Sustainability and integrated weed management in Australian winter cropping systems: a bioeconomic analysis

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Abstract

Economic evaluations of the benefits of integrated weed management often only consider the benefits of management in the crop phase, and ignore the impact of rotational options. In particular, non-crop phases such as annual and perennial pasture phases can have a substantial impact upon weed population dynamics and economic returns. Moreover, extended perennial pasture phases are being promoted to address a range of on-farm sustainability issues such as excessive deep drainage (i.e. salinity), runoff and soil erosion. A stochastic bioeconomic model is developed to evaluate potential trade-offs and synergies between the goals of long-term weed management and achieving sustainability goals.

Key words: weeds, sustainability, bioeconomic modelling, simulation, integrated weed management.

1. Introduction

Cropping systems in southern Australia face a number of serious resource management challenges. Yield losses from weed competition and the costs of weed control have been rated as the most serious financial problem by farmers in Australian winter cropping systems (Alemseged et al. 2001). Dryland salinity has emerged as a problem on lower parts of the landscape, and is primarily due to the replacement of native vegetation by annual crops and pastures resulting in water leaking past the root zone and causing excessive deep drainage (Ward et al. 2002). The need for adoption of conservation farming practices has been prompted by an array of problems caused by excessive tillage, including soil structural decline, loss of soil organic matter and fertility, and soil erosion by wind and rain (Poole 1987).

Various technologies and management strategies have been developed to address these issues not just in Australia, but in other cropping systems such as the US where similar problems (particularly soil erosion and weeds) prevail. These include integrated weed management (IWM) to provide for long-term management of weed populations, adoption of deep rooted perennial species to achieve a better water balance and reduce salinity pressures, and development of conservation tillage (particularly direct drilling and stubble retention systems) to better conserve the soil resource.

There have been a number of economic studies evaluating the benefits of technologies in weed management (eg. Marra and Carlson 1983; Pannell 1990ab, 1995; Jones and Medd 1997, 2000; Kennedy 1987; Gorddard et al. 1995; Swinton and King 1994ab; Pandey and Medd 1990, 1991), conservation tillage (eg. Ward et al. 1987; Scott and Farquharson 2004) and land use change to reduce excessive deep drainage and salinity (eg. Bathgate and Pannell

2002; Bathgate et al. 2004; O'Connell 2003; O'Connell and Young 2002; John and Kingwell 2002; Flugge et al. 2004; Pannell 2001). However, although some studies have considered whole-farm interactions, most tend to focus on measuring the benefits from amelioration of an individual problem and ignore the potential synergies or trade-offs of managing multiple resource management problems within a farming system. An outcome of a myopic approach is that the benefits of a technology or management strategy may be underestimated where multiple benefits accrue (Alston et al. 1995). For example, the inclusion of a deep rooted perennial pasture phase in a cropping system rotation primarily to manage salinity may also result in weed management benefits due to reduced weed populations from increased competition, and conservation farming benefits through reduced soil loss, improved soil structure and fertility.

The objective of this paper is to evaluate strategies for managing weeds, salinity and conservation farming within a farming systems framework. Specifically, the financial benefits from adopting IWM, alternative tillage practices, and crop and pasture rotational options are assessed. Also, the environmental consequences in terms of deep drainage, runoff and soil loss from different systems are quantified.

2. Background to the Issues

Historically crop production in the winter rainfall areas of southern Australia has been based on a combination of fallow and a rotation of one or more years of an annual legume based pasture followed by a series of cereal crops. Tillage was used extensively in the crop phase as a means of controlling weeds, maintaining soil moisture, and providing a suitable seed bed for desirable crop germination (Pratley and Rowell 1987).

A combination of reduced livestock prices and improved tractor technology resulted in an intensification of cropping throughout the 1960s and 1970s, with a consequent increase in tillage operations. This excessive tillage resulted in unnecessary soil degradation. Particular problems were a decline in soil organic matter, loss of soil aggregates, compacted soil, reduced infiltration and consequently greater runoff and evaporation, soil crusting, poor crop establishment and reduced root penetration. The most obvious and long-lasting effect was soil erosion from both wind and rain. Erosion leads to both on-site and off-site impacts. The on-site impact is reduced productivity, while the off-site impact is degraded water quality as a result of sediment loading and associated nutrients and pesticides.

Conservation farming systems were developed in response to these problems, and generally involve a combination of either reduced or zero tillage practices in conjunction with stubble retention. Conservation farming systems aim to conserve water, prevent erosion, maintain organic matter content at a high level, and sustain economic productivity. In Australia direct drilling into pasture or crop stubble is one of the main conservation farming strategies in winter cropping systems. Direct drilling has been shown to dramatically reduce soil loss and runoff under Australian conditions (Freebairn and Wockner 1986; Holland el al. 1987) while not resulting in any yield penalty (Poole 1987; Armstrong et al. 2003).

A feature of a direct drilling and minimum tillage system is the substitution of tillage for herbicides as the principal form of weed control. The development of a number of selective and non-selective herbicides through the 1970s made direct drilling and minimum tillage systems possible, however the introduction of herbicide technologies brought about a set of new management problems. Principal among these is the development of herbicide resistance of weeds in response to selection pressure that continued use of herbicides place on weed populations (Powles and Matthews 1996). In addition, there is general community concern about potential environmental pollution and human health effects from pesticide use in agriculture (van der Werf 1996).

Secondary salinisation of soil and water resources is an acute management issue over large parts of Australia (Greiner 1997). In NSW approximately 180,000 ha of land have shallow watertables, or are affected by dryland salinity. This area is expected to rise to 580,000 ha by 2020 and 1.3 million ha by 2050 if there is no change in land management (National Land and Water Resources Audit 2001).

Since European settlement there have been changes in land use that have altered the hydrological balance of the landscape, significantly impacting on the balance between plant water use, run-off, deep drainage and groundwater recharge. The on-site impact is damage to farmland from salinisation, however the off-site impact of concentration of salts in groundwater and river systems may be more significant (Salinity Research and Development Coordinating Committee 2002). Pannell et al. (2001), however, suggest that externalities as a source of market failure are not that significant and that farm level impacts from ‘internalising’ the salinity externalities would be minor.

Perennial pastures and trees have been proposed as a means of reducing the spread of salinity by increasing water use and reducing deep drainage. Including a perennial pasture phase in a cropping rotation, particularly pastures based upon lucerne, have been shown to reduce leakage of water beyond the root zone (Poole et al 2002; Ward et al 2002). Including perennial pastures on a portion of a property has been shown to increase whole-farm financial returns under certain conditions (Bathgate and Pannell 2002). However, a fundamental problem that remains is financially viable perennial solutions do not exist for some salinity affected areas (Pannell 2001).

The economic impact of weeds in Australian winter cropping systems has been estimated in terms of an economic surplus loss of $1.3 billion (Jones et al. 2005). This surplus loss represented 17% of the gross value of Australian grain and oilseed production in 1998-99, and was comprised primarily of yield losses from residual weeds and herbicide costs. Sinden et al. (2004) have estimated that weed losses to total Australian agriculture range between $3.4 and $4.4 billion per annum.

According to McInerney (1996) it is not so much the size of the problem that is important but what you can do about it, i.e. it is the avoidable cost that defines the economic size of the problem. To this end IWM has been identified as having the potential to reduce economic damage from weeds in the long-term (Swanton et al. 1991; Sindel 2000) and address problems of herbicide resistance (Powles and Matthews 1992; Powles and Bowran 2000). IWM has been defined as the application of numerous alternative weed control measures, which include cultural, genetic, mechanical, biological, and chemical means of weed control (Swanton et al. 1991). IWM has also been promoted as a means of reducing pesticide use in agriculture (Thill et al. 1991; Munier-Jolain et al. 2002).

3. Methodology

3.1 A bioeconomic model of weeds and sustainability

A bioeconomic model, based on a stochastic simulation framework, was developed that integrated weed population dynamics, deep drainage, soil loss, surface runoff, crop and pasture growth and economic outcomes (Figure 1). To accommodate environmental variation, weather data spanning 47 years for a representative cropping systems environment of south-eastern Australia (Wagga Wagga, New South Wales, Australia, Lat -35.17S, Long

147.45E) was used to derive the plant growth, water balance and population dynamics components of the model.

The simulation framework uses a 20-year bioeconomic model so as to capture the dynamic interactions of management changes. The scale of the analysis is a sub-field level. A whole-farm optimisation framework (eg. Bathgate and Pannell 2001; O'Connell and Young 2000; O'Connell 2003; Flugge et al. 2004) has the benefit of capturing on-farm interactions, however it is difficult to adequately capture the stochastic and dynamic aspects of this problem in such a framework. Dynamic programming was another framework considered for this study, however previous studies (Jones and Medd 2000; Jones et al. under review) have provided appropriate weed management decision rules for this problem and therefore a stochastic simulation approach was considered adequate. This study only considers the benefits of management change at the farm-level and does not attach financial values or external costs to the environmental outcomes. This is consistent with the arguments of Pannell (1998) that farm-level analyses are important to determine the profitability and potential adoption of technologies such as perennial plants for managing salinity.

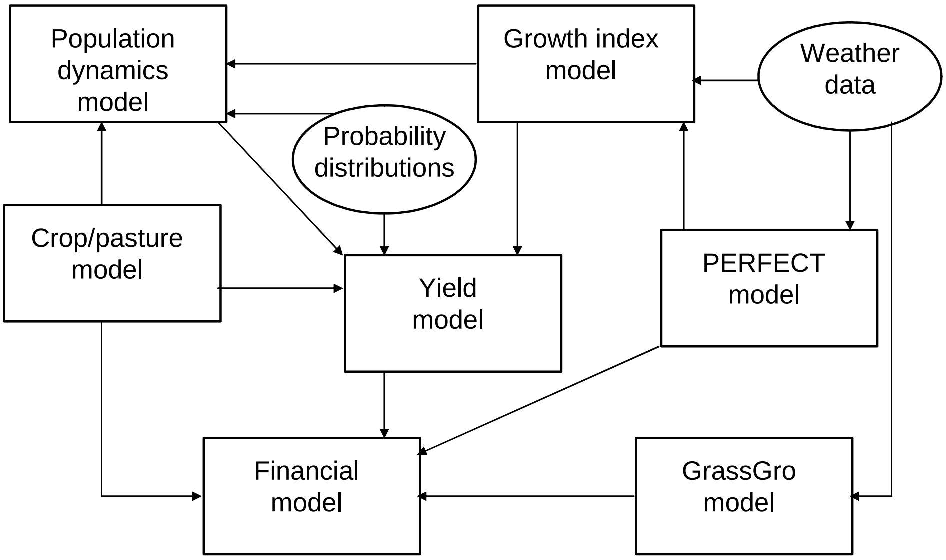

Figure 1 The bioeconomic model system.

The model derived net present value (NPV), weed seed bank, deep drainage, runoff and soil loss over a 20-year simulation period. The objective function was calculated as follows,

$$NPV = \sum_{t=1}^{20} \left(\pi_t / (1+\beta)^t \right) \tag{1}$$

$$\pi_t = \left(\sigma P_y Y + (1-\sigma) LGM \cdot SR \right) - \left(\sigma CVC + (1-\sigma) PVC \right) - \left(\sigma CWC + (1-\sigma) PWC \right) \tag{2}$$

where π is the annual net return, β is the discount rate, P_y is crop price, Y is crop yield, LGM is the livestock gross margin, SR is livestock stocking rate, CVC is crop variable costs, PVC is pasture variable costs, CWC is the weed control costs in the crop phase, and PWC is the weed control cost through a winter cleaning operation in the pasture phase. The parameter σ is scalar for the crop and pasture phase of the rotation; for a crop phase $\sigma = 1$, and for a pasture phase $\sigma = 0$. Both Y and SR are random variables, consequently the model outputs π and NPV are reported as probability distributions. The model was developed in Fortran 95 and each simulation comprised 10,000 iterations for a particular of management scenario.

The study simulates weeds in a winter cropping system using several IWM strategies, crop management, and crop/pasture rotational options. The case study weed for this analysis was wild oat (*Avena* spp.) with a relatively high initial seed bank density of 1000 seeds/m^2.

This analysis draws upon earlier work by Jones and Medd (1997, 2000, 2005) and Jones et al. (under review) by using case-study technologies that represent control at specific stages of the weed-life cycle. This study does not attempt to undertake an exhaustive analysis of all potential weed control technologies that may form an IWM strategy. Rather, by focusing on options that represent control at specific stages of the weed life-cycle it is possible to draw generalizations regarding the desirable features of an IWM strategy. This analysis also treats rotational choices, in particular the pasture phase, as part of the IWM system.

IWM strategies directly influence the values of many population dynamics parameters and equation coefficients. There is also considerable annual variability in parameters of the population dynamics model due to environmental conditions and other factors such as the efficacy of tillage and spray operations, crop seed quality and weed seed predator and disease status. Here all population dynamics parameters are specified as random variables using a triangular probability distribution. This probability distribution is fully specified using minimum, mode and maximum values (Table 1).

Because several of the weed population dynamics parameters are dependent upon environmental factors (such as soil moisture, temperature and light), a growth index model was constructed to determine the probability distribution values of selected population dynamics parameters. These probability distribution parameters were incorporated into a population dynamics model, along with probability distributions determined directly from experimental data and scientific consensus.

3.2 Management scenarios

A number of in-crop weed control technologies are considered that are targeted at specific stages of the weed life-cycle. These are an early post-emergent herbicide to control weed seedlings (PE), a pre-sowing tillage operation that stimulates weed seedling emergence (PT), higher crop seed density to increase competition between the crop and weeds, thereby raising density-dependent mortality (SD), and a selective spray-topping herbicide that regulates seed rain by reducing new seed production (ST). Following the results of earlier studies by Jones and Medd (2005) and Jones et al. (under review) a preferred in-crop IWM strategy would include the technologies PE, SD and ST. A non-IWM system would simply involve the technology PE.

A second in-crop choice involves the type of cropping system; a traditional conventional cultivation (CC) or a conservation farming represented by minimum tillage and direct-drill (DD). Third, rotational choices involve continuous cropping, and a pasture phase of either annual or perennial pasture species. Consequently, the following scenarios were derived.

Table 1 Model coefficients and probability distribution parameters

Parameter	Description				
Triangular probability distribution values:		Unit	Min	Mode	Max
Y_{wf}	Cont crop yield	t/ha	0.70	4.95	5.85
Y_{wf}	Crop plus annual pasture yield	t/ha	0.75	5.50	6.50
Y_{wf}	Crop plus perennial pasture yield	t/ha	0.80	6.05	7.15
SR_{AP}	Stocking rate annual pasture	hd/ha	2.00	5.00	7.00
SR_{PP}	Stocking rate perennial pasture	hd/ha	5.00	10.00	12.00
g	Germination		0.20	0.50	0.70
g (AP)	Germination		0.05	0.20	0.30
g (PP)	Germination		0.05	0.20	0.30
k_1	Seedling mortality from cultivation		0.90	0.95	1.00
k_2	Seedling mortality from herbicide		0.85	0.95	0.98
k_3	Natural seedling mortality		0.00	0.02	0.05
k_3 (SD)	Natural seedling mortality		0.05	0.10	0.20
k_3 (AP)	Natural seedling mortality		0.00	0.02	0.05
k_3 (PP)	Natural seedling mortality		0.05	0.08	0.10
k_4	New seed mortality from herbicide		0.90	0.95	0.98
k_5	New seed mortality from non-herbicide		0.00	0.00	0.00
k_5 (AP)	New seed mortality from non-herbicide		0.80	0.90	0.95
k_5 (PP)	New seed mortality from non-herbicide		0.85	0.90	0.95
k_6	Natural mortality of new seeds		0.20	0.25	0.30
k_7	Natural mortality of seeds in seed bank		0.20	0.25	0.30
ψ	Seed imports	seeds/m^2	0.00	0.00	0.00
χ	Seed exports		0.00	0.00	0.00
Coefficient values:				Cohort	
			$j = 1$	$j = 2$	$j = 3$
J	Days in cohort		151	45	169
Z	Julian day for germination cohort		1	152	197
g	Germination proportion		0.33	0.55	0.12
M	Maximum proportion seeds produced	seeds/m^2	0.80	0.30	0.15
M (ST)	Maximum proportion seeds produced	seeds/m^2	0.18	0.18	0.18
P_1	Crop density	plants/m^2		100	
P_1 (SD)	Crop density	plants/m^2		160	
m	Maximum seeds produced	seeds/m^2		8000	
α	Weed competition factor			5.00	
γ	Crop competition factor			1.00	
I	Yield loss equation factor			0.75	
A	Yield loss equation factor			96.71	
Financial values					
β	Discount rate			0.05	
P_y	Crop price	\$/t		180.00	
LGM	Gross margin – merino wethers	\$/hd		24.07	
LGM	Gross margin – merino ewe	\$/hd		56.30	
CVC_{CC}	Variable cost – CC	\$/ha		304.00	
CVC_{DD}	Variable cost – DD	\$/ha		280.00	
PVC_{AP}	Variable cost – annual pasture	\$/ha		15.00	
PVC_{PP}	Variable cost – perennial pasture	\$/ha		31.30	
CWC_{PE}	Crop weed control cost – PE	\$/ha		30.30	
CWC_{SD}	Crop weed control cost – SD	\$/ha		12.00	
CWC_{ST}	Crop weed control cost – ST	\$/ha		25.50	
PWC	Pasture weed control cost	\$/ha		7.50	

PE = post-emergence herbicide; SD = increased sowing density; ST = selective spray-topping; WC = winter cleaning (pasture); AP = annual pasture; PP = perennial pasture

- Conventionally cultivated crop with and without IWM (CC+IWM, CC-IWM)
- Direct drill crop with and without IWM (DD+IWM, DD-IWM)
- The above options as; continuous cropping (i.e. no pasture phase), a rotation involving crop and annual pasture, a rotation involving crop and perennial pasture.

This combination results in a 4 x 3 factorial table of scenarios. The crop (CC or DD) was simulated as a continuous cropping system or as part of a rotation with an annual or perennial pasture phase. For a rotation including annual pasture the crop sequence was assumed to be 5 years crop followed by 3 years pasture. For a rotation including perennial pasture the sequence was assumed to be 5 years crop followed by 5 years pasture. Weed control in the final year of pasture is assumed to occur through a winter cleaning operation, where a non-selective herbicide is applied to minimise seed production.

3.3 Growth index model

To calculate the impact of variable seasons upon crop growth and selected weed population dynamics parameters, a growth index model was developed by calculating daily environmental indexes for soil moisture, temperature and light (Fitzpatrick and Nix 1970; Nix 1981). These indexes were then combined to determine a daily multi-factor growth index (*GI*). Thus *GI* is defined as a multiplicative function of the three environmental indexes,

$$GI = LI \times TI \times MI \tag{3}$$

where *LI* and *TI* are respectively daily light and thermal indexes, as described by Nix (1981). The daily moisture index (*MI*) was calculated using the PERFECT model (Littleboy et al. 1999). The output obtained was daily available soil water (*ASW*), and following Nix (1981) was converted to a *MI* as follows,

$$MI = \theta - e^{-\mu SW} \tag{4}$$

$$SW = (P + ASW)/TAW \tag{5}$$

where *SW* is the amount of soil water expressed as a proportion of the total available soil water storage (*TAW*), *P* is precipitation and θ and μ govern the inflection of the soil moisture extraction relationship required for the *MI* calculation and are specific to certain soil types. For the study region the typical soil type is a clay loam and values of $\theta = 1.02$ and $\mu = 3.5$ were used (Nix 1981).

A full description of the derivation of the probabilistic population dynamics parameters from the growth index model is given by Jones and Medd (2005) and is not repeated here.

3.4 Population dynamics model

The population dynamics of an annual weed are segregated into the separate stages of the seed bank, emerged plants, seedlings, mature plants, seed production and seed rain. This approach allows the use of specific parameters for derivation of the system components such as germination, seedling mortality, plant fecundity, seed survival and death of dormant seeds.

The annual population recruited is modelled as a number of cohorts. Each cohort is specified to exert different levels of competition and experience differences in mortality and fecundity given the divergent seasonal and crop competitiveness conditions throughout a season.

The number of seeds in the soil, the seed bank (*SB*), is a measure of the underlying weed population. In more complex mechanistic models the seed bank is often segregated into different groups based upon depth in the soil profile and age, providing for potential differences in germination and dormancy responses for the individual seed classes. For simplicity, only one seed class is considered in this study, thus the parameter values represent an average of all the potential seed classes that exist in the seed bank. The variable SB_t measures the initial seed bank (seeds/m^2) in the current year and SB_{t+1} is a measure in the following year i.e. after one generation.

Germination of the weed seed bank results in seedling emergence. Most weeds are typified by staggered germination over the course of a growing season due to dormancy and other environmental factors. Therefore, newly emerged seedlings are divided into separate cohorts,

$$E_j = g_j SB_t \tag{6}$$

where E_j is emergence of cohort j, and g_j is the germination rate of the jth cohort. The values for the number of days in each cohort (Z), the Julian day at the commencement of each cohort (J) and the proportion of total emergence corresponding to each cohort are given in Table 1.

Mortality of emerged seedlings can occur through weed control prior to crop planting and after seeding,

$$S_j = \left(1 - k_{1j}\right)\left(1 - k_{2j}\right)E_j \tag{7}$$

where S is surviving seedlings, k_1 is seedling mortality from weed control prior to planting, and k_2 is seedling mortality from a traditional post-emergence herbicide.

Additional mortality of seedlings that survive weed control is expected due to competition between the weeds and between the weeds and crop. The following equation was used to derive density-dependent mortality,

$$D_j = S_j\left(1 - k_3\right) \tag{8}$$

where D is mature plant density, and k_3 is the natural mortality of seedlings.

Mature weed plants produce seeds that replenish the seed bank. Medd et al. (1995) used a rectangular hyperbola model to estimate the fecundity relationship for wild oat on a cohort basis. Monjardino et al. (2003) presented a hyperbolic seed production equation for modelling wild radish (*Raphanus raphanistrum*) and annual ryegrass (*Lolium rigidum*) population dynamics. An advantage of this equation is that it incorporates competition between the crop and weed. Consequently, this particular seed production equation was adopted, and the parameters were obtained by parametrically varying coefficient values until the estimated function equated with that of Medd et al. (1995),

$$R_j = \left(mD_j / \left(\alpha + D_j + \gamma P_1\right)\right)M_j + \left(1 - M_j\right) \tag{9}$$

where R is seed production, m is the maximum number of seeds produced in the absence of competition, α is a background weed competition factor, γ is a competition factor of the crop upon the weed, P_1 is the crop density, and M is the maximum proportion of seed production at high densities of each cohort.

Seed rain is defined as new seed input to the seed bank. Mortality of seed can occur on the plant from technologies that inhibit seed formation, thus affecting seed rain. Further mortality can occur once seeds are on the soil surface, however, this is considered to be part of the seed bank stage. Additional losses to seed rain can occur through export of weed seeds (e.g. through harvesting). Seed rain is thus defined as,

$$N = \left[\sum_{j=1}^{5} R_j (1 - k_4)(1 - k_5) \right] (1 - \chi) \tag{10}$$

where N is new weed seeds added to the seed bank, k_4 is seed mortality from a late post-emergent herbicide (e.g. selective spray-topping), k_5 is seed mortality from management (e.g. grazing by livestock in a pasture phase), and χ is the proportion of weed seeds lost or exported.

The change in the total weed seed bank is a function of the carryover of seeds from the initial year and surviving seed rain. Allowance is made for death and predation of seeds remaining in the seed bank after germination,

$$SB_{t+1} = N(1 - k_6) + \left(SB_t - \sum_{j=1}^{n} E_j \right)(1 - k_7) + \psi \tag{11}$$

where k_6 is seed predation from natural causes, k_7 is seed mortality (decay) of the non-germinated seed bank, and ψ is import of weed seeds (e.g. contaminated seed at planting, wind borne imports).

In the case of g, k_2 and k_4 the probability distribution parameter values were derived from simulations of the growth index model for the period 1957 to 2003 to obtain minimum, median and maximum values. For k_1, k_3, k_5, k_6, k_7, χ and ψ the probability distribution values were obtained from either field observations or discussions with weed scientists.

3.5 Crop and pasture yield models

Weed-free (Y_{wf}) crop yields for various cropping systems were derived from an expert panel of local agronomists and researchers. The systems considered were; continuous cropping, crop and annual pasture rotation, crop and perennial pasture rotation. To simplify the analysis it was assumed that the yield parameters were constant for each year of the crop phase of a rotation. In the field it would be expected that there would be a decline in weed free-yield with each successive crop year due to a rundown in soil nitrogen and a build-up in root diseases.

Annual crop yield (Y) is a function of weed-free yield for a given year and a yield loss (Y_L) coefficient (Cousens 1985).

$$Y = Y_{wf}(1 - Y_L) \tag{12}$$

$$Y_L = \frac{I \sum_{j=1}^{n} D_j}{1 + I \sum_{j=1}^{n} D_j \Big/ A} \tag{13}$$

where *D* is the weed density influencing yield, *I* is the percentage yield loss per unit weed density as weed density approaches zero, and *A* is an estimate of the maximum yield loss of a weedy crop relative to the yield of a weed-free crop (Table 1).

The variability in productivity from the pasture phase of a rotation was expressed in terms of the stocking rate of a merino ewe (i.e. sheep) enterprise. The GrassGro® model (Moore et al. 1997) was simulated for both annual and perennial pasture systems in the study region to obtain a series of series of gross margin results. These values were then converted to a stocking rate equivalent and the triangular probability distribution parameters derived. The resulting parameters were defined for an annual pasture stocking rate (SR_{AP}) and a perennial pasture stocking rate (SR_{PP}) (Table 1).

3.6 Deep drainage, runoff and soil loss

The PERFECT model was used to derive annual values for deep drainage, surface runoff and soil loss for the period 1957 to 2003. 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. The PERFECT model generated information for conventionally cultivated wheat, direct drill wheat, annual pasture, and perennial pasture. This data was incorporated as a temporal data series in the bioeconomic model, where the weather year (1957 to 2003) was specified as a uniformly distributed random variable. This approach to simulating deep drainage, runoff and soil loss was preferred as the PERFECT model outcomes were not well represented by standard probability distributions as measured by a χ^2 goodness of fit test.

4. Results

The results in terms of the means and standard deviation of model simulations are presented in Table 2. The results reported are the NPV and average annual values over the 20-year simulation period for the seed bank, deep drainage, runoff and soil loss. The highlighted values represent the maximum NPV and minimums for the remaining outputs. The results reported in Figure 2 present the cumulative density functions (CDFs) of selected scenarios.

4.1 Net present value

The largest NPV was associated with DD+IWM in a perennial pasture rotation ($6,515). By contrast the lowest NPV ($3,602) was CC-IWM in a continuous cropping system. Including IWM had the largest effect on NPV of all the options considered in this study. There was a slight improvement in NPV from adopting DD, which was largely related to the lower variable costs of this option. The impact of introducing an annual pasture in the rotation compared to continuous cropping was variable. In the case of DD-IWM and CC-IWM there was a marginal increase in NPV. When IWM was already a part of the farm plan, including annual pasture reduced NPV. This result, however, ignored the potential future costs if herbicide resistance developed as a result of farming practices. There were substantial increases in NPV by introducing perennial pastures for both IWM and non-IWM scenarios.

4.2 Seed bank

Adoption of IWM had the largest impact on average seed bank, with little difference in the seed bank results for all the options that included IWM (about 90 seeds/m^2). The highest mean seed bank was associated with continuous cropping without IWM (918 seeds/m^2), however this result ignores the potential development of herbicide resistance that such as strategy may encourage. In the absence of IWM in the crop phase, including either an annual pasture (701 seeds/m^2) or a perennial pasture (659 seeds/m^2) reduced the average seed bank to some extent.

4.3 Deep drainage

Deep drainage was not influenced by IWM or by adopting DD. Introducing a perennial pasture into the crop rotation reduced average deep drainage (24 mm/ha) slightly more than a rotation with an annual pasture phase (26 mm/ha) compared to continuous cropping (28 mm/ha). However, there was not a large difference in the deep drainage results among the options evaluated. The reason for this can be seen from the CDFs for deep drainage derived from the PERFECT model in Figure 2b. Although the perennial pasture option (PP) results in the least deep drainage, it is not substantially less than annual pasture in the case-study environment.

4.4 Runoff

Adoption of CC resulted in higher average runoff (42 mm/ha) than DD (23 mm/ha) for a continuous cropping system. There was a substantial reduction in runoff when a perennial pasture was included in the rotation, however this result was less pronounced when an annual pasture phase was included. The difference in annual runoff between perennial and annual pasture, and the cropping systems, is illustrated in Figure 2c.

4.5 Soil loss

There were substantial differences in average soil loss between DD (0.55 t/ha) and CC (2.20 t/ha) in continuous cropping. Introducing perennial pasture into the rotation led to a further reduction in soil loss, while a rotation involving CC and an annual pasture phase resulted in the greatest average soil loss (2.38 t/ha). IWM had no influence on the level of soil loss. The results of the PERFECT model simulation for soil loss (Figure 2d) illustrate that a perennial pasture and DD give significantly less annual soil loss than CC and annual pasture in particular.

Table 2 Summary statistics (mean and standard deviation) of the average annual values over a 20-year simulation of the model for various scenarios involving crop management (CC = conventional cultivation, DD = direct drill), integrated weed management (IWM), continuous cropping, annual pasture and perennial pasture

	Continuous cropping		Crop/annual pasture rotation		Crop/perennial pasture rotation	
	Mean	Std dev	Mean	Std dev	Mean	Std dev
NPV ($)						
CC - IWM	3,602	569	3,694	557	5,827	575
CC + IWM	4,697	625	4,340	593	6,361	618
DD - IWM	3,913	570	3,931	542	6,009	575
DD + IWM	5,013	623	4,566	595	**6,515**	634
Seed bank (seeds/m^2)						
CC – IWM	918	179	701	248	659	259
CC + IWM	**87**	231	89	231	90	231
DD - IWM	919	179	701	248	659	259
DD + IWM	**87**	231	89	231	90	230
Drainage (mm/ha)						
CC - IWM	27.78	36.11	26.07	34.98	23.61	33.89
CC + IWM	27.78	36.11	26.07	34.98	23.61	33.89
DD - IWM	27.39	36.58	25.80	35.31	**23.41**	34.11
DD + IWM	27.39	36.58	25.80	35.31	**23.41**	34.11
Runoff (mm/ha)						
CC - IWM	41.65	61.88	36.90	55.79	20.81	48.47
CC + IWM	41.65	61.88	36.90	55.79	20.81	48.47
DD - IWM	23.40	45.16	24.10	42.48	11.73	34.06
DD + IWM	23.40	45.16	24.10	42.48	11.73	34.06
Soil loss (t/ha)						
CC - IWM	2.20	3.75	2.38	4.15	1.29	2.82
CC + IWM	2.20	3.75	2.38	4.15	1.29	2.82
DD - IWM	0.55	1.51	1.22	3.15	**0.47**	1.15
DD + IWM	0.55	1.51	1.22	3.15	**0.47**	1.15

The values highlighted in bold represent the maximum for NPV and minimum for remainder.

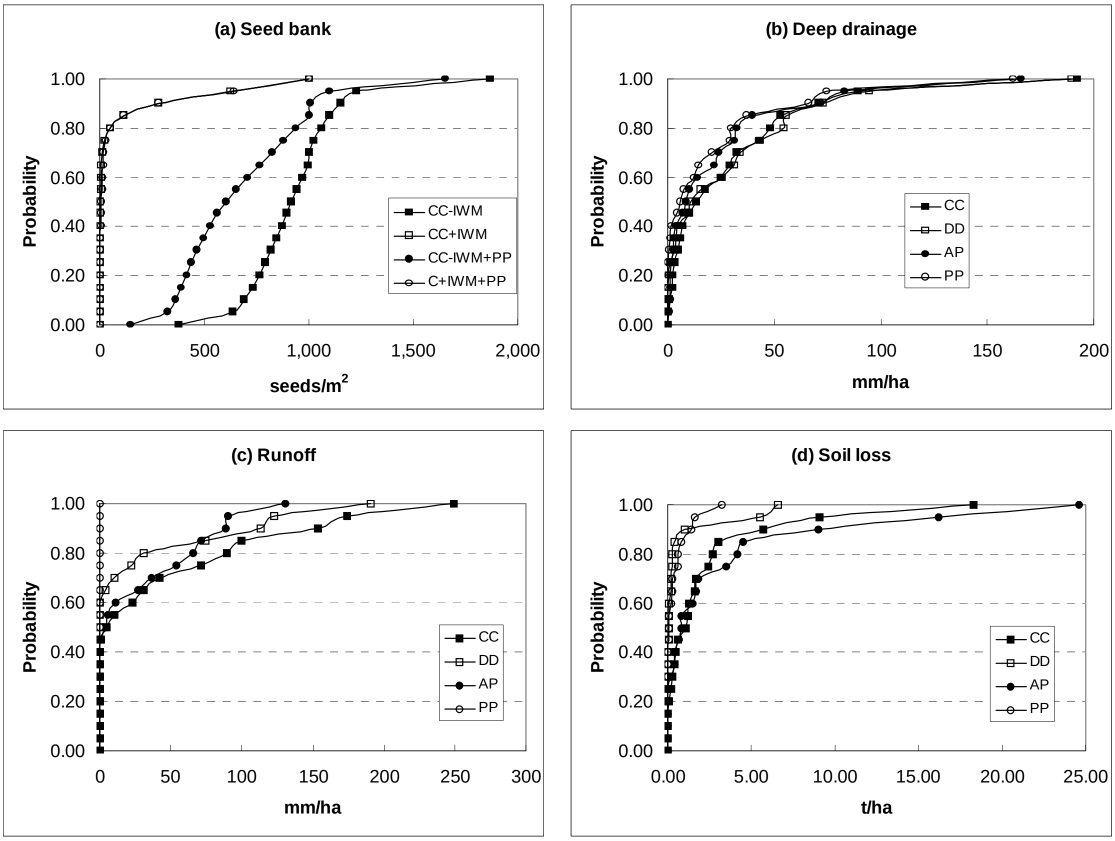

Figure 2 Cumulative density functions of average annual results of 20-year simulations for wild oat seed bank, deep drainage, runoff and soil loss (CC = conventionally cultivated crop, DD = direct drill crop, IWM = integrated weed management, AP = annual pasture, PP = perennial pasture).

5. Summary and Conclusions

This paper has presented a bioeconomic modelling framework for evaluating the benefits of IWM and sustainability issues. This involved the development of a stochastic simulation model that integrated an economic model with a number of biophysical models, including the third-party models GrassGro$^{®}$ (Moore et al. 1997) and PERFECT (Littleboy et al. 1999).

The main economic finding was that the largest financial returns involved the adoption of IWM and including a perennial pasture in the rotation. The main financial benefits attributable to a perennial pasture were the relatively high livestock stocking rates achievable and a decline in weed populations due to its greater competition than an annual pasture. The lowest financial returns corresponded to continuous cropping without IWM. However, given that this study has not accounted the potential for herbicide resistance development it is likely that the financial returns of such as strategy are overstated. Consequently, the divergence in financial returns between IWM and non-IWM is probably greater than estimated here.

Deep drainage and runoff were mostly influenced by inclusion of perennial pasture in the rotation. There was largely no difference in deep drainage between continuous cropping and a rotation with annual pasture. The perennial pasture rotation option reduced deep drainage by around 15% and runoff by 50% for the particular soil type in this case study. Large reductions in soil loss were achieved by adopting conservation farming practices and including a perennial pasture phase in the cropping system.

It is concluded from this analysis that, for this case-study area, it is financially beneficial to adopt IWM and a conservation farming system involving direct drilling and stubble retention in the crop phase and a perennial pasture in the non-crop phase of a rotation. Such a farming system would also generate environmental and other production benefits from a reduction in deep drainage, poor quality runoff to streams and soil erosion. However, given that only a 15% reduction of average deep drainage was measured, any gains from salinity management would likely be minimal on the case study soil type.

It is difficult to extrapolate these findings given the limited nature of the case-study area. Further investigations of different climatic regions with differing soil types and yield responses would help develop a better understanding of the potential financial attractiveness of perennials for both weed and sustainability management. This study does not consider the whole-farm implications of a management change. Consequently, it may be beneficial to link this analysis to a whole-farm optimisation model analysis, as each may complement the weaknesses of the other approach.

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