The economic benefits of IWM: the role of risk and sustainability in farming systems

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Summary Agricultural research is a risky activity, with uncertainty in the research process as well as the physical and economic environment. The impact of seasonal conditions upon the performance of a technology is an important source of uncertainty. One of the unrecognised benefits of an integrated weed management system is the potential for producers to tactically respond to the influences of seasons upon weed management. This paper presents a stochastic and dynamic modelling system for assessing the long-term benefits of alternative weed management strategies. A case study of an evaluation of alternative IWM strategies involving herbicide and non-herbicide options is presented along with the impact of rotational options on sustainability factors.

Keywords Risk, sustainability, economics, dynamic, model.

INTRODUCTION
Agricultural research is a risky activity, with uncertainty in the research process as well as the physical and economic environment (Anderson 1991). There may be important interactions between weather and technologies, thus new technologies may impact upon the riskiness of agricultural production.

The impact of seasonal conditions upon the performance of a technology and the potential strategic and tactical responses by farmers to the uncertain outcomes may be important in valuing the research benefits of a technology. Consequently, the measure of the expected benefits of research or a new technology has a distribution around it, which is a function of the probability distributions of uncertain input variables.

Seasonal conditions are one of the major sources of risk faced by farmers in Australian cropping systems. Both risk-averse and risk-neutral farmers can make a variety of tactical adjustments to their farming strategies in response to short-term seasonal conditions so as to lessen the economic consequences of such risks. Ignoring the role of tactical adjustments can have serious consequences in terms of underestimating the economic performance of some weed management strategies. An example of a tactical response in weed management is the application of a late-season selective spray-topping herbicide to control seed production in the case of the failure of a traditional post-emergence herbicide.

The aims of this paper are as follows. First, measure the effectiveness of a range of integrated weed management (IWM) options in managing weed seed banks over time. Second, determine the economic benefits of the IWM options while accounting for the effect of seasonal variability. Third, evaluate the sustainability impact of rotational options involving crops, annual and perennial pastures. The case study weed is wild radish (Raphanus raphanistrum L.) and the case study area is the southern New South Wales (NSW) cropping region.

MATERIALS AND METHODS

Integrated weed management scenarios A number of weed control technologies were selected to represent management at specific stages of the weed life-cycle. These were a pre-season tillage operation that stimulates weed seedling emergence (PT), a post-emergence herbicide that controls weed seedlings (PE), higher sowing rates to increase competition between the crop and weeds and thereby increase density-dependent mortality (SD), and a selective spray-topping herbicide to reduce seed rain by killing new seed production (ST). Five IWM strategies were constructed and are described in Table 1.

These strategies provide a measure of the impact of restrictions on the potential options that can be used to comprise an IWM strategy. The strategy PE restricts management to a post-emergence herbicide at the registered rate and represents the base from which

<table>
<thead>
<tr>
<th>IWM strategy</th>
<th>Strategy description</th>
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<tr>
<td>PE</td>
<td>Post-emergence herbicide</td>
</tr>
<tr>
<td>PE+PT</td>
<td>Post-emergence herbicide plus pre-season tillage</td>
</tr>
<tr>
<td>PE+SD</td>
<td>Post-emergence herbicide plus increased sowing density</td>
</tr>
<tr>
<td>PE+ST</td>
<td>Post-emergence herbicide plus selective spray-topping herbicide</td>
</tr>
<tr>
<td>ALL</td>
<td>All control options</td>
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to value the benefits of the additional weed control options of PT, SD and ST.

This study does not attempt to undertake an exhaustive analysis of all potential weed control candidates that may form an IWM strategy. By focusing on options that represent control at specific stages of the weed life-cycle the study can draw generalisations regarding the desirable features of an IWM strategy.

**Biolophysical model system** The biophysical model system used in this study is illustrated in Figure 1. The overall model process involves the interaction of water balance, weed population dynamics, crop yield, crop rotation and pasture growth models. The biophysical model system is calculated using daily weather data for the period 1900–2003 for the city of Wagga Wagga in south-eastern Australia.

The impact of variable seasons upon crop growth and weed population dynamics is derived from the water balance model by calculating daily environmental indexes for soil moisture (MI), temperature (TI) and light (LI) (Fitzpatrick and Nix 1970, Nix 1981). These indexes are then combined to determine a multi-factor growth index (GI). The water balance model is necessary to calculate soil moisture levels and consequently the moisture and growth indexes. The water balance model can also be used to derive deep drainage, runoff and soil loss as a result of rotational or weed management choices. These can be used as a guide to the relative sustainability of the agricultural system.

The water balance model used was the PERFECT model, described by Littieboy *et al.* (1999). PERFECT (Productivity, Erosion and Runoff Functions to Evaluate Conservation Techniques) is a biophysical model that simulates the plant-soil-water-management dynamics in an agricultural system, and uses daily weather inputs for precipitation, maximum temperature, minimum temperature, pan evaporation and solar radiation. Weather data were obtained for the period 1900 to 2003 for the city of Wagga Wagga, Australia (Lat. 35.17, Long. 147.45 decimal degrees) from the Silo dataset (http://silo).

The objective of the weed population dynamics model is to calculate the change in the weed seed bank from one year to the next due to a weed management decision. A number of the population dynamics parameters are dependent upon environmental factors such as soil moisture and temperature. Consequently, the outputs of the water balance model are an important input to the population dynamics model.

The crop yield model is comprised of two components: a crop growth sub-model and a yield-loss sub-model. The growth indexes derived from the water balance model are used in the calculation of crop growth and, therefore, weed-free yield. The yield-loss sub-model is based upon a density based yield-loss equation (Cousens 1987) and is linked to the population dynamics model for the determination of weed density.

There are two specific purposes of the population dynamics model. The first is to determine the plant density that results from a given initial weed seed bank, weed management decision and seasonal conditions. This is required by the crop yield model to estimate yield loss due to weed density. The second is to determine the change in the seed bank arising from a given initial seed bank, management decision and seasonal conditions. This information is used to track population changes through time and to estimate probability distributions of population change for a given weed management decision. This latter data are required to derive the probabilities used in the economic model.

Various stages of the weed life-cycle are influenced by environmental factors such as soil moisture and temperature while others were assumed to be random but independent. The stages of the life-cycle that were assumed to be a function of various growth indexes and temperature are germination (g), seedling mortality from post-emergence herbicides ($k_5$), seed production, and the mortality of seed rain due to a late post-emergence herbicide ($k_6$). The other random population dynamic parameters were represented by triangular probability distributions and are seedling mortality from cultivation ($k_1$), mortality of seed rain due to non-herbicide management ($k_3$), natural mortality of new seed production ($k_2$), natural mortality of seeds in the seed bank ($k_4$), seed exports such as from harvesting ($x$), and seed imports such as from contaminated seed at sowing ($m$).

There is a general lack of research and data to quantify the effects of soil moisture and temperature upon many of the life-cycle stages. Exceptions are the estimation of the environmental factors that determine wild radish germination patterns (Young 2001), the
efficacy of herbicides on wild oats (S. Pandey unpublished data, Medd et al. 2001) and the efficacy of selective spray-topping on wild oats (Cook et al. 1999) and wild radish (Madaﬁ glio 2002). Where no published data were present, an expert opinion approach was used to obtain parameters and functional relationships between environmental factors and the population dynamic parameters. The following functional forms were used to calculate each of the random variables. The $a$ coefficients in the following equations are shape parameters in the respective functions.

\[ g = a_1 G_l g / (1 + a_1 G_l g / a_2) \]  
\[ k_2 = a_3 / (1 + a_4 \exp[-a_5 G_l h]) \]  
\[ \psi = a_6 G_l f / (1 + a_6 G_l f / a_7) \]  
\[ k_3 = a_8 / (1 + a_9 \exp[-a_{10} T_{\text{max}}]) \]

where $G_l g$, $G_l h$ and $G_l f$ are the growth indexes at germination, post-emergence herbicide and seed production (i.e. flowering) stages respectively, $\psi$ is an adjustment factor used in a seed production function and $T_{\text{max}}$ is the maximum temperature on the day of herbicide spraying.

The rate of change in the weed population ($\lambda$) from one year to the next is represented by the following difference equation. When the seed bank ($SB$) is stable, then by definition $SB_{t+1} = SB_t$ and $\lambda = 1$. When $\lambda > 1$ population is increasing, and conversely when $\lambda < 1$ populations are in decline.

\[ \lambda = SB_{t+1} / SB_t \]

The solution process involved solving the simulation model system for 10,000 iterations using an initial seed bank of 1000 seeds m$^{-2}$. The model derived the new seed bank in the following year and from these observations the rate of population change ($\lambda$) was calculated. The model was also solved over a 20 year investment period to determine the economic returns for each IWM strategy. Summary statistics and probability density functions (PDF) for each IWM strategy were then calculated for both $\lambda$ and the measure of long term economic performance, net present value (NPV).

**RESULTS**

**Variability in weed seed banks** For the initial seed bank of 1000 seeds m$^{-2}$ considered, the IWM strategies PE, PE+PT and PE+SD resulted in an increase in the mean seed bank ($\lambda = 1.59, 1.57$ and $1.23$ respectively) (Table 2). The inclusion of the ST technology resulted in mean wild radish seed bank population declines with $\lambda = 0.77$ for PE+ST and $\lambda = 0.74$ for ALL. The PDFs of $\lambda$ (Figure 2) capture the impact of seasonal variability and allow a better comparison of the IWM strategies than simply through the mean and standard deviation. The PDFs indicate that there is little difference in the outcomes of PE and PE+PT, and likewise there was only a small difference in the $\lambda$ results for PE+ST and ALL. The PE, PE+PT and PE+SD PDFs indicate that there is close to a 100% probability of a wild radish seed bank increase (i.e. $\lambda > 1$). The PE+ST PDF differs in that the overall function has shifted to the left and no part of the PDF lies to the right of $\lambda = 1$. This indicates a 100% probability of a population decline associated with this strategy. The PDF for the ALL strategy lies further to the left of PE+ST due to the inclusion of SD along with ST in the strategy.

**Economic returns** There is a significant difference between the mean NPVs for PE and PE+PT and the remaining IWM strategies (Table 3). This is largely attributable to the large increase in wild radish seed banks over the 20 year simulation period associated with these two strategies. The two strategies involving the ST technology (PE+ST and ALL) had substantially larger mean NPVs, which is a direct function of the change in seed bank populations as illustrated in Figure 2.

**Table 2.** Mean and standard deviation rate of population change ($\lambda$) for IWM strategies.

<table>
<thead>
<tr>
<th>IWM strategy</th>
<th>Mean</th>
<th>Standard deviation</th>
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<tbody>
<tr>
<td>PE</td>
<td>1.59</td>
<td>0.27</td>
</tr>
<tr>
<td>PE+PT</td>
<td>1.57</td>
<td>0.27</td>
</tr>
<tr>
<td>PE+SD</td>
<td>1.23</td>
<td>0.15</td>
</tr>
<tr>
<td>PE+ST</td>
<td>0.77</td>
<td>0.03</td>
</tr>
<tr>
<td>ALL</td>
<td>0.74</td>
<td>0.03</td>
</tr>
</tbody>
</table>

**Figure 2.** Probability density functions associated with rate of population change ($\lambda$) for IWM strategies PE, PE+PT, PE+SD, PE+ST and ALL given an initial seed bank of 1000 seeds m$^{-2}$. 
Sustainability measures In addition to weeds, the sustainability impacts of cropping systems are significantly important issues faced by Australian farmers. In this study these impacts are measured through the calculation of runoff, deep drainage and soil loss (Table 4) associated with continuous cropping and various rotations involving annual and perennial pasture over the 20 year simulation period. The two pasture rotations are assumed to involve five years of cropping followed by either five years of annual or perennial pasture. These are simply examples and other rotational options could easily be constructed within the simulation model.

There was little difference between continuous cropping and a rotation involving annual pasture in terms of mean annual runoff, deep drainage and soil loss. The inclusion of a perennial pasture into the rotation has significant environmental sustainability implications, with substantially less deep drainage and soil loss measured through the simulation model.

DISCUSSION
A framework for considering risk, sustainability and the economics of weed management has been presented. Using wild radish as a case study, the analysis showed that adopting IWM impacted upon the probability of a change in weed seed banks and generated substantial economic benefits. The framework also showed that the choice of crop and pasture rotation can have a significant impact upon environmental variables such as deep drainage and soil loss. From a catchment management perspective, a rotation involving perennial pasture phases generates superior environmental outcomes in terms of reduced deep drainage (and therefore salinity) and soil loss. These are issues of significant concern to catchment management authorities. Consequently, the impact of IWM, particularly where it involves rotational choice, needs to consider the sustainability implications in addition to the weed management benefits.

ACKNOWLEDGMENTS
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REFERENCES


