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Source: Weed Technology, 28(4) : 703-720

Published By: Weed Science Society of America

URL: https://doi.org/10.1614/WT-D-14-00020.1

*Weed Technology* 2014 28:703–720

# Upgrading the RIM Model for Improved Support of Integrated Weed Management Extension Efforts in Cropping Systems

Myrtille Lacoste and Stephen Powles*

RIM, or "Ryegrass Integrated Management," is a user-friendly weed management software that integrates long-term economics. As a model-based decision support system, RIM enables users to easily build 10-year cropping scenarios and evaluate the impacts of management choices on annual rigid ryegrass populations and long-term profitability. Best used in a workshop format to enable learning through interactions, RIM can provide insights for the sustainable management of ryegrass through "what-if" scenarios in regions facing herbicide resistance issues. The upgrade of RIM is presented, with changes justified from an end-user perspective. The implementation of the model in a new, intuitive software format is presented, as well as the revision, update, and documentation of over 40 management options. Enterprises, establishment systems, and control options were redefined to represent current practices, with the notable inclusion of customizable herbicide options and techniques for weed seed control at harvest. Several examples of how RIM can be used with farmers to demonstrate the benefits of adopting recommended practices for managing or delaying the onset of herbicide resistance are presented. Originally designed for the dryland broadacre systems of the Australian southern grainbelt, RIM's underlying modeling was restructured to facilitate future updates and adaptation to other weed species and cropping regions.

**Nomenclature**: Annual rigid ryegrass, *Lolium rigidum* Gaud.
**Key words**: Adoption, agriculture, bioeconomics, decision support system, farmers, simulation.

RIM (por sus siglas en inglés) o "Manejo Integrado de *Lolium rigidum*" es un programa amigable con el usuario para el manejo de malezas que integra factores económicos en el largo plazo. Como un sistema de apoyo para la toma de decisiones basado en un modelo, RIM permite a los usuarios construir escenarios de producción de cultivos de 10 años de duración y evaluar el impacto de las decisiones de manejo en las poblaciones de *L. rigidum* y en la rentabilidad a largo plazo. Al usarse en un formato de taller que facilite el aprendizaje mediante interacciones, RIM puede brindar una visión para el manejo sostenible de *L. rigidum* a través de escenarios "y qué pasa si" en regiones con problemas de resistencia a herbicidas. Aquí se presenta una actualización de RIM con cambios justificados desde una perspectiva del usuario final. Se presenta la implementación del modelo en un formato nuevo e intuitivo, además de la revisión, actualización y documentación de 40 opciones de manejo. Proyectos productivos, sistemas de establecimiento, y las opciones de control fueron redefinidas para representar prácticas actuales, con la notable inclusión de opciones de herbicidas personalizables para el control de semillas de malezas durante la cosecha. Adicionalmente, se presentan varios ejemplos de cómo se puede usar RIM con los productores para demostrar los beneficios de la adopción de prácticas recomendadas para el manejo o el atraso en la aparición de resistencia a herbicidas. Aunque originalmente se diseñó para sistemas de producción extensiva sin riego de la zona productora de granos del sur de Australia, el modelaje en el que se basa RIM fue estructurado para facilitar actualizaciones futuras y la adaptación a otras especies de malezas y otras regiones agrícolas.

RIM, or 'Ryegrass Integrated Management', is a computer-based bioeconomic decision support system (DSS) originally designed to provide insights into the sustainable management of ryegrass in Australian cropping systems and support the delivery of key herbicide resistance extension messages. RIM was developed during the 1990s for the Australian southern grainbelt (Pannell et al. 2004) where ryegrass is the most common and economically important weed in broadacre cropping (Borger et al. 2012; Boutsalis et al. 2012; Doole 2008; Jones et al. 2005).

In the Australian southern grainbelt (Figure 1), approximately 25 million ha (ABARES 2010) are devoted each year to rainfed winter-grown crops (wheat-dominated). No-tillage is widely adopted in these broadacre, extensive cropping systems that heavily rely on herbicides to control weeds

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DOI: 10.1614/WT-D-14-00020.1

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Figure 1. Australian southern grainbelt. Source: ABARES 2010.

(Llewellyn et al. 2012). Within these areas, annual ryegrass is ubiquitous and has become a major problem due to widespread evolution of resistance for many herbicides (Table 1). Herbicide-resistant ryegrass threatens the productivity and sustainability of current farming systems (Doole 2008). Recommendations to mitigate the evolution of herbicide resistance emphasize the critical importance of both keeping the ryegrass seedbank low, and diversifying the farming system through rotating enterprises, control techniques, herbicide mechanism of action, etc. (Goggin et al. 2012; Norsworthy et al. 2012; Walsh and Powles 2014).

Through simulations, RIM allows users to test the impact of control methods on ryegrass numbers and crop profitability. Using a "what-if" principle (no optimization), RIM enables users to build 10-year scenarios and observe the effects of varying levels of ryegrass plant and seed densities on field crop yields and economics on a per hectare basis. Simulations are based on average cropping seasons without spatial or temporal fluctuations. Seven enterprises and over 40 management options are available to build control strategies, allowing choice among customizable options including chemical (herbicides), mechanical (burying, cultivating, cutting, catching, burning), and cultural techniques (increased competition through high seeding rates, crop competitiveness), as well as grazing pressure. These field operations and control options influence ryegrass seed germination patterns, plant and seed survival and proliferation, and crop yield loss through ryegrass competition. The 10-year scenario also allows for the incorporation of long-term rotational effects (yield advantages or penalties, fertilizer savings), seedbank carry-over, and environmental costs (Pannell et al. 2004).

RIM has been used as both a research and extension tool, supporting efforts in combating herbicide resistance with a diverse range of control methods known as Integrated Weed Management (IWM). RIM workshops, conducted from 1999 to 2006, were influential in changing farmers' perceptions and practices in Australia via what was at the time a novel medium (Doole 2008; Llewellyn et al. 2005; Llewellyn and Pannell 2009). Unfortunately,

Table 1. Incidence of resistant annual rigid ryegrass populations across the Australian southern grainbelt.

| State (winter cereal cropping regions) | Survey period | Number of fields sampled | Average percentage of resistant populations per herbicide group, U.S./Australian classification (in parentheses: number of populations tested) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 1/A | 2/B | 5/C | 3/D | 22/L | 9/M |
| Western Australia[a] | 2010 | 365 | 80 (3) | 98 (1) | 2 (1) | 27 (1) | 0 (1) | 7 (1) |
| New South Wales[a] | 2010 | 124 | 41 (4) | 43 (2) | 0 (1) | 0 (1) | n.t. | 0 (1) |
| South Australia[b] | 2007–2009 | 611 | 38 (4) | 73 (1) | n.t.[c] | 25 (1) | n.t. | n.t. |
| Victoria[b] | 2005–2009 | 928 | 22 (4) | 21 (1) | n.t. | 1 (1) | n.t. | n.t. |
| New South Wales[a] | 2007 | 137 | 48 (3) | 68 (2) | 1 (1) | 6 (1) | n.t. | 1 (1) |

[a] Resistant and developing resistance. A population is defined as "resistant" when more than 20% of plants survive the herbicide application and as "developing resistance" when survival range is 1 to 20%. Sources: Broster et al. 2011, 2013; Boutsalis et al. 2012; Owen et al. 2014.

[b] Resistant only.

[c] Abbreviation: n.t., not tested.

active delivery and maintenance of RIM ceased due to a lack of resources since 2006.

Almost a decade later, RIM is still used as a research tool in Australia, Spain, and the Philippines, whereas the model educational applications are primarily limited to university teaching programs in Australia, the U.K., and Canada. However, some consultants still run RIM workshops with farmers to raise awareness about herbicide resistance issues (Lacoste et al. 2013). RIM remains a useful medium to demonstrate the value of best management practices through simulating the impact of various of IWM techniques. Consequently, an upgrade of RIM was undertaken, with the objectives of revising both the DSS contents and its implementation in a user-friendly software. This redevelopment effort focused on making RIM more reflective of current farming practices, incorporating new technologies developed to combat herbicide resistance, notably weed seed control at harvest. Emphasis was also placed on the ability to update and adapt the program to other situations.

This upgrade of RIM is succinctly presented in this paper, with descriptions of the new software interface and revised options. Several examples of applications are then presented, to illustrate how RIM can be used with farmers and consultants to support key recommendations to best manage and delay the onset of herbicide resistance. Differences between the upgraded and the original version of RIM are then discussed, as well as its potential for wider applications.

Both RIM versions, including programming codes and supporting documents, are available online (AHRI 2013) and on request from the authors. The copyright terms were redefined, making RIM an open-source software with certain conditions.

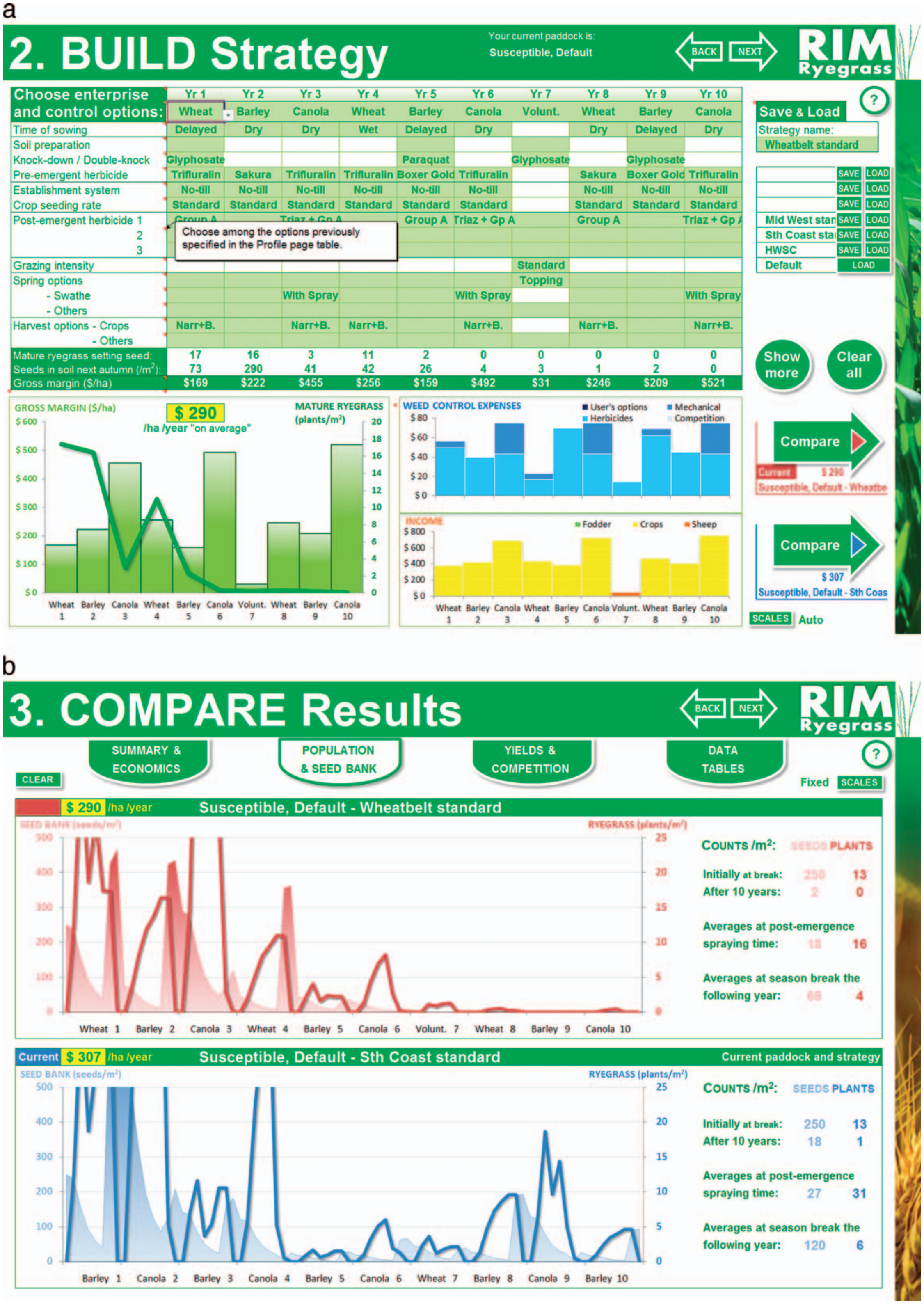
## Materials and Methods

**Interface and Programming.** An important part of the redevelopment effort consisted of reprogramming RIM and building a user interface.

*Overview.* The new interface was designed as a simple three-step progression: (1) Define Paddock, (2) Build Strategy, (3) Compare Results (see screenshots in Figure 2). A fourth optional step allows exporting these results. The visibility of inputs and outputs was enhanced, whereas the codes Visual Basic for Applications (VBA) codes were rewritten to allow for new functionalities. Such functionalities include the possibility of comparing scenarios (Figure 2b), saving parameter inputs and strategies for later upload, calling a calculator, displaying tutorials, changing graph scales, and exporting results to PDF®, XPS®, and Excel® formats. A software-like behavior was programmed featuring, for instance, automatic setup, interface protection, improved navigation, and error handling. Better overall program compatibility was achieved for Microsoft Excel® versions 2010, 2007, and 2003 for the Microsoft Windows® operating system. Added tutorials can be accessed through the help menus and in-built comments were also included to assist the users with explanations. These were complemented by a succinct user guide (Lacoste 2013) and video tutorials all available online (www.ahri.uwa.edu.au/RIM; AHRI 2013).

*User Inputs.* Faster profile customization was achieved by minimizing inputs. Only the most important 100 parameters are required to be modified by the user from a total of 600 parameters. All were set up with default values, allowing the user to customize preloaded default profiles and strategies rather than starting anew. User input was also simplified by grouping similar variables under a single entry, and asking more straightforward questions. For instance, the initial ryegrass seed density was replaced with plant density at the end of the previous season. User input was further simplified when building strategies, with emphasis placed on increasing the flexibility and decreasing the occurrence of errors. First, the pre-existing incompatibility system was minimized: more options were made available for all enterprises, letting users decide what is compatible for their own system. Then, drop-down lists were implemented, gathering over 40 options into a dozen categories such as time of sowing, POST options, spring options, etc. (see left inside of Figure 2a). This greatly limited the possibility for errors while making multiple choices well structured. Finally, the pre-existing 20-yr horizon was reduced to a more convenient 10-yr time frame.

*Outputs.* As with the original version, key results appear at the bottom of the strategy table as options are chosen (Figure 2a). However, maximum values for ryegrass plant and seed numbers were set at 300



| Choose enterprise and control options: | Yr 1 | Yr 2 | Yr 3 | Yr 4 | Yr 5 | Yr 6 | Yr 7 | Yr 8 | Yr 9 | Yr 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| | Wheat | Barley | Canola | Wheat | Barley | Canola | Volunt. | Wheat | Barley | Canola |
| Time of sowing | Delayed | Dry | Dry | Wet | Delayed | Dry | | Dry | Delayed | Dry |
| Soil preparation | | | | | | | | | | |
| Knock-down / Double-knock | Glyphosate | | | | Paraquat | | Glyphosate | | Glyphosate | |
| Pre-emergent herbicide | Trifluralin | Sakura | Trifluralin | Trifluralin | Boxer Gold | Trifluralin | | Sakura | Boxer Gold | Trifluralin |
| Establishment system | No-till | No-till | No-till | No-till | No-till | No-till | | No-till | No-till | No-till |
| Crop seeding rate | Standard | Standard | Standard | Standard | Standard | Standard | | Standard | Standard | Standard |
| Post-emergent herbicide 1 | Group A | | Triaz + Gp A | | Group A | Triaz + Gp A | | Group A | | Triaz + Gp A |
| 2 | | | | | | | | | | |
| 3 | | | | | | | | | | |
| Grazing intensity | | | | | | | Standard | | | |
| Spring options | | | | | | | Topping | | | |
| - Swathe | | | With Spray | | | With Spray | | | | With Spray |
| - Others | | | | | | | | | | |
| Harvest options - Crops | Narr+B. | | Narr+B. | Narr+B. | | Narr+B. | | Narr+B. | | Narr+B. |
| - Others | | | | | | | | | | |
| Mature ryegrass setting seed: | 17 | 16 | 3 | 11 | 2 | 0 | 0 | 0 | 0 | 0 |
| Seeds in soil next autumn (/m²): | 73 | 290 | 41 | 42 | 26 | 4 | 3 | 1 | 2 | 0 |
| Gross margin ($/ha) | $169 | $222 | $455 | $256 | $159 | $492 | $31 | $246 | $209 | $521 |

Choose among the options previously specified in the Profile page table.

Strategy name: Wheatbelt standard

Mid West stan
Sth Coast sta
HWSC
Default

$ 290 /ha /year Susceptible, Default - Wheatbelt standard

| COUNTS /m²: | SEEDS | PLANTS |
|---|---|---|
| Initially at break: | 250 | 13 |
| After 10 years: | 2 | 0 |
| Averages at post-emergence spraying time: | 18 | 16 |
| Averages at season break the following year: | 68 | 4 |

Current $ 307 /ha /year Susceptible, Default - Sth Coast standard

| COUNTS /m²: | SEEDS | PLANTS |
|---|---|---|
| Initially at break: | 250 | 13 |
| After 10 years: | 18 | 1 |
| Averages at post-emergence spraying time: | 27 | 31 |
| Averages at season break the following year: | 120 | 6 |

Figure 2. Screenshots of the upgraded RIM interface. (a) "Strategy" panel, with the 10-year option building table and the results graphs (bottom left: yearly gross margins and ryegrass survivors; bottom right: distribution of weed control expenses and income from various enterprises). (b) One of the four "Compare" panels featuring ryegrass plant and seedbank cycles for two different strategies. The other panels can be accessed using the tabs. (Color for this figure available in the online version of this paper.)

Table 2. Revised Ryegrass Integrated Management (RIM) options: major changes from the original 2004 version.

| Category | Number of available options | Applicable period[a] | Besides redefinitions and updates, notable changes from RIM 2004 |
|---|---|---|---|
| Enterprises | | | |
| Crops | 4 | | Generic crops, undefined legume crop |
| Pastures | 3 | | Generic pastures, fodder adjustments |
| Field operations | | | |
| Timing of seeding | 4 | 1, 2, 3 | Addition of dry seeding |
| Soil preparation | 2 | 2, 3 | Addition of moldboard plowing |
| Establishment system | 2 | 1, 2, 3 | Germination pattern adjustments |
| Crop seeding rates | 2 | 1, 2, 3 | |
| Preseeding herbicide(s) | 2 | 2, 3 | User-defined applicability to enterprises (most incompatibilities removed); entirely customizable herbicides; removed "shots" that automatically induced herbicide resistance |
| PRE herbicide | 5 | 2, 3, 4 | |
| POST herbicide(s) | 5 | 4 | |
| Crop sacrifice | 5 | 5 | |
| Late season spray/swathing | 3 | 5 | |
| Grazing | 2 | 5 | Removed ryegrass biomass contribution |
| Harvest weed seed control | 6 | 6 | Addition of three options; developed distinctions between seed catching techniques |
| User-defined options | 4 | 5, 6 | Addition of two options |

[a] 1. Before break of season. 2. 0–10 days after break. 3. 10–20 days after break. 4. Before POST spraying time. 5. Early spring. 6. Before harvest. 7. Summer (no option). Ryegrass cohorts emerge through periods 1 to 5, with the most important flush usually occurring during periods 2 and 3. During summer, only natural seed mortality occurs. For more details, see Lacoste 2013 and 2014.

plants $m^{-2}$ or 1,000 seeds $m^{-2}$. The corresponding graphs are now underneath the strategy table on the same panel, allowing the user to instantly monitor the effects of changing field operations or control options. Additional outputs include: ryegrass control expenses assigned to chemical, mechanical, competition, and user-defined categories; income breakdown by enterprise type (Figure 2a); ryegrass population dynamics (Figure 2b); rotational effects; and ryegrass burden on yields. In addition to the graphical form, these outputs were made available as exportable data tables. For all the above outputs, the option of comparing two sets of results from two selected scenarios was implemented, as illustrated in Figure 2b.

*Background.* Hidden from the user interface, the intermediary calculations can be accessed by unlocking the program from the information page. The entire program was reorganized, with redundancies removed and simpler connections made between input parameters, calculations, and outputs. Numerous comments were added to make those connections more convenient to identify. An important step was to untangle what is referred to as "spaghetti application," i.e., unstructured programming that results from the numerous modifications and additions over the course of successive improvements, made by usually different contributors (Walkenback 2010).

**Contents Revision.** The first step in revising the contents of RIM was to seek expert advice, through in-depth interaction with professionals (11) with extensive field experience in the Australian grainbelt. Seven experts were agricultural and weed scientists at research institutions (the University of Western Australia and the Department of Agriculture and Food, Western Australia) and four were private-sector consultants (one farmer, two agronomists, and one extension personnel). The second step of the revision process was to corroborate this expert advice with published literature, peer-reviewed whenever possible. To ease the large task of tackling over 600 parameters and achieving a reliable update within a reasonable time, published reviews were highly relied upon.

*Redefining Options.* All the original enterprises, field operations, and ryegrass control options were reviewed, leading to redefinitions, additions, and deletions. The major changes are summarized in Table 2. Minor modifications were made to the ryegrass demographic parameters, which were originally obtained through Western Australian field and trial observations (Pluske et al. 2004), inputs from other models, published literature, and expert advice (Pannell et al. 2004). The other parameters were all updated, including biological characteristics, rotational impacts, control efficacies, prices, and costs. The resulting 7 enterprises and 44 management options are described in Lacoste (2014), with references listed in the software as well. A succinct guide specifically aimed at end-users also summarizes default settings (Lacoste 2013).

*Updating Parameters.* Default values were chosen to represent best assumptions based on long-term considerations valid for the dominant conditions encountered in the dryland cropping systems of the Australian southern grainbelt. Deviations were sometimes made from average values on the basis of realistic considerations for the dominant farming systems. For instance, the average benefits of a preceding legume crop on a subsequent wheat crop are proportionally higher in low yielding contexts (Seymour et al. 2012), which was chosen for the default values because of their prevalence in the modeled dryland broadacre systems. Difficult choices had to be made for parameters with large variations, such as stocking rates, benefits following a legume phase, several ryegrass control methods, etc. Those parameters were usually made directly accessible from the interface and easily customizable by the user. Others followed specific assumptions, such as a rationale of proportionality behind machinery costs or expected production patterns for the modeled pasture species. Where estimations were particularly difficult because of high local variations or a lack of consensus or reliable published results, only relative nominal values were used. This was the case for the costs of crop residue removal, erosion risk after cultivation, and risk of uncontrolled fire following localized burning.

**Testing and Validating.** Over the course of its redevelopment, RIM was evaluated by knowledgeable individuals to gather feedback on its accessibility, test its functionalities, and check the program compatibility features. Several beta-versions were sent along with its user guide to 25 professionals including researchers, extension personnel, consultants, farmers, communication officers, and former RIM developers. Various comments were received from 16 of the solicited persons, with detailed feedback from 6 of them leading to significant improvements. A penultimate beta-version was later tested through four sessions conducted in computer labs at the University of Western Australia, Perth. Attendees were farmers and consultants, university agricultural students, weed researchers, and high-school teachers. Each group comprised a dozen participants, totaling about 50 persons. These tests confirmed that no major changes were required, and demonstrated that most users were able to learn how to use RIM quickly. However, the need for a facilitator explaining key assumptions and assisting them through a sample scenario was also highlighted.

## Results and Discssion

As a decision support tool to assess the long-term efficacy and profitability of weed control methods, RIM can be used to illustrate the value of herbicides and the potential impact of losing them to resistance, as well as to highlight the need for strategies that reduce the risk of herbicide resistance. Table 3 provides a 10-yr strategy implemented in RIM that is typical of the Australian southern grainbelt (a). This strategy manages ryegrass infestation through the diverse use of herbicides, a nonherbicide control tool (occasional burning), and by taking one year out of cropping. However, the long-term effects of persistent low to medium ryegrass plant densities are reflected in the high numbers of seeds carried over every year in the seedbank. Using this default strategy, we illustrate below the types of information that RIM can convey during a typical workshop. To exemplify more specifically the numerous possible applications of RIM, we show how simulations can be used to both demonstrate the financial damage herbicide resistance can cause, and the benefits of adopting 9 of the 12 best management practices (BMPs) recommended by Norsworthy et al. (2012).

"The costs of resistance" (p. 33). An effective way of introducing RIM is to use it to illustrate to users the potential cost of herbicide resistance – a powerful argument when advocating proactive management strategies. After building a 10-year strategy, herbicides can be removed to observe the effects of ryegrass population dynamics on profitability. Scenario (b) and (c) (Table 3) provide examples where, without any additional investment, the loss of herbicide efficacy results in high ryegrass infestation numbers, which translates into yield penalties and severe economic losses. In a normal situation, other control methods would be introduced to compensate for the loss of herbicides, increasing the cost of production. The second part of the workshop exercise is to introduce other techniques to regain control while remaining cost effective.

It should be noted that the overall herbicide expenses of scenarios (b) and (c) do not differ much, reflecting the current very low costs of off-patent herbicides trifluralin, glyphosate, and paraquat. This illustrates the importance of preserving very effective, cheap herbicide resources. Scenario (c) in particular highlights the importance of preserving nonselective herbicides that form the base of several in-crop control techniques.

"BMP 1: Understand the biology of the weeds present [. . .] with emphasis on reducing the soil seedbank" (p. 34). RIM can prompt questions and discussion about weed biology by illustrating the consequences of targeting specific biological characteristics, and determining which life stages are particularly sensitive to management. For instance, the outputs of the default scenario (a) can be used to illustrate that low, seemingly inconsequential ryegrass plant numbers can be actually associated with high seedbank levels. This is permitted by the persistence of ryegrass seeds in the soil, and the high fecundity of the species. The latter characteristic is specifically targeted in this strategy by late-season application of nonselective herbicide, which minimizes viable seed production. Omitting this practice results in rapid ryegrass infestation, demonstrating how minimizing the return of viable seeds to the soil seedbank by targeting the reproductive stage of ryegrass can affect ryegrass population size. This also supports the argument that thresholds, i.e. the idea of acceptable levels of weed densities and therefore, seed production, should be avoided in extension messages in favor of a zero or near-zero approach for prolific and resistance-prone species such as ryegrass (Bagavathiannan and Norsworthy 2012). Scenario (d) illustrates how the weed emergence pattern can be taken advantage of, through the appropriate timing of practices for controlling early-emerging cohorts that possess the greatest seed production potentials. In this example, delaying crop seeding date allowed the use of the specific double-knock technique, and then permitted greater control as ryegrass emergence typically occurs over an extended period. The topic can also prompt discussion about the impact that escapes from late-emerging cohorts can have: reduced seed production and lesser impact on the crop than early-emerging weeds, yet a potential concern from the point of seedbank persistence and herbicide resistance risk.

"BMP 2: Use a diversified approach to weed management focused on reducing weed seed production and the number of weed seeds in the soil seedbank" (p. 36). A variety of methods specifically targeting the seedbank is available for testing in RIM: depleting the seedbank through increased seed germination using a tickle or full-cut establishment system; directly decimating seeds using mouldboard plowing; or preventing seedbank replenishment. The latter can be done in numerous ways: spring options that target maturing escapes through mechanical, biological, or chemical means via the various forms of slashing, grazing, crop sacrifice; measures to minimize seed production via competition or topping; and harvest weed seed control systems targeting newly produced seeds through burning, export, crushing, and spraying. RIM calculates the extent to which those management tactics can be combined, and gross margins indicate whether the resulting diversified strategies are economically viable, while soil seedbank size can be minimized. Besides rapidly calculated simulation strategies to assess overall diversity, RIM also provides a breakdown of the costs of ryegrass management tools, be they herbicide, mechanical, crop competition, or user-defined. Although distorted by prices that are not necessarily correlated to control efficacies, this budget allocation offers a rapid diversity indicator that permits users to rapidly assess the extent of reliance on herbicides over a 10-year period. Comparing strategies (d) and (e) provides such an example. The user-defined option caters for methods not included in the default settings. For instance, the cost and efficacy of hand weeding, an approach that may be applicable under non-Australian situations, can be manually added and its impact on the overall budget can be separately examined.

"BMP 3: Plant into weed-free fields and keep fields as weed free as possible" (p. 38). RIM allows varying starting weed densities to assess the impact of high, medium, and low starting weed densities. Scenario (h), for instance, shows the consequence of not planting in a ryegrass-free field: without

Table 3. Examples of scenario comparisons and main outputs.

| Year | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| **(a) Default strategy, starting with 10 ryegrass survivors (plant/m$^2$) from previous spring** | | | | | | | | | | |
| Enterprise | Wheat | Barley | Canola | Wheat | Barley | Canola | Volunt. | Wheat | Barley | Canola |
| Time of sowing | Delayed | Dry | Dry | Wet | Delayed | Dry | Wet | Dry | Delayed | Dry |
| Soil preparation | | n.a.[a] | n.a. | n.a. | | n.a. | | n.a. | | n.a. |
| Nonselective herbicide | Glyphos. | n.a. | n.a. | n.a. | Paraquat | n.a. | Glyphos. | n.a. | Glyphos. | n.a. |
| PRE herbicide | Triflur. | Sakura | Triflur. | Triflur. | Boxer G. | Triflur. | | Sakura | Boxer G. | Triflur. |
| Establishment system | No-till | No-till | No-till | No-till | No-till | No-till | n.a. | No-till | No-till | No-till |
| Crop seeding rate | Standard | Standard | Standard | Standard | Standard | Standard | n.a. | Standard | Standard | Standard |
| POST herbicide(s) | Group A | | Triaz.+A | | Group A | Triaz.+A | | Group A | | Triaz.+A |
| Grazing intensity | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | Standard | n.a. | n.a. | n.a. |
| Spring options | | Swathe & spray | | | Swathe & spray | | Topping | | Swathe & spray | |
| Harvest options | | Field burn | | | Field burn | | | | Field burn | |
| Ryegrass survivors[b] (plants m$^{-2}$) | 35 | 65 | 11 | 75 | 35 | 4 | 2 | 8 | 13 | 1 |
| Seedbank next autumn (seeds m$^{-2}$) | 291 | > 1,000 | 281 | 662 | 396 | 110 | 82 | 138 | 96 | 28 |
| Gross margin ($ ha$^{-1}$) | 154 | 206 | 350 | 215 | 149 | 422 | 31 | 248 | 193 | 504 |
| Average gross margin ($ ha$^{-1}$ yr$^{-1}$) | | | | | **257** | | | | | |
| Proportion of control expenses dedicated to herbicides (%) | | | | | 7 | | | | | |
| Average wheat | | | | | 5 | | | | | |
| Average barley | | | | | 2 | | | | | |
| Average canola | | | | | 12 | | | | | |
| Proportion of control expenses dedicated to herbicides (%) | | | | | 80 | | | | | |
| **(b) Loss of trifluraline (PRE herbicide), no replacement** | | | | | | | | | | |
| Ryegrass survivors (plants m$^{-2}$) | 73 | 160 | 44 | > 300 | 229 | 43 | 15 | 36 | 59 | 8 |
| Seed next autumn (seed m$^{-2}$) | 714 | > 1,000 | 702 | > 1,000 | > 1,000 | 685 | 388 | 633 | 425 | 180 |
| Gross margin ($ ha$^{-1}$) | 160 | 182 | 224 | 128 | 106 | 215 | 31 | 230 | 179 | 415 |
| Average gross margin ($ ha$^{-1}$ yr$^{-1}$) | | | | | **192** | | | | | |
| Yield losses (%) | | | | | 20 | | | | | |
| Herbicide expenses (%) | | | | | 76 | | | | | |
| **(c) Loss of nonselective herbicides resulting in no spray before seeding, loss of pasture topping and swathing without spray** | | | | | | | | | | |
| Ryegrass survivors (plants m$^{-2}$) | 47 | 107 | 111 | >300 | 267 | 224 | > 300 | > 300 | > 300 | > 300 |
| Seed next autumn (seed m$^{-2}$) | 475 | > 1,000 | > 1,000 | > 1,000 | > 1,000 | > 1,000 | > 1,000 | > 1,000 | > 1,000 | > 1,000 |
| Gross margin ($ ha$^{-1}$) | 158 | 195 | 307 | 78 | 113 | 217 | 45 | 35 | 68 | 186 |
| Average gross margin ($ ha$^{-1}$ yr$^{-1}$) | | | | | **149** | | | | | |
| Yield losses (%) | | | | | 30 | | | | | |
| Herbicide expenses (%) | | | | | 76 | | | | | |
| **(d) Delayed seeding (timing), tickle (soil preparation), and double knock (nonselective herbicide) every cropping year except canola** | | | | | | | | | | |
| Ryegrass survivors (plants m$^{-2}$) | 19 | 8 | 1 | 4 | 1 | 0 | 0 | 0 | 0 | 0 |
| Seed next autumn (seed m$^{-2}$) | 202 | 146 | 42 | 46 | 19 | 5 | 4 | 2 | 1 | 0 |
| Gross margin ($ ha$^{-1}$) | 150 | 173 | 492 | 210 | 149 | 501 | 31 | 184 | 185 | 528 |
| Average gross margin ($ ha$^{-1}$ yr$^{-1}$) | | | | | **272** | | | | | |
| Yield losses (%) | | | | | 0 | | | | | |

Table 3. Continued.

| Year | 1 | 2 | 3 | 4 |  | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Herbicide expenses (%) |  |  |  |  | 77 |  |  |  |  |  |  |
| **(e) High crop seeding rates every cropping year** |  |  |  |  |  |  |  |  |  |  |  |
| Ryegrass survivors (plants $m^{-2}$) | 35 | 52 | 7 | 41 |  | 15 | 1 | 1 | 2 | 3 | 0 |
| Seed next autumn (seed $m^{-2}$) | 230 | 683 | 155 | 287 |  | 140 | 33 | 26 | 33 | 18 | 4 |
| Gross margin ($\$$ $ha^{-1}$) | 152 | 207 | 436 | 232 |  | 149 | 488 | 31 | 243 | 189 | 523 |
| Average gross margin ($\$$ $ha^{-1}$ $yr^{-1}$) |  |  |  |  | **277** |  |  |  |  |  |  |
| Yield losses (%) |  |  |  |  | 2 |  |  |  |  |  |  |
| Herbicide expenses (%) |  |  |  |  | 70 |  |  |  |  |  |  |
| Extra seeding costs (competition) (%) |  |  |  |  | 12 |  |  |  |  |  |  |
| **(f) Narrow windrow burning every cropping year (harvest options)** |  |  |  |  |  |  |  |  |  |  |  |
| Ryegrass survivors (plants $m^{-2}$) | 35 | 33 | 1 | 4 |  | 1 | 0 | 0 | 0 | 0 | 0 |
| Seed next autumn (seed $m^{-2}$) | 145 | 103 | 15 | 15 |  | 3 | 0 | 0 | 0 | 0 | 0 |
| Gross margin ($\$$ $ha^{-1}$) | 159 | 210 | 495 | 261 |  | 153 | 498 | 31 | 246 | 203 | 521 |
| Average gross margin ($\$$ $ha^{-1}$ $yr^{-1}$) |  |  |  |  | **292** |  |  |  |  |  |  |
| Yield losses (%) |  |  |  |  | 1 |  |  |  |  |  |  |
| Herbicide expenses (%) |  |  |  |  | 76 |  |  |  |  |  |  |
| **(g) Harrington seed destructor every cropping year (harvest options)** |  |  |  |  |  |  |  |  |  |  |  |
| Ryegrass survivors (plants $m^{-2}$) | 35 | 33 | 1 | 4 |  | 1 | 0 | 0 | 0 | 0 | 0 |
| Seed next autumn (seed $m^{-2}$) | 145 | 103 | 15 | 15 |  | 3 | 0 | 0 | 0 | 0 | 0 |
| Gross margin ($\$$ $ha^{-1}$) | 147 | 198 | 483 | 249 |  | 141 | 486 | 18 | 234 | 203 | 522 |
| Average gross margin ($\$$ $ha^{-1}$ $yr^{-1}$) |  |  |  |  | **281** |  |  |  |  |  |  |
| Yield losses (%) |  |  |  |  | 1 |  |  |  |  |  |  |
| Herbicide expenses (%) |  |  |  |  | 65 |  |  |  |  |  |  |
| **(h) Starting ryegrass density: 100 plants $m^{-2}$** |  |  |  |  |  |  |  |  |  |  |  |
| Ryegrass survivors (plants $m^{-2}$) | > 300 | > 300 | 61 | > 300 |  | 112 | 12 | 7 | 19 | 32 | 2 |
| Seed next autumn (seed $m^{-2}$) | > 1,000 | > 1,000 | > 1,000 | > 1,000 |  | > 1,000 | 309 | 206 | 343 | 235 | 66 |
| Gross margin ($\$$ $ha^{-1}$) | 62 | 131 | 173 | 140 |  | 129 | 321 | 31 | 240 | 187 | 473 |
| Average gross margin ($\$$ $ha^{-1}$ $yr^{-1}$) |  |  |  |  | **188** |  |  |  |  |  |  |
| Yield losses (%) |  |  |  |  | 18 |  |  |  |  |  |  |
| Herbicide expenses (%) |  |  |  |  | 80 |  |  |  |  |  |  |
| **(i) Starting ryegrass density: 100 plants $m^{-2}$ and moldboard plow (soil preparation) in year 1** |  |  |  |  |  |  |  |  |  |  |  |
| Ryegrass survivors (plants $m^{-2}$) | 6 | 8 | 1 | 11 |  | 5 | 1 | 0 | 1 | 2 | 0 |
| Seed next autumn (seed $m^{-2}$) | 35 | 140 | 40 | 102 |  | 62 | 18 | 14 | 24 | 17 | 5 |
| Gross margin ($\$$ $ha^{-1}$) | 136 | 291 | 596 | 320 |  | 224 | 592 | 31 | 324 | 265 | 630 |
| Average gross margin ($\$$ $ha^{-1}$ $yr^{-1}$) |  |  |  |  | **360** |  |  |  |  |  |  |
| Yield losses (%) |  |  |  |  | 1 |  |  |  |  |  |  |
| Herbicide expenses (%) |  |  |  |  | 67 |  |  |  |  |  |  |
| **Without permanent 15% yield benefit** |  |  |  |  |  |  |  |  |  |  |  |
| Gross margin ($\$$ $ha^{-1}$) | 70 | 225 | 493 | 252 |  | 158 | 490 | 31 | 253 | 197 | 524 |
| Average gross margin ($\$$ $ha^{-1}$ $yr^{-1}$) |  |  |  |  | **281** |  |  |  |  |  |  |

[a] n.a., not applicable; Glyphos., glyphosate; Triflur., trifluralin; Triaz. + A, triazine + group A (equivalent to group 1 in U.S. classification).

[b] Mature plants setting seeds at the end of spring.

additional investment, the higher the initial ryegrass population, the longer it takes to regain control, with considerable long-term economic losses. Alternatively, strategies that rapidly deplete ryegrass seedbank (for instance [c], [e], and [f]) avoid most of the ryegrass burden. Another benefit of keeping ryegrass numbers low is that subsequent control is easier because of the carryover of a small remnant seedbank, with much narrower population fluctuations (unlike the default strategy). Strategies such as (i) illustrate the benefit of tackling the problem as early and aggressively as possible. Alternatives to moldboarding include crop sacrifice or chemical fallow; the effect of when in the rotation and for how long such approaches should be implemented can also be assessed.

"BMP 5: Scout fields routinely" (p. 39). Surveying fields effectively to evaluate weed populations is a time-consuming but useful practice. The cost of regular scouting as part of a proactive strategy can be included in the user-defined options, leaving blank the control efficacy. If scouting is critical to ensure that application timing is optimal, a scenario with herbicide penalties can be compared with another featuring maximum possible efficacies.

"BMP 6: Use multiple, effective mechanisms of action against the most troublesome weeds and those prone to herbicide resistance" (p. 39) and "BMP 7: Apply the labeled herbicide rate at recommended weed sizes" (p. 41). RIM does not distinguish herbicide chemistries, rates, and application efficacy, which are left to the user to input. Thus, customizing herbicides in RIM provide an excellent opportunity to raise and discuss matters related to recommended herbicide practices, particularly in the context of workshops. Although it is not the objective of RIM to keep herbicide records, the strategy lays out the herbicides used over the 10-yr period. Issues such as rotation planning, sequential applications, use of mixtures, and of conventional and genetically modified crops can then be debated while visually assessing the strategy. Default settings reflect the expected efficacy when techniques are well conducted. However, actual field efficacy, which may differ for a number of reasons, can be specified—and its effects can be compared with the best-case scenario.

"BMP 8: Emphasize cultural management techniques that suppress weeds by using crop competitiveness" (p. 42). As mentioned above, scenario (d) exploits the cultural practice of delayed seeding date, enabling control of earlier emerged ryegrass cohorts with nonselective herbicides. Scenario (e) illustrates how using crop competitiveness via high seeding rates can contribute to ryegrass control with relatively lower costs compared with herbicide applications. The simulation, however, shows a slower decline in ryegrass numbers than other techniques, as illustrated for instance in strategies (d), (f), and (g). This leads to the argument that for successful ryegrass control, crop competition should be complemented with other methods. With some assumptions and adjustments, the high seeding rate setting can also account for narrow row spacing. Another way of illustrating the benefits of competition is to experiment with sequences, for instance replacing wheat crops with barley in the rotation and evaluate the increased effect on ryegrass numbers. However, this has to be balanced with lower grain prices. Legume crops may provide nitrogen fixation and break crop benefits, which overcome their characteristically poor competitiveness. Advanced users can also change the relative competitiveness of ryegrass and crops to simulate more closely the effects of certain crops or cultivars, particularly more competitive ones.

"BMP 9: Use mechanical and biological management practices where appropriate" (p. 44). As illustrated above, both tactical and strategic uses of mechanical and biological practices can be evaluated with RIM. Mechanical methods include crop establishment systems (minimal or medium soil disturbance), shallow cultivation (tickle, [d]), tillage (soil inversion, [i]; green manuring), slashing (mowing, cutting for hay or silage, swathing), and harvest weed seed control ([f], [g]). Biological management practices are represented by grazing pastures with effectiveness depending on the type and duration of pasture (establishment modalities, ryegrass control levels, pasture phases lasting one year or longer), intensity of grazing during the reproductive phase of ryegrass, and whether fodder production or green manuring is planned.

"BMP 11: Manage weed seed at harvest and postharvest to prevent a buildup of the weed seedbank" (p. 47). Five harvest weed seed control techniques are included in RIM, with scenarios (f) and (g) illustrating two of them. Users can appreciate how effective those techniques are in contributing to lowering ryegrass plant and seed number to near-zero levels. With similar levels of efficacy, diversity may become a criterion: all options fall under the cultural/mechanical category; however, no burning or herbicide use is required with the Harrington Seed Destructor and the Bale Direct System. The latter can also provide an extra source of income when baled residues (and the weed seed they contain) are sold or used on farm for fodder. Cost efficiency is a key criterion for choosing a technique over another: for instance, yearly and long-term gross margins in scenario (g) bear the repayment costs incurred by the purchase of a Harrington Seed Destructor. By varying this cost and repayment modalities, the user could assess a benchmark when this piece of equipment could become affordable in the system. Similarly, in some environments where burning is followed by the loss of essential nutrients and hence requires higher fertilizer inputs, a Harrington Seed Destructor that retains all field residues may become a more cost-effective solution in the long term than the low cost narrow windrow burning technique (for the default strategy [a], starting when extra input costs reach \$25 $ha^{-1}$ $yr^{-1}$). Likewise, whole-field burning can incur high environmental costs because of the erosion of bare land and fire risk. Although long-term effects are difficult to evaluate, estimations can be used.

**Identifying and Retaining Key Features.** The upgrade of RIM was primarily motivated by the model's application as a DSS, rather than as a research tool. Consequently, emphasis was placed on features that contributed to the success of RIM's original version as an educational tool. These features were identified by the evaluations (Llewellyn et al. 2005; Llewellyn and Pannell 2009) and surveys (Lacoste et al. 2013) conducted during the first RIM workshops, and are discussed below.

*Overall Model Principle.* The ease of use of RIM had been particularly praised by users. Consequently, when enhancing features, the program's overall simplicity was retained whenever possible. The overall principle of RIM remains unchanged, with the upgraded version essentially featuring the same types of inputs, outputs, and intermediary calculations. Most modifications consisted of parameter updates and modeling adjustments to reflect the revised options. Furthermore, the ryegrass model at the core of RIM only underwent minor modifications since its well-detailed population dynamics had largely been validated (Draper and Roy 2002). The choice was also made to retain Excel® as the implementation platform. The software ubiquity ensures that most users are already familiar with it, and that future updates could easily be facilitated. Additionally, the new versions of Excel provided convenient features catering all implementation requirements. Finally, avoiding portage to another platform avoided unnecessary programming.

*Constructing and Experimenting.* In addition to the ability to monitor both biological and economic sustainability, the interest of RIM as a DSS relied on the ability to let users explore custom-built scenarios and experiment with options, instead of relying on optimized recommendations. Through a "what-if" approach that stimulates discussions and the confrontation of ideas, RIM essentially aims to contribute to the user's decision-making process (McCown et al. 2009). As one of the features most highly valued by users, this core functionality of RIM therefore remained central.

*Importance of Economics.* A major result of RIM's evaluations was to demonstrate that specific perceptions have to be targeted to contribute to the decision process that ultimately leads to the adoption of agricultural practices. In the case of RIM, farmers' perceptions of the short- and long-term economic values of control practices were changed after attending the workshops. This demonstrated that instead of focusing on immediate economic benefits, an emphasis on future income and broader considerations are critical as well (Norsworthy et al. 2012). The survey confirmed those results, with 80% of 162 respondents specifying that their perceptions about herbicide resistance had changed after the RIM workshops, with the value of specific control techniques being most often mentioned. The importance of long-term considerations such as diversifying, rotating, and planning options ranked next, justifying retention of the detail of annual gross margins alongside the long-term discounted average. Those results also motivated the idea of providing visual representations of the economic results side by side, to allow for swift comparisons.

**Key Differences from the Original Version.** Although many aspects of RIM were retained, important modifications were made with regard to particular components, assumptions, and options that users should be made aware of when using this upgraded version.

*Removing Components.* Although the majority of the components were updated or enhanced, a few were deleted as well. Anecdotal evidence showed that the 10-yr horizon was vastly preferred over the 20-yr one, which was therefore omitted. A 10-yr period proved enough for assessing options from both a strategic and tactical perspective, whereas another decade provided little benefits and increased prediction uncertainty. A focus on low and medium densities, which hold more important managerial implications, was also gained by only displaying ryegrass density maxima beyond infestation thresholds. Lastly, the choice was made to remove the resistance component of RIM despite its contribution to raising awareness during early stages. In the original version, a drastic decrease of herbicide efficacy was induced after using up the allocated "herbicide shots," simulating the rise of herbicide resistance. However, this overly simplistic module could also easily lead to misinterpretation, such as the idea that resistance evolution solely depends on the number of applications of a herbicide. Instead, profile customization catered for assessing the impact of resistance situations without relying on any genetic assumptions: users can set up several profiles with various herbicide efficacies or use preloaded examples, thus simulating situations with and without herbicide resistance or before/after losing a mode of action, then adjusting the strategy accordingly. Consequences can be compared, for instance demonstrating the long-term benefits of a proactive, diversified strategy vs. others that would have exhausted the herbicide resource. Removing the obsolete resistance component was further justified by the availability of advanced models specifically dealing with resistance evolution mechanisms (e.g. Neve 2008; Renton et al. 2011).

*Wider Applicability through Broadened Assumptions and Increased Flexibility.* At a time when the typical broadacre system model was herbicide based (Holst et al. 2007), the first RIM truly integrated cultural and mechanical control options. This alternative to the herbicide-centered approach proved crucial when addressing herbicide resistance issues (Norsworthy et al. 2012). The diversity of options present in RIM was therefore an asset to be retained. Despite the existing large range of options chosen to represent the dominant enterprises and practices of the Australian southern grainbelt, RIM workshop surveys indicated that users still required more choices: among the 262 suggestions received, nearly all asked for adding new or developing existing options and crops (nearly two-thirds and one-third of responses respectively). Propositions were varied, although dominated by requests for including other crops such as pulse or hay crops, herbicide-resistant crop varieties, additional herbicide choices, and the need to update or adjust parameters to better suit local conditions. The new RIM version accommodated many of these requests by adding or developing several components such as mouldboard plouwing, environmental effects, swathing possibilities, etc. To conciliate other demands with the difficulties of complicating the agronomic sequences, the enterprises were redefined as generic. For instance, the lupin (*Lupinus angustifolius* L.) crop in the original RIM model was changed to a customizable unnamed legume crop; the volunteer pasture can be managed as a chemical fallow; barley (*Hordeum vulgare* L.) crop can be approximated to oat; the two improved pasture types were contrasted to represent a robust, reliable pasture vs. a more productive yet more fragile option; herbicides were made entirely customizable so as to fit any herbicide-resistant crop variety. Similarly, most options were made more broadly applicable by increasing compatibilities. For instance, swathing cereals became a possibility even if not a common practice in Australia, and mowing was made an option for all enterprises.

*Emphasizing User's Choices.* By letting the user decide what is logical and applicable, a wider variety of situations can be catered for while avoiding program bugs. Additionally, reducing incompatibilities will also facilitate the modification of options. A typical example includes the addition of herbicides, for which modeling requirements were extremely simplified by allowing selective modes of action to be decided by the user instead of coding predefined rules. Most control efficacy levels were also left to be defined by the user. Beyond modeling and implementation advantages, relying on the user's choices was justified by RIM's evaluations indicating that there was little potential to influence farmers' perceptions of the efficacy of ryegrass control practices. This may be explained by the scope of field variations that average efficacies could not render, with the importance of local calibration previously demonstrated (Draper and Roy 2002).

*Simplifying the Framework.* Simplifications were undertaken where deemed not to affect the quality of outputs. Removing some details was justified by the fact that complicated scenarios would not enhance the decision-making process of users and hence would not serve the purpose of RIM as a DSS. On the other hand, simplifications offered numerous postdevelopment advantages in terms of maintenance, future updates, and adaptations. Decisions were guided by changing circumstances leading to either broader assumptions, or to lesser need for details. For instance, to adjust to today's crop-dominant system, the pasture details were kept and the haying option was updated but their overall importance was downgraded in the interface. Also taken into account were the comprehensive sensitivity analyses conducted on various scenarios and situations from other RIM versions (inter alia Beltran et al. 2012a, 2012b; Doole 2008; Doole and Revell 2010, Monjardino et al. 2003, 2004a, 2004b, 2005; Torra et al. 2010; with further parameter investigation for crop-weed competition submodels based on those of RIM conducted by Lawes and Renton 2010; Renton 2011). Results consistently indicated that those parameters with the most impact on economic outcomes were primarily grain yields and prices, followed by initial weed seed density. Consequently, those parameters were given a prominent position in the interface, whereas those identified as having minor impacts were hidden (e.g. pasture details), deleted (e.g. biomass contribution of ryegrass to pastures, rate detail of fertilizer costs and savings), or grouped under simplified labels (e.g. establishment inputs for pesticides, seed inoculum, etc.). Often, the original calculations were kept but the overall model was simplified by rendering parameters codependent on established ratios (e.g. barley variables linked to wheat, machinery costs to harvester, second-year rotational effects to the first, nonselective late-season herbicides to knock-down costs). Last, the addition of an assumption to replace the initial ryegrass seedbank by plant densities was justified by the difficulty for users to estimate seedbank densities (Doole 2008).

*Improved Accessibility and New Functionalities.* The new interface of RIM constitutes perhaps the most evident change of the DSS upgrade. Its creation was motivated by four imperatives: increasing the program's overall accessibility, better exploiting the DSS by providing more out of what already existed, solving the issue of lengthy and demanding updates, and catering for the future of the DSS, i.e., facilitating maintenance and further modifications, but also distribution and marketing. Solving those overarching goals resulted in substantial reorganization of the program. At the core of this restructuration lies a clear segregation between the user interface and the background calculations, which constitute two separate "layers" with specific roles. For instance, regarding the issues of updates, the user interface is dedicated to profile customization, which is distinct from in-depth program modifications accessible in the background only. Using both layers, the expanded VBA framework catered for enhanced compatibility, new functionalities, and software-like behavior. The latter complemented a new design meant to facilitate the user's familiarization with the DSS. Additionally, to favor an intuitive progression through the software, RIM was given a consistent layout. A distinct visual identity (color, logo, patterns) was set for use in future marketing strategies. To contribute to this important aspect of distribution, promotional material was produced and relevant information provided online through a dedicated website (see AHRI 2013). Last, despite the addition of contents and even pictures, the final RIM file was kept very light (3 Mb) so as to ease its downloads.

**Updates and Revisions: Specific Changes to Options.** The options available in RIM were updated, and often revised, to better represent current practices and farming systems. The most important changes are described below.

*Establishment Options.* In RIM, the way a crop or pasture is established holds several key consequences for ryegrass germination pattern, early control, yield impacts, and costs. The components at play are timing and technique of seeding, as well as preseeding options such as soil preparation and nonselective herbicides. Reviewing the establishment system in RIM hence meant revising all those options and their consequences. The two major additions were the inclusions of dry seeding and mouldboard plouwing. Dry seeding (seeding into dry soil before the first season-commencing rainfall event) is a practice that has increasingly gained importance during the past decade in the Australian southern grainbelt. For instance in 2011, 44% of surveyed Western Australian farmers had, on average, about a quarter of their farm dry seeded (Minkey et al. 2013). The interest in a no-till farming system of a strategic, once-off mouldboard plouwing is more recent, and more controversial, as some see the practice as a setback in conservation agriculture. The practice is justified by the fact that a tactical, timely, and one-off return to soil inversion could represent the only method to directly target the soil seedbank, in a costly yet drastic manner, with the added advantage of possibly removing soil constraints pre-existing the adoption of no-till or built up afterward. The modeled consequences in RIM reflect these expectations, although it should be acknowledged that the scope and long-term consequences of this practice, which remains experimental in systems dominated by minimal soil disturbance, are complex and yet to be fully understood.

*Spring Options.* Spring options essentially aim at controlling ryegrass survivors and their progeny by increasing grazing intensity, sacrificing a crop, or using late-season practices such as crop-topping and swathing. Adjustments included refining pasture production dynamics, allowing all enterprises to be sacrificed and sprayed, and amending saving costs. A major change was to cater for the impact of nonselective late-season herbicides on the fertility of ryegrass survivors (Steadman et al. 2006), modeled by adding a variable in the ryegrass seed production equation.

*Harvest Options.* During the past decade, major advancements have been made in identifying harvest weed seed control as a valid alternative to herbicides and hence as a critical avenue to combat herbicide resistance. This has been reflected through the increasing interest in chaff cart and narrow windrow burning techniques, and the development of new technologies such as the Harrington Seed Destructor (Walsh et al. 2012, 2013). To reflect the increasing importance of harvest weed seed control, several options were added. New parameters were included as well, such as residue removal costs and baling income. Although all techniques provide similar levels of control, differences primarily rely in varying costs such as the investment in specialized equipment, repair and maintenance, and environmental risks. The consequences of removing and redistributing field residues were acknowledged via nominal costs only, given the complexity of the impacts of residues on nutrient cycling, on subsequent crops, and on weed seed survival and germination (McNee 2013).

*Economics.* Besides the exhaustive price and cost update, changes from the previous version included the simplification of several calculations and the deletion of the price matrix. The latter, which attributed higher returns for grain expected to provide higher protein or oil content in certain rotations, is instead accommodated through the user inputs.

*Control Efficacies.* Last, it should be noted that the efficacies achieved by the range of control techniques chosen as default values are probably greater than may be obtained in field conditions. For instance, 100% control is likely to correspond to 90 to 100%. The choice was made to represent favorable climatic, environmental, and application circumstances to highlight contrasts between practices.

**Delivering RIM.** A decision support system remains a complex tool. As with any other instrument, RIM will be used best following some instructions.

*Corroborating Recommendations.* RIM's models of application illustrate how RIM can be used to recommend best management practices, providing concrete examples of the program's practical usefulness (Holst et al. 2007) and its scope of application (McCown et al. 2009). This new version reiterates the recommendations first upheld by the original version (Pannell et al. 2004): RIM still demonstrates that ryegrass resistance to several herbicides can result in large economic losses, that optimal ryegrass densities must be kept low because of the species' high competitiveness and fecundity, and that it can be profitable to limit ryegrass competition with the crop through integrated strategies (Doole 2008). RIM also continues to demonstrate that profitable nonchemical alternatives exist, yet herbicides remain the cheapest and most efficient control tool available. RIM thus confirms user experience that farming systems in the

Table 4. Key assumptions of the ryegrass integrated management (RIM) model.

| Key assumptions and elements | Details and consequences |
|---|---|
| RIM simulates and compares trends, but is not a forecast model. | RIM assesses the impact of simulated 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 to many of the model base parameters. |
| Annual variations are not included: results are based on averages. | RIM is a deterministic model: calculations essentially modify yearly or field averages, without catering for environmental fluctuations or spatial heterogeneity (climate, rainfall patterns, soil, germination, biomass growth, pest behavior, etc.). Default values were chosen as to represent an average situation for the target area. |
| Results are based on "long-term average weed-free grain yields," defined by the user. | Each year, the final grain yields are obtained from the average yield that is to be expected for the modeled field in an average season, when all other weeds are controlled (to be distinguished from a "potential yield," which is closer to a maximum met when all conditions are optimum, hence necessarily representative conditions). |
| Crops and pastures are generic. | Enterprises do not represent a given cultivar or even species but rather a type of enterprise, defined by its management as much as its biological characteristics. |
| Weed genetics are not included. | Evolution mechanisms of herbicide resistance are not modeled. A situation with ryegrass resistance is represented through adjusting the control efficacy of herbicides. |
| Long-term average gross margin emphasizes the returns of earlier years. | This 10-year "average" is based on "net present values" that assume that most people prefer to receive returns earlier than later (interest benefits). |
| Machinery repayments only regard harvest weed seed control. | 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, sprayer. Important exceptions are harvest weed seed control tools: these involve specialist machinery and their repayment costs need to be accounted for to compare them with other weed management options. |
| RIM only deals with a partial aspect of the herbicide resistance problem: ryegrass population and gross margins. | RIM aims to provide insights into the biological and economic sustainability of control strategies. RIM does not replace expert judgment and experience, nor does it include aspects such as relevance or applicability of practices, cash flow, market volatility, climate variability, etc. |

Australian grainbelt still heavily rely on herbicides, and justifies the need for preserving their efficacy (Llewellyn et al. 2012; Norsworthy et al. 2012). Even though the base assumptions and recommendations remained essentially unchanged, RIM underwent enough modifications to justify the need for revalidation. Some of this was accomplished through expert evaluations, and by comparing RIM results against long-term observations conducted in Western Australian crop fields (Walsh et al. 2013). Nevertheless, it should be verified whether the relative impacts of the various control techniques are well represented, given the inherent variations found in an area as large and diverse as the Australian southern grainbelt.

*Need for Facilitators and a Workshop Format.* The testing sessions demonstrated that a skilled and knowledgeable facilitator is indispensable in introducing RIM to new users. A facilitator can engage with the audience, relate the options to individual circumstances, and provide information to enable users to use RIM with confidence. For instance, RIM does not provide means to prove that cutting application rates accelerates the evolution of herbicide resistance (Manalil et al. 2011). A nonspecialist audience requires clear explanations about such mechanisms and the new knowledge that has been unraveled about herbicide resistance (Norsworthy et al. 2012). A facilitator can thus add much relevant knowledge that cannot be embraced with RIM alone. Similarly, the limits of RIM's applicability and assumptions need to be explained and understood (Table 4). For instance, years with extreme weather variations could result in different patterns from those simulated in RIM. However, important assumptions are not always constraining or complicating: for instance, explaining that a barley crop can be managed similarly to oat hay can help users understand both how to increase the scope of RIM and what level of precision the DSS deals with. Additional presenters also facilitate putting the issue into context, by providing herbicide resistance expert insights such as regional status update or explanations on evolutionary mechanisms. Another critical reason to promote the use of RIM in a workshop format is that interactions play a critical role in learning, through the exchange of information, perspectives, and experiences with the experts and among the participants themselves (McCown et al. 2009). The importance of group interactions, of obtaining additional information, and of the key role of presenters were demonstrated by RIM workshop surveys where attendees judged those elements almost on par with the accessibility of RIM and the value of exploring scenarios through simulations (Lacoste et al. 2013). This reinforces the fact that any delivery effort should be thoroughly evaluated to identify the strengths and weaknesses of various avenues, as well as to inform future cycles of development.

**Wider Application of RIM.** Originally designed for the dryland broadacre systems of the Australian southern grainbelt, RIM's underlying modeling was restructured to facilitate future updates as well as adaptations.

*Adaptations.* A promising avenue for RIM would thus be to use the current upgraded version as a template for other weed species, particularly in other regions. The original RIM version has proven to be largely accessible and useful to diverse situations, as demonstrated by the various versions and applications that have spawned from it. These include RIM for ryegrass and wild radish in Australian winter cereals ("MultiSpecies RIM," Monjardino et al. 2003), poppies in Spanish winter cereals ("PIM," Torra et al. 2010), barnyardgrass in Philippines rice systems ("PhilRIM," Beltran et al. 2012a), pasture phases in Australian winter cereals (e.g. Doole 2008; Doole and Revell 2010; Monjardino et al. 2004a), and a current adaptation into a Palmer Amaranth Management model ("PAM," Bagavathiannan et al. 2014) and a brome grass model (R. Llewellyn, pers.comm.). RIM also contributed to the foundations of advanced agricultural models such as "LUSO" (Lawes and Renton 2010) and the "Weed Seed Wizard" (Renton et al. 2008). However, all those adaptations were mostly developed as modeling research tools, with few examples of DSS application specifically targeting extension. Examples of relevant situations that could benefit from the wider application of RIM as an extension and education tool include weeds of global or national significance such as wild radish (*Raphanus raphanistrum* L.), kochia (Kochia *scoparia* (L.) Schrad.), or wild oat (*Avena fatua* L.) (Heap 2013). Facilitating the adaptation of RIM was a preoccupation kept at the core of the DSS redevelopment. To simplify the task of future developers the model was restructured with clearer labeling and linkages, room for additional options, and built-in explanations about how to modify the existing ones.

*Student Target Audience.* Even though the agricultural community remains the primary target for RIM, educators also value the usefulness of the software as a teaching tool for university and other students (Lacoste et al. 2013). For instance, a simplified version of RIM was used in a national science program for younger students, as an example of human-induced evolution with practical consequences (Lacoste 2012). This would hold the potential to reach out beyond students specializing in agricultural sciences, and raise awareness of herbicide resistance issues and its consequences for global food production among the general public.

In summary, when upgrading a DSS such as RIM, identifying existing strengths was equally important as detecting weaknesses to ensure effective and efficient redevelopment efforts. At the modeling level, this meant retaining most of the original model principles, with only a few modifications of the underlying assumptions. Additionally, although most of the options were revised and parameters updated to reflect current farming practices, the ryegrass population dynamic submodel was left essentially unchanged. The approach was also applied at the implementation level. A new interface was built, outputs were further exploited, and new functionalities were developed to enhance the ease of use of the software and facilitate delivery efforts. Furthermore, the entire program was restructured to cater to postdevelopment maintenance, updates, and adaptation. Nevertheless, the core idea of letting the user customize inputs and experiment with options was retained, as was the focus on long-term economic considerations. Clearly stating the objectives of the upgrade before starting the work ensured that ambiguity and misdirected efforts were avoided. In the case of RIM, this translated into favoring a user-centered approach focusing on simplicity and flexibility rather than increasing the model's complexity. Reasserting the purpose of RIM as a DSS also permitted to highlight how critical the role of facilitators is in delivering messages. Because the issues surrounding both the evolution of herbicide resistance and the adoption of best management practices are complex, it should be remembered that computer tools such as RIM complement the extension effort, but do not replace it.

## Acknowledgments

This work was funded by the Grains Research and Development Corporation of Australia (GRDC). The authors thank all of the many individuals from various institutions who contributed to RIM throughout its development, particularly from the University of Western Australia (notably from the Australian Herbicide Resistance Initiative and the School of Agricultural and Resource Economics) and from the Department of Agriculture and Food of Western Australia. The authors also thank Muthukumar Bagavathiannan, Gayle Somerville, and Marta Monjardino for comments on the manuscript, and Christopher Preston for his support.

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*Received March 12, 2014, and approved July 21, 2014.*