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RIM: Anatomy of a Weed Management Decision Support System for Adaptation and Wider Application

Myrtille Lacoste and Stephen Powles*

RIM, or "Ryegrass Integrated Management," is a model-based software allowing users to conveniently test and compare the long-term performance and profitability of numerous ryegrass control options used in Australian cropping systems. As a user-friendly decision support system that can be used by farmers, advisers, and industry professionals, RIM can aid the delivery of key recommendations among the agricultural community for broadacre cropping systems threatened by herbicide resistance. This paper provides advanced users and future developers with the keys to modify the latest version of RIM in order to facilitate future updates, modifications, and adaptations to other situations. The various components of RIM are mapped and explained, and the key principles underlying the construction of the model are explained. The implementation of RIM into a Microsoft Excel® software format is also documented, with details on how user inputs are coded and parameterized. An overview of the biological, agronomic, and economic components of the model is provided, with emphasis on the ryegrass biological characteristics most critical for its effective management. The extreme variability of these parameters and the subsequent limits of RIM are discussed. The necessary compromises were achieved by emphasizing the primary end-use of the program as a decision support system for farmers and advisors.

Nomenclature: Annual rigid ryegrass, *Lolium rigidum* Gaud.

Key words: Adoption, agriculture, bio-economic models, DSS, extension, herbicide resistance, management simulation, weed economics.

RIM, or "Ryegrass Integrated Management," is a model-based decision support system (DSS) for testing the biological and economic performance of tactics to control ryegrass (annual rigid ryegrass, *Lolium rigidum* Gaud.) in dryland broadacre cropping systems of the Australian southern grainbelt. RIM offers users the option of customizing field characteristics such as grain yields, weed management costs, and ryegrass control efficacies before building a 10-yr strategy, thereby allowing the testing and comparison of numerous control options on ryegrass numbers and crop field economic returns.

RIM's first phase of development began in the 1990s and culminated with the release of RIM's first user-friendly version (Pannell et al. 2004b). RIM was used both as a research tool and as a DSS, primarily during workshops that successfully supported the delivery of key herbicide resistance messages to the agricultural community (Doole 2008; Lacoste and Powles 2014). RIM uses ryegrass population dynamics and allows users to explore scenarios in the long-term and at the field scale. Unlike a majority of other weed management models and DSS, RIM does not include automated optimization features (Holst et al. 2007) nor provide recommendations (e.g., Gonzalez-Andujar et al. 2011). Instead, users can easily experiment with options and visually compare the consequences of their management choices.

With the rise of herbicide-resistant weeds in global cropping systems, the need to communicate integrated, diverse weed control practices to ensure cropping sustainability is increasingly important (Norsworthy et al. 2012). To continue contributing to this effort, RIM was upgraded and made available online along with supporting documents (Australian Herbicide Resistance Initiative [AHRI] 2013). The primary objective was to use the program as a DSS in order to continue the extension efforts pertaining to herbicide resistance management. This redevelopment focused on updating the program contents to more closely reflect current farming practices and new technologies, and on increasing the ease of use of the overall software (Lacoste and Powles 2014). RIM default values, set to represent an average situation in the Australian southern grainbelt, had to be easily modifiable to better adjust to local situations. The underlying model was also restructured in order to facilitate maintenance needs as well as future

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* Decision Support Agronomist and Winthrop Professor, Australian Herbicide Resistance Initiative (AHRI), School of Plant Biology, University of Western Australia, Perth WA 6009, Australia. Corresponding author's E-mail: myrtille.lacoste@gmail.com

modifications. In particular, greater flexibility within the model would also allow RIM to be adapted to other situations.

The original RIM model was presented in Pannell et al. (2004b) and extensively described in Pannell et al. (2004a) and Pluske et al. (2004), while numerous publications further examined its core modelling notably through sensitivity analysis (see Lacoste and Powles 2014 and references within). A decade after the original release, this paper provides one concise and updated description of the entire program, to give advanced users and future developers the keys to modify the latest version of RIM. Emphasis on the practicalities of coding and the reasoning behind option choices were preferred over equations and exact values, as these were provided in the above-mentioned publications for RIM and will vary for other circumstances the model may be adapted to.

An overview of the program structure is presented, before explaining how RIM is implemented in a software format using Microsoft Excel®. The new locations of RIM components and parameters are mapped, and the conversion of user choices into modelling elements is explained. The functions of the various components are then summarized, focusing on the biological, agronomic, or economic logics that determine which elements, impacts, and linkages are modelled. The strengths and limitations of RIM's modelling are then discussed, before considering promising avenues for possible adaptations and future developments.

Model Overview

Important Assumptions. RIM assesses the impact of weed control options on ryegrass populations and on gross margins, but does not provide exact predictions. The results are trends to be evaluated in a relative manner, keeping in mind the degree of variability inherent in many of the parameters on which the model is based upon. Additionally, several assumptions behind RIM include a number of simplifications and exclusions:

- RIM is a deterministic model. Calculations modify yearly or field averages, without catering for annual or seasonal variations, environmental fluctuations, or spatial heterogeneity (climate, rainfall patterns, control efficacies, soil, germination, biomass growth, animal behavior, etc.). Default values are chosen to represent an average situation for the target area.
- Results are based on "long-term average weed-free grain yields," specified by the user. Each year, the final grain yields are obtained from the average yield that is to be expected for the modelled field in an average season, when all other weeds are controlled. Biophysical mechanisms are not modelled; agronomic consequences are limited to predetermined rotational effects such as yield benefits or fertilizer savings.
- Crops and pastures are generic. Enterprises do not represent a given cultivar or species but rather a type of enterprise, defined by adjustable characteristics and management specifics.
- Net present values are the basis of long-term economic returns, which integrate some inflation measures.
- Weed genetics and the mechanisms of herbicide resistance evolution are not modelled. Instead, the user decides whether a herbicide is effective or not. A situation with partial ryegrass resistance can thus be represented by altering the control efficacy of herbicides.

Inputs and Outputs. The inputs required by RIM mainly consist of (1) characterizing the modelled field and context (e.g., average long-term yields, starting ryegrass density, establishment costs), (2) specifying the expected impact of various farming practices (e.g. ryegrass control, yield benefits, or penalties), and (3) building a 10-year cropping sequence and defining the management options that impact ryegrass for each year. This is done by building a strategy, choosing among seven enterprise types and 44 management options, including ryegrass management practices at preseeding, in-crop, and postcrop maturity. With these information and choices, RIM provides the following outputs:

- Ryegrass plant and seed numbers (m^{-2}), calculated at seven time points during the year.
- Yield loss (%) by ryegrass competition added to other yield benefits and penalties (%) from various practices, calculated at the end of each cropping year.
- Economic returns ($ ha^{-1}), calculated both at the end of each year (gross margins) and for the 10-yr period (averaged net present value).

For screenshots of the program, illustrations of results, and how to use RIM, the reader is referred to the extensive examples provided in Lacoste and Powles (2014).

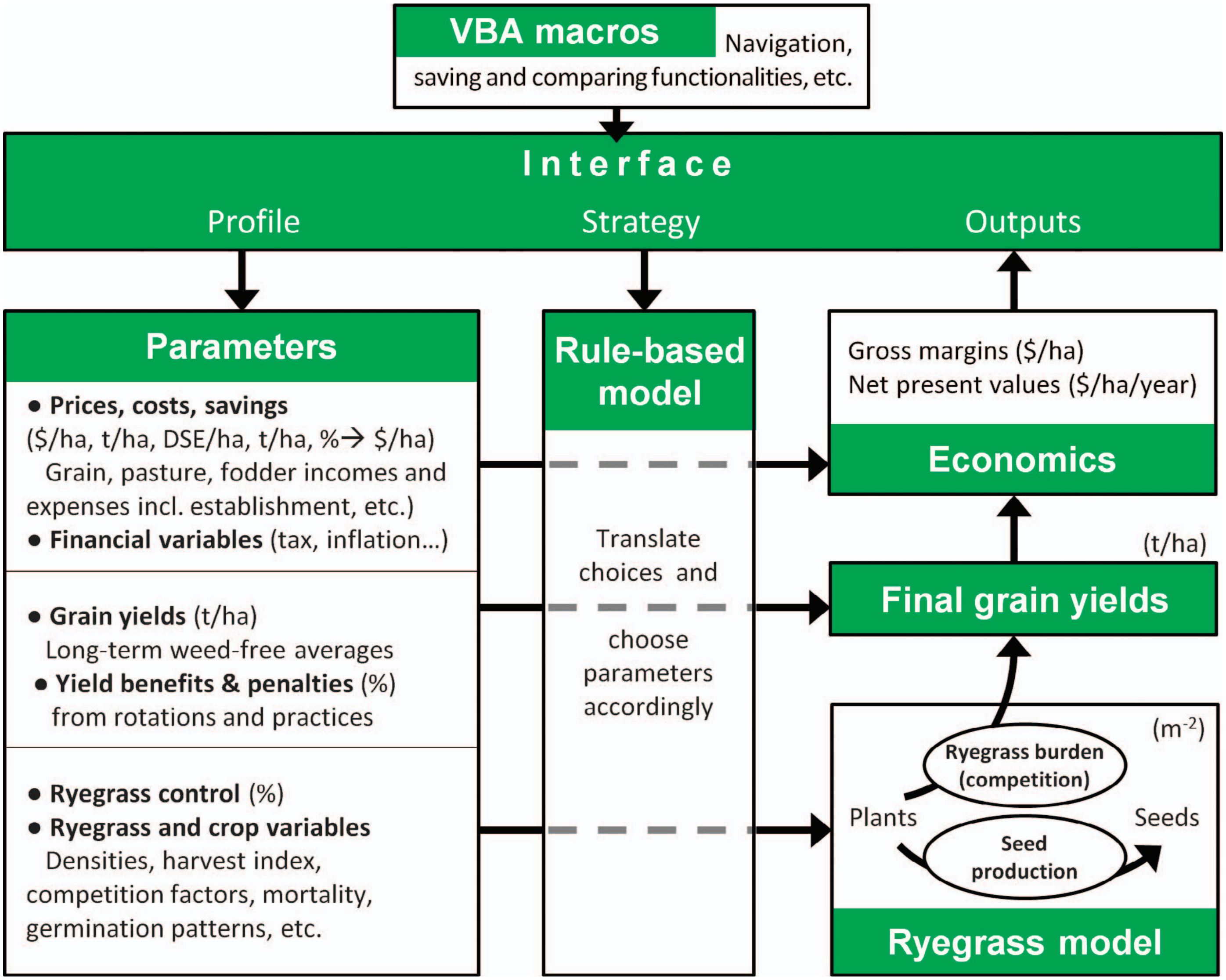

Figure 1. Structure and relationships of the main RIM components. (Color for this figure is available in the online version of this paper.)

Main Components. RIM was implemented in Microsoft Excel® for Microsoft Windows®. The program comprises several components, presented in Figure 1 along with their major interactions. Figure 2 lays out the contents of the Excel spreadsheets that constitute these components.

- The user interface was designed as a straightforward three-step progression: (1) Define Field, (2) Build Strategy, and (3) Compare Results. Additional optional panels allow users to further customize settings or export results.
- A VBA framework (Visual Basic for Applications) delivers a software-like behavior to the ensemble and provides the interface with various functionalities such as navigation, saving inputs, exporting outputs, etc.
- A population dynamic model encompasses several aspects of the ryegrass life cycle including germination, plant and seed survival, intra- and interspecific competition, seed production, and seedbank persistence.
- A rule-based model links all the components, attributing the proper set of parameters depending on which management practices are specified by the user.

Model Implementation

Two main layers can be distinguished that make up RIM, the interface and the background, which are complemented by macros.

Interface: Role and Structure, User Inputs, and Parameters. The two main tasks of the interface are to integrate the user's information and choices, and to display the corresponding

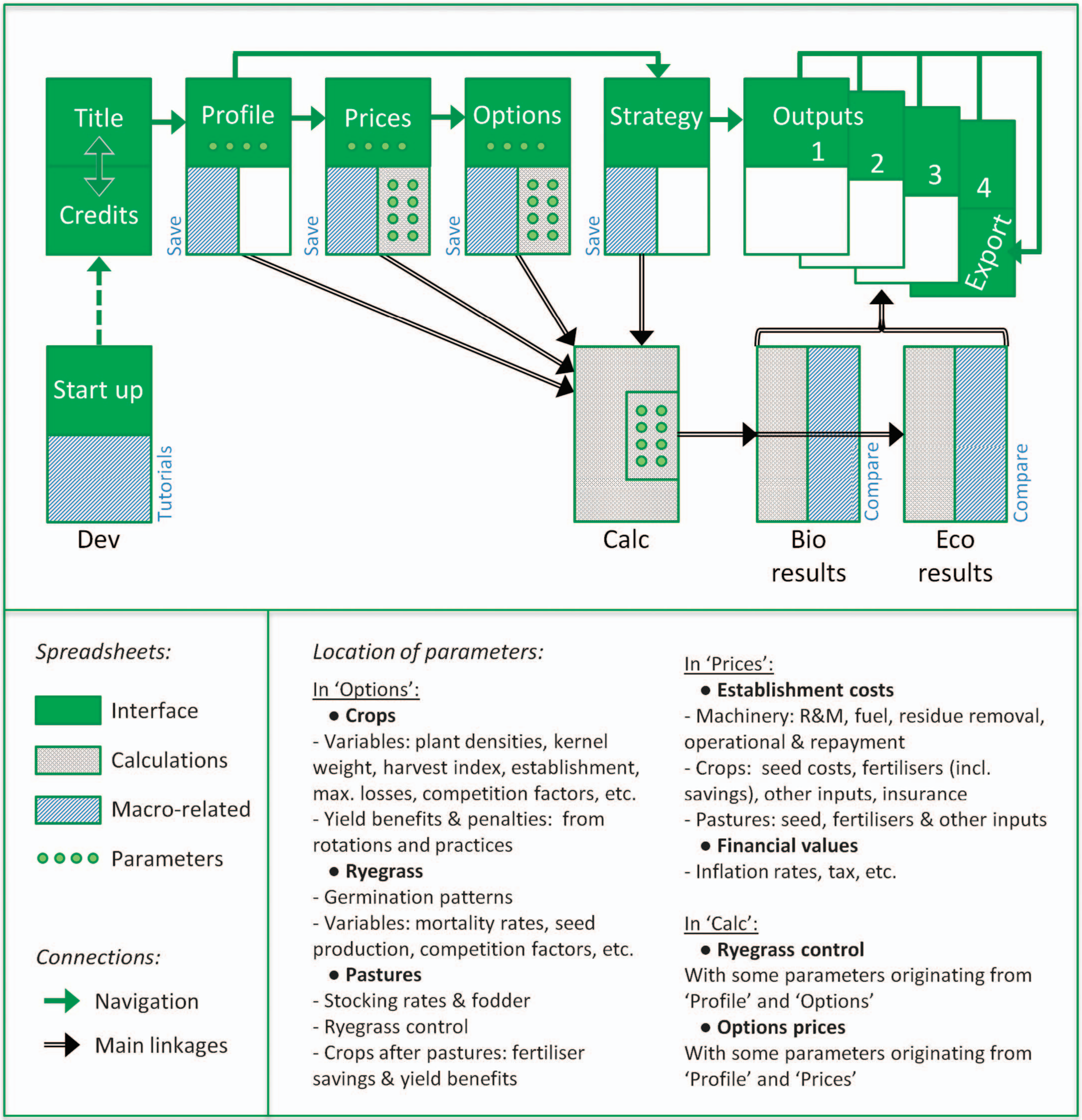

Figure 2. RIM implementation map: composition and linkages of Excel spreadsheets. The ryegrass population model is located in the "Bio results" spreadsheet, whereas most of the rule-based model is in "Calc." The Visual Basic Application (VBA) macros are coded in an interface parallel to the spreadsheets (the VBE, Visual Basic Editor). (Color for this figure is available in the online version of this paper.)

simulated results. The interface also performs specific functions such as saving and loading inputs, as well as comparing and exporting outputs, provides instructions, help, contacts for technical support, and further information. The interface is made up of a series of spreadsheets referred to as "pages" or "panels," partially protected from changes and formatted according to a consistent design that constitutes the visual identity of the software.

The user starts by customizing a profile (field and context), which involves either modifying the preloaded default settings or starting a new profile. Only essential information is needed, including the long-term average yields, herbicide efficacy, and prices for grain, fodder, sheep, herbicides, and any user-defined options. One of the optional panels (''More Options'') allows users to input further detail for some practices, including setting the efficacy of additional ryegrass control methods, while the other panel (''More Prices'') allows users to enter establishment costs and machinery repayments. Even though 600 parameters are integrated into RIM, only around 50 are featured in the interface (about 100 when considering the two optional pages).

To ensure fast customization within the limited screen space, reduced user input is achieved through several means:

- Hidden parameters: parameters deemed stable or requiring expert knowledge to modify are only located in the background, hidden from the interface. In particular, this concerns biological parameters such as competiveness indicators, germination patterns, and other ryegrass variables.
- Combinations: whenever possible, inputs are combined under a single label (e.g. ''additional inputs''), or intermediary calculations skipped (e.g. fertilizer and herbicide costs are asked directly instead of detailing rates and unit prices, etc.). A VBA macro calls a calculator to help the user when such calculations are required.
- Ratios: one parameter set in the interface is often linked to several others in the background by ratio tables. For instance, machinery costs were made proportional to the harvester's, while fertilizer savings the first year after a legume are halved the next year. Similarly, the user sets pasture production levels for clover only, these values being then used for all other pastures types according to specific proportionalities defined in the background. This approach was also used to evaluate the cost of nutrient removal for harvest options, the user being asked to evaluate a basic cost in terms of input compensation following hay cut or residue baling, which is linked to a reference table with nominal values.
- Links: whenever possible, links were made between different parameters. For instance, the incorporation cost of green manuring was assumed to be similar enough to the cost of seedbank cultivation (full-cut establishment), while the costs of spring sprays where made relative to the average cost of nonselective herbicides specified by the user. The same principle was used to link certain barley parameters to wheat, corrected with ratios when necessary (e.g., fertilizer requirements, yield boosts).

After customizing settings, the user accesses the core panel of RIM (step 2) where the ''strategy table'' allows a 10-yr rotation to be built and outputs to be produced. When incompatibilities exist between enterprises and management options, Excel's automatic formatting prevents inputs from the users, or warning error messages appear. Selecting an option in the strategy table triggers a chain of commands in the background that ultimately lead to changes in the outputs. The main outputs, ryegrass numbers, and gross margins at the end of each year are displayed at the bottom of the strategy table and as graphs, allowing visual monitoring of the effects of modifying the 10-yr rotation. Additional graphs break down information summarized in the gross margins (type of income and of weed management expenses). Two sets of results can be ''pasted'' onto the following panels for comparison. This allows comparisons on the same screen of, for instance, two different strategies with the same initial profile settings but with different management choices (or vice versa), or two completely different simulations. Comparisons produce additional outputs pertaining to ryegrass population and seedbank dynamics over the years, rotational effects and ryegrass burden on yields, and data tables on which all graphs are based. The last panel offers the user the option of exporting detailed profile settings or selected results to various file formats (to PDF, XPS, print preview, or Excel data tables). The user can then choose to start again or exit the program.

Background: The DSS Backbone, Storage Unit, and Engine Room. Unlocking RIM from the Credits/Info page gives access to the background layer. Its first function is to host most of the DSS' components, including the calculations that make up the submodels and their results, the parameters used by the models (user inputs, saved defaults, and references), and the material used by VBA macros: tutorial contents, saved information stored for later load up (strategies and profiles), and indicators that triggers various functions. These components, most of which appear as numerical tables, are connected through Excel links, formulas, and macros. A color-coded key distinguishes apart customizable parameters, fixed references, critical values, and intermediary calculations.

Table 1. RIM macros coded with Visual Basic Application (VBA).

Function	Activation	Description
Auto-entry and auto-exit	Automatic	Locks and adapts the interface to any type of screen (full screen and auto-zoom, hides toolbars, various protections, no scrolling, splash sponsors screen, saving messages, restored options on closing).
Requirements checking	Automatic	Prompts warnings if the operating system is not Microsoft Windows and if the Excel version is older than 2007.
Lock/unlock	Click on button in the Credits panel	Toggles program protection to access the background and parameters behind the interface.
Tutorial	Check tutorial box in the Title panel before starting	Prompts help screens when visiting a panel for first time. Loads the default strategy, clears the comparison function, and hides result graphs in the strategy page.
Navigation	Click buttons and RIM logo on top of panels	Changes panels forth and back or returns to title screen, as well as resetting the interface settings automatically when in lock mode.
Calculator	Click on logo	Calls the calculator to calculate herbicides rates, prices, etc.
Save/load/clear	Click on buttons	Keeps in memory up to five Profiles (including Prices and Options) and seven Strategies.
Show graphs	Click button in Strategy panel	Unhides or hides the result graphs and comparison buttons on the Strategy panel.
Comparison	Click on one of the two buttons in the Strategy panel	Freezes the current sets of results (on bottom or top-half of the screen) for each of the four types of outputs. Two sets of results can be compared.
Graph scales	Click on button	Toggles vertical axis between "auto" (shows all values) and "fixed" (hides high values but allows easier comparisons).
Exporting	Check boxes to select pages and click on buttons	Converts selected pages to PDF and/or data tables to an Excel file. Error handling includes fall back on XPS format and print preview options. File auto-naming with date and time. Page set-up necessary once only for speed-up.

The second function of the background layer is to perform the simulations. To do this, the mathematics behind the modelling are translated into a format usable by Excel through several steps. First, strategy choices are associated to codes in the "Calc" sheet (Figure 2). For instance, "0" is attributed to wheat, "2" is canola, "53" stands for a barley crop that is the second cereal after a 3-yr subclover pasture phase. No code means that a treatment was not selected and terminates the chain of command. The codes allow the model to choose the relevant parameters, directly from the interface or from the background when precalculations are required. This is done via two main types of Excel formulas, namely LOOKUP that refers to tables, and IF that follows logical steps. The latter is usually in the form "IF-THEN-OTHERWISE." Several such sequences are frequently nested in order to accommodate complex equations. The third step, which is often partly embedded with the previous one, consists of calculations. The majority are performed in "Calc," which contains most of the rule-based model, before being finalized and summarized in "Bio results" where most of the ryegrass population dynamics is simulated, and in "Eco results" for the economic calculations. Regarding the latter, repayments and long-term averages use the PMT function of Excel. Notes and in-built comments are provided to clarify the calculation linkages. The Excel functions "Trace Precedents" and "Trace Dependents" are also most useful.

VBA Macros: DSS Behavior. Some of the program features and software-like behavior come from exploiting the in-built functionalities available in the latest Excel versions, such as cell comments, drop-down lists, and the advanced formatting options of cells and shapes such as "conditional formatting" and "data validation." However, most of RIM's responses were programmed through VBA macros. The corresponding codes are located in the VBE, or Visual Basic Editor, a specific interface parallel to that of the spreadsheets. Table 1 lists the functions fulfilled by macros. Most of them are triggered by clicking on interface buttons, others are automatically prompted when opening or closing RIM. The macros were written with code compatible for the 2010, 2007, and 2003 versions of Excel

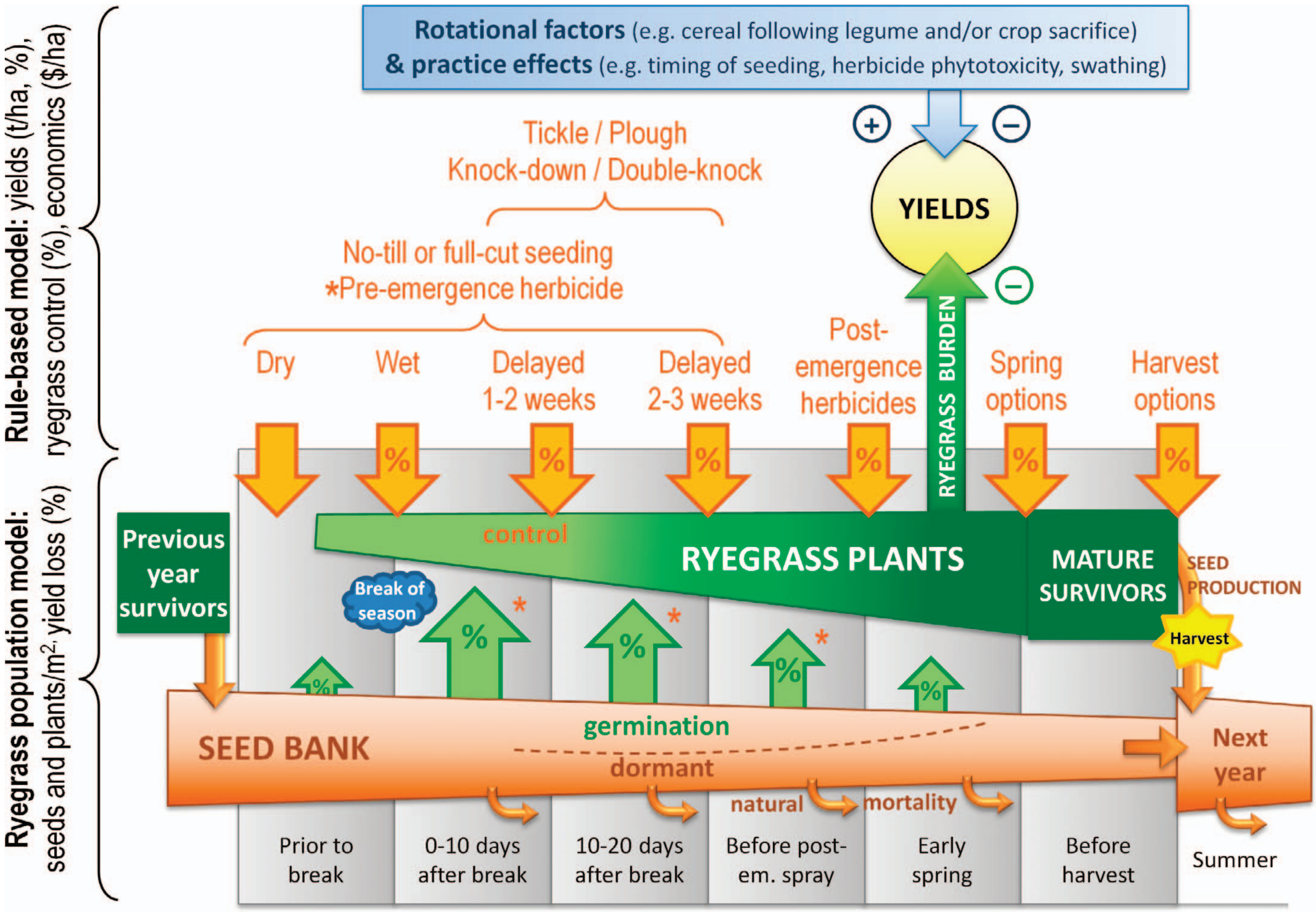

Figure 3. Main mechanisms modelled in RIM. (Color for this figure is available in the online version of this paper.)

for MS Windows®, using information available from Walkenback (2010) and from various open sources available online.

Model Mechanisms

Ryegrass Population Model. *Life Cycle.* The model formulation is based on the common iterative principle for annual weeds where the current population is equal to the product of the previous population size multiplied by rates reflecting intrinsic and extrinsic factors (Holst et al. 2007). The seedbank and plant density are updated separately several times a year rather than annually, essentially following:

- seed density at the end of each period: $N_{t+1} = g(N_t)$
- plant density at the end of each period: $N'_{t+1} = f'(N'_t) + g'(N_t)$
- model initialization: $N_1 = 50 \times N'_0$

where g, g', and f' differ for each of the seven periods that define a year, and comprise rates related to emergence, natural mortality and control (which eventually define seed dormancy or plant survival), and seed production. A time resolution shorter than one year was used to account for the interactions between the timing of practices and the ryegrass protracted emergence pattern (Figure 3). The emergence pattern, that is confounded with germination for simplicity, was modelled with different emerging rates for each time period, representing cohorts of different sizes. The model starts with N_1, the initial ryegrass seed density in the soil seedbank. Given the practical difficulties of estimating the latter compared to field scouting, the user is asked instead to enter the density of ryegrass plants that set seed the previous spring (N'_0). Not knowing the field history, each survivor is assumed to result in an average of 50 viable seeds the following year immediately prior to the break of season (20 seeds newly produced, 30 from residual seed bank).

Seed Production. Although the model does not distinguish biological stages per se (no biomass or tillering effects for instance), the phenological importance of ryegrass fecundity was recognized as critical to the infestation dynamic. Thus, seed production depends on the relative densities and competiveness of the crop and of ryegrass survivors, the time of emergence of the survivors (later germinating cohorts produce fewer seeds per plant compared to early-season escapes due to crop competition), and the sublethal effect of herbicides. Density-dependence is achieved through seed production, with a predetermined threshold for maximum seed production per ryegrass plant.

Yield Loss. The ryegrass burden on crops due to interspecific competition is calculated through a proportion of weed-free yield, which integrates relative plant densities and competitiveness of both the crop and ryegrass. The resulting grain yield loss follows a hyperbolic function plateaued by crop-specific maxima of the Cousen type (Pannell et al. 2004b).

Ryegrass seed production and crop yield loss constitute the core equations of the ryegrass population model and have been explored, among others, by Doole (2008). Adjustments to the original ryegrass model described in Pannell et al. (2004b) and Pluske et al. (2004) consisted of: initialization by seed density replaced by plant density as described above; plant and seed kill rates added to the iterative equations to account for mouldboard ploughing; proportion of weed-free yield used to calculate crop yield losses plateaued at 100% to avoid higher numbers in the case of very low ryegrass densities; translation of ryegrass biomass into hay yield deleted; sublethal effect of nonselective herbicides on ryegrass fecundity added for late-season application of nonselective herbicides; values for maximum crop yield losses and ryegrass germination pattern adjusted.

Crops and Pastures. The 10-yr land-use rotation (or sequence) can be built using seven enterprise options: two cereal crops, an oilseed crop, a legume crop, two improved pastures, and a volunteer pasture (resulting from volunteers from the existing seedbank), which can also be managed as a chemical fallow. Default crops and pastures were chosen to represent the dominant enterprises of the target region, as well as to offer contrasted responses in terms of production levels and ryegrass impacts. For instance, the two cereals differ in terms of yield average, grain prices, levels of competiveness with ryegrass, and maximum yield loss, whereas the two improved pasture types offer a choice between a robust, reliable pasture versus a more productive yet more fragile option. Unlike crops, the pasture outputs are not ryegrass-dependent: responses to grazing and cutting are specified by the user, but are not impacted by ryegrass competition. During a pasture phase (i.e. when grown continuously), stocking rates and ryegrass control levels increase before reaching a maximum after 3 years to reflect the establishment phase. Besides production levels, ryegrass competitiveness or control, the enterprises are defined by their establishment costs and by their impact on following crop(s) in terms of yield benefits (break effect), yield penalties (diseases), or nutrient requirements. Regarding the latter, input savings follow nitrogen fixation from legumes, which for simplicity are assumed to be similar for a legume crop and a well-established legume-based pasture (e.g., grown for at least 3 years consecutively).

Also for simplicity, incompatibilities between enterprises and management options were kept to a minimum, but some were deemed unavoidable. For instance, seeding is not always required for pastures (e.g. volunteer and self-seeded pastures), crops cannot be grazed, and some harvest options are only available for crops. Other restrictions prevent two oilseed or legume crops being grown consequently because of high disease risks, and one enterprise cannot be run for more than five times in the 10-yr sequence. The latter acts as a reminder for the important assumption that the average yields specified by the user have to reflect a sustainable, long-term situation, i.e., featuring some diversity in the farming system.

Management Options. Field operations and control options affect ryegrass infestation levels by varying crop density and competitiveness (rotations and seeding rate), modifying the germination pattern (soil preparation and crop establishment), reducing the number of survivors reaching maturity (modelled as a proportional kill of emerged plants) and their fecundity, and depleting the seedbank (soil preparation and harvest options). Options also incur changes in production costs (fertilizer savings, machinery repayments, environmental costs), as well as yield advantages or penalties that are additive to the ryegrass burden and rotational effects.

Seeding Times and Germination Patterns. The model is constructed for the Mediterranean type of climate of Australian southern grainbelt in which there is a hot, dry summer and an autumn–winter rainfed growing season. The break of season is defined as the first autumn rains sufficient to wet the soil and allow acceptable crop germination after the summer drought. Deciding when to seed the crop in relation to the autumn rainfall break determines when a number of field operations will occur in relation to the sequential emergence of ryegrass (first four periods of the model; Figure 3) with several critical consequences:

- The later a treatment is applied, the more ryegrass will have germinated, resulting in greater numbers of ryegrass plants controlled and greater depletion of the seedbank;
- However, early germinated ryegrass that may survive produce more seeds (competitive advantage), justifying action to control the first few cohorts.
- Besides a number of agronomic consequences (such as yield penalty due to a shortened growing season if seeding is delayed), the timing of seeding also affects the cost and availability of some combinations of options. For instance, dry seeding incurs a cost to account for increased erosion risk and, for the same reason, prohibits any prior soil preparation. Waiting for sufficient rain to allow germination and emergence of ryegrass can delay crop seeding but allows the effective application of nonselective herbicides, providing effective control of the first emergence flush of ryegrass.

Establishment Options. The default establishment system is based on a one-pass seeding operation incurring minimal soil disturbance (no-tillage), a practice that has dominated the region represented in the model for the past 20 years (Llewellyn et al. 2012). Two options are modelled, which essentially differ in cost, amount of ryegrass controlled, and impact on the ryegrass germination pattern. The germination pattern is also impacted by prior soil preparation, which in rare cases may include a shallow cultivation (tickle) or soil inversion (mouldboard plough). Shallow cultivation only stimulates the germination of ryegrass without control, whereas moulboard ploughing is a radical option targeting both ryegrass plants and seedbank, almost resetting the ryegrass population size to zero. For simplicity, given the relatively short life span of ryegrass seeds (Goggin et al. 2012), neither differential seed redistribution throughout the soil profile nor cultivation depths were modelled. However, the possibility of returning buried viable seeds to the surface was taken into account with a lower proportion of kill when the duration between two ploughs was not sufficient to allow for natural mortality to fully occur (i.e., 3 yr). This also reflects the fact that mouldboard ploughing in no-till systems is a costly, tactical tool for which the main justification lies in removing subsoil constraints. This was modelled via a one-off permanent yield benefit for all crops.

Herbicide Options. Three types of herbicides are included in the model: three preseeding nonselective, five pre-emergence selective applied at seeding, and five postemergence selective (in-crop sprays). Default settings are provided; however, all 13 herbicide options are entirely customizable by the user who can specify denomination (e.g., mode of action, active ingredient(s), brand, tank mix, rate), enterprise compatibility, cost per hectare, and efficacy (% ryegrass control). The phytotoxic effect of selective herbicides on crops was modelled with an average yield penalty for each application. To simulate multiple applications of postemergence herbicides, the user can select the same herbicide up to three times—having previously specified the cost and efficacy of the herbicide option.

Spring Options. This period covers operations occurring before ryegrass seed maturation (i.e., from around grain filling through to early maturity of the crop). The control options include grazing, crop/pasture-topping, and swathing. All options are modelled as a proportion of ryegrass kill, with survivors of nonselective herbicides late applications also causing reduced fertility and seed viability.

Several crop sacrifice options are also available. Crop sacrifice is a tactical decision resulting in losing the crop or reducing the pasture income for the benefit of achieving a complete seasonal ryegrass kill for no seed production. To ensure total control, those tactics are usually followed by a high rate spray of a nonselective herbicide targeting any survivors. Crop sacrifice is particularly justified in situations where meagre yields cannot justify harvest costs, or where ryegrass numbers are very high. Income may be salvaged in the case of hay or silage production, although no premium prices can be expected for fodder contaminated with ryegrass and trade-offs are to be made with grazing intensity, especially for fragile pastures. In the case of green manuring, depending whether the operation is opportunistic or planned in advance, costs such as crop insurance and input savings can be specified. Another advantage is potential yield benefit for the following crop, if the sacrificed crop is terminated early enough and biomass is retained on site to save moisture and nutrients.

Harvest Options. Burning field residues reduces the input of weed seeds into the seedbank (modelled as a proportional seed loss). However, results are highly variable. Additionally, the practice presents high risks of losing control of the fire and removes significant amounts of biomass that potentially decreases the quantity of nutrients available for future crops. The loss of soil residue cover also increases erosion risks. Harvest weed seed control targets seeds during harvest more efficiently through techniques involving specialized equipment (Walsh et al. 2013). Although some level of nutrient loss still occurs in most cases, considerable amounts of residues are retained on site. The impact scope of residue removal on future crops is accounted for through nominal and relative values only, related to the corresponding added fertilizer amounts that the users deem adequate for their system. These nominal values were set between the Harrington Seed Destructor (no removal) and whole-field burning (maximum removal). Although different techniques target different fractions of residues (chaff, or chaff and straw) with different methods (high intensity burn, export, crush, running over, and herbicide spray), the amounts of ryegrass seed removed are similar (Walsh et al. 2013), with management and environmental conditions such as wind strength or biomass amounts playing a greater role in the variation observed.

Economics. Each year, gross margin per hectare is calculated from the final grain yield, pasture, or fodder incomes, minus the different variable costs associated with each operation. Long-term calculations compute net present values for machinery repayments and for the 10-yr "average" economic return. The economic calculations integrate bank interest, inflation rate, tax, potential yield increases, and discounting (PMT function of Excel). Fixed costs, including capital costs, are not included since RIM considers an average farm that is already equipped with essential machinery such as seeding equipment, harvester, and sprayer. Important exceptions are harvest weed seed control techniques, involving specialist machinery which repayment costs need to be accounted for in order to compare them with other weed management options. In the case of chaff-tramlining, where the weed seeds stay on site but germination is prevented by repeated compaction on tramlines and localized herbicide applications, the implementation costs of the guidance system is not accounted for since it is assumed that the main reason for its adoption is not weed control (near zero opportunity cost), but rather timeliness and ease of operations, a decision made at the whole-farm scale. Only the extra cost of using the system for weed control such as herbicide spray is therefore accounted for.

The revised seven enterprises and 44 management options are further detailed in Lacoste (2014), with default parameter values and costs set for an average farm of 2000 ha in 2012. A concise and illustrated version for end-users is also available (Lacoste 2013).

Model Strengths

Reasserting the Modelling Objectives: RIM Updated as a DSS. RIM was upgraded primarily for use as a DSS, i.e., as a tool aiming to aid complex managerial decisions. The software fulfills this objective by allowing users to assess the impacts of various management strategies in a relative manner. However, RIM only deals with a partial aspect of the herbicide resistance problem, and does not replace expert judgment and direct observations. As such, it should be remembered that RIM is not a forecast model aiming to provide exact predictions. RIM is built with compromises, with accessibility taking precedence over representativeness, simplicity over accuracy, and modelling efficiency over complexity.

Focus on Critical Ryegrass Characteristics. The objective of RIM was not to simulate complex biophysical and environmental mechanisms, but to monitor the impact of production and management practices on ryegrass populations within farming systems dominated by annual grain crops. Consequently, the rule-based model remained simple and the ryegrass model was not further complexified. The choice of not venturing into additional biological intricacies was justified by the existing well detailed ryegrass model, already deemed advanced at the release of the 2004 version due to its integration of elaborated competition dynamics (Holst et al. 2007).

More generally, the strengths of the population dynamic model lie in its focus on biological characteristics, acknowledged as most critical to ryegrass management. First among them, the naturally high fecundity of ryegrass, influenced by both intrinsic and extrinsic factors (Goggin et al. 2012; Gonzalez-Andujar and Fernandez-Quintanilla 2004; Norsworthy et al. 2012), that was modelled via a core fecundity equation completed with the latest information. It should be noted that although biomass has been used to quantify the effect of crop competition on ryegrass (Walsh and Powles 2007), its alteration was not modelled considering that seasonal build up and mobilization of reserves are less critical for annual weeds (Holst et al. 2007). Other aspects of the ryegrass lifecycle were considered to have critical management implications. These included seed losses and dormancy of the residual seedbank (Goggin et al. 2012; Gonzalez-Andujar and Fernandez-Quintanilla 2004). The seedling emergence pattern is detailed as well, since it informs the timing of control operations with regards to ryegrass life stages and the necessity of controlling both early and late emerging cohorts. Late-emerging weeds cause less interference with the crop and experience lower reproductive success than early emerging cohorts, yet seed production from late season escapees must be considered when developing effective resistance management strategies (Bagavathiannan and Norsworthy 2012; Norsworthy et al. 2012; Walsh and Powles 2007).

Comparatively, biotic factors and pollen movements are considered less important, justifying the decision to omit pest and disease population dynamics, as well as complex mechanisms of seed dispersal. However, there is increasing evidence that ryegrass-contaminated grain seed can play a significant role in propagating resistant ryegrass (Michael et al. 2010). No immigration component was modelled; instead, ryegrass densities never reach absolute zero. This can demonstrate that even an apparently empty soil seedbank can rapidly result in infestation due to external contamination.

Lastly, assuming that all other weeds are controlled via a cost that is specifiable may seem too simplistic, or unrealistic. In many cases, interweed interactions and associated control costs are not to be underestimated. However, the prior development of a multispecies RIM model that combined ryegrass and wild radish showed that, despite results being significantly impacted when considering several weeds, the dominant weed species drives the economics of the system (Monjardino et al. 2003, 2005). Since ryegrass is the main herbicide resistance challenge of the modelled system, a sole focus on this dominant weed species was deemed reasonable for this situation.

Model Limitations

Highly Variable Parameters. A major difficulty when modelling ryegrass population dynamics is that the most important characteristics are also those which vary the most (Doole 2008). For instance, Goggin et al. (2012) reported that a reduction in ryegrass seed fertility due to competition of the maternal plants ranges from 50 to 90%, while Steadman et al. (2006) demonstrated how both seed production and seed viability are dependent on rate and timing of late-season nonselective herbicides. Gonzalez-Andujar and Fernandez-Quintanilla (2004) studied sites where very large fecundity differences were found, with values ranging from 7 to 1,250 seeds per plant. Similar to this is the unpredictability of ryegrass emergence timing and extent, because of wide variation in dormancy resulting from the interaction of genetics, environment, and other factors such as management history (Goggin et al. 2012). Examples include ryegrass establishment ranging from 25 to 55% in South Australia (Chauhan et al. 2007) and germination levels ranging from 0 to 70% across the Western Australian grainbelt with 20 to 80% at individual farm-level (Goggin et al. 2012).

Need for Further Validation. In spite of such inherent variations, the simulated low and medium ranges of ryegrass plant densities, i.e., the final biological outputs most important for management, were validated across 3 sites over 5 years (Draper and Roy 2002). Results also matched the trends of long-term field observations made across the Western Australian grainbelt (Walsh et al. 2013). Nevertheless, beyond one local validation and anecdotal evidence, further corroboration is required to test the robustness of RIM (Hochman and Carberry 2011). Controlled experiments in research stations are a valuable start (e.g. Gonzalez-Andujar et al. 2011). However, in order to be realistic, such validation should also be conducted under farming conditions, ideally on the long-term and over a vast area of the target region. In addition to ryegrass densities, yields should also be recorded, since the model's economic outputs are largely driven by the long-term average yields and modelled yield losses. Validation would allow a test of whether the simplifications and trade-offs chosen were justified, particularly regarding the rule-based agronomic model. Specifically, it should be verified whether the relative impacts of the various control techniques are well represented, in spite of the inherent variation to be found in an area as large and diverse as the Australian southern grainbelt. Additionally, and despite the argument that only weather-driven models can be validated (Holst et al. 2007), a large validation would also indicate to what extent ignoring the environment is justified. Although assuming average seasons is common in weed management modelling (e.g., Lawes and Renton 2010), not taking into account any changes in growth could have important consequences for intra- and interspecific competiveness (Holst et al. 2007). The question is particularly legitimate in many regions of the Australian southern grainbelt where high intra- and interyear rainfall variations exist. Without integrating stochastic variability or even renouncing the deterministic approach of RIM, results could indicate whether outputs would benefit from adding mechanisms that could account for extreme years.

Wider Application

The most likely future development of RIM would be the use of the current version as a template for other annual weed species. Two examples include the adaptation of the current RIM version to brome grass for Australia (R. Llewellyn, personal communication), and to palmer amaranth in the cotton, corn, and soybean production systems of the mid-southern U.S. crops (Bagavathiannan et al. 2014). The task has been made easier during model reconstruction. Adaptation would be easiest for annual weeds sharing characteristics similar to ryegrass, i.e., dominant, prolific weed with relatively short seed dormancy and longevity. In some cases, specific additions may be required such as dispersal, biomass, immigration, some consideration for biotic factors, or additional life history characteristics and management factors. In agricultural systems where cropping occurs both in winter and summer, a factor to cater for the impact of the alternate cropping season may be a useful addition (for instance the impact of autumn operations on summer germination patterns). Previous sensitivity analysis conducted on the current population dynamic model indicates that the biological weed parameters to which the most attention should be dedicated to, besides the initial weed seed bank, are crop-weed competiveness, emergence, fertility, and maximum seed production; then again, economic variables such as grain prices may prove to hold more importance to the final outputs than biological parameters (Lacoste and Powles 2014 and references within). Developers should thus remain wary of complexifying RIM much further. The increased modelling effort required to represent secondary mechanisms may overstep RIM's level of detail, for little effect on the message delivered. To this end, other advanced mathematical models are available for a variety of weed species (e.g., Canner et al. 2009).

Future Modelling Directions

Beyond redefining the model's base assumptions, possible paths to expand the current RIM version, or its adaptations, thus mostly include adding options and functionalities. However, future developers should avoid partial updates which result in "spaghetti" programming, i.e., bits of modelling often complicating coding, holding redundancies, hiding errors, and requiring increased future effort in detangling (Walkenback 2010).

Additional Options. Enterprises could be added, but may come at the cost of simplifying the existing rotational system. Adding options and field operations within the existing system would usually be a simpler avenue. Marginal options and practices of interest include wiper technology, germination stimulant (Goggin and Powles 2014), encouraged ant predation, use of animal selective eating habits, residue grazing, summer crops, and cover cropping (Goggin et al. 2012; Norsworthy et al. 2012). The latter options would require knowledge of the effect of retaining crop residues on germination patterns because of altered exposure and moisture retention. The same questions apply to the long-term effects of tactical mouldboard ploughing in no-till systems. Regarding establishment, disc-seeding would represent a valuable no-till option. The resulting minimal soil disturbance would require adjusting both the ryegrass germination and the efficacy of some pre-emergent herbicides that are conditioned by soil incorporation (Chauhan et al. 2006, 2007).

Additional Functionalities. Another avenue would be to improve profile customization. For instance, a simple herbicide performance component could be added to simulate tolerance to herbicides or suboptimal spraying conditions. Similarly, the user could be given the option of manipulating the competitiveness of crops so as to represent given cultivars with more competitive genotypes. The user could also customize the name and other aspects of the generic crop and pastures in the interface, without having to go into the background calculations.

Farmers have a high interest in investigating risky or uncertain events (Hayman 2004; Hochman and Carberry 2011). Adding stochastic elements would require too much development effort and defeat the fact that RIM purposefully ignores the environment and weather forecast aspects. Nevertheless, a simple tool could be added in RIM to allow users to evaluate the impact of nonaverage years. For instance a ''drought'' option in the strategy table could vary crop yields, ryegrass competitiveness, seedling mortality and fertility, while drastically modifying the effects of tactical decisions for the given year. Another path to explore could be to develop the sensitivity analysis function of RIM: an additional output page could be developed allowing to assess the effects of some parameter changes on long-term profitability.

Another functionality of interest could be a diversity indicator. Currently, the budget allocation segregates weed control methods into chemical, mechanical, competition, and user-defined types. This provides an appraisal of the diversity of practices implemented, albeit economically biased since a number of mechanical methods are much more expensive than most nonselective herbicides, irrespective of control levels. Furthermore, cultural aspects such as rotational diversity are not taken into account. The principle could be expanded to more accurately evaluate the extent to which the user follows the recommendation of diversifying practices so as to provide more sustainable weed control strategies.

In contrast, developing an actual indicator for the risk of evolving herbicide resistance would require much further modelling effort and the reintroduction of herbicide modes of actions, which were purposefully removed (see Lacoste and Powles 2014). Moreover, several such indicators already exist, such as those described in Stanton et al. (2008) and in Werth et al. (2011) for glyphosate use in Australia.

Next Step: Evaluation. In spite of the interest that some of those development paths may raise, further investment in RIM as a DSS should be prioritized to validation and evaluation. The first would complement previous sensitivity analysis and help identify which aspects of the rule-based model should be expanded, while the second would help assess which development efforts would be most valued by the end-users. So far RIM has benefited from the inputs of economists, weed biologists, and agronomists. New functionalities could be identified by communication experts.

The rise of herbicide resistance weeds is an increasing challenge to the agricultural industry, in Australia and worldwide. Consequently, communication and extension efforts to advocate sustainable practices are increasingly needed.

RIM is a unique tool of considerable potential to contribute to this endeavor. For this reason, RIM's underlying modelling was upgraded with the objective of minimizing future investments in further developments. Modifying or adapting RIM was made more straightforward than for most simulators, and therefore accessible to most, with minimal training requirements. The main challenges reside in clarifying the assumptions the model relies upon, and deciding to which level of detail the biological and agronomic mechanisms have to be modelled. The decision rule on such matter is that any modelling effort should be subordinated to the end-use of RIM as a decision support tool, not the opposite. This implies that modelers should first verify whether modifications alter recommendations. Then, care should be dedicated to assess how the delivered messages are perceived by the users. Therefore, future RIM developers should remember that beyond mathematical and coding efforts, modelling a DSS also implies integrating user-centered and postdevelopment considerations.

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