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CARMA: Scalability with Approximate-Model-Based Adaptation

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Abstract: Many complex physical systems such as biological systems are characterized both by incomplete models and limited empirical data. Accurate prediction of the behavior of such systems requires exploitation of multiple, individually incomplete, knowledge sources. Our approach, called approximate-model-based adaptation, utilizes case-based reasoning to provide an approximate solution and model-based reasoning to adapt this approximation into a more precise solution. This approach is implemented in CARMA, a decision-support system for grasshopper infestation advising which models experts and has been successfully used since 1996. Initially focused on rangeland grasshoppers within the state of Wyoming, CARMA's capabilities have been extended to support the development and implementation of more environmentally friendly and sustainable strategies and to support advising in nine additional western U.S. states. This paper details our approach to scaling CARMA to the wider geographic region. Prior research indicated that completeness of the model-based knowledge used for matching and adaptation is more important to CARMA's accuracy than coverage of the case library. Given the importance of the model as a tool for refinement and accuracy, and that the cases are mostly void of region-specific information, our approach is thus to continue using the cases without changes as a general source of approximate predictions, and to extend the region-specific historical information required by the model as necessary to provide regional accuracy. The relative ease with which CARMA has been scaled thus far lends confirmation to the fact that CARMA's modeling of the experts is accurate.

Keywords: scalability; environmental decision support; case-based reasoning; model-based reasoning; sustainable grasshopper management

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 (Hastings et al. [2002]). CARMA employs a variety of artificially-intelligent (AI) techniques to provide advice about the most environmentally and economically effective responses to grasshopper infestations. In the process, CARMA illustrates an approach to providing advice concerning the behavior of a complex biological system by leveraging multiple, individually incomplete, knowledge sources (Hastings et al. [1996]) including the introduction of a technique known as *approximate-model-based adaptation* which integrates case-based reasoning (Aamodt and Plaza [1994]; Kolodner [1993]) with model-based reasoning for the purpose of prediction within complex physical systems. Approximate-model-based adaptation is defined and contrasted with perfect-model-based adaptation by Branting [1998].

CARMA was designed with usability as a primary goal with the intention being to present an interface so intuitive that it completely eliminates the need for a user manual. Recent "non-biased" survey results (Hastings et al. [2010]) using a modified online form of the desirability toolkit (Benedek and Miner [2002]) suggest that the approach employed in CARMA's interface is a success. In 2003 CARMA was expanded to include a prototype cropland grasshopper advising module (Hastings et al. [2003]) in order to handle situations when grasshopper populations build up at the rangeland-cropland interface and spread into cropland such as small grains. Furthermore, the graphical user interface (GUI) has been converted to Java in a manner which illustrates a technique for integrating an artificially-intelligent Lisp reasoner with a Java GUI (Hastings and Latchininsky [2009]). The implementation follows a philosophy called *platform freedom* which emphasizes freedom from both platform dependence and software costs, and in the process demonstrates an approach to creating a web-capable Lisp application with an appealing GUI.

Initially focused on rangeland grasshoppers within the state of Wyoming, CARMA's capabilities have been extended to support the development and implementation of more environmentally friendly and sustainable strategies, and to support advising in nine additional western U.S. states: Colorado, Idaho, Montana, Nebraska, New Mexico, North Dakota, Oregon, South Dakota, and Utah. The regional extension increases CARMA's overall coverage from 97K square miles (253K km sq) to 963K square miles (2494K km sq). This paper details our approach to scaling CARMA to the wider geographic region. Prior research indicated that completeness of the model-based knowledge used for matching and adaptation is more important to CARMA's accuracy than coverage of the case library. Given the importance of the model as a tool for refinement and accuracy, and that the cases are mostly void of region-specific information, our approach is thus to continue using the cases without changes as a general source of approximate predictions, and to extend the region-specific information required by the model as necessary to provide regional accuracy. The relative ease with which CARMA has been scaled thus far lends confirmation to the fact that CARMA's modeling of the experts is accurate.

Sections 2 through 4 describe the problem domain and CARMA's evolving role as a decision support tool in the world of sustainable grasshopper pest management. Section 5 details CARMA's problem-solving approach as modeled after domain experts. Our approach to scaling CARMA is described in section 6, followed by a discussion in section 7.

2 GRASSHOPPERS AS ECONOMIC PESTS

Competing with humans and livestock for forage and crops, grasshoppers (Orthoptera: Acrididae) are a serious economic problem in 17 U.S. states west of the Mississippi. They are estimated to destroy annually about 25% of the available rangeland forage in the U.S., at an inflation adjusted cost of US$1 billion (Hewitt and Onsager [1983]). Currently, the only efficient strategy to deal with a grasshopper outbreak consists in the use of insecticide applications. During the 1986-88 outbreaks, 20 million acres of western rangeland were treated with 1.3 million gallons of insecticides at a cost of US$75 million. Besides their high economic cost, large-scale insecticidal programs that "blanket" grasshopper infestations may be detrimental to the environment (USDA [2002]) and can even aggravate grasshopper outbreaks over the long-term (Lockwood et al. [1988]).

3 CARMA: GRASSHOPPER DECISION SUPPORT

CARMA provides the end-user with advice regarding grasshopper population management options in an economically and environmentally sound fashion. Historically, rangeland infestations were considered treatable when grasshoppers occurred at densities of eight or more grasshoppers per square yard. While this treatment threshold was thought to make sense from a protectionist point of view (i.e., protect the existing forage at all costs so as not to risk forage shortages), it did not always make economic sense (Lockwood and Schell [1995]). CARMA conducts detailed analysis of infestations looking at a number of factors including grasshopper densities as well as range productivity in order to provide an economic analysis of an infestation. In cases where treatment costs will outweigh the estimated value of forage saved by treatment, CARMA advises a "no treatment" option, which provides the greatest environmental savings of all.

4 CARMA AND SUSTAINABLE PEST MANAGEMENT

In addition to conventional, blanket applications of broad-spectrum insecticides like malathion and carbaryl, CARMA considers an option called Reduced Agent and Area Treatments (RAATs) (Lockwood and Schell [1997]). In fact, CARMA was instrumental in developing the RAATs strategy. RAATs is a method of integrated pest management (IPM) for rangeland grasshoppers in which the rate of insecticide is reduced from conventional levels as untreated swaths (refuges) are alternated with treated swaths. RAATs works both through chemical control, meaning grasshoppers are killed in treated swaths and as they move out of untreated swaths, and conservation biological control, which allows predators and parasites preserved in untreated swaths to suppress grasshoppers. Less insecticide in the environment lowers the risk to native species (including fish and wildlife), water quality, and humans. The untreated swaths provide a refuge for organisms with lower mobility than grasshoppers, and even those organisms that move into the treated swaths will be largely unaffected unless they feed on the foliage. The untreated swaths harbor species essential to rangeland ecosystems, including bio-control agents of grasshoppers and weeds. Low densities of surviving grasshoppers allow predators and parasites in the untreated refuges to recolonize and thereby reestablish natural regulation of grasshopper populations. For these reasons, RAATs programs also may sustain higher densities of birds than blanket applications. This IPM approach (RAATs) can reduce the cost of control and the amount of insecticide applied to our rangelands from 50 to 75% (Lockwood et al. [2002]). In 2003, the RAATs strategy was applied to 400,000 acres in Wyoming which saved half a million US dollars for local agriculturists. The contribution that CARMA has played and continues to play in supporting the development and implementation of sustainable pest management strategies such as RAATs is detailed in Hastings et al. [2009]. RAATs became the preferred option in the USDA-APHIS Environmental Impact Statement when grasshopper control is required (USDA [2002]). CARMA is the only pest management software that includes RAATs as an option and an open-ended capacity for user-based treatment updates. In fact, Hopper (USDA [2004]), the only other grasshopper pest management tool of which we are aware, never included RAATs and its development has been indefinitely suspended by USDA-APHIS.

5 CARMA MODELS THE EXPERTS

CARMA is modeled after grasshopper pest management experts and interacts with users through the same sort of guided consultation employed by experts. The user is queried for information as needed in order to satisfy goals in an internal goal structure with the top-level goal being a completed consultation (or treatment recommendation). Much of the user input is used to construct an infestation case.

Briefly, the main steps in a consultation (as modeled after experts) are:

1. Determine the relevant facts of the infestation case from information provided by the user by means of heuristic rules.
2. Predict the proportion of available forage that will be consumed by each distinct grasshopper population using approximate-model-based adaptation.
3. Compare total grasshopper consumption with the proportion of available forage needed by livestock to determine if competition for forage will occur.
4. If the predicted forage consumption will lead to economic loss, determine which possible treatment options are excluded in the current situation.
5. Provide an economic analysis for each viable treatment option and recommend the treatment or treatments that are most economical.

For a detailed description of the rangeland grasshopper infestation advising task and the implementation of the consultation process within CARMA, the reader is referred to Hastings et al.

[2002]. Approximate-model-based adaptation from step 2 is most relevant to the later discussion on scaling CARMA and is thus described in greater detail in the following subsection.

5.1 Approximate-model-based Adaptation

Our protocol analysis indicated that entomologists estimate forage consumption by comparing new cases to prototypical infestation scenarios. These prototypical cases differ from conventional cases in two important respects. First, the prototypical cases are not expressed in terms of observable features (e.g., "Whenever I take a step, I see six grasshoppers with brightly colored wings fly"), but rather in terms of abstract derived features (e.g., "Approximately nine nymphal overwintering grasshoppers in the adult phase per square yard"). Second, the prototypical cases are extended in time, representing the history of a particular grasshopper population over its lifespan. Each prototypical case is therefore represented by a "snapshot" at a particular, representative point in time selected by the entomologist. In general, this representative point is one at which the grasshoppers are at a developmental phase in which treatment is feasible.

CARMA begins a consultation by eliciting information to determine the relevant features of a new case. CARMA can then employ approximate-model-based adaptation whereby the causal model assists case-based reasoning in four different ways: case factoring; temporal projection; featural adaptation; and critical-period adjustment. The assumption underlying approximate-model-based adaptation is that the causal models associated with a biological or other partially understood systems may be accurate in the neighborhood of a case, even if the models are insufficient for accurate prediction throughout the entire feature space.

1. Factoring Cases into Subcases. CARMA's consumption prediction module first splits the overall population into subcases of grasshoppers with distinct overwintering types (i.e., overwintering as nymphs or eggs), since forage consumption by those that overwinter as nymphs is much different from consumption by those that overwinter as eggs.

2. Temporal Projection. Before performing case matching and adaptation in order to predict the forage loss of a subcase, CARMA retrieves all prototypical cases whose life history (i.e., overwintering type) matches that of the subcase, and projects the prototypical cases forwards or backwards to align their average developmental phases with that of the new subcase.

3. Featural Adaptation. The consumption predicted by the best matching prototypical case is modified to account for any featural differences between it and the subcase. This adaptation is based on the influence of each feature on consumption as represented by featural adaptation weights learned through hill-climbing (Branting et al. [1997]).

4. Critical-Period Adjustment. Consumption is only damaging if it occurs during the critical forage growing period of a rangeland habitat. The forage loss predicted by a prototypical case must be modified if the proportion of the lifespan of the grasshoppers overlapping the critical period differs significantly in the new case from the proportion in the prototypical case.

For a more complete description of approximate-model-based adaptation in CARMA, see Branting et al. [1997].

6 SCALING CARMA

In order to scale CARMA's reasoning capabilities to cover a broader geographic area, the portions of CARMA affected by changes in location obviously need to be considered. While this might otherwise be a daunting task for systems which attempt a more precise form of simulation, an extension is actually quite manageable for CARMA given the generality of its design in dealing with domain concepts. For example, rather than reasoning with individual grasshoppers species – a level of granularity that when scaling would require adding new species because individual species vary from state to state and even location to location within a state – CARMA reasons with a general categorization of grasshopper species (i.e., bandwing, slantfaced and spurthroat) that are fully applicable across the entire western U.S.. This generality plays itself out throughout CARMA and greatly supports its ease of scalability.

Because CARMA's primary reasoning task is approximate-model-based adaptation, our work on scaling CARMA focuses on the effects of applying this task to new locations. The role of location in this task and our approach to scaling are described in the following subsections.

6.1 Determining relevant case facts

As mentioned in the consultation steps in section 5, before performing approximate-model-based adaptation, CARMA determines the relevant facts of a new case based on information provided by the user. Several case attributes default to historical values for the location. These historical values are presented to the user, at which time the user has the option to override the default. The absence of historical information for a location would prevent a user from seeing what constitute reasonable conditions (or inputs) for their location or surrounding locations thereby preventing an informed choice, and could cause CARMA's performance to degrade drastically as the user is more likely to provide values which differ greatly from what would be reasonable for their location. Given the importance of this historical information, CARMA is simply not programmed to function without it.

The primary location-specific historical information required by CARMA and its relevance to the grasshopper advising task are as follows:

1. Infestation history: A higher frequency of outbreaks for a location suggests a greater potential for damage given the presence of grasshoppers for that location.

2. Historical range productivity: Locations with higher range forage productivity are better able to replace, through rapid plant growth, any forage consumed by grasshoppers.

3. Historical weather information: Weather patterns for temperature and precipitation influence both infestation frequencies and range productivity. Variations from historical weather values suggest the potential for a greater or lesser likelihood of grasshopper damage, e.g., lower than average precipitation amounts for a location given average conditions for other relevant factors will negatively impact forage production and positively influence grasshopper survival and thus suggests an increased likelihood of an effect from grasshopper consumption of forage.

6.2 Location within the Cases

Although CARMA's cases were originally constructed with Wyoming infestation scenarios in mind, the fields within the cases are almost entirely location neutral. The only location-dependent fields are the following:

1. Infestation location: all of CARMA's cases are centered at LaGrange, WY,

2. Date: the dates are representative of outbreaks which could occur at LaGrange with the dates varying according to the timing and type of outbreak represented, and

3. Critical period dates: all of the cases, because they are centered at LaGrange have a beginning critical period date of June 12.

The other case fields vary simply based on the specifics of the outbreak being represented independent of the location of the outbreak, e.g., one case might have a per-square-yard grasshopper density of 12 while another might have a density of 35. Even the fields from the previous subsection (i.e., range value, infestation frequency, temperature, and precipitation) which default to historical values are location neutral when viewed in the context of a case. For example, range value is location neutral in the sense that a range value of "moderate" for a location in Wyoming has the same meaning as a range value of "moderate" for a location in Idaho.

6.3 Approach to Scaling

It was apparent that in extending CARMA, historical information would need to be augmented as appropriate for any new location added to CARMA. We chose to represent histories on a state by state basis because the extension has been handled incrementally state by state. For each new state, CARMA has seen the addition of state-specific infestation history maps, historical range productivity maps, and historical weather information (the extension thus far has resulted in the addition of histories for 147 weather stations per state on average). In addition, CARMA's user interface has been generalized beyond Wyoming to dynamically handle and display state-specific information, e.g., the location elicitation window has been modified to access and display the road map for the state selected by the user.

Scaling the historical information and related user windows has been relatively straightforward and has required minimal adjustments to the code itself, although the handling and conversion of the historical information itself has been somewhat time consuming. The scaling of the input windows was subsumed by the overall revamping of the user interface mentioned in section 1 and would have otherwise required more work to generalize to multiple states. CARMA's infestation history maps are generated from the USDA's ArcGIS files by first exporting to a flat image format already recognized by CARMA, and then scaling for display purposes. In the future, it would be ideal to augment CARMA so that it handles GIS source formats more directly. CARMA's existing weather histories for Wyoming had years ago been tediously hand coded into a text file from a climate history textbook. At the outset of the recent scaling process, conversion code was written to transform information from digital climate center files into the form required by CARMA.

But, what to do with the cases? CARMA's existing cases are most definitely Wyoming cases. Would an extension require state-specific cases or are the cases general enough to avoid greatly augmenting the case library? Prior research indicated that completeness of the model-based knowledge used for matching and adaptation is more important to CARMA's accuracy than coverage of the case library (Branting and Hastings [1994]). Based on the results of this research, CARMA's case library for the initial releases of CARMA for Wyoming was kept justifiably small. For Wyoming, the model was powerful enough to avoid augmenting the cases. But for a larger region, is the model powerful enough (when bolstered with the extended region specific information) to entirely handle scaling CARMA to new regions without developing state or region specific cases? Surprisingly, the answer is yes! The key turns out to be a component within critical period adjustment.

Although the cases were developed for Wyoming, as previously mentioned they are mostly location neutral. A grasshopper outbreak of similar magnitude in Wyoming will play out in a similar fashion in other western states given similar characteristics - the only features that will vary because of the difference in location are the dates at which the outbreaks occur and the critical period dates. For example, an outbreak near Ogallala, Nebraska will occur earlier in the year than LaGrange, Wyoming, and will have an earlier beginning critical period date because phenological events occur earlier in the year at Ogallala. The ability to predict the timing of biological events for genetically identical organisms is sometimes described by Hopkins' bioclimatic law (Hopkins [1920]) which states that phenological events vary at a rate of four days for each degree of latitude, each five degrees of longitude, or each 400 feet of altitude, with events being later northward, eastward, and upward.

The critical period of a specific parcel of rangeland is determined by the parcel's location (i.e., latitude and elevation). For Wyoming, CARMA accounts for differences in location from cases centered at LaGrange, WY by shifting critical period dates using an adjustment based on bioclimatic law. Longitude plays a negligible role when dealing with rangeland grasshoppers, and according to the domain experts (Dr. Jeffrey Lockwood and Dr. Alexandre Latchininsky), can be entirely eliminated from the adjustment. CARMA's function for calculating the date adjustment based on differences in location is as follows:

function `DateLocationAdjustment`($location$)
  return $(location_{latitude} - LaGrange_{latitude}) * 4$
    $+(location_{elevation} - LaGrange_{elevation}) * 0.007$

This adjustment works well for Wyoming, and in the judgment of the experts, is applicable to the entire western U.S. region within which rangeland grasshoppers are of concern. After temporal projection is applied, CARMA adjusts the date and the critical period dates of the new case based on the adjustment specified by this function. These adjusted dates are then used internally in performing critical-period adjustment.

7 DISCUSSION

Although not initially created with future extensions in mind, the extension of CARMA has been quite natural given CARMA's inherent scalability which is a combination of the scalability of the problem-solving approach and the implementation.

7.1 Scalability with approximate-model-based adaptation

CARMA's scalability beyond Wyoming is tightly bound to the applicability and relevance of the problem-solving approach (i.e., approximate-model-based adaptation) within this domain over the entire region. The experts, on which CARMA's approach is based, use this technique while traveling throughout Wyoming and beyond, and thus the scalability of CARMA itself is in fact a product of the scalability of the approach employed by experts. The effort required to scale CARMA (analogous to asking an expert to problem solve in different regions), is thus tied to the accuracy of CARMA's initial modeling of the experts' process. The fact that CARMA has been scaled with relative ease without changes to the model or the cases lends confirmation to the fact that CARMA accurately modeled the experts in the first place.

7.2 Scalability of the implementation

The implementation is a fairly direct by-product of the problem-solving approach, but nevertheless implementation choices have a strong effect on scalability. Briefly, CARMA's implementation scalability relates to:

1. The generality of CARMA's design in dealing with domain concepts: CARMA was not initially developed to be so specific that new models or cases were required to handle low-level processes and features within specialized regions.
2. The applicability and relevance of the domain concepts in the cases and model throughout the new regions (e.g., range values).
3. Minimal location specific info in cases which can be applied to new locations by the date adjustment component within the model.
4. The availability of historical regional information for the new regions without which extensions to such regions would not be possible.

5. The technologies used: the scaling of CARMA would have been hampered had CARMA not evolved through modern technologies that would benefit its long-term existence via platform freedom (i.e., freedom from platform dependence and software costs) as mentioned in section 1. Without long-term stability, the extensions would not have been likely.

To further elaborate on item 1, based on the technique employed by experts, CARMA reasons with grasshopper categories rather than individual species in a manner which is representative of grasshopper populations throughout the western U.S.. Despite the fact that there are more than 500 grasshopper species in North America, only about 20 of them are recurrent economic pests throughout the West. In Wyoming, eight species are of major economic importance. Most of these species are also the main grasshopper pests in the surrounding states. The fact that the complex of pest species varies insignificantly from one state to the next further confirms the robustness of the initial implementation and contributes to the scalability of CARMA beyond Wyoming.

7.3 Scalability of approximate-model-based adaptation in other domains

For the task of rangeland grasshopper infestation advising, CARMA has not required new region-specific cases. A positive in that respect is that CARMA scales to new locations for which expertise necessary for formulating regional cases is otherwise hard to come by or entirely lacking. Obviously, this makes extensions to new regions not only possible, but fast. However, the fact that CARMA has not needed new cases or models is as much a product of the problem domain as the reasoning approach (i.e., approximate-model-based adaptation). Additions to CARMA's cases and model were not required, and this works well for this problem domain and geographic region. CARMA reasons based on the relevant attributes of an existing and observable grasshopper population and provides suggestions based on what it predicts the grasshopper population will do. CARMA factors in, but is only required to minimally account for, any additional hatching that grasshoppers might do. However, if the problem were slightly different, regional cases or models might be required. An example is the task of predicting, prior to hatching, the number of grasshoppers that will be seen in a location on a specific date. While in temperate latitudes of Wyoming, Montana and other surrounding states where all grasshoppers are univoltine, certain grasshopper species may have more than one generation per year in southernmost locations such as south Texas or Arizona. For such a task, approximate-model-based adaptation would likely be applied on a more regional basis by plugging in regional cases or models.

7.4 Evaluation of the Model

The "accuracy" of CARMA's extension has not been assessed. Such an assessment represents a challenge to say the least. Ideally, we would attempt to determine the accuracy of CARMA in modeling the problem domain itself. Unfortunately, such an evaluation is complicated by the absence of empirical data against which to measure CARMA's predictions, and is in fact part of the rationale behind the expert-system approach employed by CARMA in the first place. Gathering such data would be a monumental undertaking in and of itself.

Since CARMA aims to model experts and not the domain directly, an evaluation could instead focus on CARMA's accuracy in modeling experts. Such an evaluation was previously performed for Wyoming (Branting et al. [1997]). Surveys were distributed to various experts to determine the amount of forage loss expected in various prototypical scenarios. CARMA was then tuned to see how accurately it could model those experts. The exercise revealed a couple things. Most importantly, it was found that CARMA can be tuned to accurately model any expert. A second and most distressing finding was that the predictions for these situations varied widely – some experts routinely predicted higher forage losses, while others predicted lower. It was hypothesized that the predictions were influenced by each expert's risk aversion (i.e., a risk-averse expert would predict a higher forage loss knowing that a treatment could be applied to end a grasshopper infestation and thus not take the risk of predicting an overly low forage loss). CARMA was ultimately made risk-neutral by tuning it on the median of the expert predictions.

In CARMA's extension to new states, an initial survey effort failed to elicit an adequate response. Given that experts felt that CARMA's approach was uniformly applicable to the new states, the survey effort was abandoned and the focus was turned toward the extensions. However, had the surveys elicited a response, it is highly likely that the returns would have been problematic in that they would have varied widely from state to state (and expert to expert) suggesting that CARMA be tuned individually for each state, not because there is something different going on in each state, but simply because each expert has a varying aversion to risk. It would be preferable to determine how effectively CARMA models that one perfect expert who is intimately familiar with all of the regions in the western U.S., but no such expert exists.

8 AVAILABILITY AND STATUS

The most recent version of CARMA, 5.051, with rangeland grasshopper advising capabilities for Colorado, Idaho, Montana, Nebraska, New Mexico, North Dakota, Oregon, South Dakota, Utah and Wyoming is available free of charge for noncommercial purposes and can be downloaded and installed from http://carma.johnhastings.org or run as a Java Web Start application.

Since its inception in 1996, CARMA has been presented to pest managers in all 17 western states in which grasshoppers present economic problems. Future work may involve extending CARMA to additional western U.S. states beyond the ten states covered in version 5.051, or adding the ability to grab real-time location specific information (e.g., weather information).

9 SUMMARY

As detailed, CARMA is a grasshopper pest management support tool which has been extended from its original target location of Wyoming in order to provide rangeland grasshopper pest management capabilities in nine additional western U.S. states. CARMA's core reasoning approach, called approximate-model-based adaptation (a combination of case-based and model-based reasoning) has been scaled accordingly. Surprisingly, the model and cases themselves did not require modification due to the robustness of the original expert approach as modeled by CARMA. Instead, the extension required the addition of region-specific historical information as required by the model in order to support accurate user input. The relative ease with which CARMA has been scaled to a much wider geographic area speaks favorably of the approach used by experts, but also lends confirmation to the accuracy with which CARMA modeled the experts in the first place. Although the scaling went quite smoothly in this domain, scaling within other biological domains might require additional work. However, the flexibility of approximate-model-based adaptation should support scalability in such domains by simply plugging in additional cases or models.

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