Sustainability of Grasshopper Management and Support through CARMA

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Abstract

CARMA is an advisory system for grasshopper infestations that has been successfully used since 1996. During CARMA's history, grasshopper control has increasingly focused on environmentally friendly and sustainable strategies. In order to keep pace with and support emerging strategies, CARMA's functionality has been enhanced in a manner which both improves maintainability and which expands CARMA beyond its original role as a grasshopper infestation advisor into that of a grasshopper research support tool. This paper details efforts to develop sustainable grasshopper management strategies and the role that CARMA has played and continues to play in supporting the development and implementation of those strategies.

Figure 1. Grasshopper *Melanoplus bivittatus*, **one of the most devastating grasshopper pests in the western United States. Photo A. Latchininsky.**

1. Introduction

CARMA, short for *CA*se-based *R*angeland grasshopper *M*anagement *A*dvisor, is an advisory system for grasshopper infestations that has been successfully used since 1996 [3, 7]. CARMA illustrates a technique for providing advice about the behavior of a complex biological system by leveraging multiple, individually incomplete, knowledge sources [6] including the application of a technique known as model-based adaptation which combines case-based reasoning with model-based reasoning [4, 5, 9, 10].

Initially focused on rangeland grasshopper infestations within the state of Wyoming, in 2003 CARMA was expanded to include a prototype cropland grasshopper advising module [8]. In recent years, CARMA's advising capabilities were extended beyond Wyoming to include the states of Montana, Nebraska, North Dakota, and South Dakota. The recent extension saw a conversion of the graphical user interface (GUI) to Java in a manner which illustrates a technique for integrating an artificially-intelligent LISP reasoner with a Java GUI [13].

During CARMA's history, grasshopper control has increasingly focused on environmentally friendly and sustainable strategies. For CARMA to remain a relevant and valuable tool, ease of maintainability in keeping CARMA consistent with the most current grasshopper management strategies is of supreme importance. This paper details efforts to develop sustainable grasshopper management strategies and the role that CARMA has played and continues to play in supporting the development and implementation of those strategies.

Section 2 describes the relevance of grasshoppers as economic pests. The difficulties of formulating sustainable response programs are set forth in Section 3. Section 4 provides an overview of RAATS, a sustainable grasshopper response strategy. Section 5 describes the role that CARMA has played in the development and refinement of RAATs. An overview of CARMA's consultation process is provided in Section 6. Section 7 details CARMA's support of the development of new treatment strategies.

2. Grasshoppers as economic pests

Grasshoppers (Orthoptera: Acrididae) are important economic pests worldwide (Fig. 1). They compete with humans and livestock for crops and forage. Hewitt and Onsager [11] estimated that grasshoppers annually consume 25% of available rangeland forage in 17 western U.S. states, at an inflation-adjusted cost of about $1 billion per year. Traditionally, grasshopper control relies on large-scale, blanket applications of broad-spectrum insecticides [22]. For example, during a major outbreak in the western U.S. in 1986-88, over 8 million hectares of native rangeland were treated with 5 million liters of non-selective organophosphate insecticide malathion at a cost of over $75 million [20].

3. Sustainable grasshopper management program: a myth or a reality?

According to the common assumptions, economic benefits from grasshopper treatments last for several years [22, 27], although some entomologists disagree [2]. A detailed study of 30 years of grasshopper treatments in Montana and Wyoming revealed that the probability, duration and stability of grasshopper outbreaks were consistently higher in Wyoming than in adjacent Montana counties [15]. The authors attributed these differences to more intensive insecticidal efforts in Wyoming, which appeared to result in the suppression of the beneficial natural enemies causing a phenomenon known as rapid pest resurgence [23]. In other words, instead of a consistent control of grasshoppers over the years, frequent insecticidal treatment actually created conditions for perpetuating the pest outbreaks [15]. Furthermore, having analyzed almost 50 years of grasshopper survey data for Wyoming, Zimmerman et al. [33] concluded that the benefits of grasshopper control should not be extended beyond the year of treatment.

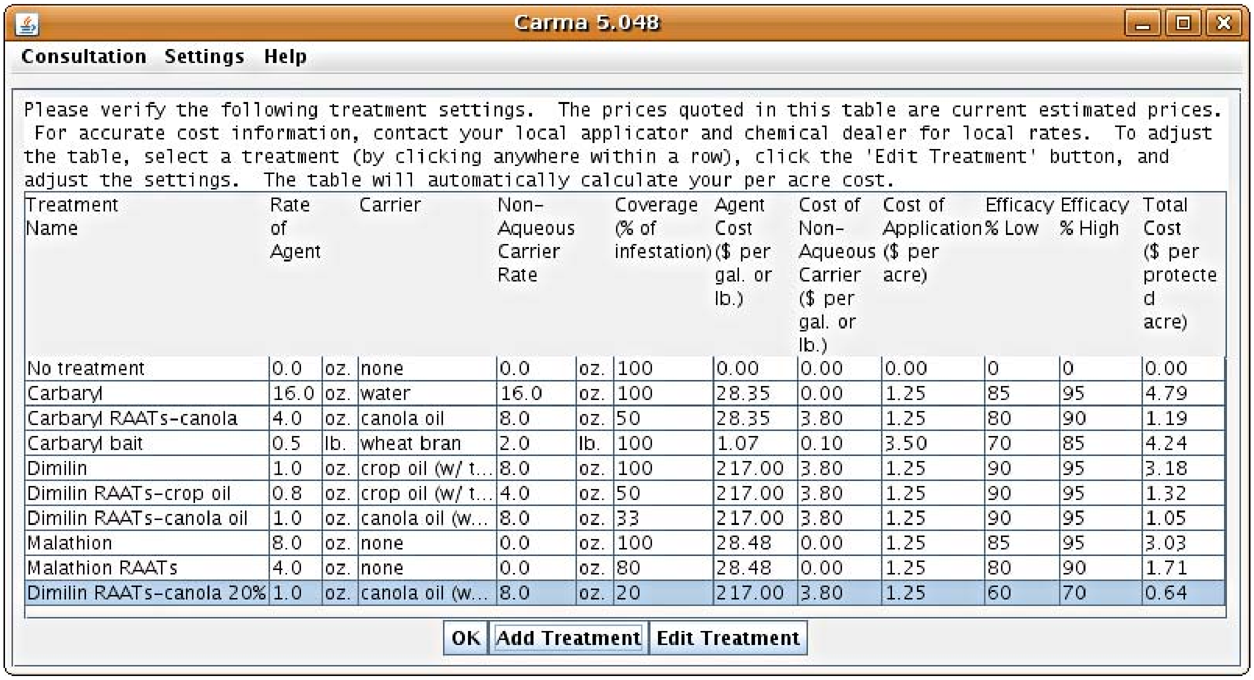
These conflicting points of view do not allow unequivocally answering the question: Can we make grasshopper control sustainable? According to Lockwood et al. [19], to be sustainable a pest management system must be environmentally rational (e.g., it cannot erode the ecological processes that allow the commodity of concern to be produced), culturally viable (e.g., it cannot require practices that would offend the sensibilities of the people), politically tenable (e.g., it cannot be legally or socially prohibited), and economically profitable (e.g., it can not cost more than the perceived benefits, however these may be interpreted). The time over which one assesses the value of acridid pest management is key to whether the program is perceived as being sustainable [19].

Grasshoppers (and even more so, their behavioral alter egos, the locusts) present serious challenges to the sustainability of their control programs. The most fundamental of them is the erratic, boom-or-bust nature of the pest when outbreaks have varying duration and occur at irregular intervals. Because of that, some specialists consider it economically unjustifiable to maintain acridid control infrastructure and conduct pest monitoring during multi-year recessions in between the outbreaks [30]. Such an approach results in a "reactive" or "curative" strategy when control is applied to large-scale, outbreak populations. However, the effectiveness of this approach is questioned by other specialists due to its very high costs and inability to achieve its main goal of ensuring crop protection [24, 26]. The alternative is a preventive strategy which relies on efficient pest monitoring and relatively small-scale treatments of incipient outbreaks or hot spots [25, 32]. According to Lockwood et al. [19], the development of a sustainable grasshopper management system requires the introduction of preventive strategies. Is this task feasible and affordable?

4. Economically and environmentally sound grasshopper control strategies: the first step to outbreak prevention

In an effort to reduce the costs and negative environmental impact of the grasshopper control programs while maintaining their efficacy, Lockwood and Schell [17] developed the Reduced Agent and Area Treatments (RAATs) in which the rate of insecticide is reduced from traditional levels and untreated swaths (refuges) are alternated with treated swaths. The strategy proved efficacious under operational field conditions [18], resulting in better economic returns compared to traditional, blanket applications of insecticide at high rates [14]. RAATs were also shown to produce a lower insecticide pressure on the treated rangeland and reduced impact on non-target arthropods [28, 29] and birds [21]. As a result, RAATs were adopted by the USDA (United States Department of Agriculture) and included in the most recent Environmental Impact Statement [31]. During the decade from the method's inception, RAATs were applied to over 10 million acres of grasshopper and Mormon cricket infested rangelands in 12 U.S. states. In 2003, over 400,000 acres were protected from grasshopper infestation in eastern Wyoming using RAATs strategy, which saved about half a million dollars to local ranchers and farmers.

RAATs are a true Integrated Pest Management (IPM) grasshopper control strategy because it works through chemical control (grasshoppers are killed in the treated



Treatment Name	Rate of Agent		Carrier	Non-Aqueous Carrier Rate		Coverage (% of infestation)	Agent Cost ($ per gal. or lb.)	Cost of Non-Aqueous Carrier ($ per gal. or lb.)	Cost of Application ($ per acre)	Efficacy % Low	Efficacy % High	Total Cost ($ per protected acre)
No treatment	0.0	oz.	none	0.0	oz.	100	0.00	0.00	0.00	0	0	0.00
Carbaryl	16.0	oz.	water	16.0	oz.	100	28.35	0.00	1.25	85	95	4.79
Carbaryl RAATs-canola	4.0	oz.	canola oil	8.0	oz.	50	28.35	3.80	1.25	80	90	1.19
Carbaryl bait	0.5	lb.	wheat bran	2.0	lb.	100	1.07	0.10	3.50	70	85	4.24
Dimilin	1.0	oz.	crop oil (w/ t...	8.0	oz.	100	217.00	3.80	1.25	90	95	3.18
Dimilin RAATs-crop oil	0.8	oz.	crop oil (w/ t...	4.0	oz.	50	217.00	3.80	1.25	90	95	1.32
Dimilin RAATs-canola oil	1.0	oz.	canola oil (w...	8.0	oz.	33	217.00	3.80	1.25	90	95	1.05
Malathion	8.0	oz.	none	0.0	oz.	100	28.48	0.00	1.25	85	95	3.03
Malathion RAATs	4.0	oz.	none	0.0	oz.	80	28.48	0.00	1.25	80	90	1.71
Dimilin RAATs-canola 20%	1.0	oz.	canola oil (w...	8.0	oz.	20	217.00	3.80	1.25	60	70	0.64

Figure 2. CARMA's treatment settings (after adding a new option).

swaths and when they move into them from the untreated swaths) and conservation biological control (beneficial predators and parasitoids preserved in the untreated swaths act as biological control agents) [14, 17, 18]. RAATs represent a significant step towards the ultimate goal of grasshopper outbreak prevention by mobilizing existing natural resources which keep grasshopper pest populations under control. Hence RAATs are a valuable tool in our efforts to make grasshopper control sustainable.

5. Role of CARMA software in RAATs development and refinement

While the environmental benefits of using less insecticide applied to a fraction of the infested area, although obvious, are difficult to quantify, it is the economics of RAATs which represent the most important factor of their rapid adoption. A serious challenge in developing RAATs consisted in optimization of the economic returns, i.e. balancing the reduction in cost (via lowering rates and coverages) with the decreasing efficacy. RAATs typically result in 10 to 15% lower efficacy compared to conventional treatments [17]. However, this reduction in efficacy may be justifiable by the significantly lower treatment costs.

CARMA, which is detailed in the following sections, includes an economic model and the necessary accompanying functionality which is sufficiently flexible to "play" different scenarios depending on the inputs (different dose rates of insecticides applied to different proportions of the infested areas) and required level of forage savings [6]. These qualities of CARMA's economic model made it instrumental in the initial developing of RAATs [17] and in subsequent refinements of the method [14, 18]. Of particular importance was the inclusion of the canola oil adjuvant into CARMA's treatment table (Fig. 2). Canola oil acts as grasshopper attractant and becomes an efficient "liquid bait" allowing a decrease in the rate of the chemical insecticide without compromising the treatment efficacy [16, 28]. Using CARMA, the end-user would exclude unprofitable treatments, such as blanket applications of high insecticidal rates [5]. As such, CARMA's advice results in choosing more economically and environmentally viable grasshopper control strategies and, consequently, in a more sustainable, preventive pest management.

Although the primary driving force for CARMA's creation was the economic motivation, the software addresses well the other criteria for sustainable grasshopper management underlined in Lockwood et al. [19]. It promotes culturally viable practices in a sense that the treatment options it advocates (particularly RAATs) are fully compatible with current strategies of grasshopper control. Furthermore, the inclusion of RAATs as a preferred option in the USDA Environmental Impact Statement [31] makes CARMA's recommendations politically tenable.

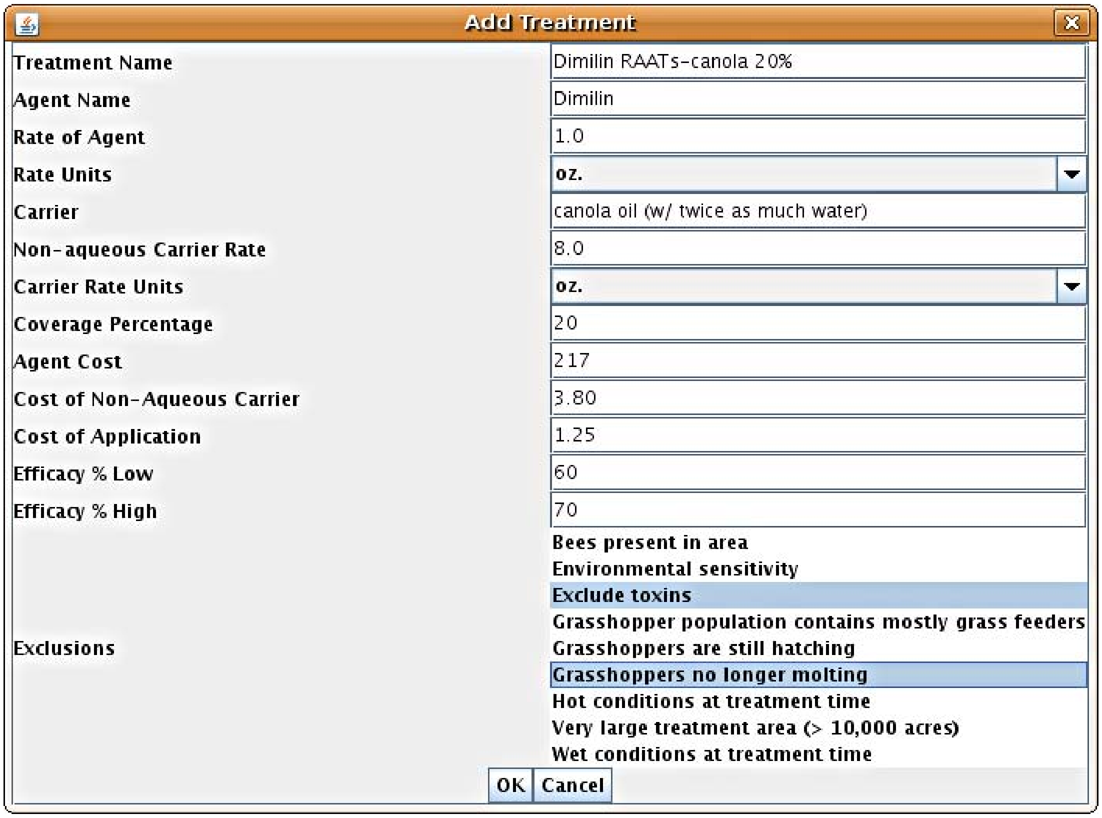


Figure 3. CARMA's add treatment window.

6. CARMA: Decision Support Tool

CARMA is a decision support tool whose original design purpose was to analyze rangeland grasshopper infestations based on information provided by the user (e.g., ranchers, land managers, pest control specialists) during an advising consultation in order to present a narrowed list of the most cost-effective responses. Ascertaining the most cost-effective responses requires, first and foremost, forecasting grasshopper forage consumption. Generating such a forecast requires predicting rangeland ecosystem behavior. The complexity of the domain precludes precise modeling and simulation, thus CARMA's goal is to closely model grasshopper pest management experts who employ a reasoning technique which is precise, efficient, explainable, and robust in the face of data inaccuracies. In estimating forage consumption, experts seem to use a technique termed case-based reasoning (CBR) [1, 12] in the artificial intelligence world by comparing new cases (i.e., new situations) to prototypical cases (i.e., previously experienced situations), and then adjusting the consumption seen in the prototypical cases to account for any differences using an understanding of the underlying domain model (through a technique known as model-based adaptation). As an example of model-based adaptation, if the population density of emerging grasshoppers in a hot, dry spring is high (rather than moderate as seen in a past case), an expert might predict high forage consumption (rather than moderately high as seen in the past case) because a higher density typically means more consumption in the absence of other factors.

The main steps accomplished by CARMA during a consultation are:

1. Estimate the forage consumption by grasshoppers:

    (a) Compile raw observables (e.g., date, location, and grasshopper density and species) entered by the user at a series of GUI input screens into a new case. In order to accommodate a variety of users with varying abilities to provide reliable observations (e.g., specifically identifying grasshopper species), CARMA uses multiple levels of rules for inferring each case feature, ordered by a qualitative estimate of each rule's accuracy or reliability. The rules are applied in succession until either the user provides the necessary information or a default rule is reached.

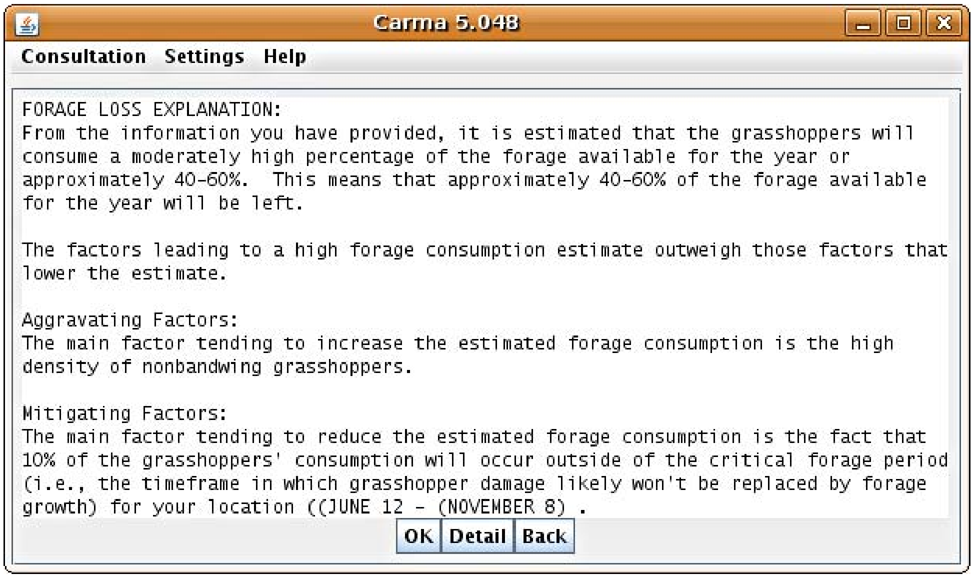


Figure 4. CARMA's forage loss estimation window.

CARMA's goal through this approach is to ultimately provide useful advice regardless of the level of user.

(b) Retrieve the closest matching prototypical case from CARMA's case library using standard case-based reasoning techniques.

(c) Account for differences between the retrieved case and the current case by using model-based adaptation to adapt the forage consumption estimate in the prototypical case to provide an estimate for the current situation.

2. If grasshopper forage consumption will interfere with livestock forage needs, determine the set of acceptable treatments by excluding those treatments which are not applicable, e.g., Dimilin should be excluded if grasshoppers are no longer molting (Fig 3).

3. Perform a cost/benefit analysis using an economic model in order to select the most cost effective response(s) from the set of acceptable treatments.

For in-depth coverage of the rangeland grasshopper infestation advising task and the implementation of the consultation process within CARMA, refer to Hastings et al. [7].

7 CARMA's support of new strategies

When analyzing treatment options, CARMA's original design included only a fixed set of treatment options that mirrored the traditional treatment strategies of the time. After several years of CARMA's existence, particularly during research on RAATs, it became apparent that CARMA could play a larger role in grasshopper management research by supporting the development of new strategies particularly through the addition of functionality which would allow a user to add new treatment formulations and apply them to hypothetical infestation scenarios.

CARMA supports the formulation of new strategies such as RAATs in a couple of ways. First, as detailed in Section 7.1, CARMA allows the user to add new treatment strategies to CARMA using a treatment settings window. Second, as described in Section 7.2, CARMA allows the user to modify consultations and rerun them in order to see the economic utility of potential treatment strategies.

7.1 CARMA treatment settings

To support the periodic and timely update of treatment settings within CARMA through the inclusion of new treatment strategies (e.g., RAATs) or through the update of existing strategies (e.g., insecticidal pricing), CARMA includes a treatment-settings window, shown in Figure 2. This window displays the set of treatment options that are considered by CARMA during a consultation, and allows the user to edit existing options or to create new options. This window is shown either during a consultation or outside of a consultation through the main menu. The treatment-settings window is automatically displayed during a consultation to ensure that CARMA provides a cost/benefit analysis for the various treatment options using the most current costs:

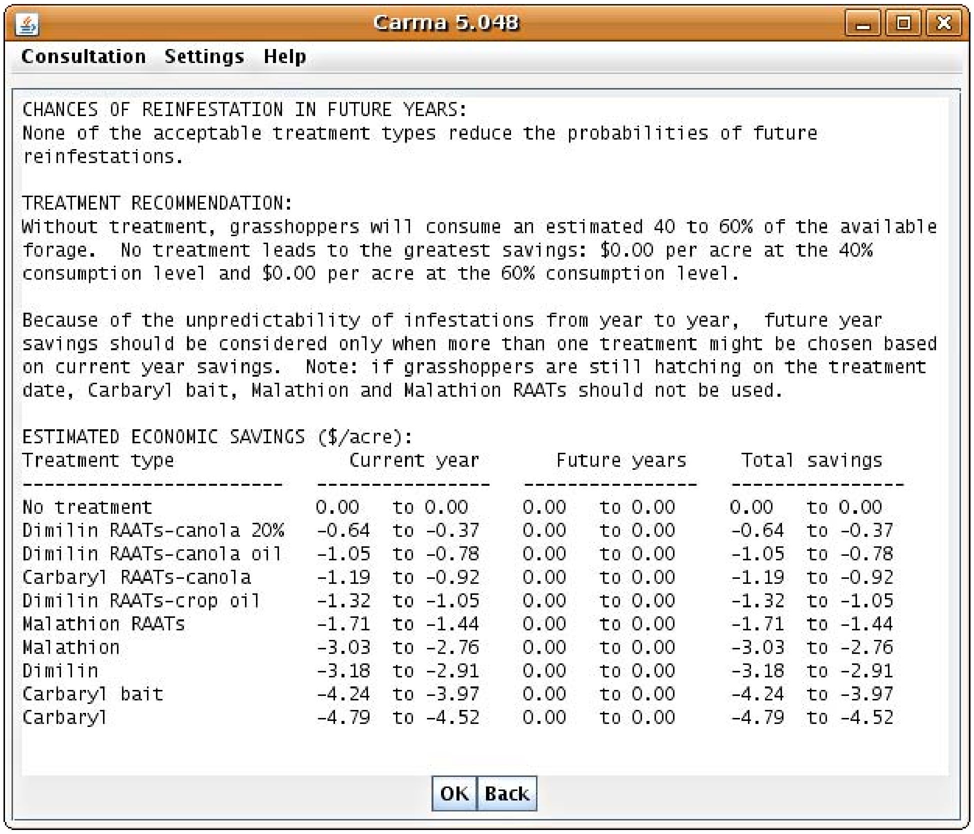


Figure 5. CARMA's treatment recommendation window.

- the cost of the chemical or biological agent which targets the grasshoppers,
- the cost of the carrier through which the agent will be distributed, and
- the cost of the applicator to apply the treatment.

The treatment-settings window can also be accessed outside of a consultation. This method of access is most typical of users wishing to add new treatment options or otherwise make wholesale changes to the treatment settings.

Figure 3 shows the window for adding a new treatment option and in this example is filled with the values for a hypothetical new treatment option. The window for editing existing treatment options is similar to the treatment-add window. In addition to the cost variables, the user can also set the following items:

- treatment name,
- agent name,
- rate of agent,
- carrier name,
- carrier rate,
- coverage percentage,
- expected efficacy (low-high), and
- conditions which would exclude consideration of the treatment option.

The last column of the treatment-settings window (see Figure 2) shows the cost per protected acre for each treatment option. Although determining the cost of an acre protected is relatively straightforward, this calculation has been a common source of errors, particularly when users attempt to compute the costs of RAATs, which involve applying an agent to only a fraction of the infested area. CARMA thus automatically calculates the cost of an acre protected for each treatment option from the editable treatment fields.

Figure 2 shows the available treatment options after the hypothetical treatment from Figure 3 was added. The hypothetical treatment appears in the last row. Through a separate menu, CARMA allows the complete set of treatment settings to be saved by name for future use. To facilitate gaming, CARMA allows treatment settings to be recalled and applied to a consultation.

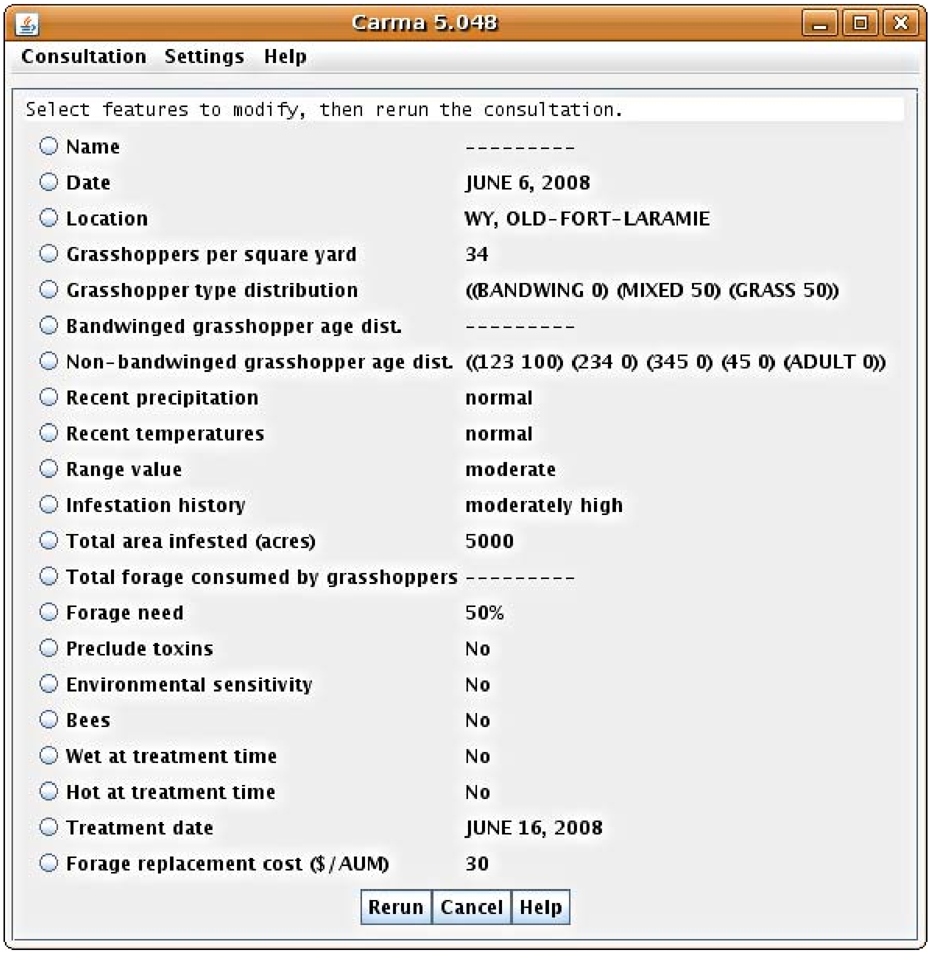


Figure 6. CARMA's consultation modification window.

The treatment-settings window supports both maintainability and gaming of treatment options.

7.1.1 Maintainability

The treatment-settings window permits new options (e.g., RAATs formulations or entirely new agents) to be added to CARMA as they are created, a necessary and valuable feature in light of rapid recent advancements in sustainable grasshopper management techniques.

7.1.2 Gaming

Easy manipulation of treatment parameters supports "gaming" to explore which combination of insecticidal agent, rate, carrier and coverage produces the greatest return on investment (and normally the lowest environmental impact). For example, such gaming can permit researchers to adjust the agent rate to a level which is economical as well as effective given a hypothetical infestation level and replacement forage cost.

7.2 CARMA consultation modification

As previously mentioned, CARMA's main purpose is to analyze a grasshopper infestation based on information provided by the user. CARMA estimates the percentage of forage that will be consumed by grasshoppers and produces an analysis such as the sample shown in Figure 4. In this example, CARMA estimates that a moderately high amount of forage (40-60% of the available forage) will be consumed by grasshoppers. If the forage lost to grasshoppers will cut into the forage needed for livestock, CARMA conducts a cost/benefit analysis for the available treatment options and provides its analysis similar to that shown in Figure 5. In this situation, CARMA determines that the most cost-effective option is to not treat, and that even if a minimal amount of competition for forage occurs, it would

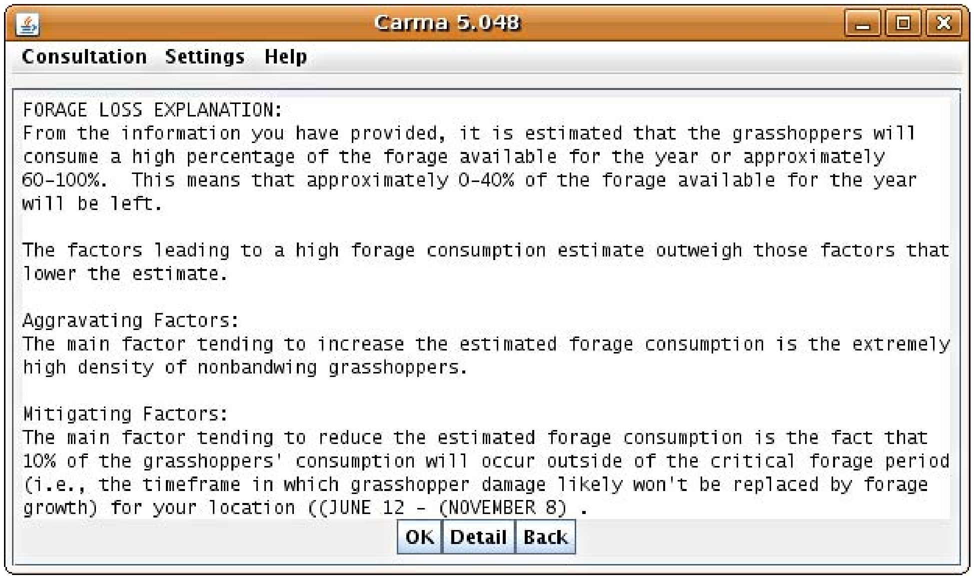


Figure 7. CARMA's forage loss estimation window after modification.

be cheaper to purchase replacement forage.

7.2.1 Gaming

To support gaming with infestation scenarios, CARMA provides the consultation modification window shown in Figure 6. By clicking on a radio button, the user may change the value of an observed infestation field. After making changes to one or more of the fields, the user may then rerun the consultation to see the effect of the changes. Such gaming serves an educational role for users simply wishing to see the effect of the various parameters, but more importantly for the purposes of this discussion, also allows a researcher to determine the types of infestations for which the various treatment options are pertinent.

The fields and values shown in Figure 6 are the result of running through the consultation that produced the analyses shown in Figures 4 and 5 with the per square yard density of grasshoppers bumped up from 24 to 34. The result of rerunning the consultation with the higher grasshopper numbers is shown in Figures 7 and 8. Notice that with the higher grasshopper densities, CARMA estimates that a high amount of forage (60-100% of the available forage) will be consumed by grasshoppers. The resulting analysis shows that treatment could become cost effective as grasshopper consumption moves toward 100% and that if consumption is high, the new hypothetical treatment added in Figure 3 is the preferred option. Note that the economic savings estimates for the 60% consumption level for Figures 5 and 8 do not align (e.g., $-2.91 for Dimilin in the first scenario and $-2.97 in the second scenario) because the cost/benefit analysis is based on the amount of forage that can actually be saved by treatment which is usually applied several days after the infestation is observed and which will allow grasshoppers to consume forage for an additional time.

8 Availability and status

The most recent version of CARMA, 5.048, with rangeland grasshopper advising capabilities for Montana, Nebraska, North Dakota, South Dakota and Wyoming is available free of charge for noncommercial purposes and can be downloaded and installed from http://carma.unk.edu or run as a Java Webstart application.

CARMA is currently being extended to handle infestations in Colorado, New Mexico, and Oregon, in addition to the five states covered in version 5.048.

Since its inception in 1996, CARMA has been presented to pest managers in all 17 western states in which grasshoppers present economic problems. The usability assessment survey for this program is being developed.

9 Conclusion

CARMA is an advisory system for grasshopper infestations that has been successfully used since 1996. During CARMA's history, grasshopper control has increasingly focused on environmentally friendly and sustainable strategies. In order to keep pace with and support emerging strategies, CARMA's functionality has been enhanced in a manner which both improves maintainability and which ex-

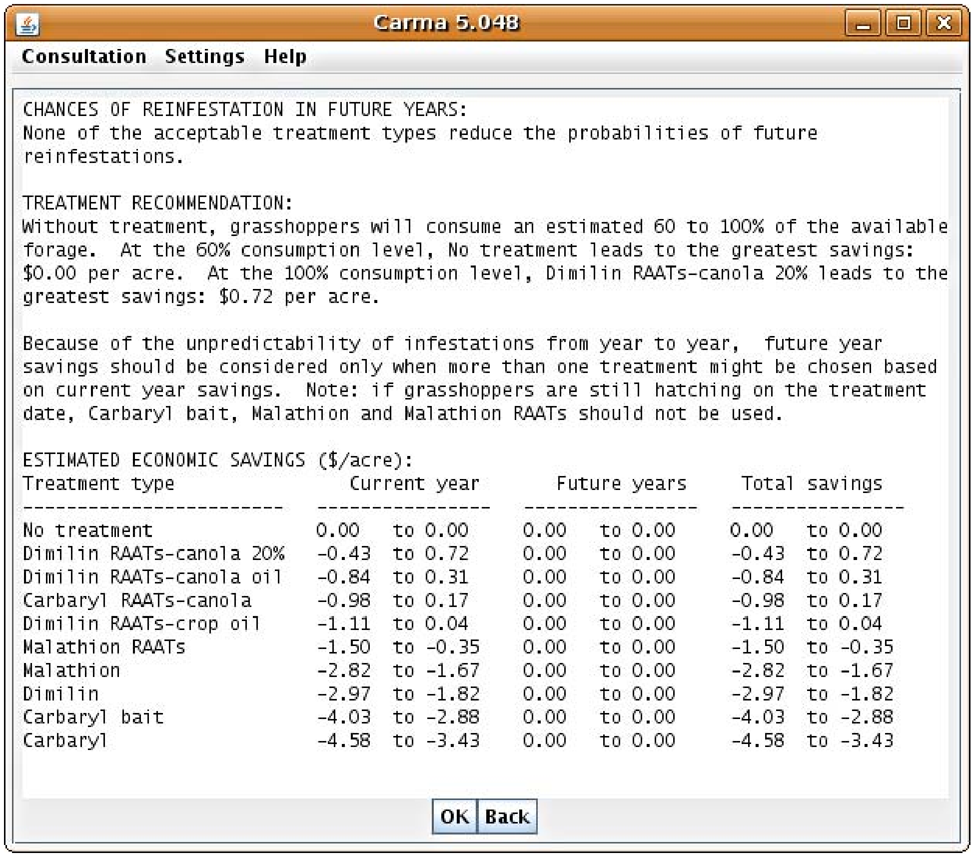


Figure 8. CARMA's treatment recommendation window after modification.

pands CARMA beyond its original role as a grasshopper infestation advisor into that of a grasshopper research support tool capable of allowing researchers to "game" with the economics of potential new treatment strategies. As a research support tool, CARMA was instrumental in the initial development of one particular sustainable management strategy, RAATs, and in subsequent refinements of the method.

10 Acknowledgments

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References

[1] A. Aamodt and E. Plaza. Case-based reasoning: Foundational issues, methodological variations, and system approaches. *AI Communications*, 7(1):39–59, 1994.

[2] C. C. Blickenstaff, F. E. Skoog, and R. J. Daum. Long-term control of grasshoppers. *Journal of Economic Entomology*, 67(2):268–274, 1974.

[3] K. Branting, J. Hastings, and J. Lockwood. CARMA: A case-based range management advisor. In *Proceedings of The Thirteenth Innovative Applications of Artificial Intelligence Conference (IAAI-01)*, pages 3–10, Seattle, Washington, August 2001. AAAI Press.

[4] L. K. Branting and J. D. Hastings. An empirical evaluation of model-based case matching and adaptation. In *Proceedings of the Twelfth National Conference on Artificial Intelligence (AAAI-94) Workshop on Case-Based Reasoning (WS–94–01)*, pages 72–78, Seattle, Washington, July 31-August 4 1994. AAAI Press.

[5] L. K. Branting, J. D. Hastings, and J. A. Lockwood. Integrating cases and models for prediction in biological systems. *AI Applications*, 11(1):29–48, 1997.

[6] J. Hastings, K. Branting, and J. Lockwood. A multi-paradigm reasoning system for rangeland management. *Computers and Electronics in Agriculture*, 16(1):47–67, 1996.

[7] J. Hastings, K. Branting, and J. Lockwood. CARMA: A case-based rangeland management adviser. *AI Magazine*, 23(2):49–62, 2002.

[8] J. Hastings, K. Branting, J. Lockwood, and S. Schell. CARMA+: A general architecture for pest management. In *Proceedings of the Eighteenth International Joint Conference on Artificial Intelligence (IJCAI-03) Workshop on Environmental Decision Support Systems (EDSS-03)*, pages 18–21, Acapulco, Mexico, August 2003.

[9] J. D. Hastings and L. K. Branting. Global and case-specific model-based adaptation. In *Proceedings of the AAAI 1995 Fall Symposium on Adaptation of Knowledge for Reuse (FS–95–04)*, pages 47–53, Cambridge, Massachusetts, November 1995. AAAI Press.

[10] J. D. Hastings, L. K. Branting, and J. A. Lockwood. Case adaptation using an incomplete causal model. In *Proceedings of the First International Conference on Case-Based Reasoning (ICCBR-95) Lecture Notes in Artificial Intelligence 1010*, pages 181–192, Sesimbra, Portugal, October 1995. Springer.

[11] G. Hewitt and J. Onsager. Control of grasshoppers on rangeland in the United States: a perspective. *Journal of Range Management*, 36(2):202–207, 1983.

[12] J. Kolodner. *Case-based reasoning*. Morgan Kaufmann, San Mateo, CA, USA, 1993.

[13] A. V. Latchininsky, J. D. Hastings, and S. S. Schell. Good CARMA for the high plains. In *Proceedings of the 2007 Americas' Conference on Information Systems (AMCIS 2007)*, Keystone, Colorado, August 9-12 2007.

[14] J. A. Lockwood, R. Anderson-Sprecher, and S. P. Schell. When less is more: optimization of reduced agent-area treatments (RAATs) for management of rangeland grasshoppers. *Crop Protection*, 21:551–562, 2002.

[15] J. A. Lockwood, W. P. Kemp, and J. A. Onsager. Long-term, large-scale effects of insecticidal control on rangeland grasshopper populations (Orthoptera: Acrididae). *Journal of Economic Entomology*, 81(5):1258–1264, 1988.

[16] J. A. Lockwood, Narisu, S. P. Schell, and D. R. Lockwood. Canola oil as a kairomonal attractant of rangeland grasshoppers (Orthoptera: Acrididae): an economic liquid bait for insecticide formulation. *International Journal of Pest Management*, 47:185–194, 2001.

[17] J. A. Lockwood and S. P. Schell. Decreasing economic and environmental costs through reduced area and agent insecticide treatments (RAATs) for the control of rangeland grasshoppers: Empirical results and their implications for pest management. *Journal of Orthoptera Research*, 6:19–32, 1997.

[18] J. A. Lockwood, S. P. Schell, R. N. Foster, K. C. Reuter, and T. Rachadi. Reduced agent-area treatments (RAAT) for management of rangeland grasshoppers: efficacy and economics under operational conditions. *International Journal of Pest Management*, 46:29–42, 2000.

[19] J. A. Lockwood, A. T. Showler, and A. V. Latchininsky. Can we make locust and grasshopper management sustainable? *Journal of Orthoptera Research*, 10(2):315–329, 2001.

[20] National Grasshopper Management Board. In *Proceedings and Resolutions of the 1995 meeting of the National Grasshopper Management Board*, Rapid City, South Dakota, January 1995.

[21] E. E. Norelius and J. A. Lockwood. The effects of standard and reduced agent-area insecticide treatments for rangeland grasshopper (Orthoptera: Acrididae) control on bird densities. *Archives of Environmental Toxicology*, 37:519–528, 1999.

[22] R. E. Pfadt and D. M. Hardy. A historical look at rangeland grasshoppers and the value of grasshopper control programs. In J. Capinera, editor, *Integrated pest management on rangeland*, pages 183–196. Westview Press, Boulder, CO, USA, 1987.

[23] W. E. Ripper. Effect of pesticides on balance of arthropod populations. *Annual Review of Entomology*, 1:403–438, 1956.

[24] A. T. Showler. Desert locust (Orthoptera: Acrididae) outbreak in africa and asia, 1992-1994: an overview. *American Entomologist*, 41:179–185, 1995.

[25] A. T. Showler. Proaction: strategic framework for today's reality. In S. Krall, R. Peveling, and D. Ba Diallo, editors, *New Strategies for Locust Control*, pages 461–465, Birkhäuser, Basel, Switzerland, 1997.

[26] A. T. Showler and C. S. Potter. Synopsis of the desert locust, *Schistocerca gregaria* (Forskål), plague 1986-1989 and the concept of strategic control. *American Entomologist*, 37:106–110, 1991.

[27] M. D. Skold and R. M. Davis. Applying economics to grasshopper management, section VI.3. In G. Cunningham and M. Sampson, editors, *Grasshopper Integrated Pest Management User Handbook, USDA-APHIS Technical Bull. No. 1809*. Beltsville, MD, USA, 2000.

[28] D. I. Smith, J. A. Lockwood, A. V. Latchininsky, and D. E. Legg. Changes in non-target arthropod populations following application of liquid bait formulations of insecticides for control of rangeland grasshoppers. *International Journal of Pest Management*, 52(2):125–139, 2006.

[29] I. M. Sokolov. How does insecticidal control of grasshoppers affect non-target arthropods? In J. A. Lockwood, A. V. Latchininsky, and M. G. Sergeev, editors, *Grasshoppers and grassland health: managing grasshopper outbreaks without risking environmental disaster*, pages 181–192. Kluwer, Dordrecht, 2000.

[30] P. M. Symmons. Strategies to combat the Desert Locust. *Crop Protection*, 11:206–212, 1992.

[31] USDA. Rangeland grasshopper and mormon cricket suppression program, Final environmental impact statement–2002. Technical report, U.S. Department of Agriculture, Marketing and Regulatory Programs, Animal and Plant Health Inspection Service, Riverdale, MD, USA, 2002.

[32] A. van Huis, K. Cressman, and J. Magor. Preventing desert locust plagues: optimizing management interventions. *Entomologia Experimentalis et Applicata*, 122:191–214, 2007.

[33] K. M. Zimmerman, J. A. Lockwood, and A. V. Latchininsky. A spatial, Markovian model of rangeland grasshopper (Orthoptera: Acrididae) population dynamics: Do long-term benefits justify suppression of infestations? *Environmental Entomology*, 33(2):257–266, 2004.