ABSTRACT The Grasshopper Integrated Pest Management Project (GHIPM) was a $15 million project that lasted from 1986 to 1994 to identify, develop, and implement rangeland grasshopper management tactics within the framework of Integrated Pest Management (IPM) in the western United States. Computer simulation has been used to fulfill many original objectives for GHIPM and help bridge the gap between theory and practice. One group of computer simulation studies was developed to probe basic mechanisms of rangeland grasshopper ecology. For example, an object-oriented simulation is being developed that can represent any number of unique grasshopper cohorts for specific species, life stages, and disease status. Soil temperature and moisture are also being simulated to support a grasshopper egg hatch model. These research models were designed for basic science with a focus on improving management of rangeland grasshoppers. Another group of models has been developed and/or used to simulate grasshopper population dynamics, forage growth and destruction, and ranch economics for essentially all rangeland areas in the western United States. These models are used in a computer decision support system called Hopper to structure and provide knowledge to land managers who make decisions about grasshopper control. Hopper provides objective analyses of management options including innovative IPM strategies that could not be effectively evaluated in the past. The development of Hopper and supporting models has caused a paradigm shift from the goal of maximizing control mortality to the IPM goal of optimizing economic, environmental, and social values. Hopper was adopted in 1994 and is used to evaluate all federal programs for rangeland grasshopper management. Now the scope of grasshopper management includes techniques that may or may not cause grasshopper mortality. For example, modifying cattle herd size and grazing management strategies may allow the IPM goal to be reached better than control options. Also, reduced control and the associated reduction in cost from a reduction in pesticide used for control can sometimes provide the best economic return in addition to other longer term benefits. Computer simulation within Hopper has provided the flexibility to apply IPM to a complex of grasshopper species over a geographically very large and ecologically diverse area.

KEY WORDS Computer simulation, IPM, economic threshold, population dynamics, Orthoptera

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Grasshoppers are the major invertebrate pests of rangelands in the western United States (Hewitt 1977). For example, Hewitt and Onsager (1983) have estimated losses to grasshoppers to be about $393 million/year on western rangeland. Grasshopper infestations often occur over large areas of land owned or managed by many private individuals and land management agencies. Therefore, coordinated management efforts are required when dealing with large infestations. The United States Department of Agriculture, Animal and Plant Health Inspection Service, Plant Protection and Quarantine (USDA-APHIS-PPQ) has been authorized to administer these cooperative management programs since 1937 under the Incipient and Emergency Control of Pests Act (1937), the Organic Act of the Department of Agriculture (1944), the Cooperation With State Agencies in the Administration and Enforcement of Certain Federal Laws Act (1962), and the Food Security Act of 1985 (see USDA-APHIS 1987).

In 1986, APHIS initiated a 5 yr, $15 million Grasshopper Integrated Pest Management Project (GHIPM) to identify, develop, and implement grasshopper management tactics in the framework of Integrated Pest Management (IPM). The project received a 3 yr extension that ended September 1994 to facilitate IPM technology implementation. A programmatic Environmental Impact Statement (EIS) of rangeland grasshopper management identified IPM as the preferred strategy for rangeland grasshopper management (USDA-APHIS 1987). In the 1987 EIS, IPM was defined as "... the selection, integration, and implementation of pest control tactics in a systems approach based on anticipated economic, ecological, and sociological consequences." IPM can also be thought of as a decision-making process that relies on information at each step. Some information, such as pest density, can be found directly by sampling the pest population in the field whereas other information is very difficult to obtain. For example, projected yield loss and future damage potential cannot be determined directly and may depend on many factors, such as weather, grasshopper species and age structure, and plant species composition (Berry et al. 1992, Davis et al. 1992).

The rangeland ecosystem is less productive per unit area and is, thus, less intensively managed than most crop systems. Also rangeland is more complex than monocultures. For example, there are more than 400 species of grasshoppers that inhabit the 17 western states (Pfadt 1988). Also, rangeland occurs from hot desert to lush mountain valleys. Within the rangeland ecosystem, weather can greatly affect a management decision (Davis et al. 1992) and can vary from year to year and site to site. Therefore, rangeland grasshoppers cannot be managed with simple decision rules such as a static economic injury level. In addition, the per unit area value of forage is low, about $2.50 to $7.50/ha (Hewitt and Onsager 1983). Consequently, decisions must be accurate and precise to efficiently deal with control measures that cost from $5.00 to $11.50/ha. The 1987 EIS (USDA-APHIS 1987) set forth seven objectives for GHIPM to account for this complexity and an essentially unlimited number of management situations. Five of these objectives related to computer simulation as follows (noted by the *).
(1)* To refine an existing [grasshopper] phenology model to maximize the efficiency of management activities.

(2) Demonstrate that early sampling can detect and classify incipient infestations that are amenable to management with alternative registered tactics.

(3)* To develop economic thresholds and prescribe selective or nonselective treatments to reduce infestations to noneconomic levels with minimum effects on nontarget species.

(4)* To quantify current-season and long-term responses of infestations following each available control tactic to support a model of population dynamics in response to treatments.

(5) Develop new selective methods for management of grasshoppers, including grasshopper virus and fungal pathogens.

(6)* To provide for coordinated research on economics, range management, and ecology of nontarget species as components of a systems approach to grasshopper management.

(7)* To integrate all pertinent data into one expert system that can be turned over to APHIS [university and extension service personnel] and private enterprise upon completion of the project.

The overall goal of GHIPM was to refine rangeland grasshopper management so that economic and environmental values could be optimized. To realize that goal, some new research was required to produce needed information and develop technologies. However, there was also a need to incorporate existing information and technologies into effective management tools. Consequently, some modeling effort in GHIPM was directed toward knowledge discovery and research. These models provide a framework to test hypotheses and explore innovative management options. Another substantial modeling effort was directly focused on building and implementing management tools. In a management setting, computer models can provide information that is otherwise impossible or very expensive to acquire. In this paper, the computer models used in GHIPM are briefly presented and their role in IPM for rangeland grasshopper management is discussed. See Berry (1995) for a more detailed review of some of these models.

Research Models

Technologies can be developed using data and knowledge from basic research. Therefore, GHIPM has supported computer simulation studies that probe basic mechanisms of rangeland grasshoppers. This research is basic science with a focus on improving management of rangeland grasshoppers.
Landscape level grasshopper simulation. GHIPM had the resources to bring together a substantial amount of expertise and effort for studying rangeland grasshoppers. Consequently, several entomologists involved with GHIPM saw that a rare opportunity existed to collaborate on formalizing knowledge about rangeland grasshopper ecology. Some of this knowledge was published, but some existed only in the minds of experienced entomologists. Therefore, Berry et al. (1993) began developing a detailed simulation of rangeland grasshopper population dynamics. Object-oriented programming was used to model individual grasshopper cohorts, habitats, parasites, and predators in substantial detail, and then aggregate them at the landscape level. Such a spatio-temporal model may provide insight into new grasshopper management strategies, prediction of outbreaks, epidemiology, and responses of populations to selective management tactics. See Logan (1994) for a discussion of the usefulness and importance of large detailed models.

In the object-oriented paradigm, generalized objects may serve as templates to build specific instances of that type of object. For example, a generic grasshopper object can be defined. This object can contain the general attributes (size, age, location, etc.) and functions (movement, feeding, starvation, oviposition, etc.) of a grasshopper. Then these attributes and functions can be inherited and slightly modified to simulate any species. Once each object is defined, any number of copies (with different ages, body sizes, etc.) can be created in a simulation. For example, new instances of grasshoppers would be created each day during spring egg hatch. Each object in the model functions autonomously. The general attributes are given specific values to represent the state of that object (e.g., sex = male, mass = 2 g, etc.) In the same way, grasshopper habitats and predators or parasites can be abstracted and modeled. Because each entity is autonomous, the model is very flexible and can handle numerous and different types of habitats, predators, and grasshoppers. The object-oriented model is essentially a collection of autonomous submodels (grasshoppers, habitats, etc.) that dynamically respond to conditions in the simulated environment, including other effects from other submodels.

Model development with the modeling team led to some very interesting discussions about grasshopper ecology. Often, data gaps have been discovered and experiments conceived. There has probably never been such a formalization of grasshopper ecology. In a sense, the model provides an uncompromising framework to formalize and assimilate current theory about grasshopper biology and population dynamics.

Object-oriented modeling has allowed this model to contain much more detail about grasshopper species differences and spatial dynamics. The ability to easily model many species in a heterogeneous environment (many different patches) may help to unravel the mysteries of rangeland grasshopper outbreaks, and to evaluate selective management strategies such as baits, range management, and biological control in an IPM framework.

Soil temperature model. Most economic species of rangeland grasshoppers spend much of their lives as eggs located just below the soil
These eggs are the overwintering stage. They may experience mortality due to predators, parasites, pathogens, and environmental conditions. In addition, timing and synchronization of spring time egg hatch can greatly influence management activities. Egg hatch is determined primarily by environmental conditions in the top 5 to 10 cm of the soil. Any accurate prediction of egg hatch and mortality depends on good estimates of soil temperature and moisture. Therefore, GHIPM included a soil hydrology team (Pierson and Flerchinger 1993, Pierson et al. 1992) to collect detailed soil environmental data and develop models to estimate soil variables related to grasshopper egg biology. This team cooperated with GHIPM entomologists to collect data and run simulations at sites with ongoing grasshopper research. The detailed research model could be used to extrapolate soil environmental variables to other grasshopper research sites where detailed soil measurements are not feasible. Also, the effect of plant canopy on soil environmental variables was evaluated with the model.

**Egg hatch model.** Fisher (1993) collected data to determine the date of the end of grasshopper egg diapause in the autumn and subsequent temperature-dependent development rate for a common rangeland grasshopper species. Diapause is a state of arrested development that requires a certain amount of chilling before development can proceed. This attribute may prevent some grasshoppers from hatching during a warm autumn only to die in freezing winter temperatures. The development rate data and soil temperature data were submitted to a generalized insect modeling system called Population Model Design System (PMDS), developed by Logan (1988). PMDS produced the parameters and computer code to simulate egg hatch.

The egg hatch model combined with the soil temperature data collection and modeling activities in the last section may provide new understanding into the population dynamics of various mixtures of grasshopper species. Ultimately, simplified hatch models may be used in a management setting to allow more precise timing of management options, such as survey and control.

**Management Models**

The main vehicle currently used to deliver computer simulation to management decision makers is a computer-based, decision support system called Hopper (Kemp et al. 1988, Berry et al. 1991, Berry et al. 1992). Hopper runs on MS-DOS microcomputers and was developed within GHIPM to provide information for real-time tactical decisions for grasshopper management at a local scale. The program is used to help a land manager determine if other ranch management alternatives are preferable to grasshopper control. Hopper can evaluate the economic return for each control option when control is justifiable. Field use for Hopper also includes preseason grasshopper problem assessment and planning by APHIS-PPQ. In severe outbreak years, this planning is critical because personnel, equipment, and time are severely strained during control operations in the summer. Hopper has also been used to analyze alternative control strategies
economic consequences of grasshopper control (Davis et al. 1992), and benefits versus costs for introducing to the United States exotic biological control organisms that attack grasshoppers (J. Berry, unpublished data).

As with many of today’s agricultural problems (Stone 1989), grasshopper management cannot be solved with expert systems or simulation models alone. Therefore, Hopper was designed to integrate an expert system with two simulation models and a linear programming model. The expert system considers current weather conditions, grasshopper life stage, and environmental concerns to qualitatively select appropriate control options. The control options selected by the expert system are then evaluated quantitatively for economic efficacy.

Expert system technology is not well suited for the economic analysis component in Hopper because economic analysis is inherently procedural and quantitative. For example, the economic analysis depends on forage yield for a given scenario that includes the effects of many variables such as weather, soil type, and grasshopper population. These effects are time-dependent and must be integrated sequentially over a growing season. Simulation models can be effectively used to represent these time-varying systems. In addition to forage yield, the simulation models can provide information to the expert system during a consultation. The simulation models also can use site-specific data (weather, site productivity, vegetation type, etc.) to simulate many of the diverse rangeland ecosystems across the western United States. This flexibility greatly expands the geographic scope of Hopper. Some information provided by simulation (such as percent of grasshopper egg laying completed) would not be feasible for the user to acquire otherwise. Six computer models that are used in Hopper to provide important information for management (i.e., a grasshopper population and forage destruction model, a forage growth simulation model, a weather simulator, a generalized grasshopper simulation model, a ranch economics model, and a grasshopper hazard prediction system) are described below.

Grasshopper population simulation model. Some of the most important information needed for grasshopper management is related to the grasshoppers themselves. For example, damage potential of a grasshopper population with and without control is needed to estimate economic benefit of a control operation. Damage potential depends on habitat, grasshopper species composition, average life stage, and density. Average life stage, species composition, and density change as the growing season progresses. In addition, species composition and density can vary between sites and years. A rangeland grasshopper model called HopMod was developed to incorporate phenological development, forage destruction, natural mortality, and control option efficacy (of the current registered treatments) for a complex of rangeland grasshopper species (Berry et al. 1995). These factors must be considered to make economically-based management decisions for rangeland grasshoppers. HopMod also provides information to Hopper’s expert system, such as percentage of egg laying completed and average life stage at the time a control option should be implemented.
Forage production simulation model. On rangeland, the crop (forage) is harvested indirectly by using cattle or wildlife. Therefore, although forage destruction by grasshoppers can be estimated by HopMod (Berry et al. 1995), total forage available for cattle is more important in a management setting. For example, during years of above average precipitation there may be enough forage available so that even high densities of grasshoppers do not compete with most other herbivores. During dry years, the same amount of forage destruction by grasshoppers may cause a severe shortage for other herbivores. Consequently, the effect of grasshoppers on rangeland depends both on the amount of forage destroyed by grasshoppers and the amount of forage produced at a site. In addition, grasshopper consumption often occurs while the forage is actively growing. There is potential for forage regrowth both while grasshoppers are present and after grasshoppers are removed through control activities. Traditional field experiments used to determine the economic injury level can only control or account for a few variables at a time. Especially for ecologically diverse rangeland ecosystems, a limited number of field experiments in a handful of locations could not provide the data required to extrapolate to the vast number of potential situations across western rangelands in the United States. Therefore, computer simulation is necessary for Hopper to account for an unlimited number of potential scenarios and locations that may occur. Consequently, a forage model called RangeMod was developed to simulate daily forage production for any given temperature and precipitation scenario at any rangeland site in the western United States (Berry and Hanson 1991). The model can simulate forage growth for the major rangeland ecosystems simply by using different parameters and weather. Users can modify the parameters, however, ecosystem-specific parameters are supplied along with each economic model. HopMod and RangeMod dynamically interact to provide yield estimates that include daily grasshopper feeding and forage growth.

Weather generator. Temperature primarily determines grasshopper and range plant phenology in both HopMod and RangeMod whereas precipitation is used by RangeMod for timing of growth. Site specific temperature and precipitation data allow both models to be used in any rangeland location in the western United States. Early in GHIPM these data were compiled from national weather records for the sites in areas of interest. As GHIPM progressed, the geographic extent of areas in the project increased. This increase required much more weather to be compiled and sent with Hopper to end users. Instead of sending weather data, a daily weather simulator developed by Hanson et al. (1993) was used to estimate daily precipitation, maximum and minimum temperatures, and solar radiation. Included with the simulator are parameters, summarized from 30 years of weather data from long-term weather stations. The weather model will use these parameters to generate a typical weather scenario for the site. Hopper has a spreadsheet-like editor so users can modify the generated temperatures and precipitation events to fit current conditions. Also, users can increase or decrease temperatures or precipitation for the entire year at once (e.g., increase all the daily maximum temperatures by 5 degrees). Using this feature, a generally hotter-colder or dryer-wetter season could be quickly set up and evaluated with Hopper.
Ranch economics linear programming model. RanchMod (Davis et al. 1992) is a linear programming model of a typical ranch in a proposed grasshopper control area. The results from the grasshopper and forage models in Hopper are used by RanchMod for economic analyses. RanchMod calculates the net return for the typical ranch using each control option submitted by Hopper. The benefit for any control option is calculated by Hopper as the difference between the net return for the control option less the net return for a no control scenario. Costs are calculated by Hopper as the control cost per unit area times the area. A benefit-cost ratio is calculated and displayed to the user along with the expected total forage production obtained when each control option is used. RanchMod is linked in Hopper to the grasshopper simulation model and the forage production model. Therefore, the economic analysis is based on a very multidisciplinary effort and is very dynamic. Consequently, Davis et al. (1992) could evaluate the effects of important factors not explicitly included in RanchMod, but were included in the other two models. For example, they showed that rangeland productivity per unit area can have a substantial effect on a management decision. This model linkage in Hopper allows the economic consequences of biological, environmental, and economic factors to be evaluated in a seamless operation for an essentially unlimited number of situations. Hopper users can evaluate the economic effects of factors such as grasshopper species composition, site productivity, grasshopper density, treatment timing, cost and amount of alternative forage, herd size, cost of treatment, etc. Therefore, computer simulation has eliminated the need for static economic thresholds for rangeland grasshoppers and allows non-control options to be evaluated.

General grasshopper simulation. Hopper users expressed a need for a general grasshopper model that could be used to evaluate timing of control options relative to grasshopper phenology. Therefore, a simulation model called SimHop was developed and included as a module in Hopper to simulate the general pattern of grasshopper development, forage consumption, and control-option mortality. This information from SimHop is useful for teaching or explaining why it may be too late or too early in the year to use a control option. Furthermore, effects of longlasting (long-residual) treatments and timing of control options can be demonstrated using text and graphics to display the results. Users can modify all of the life history parameters and treatment mortality. Entomologists have used SimHop to evaluate the effects of sustained low mortality on total egg production and forage consumption. This type of mortality might be caused by different cattle grazing management strategies or introduction of a biological control agent.

Grasshopper hazard prediction. An adult grasshopper survey is done each year during mid to late summer by APHIS-PPQ. The data are used to produce maps of grasshopper density throughout the western United States. These maps show potential grasshopper densities for the following year and provide opportunities for advance planning of grasshopper management activities. The grasshopper density contours on the maps have traditionally been drawn by hand and represent only current conditions, not a true forecast. Kemp (1993) developed methods to produce maps that represent true forecasts. First, geostatistics are used to spatially interpolate field data (2400
sites) at a scale of 5 km by 5 km grids throughout the area surveyed (Kemp et al. 1989). Second, a statistically-based projection to account for historical patterns of grasshopper population dynamics in a given region is applied to the interpolated data (Kemp and Dennis 1993). The result is a map of predicted grasshopper densities. These techniques have only been applied to the state of Montana, but could be applied to other states where the historical data are available. Hopper users can display on-screen any of the available maps.

Discussion

Research models are part of the knowledge and technology discovery process. Some things learned while developing detailed and large research models can be incorporated into management guidelines or software systems (Logan 1994). For example, the object-oriented modeling techniques developed for the landscape level grasshopper simulation have already been used to change Hopper's rule-based expert system to an object-oriented style. This change provides more flexibility in the user interface requested by field practitioners. In addition, there are plans to redesign Hopper's grasshopper models into objects to allow simulation of individual grasshopper species. This redesign is important because species have different forage consumption rates, intrinsic rates of increase, and susceptibility to management options (e.g., range management, baits, and biological control agents).

Computer simulation also plays a direct role in rangeland grasshopper management. For example, the Hopper software was adopted by APHIS-PPQ in 1994 as part of its decision-making process for rangeland grasshoppers management. In fact, APHIS-PPQ no longer uses static economic thresholds, but uses dynamic evaluations from Hopper to help evaluate the need for control (USDA-APHIS 1994). This use of Hopper shows that the technology exists to shift from simplistic static thresholds to more realistic dynamic thresholds as part of an IPM Program.

The development and implementation of Hopper have facilitated a paradigm shift in rangeland grasshopper management. The goal in many IPM systems is to kill or control a pest below some fixed density. Higley (1993) calls this the “body bag” mentality of pest management. In this paradigm, a tactic (pest control) has been confused with the objective (profit, increased yield, predictable yield, etc.). Under the new paradigm the ultimate objective becomes the focus rather than the tactics. A better definition for IPM (modified from the January 1994 newsletter of the National Coalition on Integrated Pest Management) would be: a sustainable approach to managing agroecosystems and associated pests by combining biological, cultural, physical, and chemical tools in a way that optimizes economic, health, social, and environmental values. With this definition the focus is on managing the entire system to optimize the ultimate objectives. The tactics can be used to control a pest directly or to modify the agroecosystem without directly controlling the pest. For example, in a rangeland system, ranchers may prefer to reduce herd size rather than control grasshoppers. Hopper allows this type of option to be evaluated and compared to control. APHIS-PPQ is embracing
this new paradigm by considering management options that produce less than maximum control of grasshoppers. Hopper has also been used to show the feasibility of these innovative grasshopper management schemes that involve reduced pesticide use with a corresponding reduction in treatment cost and grasshopper control (Larsen and Foster 1996). A key for success of Hopper in GHIPM is the blending of qualitative reasoning, simulation, and a robust and intuitive user interface. Also, development and implementation were guided by the Hopper Implementation Team that consisted of scientists and field practitioners from several federal and state agencies. By including these people, Hopper developed into a product that was actually usable in management settings. In addition, Hopper’s models contain or use vast amounts of scientific knowledge (from many sources) and data. Without the automation and speed of computers, most of this information could not be used in a management setting and would not be used effectively for research purposes.

Another important aspect of these models is that they provide a focal point of interaction for a development team that consists of both scientists and practitioners. This focal point occurs because models are tangible products that can hold the attention of administrators and a development team. People enjoy seeing their knowledge synergistically used and integrated with others’ knowledge into a form that is greater than the sum of its parts.

An unusual feature of IPM in rangeland is rangeland’s extensiveness and low productivity per unit area. The value of rangeland resource in the western United States is enormous. However, its value on a local scale (rancher or community) is not great enough to provide funding for a project like GHIPM and the resulting Hopper software. Yet, the low productivity of rangeland makes correct management even more important than for a high value crop. For a high value crop, one extra treatment may mean less profit but for rangeland it may mean no profit, the difference between success and failure. Hopper and its directly associated models (not including the research models) probably cost over $500,000 to produce. This cost seems like a high price but a typical 30,000 acre treatment of rangeland for grasshoppers could cost more than $100,000. In addition, Hopper can be applied to essentially all rangeland areas in the United States and Canada west of Iowa.

The goal of GHIPM was to refine rangeland grasshopper management across the entire rangeland areas of the western United States. The Hopper software, through the use of computer simulation, provides the flexibility that would have been very difficult and expensive to achieve through site-specific field work that is typically associated with the development of static economic thresholds.

A major challenge faces the modeling efforts I have described. Most of these modeling projects have been funded or, at least, administratively focused by GHIPM. However, GHIPM officially ended September 1994. Without an administrative sponsor or funding source, many of the modeling efforts will probably not continue. Therefore, APHIS-PPQ plans to support maintenance of the Hopper software and has created a position to do so. This support is critical because Hopper and its associated models will need to be updated to account for new management options and fix any program errors.
encountered. Often research grants will pay for model development but sources of funding for maintenance are difficult to locate. The commitment by APHIS-PPQ will provide some funding and an important focal point for research and development. However, the success of these modeling projects was the result of an individual programming effort and the cooperation and scientific development among a diverse team of individuals, including field ecologists, computer programmers, modelers, land managers, and economists. In addition, field practitioners added critical knowledge needed to apply the scientific knowledge to management problems. This project successfully applies interdisciplinary research and modeling to help bridge the gap between rangeland grasshopper IPM theory and practice.

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