The Australian Journal of
Agricultural and
Resource Economics

Journal of the Australian Agricultural and Resource Economics Society

The Australian Journal of Agricultural and Resource Economics, 53, pp. 193–212

Economic contribution of French serradella (*Ornithopus sativus* Brot.) pasture to integrated weed management in Western Australian mixed-farming systems: an application of compressed annealing*

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Sowing phases of French serradella (*Ornithopus sativus* Brot.) pasture between extended cropping sequences in the Western Australian wheatbelt can sustain grain production through restoring soil fertility and reducing selective herbicide use. The objective of this article is to investigate the profitability of rotations involving this pasture under a variety of weed management scenarios to obtain greater insight into its value for mixed farming systems in this region. A stochastic search procedure, compressed annealing, is used to identify profitable sets of weed management strategies in a simulation model representing a large number of potential combinations of chemical and non-chemical forms of weed control. In contrast to a continuous-cropping sequence, the inclusion of a serradella phase in a rotation is profitable at high weed densities and with increasing levels of herbicide resistance. A single year of pasture in the rotation is optimal if resistance to Group A selective herbicides is present at the beginning of the planning horizon, but a three-year phase is required if resistance to multiple herbicide groups is observed. Sowing a serradella pasture twice over a two-year phase is also shown to be economically attractive given benefits of successive high weed kills.

Key words: French serradella, herbicide resistance, *Lolium rigidum*, *Ornithopus sativus*, rotation, weed management.

1. Introduction

Intensive cropping has been a feature of land-use rotations throughout the Western Australian Wheatbelt over the last 30 years. Important drivers of

* The authors would like to acknowledge the valuable comments made by the Editor and two anonymous referees. In addition, the provision of information by Michael Ewing, Stephen Powles, and Michael Robertson is gratefully acknowledged.

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doi: 10.1111/j.1467-8489.2007.00448.x

increased cropping activity have been the (i) sustained high relative profitability of cereal production, (ii) cost savings and improved timeliness of sowing through the use of reduced tillage (D'Emden and Llewellyn 2006), (iii) weed control advantages offered by use of selective herbicides, and (iv) the rotational benefits bestowed by crop legumes. However, decreasing the proportion of pasture in land-use rotations threatens the future productivity of farming systems in this region. First, extended periods of cropping promote soil structure decline and impair nitrogen mineralisation from organic sources (Reeves and Ewing 1993). Second, the frequent application of selective herbicides in prolonged crop sequences, particularly with the majority of producers now using reduced tillage (D'Emden and Llewellyn 2006), has promoted herbicide resistance among a number of major crop weeds, such as annual ryegrass (*Lolium rigidum* Gaud.) and wild radish (*Raphanus raphanistrum* L.), throughout Western Australia (Walsh and Powles 2004). This reduces farm profit through motivating the use of less-efficient weed control practices and decreasing crop yield if weed populations consequently increase (Doole 2007).

The inclusion of pasture phases in land-use rotations can help to overcome these constraints to sustained crop production. A period of legume pasture improves soil structure and levels of organic nitrogen. It also has the potential to delay, or minimise the effects of, herbicide resistance through its ease of integration with cost-effective forms of weed control that do not rely on selective herbicides. This reduces the intense selection pressure for resistance inherent in the application of selective herbicides (Powles *et al.* 1997). Primary methods of control are cultivation of the actively-growing pasture ('green-manuring'), grazing, hay or silage production, mowing, sterilisation of weed seed through the application of a non-selective herbicide to flowering plants ('spray-topping'), and the use of non-selective herbicides to kill the entire pasture before weed seed-set ('brown-manuring') (Doole and Pannell 2008b).

Crop phases also possess a host of weed control options that do not require the use of selective herbicides. Available treatments are increased seeding rates, application of non-selective herbicides before crop emergence (i.e. knockdown applications) or while the crop is actively growing (i.e. crop-topping), hay and silage production, green- and brown-manuring, catching weed seeds in a trailer behind a harvester, and the burning of crop residues. The interest in the value of pasture phases for weed control is motivated by the low relative efficiency of these in-crop treatments, especially as some (e.g. green-manuring) entail sacrificing crop yield.

Legume pastures must be sown mechanically if they are to be grown between extended cropping sequences as long periods of crop prevent vigorous regeneration. This approach to management differs from that used traditionally, where short cropping phases were maintained to permit regeneration of viable subterranean clover (*Trifolium subterraneum* L.) and annual medic (*Medicago* spp.) pastures. This modern system where pastures are resown at the beginning of each pasture phase is known as 'phase farming'

(Reeves and Ewing 1993; Loi *et al.* 2005). A recently developed aerial-seeded legume, French serradella (*Ornithopus sativus* Brot.), is highly suited to sowing between extended crop phases (Revell and Thomas 2004) as its seed may be gathered with the machinery typically used for cereal harvesting, significantly reducing the cost of subsequent establishment. A survey conducted in 2005 highlighted that French serradella is now the most popular sown pasture in Western Australia (Nichols *et al.* 2006).

However, despite this popularity, only limited economic analysis pertaining to its value in crop rotations in mixed farming systems has been performed, particularly in terms of its importance for the control of herbicide-resistant weeds. The assessment of Monjardino *et al.* (2004) did not include one- and two-year phases of serradella, which are more common given the high relative value of cereal production. In contrast, Doole and Pannell (2008a) explored the profitability of these shorter phases, but ignored the impact of herbicide resistance on the relative profitability of pasture. In addition, unsown pasture was not considered as an alternative to serradella, despite its popularity in the Western Australian Wheatbelt.

The objective of this analysis is therefore to improve the understanding of the circumstances in which French serradella is a profitable break pasture in Western Australian mixed farming systems. This is important (i) to increase the understanding of how this pasture should be managed for profitable cropping in the Western Australian Wheatbelt, and (ii) to identify those agronomic aspects for which further trials could be conducted to improve current knowledge of this legume's agronomic and economic value.

Herbicides in Australia are grouped according to the mechanism by which they are toxic to plants using the Herbicide Resistance Action Committee (HRAC) system (Kramer and Schirmer 2007). Recent research highlighted that 68 per cent of randomly-selected ryegrass populations in the Western Australian Wheatbelt were resistant to diclofop-methyl (a Group A 'fop' herbicide according to the HRAC system), 61 per cent were resistant to sethoxydim (a Group A 'dim' herbicide), and 88 per cent were resistant to the Group B herbicide sulfometuron (Owen *et al.* 2007). However, Owen *et al.* (2007) also found that a lesser-used Group A 'dim' herbicide (clethodim) remains effective. In addition, new Group A chemicals (butroxydim and pinoxiden) and a Group E/K herbicide (Boxer Gold®) (Newman 2008), which contains the active ingredients prosulfocarb and S-metochlor, have recently been released for the control of grass weeds in cereal crops in Western Australia.

Nonetheless, this study focuses on a situation where resistance to selective herbicides may develop rapidly. This is pertinent because:

1. Integrated weed management (IWM) and serradella are of most value under these circumstances (Doole and Pannell 2008a).
2. The continued development of herbicide resistance is a reality since the combination of selective herbicides and reduced tillage is very profitable, compared to alternative approaches.

3. Preserving the susceptibility of selective herbicides is uneconomic due to the high efficacy of selective herbicides, the low efficacy of substitutes, the uncertainty inherent in an alternative system, and the presence of discounting (Pannell 2001; Doole 2007).
4. Producers in the Wheatbelt retain a focus on chemical control given the lower efficacy and variability surrounding non-chemical methods (Llewellyn *et al.* 2004).
5. The development of new herbicides and the continued efficacy of clethodim may delay the time at which output from this analysis is useful to producers, but the existing analysis remains relevant. In particular, these results are valuable because (i) the severity of herbicide resistance differs by farm, and (ii) cross resistance (i.e. the capacity of a plant to develop resistance to chemically unrelated herbicides, including those that it has never been exposed to) may reduce the efficacy of these herbicides rather rapidly.

Section 2 describes the modelling framework used in this study. Section 3 presents the results and discussion, before a summary and conclusions are given in Section 4.

2. Methodology

The profitability of serradella is determined in the resistance and integrated management (RIM) model (Pannell *et al.* 2004). This model was constructed to analyse the agronomic and economic implications of alternative IWM strategies for the control of herbicide-resistant weeds in the Wheatbelt of Western Australia. Users of the standard simulation version of RIM must search for good management strategies based on their knowledge, and using trial and error. However, the number of potential IWM combinations that may potentially be adopted by producers is vast. For example, there are around 2^{395} possible solutions in the continuous-cropping rotation described below. Accordingly, this analysis uses an innovative search algorithm, compressed annealing (Ohlmann *et al.* 2004), to identify near-optimal management strategies. The addition of the compressed annealing algorithm to the RIM model is described in detail in Doole and Pannell (2008a).

2.1 Resistance and integrated management (RIM) model

This section follows existing descriptions of the RIM model (Monjardino *et al.* 2003; Pannell *et al.* 2004; Doole and Pannell 2008a,b). Wild radish poses an increasing threat to crop production in the Wheatbelt, particularly given recent evidence concerning the ability of individual plants to develop multiple-herbicide resistance (Walsh *et al.* 2004). Nevertheless, the annual ryegrass version of the RIM model is used here as (i) the RIM model incorporating both annual ryegrass and wild radish (Monjardino *et al.* 2003) is the subject of ongoing calibration, (ii) annual ryegrass remains the most important weed constraining crop production in the Western Australian Wheatbelt (Pannell *et al.* 2004; Walsh and Powles 2004; Owen *et al.* 2007), and (iii) multiple-herbicide resistance remains more widespread in annual ryegrass populations (Owen *et al.* 2007).

The RIM framework is a deterministic simulation model, implemented in Microsoft Excel®, incorporating a 20-year horizon. A shorter period (e.g. 10 years) is generally not of sufficient duration for resistance to greatly affect profit in RIM. Thus, a 20-year horizon is preferable because it allows for a more comprehensive understanding of herbicide resistance management.

The RIM model does not incorporate annual variation in markets, treatment efficacy, yield, and the effects of legumes on soil fertility. Instead, it computes the (deterministic) net present value (NPV) accruing to different IWM strategies. NPV is defined as $\mathrm{NPV} = \sum_{t=1}^{20}(1+r)^{-t} I_t$, where r is a discount rate and I_t is income in year t. Calculating profit for an expected year sharpens the focus on profitable IWM and the value of pastures. The model could be extended to incorporate stochastic processes; however, this would require much more information for a problem characterised by a paucity of data. It was thus judged sufficient to use point estimates and apply detailed sensitivity analysis (Doole 2007).

Seven different land uses may be grown over the 20-year horizon in a sequence selected by the user. The land-use options are wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), canola (*Brassica napus* L.), lupins (*Lupinus* spp.), self-regenerating subterranean clover, French serradella, and a volunteer pasture. A volunteer pasture is not sown, but instead germinates from residual seed pools present in the soil. The RIM model describes the multiple-cohort dynamics of both annual ryegrass plants and seeds and their interaction with a broad range of weed control strategies, including crop sequence, biological methods (e.g. grazing), selective and non-selective herbicides, and cultural methods, such as burning. The size of these populations is calculated at seven times during each year in the model. These times are selected according to critical biological (e.g. germination) and management (e.g. time of post-emergent herbicide application) periods.

A detailed description of the treatments, functional relationships, and operation of the RIM model is given in Pannell *et al.* (2004). Around five hundred parameters are incorporated in the RIM model to adequately describe the underlying agronomic, biological, and economic relationships (Pannell *et al.* 2004), some of which are strongly non-linear. Production parameters and permissible management options are based on those available to producers on an average quality sandplain soil in the Central Wheatbelt of Western Australia.

The availability of weed treatments is enterprise-specific as some forms of weed control are not permissible in a given land use due to logical agronomic constraints. For example, seed catching cannot be used in a pasture phase.

Herbicide resistance is represented through the specification of the number of chemical applications in a given herbicide group that are available to a user before chemicals with this mode-of-action are ineffective against ryegrass. This approach is appropriate since it allows a high number of alternative resistance scenarios to be investigated and the sudden loss of herbicide efficacy reasonably represents the development of herbicide resistance in annual ryegrass in the study region (Pannell *et al.* 2004).

Resistance present at the beginning of the horizon is referred to throughout this application as 'initial resistance' to distinguish it from herbicide resistance that develops during the planning period (i.e. the time period examined in the model). The standard model results (see Section 3.1) are computed for a scenario of no initial resistance; however, resistance may develop over the subsequent 20-year horizon if all permissible applications of a herbicide group are exhausted.

Infeasible treatment combinations are possible. These are (i) the incompatibility of spring treatments (e.g. cannot cut a crop for both hay and silage), (ii) the use of full application rates for simazine and atrazine herbicides in the same year, (iii) the simultaneous use of green-manuring and burning in one year, or (iv) burning crop residues twice in one year. Infeasibility also occurs if a herbicide is applied after the maximum number of herbicide applications available for the relevant mode-of-action has been exhausted. Reaching this upper limit represents the development of resistance, as discussed previously.

The revenue function varies markedly for grain and pasture enterprises. Crop yield is a function of ryegrass density, phytotoxic damage from selective herbicide application, and soil fertility as determined by prior agronomic management (e.g. yield is enhanced by the use of green-manuring or the planting of a legume pasture in the previous year). The employment of brown- or green-manuring sacrifices all crop production in that year. Yield loss (ϑ^L) arising from competition with annual ryegrass, where the superscript denotes that this value is specific to land use L (e.g. wheat, barley, etc.), is described through the following function:

$$\vartheta^L = (1 - z) + z\left(\frac{(1 + a^L)}{d_s}\right)\left(\frac{d_o}{a^L + d_o + kw}\right), \tag{1}$$

where z is the maximum proportion of grain yield lost at high weed density, a^L is the background competition factor for land use L, d_s is the standard crop density, d_o is the observed crop density, k is a constant representing the degree of competition between the weed population and the grain crop, and w is the weed population surviving all weed control. This is similar to the function described by Cousens (1985), but allows for varying crop densities (Pannell *et al.* 2004).

The revenue function for the pasture enterprises (French serradella, subterranean clover, and volunteer pasture) is less detailed. Profit for each pasture phase is calculated through the multiplication of an appropriate stocking rate, measured in dry sheep equivalents (DSE), with the gross margin received for a standard sheep enterprise ($/DSE). Stocking rate depends on the type of pasture and the length of the phase. For example, stocking rates for serradella are 2, 6, and 7 DSE/ha in Years 1, 2, and 3 of a three-year phase, respectively (Pannell *et al.* 2004). Hay and silage production also contribute to pasture profitability, though both require a concomitant decrease in stocking intensity.

The value of nitrogen fixation by legumes is incorporated through the definition of (Pannell and Falconer 1988):

1. The reduction in nitrogenous fertiliser required following nitrogen fixation by legumes.
2. The percentage increase in the yield of cereal crops that follow the legume in the rotation. Such increases occur due to disease reduction and improved soil organic matter.

This approach is necessary since biological and fertiliser nitrogen (N) are interdependent in this farming system.

The initial ryegrass seed population is set exogenously. The seed population changes over time through natural mortality, germination, seed production, and various forms of weed control. The function describing seed production for annual ryegrass (R_{SET}), adapted from Maxwell *et al.* (1990), is dependent on the density of annual ryegrass and the crop/pasture. Its functional form is:

$$R_{SET} = \frac{s w_{5,t}^{adj} R}{w_{5,t}(\varpi + w_{5,t}^{adj} + \psi d_o}, \tag{2}$$

where s denotes the sub-lethal effect of selective herbicides, $w_{5,t}^{adj}$ is the weed population in early spring adjusted downward to represent the lower seed production of younger (later-germinating) plants, R denotes the maximum seed production of ryegrass (in seeds/m^2/year), $w_{5,t}$ is the weed population in early spring, $\bar{\omega}$ represents the effect of intra-specific competition on seed production, and ψ represents the strength of the relationship between grain crop density (d_o) and seed production. Appropriate parameter values for Equations (1) and (2) are described in Monjardino *et al.* (2003) and Pannell *et al.* (2004).

Estimates of an average seed burden in the study region range from around 300 to 600 seeds/m^2 (S. Powles, personal communication 2007). The standard RIM model incorporates a default initial ryegrass seed burden of x_0 = 500 seeds/m^2. This figure is used given its consistency with field observations and previous analysis (e.g. Pannell *et al.* 2004). The terminal seed population must (i) be no great than 500 seeds/m^2 if the initial seed population is above 500 seeds/m^2, and (ii) be no larger than the initial seed density if this is below 500 seeds/m^2. These constraints provide a strong incentive for sustained weed control and ensure the field is left in an average state at the end of the planning horizon.

The weed population changes over time through weed control, natural mortality, and the germination of seeds. The latter relationship introduces interdependency between the growth of the weed and seed populations.

A valuable species in volunteer pastures is annual ryegrass, particularly during early winter when legumes, such as subterranean clover, are less productive (Pearce and Holmes 1976). The standard RIM model overstates the value of volunteer pasture when ryegrass is adequately controlled during a crop sequence since its stocking rate is independent of ryegrass density. Two production states (low and high volunteer pasture production) are represented in this study to overcome this limitation. The stocking rates of unsown pasture in this application are 1 DSE/ha in year 1 and 1 DSE/ha in year 2 in the low-production state. In comparison, stocking rates are 4 DSE/ha in year 1 and 2.5 DSE/ha in year 2 in the high-production state. The high-production state requires the addition of 20 kg/ha of nitrogen and a ryegrass population of 1500 plants/m^2 at the break of season in the first year of the phase.

2.2 Compressed annealing

Optimisation in applied economics is typically performed using mathematical programming (MP) (Intrilligator 2000). However, this method requires non-trivial adaptation to identify optimal solutions when discontinuities in the system equations (i.e. the objective and motion functions) complicate gradient calculation, a high number of discrete decision variables prevents efficient exploration, and solution landscapes contain a high number of local optima. Thus, flexible algorithms that use stochastic processes to drive exploration have recently been touted as a tool of potential wide applicability in economics (e.g. Doole and Pannell 2008a). One such procedure, compressed annealing, is used here to identify the IWM strategy (i.e. the set of weed treatments implemented over the planning horizon) that maximises NPV for a given land-use rotation.

Simulated annealing is a stochastic-search technique that involves randomly perturbing a current estimate of the optimal solution for a predetermined computational effort. All solutions that increase profit are accepted as estimates of the optimal configuration, while those that decrease profit are also accepted, but with a probability that declines with increases in iteration time and their degree of suboptimality (Aarts and Korst 1989). Allowing these 'backward' steps allows the annealing algorithm to escape from local maxima, thereby improving its capacity to identify global solutions.

Compressed annealing (Ohlmann *et al*. 2004; Doole and Pannell 2008a) is a recent derivative of simulated annealing that allows the explicit inclusion of resource constraints. Infeasible solutions are typically handled in simulated annealing through coding models to avoid or discard solutions that violate constraints or through penalising them at a constant rate in the objective function. In contrast, compressed annealing involves the definition of a penalty term (which is multiplied by the number of infeasibilities at each iteration) that increases in magnitude as the search progresses (Doole and Pannell 2008a). This improves efficiency by avoiding the extensive coding required to avoid violations, while improving convergence through allowing another means of escape from local maxima early in the iterative procedure.

The application of compressed annealing in this study is appropriate since the decision space possesses multiple discontinuities in the objective and state equations, around 2^{420} possible solutions, and copious local maxima.[1] As observable in this application, compressed annealing is likely to be of value to any practitioners who need to solve complex constrained models that do not conform to the standard MP format. This includes those that possess a large number of discrete decision variables, those that incorporate numerous discontinuities, and those defined in a simulation environment.

The RIM model is too large for the exact global maxima to be identified with certainty for a given problem instance. Nonetheless, the capacity of stochastic search algorithms to identify robust local solutions in complex models in a reasonable period of time is one of their key advantages over MP. Moreover, the use of compressed annealing appears to be significantly more efficient than selecting alternative solutions manually, as done in the original simulation model.

The compressed annealing procedure applied here operates as follows. Each weed treatment in each year is represented by a single binary decision variable in the RIM model; its two values represent the use or non-use of this treatment. An initial IWM strategy is determined by filling the treatment matrix (of dimension year × number of treatments) with a random assortment of binary values. This is defined as the existing estimate of the optimal solution. Each subsequent trial consists of:

1. randomly selecting a treatment in any year and swapping its binary value;
2. evaluating the profitability and the number of infeasibilities present in the new configuration in the simulation model;
3. penalising the profitability of the configuration according to the number of infeasibilities in the solution; and
4. comparing the value of the modified strategy to that of the existing estimate of the optimal configuration.

The perturbed solution is only accepted as the new estimate of the optimal solution if $\exp(\Delta J \cdot T^{-1}) > \alpha$, where ΔJ is the difference in penalised profit ($J_{\text{current}} - J_{\text{perturbed}}$), T is a temperature variable that declines towards zero in discrete stages so that the likelihood of taking suboptimal steps declines as the computation progresses, and α is a random number generated from a uniform distribution on (0, 1).

[1] Discontinuities in system equations is a reality in most multiple-crop systems since each crop will typically have unique profit and competition functions and also possess its own set of admissible controls.

The steps of selection, evaluation, and comparison in this application are structured according to standard annealing theory (Aarts and Korst 1989; Ohlmann *et al*. 2004) to maximise the efficiency of the search. The compressed annealing algorithm is programmed in this study using Visual Basic for Applications (Cottingham 1999) in the workbook containing the RIM model. It interacts directly with the treatment matrix and the cells containing the NPV and the number of infeasibilities corresponding to each IWM strategy. The ease with which annealing algorithms may be incorporated into existing spreadsheet models is a key benefit of their use, as information defined in the spreadsheet environment does not have to be restructured to permit optimisation (Doole and Pannell 2008a).

The profitability of each rotation is described by the most-valuable configuration identified over 10 runs of the algorithm for each problem instance. This approach is required because the annealing algorithm starts from a random configuration and searches the solution space stochastically. Sowing strategies (i.e. date of sowing, seeding rates, and the use of a shallow autumn cultivation to stimulate weed germination) are determined exogenously to simplify the coding of the compressed annealing procedure and reduce solution time. This is necessary as the sowing requirements for each land use differ greatly. Seeding strategies are selected according to standard practice in the study region and through the comparison of the profitability of alternative combinations.

2.3 Evaluated rotations

The value of serradella for resistance management is estimated through the evaluation of the profitability of nine rotations (Table 1). The selected rotations are based on those observed in the study region, past work (e.g. Monjardino *et al*. 2004), or those that are of potential interest for increasing

Table 1 The rotations studied in this application

Notation	Components of the rotation
C	Lupin–wheat–wheat–barley
V+3C	Volunteer pasture–wheat–wheat–barley
S+3C	Serradella–wheat–wheat–barley
V+7C	Volunteer pasture–wheat–wheat–barley–lupin–wheat–wheat–barley
S+7C	Serradella–wheat–wheat–barley–lupin–wheat–wheat–barley
2V+7C	Volunteer pasture–volunteer pasture–wheat–wheat–barley–lupin–wheat–wheat–barley
2S+7C (1s)	Serradella (sown)–serradella (regenerates)–wheat–wheat–barley–lupin–wheat–wheat–barley
2S+7C (2s)	Serradella (sown)–serradella (sown)–wheat–wheat–barley–lupin–wheat–wheat–barley
3S+7C	Serradella–serradella–serradella–wheat–wheat–barley–lupin–wheat–wheat–barley

productivity. Each rotation is described by a sequence of capital letters for ease of reference. Rotations incorporating a single year of pasture retain dependence on the primary cropping enterprises, but employ a regular pasture phase for weed control and the restoration of soil organic matter. Serradella is more expensive to establish than volunteer pasture ($37 per ha compared to no cost), but has a higher livestock carrying capacity and a high legume content. Sowing serradella once in a two-year phase prevents heavy grazing and the use of destructive treatments in the first year. This is necessary to provide adequate seed-set for pasture regeneration. In comparison, sowing serradella twice in a two-year phase allows high weed kill in both years, but incurs additional establishment costs.

The enterprise defined in Year 1 for each rotation in the model is that in which the most efficient weed control is typically achieved. The lupin crop is first for the continuous-cropping rotation, while the first year of the pasture phase is used for those sequences containing pasture.

2.4 Model scenarios

Several different scenarios are explored in the analysis (Table 2).

Typical initial weed seed densities are around the lower set considered here (i.e. around 250 and 500 seeds/m^2). However, the high seed production of *L. rigidum* is a key factor underlying its current position as a major crop weed in Western Australia. Producers are unlikely to enter a crop phase at the higher seed densities considered in the analysis. Nevertheless, this demonstrates the value of pasture under these circumstances.

The profitability of each rotation is also evaluated with the presence of herbicide resistance to Group A, Group A–B, Group A–C, and Group A–D chemicals in the initial year. This allows the value of pasture to be ascertained as the stock of effective selective herbicides becomes more limited. The unavailability of all selective herbicides (Group A–D) is referred to concisely as 'full resistance' in the following.

The number of selective herbicide applications available to a typical producer in the Wheatbelt is very difficult to approximate. Those defined in the

Table 2 Scenarios investigated in the model

Description	Parameter values
Initial weed seed density	Initial seed densities of 100, 250, 500, 1000, 2500, 5000, and 10 000 seeds/m^2
Presence of herbicide resistance	Number of applications for {Group A 'fop', Group A 'dim', Group B, Group C, Group D} herbicides before resistance occurs: Standard: {2, 2, 2, 5, 5} No Group A herbicides available: {0, 0, 2, 5, 5} No Group A–B herbicides available: {0, 0, 0, 5, 5} No Group A–C herbicides available: {0, 0, 0, 0, 5} No Group A–D herbicides available: {0, 0, 0, 0, 0}

RIM model (Table 2) are based on the best agronomic information available (see Pannell *et al*. 2004 and references therein; S. Powles, personal communication 2007) and, consistent with reality (Owen *et al*. 2007), represent a state in which herbicide resistance can develop rather rapidly. This approach is deemed most appropriate for the reasons stated in the Introduction.

3. Results and discussion

3.1 Initial weed density

The profitability of each rotation, in terms of NPV ($/ha), is presented in Table 3 for a range of initial ryegrass seed densities. These results are determined in the absence of initial herbicide resistance (see Section 2.1). For densities up to and including 1000 seeds/m^2, the profit-maximising rotation is *C*, while for densities of 2500 per m^2 or more, the optimum changes to *S+7C*. The difference in NPV between these two rotations is small at all seed densities, being at most $24 per hectare over 20 years for the highest weed density. Also, the use of a three-year serradella phase is similarly profitable to the *S+7C* rotation at 5000 and 10 000 seeds/m^2. This reflects the value of an extended pasture phase for ryegrass control at high weed densities.

Those sequences incorporating serradella pasture phases are generally more profitable than those including volunteer species (Table 3) (with some exceptions at the highest seed densities). Serradella supports a high stocking rate, even if annual ryegrass is adequately controlled, whereas volunteer pasture is less productive given good weed control. The high legume content of serradella pastures also increases their value to successive crops.

Some rotations are quite similar in value in a number of the instances reported in this analysis (see, for example, the last column in Table 3). This

Table 3 Net present value of each rotation ($/ha) over a 20-year planning horizon for a range of initial ryegrass seed densities (seeds/m^2) (no initial resistance). (See text for description of rotations.)

	Initial ryegrass seed density (seeds/m^2)						
Rotation	100	250	500	1000	2500	5000	10 000
C	693†	698	695	689	672	670	643
S+3C	673	664	659	654	659	653	649
S+7C	685	691	681	676	683	673	667
2S+7C (1s)	624	631	635	621	540	533	556
2S+7C (2s)	652	642	645	633	638	619	627
3S+7C	671	667	661	662	669	668	665
V+3C	615	627	615	640	634	647	618
V+7C	590	597	579	598	604	608	605
2V+7C	513	486	490	486	498	520	525

† A shaded cell denotes the most-valuable sequence at that initial seed density.

identifies that producers, in certain circumstances, have great latitude to select among profitable rotational configurations. This phenomenon arises from the flat response surfaces (Pannell 2006) typical of complex economic models. Doole and Pannell (2008a) also noted this in the context of generating multiple solutions with the compressed annealing procedure. This relationship is determined by the structure of the problem and is particularly complicated by the multiple ways that pasture affects profit. Pasture phases provide grazing income and improve crop production through (i) intensive weed control, (ii) nitrogen fixation and increases in soil organic matter, and (iii) reduced disease incidence. However, they also displace crop production, which has a considerable opportunity cost by virtue of its high relative profitability.

The incorporation of a three-year serradella phase in a rotation is always more profitable than the incorporation of a two-year serradella phase in the scenarios reported in Table 3. High biomass production over a three-year phase improves stocking capacity and the yield of subsequent crops. These benefits are sufficient to offset the cost of establishment and the light grazing required in the first year of the phase. In contrast, the two-year phase is too short to improve profit substantially through these means (Doole and Pannell 2008a).

Sowing the serradella pasture twice in a two-year phase (2S+7C (2s)) is more profitable than sowing once (2S+7C (1s)), especially at high ryegrass densities. Brown-manuring and grazing in both years of the serradella phase allows a higher level of weed control to be achieved. For example, the mean annual starting seed density over the 20 years is 33 for 2S+7C (2s) and 56 for 2S+7C (1s) (at an initial seed density of 500 seeds/m^2).

Model results (not shown) indicate that, for the *C* rotation, Group A and B herbicides are exhausted (i.e. driven to resistance) in the optimal strategy for each initial weed seed density. This reflects the high effectiveness and relatively low cost of these herbicides as weed control measures. A number of applications of Group C and D herbicides are also used to reduce in-crop competition with annual ryegrass in rotation *C*. In comparison, grazing and non-selective herbicides are important for exhausting weed seed banks during a pasture phase. Grazing and spray-topping with Gramoxone® or glyphosate are valuable treatments in the first year of pasture in the 2S+7C (1s) rotation and in the first two years of pasture in the *3S+7C* sequence. Volunteer pasture and the last year of a serradella phase are always grazed and brown-manured under optimal management.

NPV should decline at a higher initial ryegrass seed density as crop yield declines in response to weed competition. Nonetheless, this inverse relationship is not clearly defined for any single rotation in Table 3. The primary reason is that an initial pasture phase may reduce the weed seedbank so greatly that competition is minimised in subsequent crop years. This reinforces the value of pasture for IWM and, in effect, resetting the weed seedbank between crop phases. The search algorithm is also unable to find a global optimum in the available solution time given the enormous number of potential IWM

Table 4 Net present value of each rotation ($/ha) over a 20-year planning horizon for alternative herbicide-resistance scenarios (initial weed seed density 500/m^2). (See text for description of rotations.)

	Herbicide groups to which annual ryegrass is resistant in year 1				
Rotation	None	A	A, B	A, B, C	A, B, C, D
C	695†	654	591	461	234
S+3C	659	657	629	572	456
S+7C	681	649	619	559	412
2S+7C (1s)	635	604	594	533	439
2S+7C (2s)	645	647	622	583	471
3S+7C	661	647	632	589	532
V+3C	615	590	558	558	469
V+7C	579	545	510	471	409
2V+7C	490	450	441	441	440

† A shaded cell denotes the most-valuable rotation at that level of herbicide resistance.

strategies. This highlights that although stochastic-search algorithms can be used to identify good solutions in large solution spaces, it will typically become increasingly difficult to accurately discern detailed trends as model size increases.

3.2 Herbicide resistance

Table 4 presents results for scenarios that vary in terms of initial herbicide resistance status. This output shows that the presence of resistance to different herbicide groups is a critical determinant of the most-profitable rotation among those considered in this analysis.

Income earned in the *C* rotation declines markedly following the development of herbicide resistance, such that it is only optimal if there is no resistance present (Table 4). The distribution of annual returns and weed seed density in the *C* rotation with no initial herbicide resistance are illustrated in Figure 1. The lupin crop is the first enterprise in this four-year rotation and thus is planted in years one, five, nine, and so on in Figure 1. The stock of available selective herbicides allows annual ryegrass to be controlled cost-effectively over the planning horizon (Figure 1). Accordingly, crop income is sustained at positive levels and the seed burden is low throughout.

However, losses are incurred in every lupin crop when no selective herbicide options are available (Figure 2). This crop is regularly destroyed to obtain high weed control, despite this involving the sacrifice of crop yield, due to its lower profitability relative to the primary cereal crops. Various destructive methods are selected by the compressed annealing algorithm in this run, explaining the variation evident in later years and reflecting the need to maintain intensive weed control to satisfy the terminal condition. Moreover, these losses must be incurred since the simulation of fixed rotations precludes

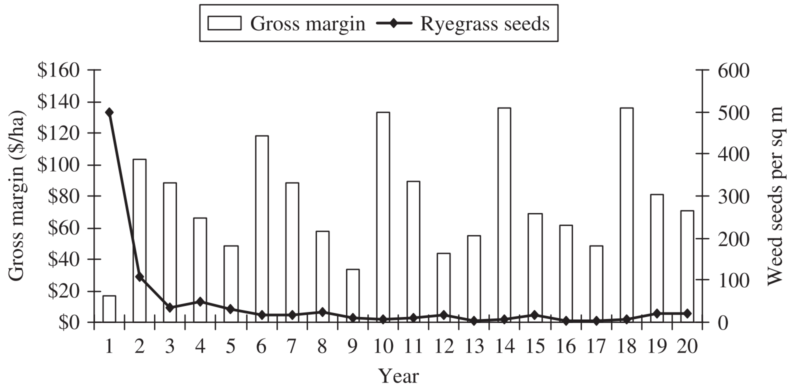

Figure 1 Annual gross margin ($/ha) and ryegrass seed density (seeds/m^2 at the beginning of the growing season) for the C rotation (lupin–wheat–wheat–barley) with no initial herbicide resistance. (The first year of each rotation is the lupin phase.)

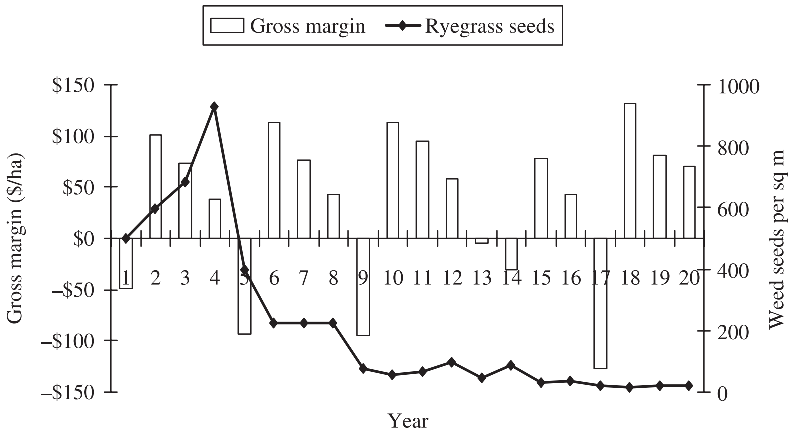

Figure 2 Annual gross margin ($/ha) and ryegrass seed density (seeds/m^2 at the beginning of the growing season) for the C rotation (lupin–wheat–wheat–barley) with initial herbicide resistance to Group A–D chemicals. (The first year of each rotation is the lupin phase.)

the tactical use of a pasture phase to achieve a high weed kill at reasonable cost. Besides regular destruction of the lupin crops, a wheat crop is also cut for hay in year 14 to improve weed management. These factors highlight the limited number of efficient forms of in-crop weed control available to producers in the absence of effective selective herbicides.

Weed numbers under the near-optimal strategy are reasonably low for all rotations throughout the 20-year period, even for the full-resistance scenario shown in Figure 2. Jones and Medd (2000) identified the economic importance of maintaining low weed populations in their analysis of wild oat (*Avena fatua* and *A. ludoviciana*) infestations. In addition, Monjardino *et al*. (2004) and Pannell *et al*. (2004) stated the high value of maintaining low ryegrass populations across time, both with and without herbicide resistance. The high relative profitability of maintaining a low ryegrass population is motivated by the competitiveness (Lemerle *et al.* 1995) and large seed production (Davidson 1990) of annual ryegrass plants. This high seed production and the short dormancy of ryegrass seeds (Peltzer and Matson 2002) also suggests that these seed banks have significant potential to rapidly increase in size.

In contrast to previous work, the total number of treatments used that do not involve selective herbicide application varies only moderately between the no-resistance and full-resistance scenarios in the *C* rotation. For example, the mean number of these treatments used each year in the most-valuable configuration, at an initial weed density of 500 seeds/m^2, increases from 1.55 to 2.11 on movement from the no-initial-resistance state to the full-resistance state. This contrasts previous work that found that the number of such treatments should nearly double as resistance develops (Pannell *et al.* 2004). This demonstrates the capacity for compressed annealing to broadly search the available set of IWM strategies as its method of search is not biased by preconceived ideas of profitable management. However, this feature must be balanced with the time that the algorithm typically spends exploring unprofitable regions of the solution space that the advanced user may instinctively disregard.

The profitability of those rotations incorporating pasture phases is relatively less sensitive to the development of resistance (Table 4). Profit decreases by 15, 4, and 5 per cent in the C, 3S+7C, and S+3C sequences, respectively, going from a state of no resistance to where resistance to Group A–B chemicals is observed. These decreases are reasonably low as efficient in-crop weed control can be still be attained by Group C and D herbicides. In comparison, profit falls by 60, 16, and 28 per cent in the *C*, 3S+7C, and S+3C sequences, respectively, going from Group A–B resistance to full resistance. This reflects the efficient weed control offered by selective herbicides in the absence of resistance and the intensive weed control that may be implemented in a rotation incorporating a high proportion of pasture.

The value of a pasture phase for cost-effective weed control is also observable in Figure 3. Income always decreases in the first year of a 3S+7C rotation in the model due to the cost of pasture establishment. However, annual gross margins are more robust to the development of herbicide resistance than in the *C* rotation given the maintenance of a productive pasture over a prolonged period, the high degree of weed control attainable in a serradella phase, and the improvement in soil fertility that occurs with this pasture (Figure 3). Nevertheless, expensive weed management techniques are employed in each lupin crop (years 7 and 17) to maintain a low seed burden.

The development of new herbicides modifies these assertions to some degree, but not significantly. The high profitability of combining reduced tillage and chemical weed control indicates that this approach will likely continue for some time to come, subsequently promoting the development of herbicide resistance (Walsh and Powles 2004). Moreover, reliance on non-chemical forms of control is not warranted, especially at high grain prices,

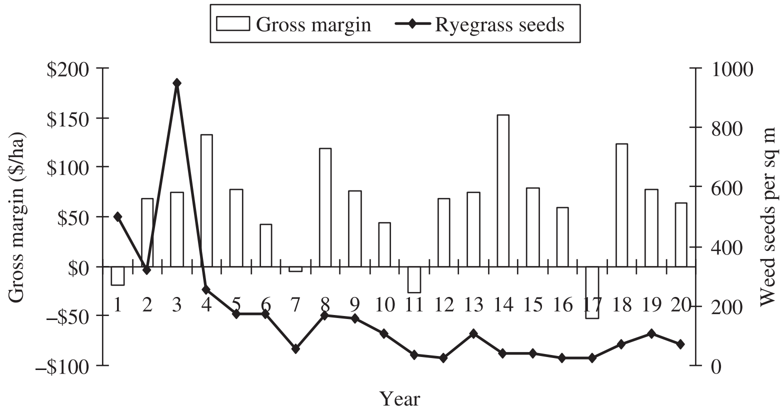

Figure 3 Annual gross margin ($/ha) and ryegrass seed density (seeds/m^2 at the beginning of the growing season) for the 3S+7C rotation (serradella–serradella–serradella–wheat–wheat–barley–lupin–wheat–wheat–barley) with initial herbicide resistance to Group A–D chemicals. (The first year of each rotation is the first year of the serradella phase.)

given their overall low efficacy and variable performance (Llewellyn *et al.* 2004; Doole 2007). Also, model output suggests that the recent introduction of the prosulfocarb and S-metochlor combination (under the trade name of Boxer® Gold) will have little impact on the profitability of pasture outlined in this research. This chemical is a pre-emergent selective herbicide with a similar efficacy to a standard (effective) application of trifluralin (Newman 2008). This suggests that its economic value may be approximated by considering it as extending the susceptibility of annual ryegrass to trifluralin. If only Group A–C resistance is evident and Group D applications are assumed non-limiting due to the introduction of the new herbicide, model output shows that pasture will remain an important management option (Table 4) as the staggered germination of annual ryegrass lowers the general efficacy of pre-emergent options.

4. Conclusion

This study compares the profitability of a number of land-use sequences under different scenarios to identify the circumstances in which French serradella is a profitable break pasture in Western Australian dryland agriculture. Heavy reliance on selective herbicides in the continuous-cropping rotation renders the profitability of this sequence very sensitive to changes in herbicide-resistance status. This reflects the low relative efficiency of alternative forms of in-crop weed control, particularly destructive methods that require crop production to be sacrificed to achieve high levels of weed control. The relative value of a pasture phase for weed management increases at higher initial ryegrass seed burdens and where herbicide resistance increasingly constrains crop production. This arises because, in a pasture phase, ryegrass may be effectively controlled with a broad range of treatments – such as brown-manuring, grazing, and spray-topping – that do not rely on selective herbicides.

Volunteer pasture performs poorly compared to serradella as in-crop weed control directly affects pasture production in unsown stands. In contrast, serradella may be brown-manured for highly-effective weed control, is a valuable grazing plant, and enhances the yield of successive crops through nitrogen fixation. Model output shows that pasture will become increasingly valuable as herbicide resistance grows in severity. Although some Group A, C, and D herbicides remain largely effective against annual ryegrass in cereal and broadleaf crops in this region, resistance to these chemicals is evolving according to their level of adoption (Owen *et al*. 2007). Thus, the results of this analysis are both timely and important to guide future management.

As shown by Doole and Pannell (2008a), this application demonstrates the efficacy of compressed annealing for constrained optimisation in frameworks not easily amenable to solution with mathematical programming. Moreover, this method has a number of implications for agronomic research and extension concerning IWM practices in the Western Australian Wheatbelt. First, the model generated solutions that differ widely in their composition of treatments, but vary little in their overall profitability. This knowledge may be used to generate a range of relevant strategies for producers whose preferences may differ (e.g. in their degree of risk aversion).

Second, this study has shown that herbicide resistance is a key determinant of the relative profitability of a pasture phase. Accordingly, it is pertinent that more resources be allocated to field research addressing the interaction between the agronomy of phase pastures and the control of herbicide-resistant weeds. In particular, this study has highlighted that brown manuring is a key strategy for IWM in mixed farming systems. Hence, its efficacy across both time and space should be a subject of future field research.

Third, this modelling study has highlighted that superior assessment of serradella pasture would be possible if better information relating to its biomass production and the rate of ryegrass control by grazing were available. These are also consequently important areas for further work.

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