\pi_W - \pi_0)_i > (<) 0$.

Note that if a patch is not sprayed, weed density in subsequent years will be increased. This is captured in the numerical model below via a shadow cost of allowing weed survival.

4. Assumptions for the numerical model

4.1 Dynamics

One important decision regarding model structure was how to represent dynamics. Weed populations and spatial distributions clearly change over time, and these changes would be affected by the use or non-use of WASP technology. Ideally, to fully capture these effects, the problem should be modelled in a multiperiod framework, with weed spatial distribution a state variable. However, combining such a multiperiod approach with representations of spatial variability and the Bayesian-style framework outlined above would be extremely challenging in a numerical model. In practice it was necessary to prioritise. The representation of spatial variability was clearly essential to the problem, since WASP has no conceivable value without it. The importance of the Bayesian framework was difficult to judge *a priori*. However, we chose to include it at the cost of the dynamic representation, partly on the basis that it was easier to approximate the dynamic effects on the economic results of weed survival or mortality. This was done by including a shadow price for weed survival based on results from a modified version of the deterministic dynamic model of Gorddard, Pannell and Hertzler (1995). As reported later, sensitivity analysis was conducted on this shadow price to test whether this simplified static approach was likely to seriously affect the results.

4.2 Parameter values

Parameters for the evaluation are specified to represent a wheat producer in the south-west of Western Australia. A typical area of crop for such producers is 1 000 hectares per year. The analysis is based on a 'knock-down' herbicide such as glyphosate applied with WASP prior to emergence of the crop. Additional weed control is assumed to be conducted in the crop with a traditional boom sprayer; WASP is only used prior to seeding.

Different weed densities are examined with the standard assumption corresponding to an average of 700 weeds m^{-2} as observed in a set of field measurements after weed germination in May 1994 on a farm at Cunderdin, in Western Australia's central wheatbelt. The alternative assumptions were for this density to be doubled or quartered. The distribution of weed densities within a paddock is important to the analysis. We used as a standard the distribution measured at Cunderdin, as shown in figure 1. For higher and

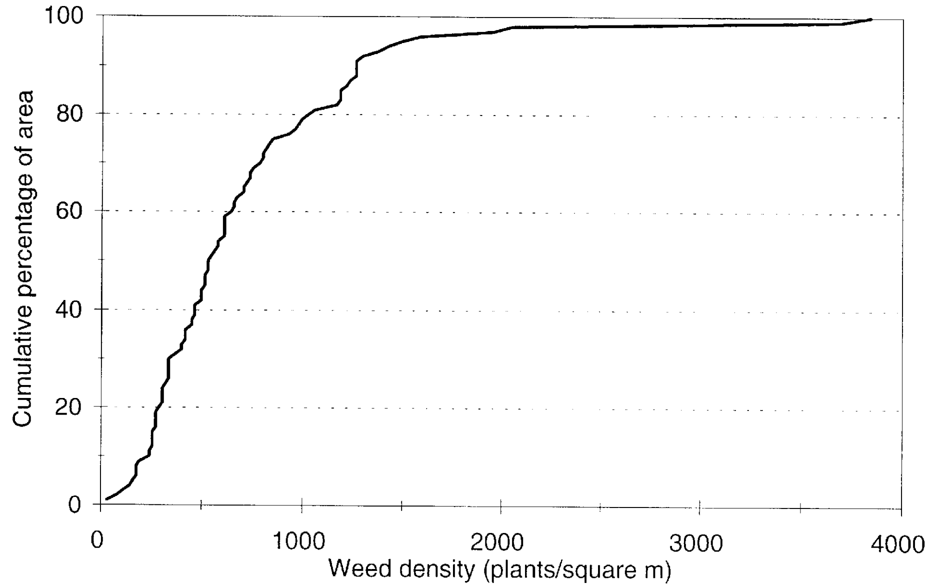

Figure 1 Cumulative distribution function for spatially variable untreated weed density in the crop

lower density scenarios, this distribution was scaled proportionately to the change in mean density.

Crop yield losses from competition of the weeds with the crop were based on the equation estimated by Pannell (1995) for ryegrass in the same region, so that parameters a and b from equation 2 are set at 0.75 and 0.002, respectively. We do not specify exactly what mixture of weed species is present. Implicitly, the competitiveness of a given population of ryegrass is assumed to be a good approximation of the competitiveness of a mixed population of weeds. This assumption is justified on the bases that (a) ryegrass is the most widespread and economically important weed in the region and will be present in most weed populations; (b) there are few other weeds for which the information is available; (c) the available evidence indicates it to be a reasonable assumption; and (d) even if it is a little inaccurate, the sensitivity of model results to weed competitiveness is amongst the lowest of any of the model's parameters.

The 100 sample patches underlying figure 1 are assumed to be representative of the whole area of crop. Yield loss is calculated separately for each of the patches and scaled up to an average value per hectare. Allowance is made for the probability that the patch will be sprayed, based on its weed density, the threshold field of view and the probability of a WASP error.

Not all weeds germinate and emerge from the soil in time to be sprayed by the WASP, which must be used prior to crop emergence because of WASP's inability to distinguish crop from weeds. A wide range of emergence assumptions are tested, reflecting the range which occurs in practice.

As noted earlier, allowance is made for the cost in future years of allowing weeds to survive and set seed in the current year. This is achieved by assigning a shadow cost of A$0.10 per plant based on results from a modified version of the dynamic model of Gorddard *et al.* (1995).

4.3 Procedure for sensitivity analysis

Many of the parameters of the model are subject to uncertainty or to change over time and space. For this reason, results are subjected to a sensitivity analysis. The general approach is consistent with Pannell's (1997) Strategy A for sensitivity analysis. It proceeds by (a) identifying those parameters most subject to change or uncertainty; (b) selecting minimum, maximum and standard or most-likely values for each of these parameters; (c) assessing the sensitivity of results to parameter changes within the ranges selected in (b); and (d) for a subset of the most sensitive parameters, conducting a complete factorial experiment. Steps (a), (b) and (c) are undertaken assuming that the threshold field of view for WASP is set at its current minimum value of 3 per cent. Step (d) is repeated for the threshold set at 3 per cent and at its optimal value for the scenario being considered. Results for several different output variables are presented: the impact of the WASP technology on per-hectare profits from cropping, the optimal threshold level of weeds in the field of view, and the proportion of the paddock area which is sprayed by the WASP technology.

Table 2 Values and sensitivity index results for parameters of the model

Parameter	Minimum value	Standard value	Maximum value	Sensitivity index[a]
Weed mortality: in-crop spray (proportion)	0.80	0.95	0.99	– 7.08
Weed emergence for WASP spray (proportion)	0.20	0.50	0.80	– 5.35
Cost of WASP herbicide ($/ha)	10.00	15.00	25.00	5.01
Weed-free yield of crop (tonne/ha)	1.00	2.00	3.00	– 4.88
Mean weed density (proportion of standard)	0.25	1.00	2.00	– 4.47
Net sale of wheat ($/tonne)	100.00	150.00	200.00	– 3.25
Shadow cost of allowing weed survival ($/plant)	0.00	0.10	0.20	– 2.27
Probability of WASP error if density < threshold	0.01	0.05	0.15	1.36
Weed mortality by WASP (proportion)	0.80	0.95	0.99	– 1.29
Weed competition parameter *a*	0.50	0.75	1.00	– 1.00
Probability of WASP error if density > threshold	0.01	0.05	0.15	0.22
Threshold field of view for WASP spraying	0.02	0.03	0.04	0.14

Note: [a] Sensitivity to parameter changes of the impact of WASP sprayer on profits from cropping, based on equation 12.

The selection of parameter values for the sensitivity analysis was based on previous studies (Pannell 1995; Gorddard *et al.* 1995), discussions with the developers of WASP and with weed scientists at the government agency Agriculture Western Australia. The parameters used are shown in table 2.

5. Results and discussion

The model is used to estimate the impact of the WASP technology on profit per hectare from cropping. This is calculated as the improvement in average profit per hectare relative to the best alternative other than WASP. This best alternative might be a conventional sprayer or no spray at all, depending on the scenario. Results are presented first for the case where the threshold field of view for WASP is set at 3 per cent.

Table 2 shows the minimum, standard and maximum values for each parameter used in the sensitivity analysis. The parameters are ranked according to the absolute value of a 'sensitivity index', defined as follows:

$$I = (B_{\max} - B_{\min})/B_{\mathrm{st}} \tag{12}$$

where $B_{\max}$ is the benefit of WASP when the parameter in question is set at its maximum value, $B_{\min}$ is the benefit given the minimum parameter value and B_{st} is the benefit for the standard parameter value. This index is almost the same as one proposed by Hoffman and Gardner (1983) (who used $B_{\max}$ in place of B_{st}). Hamby (1995) conducted a detailed comparison of the performances of fourteen sensitivity indices (of various levels of complexity) relative to a composite index based on ten of them. None of the complex indices tested performed as well as Hoffner and Gardner's simple one.

The purpose of this ranking is to select the most important parameters for more detailed analysis. The five top-ranked parameters were subjected to a complete factorial experiment using all three parameter levels in table 2, giving $3^5 = 243$ solutions. Table 3 shows a selection of these; for the two top-ranked parameters, results are given for all three levels, but to save space the results for standard values of the other three parameters are omitted.

A striking aspect of these results is how many of them are negative (60 out of 72). Even without considering the cost of purchasing and maintaining WASP, it actually reduces the profitability of cropping relative to the best non-WASP option in many circumstances.

In interpreting the individual results, note that the best non-WASP option is the traditional sprayer in some cases (e.g., the top, right-hand corner result of −A\$8.29) and no spray in others (e.g., the left-hand adjacent result of −A\$0.23). Because the best non-WASP option varies in this way, the trends in table 3 are very complex. The twelve positive results are sprinkled

Table 3 Impact of WASP sprayer on profits from cropping ($/ha) if threshold field of view set at 0.03

			Yield (t/ha)	1	1	3	3
Weed mortality: in-crop spray (proportion)	Weed emergence for WASP spray (proportion)	Cost of WASP herbicide ($/ha)	Weed density (multiplier)	0.25	2	0.25	2
0.8	0.2	10		−0.39	0.48	−0.23	−8.29
0.95	0.2	10		−0.47	−0.31	−0.42	0.52
0.99	0.2	10		−0.49	−0.82	−0.48	−0.52
0.8	0.5	10		−0.21	−4.87	−3.71	−17.53
0.95	0.5	10		−0.42	1.96	−0.30	−2.88
0.99	0.5	10		−0.48	−2.89	−0.46	−0.34
0.8	0.8	10		0.51	−5.82	−10.89	−17.67
0.95	0.8	10		−0.32	0.46	0.21	−3.62
0.99	0.8	10		−0.60	−3.27	−0.49	1.75
0.8	0.2	25		−1.14	−0.82	−0.98	0.22
0.95	0.2	25		−1.22	−1.87	−1.17	−1.04
0.99	0.2	25		−1.24	−2.38	−1.23	−2.08
0.8	0.5	25		−0.96	3.17	−0.55	−9.49
0.95	0.5	25		−1.17	−4.75	−1.05	4.19
0.99	0.5	25		−1.23	−9.85	−1.21	−7.30
0.8	0.8	25		−0.51	−0.88	1.09	−12.73
0.95	0.8	25		−1.34	−2.46	−0.81	1.31
0.99	0.8	25		−1.62	−13.33	−1.51	−8.27

unsystematically throughout the table. For each of the parameters, higher values are better in some cases but worse in others. The strongest individual trend appears to be that WASP is usually especially unfavourable when there is a combination of: low weed mortality from in-crop spraying;[1] high potential yield and high weed density. It appears that this is largely because the threshold weed density at which WASP activates spraying is uneconomically high. That is, the true economic threshold is lower than that used by WASP. Higher potential yield reduces the economic threshold (Pannell 1990), so the cost of the error from having a fixed high WASP threshold would increase. In cases of low weed mortality from in-crop spraying and high weed density, a high WASP threshold means that it is more likely that many weeds will survive and compete in circumstances where this is uneconomic.

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[1] To avoid confusion, it should be noted that this in-crop spraying refers to subsequent application of selective herbicides using traditional spraying technology. This is a separate, additional application, distinct from the pre-crop application of broad spectrum herbicide using WASP. The additional post-emergence spraying is included as it is consistent with likely farmer behaviour if WASP were used.

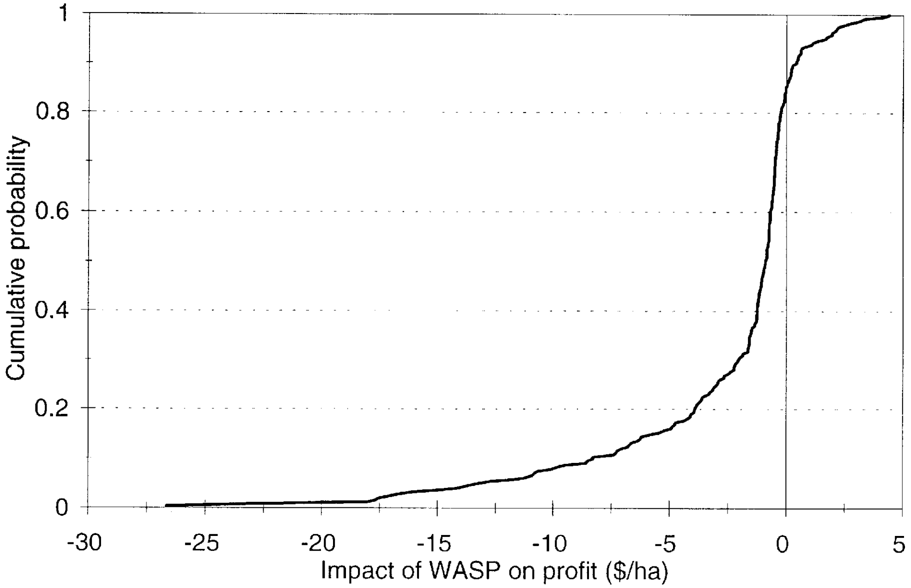

Figure 2 Cumulative distribution function for impact of WASP sprayer on profits from cropping based on threshold field of view of 0.03.

If we assigned probabilities to each of the 243 scenarios, we could identify the probability distribution of the benefits of WASP (conditional on other parameters being set at their standard values). Figure 2 shows the cumulative distribution of benefits assuming, for illustrative purposes, that each of the scenarios is equally likely. (Other assumptions about the probability distributions were investigated and found to make only small differences to the results). In this case, the probability of WASP having a benefit of less than zero is 85 per cent. The mean of this distribution is −A$2.47 per hectare.

From these results, the prospects for current WASP technology for pre-crop weed control appear bleak. The benefits are small at best and substantially negative at worst. The benefit in the single most favourable scenario (A$4.19) would need to be generated over more than 1 000 hectares of crop to cover the annuity cost of purchasing the WASP technology even under the most favourable assumptions regarding discount rate and machinery life and ignoring maintenance and repair costs.

It was noted that a factor contributing to the poor performance of WASP in some scenarios is the high value of the threshold weed density at which it activates spraying. The limited sensitivity of the current technology means that the lowest possible threshold setting is 3 per cent of the area of the field

Table 4 Impact of WASP sprayer on profits from cropping ($/ha) if threshold field of view set at optimal level

			Yield (t/ha)	1	1	3	3
Weed mortality: in-crop spray (proportion)	Weed emergence for WASP spray (proportion)	Cost of WASP herbicide ($/ha)	Weed density (multiplier)	0.25	2	0.25	2
0.8	0.2	10		0	1.50	−0.01	−0.35
0.95	0.2	10		0	−0.25	0	1.35
0.99	0.2	10		0	0	0	−0.37
0.8	0.5	10		0.16	−0.74	1.07	−2.24
0.95	0.5	10		0	1.97	−0.12	−0.40
0.99	0.5	10		0	−0.34	0	0.41
0.8	0.8	10		1.97	−1.85	−0.21	−4.58
0.95	0.8	10		−0.32	0.46	0.58	−1.41
0.99	0.8	10		0	−0.11	0	2.39
0.8	0.2	25		0	−0.60	0	0.48
0.95	0.2	25		0	0	0	0
0.99	0.2	25		0	0	0	0
0.8	0.5	25		0	3.20	0.16	−1.17
0.95	0.5	25		0	−0.55	0	4.26
0.99	0.5	25		0	0	0	−0.89
0.8	0.8	25		−0.51	−0.30	4.40	−3.67
0.95	0.8	25		0	1.28	−0.81	1.32
0.99	0.8	25		0	0	0	−0.32

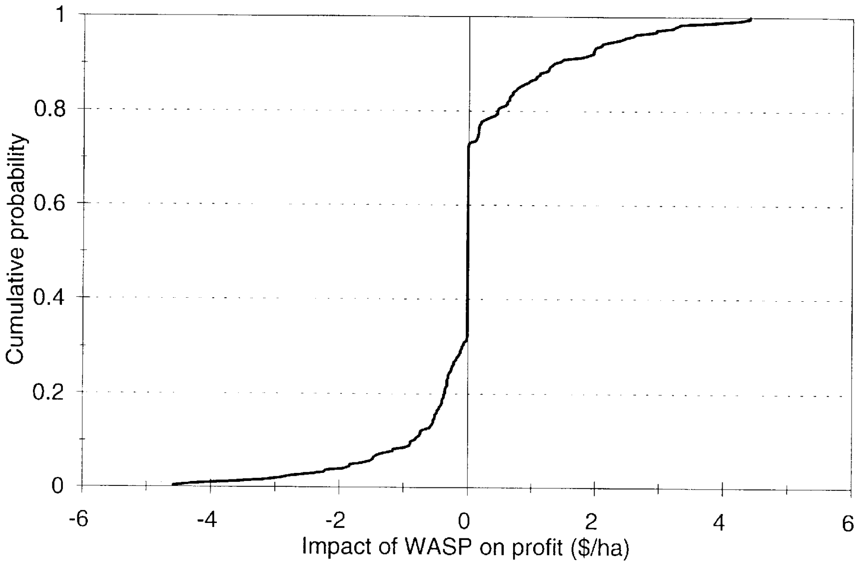

Figure 3 Cumulative distribution function for impact of WASP sprayer on profits from cropping based on economically optimal threshold field of view

of view. It is plausible that in future the technology may be improved to allow a greater sensitivity and a lower threshold. To investigate the extent to which this will improve the economic performance of WASP, the complete factorial experiment was repeated, but with the threshold weed density for spraying set to the economically optimal value for the particular scenario. Results are shown in table 4 and figure 3 (which, like figure 2, is based on the assumption that each scenario is equally likely).

While the risk of very bad outcomes has been reduced by adjusting the threshold to suit the situation, and the probability of making a positive benefit increased from 15 to 27 per cent, the overall magnitude of benefits is still low; the mean of the distribution in figure 3 is only A$0.09 per hectare. Partly this is because of the cost of errors by WASP and partly because the average magnitude of benefits generated is small. To understand why it is so small, consider tables 5 and 6. Table 5 shows the optimal setting of WASP's threshold for spraying (expressed as a proportion of the area of the field of view). In many cases, the threshold is 1, indicating that no spray should be applied. Apart from these scenarios, many of the optimal threshold levels are either very low, so that most of the paddock is sprayed, or so high that very

Table 5 Optimal threshold level of weeds in the field of view for WASP sprayer (proportion of field of view covered)

			Yield (t/ha)	1	1	3	3
Weed mortality: in-crop spray (proportion)	Weed emergence for WASP spray (proportion)	Cost of WASP herbicide ($/ha)	Weed density (multiplier)	0.25	2	0.25	2
0.8	0.2	10		1	0.012	0.004	0.003
0.95	0.2	10		1	0.074	1	0.014
0.99	0.2	10		1	1	1	0.074
0.8	0.5	10		0.008	0.008	0.003	0.004
0.95	0.5	10		1	0.032	0.012	0.012
0.99	0.5	10		1	0.187	1	0.059
0.8	0.8	10		0.007	0.009	0.003	0.006
0.95	0.8	10		0.037	0.029	0.011	0.011
0.99	0.8	10		1	0.158	1	0.057
0.8	0.2	25		1	0.074	1	0.019
0.95	0.2	25		1	1	1	1
0.99	0.2	25		1	1	1	1
0.8	0.5	25		1	0.027	0.009	0.008
0.95	0.5	25		1	0.187	1	0.034
0.99	0.5	25		1	1	1	0.187
0.8	0.8	25		0.037	0.022	0.007	0.009
0.95	0.8	25		1	0.085	0.037	0.029
0.99	0.8	25		1	1	1	0.158

Table 6 Proportion of paddock area sprayed with herbicide when threshold field of view set at optimal level

			Yield (t/ha)	1	1	3	3
Weed mortality: in-crop spray (proportion)	Weed emergence for WASP spray (proportion)	Cost of WASP herbicide ($/ha)	Weed density (multiplier)	0.25	2	0.25	2
0.8	0.2	10		0	0.46	0.05	0.96
0.95	0.2	10		0	0.02	0	0.37
0.99	0.2	10		0	0	0	0.02
0.8	0.5	10		0.13	0.96	0.59	0.99
0.95	0.5	10		0	0.41	0.04	0.91
0.99	0.5	10		0	0.02	0	0.19
0.8	0.8	10		0.37	0.98	0.80	0.99
0.95	0.8	10		0.02	0.70	0.19	0.97
0.99	0.8	10		0	0.04	0	0.37
0.8	0.2	25		0	0.02	0	0.24
0.95	0.2	25		0	0	0	0
0.99	0.2	25		0	0	0	0
0.8	0.5	25		0	0.50	0.07	0.96
0.95	0.5	25		0	0.02	0	0.38
0.99	0.5	25		0	0	0	0.02
0.8	0.8	25		0.02	0.85	0.37	0.98
0.95	0.8	25		0	0.20	0.02	0.70
0.99	0.8	25		0	0	0	0.04

little of the paddock is sprayed. This is apparent from table 6 which shows the proportion of the paddock area sprayed when WASP threshold is set at the values shown in table 5. In 54 of the 72 scenarios, the proportion of the paddock sprayed by WASP is either less than 0.1 or greater than 0.9. It is not surprising that in these cases, where the WASP is not behaving very differently to a traditional sprayer or to no sprayer at all, the value of WASP is low. All of the seventeen scenarios in table 4 which have positive values for WASP correspond to cases where the proportion of the paddock sprayed is intermediate — in other words, where WASP is least like the existing technology. Unfortunately for WASP, these scenarios are relatively uncommon.

Finally, figure 4 shows the distribution of gross benefits of WASP if the probability of errors by WASP is set to zero. The mean of the distribution of benefits is increased slightly to A$0.55 per hectare. This demonstrates that these errors are not the primary cause of WASP's disappointing economic performance, since removing the errors makes so little difference to the estimated benefits. The primary issue is that WASP has to compete economically with the better of two existing technologies: a standard boom

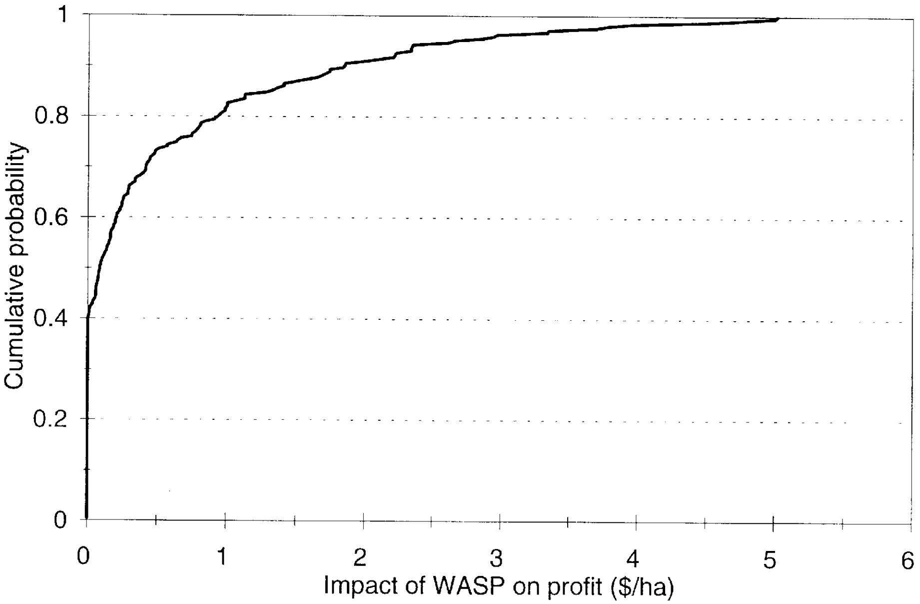

Figure 4 Cumulative distribution function for impact of WASP sprayer on profits from cropping based on economically optimal threshold field of view and zero probability of spraying errors

sprayer or no sprayer at all. In most cases it is not much better than the better of these two options.

Figure 4 also serves to underline the difficulties WASP's developers face. Even if the technology can be improved such that the field of view can be set at any level and *all* errors of spraying or not spraying are removed, the use of the technology for pre-crop weed control is still unlikely to generate benefits in excess of costs for most farmers in extensive systems.

It is worth noting the result for the shadow cost of allowing weed survival (table 2). To ensure numerical tractability, given the complexity of the Bayesian elements of the model, a single period framework was used with dynamics captured by inclusion of the shadow cost. As shown in table 2, even with an unrealistically large range used for the shadow cost, it is not one of the more important variables in the model, vindicating the simplified approach. Further, if a fully dynamic model had been used, the effect on results would have been to reduce the value of WASP even further. This would occur because of the tendency to move towards a uniform weed density across the field with repeated use of WASP. The nearer the density moved towards uniformity, the lower would be the value of WASP.

6. Conclusion

Even if the sensitivity and accuracy of the WASP technology can be improved substantially from current levels, there appears to be little prospect of the technology playing a major role in pre-crop weed control in Australian extensive agriculture. This negative outlook stems primarily not from limitations of the technology, but from the nature of the farm management problem which it is intended to address. The model developed here indicates that in most plausible scenarios, the area of a crop which should optimally receive a herbicide spray is either so high that WASP is little different to a conventional sprayer, or so low that WASP is little different to not spraying at all. Even in the minority of scenarios where WASP improves the profitability of cropping, the purchase cost of the technology would have to be reduced substantially from current levels for the net benefits to be positive.

These conclusions are based on very wide-ranging sensitivity analysis, so we have a high degree of confidence that they apply broadly. The only circumstance not investigated here which may result in a more valuable role for WASP is where the shape of the spatial distribution of weeds is different than used here. For example, a paddock in which the spatial distribution of weed density has a pronounced positive skew would better suit WASP. The minority of high density patches could be sprayed without wasting herbicide on the majority of low density patches. This may occur, for example, in a Mediterranean climatic environment following summer rains, when weed germination is sometimes limited to clearly defined patches. Whether WASP would be preferable to 'spot' spraying targeting only these patches is another question.

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