

Delayed pasture germination allows improved rigid ryegrass (*Lolium rigidum*) control through grazing and broad-spectrum herbicide application

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ABSTRACT

Eastern star clover (*Trifolium dasyurum* C. Presl.) is a new pasture legume developed for use in short phases between extended cropping sequences in Western Australian dryland agriculture. Its delayed germination provides an opportunity to obtain almost complete control of the highly-competitive crop weed rigid ryegrass (*Lolium rigidum* Gaudin) through non-selective herbicide application and/or grazing. Given the recent development of a commercial cultivar of eastern star clover (cv. AGWEST[®] Sothis), a complex simulation model is used to evaluate its potential profitability relative to continuous-cropping and rotations employing a popular pasture, French serradella (*Ornithopus sativus* Brot. cv. Cadiz). The profitability of those sequences containing eastern star clover is robust to high initial ryegrass populations and increasing severity of herbicide resistance. Moreover, the weed control benefits accruing to this pasture's delayed germination are of sufficient magnitude to offset the low establishment cost and higher biomass production of French serradella. This highlights the value of eastern star clover to producers in the Western Australian wheatbelt and offers an additional trait that plant breeders and selectors can exploit when seeking to expand weed control options in land-use sequences.

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1. Introduction

Worldwide agricultural production has grown steadily over the last 40 years; however, it must increase by around 40 per cent over the next 20 years if increased demand due to population growth and wealth accumulation is to be satisfied (OECD–FAO, 2009). Moreover, 90 per cent of future gains in crop production must be achieved through increased yield and crop intensity, as current and projected expansion of arable land, particularly in developing nations, is limited by inherent soil constraints, land degradation, population growth, and urbanisation (Bruinsma, 2009). Expected growth rates in crop yields are substantially lower than historical levels, with annual yield increases in global wheat crops forecast to decrease from the 2.1 per cent rate observed over the 1961–2007 period to 0.7 per cent over the next 40 years (Fischer et al., 2002; Bruinsma, 2009). This highlights the importance of identifying affordable and effective methods of weed control, particularly in Australia where weeds have been estimated to impose a cost to agriculture of around 3.5 billion dollars each year (Sinden et al., 2005).

Implementing weed control prior to crop emergence is a critical activity in many agricultural systems. Its importance is enhanced where herbicide resistance reduces the effectiveness of post-emergent chemical control (Llewellyn et al., 2004; Owen et al., 2007). Repeated tillage can stimulate emergence and kill young weeds by influencing the distribution of weed seed throughout the soil profile (Buhler, 1995, 1997). Accordingly, this practice remains extensively utilised and studied throughout the world (e.g. Cox et al., 1999; Bailey et al., 2001; Amador-Ramirez et al., 2007), despite increasing fuel and labour costs and concerns over land degradation (Sindel, 2000). In addition, knockdown herbicides, particularly glyphosate, can be used to efficiently kill weeds if light cultivation is used to promote weed emergence (Llewellyn et al., 2004). However, while delaying sowing to utilise such techniques can increase weed kill, this can incur a yield penalty in most economically-important crops—such as wheat (*Triticum aestivum* L.) (Gill, 1996) and canola (*Brassica napus* L.) (Ozer, 2003)—and pastures.

An alternative method, conceptually similar to delayed sowing, is the use of interspecific differences in germination patterns to improve weed control. This strategy appears to have been first proposed by Revell and Taylor (1998), who suggested that late seed imbibition in yellow serradella (*Ornithopus compressus* L.) could permit control of weeds that emerge with the first significant rains

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Nomenclature

Rigid ryegrass *Lolium rigidum* Gaudin
 Eastern star clover *Trifolium dasyurum* C. Presl
 French serradella *Ornithopus sativus* Brot. cv. Cadiz.

of the growing season (usually in May–June) in Western Australia (WA), without threatening pasture persistence. The success of this strategy for improving weed control was subsequently proven in field trials (Ferris, 2008) and on farms (Taylor, 2005). Widespread use of reduced cultivation to conserve soil moisture throughout WA has placed a high dependence on chemicals for weed control during a crop phase, promoting the onset of herbicide resistance among major crop weeds, particularly rigid ryegrass (*Lolium rigidum* Gaud.) that is now considered the world's most herbicide-resistant weed (Pannell et al., 2004; Owen et al., 2007). Improving weed control in a pasture phase within a land-use rotation, such as through delayed pasture germination, can improve farm income by depleting weed seedbanks before the subsequent cropping phase, reducing the use of selective herbicides, and improving the control of herbicide-resistant weeds.

Critical weed control practices available in a pasture phase are grazing and the use of glyphosate to sterilise weed seeds in the pasture (spray-topping) or kill the entire sward (brown-manuring) (Revell and Thomas, 2004; Doole et al., 2009). French serradella (*Ornithopus sativus* Brot. cv. Cadiz) is a highly-productive annual legume that produces seed that may be harvested cheaply on-farm using a standard cereal harvester (Doole and Pannell, 2008; Doole et al., 2009). It is currently the most widely-sown pasture species in WA (Nichols et al., 2006) and is often sown as a one-year sacrificial pasture where brown-manuring is employed for weed control.

However, a new species offers a greater opportunity for effective rigid-ryegrass control. Eastern star clover (*Trifolium dasyurum* C. Presl cv. AGWEST[®] Sothis) (henceforth referred to as “star clover”) is an annual legume pasture that was commercially released in WA in 2007.

Similar to yellow serradella, star clover regenerating from the seed pool (second year of the pasture phase or greater) germinates 4–6 weeks later than ryegrass and hence non-selective herbicide application and/or grazing prior to pasture germination can kill nearly all weeds that are present, without jeopardising legume persistence (Norman et al., 2005). Star-clover pastures can be sown later than conventional pastures and grow vigorously in late winter and spring to provide feed for livestock (Loi et al., 2007a,b; Gibson et al., 2008). In comparison, the application of non-selective herbicides to a traditional pasture species used in WA, such as subterranean clover (*Trifolium subterraneum* L.), at this time would kill a large proportion of the rigid ryegrass and the sown pasture. Star clover has a distinct advantage over yellow serradella since the delay in germination tends to be longer, but germination is more rapid once it occurs. This is important as rigid ryegrass germinates in multiple cohorts over an extended period (see review of Doole, 2009), particularly when soil moisture is marginal. It should be noted that French serradella does not exhibit the same delay in germination as yellow serradella, and consequently does not present the same opportunity for early control of weeds with knockdown herbicides and/or grazing.

Gibson et al. (2008) determined the economic value of star clover at the whole-farm level. However, their analysis was limited to the consideration of a single year and weed population dynamics were ignored. Thus, there was no capacity to represent the ability of star clover to prevent herbicide resistance, its primary benefit given the high cost of resistance in WA cropping systems (Doole and Pannell, 2008; Doole et al., 2009). Moreover, by design, this approach could not assess the economic value associated with

Table 1
Weed control options represented in the RIM model.

Weed control option	Description	Percentage of weeds killed ^a
High crop seeding rates	Increasing the sowing density of a crop may increase crop yield and improve its competitiveness with weeds.	–
Shallow cultivation	Shallow cultivation prior to sowing can encourage weed germination.	5
“Knockdown” herbicides	This describes the use of a non-selective herbicide, such as glyphosate, to kill rigid ryegrass prior to crop and pasture emergence.	97 (glyphosate), 100 (double knockdown)
Selective herbicides	Selective herbicides may be incorporated into the soil prior to sowing or applied after the crop has emerged.	Examples: 70 (trifluralin), 85 (chlorsulfuron pre-emergence), 95 (diclofop)
Grazing	The grazing of the seed heads of rigid ryegrass by sheep can attain high weed control.	30 (1st year), 40 (2nd year), 60 (3rd year)
Brown-manuring	Non-selective herbicides may be used to kill an entire field of pasture or crop to prevent seed-set in existing weeds.	98
Green-manuring	Cultivation of a growing pasture or crop before ryegrass seed production occurs can also achieve high weed control. Both brown- and green-manuring require sacrifice of the crop or pasture.	98
Spray-topping	Non-selective herbicides may be applied to weed seed heads in a pasture to sterilise seed (referred to as crop-topping when used in grain legumes).	85
Mowing and hay/silage production	Seed production can be decreased through the physical cutting of ryegrass plants before seed formation. These methods are followed by an application of glyphosate.	98 (mowing), 95 (hay production), 98 (silage production)
Swathing	Cutting a crop before it reaches maturity may sever the heads of ryegrass plants before seed production.	45 (in barley crop)
Windrowing	Harvest residue containing ryegrass seed can be collected into narrow rows and subsequently burnt.	50
Seed catching	Ryegrass seeds may be collected during harvest to prevent their return to the soil. This is usually followed by the burning of the collected residue.	60
Burning	Ryegrass seed may be destroyed when an entire field is burnt.	30

^a These percentages are for a wheat crop for crop options and for a French serradella pasture for pasture options. Source: Doole and Pannell (2008).

delaying pasture germination to facilitate the greater destruction of early-germinating weed cohorts. Accordingly, this paper focuses on the derivation of these values, with a particular focus on providing insights for practical weed management. This is valuable because little information is available to guide the use of star clover for profitable weed management by producers; profitability will be a key driver in determining its level of adoption; and the most economically-important agronomic traits of star clover are unknown, thus complicating the identification of those features to develop further in field studies. Bioeconomic modelling is used since the determination of the economic value of a leguminous pasture to a farming system is complex and cannot be accurately ascertained from field trials alone (Pannell, 1995a).

2. RIM model

2.1. Empirical framework

This account of the RIM model follows similar descriptions in Pannell et al. (2004), Doole and Pannell (2008), and Doole et al. (2009). A detailed description of the model is provided in Pannell et al. (2004). In addition, a comprehensive description of all of the equations in RIM and a copy of the model is freely available from the primary author.

RIM is a framework designed for analysing the management of herbicide-resistant rigid ryegrass in WA. It is a deterministic simulation model describing the multiple-cohort dynamics of both ryegrass plants and seeds and their interaction with a broad range of weed control strategies, including crop sequences, selective and non-selective herbicides, biological control (e.g. grazing), and cultural methods (e.g. burning). This model represents a single field on a typical sandplain soil in the Central Wheatbelt of WA. RIM is widely used by both researchers and farmers and has undergone extensive field validation (Pannell et al., 2004).

The seven land uses included in the standard RIM model are wheat, barley (*Hordeum vulgare* L.), canola, lupins (*Lupinus* spp.), self-regenerating subterranean clover, and French serradella. The model is extended in this study to incorporate star clover as an additional land-use option. This study compares the profitability of

IWM strategies in RIM (e.g. Doole and Pannell, 2008). However, simulation is preferred in this study since it provides insight into the implications of more common strategies, rather than those that are identified as most profitable in the context of a fixed rotation.

Ryegrass population dynamics are described by state variables representing both plants (p) and seeds (s); these interact through their growth equations. The ryegrass seed population is calculated at eight discrete points (denoted ds) across the growing season. In comparison, the ryegrass plant population is calculated at six points (denoted dp) across the season.¹ Inclusion of a more refined time step (e.g. daily) is not justified given a lack of data for many model processes (Pannell et al., 2004).

The initial seed population (S_0) for the first year is predefined. The initial seed population in subsequent years is the terminal population from the previous year. The equations describing evolution of the seed population are:

$$S_{ds+1,t} = \begin{cases} S_{ds,t} (1 - M_{seed,ds}) (1 - g_{ds}), & \text{for } ds = [1, 2, \dots, 5], \\ S_{ds,t} (1 - M_{seed,ds}) + b \left(\frac{p_{5,t}^{adj}}{p_{5,t}} \right) \left(\frac{R}{(\varpi + p_{5,t}^{adj} + \psi w_o)} \right), & \text{for } ds = 6, \\ S_{ds,t} (1 - M_{seed,ds}) (1 - f_x^L u_t), & \text{for } ds = 7, \end{cases} \quad (1)$$

where $S_{ds,t}$ is the seed population at period ds in year t , $M_{seed,ds}$ is the rate of natural mortality in period ds , g_{ds} is the proportion of seeds germinating in period ds , b denotes the sub-lethal effect of selective herbicides, $p_{5,t}^{adj}$ is the weed population in early spring adjusted downward to represent the lower seed production of later-germinating plants, R denotes the maximum seed production of ryegrass (in seeds $m^{-2} yr^{-1}$), ϖ represents the effect of intra-specific competition on seed production, ψ represents the strength of the relationship between grain crop density (w_o) and seed production, and f_x^L is a $1 \times j_{max}$ vector with each element describing the proportion of the seed population killed by the associated weed treatment (e.g. burning) in land use L (Doole and Pannell, 2008).

The initial weed plant population is zero at the beginning of each year. The equations describing evolution of the plant population are:

$$p_{dp+1,t} = \begin{cases} p_{dp,t} (1 - M_{plant,dp}) (1 - f_w^{dp,L} u_t) + g_{ds} S_{ds,t}, & \text{for } dp = [1, 2, \dots, 4] \text{ and } ds = dp + 1, \\ p_{dp,t} (1 - M_{plant,dp}) (1 - f_w^{dp,L} u_t), & \text{for } dp = 5, \end{cases} \quad (2)$$

a set of predefined land-use rotations that are generated in accordance with field observations and previous analyses.

There are thirty-five weed-management treatments incorporated in the model, with compatibility varying by land use. The broad groups to which these strategies belong and representative levels of control are outlined in Table 1. Management options vary by timing of application and also by enterprise. An example of the latter is that grazing reduces weed seed production in a pasture, but is not permitted in a crop year (Table 1). The level of weed control obtained by grazing differs by pasture species and the year of the phase in which defoliation occurs (Pannell et al., 2004).

Users typically compare the profitability of different Integrated Weed Management (IWM) strategies by simulating different combinations of weed control options for a given rotation. Combinatorial optimisation has recently been used to identify profitable

where $p_{dp,t}$ is the plant population at period dp in year t , $M_{plant,dp}$ is the rate of natural mortality for ryegrass plants in period dp and $f_w^{dp,L}$ is a $1 \times j_{max}$ vector with each element describing the proportion of the weed population killed by the associated treatment in period dp in land use L (Doole and Pannell, 2008). Parameter values for equations (1) and (2) are available in Pannell et al. (2004) and Table 1.

¹ The eight periods for the seed population are immediately prior to the break of the season, the first chance to seed, 10 days after the break of season, 20 days after the break of season, the time of post-emergent herbicide application, spring, prior to harvest, and after summer. The six periods for the plant population are the first chance to seed, 10 days after the break of season, 20 days after the break of season, the time of post-emergent herbicide application, early spring, and weed seed production.

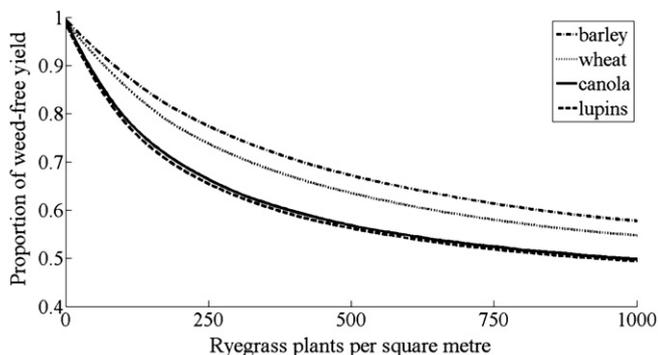


Fig. 1. Relationship between ryegrass density (plants m^{-2}) and the yield of wheat, barley, canola, and lupins in the Central Wheatbelt of Western Australia.

Standard yields for the barley, canola, lupin, and wheat crops incorporated in RIM are determined from regional averages. Base yield is promoted to different degrees depending on the type of legume plants that have been grown in previous years in the rotation and their frequency. Conversely, yield is depressed due to late sowing or due to phytotoxic damage from herbicide application. Most important in the context of this application, yield is detrimentally affected in each of the four crops by ryegrass competition. This is described in the model using the hyperbolic function of Pannell (1995b) (Fig. 1). (This function is described in more detail in Pannell et al. (2004).) The parameters for this function have been estimated from non-linear regression of data collected from field trials conducted throughout the WA Wheatbelt over the last decade.

No interaction is defined between weed burden and pasture biomass due to a lack of information. Annual pasture production is defined in terms of the number of standard dry sheep equivalents (DSEs) (a standard Australian measurement representing one non-lactating sheep of average size) supported by a pasture in a single year. This increases over the length of most pasture phases as these stands become more productive with age. For example, stocking rates for French serradella are 3, 6, and 7 DSE/ha/yr in Years 1, 2, and 3 of a three-year phase respectively. These stocking rates are multiplied by a gross margin expressed per DSE to obtain total revenue for each year of pasture.

Crops and pastures can both be cut for hay or silage production. RIM involves all costs and revenues accruing to the harvest and sale of these products. Hay or silage production decreases the stocking rate in pasture phases and sacrifices grain production in all crops.

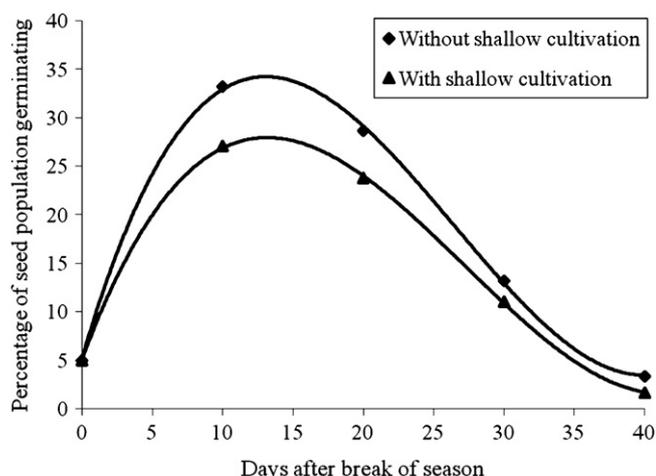


Fig. 2. Emergence curve for *Lolium rigidum* in the RIM model.

Nevertheless, it may be economic in the latter case where resistance constrains control outside of a pasture phase and such extreme measures are required to minimise competition in subsequent crops.

Germination of annual ryegrass in the model is described through the emergence curves depicted in Fig. 2. This curve was generated from field experiments, expert opinion, and an extensive literature concerning the germination dynamics of *L. rigidum* in the WA Wheatbelt (e.g. Steadman et al., 2004). Fig. 2 clearly displays that the majority of rigid-ryegrass seeds will germinate in the first three weeks of the growing season, and most that remain will germinate in the subsequent four weeks. Star clover can greatly improve the control of this weed by almost eradicating these cohorts with little detrimental effect on ensuing legume production (Loi et al., 2006, 2007b).

A standard initial seed burden of 500 seeds m^{-2} is incorporated in the model to represent an average weed population in this region. This magnitude is consistent with field observations (S. Powles, pers. comm., 2007; Doole et al., 2009) and previous analysis (e.g. Pannell et al., 2004). However, other densities are also considered to provide insight into their impact on the relative value of a number of candidate rotations. This heuristic approach is necessary as little appropriate information is available.

The rigid-ryegrass seed population must be less than or equal to 500 seeds m^{-2} in the final year of the planning horizon for an IWM strategy to be considered (Pannell et al., 2004; Doole and Pannell, 2008; Doole et al., 2009). This ensures that the field is left in an average condition at the end of the planning horizon. Results could be biased if control costs were reduced for one rotation by letting a high weed population establish at the end of the model horizon. Use of this terminal condition reduces this bias.

Rapid proliferation of rigid ryegrass is encouraged through its high seed production. Ryegrass seed production is defined in the model as a non-linear function incorporating both intra- and inter-specific competition (Pannell et al., 2004).

Herbicide resistance is represented in the model through the specification of upper limits on the number of selective herbicide applications available to individual producers. This limit is zero if resistance is present. This method of representing herbicide resistance abstracts away from the genetic factors underlying resistance development, but is effective and sufficient given the predictable and rapid development of resistance in WA cropping systems (Tardif et al., 1993; Pannell et al., 2004).

Resistance risk varies according to herbicide mode-of-action. Each mode-of-action is described in the RIM model according to the Herbicide Resistance Action Committee system (Kramer and Schirmer, 2007). A lower number of applications are available for ACCase inhibitor (Group A) and sulfonylurea (Group B) herbicides in RIM, compared to that permitted for photosynthesis inhibitors (Group C). This is consistent with the rapid development of resistance to these chemicals in rigid ryegrass populations (Owen et al., 2007).

A recent field survey highlighted that 68 per cent of ryegrass populations in the WA Wheatbelt were resistant to the Group A herbicide diclofop-methyl, 88 per cent were resistant to the Group B herbicide sulfometuron, and 64 per cent were resistant to both (Owen et al., 2007). Notwithstanding these high and increasing frequencies, Group A herbicide clethodim was found to remain largely effective. Moreover, Group A herbicides butoxydim and pinoxiden and a Group E/K combination of prosulfocarb and S-metochlor are new selective herbicides available for ryegrass control in WA.

Nonetheless, the development of resistance is still studied in this paper because the severity of multiple and cross resistance varies by farm and the development of herbicide resistance in WA is both rapid and ongoing given the reliance of most producers on selective herbicides for weed control (Owen et al., 2007). The high

cost of alternative sowing methods and non-chemical forms of weed control provide strong incentives to intensively apply herbicides in the current economic climate. Thus, the introduction of new chemicals can only delay, and not prevent, the development of resistance. Moreover, the level of ongoing investment in new chemical modes of action is unknown; hence, a precautionary approach, as espoused in this analysis, is adopted here.

2.2. Addition of star clover to the RIM model

The model parameters for star clover are derived from discussions with scientists from the Pasture Science Group at the Department of Agriculture and Food Western Australia. A scientific consensus approach was required given there was little alternative information to provide guidance.

There are no differences expected in the weed control parameters for star clover compared to French serradella. The exception being that “knockdown” herbicide applications are defined to be effective in star-clover pasture one month after the start of the growing season. This is strongly indicative of the late emergence typical of star-clover pastures in WA conditions, as germination requires persistent cold after seed is imbibed (Loi et al., 2007a,b). The high level of weed kill obtained in the RIM model through the late knockdown application is consistent with field results reported by Loi et al. (2007a,b) and in unpublished data.

In the first year of the star-clover pasture phase a single insecticide application is used for red-legged earth mite control. The standard cost of seed obtained from commercial sources is assumed to be A\$4 kg⁻¹ and this pasture is sown at 10 kg ha⁻¹. It also costs A\$0.50 kg⁻¹ to inoculate seed with the appropriate rhizobial strain. Superphosphate is applied at the same rate (30 kg/ha/yr) as in the French serradella pasture represented in the model. This is a low rate given that considerable quantities of residual phosphate are generally available to pastures given their standard use between long cropping sequences.

Stocking rates for star clover are 2, 3, and 3 DSE ha/yr in Years 1, 2, and 3 respectively. The impact of higher grazing rates is explored in sensitivity analysis; however, these lower rates are particularly relevant as star clover germinates later than other annual pastures and only produces biomass during the “spring flush” in which feed is of low marginal value to WA farming systems (Kingwell and Schilizzi, 1994).

The benefits of star clover to subsequent crops through nitrogen fixation and improved levels of soil organic matter are assumed to be equivalent to French serradella. This is appropriate because star clover produces less biomass than French serradella due to its late germination, but the stocking rates defined for star clover in this study are conservative.

Table 2
Rotations and corresponding labels.

Rotation	Label
Lupin–wheat–wheat–barley	C
French serradella–wheat–wheat–barley– lupin–wheat–wheat–barley	S + 7C
French serradella–French serradella–wheat– wheat–barley–lupin–wheat–wheat–barley	2S + 7C
French serradella–French serradella– French Serradella–wheat–wheat–barley– lupin–wheat–wheat–barley	3S + 7C
Star clover–wheat–wheat–barley–lupin– wheat–wheat–barley	D + 7C
Star clover–star clover–wheat–wheat– barley–lupin–wheat–wheat–barley	2D + 7C
Star clover–star clover–star clover–wheat– wheat–barley–lupin–wheat–wheat–barley	3D + 7C

3. Model scenarios

3.1. Rotations

The analysis compares the relative profitability of a number of rotations (Table 2). Rotation C is representative of continuous-cropping systems in which herbicides are relied upon for efficient weed control. It was also studied by Monjardino et al. (2004), Doole and Pannell (2008), and Doole et al. (2009).

French serradella provides an important comparison for star clover since recent survey results show it is the most popular sown pasture in WA (Nichols et al., 2006). Recent economic analysis also reports that it is a valuable pasture for IWM as rigid-ryegrass populations increase or herbicide resistance grows in severity (Doole and Pannell, 2008; Doole et al., 2009). A long crop sequence (seven years) is employed after each pasture phase to fully reflect the benefit of each phase for weed management and due to the high relative profitability of cereal crops.

The aim of management is to identify the IWM strategy that maximises the profitability of the field over an extended period. The profitability of alternative investments is typically compared using the net present value (NPV) criterion. The NPV for a rotation of T years length is defined as $NPV = \sum_{t=1}^T (1+r)^{-t} I_t$, where r is a discount rate and I_t is income in year t . The NPV concept considers the opportunity cost of the net income available in each year as this can be alternatively invested at the discount rate. Under the NPV criterion, the most-profitable rotation is that which maximises NPV.

However, a number of rotations are of different length in this analysis (see Table 2). Use of a fixed horizon length may consequently introduce bias when a higher number of less-profitable phases (such as the initial year of a multi-year pasture phase or a lupin crop) are present over a fixed planning period (e.g. ten years) for one rotation and not another. Therefore, the profitability of each rotation is reported using the equivalent NPV approach (Robison and Barry, 1996). This method involves the derivation of the infinite-life NPV (i.e. $INPV$)² based on the intuition that investments should be compared over a common time frame and perpetuity is a consistent benchmark that is technically accurate and simple to incorporate arithmetically (Robison and Barry, 1996).

3.2. Weed control strategies

Selected weed-management strategies are based primarily on typical practice, with some treatments (e.g. seed catching) used given their high value in certain circumstances (e.g. where the supply of effective selective herbicides is low). Group A, B, and C herbicides are used tactically within the basic IWM strategy defined in this section to maximize the equivalent NPV. This is necessary since prior analysis (e.g. Doole and Pannell, 2008) has highlighted that the profitable application of selective herbicides across time is highly context-dependent (e.g. dependent on different initial seed burdens and grain prices) and thus use of a fixed strategy will reduce flexibility and, consequently, income.

The non-selective herbicides applied prior to crop and pasture emergence are glyphosate (Group M) at 0.45 kg/ha (kilograms of active ingredient per hectare) and a mixture of 0.20 kg/ha paraquat (Group L) and 0.17 kg/ha diquat (Group L). These herbicides are

² The method involves (a) calculation of the NPV for a rotation, (b) determination of the constant annual benefit (i.e. annuity) consistent with this NPV, and (c) identification of the infinite-life NPV (i.e. $INPV$) by dividing this value by the appropriate discount rate. Two successive cycles of the C rotation are investigated for this sequence given its short length relative to the other rotations, although weed dynamics are presented for a ten-year period in Fig. 3 in Section 4.2 to allow ease of comparison with similar figures presented in this section.

rotated to reduce the probability of resistance developing to non-selective herbicides. Trifluralin (Group D) is applied at 0.77 kg/ha in alternate crop years.

The French serradella pasture is sown in its first year and regenerates in subsequent years in a multi-year phase. Sowing involves the direct drilling of 15 kg of seed (in pod form) per hectare with seed costing A\$0.50 kg⁻¹. This cost is consistent with the harvesting of seed on-farm with a standard cereal harvester. A shallow cultivation is used prior to sowing to stimulate weed germination and hence increase the efficacy of subsequent weed control. This is also used to stimulate pasture regeneration in the second and third years of a multi-year phase. All except the final year of each multi-year French serradella phase is spray-topped with paraquat at 0.08 kg/ha in spring. The pasture is killed near the end of its final year using glyphosate at 0.4 kg/ha. This achieves excellent weed control and reduces competition between regenerating French serradella plants and the subsequent crop.

Sowing or regeneration of the star clover pasture is always preceded by:

1. a shallow cultivation to improve weed germination and therefore the efficacy of herbicide application prior to pasture emergence; and
2. a knockdown herbicide application applied one month after the first germinating rains.

The establishment of star clover is similar to French serradella, although sowing time is obviously later, conferring better weed control. The key difference between these species is the application of a knockdown herbicide in all years of star clover regeneration and this has greater efficacy for ryegrass due to its application later in the growing season when more ryegrass plants have germinated. All except the final year of each multi-year phase is spray-topped with paraquat at 0.08 kg/ha in spring. The star-clover stand is killed near the end of its final year using glyphosate herbicide applied at 0.4 kg/ha. The combination of the knockdown and brown-manuring applications in a single-year phase is very effective since the high efficacy of each activity complements that of the other.

The IWM strategy proposed for each pasture phase relies heavily on non-selective herbicides. Resistance to paraquat and glyphosate has been observed in a number of Australian rigid ryegrass populations (Borger and Hashem, 2007). Nevertheless, resistance to these chemicals is unlikely to develop under the scenarios considered here given the regular use of selective herbicides; use of paraquat and glyphosate, rather than just one of these groups, for spray-topping and brown-manuring respectively; and the rotation of glyphosate and a double-knockdown treatment prior to sowing.

Weed seed is collected in a chaff and seed cart at crop harvest. This is a cost-efficient means of reducing the weed seedbank, particularly following insufficient seed-set control. Use of this technique is increasing in the WA Wheatbelt and recent economic analysis identifies its significant contribution to efficiently minimising the weed seedbank across time (e.g. Doole and Pannell, 2008).

The development of resistance motivates the use of in-crop, non-selective weed-management strategies. Crop-topping is used in the lupin crops when Group A–B resistance reduces the number of options available for in-crop ryegrass control. However, more severe herbicide resistance promotes cutting lupin crops strategically for silage production. This incurs an opportunity cost accruing to foregone grain harvest. However, silage production is more profitable than grain production in lupin crops with the presence of severe resistance given benefits for reducing weed competition in future cereal crops (Doole et al., 2009). High crop seeding rates also become economic with an increasing severity of herbicide resistance.

Table 3
Scenarios investigated in the model.

Description	Parameter value
Initial ryegrass seed densities	100, 500, 1000, 2500, 5000, and 10,000 seeds/m ²
Herbicide resistance	Loss of Group A, A–B, and A–C herbicides
Grain prices:	{wheat, barley, lupins}
Low (–20%)	{A\$240, A\$228, A\$224}
Low-medium (–10%)	{A\$270, A\$256.50, A\$252}
Standard	{A\$300, A\$285, A\$280}
Medium-high (+10%)	{A\$330, A\$313.50, A\$308}
High (+20%)	{A\$360, A\$342, A\$336}
Cost of star clover seed	{A\$0.01/kg, A\$0.50/kg, A\$1/kg, A\$1.50/kg, A\$2/kg, A\$2.50/kg, A\$3/kg, A\$3.50/kg, A\$4/kg}
Grazing rate in star clover phase	
Standard	Yr 1 = 2 DSE/ha, Yr 2 = 3 DSE/ha, Yr 3 = 3 DSE/ha
Medium-high	Yr 1 = 2 DSE/ha, Yr 2 = 4 DSE/ha, Yr 3 = 4 DSE/ha
High	Yr 1 = 2 DSE/ha, Yr 2 = 5 DSE/ha, Yr 3 = 5 DSE/ha

3.3. Alternative runs

The profitability of each fixed rotation (Table 2) is evaluated under different scenarios (Table 3). Some scenarios would seldom be observed in reality. For example, producers would not maintain a continuous-cropping rotation if severe herbicide resistance exists. Nonetheless, these are valuable to improve insight into the drivers of pasture adoption and the relative value of star clover in different circumstances.

The profitability of each rotation is presented over a range of initial ryegrass seed densities to investigate how each sequence is affected by an increasing initial weed burden.

The effect of differing degrees of herbicide resistance on profit is also explored. This is done through restricting the availability of Group A, Group A–B, and Group A–C herbicides in different runs. This pattern is observed in practice since the most-efficient selective herbicides (Groups A and B) are usually employed until the development of resistance to these chemicals promotes increasing use of the less-efficient Group C herbicides (Owen et al., 2007). This aspect of the study helps to determine the reliance on selective herbicides and the cost of substituting these chemicals with non-selective treatments in each rotation. Group D resistance is not incorporated in this study given its minor occurrence in the study region (Owen et al., 2007) and the introduction of a new pre-emergent Group E/K herbicide, discussed in Section 2.1, which agronomic work has highlighted is an effective substitute for trifluralin in WA conditions.

Mixed-farming systems in WA typically encounter temporal variation in the relative profitability of livestock and crop production. This is explored through decreasing and increasing the standard grain prices defined in the model by 10 and 20 per cent.

The effect of increasing stocking rates in the star-clover phases is also evaluated (see Table 3), as the estimates included in the standard model are conservative. The grazing rate in the first year is never enhanced given the low productivity of newly-sown star-clover pastures.

The impact of improved ryegrass control through grazing at higher stocking rates is explored, but has little impact on model output due to the effective weed management already occurring in the star-clover phase. It is therefore not considered further in this study.

The profitability of those rotations containing star clover is also evaluated at a range of star-clover seed prices (Table 3). The existing commercial price for seed is A\$4 kg⁻¹, but this is expected to decline as the available commercial supply increases.

Table 4

Profitability (infinite-life NPV in A\$ ha⁻¹) of each sequence for a range of initial rigid-ryegrass seed densities and no initial herbicide resistance.

Rotation	Initial ryegrass seed density (seeds/m ²)					
	100	500 ^a	1000	2500	5000	10,000
C	2609 ^b	2550	2467	2247	1998	1931
S + 7C	2210	2194	2183	2160	2132	2084
2S + 7C	1957	1916	2000	1882	1869	1852
3S + 7C	2102	2099	2088	2086	2085	2084
D + 7C	2212	2204	2197	2179	2152	2127
2D + 7C	1876	1872	1867	1855	1842	1824
3D + 7C	1913	1913	1912	1911	1910	1908

^a Standard case.

^b The bold values represent the most-profitable rotation at that initial ryegrass density.

4. Results and discussion

4.1. Initial weed seed density

The most-profitable rotation at low seed densities is the continuous-cropping sequence (Table 4). However, it is surpassed by the D + 7C rotation at initial densities above and including 5000 seeds/m². This threshold is higher than that reported by Doole and Pannell (2008) since grain prices are higher here, which provides a greater incentive to maintain a continuous-cropping rotation.

Profit declines by around 24 per cent in the C rotation as the initial seed density increases from 100 seeds/m² to 10,000 seeds/m². This reflects the inability of in-crop weed management in a continuous-cropping rotation to effectively restrain an enormous residual weed burden, even with a suite of available selective herbicides.

The inclusion of a pasture phase becomes more profitable as the initial seed density increases. A pasture phase allows effective weed control through grazing, spray-topping, and brown-manuring; hence, profit is more stable in such rotations as the initial weed burden increases. For example, INPV decreases by around 6 (4) per cent as the initial seed density increases from 100 seeds/m² to 10,000 seeds/m² in the S + 7C (D + 7C) sequences. Moreover, INPV falls by only 0.9 (0.3) per cent in the 3S + 7C (3D + 7C) rotation under the same circumstances.

The rotations incorporating one-year phases of star clover and French serradella are similarly valuable over all initial weed densities (Table 4). Moreover, they are more profitable than longer phases, holding all other factors constant. A one-year phase of French serradella supports 3 DSE/ha, in contrast to 2 DSE/ha maintained in a star-clover phase of the same duration. The relative profitability of French serradella is also promoted by its low seed cost, as its establishment cost is typically nearly half of that of star clover. Nonetheless, these factors are offset by the weed-control benefits accruing to the use of star clover to intermittently reduce the ryegrass seedbank. This reflects the higher value of the increases in grain yield associated with reduced weed burdens (Fig. 1).

However, French serradella is a more profitable break pasture than star clover in a two- or three-year phase (Table 4). Here, the value of greater livestock production supersedes the contribution of a multi-year star clover phase to improved weed control in the absence of herbicide resistance.

4.2. Management of herbicide-resistant weeds

Profit declines greatly in the C rotation as selective herbicide groups become ineffective against rigid ryegrass since this promotes substitution with less-efficient forms of control (Table 5).

Table 5

Profitability (infinite-life NPV in A\$ ha⁻¹) of each sequence for different herbicide resistance scenarios at an initial weed density of 500 seeds/m². (Star clover seed cost: \$A4 kg⁻¹).

Rotation	Initial herbicide resistance			
	None	A	A, B	A, B, C
C	2550 ^a	2448	2193	1629
S + 7C	2194	2018	1904	1903
2S + 7C	1916	1719	1670	1647
3S + 7C	2099	2029	1966	1745
D + 7C	2204	2204	2204	2123
2D + 7C	1872	1872	1872	1872
3D + 7C	1952	1952	1952	1952

^a The bold values represent the most-profitable rotation at that level of initial herbicide resistance.

INPV declines by 4 per cent with the development of resistance to Group A chemicals, 14 per cent with the loss of Group A–B chemicals, and 36 per cent with the loss of Group A–C chemicals.

Non-selective treatments adopted in the C rotation following the development of herbicide resistance are primarily implemented in the lupin crops, which are of lower value than the cereal crops. For example, all lupin crops are cut for silage production when no Group A–C herbicides are effective. Cutting a lupin crop for silage production greatly reduces the weed seed population, but the absence of efficient selective herbicides means that the seed population soon builds to critical levels during the subsequent cereal phase (Fig. 3).³

The inclusion of pasture phases allows effective weed control, even with the development of resistance following herbicide application during the crop phase. Profit falls by 13, 14, and 17 per cent for the S + 7C, 2S + 7C, and 3S + 7C sequences respectively going from a state of no initial herbicide resistance to a state where resistance to Group A–C herbicides is observed (Table 5). Hence, the profit declines experienced in each rotation containing French serradella are much lower than the 36 per cent observed for the C rotation. This is directly attributable to the level of ryegrass control achieved over the pasture phases and the lower economic losses incurred to attain this level of weed kill, as crop income does not have to be sacrificed as regularly as in the C rotation (Fig. 4).

INPV is much more robust to the development of herbicide resistance in those sequences containing star clover. Profit falls by only 4 per cent in the D + 7C rotation; thus, this is the most-valuable configuration once resistance is observed to Group A–B herbicides. Moreover, profit is not affected in the 2D + 7C and 3D + 7C sequences going from a state of no initial resistance to a situation where Group A–C herbicides are ineffective (Table 5). This reflects that the loss of selective herbicides through resistance does not reduce profit in these rotations because sufficient weed control can be attained in their absence.

Although a moderate loss is incurred in the initial year of the 3D + 7C rotation as the star-clover pasture is established, this three-year phase attains high weed control (especially in comparison to the IWM strategy employed in the C rotation in Fig. 3) and thereby significantly enhances subsequent crop production (Fig. 5). Even in comparison to the 3S + 7C rotation (Fig. 4), maintaining three years of star clover pasture achieves much greater control over the ryegrass seedbank. Thus, even with the loss of all selective herbicides, it is still not necessary to sacrifice any crop income, as

³ This scenario is used solely to illustrate the high cost of herbicide resistance in a continuous-cropping rotation. In reality, producers are likely to adopt cheaper forms of weed management, for example those available in a pasture phase, when weed populations reach such a high level.

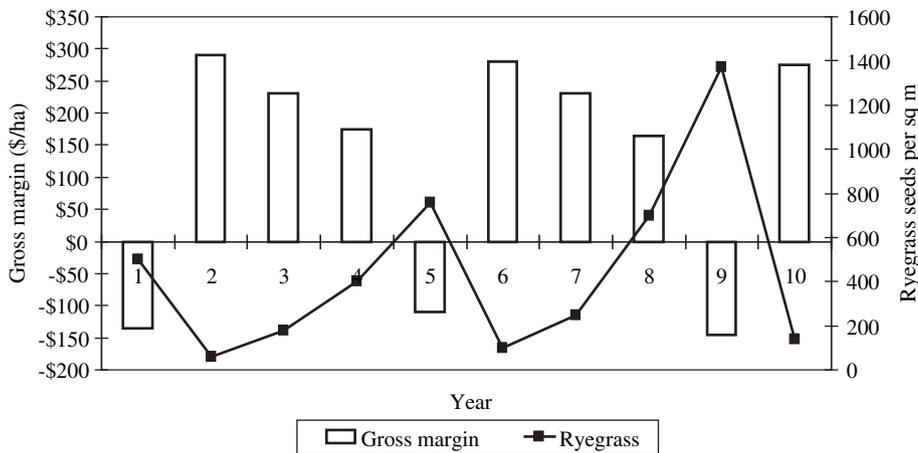


Fig. 3. Annual gross margin (A\$ ha⁻¹) and rigid-ryegrass seed density before the start of the growing season for the C rotation (lupin-wheat-wheat-barley) with Group A-C resistance in Year 1. (Initial weed density: 500 seeds/m²).

required in the lupin crop grown in Year 7 of the 3S + 7C rotation (Fig. 4).

4.3. Variation in grain prices

Variability in grain prices changes the relative value of crops and pasture in rotation. The continuous-cropping rotation is more valuable than any of those containing pasture across all price changes considered here at an initial seed density of 500 seeds/m² and in a state of no initial herbicide resistance (Table 6). However, pasture becomes more profitable at a lower herbicide-resistance threshold at depressed grain prices. This reflects the higher relative value of livestock production and decreases in the value of weed control in terms of its associated yield benefits. Conversely, the use of a pasture phase for the control of herbicide-resistant weeds becomes less valuable at the highest set of grain prices considered.

The magnitude of the loss incurred by lower grain prices is higher in those rotations containing French serradella, relative to those incorporating star clover. For example, the 10 (20) per cent decline in grain prices incurs a 16 (32) per cent decline in profit in the S + 7C rotation, whereas the same trend incurs a 12.2 (27.4) per cent decrease for the D + 7C sequence (Table 6). The change in profit observed in each rotation arises from the price*yield interaction defined in each crop year. Greater weed control in the star-

clover phases increases subsequent crop yield holding all other factors constant. Accordingly, rotations containing this pasture will be less adversely affected by decreases in the prices received for crop output.

4.4. Star clover establishment costs

French serradella seed may be harvested cheaply on-farm for A\$0.50 kg⁻¹. In contrast, star clover is unlikely to be harvested by individual producers for their own use since it requires considerable modification of a standard cereal harvester and also swathing to aid uniform drying. A decrease of A\$0.50 kg⁻¹ for star-clover seed at any level of simulated seed cost (Table 3) increases the INPV for each of these rotations by around A\$10 (data not shown). Hence, the value of star clover for WA farming systems will be further enhanced by technical innovation that succeeds in lowering its establishment cost.

4.5. Different stocking rates

The 2D + 7C and 3D + 7C rotations are never more profitable than the D + 7C sequence if the stocking rates in the second and third years of a star clover phase are elevated to those levels defined in Table 3. This reflects the higher opportunity cost accruing to

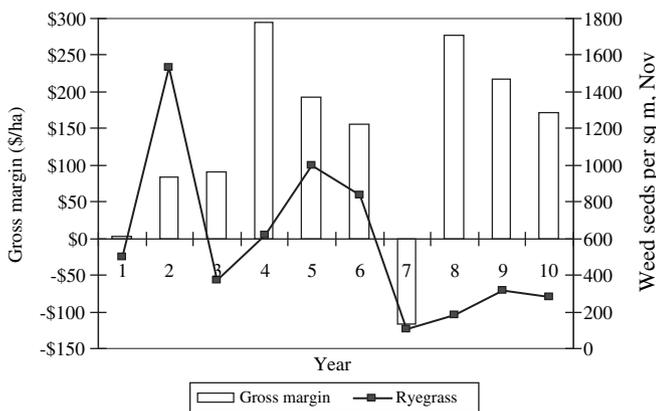


Fig. 4. Annual gross margin (A\$ ha⁻¹) and rigid-ryegrass seed density before the start of the growing season for the 3S + 7C (French serradella-French serradella-French serradella-wheat-wheat-barley-lupin-wheat-wheat-barley) rotation with Group A-C resistance in Year 1. (Initial weed density: 500 seeds/m²; Star-clover seed cost: A\$4 kg⁻¹).

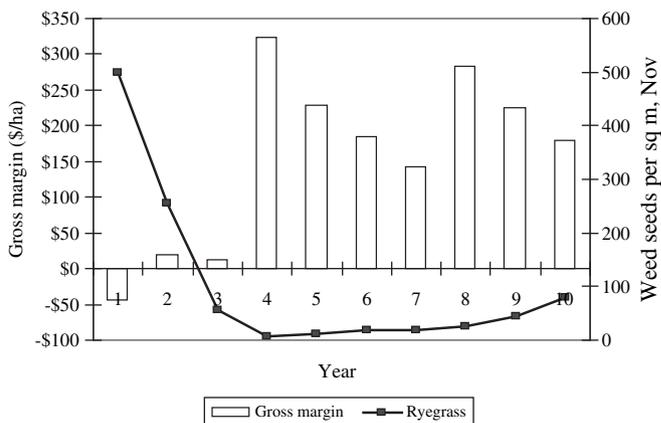


Fig. 5. Annual gross margin (A\$ ha⁻¹) and rigid-ryegrass seed density before the start of the growing season for the 3D + 7C (star clover-star clover-star clover-wheat-wheat-barley-lupin-wheat-wheat-barley) rotation with Group A-C resistance in Year 1. (Initial weed density: 500 seeds/m²; Star clover seed cost: A\$4 kg⁻¹).

Table 6

Profitability (infinite-life NPV in A\$ ha⁻¹) of each sequence for different grain prices and different severities of herbicide resistance in the continuous-cropping rotation at an initial weed density of 500 seeds/m².

Rotation	Grain price scenario				
	(-20%)	(-10%)	No change	(+10%)	(+20%)
C	1620	2058	2550	2947	3391
C (Group A resistance)	1526	1939	2448	2766	3179
C (Group A–B resistance)	1451	1856	2270	2667	3072
C (Group A–C resistance)	1284	1666	2066	2429	2811
C (Group A–D resistance)	829	1135	1442	1749	2056
S + 7C	1491	1849	2194	2479	2805
2S + 7C	1296	1607	1916	2168	2458
3S + 7C	1491	1798	2099	2329	2617
D + 7C	1602	1935	2204	2598	2944
2D + 7C	1361	1634	1872	2181	2490
3D + 7C	1454	1703	1913	2197	2477

a two- or three-year phase given the high relative profitability of cereal cropping. This finding suggests that little economic benefit accrues to the development of those strains of star clover with greater biomass production.

4.6. Limitations

Existing knowledge of star clover agronomy is limited as *T. dasyurum* L. cv. AGWEST[®] Sothis is the first commercial cultivar of this species. This motivates extensive sensitivity analysis and the use of expert opinion to identify suitable parameters for the model.

The model is deterministic and therefore does not incorporate temporal variability in output prices, input prices, technical innovation (e.g. the supply of effective chemicals is assumed constant over the planning horizon), resistance development, and crop/pasture production. Incorporation of stochasticity is difficult to justify since little information is available to guide the formulation of appropriate frequency distributions, particularly for those variables that follow a generally random process (i.e. yield/price covariance). Thus, it is deemed most appropriate to minimise bias through the use of parameters for an expected year (Pannell et al., 2004).

The model is focussed on the management of a single weed species (rigid ryegrass), which has an early pattern of germination in the WA Wheatbelt. Extension of this analysis to consider weeds with a more staggered germination pattern, such as wild radish (*Raphanus raphanistrum* L.), hence would be an interesting area for further research. A multiple species version of RIM (incorporating both rigid ryegrass and wild radish) exists, but is not used here due to its lack of effective calibration and to focus on the more widespread and economically important *L. rigidum*. Nevertheless, inclusion of weed species with staggered germination may be expected to dampen the marginal benefit for weed control accruing to the delayed emergence of star clover.

5. Conclusions

Crop production in the Western Australian Wheatbelt has traditionally centred around cereals, but this has been challenged significantly in recent years since herbicide-resistant rigid ryegrass is expensive to control and typically emerges at a similar time to crops. This study shows that use of a one-year phase of eastern star clover between cropping phases is profitable at initial weed seed densities above 5000 seeds/m² and/or when resistance prevents the use of Group A–B chemicals. The former arises if poor or no weed control is attained in a single year; thus, it is realistic if resistance causes an herbicide application to have little effect. The latter is not observed on many farms as yet, particularly since new

Group A chemicals (i.e. butoxydim and pinoxiden) have recently been introduced. However, many producers still favour chemical control and thus resistance will continue to evolve in this region in response to the lack of diversity in weed control.

Interestingly, eastern star clover is shown here to be of comparable value to French serradella, currently a popular legume pasture in WA. This is surprising given eastern star clover's higher seed cost and lower biomass production. However, it highlights the importance of bioeconomic modelling for weighing up the multiple components that determine the value of a pasture legume in a land-use rotation (Pannell, 1995a). The value of eastern star clover identified in this study suggests that, even with the conservative production assumptions considered here, the focus of efforts in the near-term should be the development and promotion of agronomic packages to streamline its adoption by producers in a range of agroecological regions.

Model output also suggests that reducing seed cost should be an important focus of field research. In contrast, increasing biomass production is unimportant as this pasture's relative value is primarily determined by its delayed germination and the associated benefit for the control of early-germinating weeds. This finding suggests that exploiting the delayed germination of crop or pasture species to obtain high levels of weed kill in other farming systems worldwide is an important and interesting area for further research.

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