

VII. Future Directions



Grasshoppers that die from exposure to fungi in the *Entomophaga* genus characteristically do so in a heads-up position. The GHIPM Project studied the use of *Entomophaga grylli* in the hope of lessening overall dependence on chemical control to manage range-land grasshopper populations. (APHIS file photo.)

VII.1 Future Directions in Grasshopper Management—An Introduction

Jerome A. Onsager

The following chapters about future directions in grasshopper management fall into three general categories. These categories can be described as potential new agents for grasshopper suppression, emerging new ecological information that could be integrated into grasshopper management systems, and issues that could affect grasshopper management priorities, especially on public lands.

Chapters VII.2, 3, 5, 6, 7, and 8 discuss a number of promising new candidate agents for conventional short-term control of economic infestations of grasshoppers. The agents' eventual viability will be dictated primarily by the same practical elements that affect current control tactics. These elements include

- approval by regulatory agencies,
- reasonable production costs plus economical volume for the producer,
- reasonable shelf life and consistency of demand for the distributor, and
- satisfaction plus reasonable profit for the consumer.

A candidate agent that is deficient in any critical element will not compete strongly with current technology until the deficiency is corrected.

Chapters in this section also discuss two exotic biological control agents that were considered by the Federal Government for nonconventional long-term suppression of grasshopper populations. Grasshopper Integrated Pest Management (GHIPM) Project scientists evaluated a fungal pathogen (chapter VII.4) and an egg parasite (chapter VII.9) from Australia as candidates for release in the United States to build a reservoir of biological control.

Such a strategy, called inoculative release, appeals to some pest managers because the organisms could become self-perpetuating and therefore permanent deterrents to grasshopper populations. Conversely, inoculative release is worrisome to others because it could produce undesirable side effects that also could become permanent. At this time, it appears unlikely that current regulatory guidelines will allow the release of the two exotic agents.

Chapters VII.11, 13, 14, and 15 discuss areas of unfinished long-term research on grasshopper ecology. Hopefully, the finished products someday will be incorporated into improved land-management systems. An understanding of how grasshoppers respond to controllable attributes of habitat can be exploited in management systems that reduce the frequency and intensity of grasshopper depredation.

Finally, this handbook would be incomplete without some direct input into the complex and competing social, political, and environmental issues that affect grasshopper management on public lands. Chapters VII.10, 12, and 16 are contributions that obviously are within the competence and responsibility of GHIPM and are of interest to the Project. The information is intended not to provide definitive solutions to problems but rather to be available when conflicts of interest must be resolved.

VII.2 Dimilin® Spray for Reducing Rangeland Grasshopper Populations

R. N. Foster and K. Christian Reuter

Introduction

The insecticides used to control outbreaks of grasshoppers on rangeland are active against a broad spectrum of insects, in both adult and immature stages. For rangeland use in Animal and Plant Health Inspection Service (APHIS) cooperative programs, pest managers apply insecticides at doses and in formulations that have a minimal but acceptable impact on nontarget insects while substantially reducing grasshoppers. Because their activity is broad, these insecticidal sprays sometimes reduce some nonpest insect species in the target areas. However, populations of nontargets have been seen to rebound relatively quickly following treatments on rangeland, even over large areas (see chapter III.3, “Impact of Control Programs on Nontarget Arthropods”). While undesirable, the effects of these sprays on nontarget insects are acceptable. Short-term reductions in nontargets are part of the price pest managers currently pay for artificially bringing an outbreak of grasshoppers back to a normal level.

The goals of insect control today are rapidly expanding. It is environmentally advantageous to reduce the minimal effects of sprays on nontargets even further. Increasing protection to nontargets, particularly those that naturally work to keep grasshopper populations in balance, supports basic integrated pest management (IPM) objectives that encourage and emphasize the use of naturally occurring organisms.

Some insecticides, called insect growth regulators, have a narrower spectrum of activity and cause death in a manner different from most broad-spectrum insecticides. The Dimilin® brand of diflubenzuron, (1-(4-chlorophenyl)-3-(2,6 difluorobenzoyl)-urea, is one of these growth regulators. It inhibits chitin biosyntheses and thereby interferes with the formation and deposition of the chitin in the cuticle in an insect exoskeleton. This disruption of normal development may result in death to the insect when molting is attempted.

Diflubenzuron has been shown to be effective against immature stages of several insect pests and is registered in the United States for control of beet armyworm, fall

armyworm, and boll weevil on cotton, several insects on soybean, several forest pest insects, and in California on mosquito larvae. Because of its mode of action, nonchitin-forming animals and adult insects and spiders enjoy a reduced risk compared to that of conventional insecticides.

Several studies have been conducted with Dimilin formulated into a bran-based bait for grasshoppers. Wang and Fuller (1991) demonstrated the effectiveness of 1 and 2 lb of 1 percent diflubenzuron bran bait per acre against rangeland grasshoppers on 12-acre plots in southwestern South Dakota. Bomar and Lockwood (1991) demonstrated the effectiveness of the same formula and rate against rangeland grasshoppers on 10-acre plots in eastern Wyoming. Both of these studies utilized ground equipment for application. In two 2-year studies where bait was aerially applied to replicated 40-acre plots, Jech et al. (1993) showed diflubenzuron and carbaryl bran bait treatments to be equally effective on mixed populations of grasshoppers. (Figures VII.2–1 and –2 illustrate technical challenges in using bran materials in aerial spray programs.) However, the study indicated that the species *Phliobostroma quadrimaculatum* (Thomas) could be controlled with diflubenzuron when not controlled with carbaryl bait.

Results of these studies are very promising. However, some damaging species of grasshopper do not readily accept the bran baits and may remain at undesirable levels (Jech et al. 1989 unpubl., 1992 unpubl., and 1993; Onsager et al. 1990; Quinn et al. 1989). Additionally, levels of reduction with all bran-based baits on susceptible species tend to be lower when compared to spray treatments that are deposited directly on both the pest and the preferred food of the pest.

In an effort to take advantage of the desirable qualities of Dimilin while avoiding the general limitations of bran baits, APHIS scientists at the Phoenix Methods Development Center studied spray formulations. Compared to currently used broad-spectrum insecticides, Dimilin should lessen the impact on those nontarget insects and arachnids that are in an adult stage at the time the grasshoppers are treated.



Figure VII.2-1—A load of bran is delivered for onsite mixing with chemicals or insect growth regulators at an airstrip in the Dakotas. (Agricultural Research Service photo by John Kucharsky.)

Evaluating Potential Treatment Rates—A Field Study

In 1991 we conducted a detailed study to (1) generally evaluate an aerially sprayed formulation for control of grasshoppers on rangeland, (2) determine the most effective dose of three candidate doses for achieving immediate and seasonlong effectiveness on both the total grasshopper population and the individual component species of the population, and (3) determine the usefulness of the treatments for suppression or controlling migration into the treated area during the season of treatment.

In this study, we applied three doses of Dimilin 25W spray in volumes of 32 oz/acre to 40-acre mixed-grass rangeland plots in western South Dakota. Three sets of plots were treated with Dimilin spray at 0.015, 0.030, and 0.045 lb active ingredient (AI) per acre. An additional set of plots was sprayed with the standard carbaryl rangeland treatment (Sevin[®]-4 Oil ULV at 0.5 lb AI/acre) for comparison. A fifth set of plots was left untreated. When applications were made, most grasshoppers were in the second or third instar.

We found that all three dosages of Dimilin caused reduction as great as the standard carbaryl treatment after 1 week. After 2 weeks, all treatments showed reduction in the range of 94 to 96 percent. Reductions continued to increase to the end of the study and 9 weeks after treatment ranged from 96 to 98 percent.

Overall, we found no differences in the effects of Dimilin and carbaryl. Dimilin showed almost immediate acceptable reduction of grasshoppers within 7 days and continued to be effective throughout the season of treatment. Measurable migration into the Dimilin-treated plots was undetectable. Surviving hatch that might have occurred was also undetectable. In this study, in terms of providing acceptable control, Dimilin proved to be an excellent alternative for consideration when treating grasshoppers on rangeland.



Figure VII.2-2—The treated bran bait is sacked and then dumped into a chamber in the fuselage of the spray plane. Inside that chamber, APHIS-developed aerating equipment keeps the bran bait from clumping, which would cause uneven applications of product. (Agricultural Research Service photo by John Kucharsky.)

Use of Dimilin Spray Under Operational Conditions

In 1993, we conducted a study to evaluate the usefulness of two formulations of Dimilin for control of grasshoppers on rangeland under operational conditions that could be experienced during a large-scale grasshopper control program. In this study, we aerially applied Dimilin 25W, Dimilin 2F, and carbaryl (Sevin-4 Oil ULV) to mixed-grass rangeland plots in western North Dakota. All three formulations were sprayed in a diesel carrier. We applied each treatment to a square 640-acre block. Both Dimilin treatments were applied at the dose of 0.0156 lb AI/acre in 32 fluid oz of mix. The carbaryl treatment was applied in 20 fluid oz of mix per acre at the dose of 0.5 lb AI and was used as a standard rangeland treatment for comparison. We compared reduction in grasshopper populations within the operational plots to populations of untreated grasshoppers in adjacent areas surrounding the treated plots. Most grasshoppers treated were in the second or third instar.

We found that the standard (Sevin-4 Oil ULV) treatment caused greater reductions in grasshoppers after 1 week than the Dimilin treatments. After 2 weeks, all three treatments caused reductions in grasshoppers that would be acceptable in large-scale program efforts. However, the Dimilin 2F and carbaryl treatments were causing greater reductions than the Dimilin 25W. Mortality at 3 weeks after application showed that all three treatments were performing equally well. After 4 weeks, we found that the Dimilin 2F formulation caused greater reductions in grasshoppers compared to the other treatments. Trends in our study showed that mortality increased over the 4 weeks after treatment with Dimilin 2F and started to decline with Dimilin 25W and Sevin-4 Oil ULV between the second and third week after treatment.

From a cursory examination of the study area 16 weeks after treatment, we found that no obvious additional hatch had survived, nor had any migration into the treated area occurred. Densities of grasshoppers were no greater than at 4 weeks after treatment.

In our operational study, the 2F formulation proved to be more compatible with the spraying system. The 25W formulation mixed with diesel resulted in a precipitant that could potentially cause a clogging problem with the spraying system and made cleanup significantly more difficult.

Results from our study demonstrated that a low amount of Dimilin active ingredient per acre with the 2F formulation can be used in a large-scale control program manner for control of grasshoppers on rangeland. Upon final Environmental Protection Agency registration, Dimilin—because of its mode of action and its reduced spectrum of activity—could be an attractive option to be considered for controlling grasshoppers on rangeland.

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VII.3 Impact of Dimilin® on Nontarget Arthropods and Its Efficacy Against Rangeland Grasshoppers

Michael A. Catangui, Billy W. Fuller, and Arnie W. Walz

Introduction

Dimilin® (diflubenzuron) is a chitin-synthesis inhibitor and causes death in insects during the molting process (van Daalen et al. 1972, Post and Vincent 1973). Chitin, a nitrogenous polysaccharide, is the organic foundation of the exoskeleton of all insects and the entire phylum Arthropoda (Snodgrass 1935). Therefore, some concern exists that widespread use of diflubenzuron may affect not only the target insect pest but also nontarget arthropods that are essential for the diversity and stability of rangeland ecosystems. Other studies have shown the potential of diflubenzuron against rangeland grasshoppers (Foster et al. 1991 unpubl. and 1993 unpubl.).

Our key research objective was to determine whether diflubenzuron negatively affected the abundance and diversity of nontarget arthropods (including ants, spiders, predatory beetles, and pollinator bees) in rangelands, and if so to determine if the effect was greater than the effect of one of the current standard treatments. Another research objective was to develop additional data on the potential of diflubenzuron as an alternative insecticide against rangeland grasshoppers.

Previous studies indicate that diflubenzuron spares most nontarget arthropods. Ables et al. (1975) reported diflubenzuron to be harmless to a pupal parasitoid of the house fly. Compared to dimethoate-treated poultry farms in North Carolina, diflubenzuron-treated farms had greater parasitoid abundance and species diversity. In cotton fields, Keever et al. (1977) observed that arthropod predators belonging to orders Hemiptera, Coleoptera, and Neuroptera were not affected by diflubenzuron when it was sprayed aerially at 0.12 lb active ingredient (AI) per acre (0.14 kg AI per hectare). Wilkinson et al. (1978) evaluated various rates and formulations of diflubenzuron on adult and immature stages of selected parasitoids and predators found in cotton fields. The authors found test insects to be unaffected by diflubenzuron even at high concentrations except for immatures of a lacewing species.

In contrast, diflubenzuron may be detrimental to some freshwater crustaceans and immature aquatic insects (fig. VII.3-1). Miura and Takahashi (1974, 1975) observed temporary population reductions in tadpole shrimp, clam



Figure VII.3-1—To minimize insecticide drift, spray booms are turned off well before this plane flies over a pond in the Great Plains. (Agricultural Research Service photo by John Kucharsky.)

shrimp, water fleas, copepods, cladocerans, mayfly naiads, and midge larvae in treated (0.1 lb AI per acre) mosquito breeding areas in California. Adult aquatic beetles, spiders, and mosquito fish were not affected by diflubenzuron even at the highest rates tested. Farlow et al. (1978) studied the impact of diflubenzuron on nontarget organisms of a Louisiana coastal marsh. Those authors reported significant reductions in amphipods, dragonfly naiads, nymphs of corixid and notonectid bugs, as well as adult hydrophilid beetles in marshlands treated six times with 0.025 lb AI per acre (28 g AI per ha) over an 18-month period. On the other hand, significant increases were observed among mayfly naiads, larvae of noterid and dytiscid beetles, adult corixid bugs, and mosquito fish. Numerous immature and adult insects were listed as unaffected by the diflubenzuron treatments.

The environmental fate and degradation of diflubenzuron in a laboratory model ecosystem, a soil bacterium, sheep liver microsomes, and ultraviolet light were investigated by Metcalf et al. (1975). They found diflubenzuron to be moderately persistent in organisms such as algae, snails, caterpillars, and mosquito larvae but efficiently degraded by mosquito fish, however. Ecological magnification may not be a problem: the lowest concentration of diflubenzuron was found in the mosquito fish, at the top of the model food chain. Sheep liver microsomes and the soil bacterium were not able to degrade diflubenzuron under the experimental conditions imposed.

Other studies have shown the potential of diflubenzuron against rangeland grasshoppers. Foster et al. (1991 unpubl.) reported aerial treatments of diflubenzuron spray at 0.015, 0.030, and 0.045 lb AI per acre to reduce second- and third-instar grasshoppers as well as a standard treatment of carbaryl (0.5 lb AI per acre) after 1 week. Foster's team showed reductions for all treatments in the range of 94 to 96 percent after 2 weeks. Under simulated control program operational conditions, Foster et al. (1993 unpubl.) reported two formulations of diflubenzuron at 0.0156 AI per acre and a carbaryl standard performed equally well (control ranged from 87 to 91 percent).

Our Study in South Dakota

Different rates and formulations of were tested in an open rangeland near Ludlow (Harding County), SD, during the 1993 season. Dimilin 2F (0.0075 and 0.015 lb AI/acre) and Dimilin 25W (0.015 lb AI/acre) were compared with Sevin® 4-Oil (0.5 lb AI/acre) and untreated plots. The lower rate of Dimilin 2F was evaluated only for efficacy against grasshoppers. The remaining treatments were evaluated for impact on nontarget arthropods and efficacy against grasshoppers. We used a completely randomized design with each treatment replicated four times. A fixed-wing airplane applied chemical treatments over 40-acre plots from July 2 to July 7, 1993.

Our study used pitfall traps to sample soil surface-associated nontarget arthropods (ants, spiders, predatory beetles, and scavenger beetles). A pitfall trap consisted of a wide-mouth 1-qt canning jar filled with approximately 4 inches of mineral oil. Each pitfall trap was buried so that the opening was flush with the soil surface. The oil killed and temporarily preserved crawling insects that fell into the traps. Six pitfall traps spaced 15 ft apart and arranged in hexagonal pattern were installed near the center of each 40-acre plot.

Malaise traps were used to sample flying nontarget arthropods such as parasitic and predatory wasps, lacewings, flies, and pollinator bees. Each malaise trap was a 12- by 4- by 6-ft rectangular tent made of nylon screen that intercepted and directed flying insects to killing jars. Two malaise traps were placed near the center of each 40-acre plot.

We used rings to count live grasshoppers (fig. VII.3–2). Forty aluminum rings, each 0.1 m², were arranged in grids near the center of each plot. We counted grasshoppers within each ring using a tally counter. Sweep-net samples determined grasshopper species and their age composition.



Figure VII.3–2—A grasshopper's eye view of the kind of ring field crews use to delimit a sampling spot before counting resident 'hoppers. (Agricultural Research Service photo by John Kucharsky.)

Sampling for nontarget arthropods was carried out before and after treatment application. The malaise and pitfall traps were run a week before treatment, then resumed 1 week after the last chemical treatment application. Traps were maintained continuously thereafter, and catches were collected at weekly intervals for 10 weeks from July to September. Plot and trap location markers remained onsite over the winter months, and an additional sample was collected about 1 year after treatment. We took grasshopper counts from rings and sweep-net samples (fig. VII.3–3) once before chemical treatment and at weekly intervals for 7 weeks after treatment. Additional grasshopper counts and samples were taken the end of season (11 weeks after treatment).

We sorted nontarget arthropod samples and counted them in the laboratory. Arthropods were identified to family level then grouped according to their biological function (such as predator, parasite, scavenger, or pollinator). Identification of ants to the species level (Wheeler and Wheeler 1963) was used to calculate a measure of species diversity referred to as the probability of interspecific encounter (PIE) (Hurlbert 1971, Washington 1984).



Figure VII.3-3—Sweep-netting grasshoppers is a labor-intensive but time-tested method for sampling insect populations. (Agricultural Research Service photo by John Kucharsky.)

Hurlbert defined PIE as the probability that two individuals encountered at random in a community will belong to different species. In our present paper, PIE may be interpreted as the probability that two individual ants randomly encountered in rangeland will be of different species. The higher the probability, the more diverse, and presumably more stable, is the ant community.

Findings and Discussion

Arthropods collected from the experimental site were grouped arbitrarily as follows: (1) soil surface-associated nontarget arthropods, (2) flying nontarget arthropods, and

(3) grasshoppers. Each group was sampled using techniques appropriate for their mobility and biological characteristics.

Impact of Dimilin on Soil Surface-Associated Nontarget Arthropods.—There were four major groups of soil surface-associated arthropods: (1) ants (order Hymenoptera: family Formicidae), (2) spiders (order Araneae: families Agelenidae, Amaurobiidae, Clubionidae, Dictynidae, Gnaphosidae, Hahniidae, Lycosidae, Mimetidae, Philodromidae, Salticidae, Tetragnathidae, Theridiidae, and Thomisidae), (3) predatory beetles (order Coleoptera: families Carabidae, Cicindelidae, Histeridae, Meloidae, and Staphylinidae), and (4) scavenger beetles (order Coleoptera: families Scarabaeidae, Silphidae, and Tenebrionidae).

In terms of biological function on the rangeland ecosystem, ants may be regarded as both general predators and scavengers (Wheeler and Wheeler 1963). All spiders are predators (Kaston 1972). Beetles belonging to families Carabidae (ground beetles), Cicindelidae (tiger beetles), Staphylinidae (rove beetles), and Histeridae (hister beetles) are also general predators (Borror and DeLong 1964). Blister beetle (Meloidae) larvae feed on grasshopper eggs, but adults are considered pests of certain crops. Scavengers were composed of families Scarabaeidae (scarab beetles), Silphidae (carrion beetles), and Tenebrionidae (darkling beetles). Certain scarabs like the dung beetle feed on cattle manure; carrion beetles feed on dead animal carcasses. Darkling beetles feed on decaying plant materials but some, like the false wireworms, feed on the roots of wheat and are considered pests. All arthropods mentioned above are important components of the rangeland food chain because they are potential food for vertebrate animals like birds, frogs, mice, moles, and shrews.

In general, Dimilin 2F (0.015 lb AI/acre), Dimilin 25W (0.015 lb AI/acre), and Sevin 4-Oil (0.5 lb AI/acre) did not significantly reduce the number of ants, spiders, predatory beetles, or scavenger beetles from 7 to 76 days after treatment (DAT). Even at 1 year after treatment (350 to 357 DAT), no significant reductions in any of the soil surface-associated arthropods were detected. Ant numbers temporarily (49 to 55 DAT) declined after Dimilin 2F and Sevin 4-Oil treatments by 43 and 56 percent, respectively. The temporary decline in ant numbers

may or may not be due to chance alone. What is important is that ant numbers rebounded immediately and that in most of the sampling periods, the Dimilin and Sevin treatments were consistently shown to have no detrimental effects on ant numbers. Additionally, ant diversity (based on PIE calculations) was not significantly affected by the Dimilin or Sevin treatments from 7 to 357 DAT. This result may indicate that no ant species was particularly susceptible to the Dimilin and Sevin treatments at the dosages studied.

Impact of Dimilin on Flying Nontarget Arthropods.—

The arthropods collected in malaise traps were subdivided into the following 3 groups: (1) pollinator bees (order Hymenoptera: families Apidae, Halictidae, Colletidae, Andrenidae, and Megachilidae), (2) predators (order Hymenoptera: families Sphecidae, Pompilidae, and Vespidae; order Diptera: families Asilidae and Therevidae; order Coleoptera: family Coccinellidae; order Neuroptera: families Chrysopidae, Hemerobiidae, and Myrmeleontidae), and (3) parasites (order Hymenoptera: families Ichneumonidae, Braconidae, Tiphidae, Chalcididae, Chrysididae, Mutillidae, Proctotrupidae, and Pteromalidae; order Diptera: families Bombyliidae and Nemestrinidae).

In general, no significant reductions in flying nontarget arthropods were observed in the Dimilin 2F, Dimilin 25W and Sevin 4-Oil treatments. Dimilin 25W reduced predator numbers during the 15- to 20-DAT period by 59 percent. Predator numbers subsequently recovered, and in most of the sampling periods, no significant reductions in predator numbers were observed. A temporary decline of 18 percent in parasite numbers was recorded in the Dimilin 2F treatment at 35 to 41 DAT. No significant reductions were observed in the number of pollinator bees. About 1 year after treatment (350 to 357 DAT), no significant reductions in numbers of predators, parasites or pollinators were observed for any treatment.

Efficacy of Dimilin Against Rangeland Grasshoppers.—Nineteen grasshopper species were present on the 800-acre experimental area immediately before spraying (0 DAT). *Melanoplus sanguinipes* F., *M. infantilis* Scudder, and *Trachyrhachys kiowa* Thomas were the

dominant grasshopper species. Grasshopper age structure was 46.8, 24.6, 23.5, 3.7, 0.2, and 0.1 percent for 1st, 2d, 3d, 4th, and 5th instars and adults, respectively, at 0 DAT. This age composition was ideal for a chitin-synthesis inhibitor like Dimilin because the majority of grasshoppers had several molts remaining in their life cycle.

All Dimilin treatments were comparable to Sevin 4-Oil starting at 14 DAT. From 14 DAT to 49 DAT, grasshopper numbers in the Dimilin- and Sevin-treated plots were significantly lower than those of the untreated plots. Dimilin provided consistent grasshopper control from 14 DAT to 49 DAT; Sevin-treated plots revealed temporarily elevated grasshopper numbers at 35 DAT and 42 DAT. No differences between plots treated with Dimilin at different rates or formulations were detected after 14 DAT.

Dimilin was not as effective as Sevin at 7 DAT. This delayed response is most likely due to its mode of action. Dimilin exerts its effect at molting while Sevin (a cholinesterase inhibitor) acts at any time of development. Grasshopper population reductions (adjusted for natural population changes) in Dimilin-treated plots ranged from 65 percent to 90 percent from 14 DAT to 49 DAT. In this study, all treatments lost effectiveness against grasshoppers by 76 DAT. For more information about diflubenzuron efficacy on rangeland grasshoppers, see chapter VII.2, "Dimilin Spray for Reducing Rangeland Grasshopper Populations."

In summary, our study showed that Dimilin and Sevin sprays did not appear to significantly reduce the abundance of soil-surface-associated or flying nontarget arthropods while providing good grasshopper control in rangeland. Our observations extended only through about 1 year after treatment. Interpretation of our results is limited to this period.

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VII.4 An Attempt at Classical Biological Control of Rangeland Grasshoppers With *Entomophaga grylli*, Pathotype 3

Donald L. Hostetter

The primary objective of this project, conceived and developed by R. I. Carruthers, was to develop and implement a classical biological control program against rangeland grasshoppers using an Australian isolate (pathotype 3) of the grasshopper obligate *Entomophaga grylli* (Zygomycetes: Entomophthorales) species complex (Ramoska et al. 1988). Pathotype 3 was isolated from *Praxibulus* sp. grasshoppers in Australia in 1985 by R. S. Soper and R. J. Milner during an epizootic (grasshopper outbreak) (Milner 1985).

The project was based on the collaborative findings of Soper and Milner and a 5-year study of the two native species designated pathotype 1 and 2 in Arizona and New Mexico (Carruthers and Humber 1988 unpubl.).

Implementation of the attempt (Carruthers and Humber 1988 unpubl.) was through the U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Plant Protection and Quarantine (USDA, APHIS, PPQ), Grasshopper Integrated Pest Management (GHIPM) Project initiated in 1987.

The proposed and pursued approach was the introduction, establishment, evaluation, and dispersal of an Australian isolate, pathotype 3, to augment the two native pathotypes (1 and 2). Previous laboratory studies indicated that pathotype 3 had a wider host range than either of the native species plus other attributes that led to its selection (Ramoska et al. 1988).

These fungi, along with other biotic agents could theoretically provide long-term, nonchemical suppression of grasshoppers between outbreaks.

An ecological survey of sites with histories of grasshopper populations and densities suitable for introduction was made within the 17 Western States. The Little Missouri National Grasslands in McKenzie County, ND, was selected as the initial study area for field evaluation of pathotype 3 (Carruthers et al. 1989 unpubl.).

The use of biological control methods for grasshopper management, and specifically the introduction of the Australian fungus, was supported by the membership of the McKenzie County Grazing Association, Watford City, ND.

Administrative policies and technical procedures within Federal agencies and the State of North Dakota in effect at the time were observed and provided guidance for introduction. Permission was granted for field studies in North Dakota (Carruthers et al. 1989 unpubl., and in press).

The goals of proposed releases were to reduce populations of economically important grasshoppers on western rangeland to, or below, threshold densities; to establish pathotype 3 as a biorational agent that would augment native fungi; and to determine the plausibility of future large scale releases throughout the Western United States by PPQ's Plant Protection Laboratories.

Pathotype 3 was introduced into susceptible grasshopper populations at several sites in McKenzie County in 1989, 1990, and 1991 and at two sites near Delta Junction, AK, in 1990 (Carruthers et al. 1989 unpubl., 1990 unpubl., 1991 unpubl.).

Introduction was by randomly releasing laboratory-infected fifth-instar and adult *M. differentialis* (Thomas), each injected with 10 μ l of 10⁴ pathotype 3 protoplasts, into grasshopper populations in alfalfa/mixed grass or crested wheatgrass fields with no history of pathotype 1 or 2 fungus infection. Each field was about 44.5 acres (18 ha) in size. Releases were made at 2- to 3-day intervals 3 days postinjection (just prior to death of the grasshopper). Weekly releases in lots of 500 infected grasshoppers totalled from 500 to 3,500 at each site.

The initial release of pathotype 3 was made July 24, 1989. Five hundred (500) infected grasshoppers were released in an alfalfa/mixed-grass hayfield at Wold's ranch (T153N, R97W, Sec. 33), 25 miles north of Watford City, ND. Incidence of fungus infection among grasshoppers within this release site was 13 percent 2 weeks after the release (Carruthers et al. 1989 unpubl.).

Additional releases of ca. 500 per day were made at Wold's on July 8, 11, 15, 19, 25, and 30, 1990. A 20-percent incidence of infection was observed at this site within 2 weeks of the 1990 releases. No additional releases were made at this site after 1990.

Similar releases were made in crested wheatgrass fields at three other sites in McKenzie County, ND, during 1990. Incidence of fungus infection among grasshoppers at these locations was less than 3 percent. Low incidence of infection in these fields was attributed to the open canopy of the crested wheatgrass, which likely resulted in a less favorable habitat for the fungus (Carruthers et al. 1990 unpubl.). Seasonal monitoring of grasshopper populations at these sites (1991–94) has failed to detect fungus-infected individuals.

The releases of pathotype 3 into *M. sanguinipes* populations at two sites in Alaska were considered unsuccessful in that only a single sporulating cadaver was recovered 2 weeks after release. Grasshopper populations at these release sites have been monitored annually for incidence of fungal infection.

Overwintering of pathotype 3 was thought to occur in Wold's field based on recovery of sporulating *M. bivittatus* (Say) cadavers in June, 1991. Fungal mortality among grasshoppers at this site reached 26 percent in 1991 even though no additional introductions were made (Carruthers et al. 1991 unpubl.).

Releases of infected grasshoppers (500–1,000 each) were made on land managed by the U.S. Army Corps of Engineers near Lake Sakakawea (T154N, R95W, Sec. 32) on June 6, 8, 11, and 13, 1991. The incidence of fungus infection at this location reached 25 percent 2 weeks after the last release. No additional releases were made after June 13, 1991. Grasshopper populations at this site continued to be monitored for incidence of fungal disease through 1994. Populations and incidence of fungal infection have been diminishing since 1991.

The initial success in North Dakota was encouraging, and a plan for additional releases of 150,000 infected *M. differentialis* (10,000 per week per location for 5 consecutive weeks) at 3 other locations was drafted. Additional releases were contingent upon production and supply of suitable hosts by a commercial insectary in Colorado. The number of sites and infected grasshoppers to be released was based on available human and fiscal resources as well as host population densities.

This project and plans for future releases of nonnative pathogens and parasites within the GHIPM Project caused intense debate among certain researchers and between agency administrators in 1991 (Bomar and Lockwood 1991, Lockwood 1993a and b, Carruthers and Onsager 1993). In August 1991, amid the beginning controversy of the legality and wisdom of this approach, the principal investigator (R. I. Carruthers) was reassigned, and the project was transferred from Ithaca, NY, to me at Kimberly, ID.

Additional documentation was drafted and submitted (April 1992) and revised and resubmitted (October 1992) seeking a policy decision on the need for an environmental assessment (EA) before proceeding with additional releases of pathotype 3.

Additional releases of pathotype 3 are stalemated. No releases of pathotype 3 have been made since June 1991. Efforts since that time have been relegated to monitoring (population densities, composition, species fluctuations, incidence of mortality due to fungus infection, dispersal studies) in the release field and surrounding areas.

Laboratory studies were conducted to establish basic parameters of conidia production, germination and viability, and dose/mortality curves, as well as mass inoculation methods that would be required if the project was to be assumed and enlarged by PPQ's Plant Protection Laboratories.

The development of DNA probe technology for separation and identification of three *Entomophaga* spp. of the *E. grylli* complex has also been successful. Cooperation between USDA's Agricultural Research Service staff scientists at Ithaca, NY, and Kimberly, ID; the Boyce Thompson Institute for Plant Science; and the University of Toronto, Scarborough campus led to the development of a positive DNA identification probe whereby pathotypes 1, 2, and 3 can be separated and positively identified (Bidochka et al. 1995). This is a critical accomplishment and provides a tool necessary to delineate dispersal and distribution of pathotype 3 in the field.

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VII.5 Lab Studies and Field Trials With the Fungus *Beauveria bassiana* Against Grasshoppers

R. Nelson Foster, K. Christian Reuter, Jim Britton, and Cliff Bradley

More than 150 years ago, the Hyphomycete fungus *Beauveria bassiana* was recognized as the cause of a disease fatal to insects (Steinhaus 1967). *B. bassiana* is a common insect pathogen (an agent that causes disease) found on all continents except Antarctica (Humber 1992). Hundreds of isolates of the fungus, including five from grasshoppers, are listed in the U.S. Department of Agriculture (USDA) collection of Entomopathogenic Fungal Cultures (Humber 1992).

In the fungus' life cycle, conidia (spores) adhere to the grasshopper cuticle (part of the exoskeleton). The conidia germinate, and the germ tube penetrates the cuticle. The fungi replicate inside the insect haemocoel (body cavity) in the form of blastospores (spores produced by a budding process). Degradative enzymes destroy the internal structures of the grasshopper.

When in sufficient quantity, the fungus causes sickness within 3 days. The grasshopper reduces its feeding and becomes immobile. Typically, infected grasshoppers die between 4 and 10 days after infection depending on their species, age, and size, and the dose of conidia. After death, under conditions of high humidity, blastospores form hyphae (filaments of the vegetative structure of the fungus) that emerge through the insect's cuticle, sporulate (produce spores), and cover the insect in a characteristic white growth (fig. VII.5-1).



Figure VII.5-1—An immature rangeland grasshopper, *Melanoplus sanguinipes*, exhibits the fungus *Beauveria bassiana*, which caused its death. (Photo by K. Christian Reuter.)

In 1987, Mycotech Corporation in Butte, MT, isolated, from an infected grasshopper found in Montana, a strain of *Beauveria bassiana* that is virulent (disease-causing) to several grasshopper species in laboratory bioassays. Since that time, Mycotech has developed and refined production capabilities to the point that large-scale commercialization is planned upon the final development of an acceptable formulation for delivering the pathogen to grasshoppers in the field. The following summarizes some of the research conducted since early 1991 in the development of formulations of *Beauveria bassiana* usable against grasshoppers on rangeland.

Laboratory Studies, 1991-93

During this period, we conducted more than 20 different replicated studies. The objectives provided for (1) developing equipment and procedures for our laboratory studies, (2) studying the effect of *Beauveria bassiana* on different age groups of grasshoppers, (3) comparing of formulations, and (4) comparing the virulence of different batches of commercially produced *B. bassiana*.

Test formulations were sprayed from a tower apparatus in the lab to simulate aerially applied sprays (fig. VII.5-2). Applications were conducted according to a detailed standard operating procedure (Foster and Reuter 1991 unpubl.). Laboratory-reared *Melanoplus sanguinipes* grasshoppers supplied by South Dakota State University were used for all studies. All tests focus on a dose of 1×10^{13} (1 trillion) spores/acre as a standard. Depending on the specific test protocol, we sprayed grasshoppers and/or live vegetation upon which the grasshoppers were to be confined.

When grasshoppers were sprayed, third instars through adult stages were sprayed singly or in groups consisting of from 5 to 20 grasshoppers per group. After spraying, the grasshoppers were monitored daily for death, usually for 2 weeks. In tests where grasshoppers were sprayed, fresh food was provided to surviving grasshoppers daily, and dead grasshoppers were held singly under high humidity conditions for observance of sporulation.



Figure VII.5-2—Spray tower used to simulate aerially applied sprays for bioassaying grasshoppers in the laboratory. (APHIS photo by Lonnie Black.)

Initial studies demonstrated the superiority of an oil formulation over a water formulation. A typical example of results from one of these tests is shown in figure VII.5-3. In later studies where candidate field formulations were compared, we focused primarily on different oil types with various additives selected for ultraviolet light protection and emulsion stabilization (formulation stability). Two petroleum oils performed equally well as base carriers; however, one is significantly less expensive. We found that formulations involving emulsifiable concentrates tend to be more difficult to spray consistently in the laboratory. However, our results indicate that such compounds may provide higher mortality in field application.

In studies where untreated grasshoppers were confined on sprayed vegetation, we showed a significant decrease in mortality on vegetation that had been exposed to sunlight for longer than 24 hours (fig. VII.5-4). However, two formulations currently under development show promise for extending protection beyond 24 hours.

Third-, fourth-, and fifth-instar grasshoppers were easily infected and very susceptible to sprays equivalent to 1×10^{13} spores/gal/acre. However, compared to these results, two separate studies with adult grasshoppers showed a greatly reduced level of mortality at the same dose. Subsequent studies in which adults with amputated wings were sprayed showed that reduced mortality in adults cannot be attributed to physical protection provided by wings, which shield a major portion of the abdomen from the spray.

We conducted several studies to compare spores from different productions and to evaluate shelf life. Spores stored in oil for up to 1 year performed as well as dry conidia powder stored for an equal period. A 1992 spring production as well as a new isolate both performed similarly to spores produced in 1991. However, a 1992 fall production sampled resulted in some inconsistencies during the physical spraying. Slightly cooler temperatures during the spray operation may have affected the sprayability of the formulation. Also, a new harvesting method at the production facility resulted in some larger particles of spore powder, increasing spray problems.

Field Studies—1991

A 9-acre rangeland plot near Edgemont, SD, infested with predominantly second- and third-instar grasshoppers of mixed species, was aerially sprayed with an oil formulation containing 8×10^{12} spores/gal/acre (fig. VII.5-5). Grasshopper mortalities measured in this plot were compared to a similar untreated adjacent plot (Foster et al. 1991 unpubl.).

We evaluated mortality on six grasshopper species by collecting grasshoppers from both plots after application and confining them in (1) small rearing cups (fig. VII.5-6), which we moved to the laboratory for daily monitoring, and (2) bottomless field cages (fig. VII.5-7) estab-

lished after treatment in both plots. Additionally, 0.1-m² rings (Onsager and Henry 1977) were used to delimit counting areas for estimating total field populations of grasshoppers.

Beauveria bassiana caused mortality in all six species of the grasshoppers tested. Both grasshoppers held in rearing cups in the laboratory and those caged on native vegetation in the field demonstrated significant mortality in treated populations compared to untreated populations. Some species were killed faster than others, but we do not know if this is due to inherent susceptibility or behavioral differences between the species.

In rearing cups, the average reduction of all species combined in treated populations was about 96 percent at 8 days after treatment. Mortality in the controls during the same period was about 34 percent. In field cages, the mean reduction of all species combined was 79 percent and 11 percent for treated and untreated populations, respectively, at 9 or 10 days after treatment.

In field plots, counts of unconfined populations in treated and untreated plots showed average differences in mortality that ranged from about 39 percent to 63 percent at 3 to 15 days after treatment (fig. VII.5–8).

We also used field cages to determine the general manner in which grasshoppers pick up the spores. Immediately after application, grasshoppers from the untreated plots were collected and caged in the treated area to determine pickup through feeding activity. Treated grasshoppers were caged in the untreated plot to determine the mortality associated with direct contact. Treated grasshoppers were caged in the treated plot to determine the total mortality, and untreated grasshoppers were caged in the untreated plot as a control.

At 11 days after treatment, there were no significant differences in grasshopper mortality between the direct deposition, feeding activity, or combined direct deposition/feeding activity treatments. All three treatments showed significantly greater mortality than the untreated

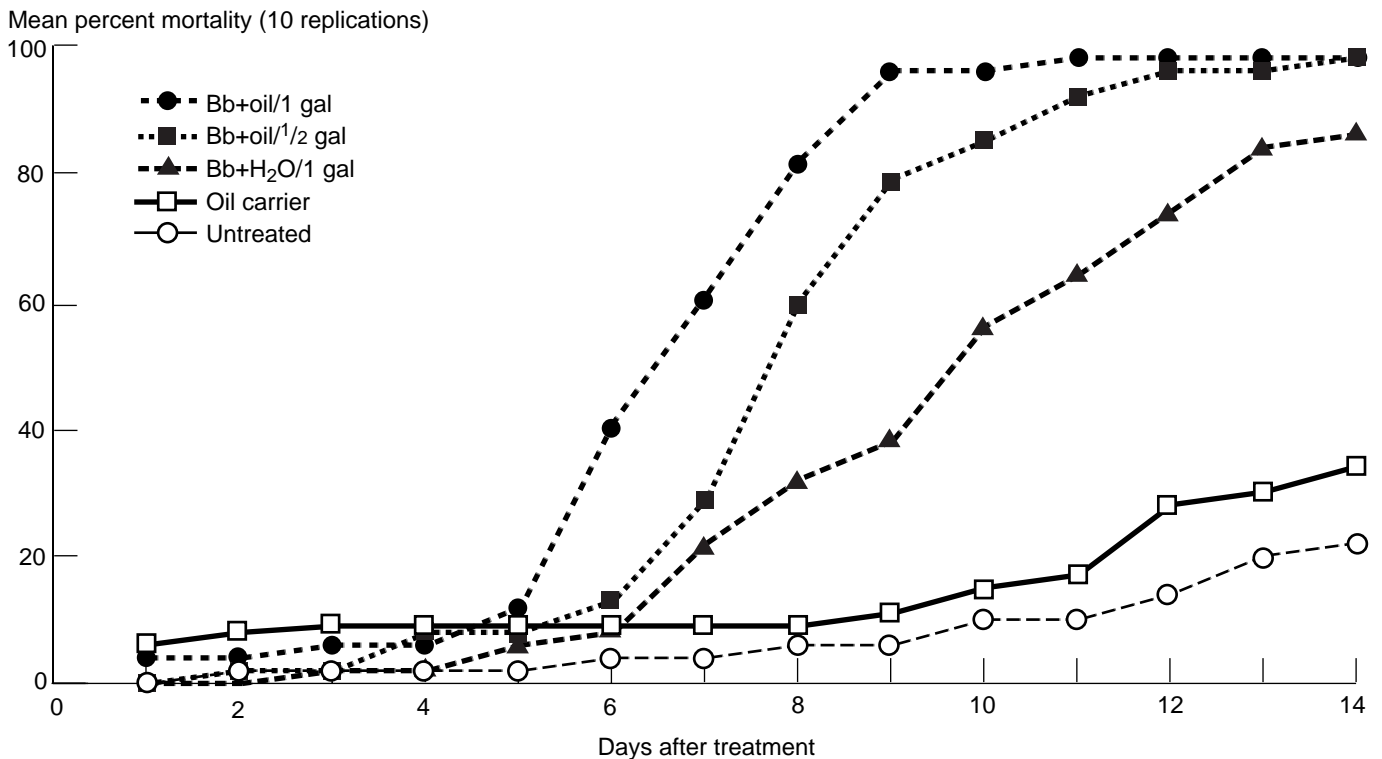


Figure VII.5-3—Mortality of caged grasshoppers treated with experimental formulations of *Beauveria bassiana* at 1×10^{13} conidia per acre.

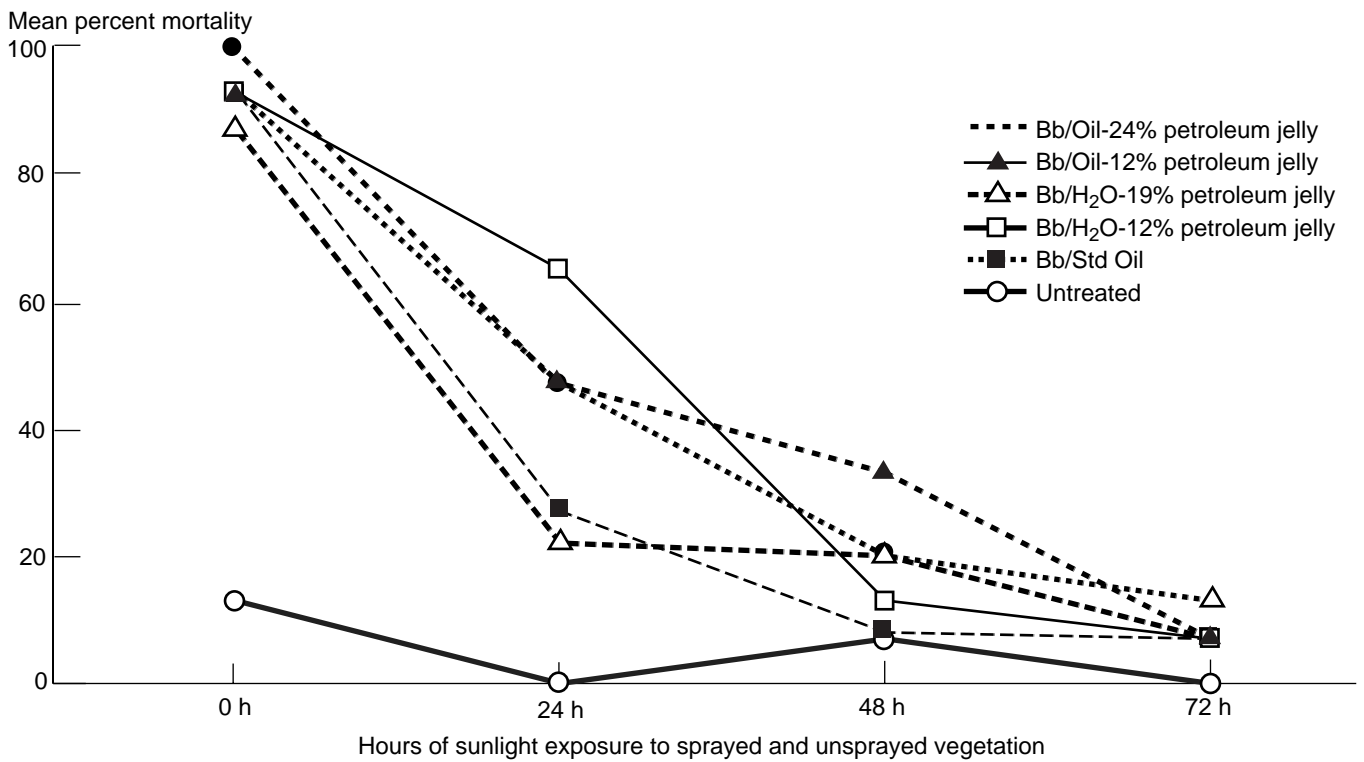


Figure VII.5-4—Effect of grass treated with selected formulations of *Beauveria bassiana* and exposed to several periods of sunlight on grasshopper survival after 9 days. All treatments were applied at a volume of 1 gal/acre containing 1×10^{13} spores.



Figure VII.5-5—The first aerial application of the fungus *Beauveria bassiana* was applied at 1 gal/acre to a rangeland plot near Edgemont, SD in 1991. (Photo by Cliff Bradley.)



Figure VII.5-6—Four-ounce rearing cups used to confine test grasshoppers after they have been treated. (APHIS photo by R. Nelson Foster.)

check. Our data indicate that pickup may occur through either direct impingement (direct striking by spray droplet) or feeding activity. We do not know if the feeding activity component is simply due to contact with the mouthparts of the grasshopper during feeding or actual ingestion of spores.

We evaluated the short-term residual activity of the spores by caging untreated grasshoppers approximately 10 hours after treatment in the treated plot. Survival of the conidia on vegetation was evaluated in the sprayed plot by taking vegetation samples at three posttreatment



Figure VII.5-7—Bottomless field cages used to confine test grasshoppers in the field are inspected carefully to determine the daily insect mortality. (APHIS photo by R. Nelson Foster.)



Figure VII.5-8—Mortality of unconfined field populations of grasshoppers is estimated by counting grasshoppers in metal rings. (APHIS photo by R. Nelson Foster.)

intervals. These samples were washed, diluted, and placed on selective agar plates, where fungus colonies developed from each colony-forming unit. The colonies then were counted to estimate the number of viable (living) conidia.

Untreated grasshoppers exposed to the treated vegetation in the field approximately 10 hours after application died at about 3.3 times the mortality rate of untreated grasshoppers over the same period of time, 11 days. The delayed exposure demonstrates the infectivity of spores at least 10 hours after field application and indicates that, in field situations, at least several hours are available for a grasshopper to become infected with the fungus. Results of the study to determine survival of conidia on vegetation in the field showed relatively uniform coverage in the plot and indicated no loss of activity over at least the first 10 hours after application.

Field Studies—1992

Three adjoining 9-acre rangeland plots near Amidon, ND, infested with predominately fourth- and fifth-instar grasshoppers of mixed species were the basis for studies in 1992. One plot was aerially sprayed with 9.5×10^{12} spores/64 oz/acre. One plot was sprayed with 64 oz/acre of the oil carrier (without spores), and the other plot was left untreated for comparison (Foster et al. 1992 unpubl.).

Mortality evaluations were conducted as in 1991, by confining, after treatment, the six predominant grasshopper species in cages held in the laboratory or in the field. The methods used for maintaining the cages and confirming fungus-induced death by sporulation were similar to those employed in 1991. Reduction in the total field population was again estimated by using 0.1-m² rings to delimit counting areas.

In this study, the aerial application of *B. bassiana* resulted in substantial mortality of all six species of grasshoppers evaluated. Both grasshoppers held in rearing cups in the laboratory and those caged on native vegetation in the field demonstrated significant mortality in fungus-treated populations compared to untreated populations and populations treated with oil only. These results were generally similar to those obtained in 1991, and again time to mortality varied among species, begin-

ning in as little as 3 days for some species and as much as 4 to 6 days for other species. These differences may be attributed to individual species susceptibility or a result of behavioral avoidance, which limits physical exposure of individual species to direct impingement of the spray droplet.

In rearing cages, the mean reduction of all species combined in treated populations was 95 percent at 8 days after treatment. During the same time period, mortality in the untreated population and the population treated only with oil was 10 percent and 4 percent, respectively. Three species common to both the 1991 and 1992 studies demonstrated very similar responses to the aerially applied *B. bassiana* treatment.

In field cages, the mean reduction for 5 of the 6 species confined in treated populations was 91 percent at 15 to 17 days following treatment. This reduction compared to mortality during the same period in the untreated population and the population treated only with oil of 23 percent and 11 percent, respectively. The sixth species in the study was reduced much quicker: 100-percent mortality occurred by the eleventh day. Its counterparts in the untreated plots and the plots treated with oil showed 26 percent and 16 percent reduction during the same period.

Comparisons of the in-field posttreatment population estimates in single, small plots are difficult to interpret. High densities of grasshoppers, sparse vegetation, small plot size, and local movement all contribute to confounding estimates of nonrestricted in-field populations. Compared to 1991, in-field mortality was lower in this study. In 1992, apparent mortality at 9 days after treatment was only about 20 percent. We did note that vegetation in the 1992 study was much sparser than in the 1991 study and may have offered the spores less protection from sunlight. Using large field plots in future studies should reduce many of the difficulties commonly encountered when comparisons of in-field grasshopper populations on rangeland are attempted.

Field Studies—1993

We focused studies for the first time in 1993 on larger plots than previously used (Foster et al. 1993 unpubl.). That year, we aerially sprayed 24 adjoining 40-acre

rangeland plots located near Amidon, ND, infested with predominantly second-, third-, and fourth-instar stages of grasshoppers of mixed species. Two formulations of *Beauveria bassiana* spores were each applied to eight plots. One treatment consisted of 9.9×10^{12} spores/64 oz/acre in an oil formulation, and the other treatment consisted of 9.4×10^{12} spores/64 oz/acre in an oil plus additive (adjuvant) formulation. An oil-only treatment was applied at 64 oz/acre to four plots. Carbaryl was sprayed at 20 oz/acre (0.5 lb/active ingredient [AI] per acre) to four plots as a standard treatment for comparison. Four plots were left untreated to determine the natural changes in the grasshopper population and for comparison with all applied treatments.

In field populations, estimates were again made using 0.1-m² rings. A monitoring site located near the center of each 40-acre plot consisted of 40 rings arranged in a circle with rings separated by 5 paces. Field cages were placed adjacent to the ring site in each plot after the treatment was sprayed. Sprayed grasshoppers of two of the dominant species were confined in these cages in a manner similar to that employed in 1991 and 1992 field studies.

Additional field cages were set up in each fungus- and oil-only treated plot and in the untreated plots. These cages were used to study the residual activity of *Beauveria bassiana* over a 5-day period after treatment. Untreated grasshoppers were confined in some cages on the day of treatment and on each of the 5 days following treatment.

Unfortunately, the study's value was lessened by measurable rain (heavy at times) that occurred on 9 of the 13 days that population estimates were made. During the entire study, measurable rain was recorded on 15 of 21 days.

Although incomplete, analysis of counts from rings to date shows that the carbaryl standard was statistically superior to all other treatments at each of the posttreatment interval readings. Good performance of carbaryl under these conditions was expected and is consistent with two of our previous studies where carbaryl was used (Foster et al. 1991 unpubl. and Foster et al. 1993 unpubl.). All other experimental treatments (including the untreated checks) showed erratic results, undoubtedly

confounded by the weather conditions experienced during the study, and were statistically inseparable.

Results from the field cages for the two species studied at 15 days after treatment indicated that both fungus treatments and the carbaryl treatment produced mortality significantly greater than what occurred in the untreated populations. However, mortality in the field cages was somewhat lower than in 1991 and 1992 for the one species that was common to studies in all 3 years.

Residual activity was evident only during the day of treatment. Beyond 1 day, no significant differences in mortality were detected between fungus-treated or untreated grasshoppers.

Under the conditions of this study, evaluations of unproven formulations are confounding and inconclusive at best. However, there is no doubt that carbaryl performed well under these conditions and that the current formulation of *Beauveria bassiana* will need to be improved if it is to be employed under these conditions, or excluded from use under such conditions. Additional replicated studies to obtain information on the original objectives of the 1993 field study and new formulation evaluations are planned for the future.

Summary of Additional Foreign Studies

During the past 5 years, Mycotech has been working to develop fungal pathogens of locusts and grasshoppers for use in integrated pest management (IPM) programs in Africa. This work is in collaboration with Montana State University, the U.S. Agency for International Development, and several African government agencies. These efforts were undertaken to devise alternatives to chemical grasshopper/locust control measures commonly used in Africa. Fungi can fit well into an IPM scheme because they provide control alternatives where chemical insecticides are inappropriate. In fact, because of their relatively slow action, fungi will work best as part of a continuous pest-control strategy, where they can be applied before populations are able to reach damaging levels.

A Mycotech strain of the fungus *Beauveria bassiana* has been tested against grasshoppers and locusts in several

small-plot field trials in the west African countries of Cape Verde and Mali. Fungal spores were applied at a rate of 1×10^{13} per acre. Low-volume application of an oil-based formulation (27 ounces to 2 quarts per acre) was made with hand-held spinning disc sprayers. High-volume application of an emulsifiable formulation (2–10 gal/acre) was made with motorized or hand-pumped backpack sprayers. Spores were also formulated on wheat bran bait with a molasses sticker.

In all trials, 80 to 100 percent of treated, caged insects died from *Beauveria bassiana* infection after 7 days. More significantly, replicated 5-acre blocks in Cape Verde, treated with either oil-formulated or emulsion-formulated fungus, showed approximately 50 percent population density reductions measured in the field after 7 days. It is quite encouraging that the insect population in these tests consisted primarily of older nymphs and adults, which have demonstrated more resistance to the fungus in laboratory bioassays.

Mycotech and Montana State University have taken part in an expedition to Madagascar to collect new fungal pathogens of locusts and grasshoppers. The fungi isolated from infected insects are presently being examined for virulence, target specificity, production characteristics, and impact on mammals. The government of Madagascar is particularly interested in using fungi to treat locust populations before the insects expand out of their recessionary (nonoutbreak) areas. When a suitable fungus is identified, field trials will begin.

These promising results indicate that fungal insecticides may be able to play an important role in grasshopper/locust control. This field experience in the harsh African conditions will continue to yield information valuable to the development of fungal insecticides for North America.

Summary and Conclusion

A strain of the entomopathogenic fungus *Beauveria bassiana* has been isolated from U.S. grasshoppers by Mycotech Corporation. Development of mass production capabilities with a potential for large-scale commercialization has resulted in extensive testing of the commercially produced fungus for use against grasshoppers and

locusts. Laboratory studies have demonstrated the insecticidal value of the fungus against several species of grasshoppers and locusts. In 1991, 1992, and 1993, we conducted field studies using cages to demonstrate successful control of several species of confined grasshoppers in the United States when liquid formulations of *Beauveria bassiana* were aerially applied with conventional commercial application equipment. Results of field studies with unconfined grasshoppers in this country are inconclusive to date. Foreign field studies on unconfined populations showed good potential for providing control. Results from the last 3 years suggest the potential for controlling several species of grasshoppers and locusts using a liquid formulation of *B. bassiana*, as a bioinsecticide, and applied with conventional aerial application equipment.

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VII.6 *Beauveria bassiana* for Mormon Crickets

D. A. Streett and S. A. Woods

Introduction

The first crops planted by the Mormon settlers in Utah were damaged by the insect now referred to by the common name “Mormon cricket” (Cowan 1990). The Mormon cricket, *Anabrus simplex* Haldeman, is not a cricket at all but a longhorned grasshopper from the family Tettigoniidae (fig. VII.6–1). This pest can reach outbreak levels before Mormon crickets begin migrating into range and cropland. Mormon crickets can cause significant damage when bands of huge numbers of insects move onto cropland in the Western United States (Pfadt 1991, MacVean 1990, Swain 1944). Our studies evaluated the effectiveness of a fungal pathogen, *Beauveria bassiana*, to suppress Mormon cricket populations.



Figure VII.6–1— The Mormon cricket is mainly a pest on rangelands but sometimes moves into planted crops and causes economic damage. (Agricultural Research Service file photo K4797–1.)

How *Beauveria bassiana* Works

Interest in insect–fungi interactions has centered, for the most part, on the pathogenic (disease-causing) nature of fungi and their use as microbial control agents. Unlike other insect pathogens that must be eaten to infect insects, fungi can infect an insect through its cuticle (outer skin). The development of fungi pathogenic to insects typically follows this pattern:

- (1) Attachment of an infectious stage (called a conidium or spore) to the insect cuticle,
- (2) Germination of the conidium and penetration of the insect cuticle by a germ tube from the conidium,
- (3) Growth of the fungus inside the insect body (hemocoel) and eventual death of the insect,
- (4) Penetration of the fungus to the surface of the dead insect and formation of conidia (plural of conidium) under conditions of high relative humidity, and
- (5) Dispersal of the conidia to locations where they may encounter susceptible insects and start the process again.

Among the insect-pathogenic fungi that follow this pattern of development is *Beauveria bassiana*. It is commonly known as the white-muscardine fungus because of the characteristic white covering of conidia (spores) found on the surface of dead insects. Insect cadavers infected with the fungus are transformed into white, mummified bodies resembling in appearance a bonbon candy (“muscardin” means “bonbon” in French [Steinhaus 1949]).

Isolate of *B. bassiana* for Mormon Cricket

The *B. bassiana* strain used in these studies was originally obtained from Mycotech Corporation in Butte, MT. Mycotech has obtained Environmental Protection Agency registration of this *Beauveria* strain for the suppression of several insect pests, including grasshoppers and Mormon crickets. Mycotech recently developed a solid culture system for the production of *B. bassiana* conidia (Goettel and Roberts 1992). Mycotech prepared and supplied a *B. bassiana* dry conidia powder for the laboratory studies and *B. bassiana* formulated in oil (OF) and in an emulsible suspension (ES) for the 1992 and 1993 Idaho field trials (Onsager et al. 1992, Kemp and Streett 1993).

Laboratory Studies

Conidia were suspended in ES1 and ES2 oil and applied to Mormon crickets as 0.08 μ L (microliter) droplets beneath the pronotum (on the thorax) at dosages ranging from 0 to 10^6 spores per Mormon cricket. Mormon crickets were reared individually in plastic cups and main-

tained in an incubator at 77 °F (25 °C). Mormon crickets were fed every 2 days with romaine lettuce, kale, and wheat bran. Mortality was recorded during feeding, and a damp cotton ball was added to cups containing cadavers. The cadavers were then stored at room temperature for 4–6 days to diagnose *Beauveria* infection by observing the characteristic white muscardine appearance on the insect surface.

The median lethal dose (LD₅₀) is commonly used to assess the infectivity of a pathogen. The LD₅₀ for the *B. bassiana* isolate against fifth-instar Mormon crickets at 12 days was 1,000 conidia (fig. VII.6–2). The two oil formulations that were compared in laboratory assays showed no consistent differences in overall mortality or percentage of Mormon crickets with confirmed infections (table VII.6–1).

Four replicates of 200 adult Mormon crickets each were treated with 5×10^5 or 5×10^6 conidia in oil according to the procedures described by Kemp and Streett, 1993. A check preparation consisting of oil without conidia and an untreated control were included for each replicate. Each treatment within a replicate was separated into two groups and reared either individually in an incubator at 77 °F or transferred to field enclosures. Four field enclosures 16 ft² (1.5 m²) for each treatment were stocked with 25 Mormon crickets. Mormon crickets were fed lettuce daily. Counts of Mormon crickets were made for each cage, and cadavers were collected for incubation in cups with a moistened cotton ball to diagnose *Beauveria* infection (Kemp and Streett 1993).

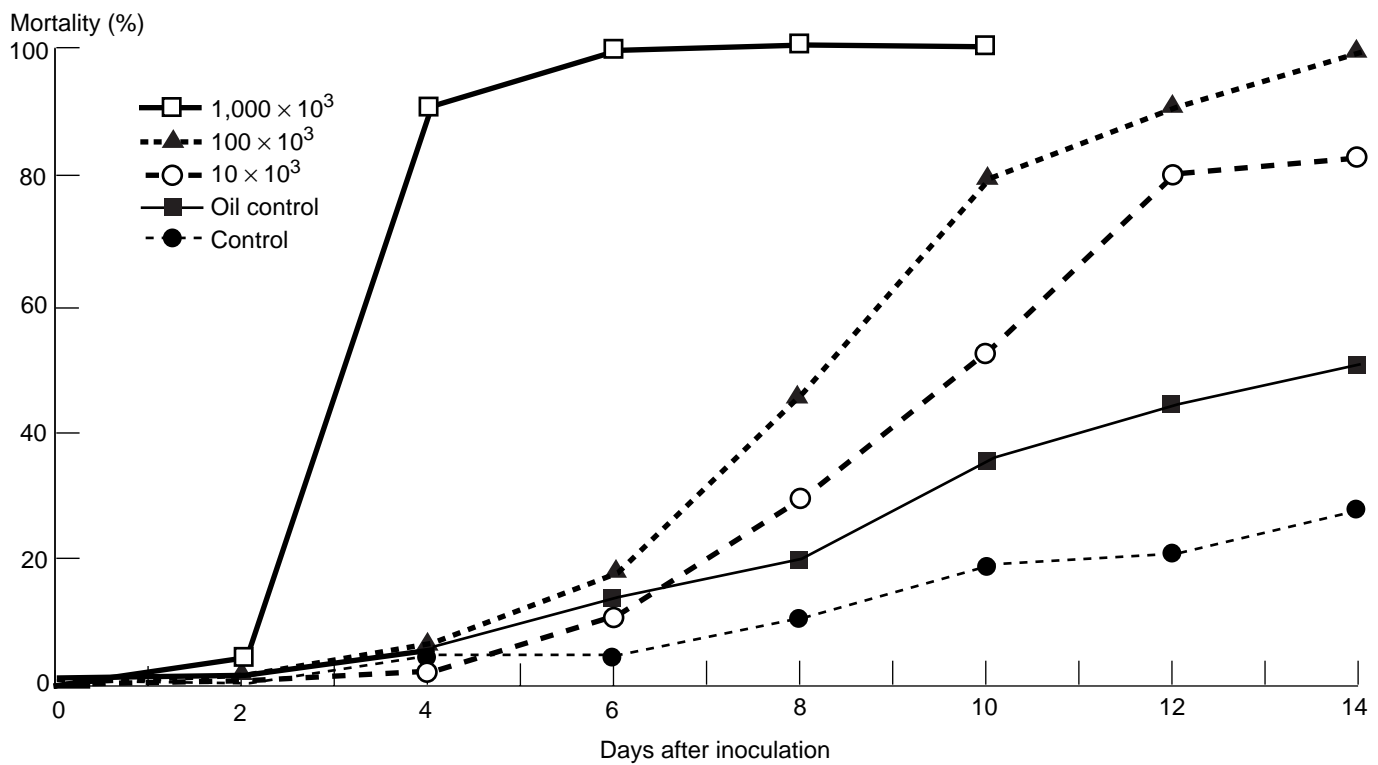


Figure VII.6–2—Cumulative mortality among fifth-instar Mormon crickets in a bioassay of *Beauveria bassiana*.

Table VII.6–1—Laboratory comparison of ES1 versus ES2 oil as a carrier for *Beauveria bassiana*. Cumulative mortality and incidence of infection for Mormon crickets.

Dose	Mortality		Infection	
	¹ ES1	ES2	ES1	ES2
Conidia/ grasshopper	— — — — — Percent — — — — —			
0	34	46	8	12
10 ²	50	38	20	18
10 ³	71	87	42	44
10 ⁴	90	98	65	62

¹ES = emulsifiable suspension.

Adult Mormon crickets that were inoculated with 5×10^6 conidia per Mormon cricket showed a significant difference in mortality in laboratory versus field cages (fig. VII.6–3). Adult Mormon crickets reared in the field enclosures survived more than 3 weeks longer than Mormon crickets reared in the laboratory. One possible explanation for these results is that Mormon crickets in the field use a behavioral thermoregulation to increase body temperature to a point that restricts fungal development and allows the insect to survive.

Field Studies

Field trials against Mormon crickets were conducted near St. Anthony, ID. Oil (ES1 oil) and clay–oil–water (COW)—100 g clay: 1 liter (L) oil: 2 L water—formulations were applied at rates of 4.9×10^{11} and 4.9×10^{12} conidia/acre (1.2×10^{12} and 1.2×10^{13} conidia per ha) and application volumes of 0.9 and 2.7 qt/acre (2.5 and 7.5 L/ha). Each replicate consisted of 10 arenas of 14.4 yd² (12 m²) constructed of aluminum flashing approximately 10–18 inches (25–45 cm) in height. Each arena was stocked with more than 250 Mormon crickets prior to application.

Treatments were replicated four times, and treatments within each replicate were applied on the same day (weather permitting) in the sequence outlined by Onsager et al. (1992). An ultralow-volume sprayer (North American Micron) was used for the applications. After application, Mormon crickets were collected from each arena for rearing. Approximately 30–50 Mormon crickets per arena were reared individually in the laboratory; mortality and infection data were recorded as described earlier. Three field cages (16 ft²/cage) were each stocked with 30–50 Mormon crickets from each arena and covered with chicken wire to keep out birds. Mormon crickets were fed lettuce and sagebrush daily. Mormon crickets were counted daily, and cadavers were collected and incubated in cups with a moistened cotton ball to diagnose *Beauveria* infection.

Results differed somewhat between the formulations that were used in the field. The statistical results suggested that the ES1 formulation produced less mortality but similar rates of infection than the OF formulations at the 2.7 qt/acre application volume. There were no differences in overall mortality or infection rates between the

0.9 qt/acre and 2.7 qt/acre application volumes of oil alone formulations. It should be noted that while the differences in mortality between formulations at the 2.7 qt/acre application volume may have been statistically significant, they were not substantial (80 v. 74 percent at the low conidia concentration).

The application rate of conidia had a more substantial impact on both the overall mortality and percentage of confirmed infections. Adjusted for controls, overall mortality averaged 55 percent and 89 percent for the low and high conidia concentrations, respectively. All comparisons between conidia concentrations were statistically significant.

Conclusions

A detailed understanding of the disease dynamics of the *B. bassiana* isolate will be necessary before this product can be considered for use in an integrated pest management program. Gaining this understanding will entail both laboratory and field studies to evaluate short-term and longrange impacts of *Beauveria* on Mormon crickets. The effects of cannibalism, behavioral fever, and host behavior will need further evaluation before the potential of *B. bassiana* as a microbial control agent against Mormon crickets can be determined. Formulation of *B. bassiana* for Mormon cricket control will also require additional research.

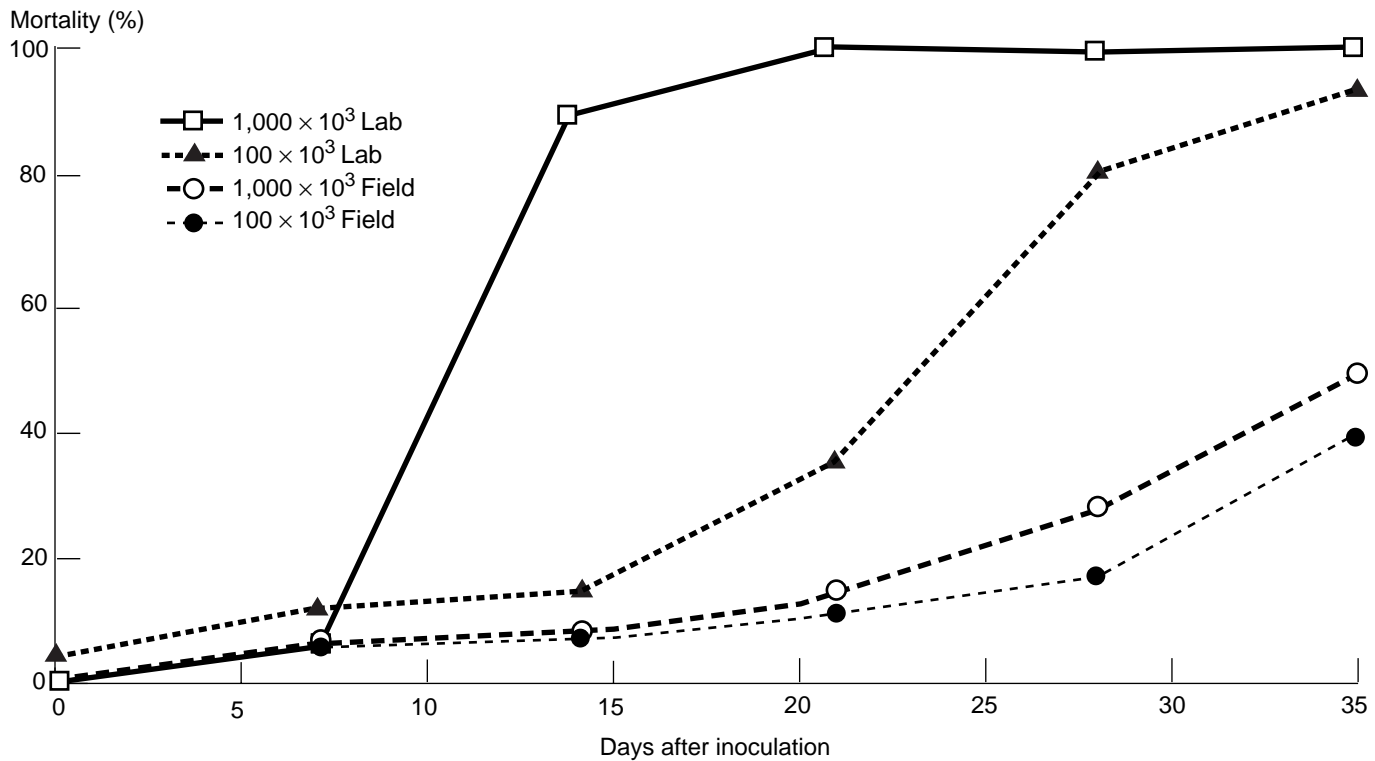


Figure VII.6-3—Cumulative mortality among adult Mormon crickets treated with *Beauveria bassiana* in the lab and reared in the lab or in field cages.

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VII.7 Effects of the Fungus *Beauveria bassiana* on Nontarget Arthropods

Mark A. Brinkman, Billy W. Fuller, and Michael B. Hildreth

Introduction

Beauveria bassiana is currently being developed as a potential bioinsecticide alternative to traditional chemical pesticides for controlling grasshopper populations. Currently, *Nosema locustae* is the only other nonchemical treatment registered for control of grasshoppers on rangeland. *B. bassiana* offers at least two major advantages over *N. locustae*: (1) *B. bassiana* appears to kill grasshoppers more rapidly than does *N. locustae* (see VII.5 and I.3), and (2) *Beauveria* does not rely on the ingestion of its spores in a bait formulation by grasshoppers but is capable of directly penetrating through their exoskeleton (Goettel 1992).

Unfortunately, *B. bassiana* may possess at least one potential disadvantage. Unlike the narrow specificity of *N. locustae* for orthopterans (i.e., grasshoppers, locusts and crickets), *B. bassiana* is known to infect a wide variety of insects (Goettel 1992). The wide specificity of *Beauveria* is of concern because distribution of its conidia into the environment also might diminish beneficial insect populations. Attempts have been made to select strains of *B. bassiana* with increased specificity for grasshoppers by selecting stains isolated from grasshoppers (Prior 1992).

Mycotech Corporation (Butte, MT) has mass-produced a strain of *B. bassiana* isolated from an infected grasshopper found in Montana. Laboratory and field studies have indicated that this strain is infectious and lethal in confined populations of several species of grasshoppers (see VII.5). However, no information existed on its virulence in nontarget insects.

In 1993, South Dakota State University (SDSU) assisted the Animal and Plant Health Inspection Service (APHIS) by monitoring the population levels of nontarget arthropods in a *B. bassiana* field study located near Amidon, ND (Brinkman 1995). The grasshopper control data for this study are described in chapter VII.5. Important nontarget arthropods on rangeland include beneficial pollinators (flies and bees), predators (spiders, ants, ground beetles, robber flies, green lacewings, brown lacewings, antlions, ladybird beetles, blister beetles, and wasps), parasites or parasitoids (flies and several hymenopterans) and general scavengers (ants and darkling beetles).

Spray-tower laboratory bioassays as developed by Foster and Reuter (1991) also were used at SDSU to determine the effects of *B. bassiana* on nontarget insects. A spray tower consist of a small airbrush, such as artists use, mounted on a stand and connected to an air pump. A solution of fungal conidia (sporelike stage) can then be injected into the airstream and sprayed onto the insects. This method of conidia application should more closely simulate the field aerial application of conidia than would applying the conidia in a large single drop or by submerging the insects in a solution of conidia (Foster and Reuter 1991).

Adult yellow mealworm beetles (*Tenebrio molitor*) were evaluated with the bioassay because they are easily acquired commercially and have therefore served as research models in many laboratory studies. The species *T. molitor* belongs to the family Tenebrionidae, which is an important group of beetles on western rangeland. This beetle was selected also to represent the many species of beetles evaluated in the field study whose population levels appeared unaffected by the release of *B. bassiana* conidia into their locality.

According to Goerzen et al. (1990), alfalfa leafcutting bees (*Megachile rotundata*) should be considered in evaluations of potential microbial agents. Unfortunately, the low numbers of alfalfa leafcutting bees recovered in field plots prior to the North Dakota study made it impossible to evaluate the effects of *B. bassiana* on this species. Therefore, *M. rotundata* was evaluated in the laboratory bioassay. Spray tower bioassays were first conducted with fourth-instar *Melanoplus sanguinipes* grasshoppers in order to standardize our results with those reported in VII.5.

Field Studies

Methods.—Thirteen days prior to aerial treatments, sampling traps were placed in 4 control plots, 4 carbaryl plots, and 4 plots that were to receive *B. bassiana* at the rate of 9.9 trillion spores/64 oz/acre in oil formulation. Ground-dwelling arthropods were sampled with the use of pitfall traps. Pitfall traps are widemouth quart canning jars placed in the ground with the opening level with the soil surface. Ground-dwelling arthropods were captured, killed, and preserved as they fell into the jars, which contained 70 percent alcohol.

Aerial insects were sampled using malaise traps. Insects were captured by malaise traps as they flew into the netting, and instinctively crawled or flew up into jars at the top. Sampling traps were left in plots for 5 days, and then jars and samples were retrieved. Immediately after treatments, jars were replaced in plots and retrieved every 6 days for the duration of the summer season. Arthropod samples were taken to SDSU to be sorted and identified.

Results.—During the study period, an abnormally high level of precipitation fell on the study plots. The resulting high moisture level was favorable for the natural outbreak of *Beauveria* infections identified in the control grasshoppers from the untreated plots. This natural *Beauveria* outbreak may then have been at least partially responsible for the unexpected erratic results seen in this study in both the treated and untreated plots.

Ant and spider abundance declined in all plots following treatment but rebounded the next week. The sporadic heavy precipitation that occurred following treatment may have resulted in decreased activity of those ground-dwelling arthropods, and thus diminished their chances of falling in the pitfall traps. Therefore, the temporary decrease in ant and spider abundance did not appear to be due to *B. bassiana* or carbaryl treatments. Ground beetle (Carabidae) densities remained stable throughout the summer season.

Flies (Diptera) were the most prevalent aerial insects captured in malaise traps. Abundance of flying Diptera, Hymenoptera, Lepidoptera, Neuroptera, and Coleoptera increased in all plots following treatments. *B. bassiana* and carbaryl applications did not result in any noticeable declines in aerial insect abundance.

Alfalfa leafcutting bees were very rare at the study site. Only three individual Megachilidae were collected in malaise traps during the sampling season. The study site was dominated by mixed grasses, so there was little attraction for pollinating bees. Consequently, we were not able to determine if field applications of *B. bassiana* affected alfalfa leafcutting bees.

Laboratory Studies

Methods.—Fungal conidia (spores) and an oil carrier solution were supplied by Mycotech Corp. Aerial application of *B. bassiana* was simulated in the laboratory with the use of a spray tower. A favorable spray pattern was established in practice tests with the oil solution and the aid of oil-sensitive paper. Procedures, equipment and *B. bassiana* dosages were similar to those described in VII.5 and were selected based on recommendations by Foster and Reuter (1991).

A total of 360 individuals of each species were tested in the laboratory experiments. Prior to each spray event, clean newsprint was placed on the floor of the spray room. In addition, test insects (in groups of 10) were slowed by cooling to 35 °F (1.7 °C). Thirty individuals were sprayed with air for approximately 15 seconds first and were kept as controls. Thirty insects were sprayed with 0.09 mL of the oil carrier. Thirty insects were sprayed with 0.09 mL of oil containing 2.64 billion conidia/mL. Treatments were replicated four times. Insects were then observed for 10 days after treatment.

Results.—Grasshoppers treated with *B. bassiana* began expiring on day 5. After 10 days, more than 73 percent of treated grasshoppers had died. Mortality of beetles treated with *B. bassiana* was extremely low, and beetles did not appear to be susceptible to infection.

B. bassiana was extremely virulent to alfalfa leafcutting bees. Alfalfa leafcutting bees sprayed with *B. bassiana* began expiring on day 4. After 10 days, more than 87 percent of alfalfa leafcutting bees had died. However, mortality of alfalfa leafcutting bees sprayed with oil and air (control) was low. Dead alfalfa leafcutting bees were individually placed in glass vials with a moist cotton ball and were observed for evidence of infection. After approximately 7 days, external sporulation of hyphae (filaments of the vegetative structure of the fungus) was observed on 99 percent of alfalfa leafcutting bees treated with *B. bassiana*.

Conclusions

Treatment of the study sites with *B. bassiana* caused no measurable permanent decrease in populations of any of the monitored beneficial insects. This lack of effect occurred during a time period when moisture levels in the fields were abnormally high, and thus, environmental conditions should have been very good for the spread of the infection into beneficial insects. In fact, even some of the grasshoppers recovered from the control sites also were infected with *Beauveria*, but at low levels and most likely from a natural outbreak.

Spray-tower results on lab-reared grasshoppers were similar to those described in VII.5. The nonsusceptibility of the *Tenebrio molitor* to *B. bassiana* in the spray-tower bioassay was consistent with *Beauveria*'s apparent lack of effect on beetles in the field study. The effects of *B. bassiana* on alfalfa leafcutting bees were evaluated only with the spray-tower bioassay because few bees were recovered in the field. Existing bioassay data indicate that these insects are very susceptible to this strain of *B. bassiana*. Injury to the entire population of alfalfa leafcutting bees might be reduced through management.

B. bassiana conidia can persist if protected from environmental extremes (soil is the natural reservoir for conidia), but become nonviable after only a few hours of exposure to sunlight (Gaugler et al. 1989, see VII.5). Alfalfa leafcutting bees readily accept artificial nesting structures, which could be moved during spray operations and returned later.

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VII.8 Grasshopper Viruses

D. A. Streett and S. A. Woods

Introduction

Insect poxviruses or “entomopoxviruses” (EPV’s) infect insects from the following five insect orders: Coleoptera (beetles), Lepidoptera (moths and butterflies), Orthoptera (grasshoppers and crickets), Diptera (flies), and Hymenoptera (bees and wasps). The grasshopper EPV’s are found in the genus Entomopoxvirus B, which also includes viruses from Lepidoptera and Orthoptera (Esposito 1991). All grasshopper viruses are physically similar and have roughly the same deoxyribonucleic acid (DNA) size. They differ from EPV’s in other insect orders and other animal poxviruses. Indeed, there is no evidence to suggest any close relationship or similarity between grasshopper entomopoxviruses and other viruses of vertebrate or invertebrates (Langridge 1984).

Virus particles are embedded in a crystalline proteinaceous matrix referred to as an occlusion body (OB). OB’s vary in size from 3 to 12 microns (μm) in diameter and may each contain up to several hundred virus particles. Twelve μm equal about 1/20,000th of an inch. OB’s offer the virus particles some protection from environmental conditions and are thought to be responsible for transmission of a virus from one grasshopper to another. When OB’s are ingested by a grasshopper, the virus particles are released and penetrate through the digestive tract into the body of the grasshopper. Infection by grasshopper EPV’s appears to be restricted to the fat body, a tissue which is used to store food reserves and metabolize food. After the virus particles enter a fat body cell, they replicate and pack the cytoplasm with new OB’s that contain virus particles. Virus particles will also spread to other fat body cells until nearly all the cells in the fat body are infected with virus (Henry et al. 1969, Granados 1981).

EPV’s are the only viruses containing DNA that have been found in field grasshoppers. Typically, an EPV will be named after the host species of the original isolation. Following this convention, there are at least 15 grasshopper EPV’s reported in the literature (Henry and Jutila 1966, Langridge et al. 1983, Oma and Henry 1986, Henry et al. 1985, Wang 1994).

EPV Laboratory Studies

Cross-infection studies have been reported for only seven grasshopper and locust EPV’s (Henry et al. 1985, Oma and Henry 1986, Streett et al. 1990, Lange and Streett 1993). Relative susceptibility of grasshoppers to a given EPV is usually limited to grasshoppers within the same subfamily (Lange and Streett 1993). However, it is interesting to note that some grasshopper EPV’s have been found to infect grasshoppers from several different subfamilies.

Henry and Jutila (1966) isolated the first grasshopper EPV from the lesser migratory grasshopper, *Melanoplus sanguinipes*, a frequent pest on crops and rangeland. The virus, referred to as the *Melanoplus sanguinipes* entomopoxvirus (MsEPV), infects mostly species in the genus *Melanoplus* (Oma and Henry 1986). Grasshoppers infected with a sufficient amount of the virus develop slowly, are sluggish, and die from the effects of the virus (Henry and Jutila 1966).

MsEPV is the only grasshopper EPV that has been grown in vitro (outside the body) (Kurtti et al. 1990 unpubl). The *M. sanguinipes* cell culture lines designated UMMSE-1A, UMMSE-4, and UMMSE-8 have proven susceptible to infection by MsEPV. The UMMSE-4 cell cultures show cytopathic effects (undergo cell changes) when inoculated with MsEPV. The virus produced in vitro is both infectious and virulent (poisonous) against *M. sanguinipes*. Occlusion bodies produced in vitro, though, were somewhat smaller—each about 6 μm in diameter (1/40,000 of an inch)—than occlusion bodies produced in vivo (inside the body). The latter were each about 12 μm in diameter.

In the laboratory, mortality from MsEPV occurs in two distinct timeframes over 5 or more weeks. Infectious OB’s are not present in grasshoppers that die during the first interval of mortality, so these cadavers are of little importance for pathogen transmission. As dosage increases, the proportion of inoculated grasshoppers that die prior to OB formation increases dramatically. Consequently, the proportion of infected grasshoppers that survive long enough to produce OB’s actually decreases

with dosage (Woods et al. 1992). These observations suggest that the strategy for using this virus in an integrated pest management program may well depend on the specific objectives at the time of application. Maximum transmission rates are likely to be attained by applying the virus at low rates, and so an EPV treatment may be an appropriate strategy for grasshopper populations that are increasing in density. A high-density population that is already causing significant damage should be treated with high rates to cause substantial early mortality.

Sublethal effects that have been observed for virus-infected grasshoppers include a delay in development, reduction in food consumption, and potential reduction in egg production by the female. All of these sublethal factors can have a profound effect on grasshopper populations.

The delay in development was reported first by Henry et al. (1969) and later by Olfert and Erlandson (1991). In some cases, grasshopper nymphs infected with MsEPV will remain 9 to 18 days longer in an instar. Total food consumption by grasshoppers infected with MsEPV was reduced by 25 percent at 5 days after infection and up to 50 percent at 25 days after infection. This reduction in food consumption in MsEPV-infected nymphs was directly related to dose.

The effects of MsEPV infection on *M. sanguinipes* egg production are unclear. While it has been difficult to thoroughly describe the effects of MsEPV on *M. sanguinipes* egg production, we have observed that development to the adult stage is delayed by infection, and none of the infected adults in our laboratory studies have produced any eggs.

Routes of Transmission

One of the more likely routes of EPV transmission is through the consumption of infected cadavers. Grasshoppers will commonly consume other grasshoppers that are sick or dying. When grasshopper cadavers were placed in the field, nearly 92 percent of the cadavers were almost entirely consumed after 30 minutes (O'Neill et al. 1994).

Under high density conditions, there may be considerable competition for these cadavers with the larger individuals successfully defending the resource against smaller intruding grasshoppers (O'Neill et al. 1993). When both infected and uninfected cadavers were placed in the field, there were no significant differences in the number of cadavers that were partially consumed (K. M. O'Neill, unpublished data).

EPV Field Studies

The Environmental Protection Agency granted an Experimental Use Permit (EUP) for field evaluations of MsEPV in 1988. Field evaluations were conducted from 1988 to 1990. Human and domestic-animal safety studies were completed, and no evidence of infectivity was detected in any of the studies. Toxicology data to identify hazards that MsEPV might present to nontarget organisms were also conducted with no evidence of toxicity or pathogenicity (poisonous or disease-related effects) observed in any of the animals examined in these studies. In addition, Vandenberg et al. (1990) did not observe reductions in longevity or pathological effects when MsEPV was tested against newly emerged adult workers of the honeybee, *Apis mellifera*.

Field evaluations of the potential for using MsEPV for grasshopper control were conducted during 1989. Plots were treated with virus that was formulated in starch granules (McGuire et al. 1991). At 13 days after application, prevalence (the number of diseased insects at any given time) was estimated at 14 percent and 23 percent in the plots receiving the low or high application rates, respectively. Prevalence was estimated at 9.2 percent in the control plots at 13 days after application, indicating that considerable dispersal between plots had already occurred (Streett and Woods 1990 unpubl.). Our field studies from 1989 emphasize the problems associated with evaluation of microbial insecticides against insects with considerable dispersal capabilities. That we can infect at least 23 percent of the population with a rate of 10 billion OB's/acre (24.7 billion OB's/ha) is clear. The actual infection levels, in view of the dispersal problem and early mortality from the pathogen, are probably much higher.

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VII.9 Use of an Australian Parasite of Grasshopper Eggs as a Biological Control Agent

Richard J. Dysart

Introduction

In order to increase the existing mortality level of any pest grasshopper, entomologists are generally limited to two biological control approaches: augmentation or introduction. In the former, some parasite or predator species must be reared in great numbers and distributed evenly over the crop or rangeland to be protected. The augmentation process must be repeated year after year as needed. In the introduction approach, a parasite or predator species, from outside of the system, is imported and colonized, with the intention of obtaining permanent establishment of the natural enemy. Ideally, the natural enemy species would be colonized only once and would spread and distribute itself once established.

Augmentative Approach

In my opinion, using insect parasites or predators augmentatively, as substitutes for chemical insecticides, is not feasible for the control of grasshoppers. The chief obstacle to this approach is the cost. Although certain *Scelio* egg parasites can be reared easily in the laboratory, the rearing process is dependent upon a constant supply of live grasshopper eggs of a certain age. Considering the immense areas that would require treatment with parasites, plus the logistics of rearing and delivery, it is certain that the costs of using *Scelio* wasps augmentatively would be unacceptable.

Classical Introduction Approach

Historical.—According to a worldwide review article by Prior and Greathead (1989), classical biological control of a grasshopper with scelionid wasps has been attempted on only one occasion. The attempt was made in Hawaii, during 1930 and 1931, against the Chinese grasshopper, *Oxya chinensis* (Thunberg), using two parasite species from Malaysia, *Scelio serdangensis* Timberlake and *S. pembertoni* Timberlake (Pemberton 1933, Clausen 1978). *Scelio serdangensis* failed to establish, but *S. pembertoni* became established and is reported to have successfully controlled the pest (Pemberton 1948, Clausen 1978). As pointed out by various authors (Commonwealth Institute of Biological Control 1981, Siddiqui et al. 1986, Greathead 1992), the possibilities for classical introduc-

tions against grasshoppers certainly have not been exhausted, particularly with scelionid egg parasites. Worldwide in distribution, the species of the genus *Scelio* are all egg parasites of acridid grasshoppers and there are no host records from any other group of insects (Greathead 1963, Muesebeck 1972, Galloway and Austin 1984).

Rationale for Classical Introduction.—Although there are several native *Scelio* spp. present in western North America, they cause only minor levels of egg mortality. The most abundant and most widespread of our native egg parasites is *Scelio opacus* (Provancher). During an 8-year study in Wyoming, Lavigne and Pfadt (1966) found only trace numbers of *Scelio* parasites in rangeland grasshopper eggs. Results of a long-term study in Saskatchewan (Mukerji 1987) showed that egg parasitism by *Scelio* averaged about 5 percent and had no detectable impact on field populations. In my own field studies in northeastern Montana and northwestern North Dakota from 1988 to 1994, egg-pod parasitism by native *Scelio* spp. averaged 10.7 percent (Dysart 1995), but parasitism of individual eggs was only 4.1 percent (Dysart 1994 unpubl.).

Although the ecological niche is occupied by several native parasites, their total impact on the eggs of pest grasshoppers probably does not affect infestations. Therefore, in 1989, I proposed to the Animal and Plant Health Inspection Service (APHIS) that I try to import and establish an additional species of *Scelio*. If this new parasite became established on one or more of the destructive grasshoppers in the West, it could increase egg mortality and thereby reduce initial densities of nymphs. That scenario could greatly enhance the probability of other indigenous (native) natural enemies maintaining suppression of pest grasshopper densities at or below economic thresholds for greater time intervals.

Periodic outbreaks probably would not be eliminated, but the interval between them might be lengthened or the duration of outbreaks might be shortened. Introduction of exotic parasites to help control indigenous pests is controversial, but as pointed out by Huffaker et al. (1971), there is no pest that should be judged in advance as not amenable to biological control. A good review article on this subject is presented by Carl (1982).

Search for a Candidate *Scelio* in Australia.—In September 1990 and again in 1992, my Australian colleagues and I collected egg-pods of several different grasshoppers and locusts at 10 localities in the States of New South Wales, South Australia, and Western Australia. In September 1992, we made collections in 11 different localities in the same states. A summary of these collections is found in Dysart (1993 unpubl.) and in Baker et al. (in press). In 1990, overall parasitism of egg-pods by *Scelio* spp. was 28 percent (128 of 460 egg-pods), but was highest (36 percent) in Western Australia (66 of 181 egg-pods). During 1990, *Scelio parvicornis* Dodd was the most abundant parasite of the five species reared, and at one locality, Nungarin (Kittyeyah ranch), in Western Australia, it parasitized about 25 percent of the host egg-pods (Australian plague locust, *Chortoicetes terminifera* [Walker]). Two articles, Baker and Pigott (1993) and Baker et al. (in press), provide additional parasitism and host-range information on *S. parvicornis*. The egg-pod parasitism figures from Australia are considerably higher than those reported above for western North America.

Quarantine Screening in the United States.—Grasshopper egg-pods collected in Australia were kept chilled and were hand-carried to the Montana State University quarantine facility in Bozeman. There the eggs were allowed to hatch, and all Australian grasshopper nymphs were identified and then destroyed. Of the five species of *Scelio* that emerged from the 1990 collections, we investigators selected *Scelio parvicornis* (Nungarin strain) as our primary candidate, based on its dominant position in the Australian collections and its ease of rearing in the quarantine laboratory.

Rearing and Host-Range Tests.—Using nondiapausing eggs of a native pest grasshopper, *Melanoplus sanguinipes* (Fabricius), as hosts, my research team was able to propagate a nondiapausing culture of *S. parvicornis* in the laboratory. Under our lab conditions, we produced a new generation of parasites about every 32 days. In laboratory comparison tests with the native *S. opacus*, females of the Australian *S. parvicornis* were clearly superior: they parasitized more egg-pods and killed more eggs during their respective lifetimes (Dysart 1991 unpubl.). In laboratory host-range tests, we exposed the Australian parasite to about 1,808 egg-pods of 49 species of North American grasshoppers. We

obtained emergence of adults of *S. parvicornis* from 33 species, and it failed to emerge from egg-pods of 16 grasshopper species (Dysart 1993 unpubl.). About half of the 33 successful lab hosts of *S. parvicornis* are considered to be our most serious rangeland pests (Hewitt 1977) (see also chapter VI.6).

Plans for Field Releases and Recovery Attempts.—Assuming that permission to release parasites was granted by the Federal and State authorities, I had planned to proceed as follows: colonies of several thousand adult parasites would be released over a period of several weeks at one or more sites in Arizona, Montana, and North Dakota. Prior to releases at proposed sites, screened cages would be erected on sandy soil and furnished with wild female grasshoppers (*M. sanguinipes*). After egg-laying was well under way, adult parasites would be introduced into the cages. The cages would be removed the following spring, and during the next two seasons, egg-pods would be excavated at the site and held for emergence in the laboratory to determine if the Australian parasite had successfully overwintered. If *Scelio parvicornis* is released and becomes established, it will be necessary to conduct additional field studies to assess its impact on pest grasshopper populations.

Addendum.—I made my initial request to U.S. Department of Agriculture, APHIS, Plant Protection and Quarantine, Biological and Taxonomic Support (USDA, APHIS, PPQ, BATS) for permission to release *Scelio parvicornis* in the summer of 1991. Periodically during 1992 and 1993, I provided BATS with revisions and support documents as they continued to prepare their risk assessment (Lakin 1994 unpubl.). The question of whether or not the Australian parasite should be released in North America has been the subject of active debate in the literature, between Lockwood (1993a and b) and Carruthers and Onsager (1993). Lockwood is opposed to the field release of the parasite because he feels that its potential host range is too broad, and he speculates that it might have a detrimental effect on benign, nonpest grasshoppers as well as a few grasshoppers thought to be beneficial because they feed on rangeland weeds. Carruthers and Onsager believe that the release of the Australian egg parasite is warranted and that the risk of harm to nontarget species is negligible at best.

On April 6, 1994, I received word from the permitting agency, USDA, APHIS, PPQ, BATS, that my application for the release of *Scelio parvicornis* had been denied. As a result, I have destroyed the laboratory colony and have abandoned my plans for field releases of the parasite. I still believe that the overall benefits of the proposed biological control introduction would outweigh any potential risks, but for the time being, the outcome will remain a matter of conjecture.

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VII.10 Ongoing Environmental Concerns

L. C. McEwen

NOTE: Acephate is no longer approved by EPA for rangeland grasshopper control.

Perhaps the greatest continuing environmental concern in a Grasshopper Integrated Pest Management (GHIPM) program is providing safeguards and protection for threatened and endangered (T and E) plant and animal species. These problems complicate grasshopper control programs and make them more costly but must be dealt with in a straightforward manner. Plenty of lead time should be allowed to identify species and habitats and to work out solutions with agencies responsible for T and E species' protection and management.

Recognition of the fact that individual vertebrate animals can vary greatly in their sensitivity to a given toxic chemical should help all workers understand that toxic exposure of the T and E species must be kept to a minimum. Toxic hazard is minor for mature animals lightly exposed to the current GHIPM pesticides—carbaryl, malathion, and acephate—but is probably more of a factor for young animals (chicks, nestlings, amphibians, and larval fish). Any toxic mortality would be of concern because species differ in their lower threshold of numbers of animals necessary for maintaining a viable population. Those limits are not known precisely for each species, but land managers should try hard not to cause unnecessary losses with toxic chemicals.

In the larger picture, it would seem that concern for geographic variants that have been given T and E status should not be on the same level as for T and E species that are the sole remaining population or individuals. Technically and legally, however, there is no distinction at this time.

T and E species can be protected in several ways in a rangeland grasshopper cooperative control program. Nonspray buffer zones are one of the main tools (see chapter III.8). Width and size of buffer zones will vary with the T and E species and on the outcome of consultation with managing agencies. Carbaryl bait treatments or other dry baits, including biological control agents such as *Nosema locustae* and *Beauveria bassiana*, can be used safely much closer to the T and E species habitat or even with no buffer zone in some cases.

Baits and biologicals add expense and sometimes cause equipment problems when used but should be recognized and accepted as important and necessary components of

many successful programs. The degree of grasshopper reduction will probably be less than where liquid insecticide spray is applied, but the higher densities of grasshoppers remaining after the treatment often will be beneficial to the T and E species.

Another possible option for protecting T and E species is the timing of the grasshopper control program. This aspect can be explored for T and E insects and pollinators of T and E plants (also see chapter III.5). If the T and E insects are in the adult stage for a relatively brief period, then pest managers may conduct treatments safely before or after the adult stage.

For aquatic species, there are significant differences in toxicity among the three chemicals. Acephate is much less toxic to fish than carbaryl or malathion (Johnson and Finley 1980) and is referred to in other publications as practically nontoxic to fish. Acephate is highly effective against grasshoppers at the low application rate of 1.5 oz/acre (0.105 kg/ha) (U.S. Department of Agriculture 1987). Although acephate has been little used in cooperative control programs, it could be an excellent alternative to other pesticides where T and E fish are of concern. Another safety factor for fish would be to use dry bait treatments because less chemical is used per unit area and there is much less potential for drift into aquatic habitat. The entire problem of T and E species protection in GHIPM programs could benefit from further research.

Indirect Effects on T and E Species

The question of indirect effects of grasshopper control programs, primarily reduction or loss of the food base for birds, now comes up more frequently than potential toxic effects. Colorado State University (CSU)-led studies have shown that when grasshopper availability is reduced, birds generally switch to other insects or invertebrates for food and maintain their nesting success and populations (Miller 1993, Miller and McEwen 1995, Miller et al. 1994, George et al. 1995, Fair et al. 1995). Regarding the concern for peregrine prey effects, CSU investigators have shown that total bird population numbers do not decline following a grasshopper control program, even though some individual species might decrease (George et al. 1995). Since peregrines prey on such a wide variety of avian species (DeWeese et al.

1986, Hunter et al. 1988), the decline of one or two species should have no significant effect on their prey base. Use of dry baits, such as carbaryl bait, also could be a safeguard since the baits are selective formulations and consequently leave many unaffected insects for avian food (Adams et al. 1994).

Nevertheless, each T and E species must be examined individually for potential response to GHIPM treatments. The situation is such that T and E species and their habitats cannot be dealt with routinely by generalized procedures. Each T and E situation must be treated as a unique "case history," although as knowledge is acquired, some will be more standardized than others.

New Chemicals and Biologicals

New materials for range grasshopper control, such as Dimilin® (diflubenzuron) and *Beauveria bassiana*, will require close monitoring until their environmental safety is determined. The two materials appear quite safe for terrestrial vertebrates, but final determinations cannot be made until the materials are applied in large-scale operational control programs. Aquatic effects are especially of concern as well as Acridid (grasshopper) specificity and effects on nontarget invertebrates. Any other candidate chemicals and biologicals that are considered for GHIPM must also be closely examined for environmental effects before being approved for large-scale use.

Species of Concern

State and Federal wildlife agencies in recent years have endorsed a philosophy of giving attention to declining species **before** they reach T and E status. If a declining species can be managed for recovery before listing, management efforts are simplified. Declining species may be designated as "species of concern." Some examples are the long-billed curlew (*Numenius americanus*), the western burrowing owl (*Athene cunicularia*), and the ferruginous hawk (*Buteo regalis*). The curlews and burrowing owls use grasshoppers heavily, especially as a source of protein and nutrients important for breeding and for feeding their young. The golden eagle (*Aquila chrysaetos*) is another species of concern in some areas of the West and is a protected species. There is a need to conduct a study of the response of nesting golden eagles to malathion

spray as was done with Sevin® 4-Oil. One or more of several species of concern are apt to be present in GHIPM treatment areas and should be treated as T and E species if necessary in the opinion of the biologists and land managers involved.

Gallinaceous birds, such as prairie chickens and sharptailed grouse (*Tympanuchus* spp.), sage grouse (*Centrocercus urophasianus*), chukars (*Alectoris chukar*), and wild turkeys (*Meleagris gallopavo*), also often are considered species of concern. The effects of grasshopper control on the growth and survival of the young chicks and poults is the primary question. More study is needed on the effects of GHIPM programs on species of concern.

Function of Wildlife in a GHIPM System

Scientists and land managers have made a lot of progress in showing the role and benefits of wildlife, especially birds, as important contributors to regulation of grasshopper densities (Joern 1986, Fowler et al. 1991, Bock et al. 1992). However, the overall ecology of native wild vertebrates in preventing insect pest outbreaks is virtually unexplored. The interrelationships of range condition, vegetative cover types, native plants *vs.* introduced species for reseeding (such as crested wheatgrass, *Agropyron cristatum*), and associated wildlife populations need much more investigation. Large expanses of crested wheatgrass become devoid of almost all the breeding avian species (Reynolds and Trost 1980). In the northern Great Plains, grasshopper outbreaks frequently originate in crested wheatgrass, where grasshopper densities are usually higher than on native grass range (Hirsch et al. 1988 unpubl., Kemp and Onsager 1994 unpubl.). This fact should not be surprising because the lack of birds as grasshopper predators is coupled with >40 percent bare ground (compared to <5 percent in native grassland (Dormaar et al. 1995), which is favored by many grasshoppers for egg-laying.

Range condition criteria are currently undergoing review and revision (Task Group on Unity in Concepts and Terminology 1995). Land managers need to relate range wildlife habitat use and populations to condition classes and to grasshopper population fluctuations. Improving range condition is a long, slow process, but range in good

condition with a full complement of native wildlife can reduce grasshopper population fluctuations in the central and northern Great Plains (McEwen 1987). Improving the condition of degenerated sagebrush (*Artemisia* spp.) range found farther west is more difficult than improving other range types, but it should be a long-term goal (McEwen and DeWeese 1987). New range management practices (Biondini and Manske 1996; Onsager, in press) should be examined for wildlife responses.

The status and function of wild vertebrates in relation to range condition also need more investigation. Basic knowledge of range wildlife ecology connects with the efforts to improve the vegetative cover on western rangelands. Preventing the extinction of animal and plant species is the goal of conservation biology and will be a benefit of better range condition. This will also be an important factor contributing to grasshopper management in an IPM system.

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VII.11 Implications of Ecosystem Management and Information-Processing Technologies

W. P. Kemp, D. McNeal, and M. M. Cigliano

Ecosystem Management and Public Lands

A very large portion of the millions of rangeland acres in the 17 Western United States resides within the boundaries of what many refer to as the public land trust, or federally managed lands. Voters have demanded that the public servants who manage these lands employ “ecosystem management” to provide, among other things, a safe food supply while not compromising natural resources like clean air, clean water, productive soils, and biodiversity. Private interests who lease grazing rights from the various public agencies charged with managing our national land treasure must comply with the public’s wishes regarding resource management issues or risk losing the opportunity of using those public lands.

At present, agencies involved in managing the natural resources on public lands are struggling to define just what constitutes ecosystem management, how to manage ecosystems whose limits do not agree with political or ownership boundaries, and how to conduct such management with dwindling agency resources. For example, there is general agreement throughout public land-management agencies that an ecosystem focus is desirable in managing the natural resources of public lands. There also is a nagging concern that agencies don’t have a very clear vision of just how much information is necessary to meet national objectives. Furthermore, it is obvious that agencies will have to make natural resource management decisions without complete information. Unfortunately, just what constitutes “enough” or “sufficient” ecosystem management will likely emerge only after and as a direct result of a series of court decisions.

Agencies cannot predict with absolute certainty what the result of the ecosystem management consensus-building process will be, nor can they forecast the specific impacts ecosystem management will have on integrated pest management (IPM) of public lands. The executive branch of the Federal Government has provided some expected outcomes, at least in general terms (Gore 1993, National Research Council 1993).

In the case of rangeland grasshopper integrated pest management (IPM), many believe that the amount of information needed to conduct management action (for example, chemical, biological, or cultural control) will be

staggering in an effort to satisfy the need of policymakers to feel confident in presenting results for public viewing. Add to this the challenge of a short interval between problem identification and the time when action must be taken if it is to be effective for rangeland grasshopper IPM on public lands. It is clear that scientists and land managers face an information-gathering and -processing crisis. The remainder of this chapter will focus on ways that agencies can address this crisis that is already upon the country.

Present and Future IPM Technologies

In spite of the information crisis faced with IPM on public lands, there are technologies available that agencies managing public lands can use in an attempt to comply with societal mandates. Other chapters in this Handbook discuss global positioning system (GPS) and geographic information systems (GIS) for aircraft guidance (see section II) as well as for IPM in general (see chapter VI.9). The current role of modeling and decision support systems (DSS) also is discussed in the Decision Support Tools section. This chapter will focus on information processing technologies and a new paradigm (example or model) in the context of IPM systems to be developed for rangeland grasshoppers on public lands.

There are at least five areas of information-processing technology that deserve additional attention in the development of IPM systems for rangeland grasshoppers on public lands, under the umbrella of ecosystem management. These are GPS, GIS, remotely sensed information, DSS, and networks. Three of the five areas—GPS, GIS, and remotely sensed information (see details in chapter VI.9) can be classified as technologies that assist land managers in collecting and storing information about the ecosystems that they are responsible for managing. On the other hand, DSS and networks will be central to actually processing the mountains of available information and developing the most appropriate management of a rangeland grasshopper problem on a particular piece of public rangeland.

Fortunately for public land-management agencies, there is a very competitive software and hardware market associated with GPS, GIS, and remote sensing technologies at present. This competition is likely to continue well into

the future. Such competition in the private sector of the U.S. economy will result in a steady and timely stream of products for use in collecting and storing information about the ecosystems that must be managed. Similar statements can also be made for the networking industry as everyone anticipates “information highways” of the future.

Perhaps the most serious challenge that agencies face in attempting to implement ecosystem management in general, and rangeland grasshopper IPM in particular, is the development and maintenance of DSS. DSS such as Hopper, developed from funding provided by the Grasshopper Integrated Pest Management (GHIPM) Project, must continually be updated and expanded to have any hope of processing the ecosystem information that is accumulating. In addition to defining who will be responsible for the continued development of DSS, agencies need coordinated planning to ensure that research emerging from Federal, private, and State laboratories will continue to support DSS improvements.

We must note that, although technologies may be sufficiently well developed for implementation and public land-management agencies may be interested in adopting such technologies, costs will increase. This is true because of the significant increase in the information-processing tasks presented by the implementation of ecosystem management on public lands. The efficiencies of operation with the equipment that is available today exceed even wild dreams of 10 years ago. Public land-management agencies are working feverishly to embrace new technologies. There now is uncertainty whether the resources will be forthcoming to do the job right.

Getting Organized

In this section, we offer some specific suggestions on how to coordinate future rangeland grasshopper IPM with Federal land-management agencies. First, the concept of ecoregion—regional areas (fig. VII.11–1) with similar environmental resources, ecosystems, and sensitivities to human impacts (Bailey 1980, Omernik 1987 and 1995) is useful for organizing information concerning all aspects of grasshopper management. This is a somewhat different use of the concept than was discussed in the environmental impact statement that governed the

GHIPM Project (U.S. Department of Agriculture, Animal and Plant Health Inspection Service [APHIS] 1987).

Instead of simply acknowledging that there are broad ecological differences in the Western United States, agencies should use the concept of the ecoregion as a fundamental organizational paradigm. Bailey (1980) suggested that the regionalization (for example, fig. VII.11–1) that results from accepting this paradigm helps “(1) planning at the national level, where it is necessary to study management problems and potential solutions on a regional basis; (2) organization and retrieval of data gathered in a resource inventory; and (3) interpretation of inventory data, including differences in indicator plants and animals among regions.” In our opinion, the capabilities that agencies have with GIS presently permit them to apply the ecoregion concept in ways that have until now escaped scientists and land managers.

“Ecoregion” relates to the ability of the land to produce goods and services that humans can use. Furthermore, historically sustainable activities related to grasslands have to a large extent been molded by the prevailing conditions—expressed by ecoregion. For example, the differences in ranching styles and associated economics across the Western United States that economists have been talking about are no doubt related to the fact that ranching has evolved in each region in response to the environmental limitations (again, expressed as ecoregion).

Currently, Hopper (see VI.2) has been developed for only a part of the total area over which there is the opportunity to use it. Furthermore, when land managers look at rangeland grasshopper economic injury levels (EIL) for widely separated areas, such as Wyoming and New Mexico, it is becoming more and more clear how important the regional perspective can be. For example, recent results suggest that it may take three to four times as many grasshoppers in New Mexico versus Wyoming before management treatments would be justified economically. In any case, whether agencies call them ecoregions or rename them as management regions for the needs of APHIS, Plant Protection and Quarantine (PPQ) activities, figure VII.11–1 represents a scale that is a good first attempt to capture the variability across the grasslands of the United States without overburdening people with too much detail.

Ecoregions of the Conterminous United States (Revised 1993)

Corvallis Environmental Research Laboratory
U.S. Environmental Protection Agency

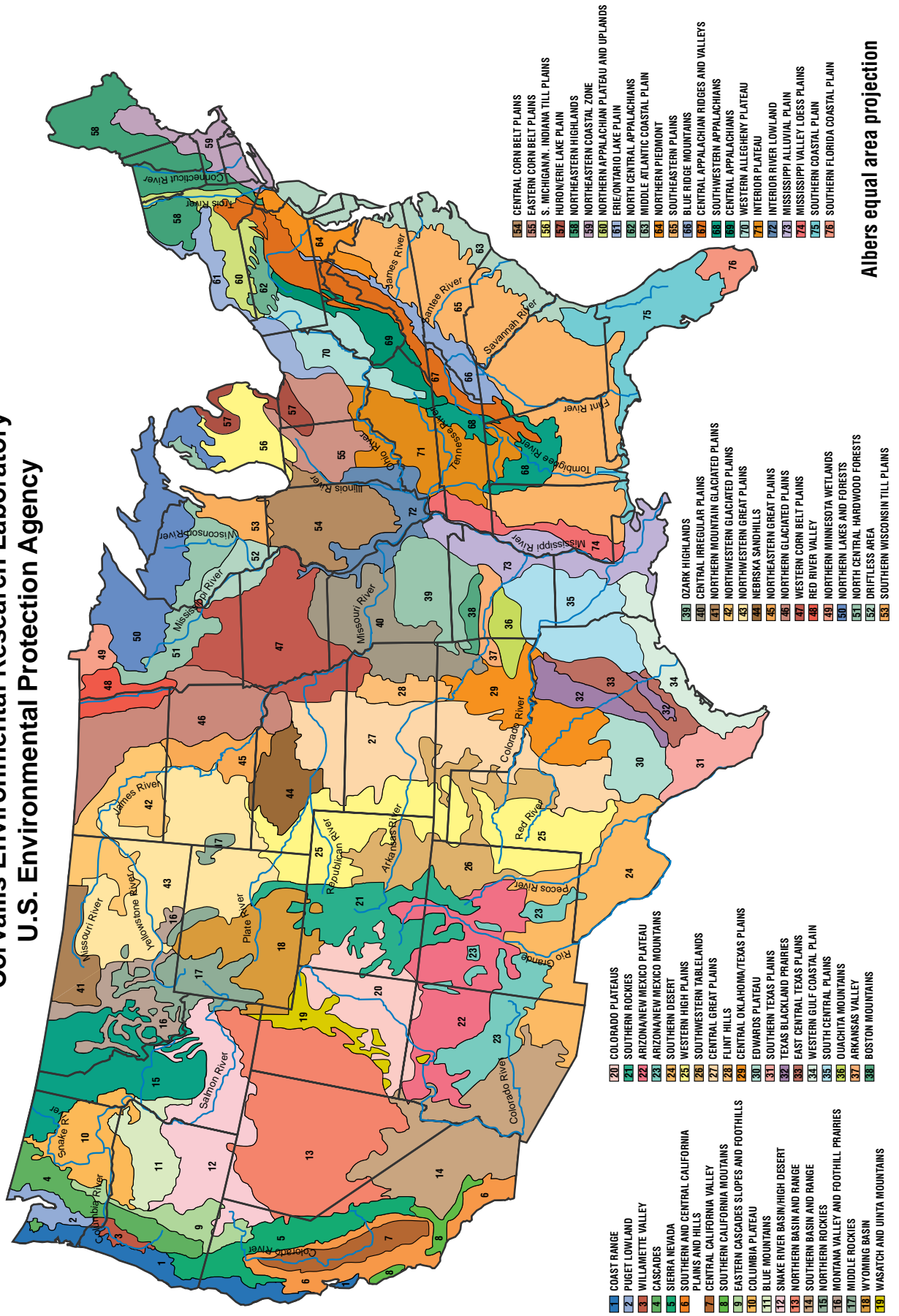


Figure VII.11-1—Ecoregions of the conterminous United States (adapted from a map in Omernik 1987 and 1995.)

The ecoregion concept is useful for exchanging information about environmental conditions, plant production, ranching, and grasshopper ecology and management (from hatching to outbreak frequency and probability and more). There is a credible argument for the use of the concept of ecoregion as a framework for the development of future rangeland grasshopper cooperative management program final environmental impact statements (FEIS's). The ecoregion concept also has potential application for other pest-related issues (for example, noxious weeds) with which APHIS, PPQ and Federal land-management agencies must deal.

In the development of any future FEIS activities, pest managers first should organize rangeland grasshopper IPM activities to be responsive to the situations recognized within each ecoregion. Next, agencies should acknowledge that IPM is the collection of options (including no action) and philosophies most appropriate for addressing grasshopper management. Considering the variation in grassland vegetation and climate depicted in figure VII.11-1 and associated variations in grasshopper populations (for example, Kemp et al. 1990), it is very unlikely that all management options will be equally viable (as viewed by environmentalists, economists, and the public) or of constant efficacy across the rangelands of the 17 Western United States. If this approach to management is acceptable, then there is a logical manner for studying and determining what to emphasize in terms of IPM components at the ecoregion level.

Using this approach as an example, the tabulation in the right column illustrates one way to organize an FEIS.

Organization scheme for a Final Environmental Impact Statement for a Rangeland Grasshopper Cooperative Management Program

Level 1: Ecoregions—regional variations in climate, vegetation, and landform. This is the basis for organizing what agencies know as well as what and how agencies will manage.

Level 2: Things that are likely to be different by ecoregion and that should be considered in any future activities related to the Rangeland Grasshopper Cooperative Management Program FEIS (this list is not meant to be all-inclusive):

- Grasshopper community species composition,
- Likelihood of grasshopper outbreaks,
- Spatial extent of grasshopper outbreaks,
- General insect–animal community composition,
- Grassland plant community composition,
- Forage production on grasslands,
- Economics of ranching and farming (and thus land use and human population density),
- Economics of grasshopper control and EIL,
- Endangered species,
- Soils (and thus water and pesticide movement), and
- Water resources.

1993 Grasshopper Survey

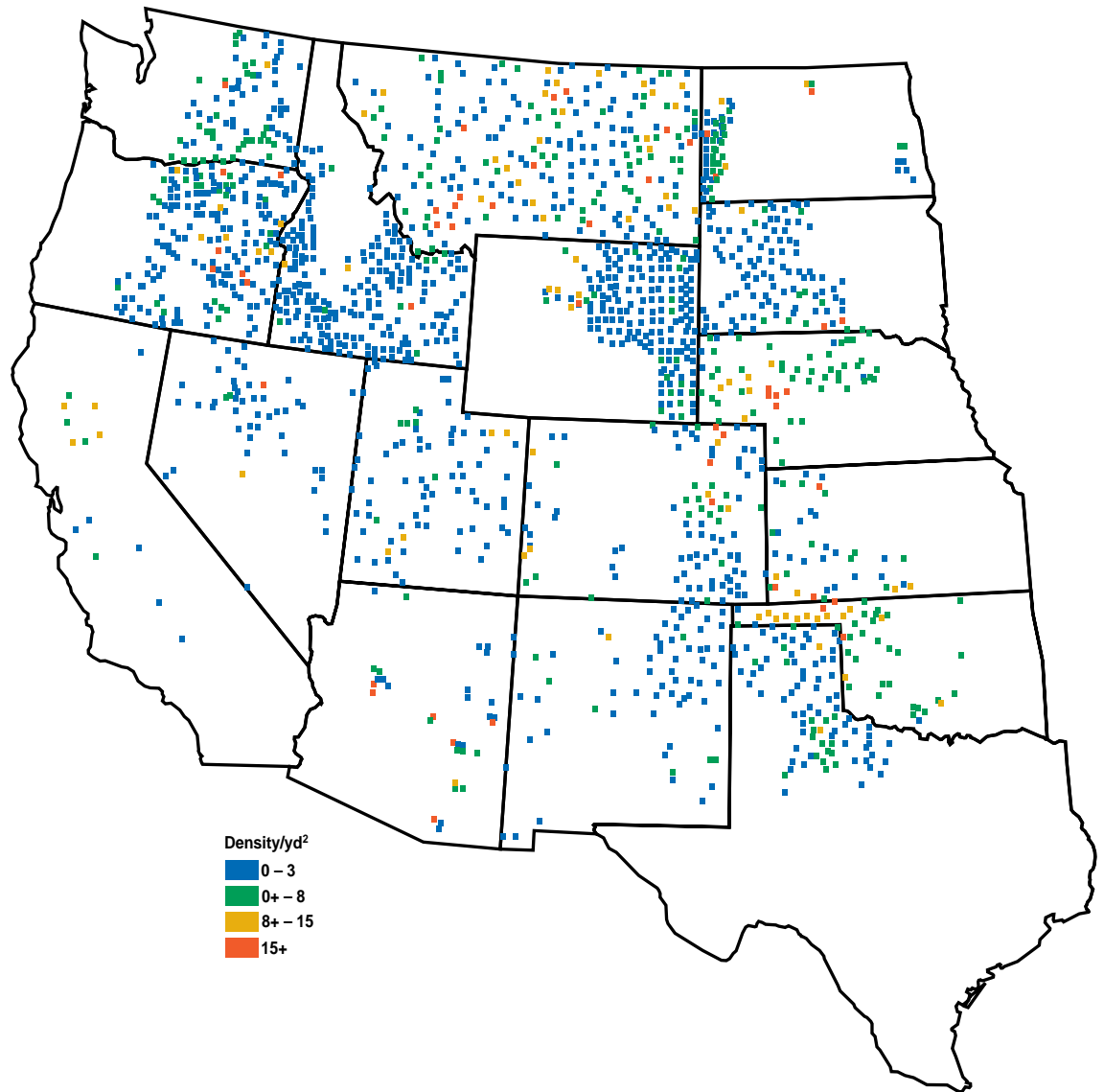


Figure VII.11-2—Locations in the 17 Western United States where (starting in 1993) rangeland grasshoppers were sampled annually for density and species composition by USDA, APHIS, PPQ and cooperators for the Grasshopper Common Dataset Project. Colors indicate grasshopper density at each location in 1993.

The ecoregion paradigm, in addition to being politically and environmentally acceptable (see Gore 1993, National Research Council 1993), can provide Federal land management agencies and APHIS, PPQ with a powerful tool for organizing and interpreting research results relative to rangeland grasshoppers. For example, discussions among a number of GHIPM Project participants and APHIS, PPQ staff eventually resulted in the initiation of the Grasshopper Common Dataset (GCD) during 1993. Scientists now are monitoring rangeland grasshopper communities annually at more than 1,500 locations throughout the 17 Western United States (fig. VII.11–2). Results from ongoing research by GHIPM Project cooperators, with data from the GCD, will tell to what extent grasshopper communities are sensitive to the ecoregion boundaries shown in figure VII.11–1. Given that scientists are able to identify ecological boundaries that are in some way meaningful to the insects, scientists and land managers should apply this concept to assist them in organizing the way that they think about things like rangeland grasshopper management on grasslands west of the 100th meridian of the United States.

In summary, the four main points that we wish to emphasize are

1. GPS, GIS, remote sensing, networking, and DSS will be necessary for ecosystem management of public rangelands.
2. The ecoregion concept is useful, deserves additional consideration by Federal land-management agencies and APHIS, PPQ, and could serve as a useful paradigm for organizing future environmental impact statements related to rangeland grasshoppers (and possibly other insects).
3. By accepting the ecoregion concept, agreeing that IPM is the basis for all grasshopper management, and accepting that IPM consists of all possible alternatives and philosophies as above, agencies eventually could develop ecoregion-specific IPM prescriptions for rangeland grasshopper management.
4. Given 1–3, the regionality provided by the ecoregion concept has great potential for clarifying the goals and objectives of research that Federal land-management agencies and APHIS, PPQ should obtain through contracts and cooperative ventures.

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VII.12 Rangeland Environmental Amenities and Grasshopper Management Programs

Melvin D. Skold and Andrew W. Kitts

Range Ecosystems

Rangelands are increasingly recognized as important for their environmental and recreational amenities. Because they are managed much less intensively than many other types of agricultural lands, rangelands are seen to represent closer approximations to natural ecosystems.

Rangelands are managed for a variety of outputs; in recent years, the contribution of natural rangeland systems to biological diversity has become increasingly recognized.

Rangelands provide two major values, those associated with use (use values) and those realized in the absence of direct use (existence and option or nonuse values). The major commercial use (use values) of rangelands is livestock grazing to produce food, fiber, and draft animals. Other, less significant, commercial uses such as wild game and bird hunting also are associated with rangeland habitats. In addition, rangelands are viewed as important contributors to watersheds: because rangelands usually have lower rates of soil erosion than cropland, they enhance water quality. Further, the natural system that exists on well-managed rangelands makes them increasingly recognized as places for nonconsumptive wildlife associated recreation.

Rangelands also produce intangible products (or nonuse values) that are the result of use. These products include natural beauty, open space, and the mere existence as a natural ecosystem (National Research Council 1994). Others emphasize biological diversity and the associated potential array of products and services as a distinct intangible product (West 1993). In contrast to use values, nonuse values occur almost entirely outside the market system. However, methods are evolving to quantify and assign monetary value to these existence values. As with use values, the costs and/or trade-offs associated with nonuse values can be compared to the estimated benefits (Bishop and Welsh 1992.)

Rangelands possess attributes that give them potential for biodiversity. Since they have not been “put to the plow,” rangelands are attributed value as a natural system. Further, rangelands cover vast areas, often contiguously, and thereby possess the scale necessary for biodiversity of communities, ecosystems, and landscapes (West 1993).

The biodiversity of rangelands contributes to the intangible products mentioned in the National Research Council (1994) report. Recognition of the importance of biodiversity arises for several reasons: (1) morality, (2) esthetics, (3) economics, and (4) “biological services.”

Increasingly land managers are learning of the effects of the impacts of management or lack of management on the ability for various species to survive. Some assert that mankind has a moral obligation to protect fellow creatures. Social awareness has also made managers and others aware of the need to protect spaces, natural systems, and historic sites. In addition to the value of present consumptive and nonconsumptive uses, rangelands also possess esthetic values, and other economic potentials exist. Potentially these natural systems include yet-to-be-identified goods that could be of value to people. Finally, ecosystems are important components of natural cycles affecting the gaseous composition of the atmosphere; genesis, fertility, and stability of soils; disposal of wastes; cycling of nutrients; and natural control of pathogenic and parasitic organisms (West 1993).

A healthy range is recognized as one in which the integrity of the soil and ecological processes of the rangeland ecosystem are sustained (National Research Council 1994). Whenever management intervenes in the natural processes, for whatever reason, the impact of those interventions on the rangeland’s ability to sustain commercial as well as intangible products must be considered. Rangeland grasshoppers also can disrupt the natural ecosystem in two ways. First, grasshopper infestations can reach plague proportions. Serious and widespread outbreaks can lead to soil erosion and reductions in water quality and make it difficult—if not impossible—for the range to recover to its original state. Major infestations of grasshoppers destroy cover for ground-nesting birds and mammals and damage the habitat for other wildlife. The desire to protect the range ecosystem and adjacent croplands was an important part of the rationale for initiating the publicly assisted rangeland grasshopper control programs that exist today.

Second, grasshoppers are recognized as an integral and necessary part of a range ecosystem. Grasshoppers and other rangeland insects are an important part of the food

chain of some birds and mammals. Some species of grasshoppers are beneficial, feeding on plant forms that are not consumed by other users of the range. Because grasshoppers cut off vegetation as well as consume it, they create litter that becomes an important part of the nutrient cycle on rangelands. The strategy for managing rangeland grasshoppers has to be one of maintaining balance within range ecosystems.

The Grasshopper Integrated Pest Management (GHIPM) Project recognized the potential environmental costs associated with applying grasshopper management programs. One component addressed the safe use of grasshopper management programs around threatened and endangered plant species (Tepedino and Griswold 1993 unpubl.). Another chapter (III.6) in the environmental monitoring and evaluation section of the User Handbook evaluates the effects of grasshopper treatments on wildlife and aquatic species. The economics component of the Project developed procedures to make estimates of the environmental costs of control programs. This valuation recognizes, as the reader shall subsequently see, that fish and wildlife possess a value for recreation that considers both nonconsumptive (bird watching, photography, hiking) and consumptive (fishing, hunting) forms of wildlife-associated recreation.

Grasshopper program managers have been conscious of possible environmental side effects, undesired and beneficial, from these programs. Chemical applications may affect populations of some nontarget insect species as well as grasshoppers. Treatment program managers warn keepers of commercial insects so that those populations are protected. Managers of treatment programs take care to spray chemicals under conditions that minimize drift and to refrain from applying certain chemicals near water.

Evaluating Losses in Wildlife-Associated Recreation

Economists have made estimates of the value of some of the nontraditional outputs from rangelands (Bernardo et al. 1992, Kitts 1992, Loomis et al. 1989, Standiford and Howitt 1993, Young et al. 1987). Most of these studies have focused on consumptive and nonconsumptive forms of wildlife-associated recreation. However, a recent Colorado study estimated the value of open space. It

found 80 percent of those spending summer vacations in the Steamboat Springs area indicated that ranch open space added significantly to their willingness to pay for summer visits. Willingness to pay for ranch open space averaged about \$20 per day (Walsh et al. 1993).

Many of the biological–physical–management interactions associated with rangeland biodiversity are yet to be understood (West 1993). Consequently, very little has been done to evaluate the contributions of rangelands to biodiversity. Yet, under the Forest Management Act of 1976 and the Surface Mining Control and Reclamation Act of 1977, rangelands must be managed for biodiversity. Intangible values are reflected in policy directives even if quantification of those values has not occurred.

Reported here is an example of how rangeland environmental amenities can be evaluated. Chapter VI.3 of this Handbook discusses the method of estimating the economic loss to ranchers from an uncontrolled grasshopper outbreak. Applying chemical treatments reduces damages for the livestock grazer, and the damage reductions are the benefits of grasshopper controls. Pest managers also can estimate the economic loss if grasshopper control activities deplete wildlife populations. Figure VII.12–1 shows the flow of events.

If grasshopper management programs deplete wildlife populations, a reduction in the wildlife base will result in fewer people participating in wildlife-associated recreation. Because people place an economic value on recreation, less recreation means an economic loss. Investigators link the economic evaluation of wildlife depletion to grasshopper management and take the economic losses from wildlife-associated recreation as a measure of the portion of the environmental costs of the grasshopper treatment programs.

Calculations can start with the net economic values of wildlife-associated recreation estimated by Hay using willingness-to-pay techniques (1988a and b). Using the net economic value estimates for specific regions, it is possible to make estimates of the reduction in consumptive and nonconsumptive forms of wildlife-associated recreation resulting from a decrease in the wildlife resource base.

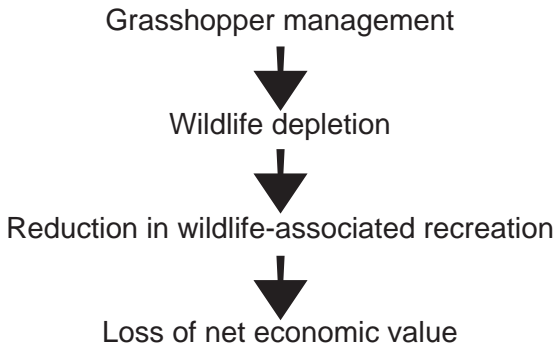


Figure VII.12-1—Sequence of events from grasshopper management to loss of value.

Analyzing the information reveals how participation in wildlife-associated recreation depends on demographic variables, price (cost of participating in recreation) and the wildlife resource base. Managers can use analyses for each type of wildlife-associated recreation (fishing, hunting, and nonconsumptive recreation) in the States for which control of rangeland grasshoppers is a problem.

The economic analysis involves the last two linkages of figure VII.12-1. Potential wildlife depletion results in a reduction in wildlife-associated recreation that, in turn, results in a net economic loss. This loss is a measure of a part of the potential environmental costs associated with grasshopper management programs.

Potential Environmental Costs

Table VII.12-1 shows Hay’s net economic values for wildlife-associated recreation. These are the average net economic values for the eight States included in and surrounding the GHIPM demonstration sites. The net economic values are from surveys designed to determine how much participants value a day of recreation in these activities.

The next step to estimating the potential loss in wildlife-associated recreation resulting from grasshopper management programs is to look at the relationship between the wildlife resource base and the amount of participation in wildlife-associated recreation. The U.S. Fish and Wild-

life Service conducts periodic surveys of fishing, hunting, and wildlife-associated recreation. The year for which the most recent survey data are available is 1985. Many factors determine the likelihood that an individual will participate in wildlife-associated recreation. For discussion in this chapter, we are primarily interested in one variable—the effects of the wildlife resource base on the probability of participation. If the wildlife resource base declines, we expect that the rate of participation in wildlife-associated recreation also will decline. Since grasshoppers and grasshopper treatments affect the habitat of wildlife, a measure of the wildlife resource base is habitat.

For hunting and nonconsumptive forms of wildlife-associated recreation, the amount of participation was sensitive to changes in the wildlife resource base. Fishing was not responsive to an estimate of changes in the fishing resource base. For hunting, a reduction of 1 percent in the range habitat of wildlife (for example a 1-percent reduction in the capacity of a range to support game wildlife) results in a 3.2-percent reduction in hunting participation. Similarly, a 1-percent reduction in the rangeland wildlife base results in a 2.9-percent reduction in participation in nonconsumptive forms of wildlife recreation.

Table VII.12-1—Net economic values per day of wildlife-associated recreation, by recreational activity in the eight-State region¹

Activity	Net economic value (dollars/day)
Hunting	
Deer	\$35
Elk	\$36
Waterfowl	\$20
Fishing	\$11
Nonconsumptive	\$22

¹Idaho, Montana, Nevada, North Dakota, Oregon, South Dakota, Utah, Wyoming.
Source: Hay (1988 a and b).

The statistical equations give estimates of the number of participants in each wildlife-associated recreation activity. In this chapter, we focus on how wildlife-associated recreation changes in response to changes in the resource base. Table VII.12–2 shows the base level estimate of the number of hunters in the eight-State region, their expenditures, participation days, and the net economic value from hunting in the region.

The table also shows the potential impact of a 1-percent decline in the game wildlife resource base and the associated economic impact. We can interpret the analysis two ways. A 1-percent increase in the wildlife resource base would result in an increase of the same magnitude in participation, expenditures, hunting days, and net economic value, as would a 1-percent decrease. Thus, if the use of a grasshopper treatment program reduces the wildlife resource base, we can measure the cost (loss in net economic value). Conversely, if grasshoppers destroy the habitat for wildlife and a reduction in game wildlife occurs, we also can estimate the potential losses from less hunting on grasshopper-damaged rangeland.

Using the estimated equations for nonconsumptive forms of wildlife recreation, table VII.12–3 shows the base economic activity and potential losses if a grasshopper invasion reduces the wildlife resource base. As with hunting, nonconsumptive wildlife-associated recreation also may suffer if an uncontrolled grasshopper outbreak reduces the wildlife resource base.

Potential Recreation Losses

The economic losses associated with changes in the wildlife resource base are only potential losses. The environmental monitoring component of the GHIPM Project has not found adverse effects on wildlife resulting from use of grasshopper control programs. Approved treatment options are the result of careful evaluation and selection to determine materials and methods which minimize the threat to the environment. When there are grasshopper treatments, these precautions to minimize the environmental damage apparently are successful. So long as the first linkage in figure VII.12–1 remains zero, meaning grasshopper treatments do not result in wildlife depletion, the economic losses from reductions in wildlife-associated recreation are also zero. However, should damages to the wildlife resource base occur, the changes in net economic value due to wildlife-associated recreation can be estimated by applying this procedure.

Conclusions

With increased understanding of the linkages and relationships present in rangeland ecosystems, it will be possible to quantify more of the identified benefits from rangeland biodiversity and other intangible values. Until that time, rangeland management and actions taken to control rangeland pests must proceed with the best available understanding of the results from those management interventions.

Table VII.12–2—Hunting: Effect of reduced wildlife resources on the number of participants and trip-related expenditures and on participation-days and net economic value

Wildlife resource level	Number of participants	Trip-related expenditures	Participation-days	Net economic value
	<i>Thousands</i>	<i>\$ million</i>	<i>Thousands</i>	<i>\$ million</i>
Base level	790,000	\$191.2	11,847	\$355.4
1% decline	–25	–6.1	–371	–11.1

Table VII.12–3—Nonconsumptive: Effect of reduced wildlife resources on number of participants and trip-related expenditures and on participation-days and net economic value

Wildlife resource level	Number of participants	Trip-related expenditures	Participation-days	Net economic value
	<i>Thousands</i>	<i>\$ million</i>	<i>Thousands</i>	<i>\$ million</i>
Base level	1,501	\$253.7	15,009	\$330.2
1% decline	–43	–7.3	–429	–9.4

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VII.13 Grasshopper Communities and Methodology

Anthony Joern

Grasshopper populations do not exist in an ecological vacuum. Instead, individual species populations interact with several other species, other individuals, other herbivores, a range of potential host plants and many natural enemies. In western North America, 30 to 50 grasshopper species may coexist, and each may respond individually to environmental change. Although science's interest lies mainly in the ecology and population dynamics of a single or a few species, one species cannot exempt itself from a network of interactions among all species that are present. Consequently, the grasshopper community becomes a central focus in any rational integrated pest management (IPM) project.

Communities are significantly more complex to evaluate and study than single-species populations. Manipulating one small component of the community network (e.g., of one or a few species) may not evoke the desired, long-term control objectives. Consideration of only one or a few species may lead to unnecessarily short-term solutions or even to unexpected problems. Besides problems associated with community complexity, species assemblages vary greatly from year to year at the same site and vary even more dramatically among sites. Scientists require descriptive and analytical methodologies to clearly devise and assess community management practices. Scientists also must simplify the scope of the problem without sacrificing important connections that prescribe creative solutions.

In this section, I summarize simple, standard approaches and methodologies for describing communities and for assessing the importance of key interactions. Some of these methods are best for sporadic evaluation of random sites on a hit-or-miss basis. Others are designed for developing long-term understanding at sites that are regularly monitored for potential grasshopper problems. Government agencies and private organizations that manage the same large tract over many years can expect to develop comprehensive, community-based IPM programs. But individual ranchers with only intermittent grasshopper problems and few resources cannot. As a result, managers must select which of the following approaches to community evaluation meets their situation. Complete annual censuses and evaluations of environmental conditions are the cornerstones of community studies. These require significant effort, and that

cost-benefit ratios ultimately determine the value of studying community relationships.

As I list accepted methods to evaluate grasshopper communities, I will stress the difference between merely describing community composition (species identities) and understanding mechanisms driving species interactions and coexistence. IPM measures interrupt dynamic, often subtle, ecological interactions within and among species. Until we work out the impact of these key interactions for many species combinations in detail, species lists alone provide little insight into future system dynamics surrounding IPM efforts.

Community Descriptions: List of Grasshopper Species Present

A list of grasshopper species is the simplest description of a community and is required in any community-level assessment. A good description includes the relative abundance and absolute density of individual species in a community. Density is important because the number of individuals that are available to interact determines, at least in part, what really happens.

Based on past studies, experts can sometimes develop insights regarding community dynamics from such lists—if certain conditions and species are present. Shifts in species composition among years or among sites suggest that different grasshopper species react differently to changing environments. Such variation in the response to different environmental conditions indicates that either the community shifts from one state to another or that the internal dynamic interactions among species shift. Consequently, the same IPM management practice employed under different conditions may produce different long-term responses depending on the state of the community.

Sampling efficiency can vary with habitat type and its three-dimensional structure as well as overall grasshopper densities. Typical methods include sweeping some predetermined number of times or counting grasshoppers at stationary sample sites (e.g., the “ring technique” of Onsager and Henry 1977, Thompson 1987). Berry et al. review appropriate sampling methods and their justification in chapter VI.10 of this handbook. Remember, in obtaining lists of species' relative abundances, the

accurate sampling of rare species is the biggest problem. More samples will reduce the chance of missing rare species. To estimate a sampling intensity that will detect most of these species at your site, plot the cumulative number of grasshopper species collected against some measure of sample intensity (number of individuals collected, number of sweeps, number of rings examined, number of transects, area sampled, and number of habitat types sampled). Figure VII.13–1 illustrates a reasonable sampling schedule. In designing sampling plans, be aware that you will probably encounter some unrecorded species if new habitat types are included. Because of this, plan to sample all habitat types found in the area in the proportion that they occur in the environment.

What rules-of-thumb emerge from species lists? Many species thrive only in areas with open bare areas (e.g., *Ageneotettix deorum*). Other species (e.g., *Paropomala wyomingensis*) require significant vertical structure such as that provided by bunchgrasses. Still other species (e.g., *Melanoplus sanguinipes*) occupy a variety of microhabitats, so that little insight can be gained just by knowing what microhabitats exist at a site. Similarly, even among grasshopper species that eat many plants, the

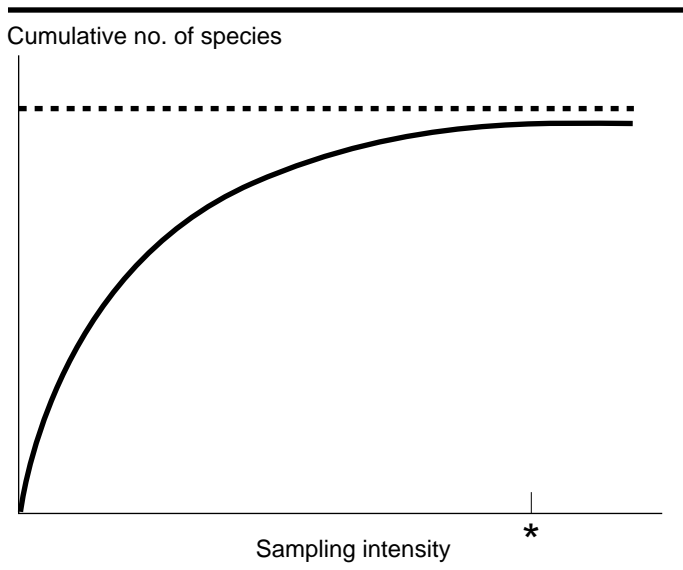


Figure VII.13–1—The number of species sampled is dependent on the sampling intensity. To obtain a good estimate of the number of species at a site, sampling intensity should equal that indicated with an asterisk, near the asymptote for the entire assemblage. If sampling intensity is less than this point, many rare species will likely be missed.

range of readily consumed plant species will be similar among sites. Based on use of both food plants (Joern 1979a, 1983) and microhabitat resources (Joern 1982), community level patterns emerge that may help a manager make decisions (Joern 1979a,b, 1986a). The usefulness of such an approach for developing sound grasshopper IPM tactics is idiosyncratic and case-specific at this time.

Using Statistics To Estimate Species Replacements and Community Associations

Species replacements and community associations along environmental gradients can be identified using standard multivariate statistical techniques (e.g., discriminant function analysis, principle components analysis, detrended correspondence analysis) or some combination of the statistical techniques developed for ordinating communities (Gauch 1982). As a technique, ordination simplifies multiple species associations by representing the relationships in fewer dimensions using multivariate descriptive statistics. By using these techniques, you can identify the combinations of species that tend to occur together (and their relative abundances) in association with key attributes of the environment such as vegetation type or soil moisture (fig. VII.13–2). Such community analyses allow you to simplify the community associations along a spatially varying environmental gradient. Be aware of the correlational nature of these results from these analyses. The patterns that you uncover will fully depend on what you include in your initial sampling design. If you add species or sites with different combinations, the ultimate patterns may shift. Ordination provides a refined fit between grasshopper community composition and some environmental gradient, but *you cannot identify dynamic and causal relationships between the two features by using this approach.*

Plotting Against an Environmental Gradient.—You can readily visualize species replacements along gradients by plotting the change in the abundance (or relative abundance) of each species along some environmental gradient (fig VII.13-2a). In this hypothetical analysis, I assess a series of independent sample sites as in number 1 above (a list of grasshopper species). Then, on a species-by-species basis, I plot the abundances (or relative abun-

dances) along the gradient. By comparing these plots among species, you can identify possible environmental conditions at your site best suited and worst suited for each species. In addition, you can compare responses of multiple species along the same gradient.

Multivariate Ordination Techniques.—Species associations can be identified using standard, multivariate ordination techniques (fig. VII.13-2b). While these techniques typically require commercially prepared computer software, the analyses are readily accessible, even on laptop computers. Standard references exist to help the user understand both the statistical guts of the analysis as well as providing insights to interpreting results (Cornell Ecology Programs discussed in Gauch 1982). The com-

puter algorithms help put boundaries around species combinations from each location, largely based on changes in relative abundances rather than in response to massive replacement of individual species. Remember, these boundaries of species composition represent “probability boundaries” and much overlap typically exists in grasshopper species composition among adjoining communities or even when comparing sites some distance away. As a warning: many users of this technology tend to become typological in describing communities and often confuse pattern with a dynamic process. For example, I foresee some managers ordinating grasshoppers from a group of sites and then prescribing specific management options for those assemblages in group A versus group B or C and so on. The assumption that all

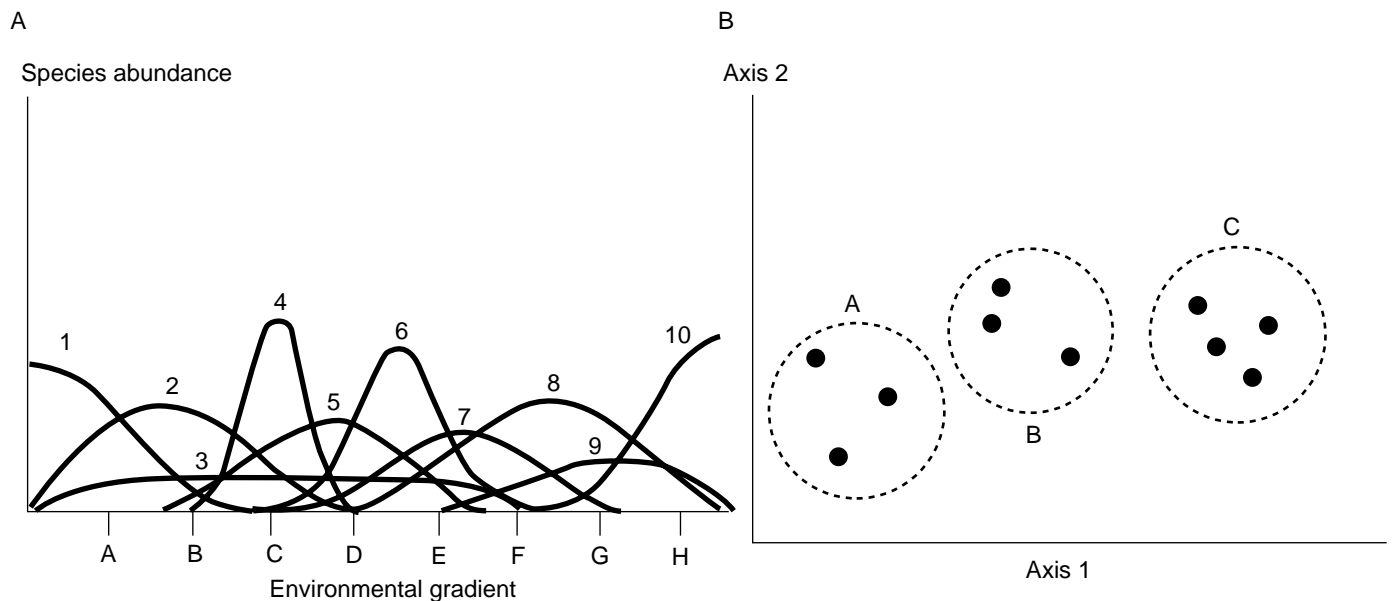


Figure VII.13-2—A: Hypothetical distribution of species along some environmental gradient based on sampling at 8 sites (A–H) along a transect. Each curve indicates the distribution along this gradient for a hypothetical grasshopper or plant species. For example, species 4 does best at site C but does not exist at site E while species 3 does not do particularly well at any site but is found along the entire gradient. B: This multivariate distribution can be “boiled down” into a simpler relationship using ordination techniques following those outlined in Gauch (1982). Each of these new axes (1 and 2) represent a composite of multivariate data. The points indicated in B represent the average position for each species indicated in A for the two multivariate resource axes developed from a composite of environmental variables. The groupings of species indicated by the dashed lines suggest species that react to environmental conditions in the same fashion. Examples of gradient analyses of grasshopper species along a topographic gradient in Montana are presented in Kemp et al. (1990) and Kemp and O’Neill (1990).

sites exhibiting type A species associations also categorically exhibit the same underlying dynamics is unfounded.

Unless a conceptual framework exists that predicts unique, species-specific relationships, the results will not explain why specific patterns emerge. For example, grasshopper species assemblages often change predictably as the species composition of the plant community changes (see chapter IV.3). What dynamic relationship exists between the two components of this analysis to explain the results? Unfortunately, insufficient information exists to tease apart such relationships, even if the pattern is very strong. Sometimes specific theories exist that predict particular species responses in abundance or in association with specific habitats. In these situations, additional insights regarding dynamic, causal mechanisms might emerge from pattern analysis, but this notion still requires experimental testing to uncover the underlying reasons for the relationships fully. Scientists must base management options on *processes* driving community dynamics, not on easily measured patterns. This fact is unfortunate because scientists can more readily establish measures of pattern than uncover the underlying dynamic mechanisms.

Using Controlled Manipulations To Uncover Site-Specific Dynamics

Experimental manipulation of species interactions can provide powerful community level insights into the dynamic forces that organize communities. However, the effort is great. From an IPM framework, subtle shifts in species composition that changes in the underlying interaction dynamics may provide the key for developing the correct management strategy. After all, those IPM practices that work in concert with naturally occurring dynamic processes will most likely lead to long-term success. However, uncovering the specific nature and strength of interactions among species, including their impact on resulting population densities and community structure, will require experimental manipulations under field conditions. Standard experiments that might uncover these relationships are time consuming and complex.

Consequently, an efficient experimental approach requires a strong conceptual framework so that science can simultaneously evaluate key competing possibilities and that investigators can reject alternatives based on experimental results. The conceptual framework identifies alternate hypotheses. By simultaneously testing competing explanations of community pattern and process through experimentation, the manager can rapidly narrow the options. Then it becomes possible to uncover the best explanations upon which to base management options. Despite the difficulties and cost, I strongly believe that the intense effort required to uncover site-specific dynamics using controlled manipulations will pay off, in the long term, for grasshopper IPM managers. Examples of sites that should profit from intensive studies include public lands and large private holdings with constant or predictable land-use practices and a history of grasshopper problems. If managers feel insecure about performing all of the above work by themselves, they should allocate some management funds to contract for research by competent scientists.

A current example illustrates the above process. A conceptual framework that defines alternate views of the problem, combined with experimental manipulation and coupled with appropriate comparisons and descriptive analyses, allows recognition and interpretation of the dynamic interactions that regulate community-level processes. As a general framework, the alternatives include “top-down” versus “bottom-up” processes (Hunter et al. 1992). As herbivores, grasshoppers occupy an intermediate trophic (nutrition) position in the food web, with food plants below them and natural enemies (e.g., parasitoids, invertebrate and vertebrate predators, or fungal, bacterial, or viral pathogens) positioned above them.

What major forces limit grasshopper populations in this food web? From a control standpoint, this information provides the clue to appropriate management planning. Bottom-up forces can arise from insufficient nutrients either when grasshoppers compete for limited food or when time constraints interfere with feeding and digestive capability. Top-down forces can arise from the actions of natural enemies. Other chapters of the Grasshopper Integrated Pest Management User Handbook provide detailed examples of each type of interaction.

Descriptive studies cannot untangle this set of potential interactions, but manipulative experiments can. In fact, under natural conditions, bottom-up (Belovsky and Slade 1995) and top-down (Joern 1986b, 1992) forces operate simultaneously, and either one can drive the interactions and can thus determine the final densities of coexisting grasshoppers (Belovsky and Joern 1995). More importantly, reciprocal indirect effects of species on each other can potentially be more important than the direct interactions. Scientists can see such responses only through experimentation.

The Role of Experimentation in Developing “True” IPM for Grasshoppers

True IPM will require successful description of the above relationships in its development, and perhaps will lead to the development of “ecotechnology” based on a firm conceptual foundation. For example, here are the types of questions that we must address experimentally: How do grasshoppers compete for scarce food resources? Which species are the best competitors for the available food supply? What impacts do such interactions exert on the resulting grasshopper community structure? Will the food resource base change as environmental conditions change and with what consequences? Are competitive interactions altered in response to changing food supplies? How important are natural enemies in deciding which grasshopper species survive and in what relative abundance? How do competition and predation interact to affect grasshopper communities? How do abiotic (weather) and biotic (species-interaction) features of the environment interact to affect grasshopper communities, if they exert any influence at all? Results from experiments to answer these and related questions will allow land managers to define explicitly the key interactions that describe the community relationships a particular grasshopper infestation. Managers can then identify links that will provide the desired IPM results, or those that are susceptible to disruption and will lead to unwanted and unintended results.

Final Comments

Grasshopper IPM must focus on entire grasshopper assemblages, even if only a small proportion of the species are economic targets. Interactions among species

may lead to unexpected consequences from control efforts if we ignore rare but otherwise functionally important taxa. Both species lists and more complicated statistical descriptive techniques of grasshopper communities will provide some guidelines, but neither will provide direct insights about dynamic relationships. Because effective control will result in permanent or at least long-lasting alteration of species interactions, scientists would like to understand the dynamics of these interactions. Frankly, much work remains before this approach bears fruit. However, the rich conceptual framework that underlies community dynamics suggests that many important insights will emerge and hopefully will revitalize the basis of control and management planning.

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VII.14 Grasshopper Population Regulation

G. E. Belovsky

Factors controlling the dynamics of a population are often referred to as either limiting or regulating a population (Sinclair 1989). Limiting factors operate to depress a population without regard to its number; limiting factors are density independent. Regulating factors are special depressing factors that tend to bring the population to a specific number; to reach the specific number, the depressing effect must be great when the population is much larger than the specific number and less when the population is below or near the specific number. Regulating factors are density dependent.

Population ecologists have demonstrated that, although there may be a correlation between weather and population numbers, this correlation does not mean that weather is the causal factor determining population dynamics or even the most important factor—even if it is a limiting factor (Horn 1968). In fact, it is well established that the density-independent effects of weather on survival and reproduction cannot regulate populations. The effects can only interact with regulating mechanisms to set population numbers because regulation requires the negative feedback of density dependent processes.

Science's understanding of grasshopper population dynamics has been largely built on long-standing observations that grasshopper numbers in a given year are correlated with temperature and precipitation (Joern and Gaines 1990). While these correlations provide convenient forecasting tools for pest managers, the correlations do not imply that weather is the causal mechanism limiting or regulating populations, nor that scientists understand grasshopper population dynamics. Furthermore, correlations between grasshopper numbers and weather, while statistically significant, are weak and are not consistent between different western rangelands with grasshopper numbers sometimes being greater in hot-dry years and sometimes greater in cool-wet years (see chapter IV.8).

Variability in the response to weather suggests that grasshopper populations may respond to other factors that are correlated with weather and not to the weather directly (for example, the abundance and nutritional value of food, the cover providing protection from predators, diseases, etc.). Consequently, the value of weather as a

forecasting tool for particular western regions and the concept of weather as the driving factor in grasshopper population dynamics should not be confused.

A number of general models have been developed to portray insect population dynamics (Southwood and Comins 1976, Berryman 1987). These models are generic and are not based upon specific mechanisms that operate upon the insect's population but attempt to depict the insect's population dynamics in terms of the shape of a Ricker curve. A Ricker curve (fig. VII.14-1) is a plot of a species' number (N) at time t (N_t) against its number at a later time, $t+1$ (N_{t+1}). This type of population analysis is appropriate for insects that have a single generation each year, which includes nearly all western rangeland grasshoppers (Varley et al. 1973). Ricker curves are depictions of population dynamics because their intersection with a reference line ($N_t = N_{t+1}$) defines the number to which the population is being drawn by regulating factors (fig. VII.14-1).

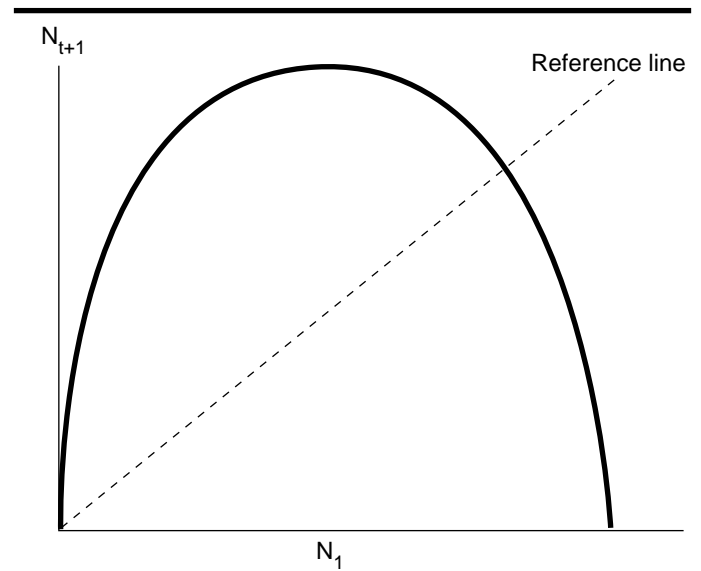


Figure VII.14-1—A simple Ricker curve relating the number of individuals starting the population in generation t (N_t) to the number of individuals produced by them to start the next generation (N_{t+1}). The point where the reference line ($N_t = N_{t+1}$) intersects the Ricker curve is an equilibrium point that the population may approach.

Three Relationships Important in Grasshopper Population Dynamics

The shape of the Ricker curve depends upon the ecological mechanisms that operate on the population and how they change in intensity with density. Three mechanisms may be particularly important for grasshoppers: (1) the relationship between density and the probability of surviving to the adult stage in the absence of natural enemies, (2) the relationship between density and the probability that an individual is killed by a natural enemy, and (3) the relationship between the current year's density and the number of hatchlings produced for the next year by each current female. In each case, density refers to the number of hatchlings per area that initiates the year's population. I will review each of these functions.

Density and Survival.—In the absence of natural enemies, the relationship between initial grasshopper hatchling density and survival determines the density of adult females that can produce hatchlings. First, at low densities, survival should be a constant proportion of the population set by weather and the nutritional value of foods because the individuals consume as much food as they can potentially process. This survival is **density independent** because it does not vary with the density of grasshoppers present. Second, at higher densities, survival becomes **density dependent**, as competition reduces the food available per individual, and the mortality rate increases.

This survival relationship leads to a pattern where the density of adults increases as hatchling density increases and then becomes a constant set by the maximum adult density that the available food can support. This relationship can be seen at a Palouse prairie site in western Montana for *Melanoplus sanguinipes* where the addition of food increases survival to the adult stage (fig. VII.14–2A) (Belovsky and Slade 1995). Weather can increase or decrease food: cool–moist conditions tend to increase plant production, but tend to decrease the nutritional quality of the plants.

Density and Predation.—The relationship between the initial density of hatchling grasshoppers and an individual's probability of being killed by natural enemies

depends upon the rate at which an individual enemy can kill grasshoppers (functional response) and the number of enemies present (numerical response). The functional and the numerical responses for a natural enemy frequently increase to constant values as the density of prey increases; this phenomenon is observed in predator–prey systems ranging from insects and spiders to wolves and deer.

The implication is that as density of the grasshoppers increases, the proportion killed (probability of an individual being killed) will first increase with density and then decrease. An example can be seen at a Palouse prairie site in western Montana for the grasshopper *M. sanguinipes* where vertebrate predators, especially birds, are the principal natural enemies (fig. VII.14–2B) (Belovsky and Slade 1993). Weather can modify the effects of these natural enemies. For example, cool–moist conditions can increase plant production, and increased plant biomass enables grasshoppers to conceal themselves from predators. But cool–wet conditions do not always enhance grasshopper survival: they can increase the virulence of some diseases.

Density and Reproduction.—The relationship between the current year's density of hatchlings and the hatchlings produced for the next year's generation by each current female reflects two conditions. First, at low densities, hatchling production per female should be constant because each female has all of the food that she can utilize for egg production. This level of reproduction is **density independent** because it does not vary with the density of hatchlings present. Second, at higher densities, hatchling production per female should decline as the density of current hatchlings increases because each female acquires less and less of the available food. This level of reproduction is **density dependent** because it declines with the current density of hatchlings present. This decline emerges as females acquire less and less food because the increasing number of grasshoppers depletes the available food. The above pattern in reproduction can be seen at a Palouse prairie site in western Montana for *M. sanguinipes* where the addition of food increases reproduction (fig. VII.14–2C) (Belovsky and Slade 1995). Weather can increase or decrease food availability. For example, cool–moist conditions tend to increase plant production but tend to decrease the nutritional quality of the plants.

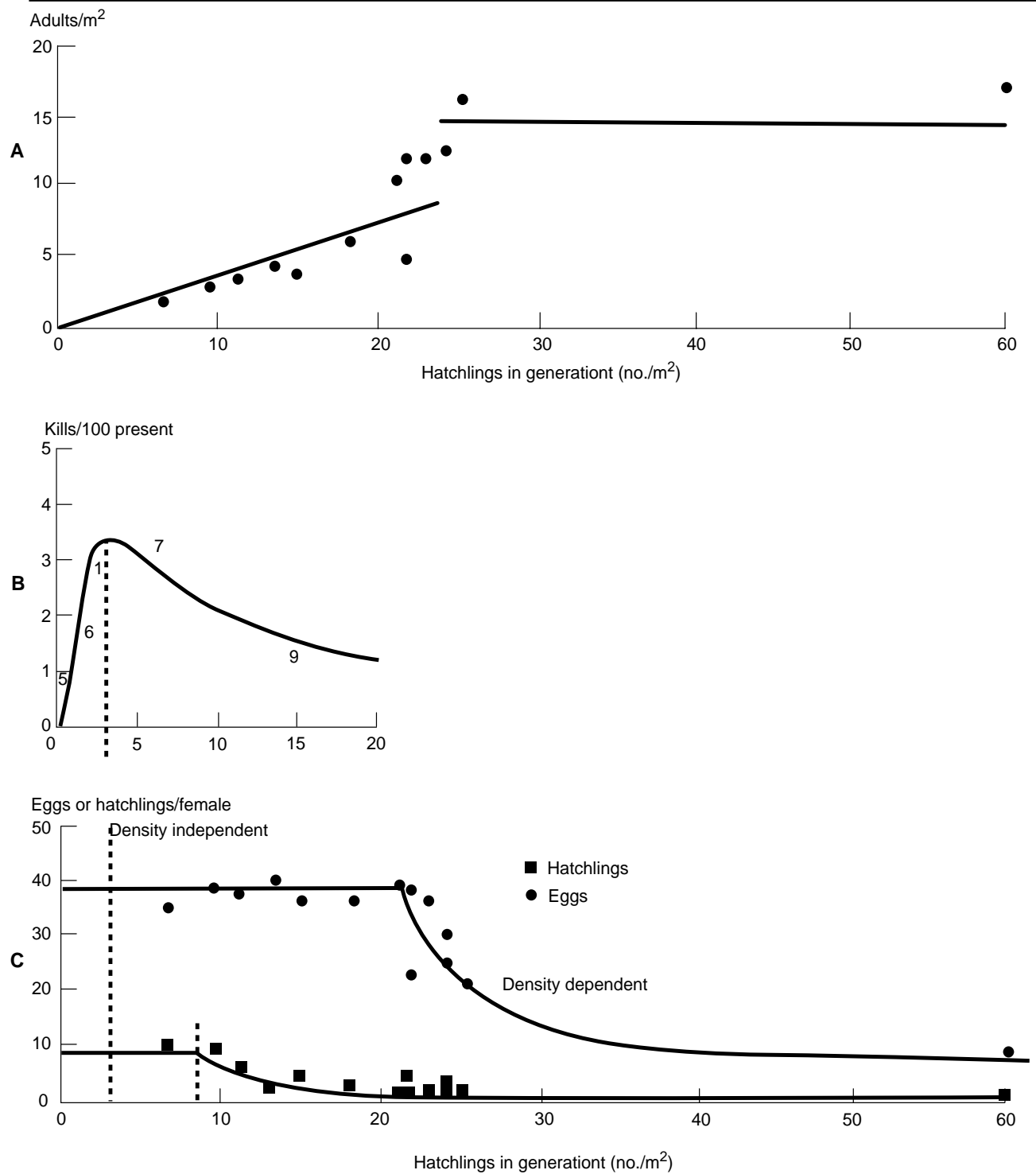


Figure VII.14-2—The relationships between hatchling density of *Melanoplus sanguinipes* and (A) adult density, (B) the probability of an individual being killed by a predator, and (C) the production of eggs and hatchlings per adult female, as observed at a Palouse prairie site in western Montana. The vertical dashed lines relate the points where the probability of predation and reproduction per adult female begin to decline with hatchling density. (A and C are adapted from Belovsky and Slade [1995]. B is adapted from Belovsky and Slade [1993].)

Using the Ricker Curve

The above three relationships can be combined to construct a Ricker curve, which enables scientists to integrate the effects of weather-induced density-independent mortality, natural enemy-caused mortality, and food resources. This integration produces three possible Ricker curve shapes, each reflecting a different dominant form of population regulation.

Population Regulated Only by Natural Enemies.—

This type of regulation occurs when the peak of the function relating the probability of being killed by a natural enemy occurs at a grasshopper density that is greater than the density at which hatchling production begins to decline and/or adult densities attain their maximum level. In this case, a Ricker curve emerges with a single peak or two peaks, where the reference line intersects the Ricker curve only on the first peak (fig. VII.14–3A). This case emerges if the actions of the natural enemies (a) are so strong that grasshopper density cannot attain a level at which competition for food occurs or (b) continue to increase as competition for food increases.

Population Regulated Only by Food Availability.—

This type of regulation occurs when the peak of the function relating the probability of being killed by a natural enemy occurs at a grasshopper density that is much less than the density at which hatchling production begins to decline and/or adult densities attain their maximum level. The Ricker curve emerges with two peaks, where the reference line intersects the Ricker curve only on the second peak (fig. VII.14–3B). In this case, the population is capable of “escaping” the effects of natural enemies, because (a) the natural enemies are not very effective and/or (b) the impact of the natural enemies rapidly diminishes as grasshopper density increases.

Population Regulated by Either Natural Enemies or Food Availability Depending Upon the Density of Hatchlings Initiating the Population.—This type of regulation occurs when the peak of the function relating the probability of being killed by a natural enemy occurs at a grasshopper density that is less, but not much less, than the density at which hatchling production begins to decline and/or adult densities attain their maximum level. In this case, a Ricker curve emerges with two peaks,

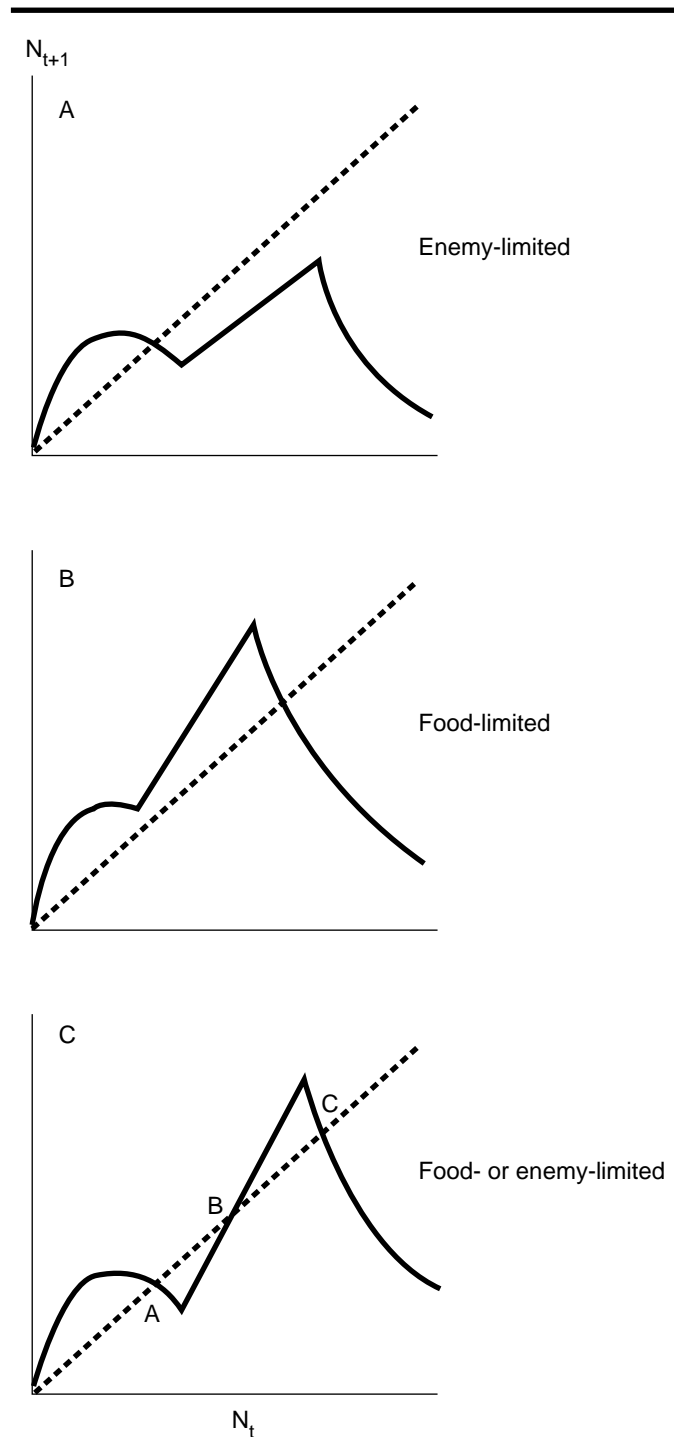


Figure VII.14–3—The three Ricker curve shapes that emerge (see text).

where the reference line intersects the Ricker curve at three points (fig. VII.14–3C).

The intersection with the first peak represents a population state regulated by natural enemies. The intersection with the second peak represents a population state regulated by food availability. The intersection lying between the above two intersections defines the “watershed,” where populations initiated with densities less than this point become limited by natural enemies and with densities greater than this point become limited by food availability. In this case, the population can “jump” from one mode of regulation to the other depending upon the densities of hatchlings initiating a population from year to year.

The picture of grasshopper population regulation described above can be validated experimentally. From experimental (enclosed) populations established at different densities of *M. sanguinipes* at the Palouse prairie site in western Montana, the Ricker curve has been measured (fig. VII.14–4). The curve has two peaks and is intersected by the reference line at three points, indicating a population that can be regulated by either natural enemies or food availability depending on initial hatchling densities.

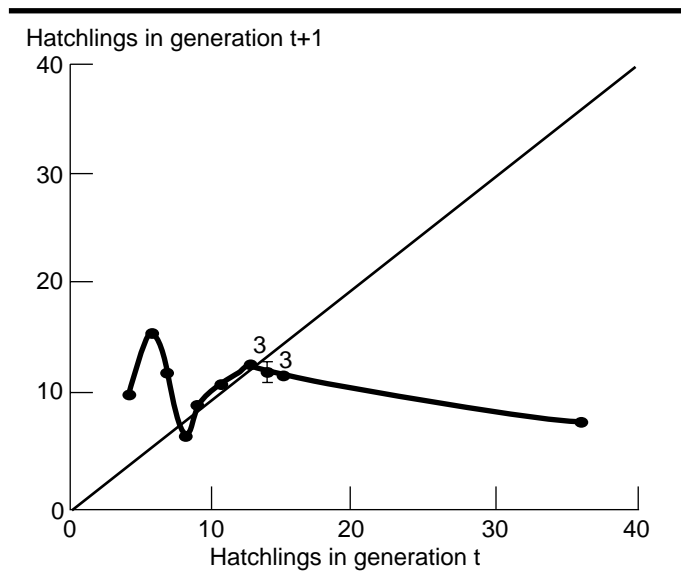


Figure VII.14–4—The Ricker curve for a *M. sanguinipes* population during a single year at a Palouse prairie site in western Montana. Error bars and sample sizes are presented for populations initiated at the same hatchling density.

More than 12 years of observation of this population disclosed that it has consistently been regulated by food availability, not by natural enemies (Belovsky and Slade 1993, 1995). This fact suggests that the population is near the intersection with the second peak of the Ricker curve. Furthermore, this conclusion was expected given the three underlying functions measured at this site and presented in figure VII.14–2.

What Weather Can Do

A new perspective toward weather and grasshopper population regulation can be gained from the Ricker curve model by appreciating that weather can affect both density-independent mortality and food availability.

Weather-induced density-independent mortality can operate in conjunction with natural enemy mortality to prevent populations from attaining levels where food availability becomes regulating. For the density-independent mortality to be important, it would have to accomplish at least one of three things. First, inclement spring weather can kill a high proportion of hatchlings, most likely through cold-induced starvation. Second, weather might be sufficiently severe over the entire life cycle of the grasshoppers so that few individuals can survive to become adults. Third, weather might shorten the period of time that adults have to live so that the number of hatchlings produced is dramatically diminished.

On the other hand, weather exerts a far more pervasive influence by altering food availability from year to year (see chapters IV.4 and IV.5). This variation in food abundance can be as great as sixfold between years and more than twofold within a summer (Belovsky and Slade 1995). The variation in food abundance could easily shift the shape of the Ricker curve from producing a population regulated by natural enemies in years with low food abundance to a population regulated by food abundance in years with high food abundance, and vice versa.

Weather Interacts With Enemies and Food Availability

The weather-induced shifts in food abundance, and perhaps to a lesser extent, changes in density-independent mortality result in domains of attraction (shaded regions

in fig. VII.14–5), where the grasshopper population fluctuates with weather, but is regulated by either natural enemies or food availability at any one time. This is the point made by Horn (1968) that weather can create population fluctuations by varying density-independent or density-dependent (such as food availability) factors, but the density-dependent factor(s) must still regulate the population (attract it to particular levels).

In some environments, the points of attraction may be set by population levels created by natural enemies in different years (fig. VII.14–5A). In other environments, the points of attraction may be set by population levels created by food availability in different years (fig. VII.14–5B). In still other environments, the points of attraction may vary between levels set by natural enemies in some years and food availability in other years (fig. VII.14–5C).

Unique spatial relationships for population regulation emerge when several populations are placed in juxtaposition. The above discussion considers that each population is isolated from other populations. The conclusions concerning the regulation of a single population may have to be modified when adjacent populations are considered. For example, consider two adjacent or near populations. One population is regulated by natural enemies (fig. VII.14–3A) and the other population, by food availability (fig. VII.14–3B). It is possible that the food-regulated population will produce individuals that migrate rather than die. Therefore, if the two populations are close enough in relation to the dispersal ability of the grasshopper, the population that would otherwise be regulated by natural enemies may be able to increase in density with the addition of immigrants and, thereby, become food regulated. The immigrants permit the population to escape the effects of natural enemies.

The above simple scenario says that in some situations pest managers need to understand not only how individual populations are regulated but also the juxtaposition (landscape) of populations to determine the potential for population regulation to be complicated by dispersal. For example, the population receiving dispersers and thereby escaping regulation by natural enemies might be causing economic damage, and pest managers might decide to control it. However, control of this population

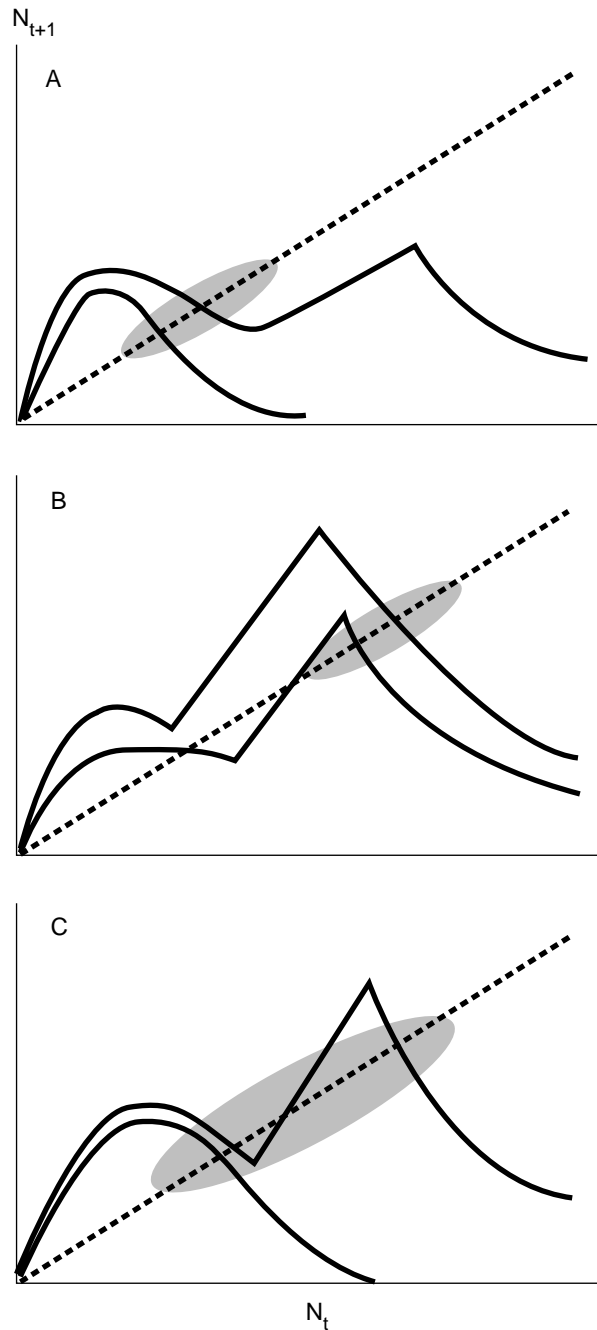


Figure VII.14–5—Domains of attraction might emerge for grasshopper population regulation, where natural enemies along with weather—which primarily affects density-independent survival and reproduction—sets the bounds of population fluctuations (A); competition for food along with weather—which primarily affects food abundance—sets the bounds of population fluctuations (B); or natural enemies and food competition in different years with weather set the bounds of population fluctuations (C).

might be largely ineffective unless the nearby population providing dispersers is controlled, too. In this scenario, the population causing damage is not the population that should be controlled because the dynamics of the former are dependent on the latter.

The implications of population regulation for grasshopper management may seem of little importance to managers entrusted with reducing the economic damage caused by pest grasshoppers. However, understanding how particular populations entrusted to a manager are regulated can provide critical insights that could make monitoring and control more cost effective.

General Conclusions

In terms of monitoring, the following generalizations might be reached:

1. Populations consistently within a domain that is regulated by natural enemies seldom reach densities at which economic damage is sufficient to warrant control; therefore, these populations may not warrant monitoring.
2. Populations consistently within a domain that is regulated by food availability often reach densities that cause economic damage and regularly warrant control; therefore, these populations may not warrant monitoring.
3. Populations in a domain where regulation can frequently “jump” between natural enemy limitation and food limitation will only periodically cause economic damage and warrant control; therefore, these populations may warrant monitoring.

If a manager knows the mode of regulation operating on a specific grasshopper population, monitoring efforts can be more effectively carried out, and that will save time and money.

In terms of control strategies, with the knowledge of how a population is regulated, a manager may be able to enhance efficiency by creating strategies that are tailored to the particular population. For example, I found (1992 unpubl.) that an insecticide application that killed less

than 20 percent of the grasshopper nymphs—an application level much less than commonly employed—could shift a population from being regulated by food availability to being regulated by natural enemies. Switching to such a spray regimen would lessen control costs directly and also indirectly, by taking advantage of the more effective actions of natural enemies. Low-mortality spraying also would lead to less future management activity, with further cost reductions, because natural enemies would help to suppress future population increases.

Understanding how grasshopper populations are regulated and how regulation differs between regions of the western rangelands is essential for the development of new control strategies that involve reduced insecticide use, biocontrol agents, and grazing and habitat manipulation.

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VII.15 Grasshopper Habitat Manipulation

G. E. Belovsky, M. A. Brusven, D. J. Fielding, and L. Manske

Introduction

Managing grasshopper populations through habitat manipulation (changes) is poorly understood and consequently, seldom considered. However, it may be a very reasonable strategy given the diversity of grasshopper species found in any single habitat (vegetation type) and the large area that pest managers must deal with in the rangelands of the Western United States. In fact, habitat management, such as destruction of prime egg-laying sites, was one of the earliest and most common forms of grasshopper control (Pfadt and Hardy 1987).

Habitat manipulation would seem particularly useful today because many grasshopper outbreaks occur in habitats that have been changed by human activities. Overgrazing, modified fire regimes, and introduction of exotic plants on American rangelands have led in some instances to replacement of relatively grasshopper-resistant native vegetation with vegetation that supports more frequent grasshopper outbreaks. An example may be when the native, perennial sagebrush/bunchgrass of the Intermountain regions are replaced with annual grasses and forbs. Therefore, restoration of the land's productivity can go hand in hand with grasshopper control by habitat manipulation.

The potential use of habitat manipulation as a control strategy is apparent when the following two possibilities are taken into consideration: (1) Most grasshopper species do not reach outbreak levels or cause economic damage (Pfadt 1988). What if managers could replace species that reach outbreak levels and cause economic damage with species that do not? Species substitution on this scale might be possible through habitat manipulation. (2) Even if outbreak species cannot be totally replaced, habitat manipulations may reduce their abundance and lessen the likelihood of outbreaks.

To address these habitat manipulation prospects, we can provide some potential examples but cannot present general strategies because this issue has not been broadly examined. When we refer to habitat manipulation, we are largely concentrating on vegetation changes because both the absolute and relative abundance of grasshoppers are related to vegetation (Kemp et al. 1989, Belovsky and Slade 1995). Vegetation changes can have a variety of impacts.

Fostering Natural Enemy Abundance

If pest managers could change the vegetation, doing so might increase natural enemies of grasshopper species that reach outbreak levels. Such increases could reduce abundance of the pest grasshoppers and the frequency of outbreaks (Belovsky and Slade 1993).

Predators as Grasshopper Population Regulators.—Predators, especially vertebrates such as birds and rodents, are potentially important in regulating grasshopper numbers under certain circumstances (see chapter VII.14). It may be possible by habitat manipulations to extend the circumstances under which predators effectively limit grasshopper numbers. First, greater vegetative cover may increase the numbers of these predators by protecting rodents and bird nests from their predators. Second, less vegetative cover (open vs. thick areas) can make grasshoppers more vulnerable to predators (fig. VII.15–1). The figures in this illustration were measured by placing tethered grasshoppers in areas of different vegetative cover and determining how many were killed by predators.

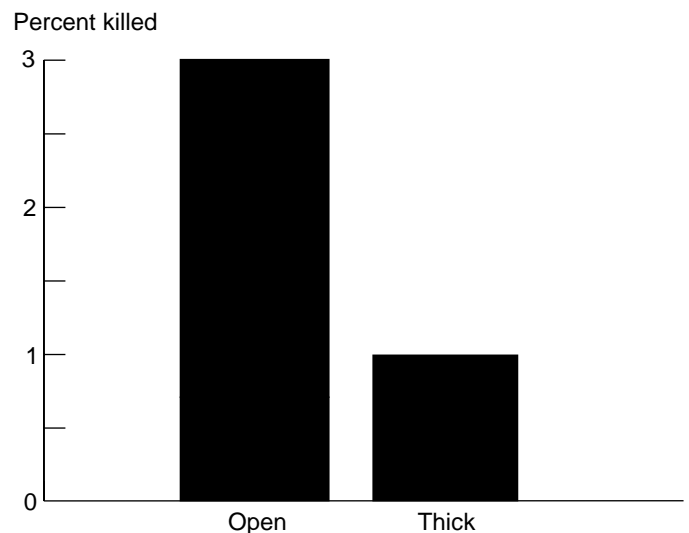


Figure VII.15–1—Comparison of the effectiveness of predators at killing grasshoppers in grasslands with more than 40 percent bare ground (open) versus less than 20 percent bare ground (thick) in western Montana.

The effects of habitat on predation might seem in opposition—on one hand increasing cover for birds and on the other hand decreasing cover for grasshoppers. However, on rangelands, the management trend is to make them more uniform. For example, overgrazing tends to reduce the height of vegetation; while this factor can make the grasshoppers more vulnerable to predation, there are now fewer predators to take advantage of the more open conditions for hunting, so the potential for greater predation on grasshoppers is seldom fully realized.

Manipulation might restore some of the natural variation in the habitat. Changes of that sort might be accomplished by providing small patches of thick cover for protection of the grasshoppers' predators, especially bird-nesting sites. Simultaneously, a pest manager might maintain habitat openness or even reduce cover in the intervening larger areas between patches of thick cover to increase the effectiveness of the predators in capturing grasshoppers. In doing this, a manager might be able to increase the predators' numbers and efficiency and thereby enhance the ability of predators to limit grasshoppers when predators otherwise might not be effective.

Parasitoids and Parasites.—As with predators, parasitoids and parasites might have their numbers and efficiency enhanced by manipulating the vegetation. For example, mites (parasites that attach themselves to a grasshopper's exoskeleton and "suck" the grasshopper's "blood") can dramatically reduce grasshopper survival and egg production, but these parasites generally do not appear to reach high enough densities to limit grasshoppers (see chapter I.9).

The inability of mites to reach high enough densities to limit grasshopper populations appears to be due in many areas to soils that have reduced drainage. Poor drainage should not be confused with moist conditions, a rarity in most western rangelands; poor drainage pertains to soils, such as clays, that tend to hold moisture longer. As with cover for predators, a manager might consider creating patches favorable to mite production that are interspersed throughout the larger area. Changing vegetation composition or cover or even providing small areas of better draining soils in small areas could achieve this end.

Reducing Grasshopper Food Abundance

In many areas of western rangeland, food abundance may be limiting grasshopper populations (see chapter VII.14). It may be possible to diminish food abundance using habitat manipulations in ways that will not negatively affect the forage available to livestock.

Increasing Competitors' Abundance.—If other species compete with the pest grasshoppers for food, then increasing the abundance of these competitors might reduce the abundance of pest grasshoppers. Unfortunately, enhancing the numbers of competitors might simply substitute one pest for another so that the forage available to livestock is not enhanced. However, limiting pest grasshoppers by reducing their available food through consumption by competitors, without simultaneously diminishing the forage available to livestock, might be accomplished under two conditions. First, livestock grazing might be used to reduce grasshopper numbers; this substitutes livestock consumption for grasshopper consumption of the forage. Second, habitat manipulations might be used to replace pest grasshopper species with species that do not reach outbreak levels, especially if these other species do not reduce the forage for livestock to as great a degree as the pest species.

Different studies have disclosed that livestock grazing decreases grasshopper densities (Hutchinson and King 1980; Jepson–Innes and Bock 1989; Capinera and Sechrist 1982; Fielding and Brusven 1995), increases densities (Coyner 1938 unpubl., Nerney 1958, Anderson 1964, Holmes et al. 1979), and has no effect (Miller and Onsager 1991) on grasshopper densities. In cases where grazing reduced grasshopper abundance, it appeared that the grasshoppers encountered a shortage of food. In cases where grazing increased grasshopper abundance, it appeared that the grasshoppers either responded to decreased cover (see thermal cover, below) or increased forb abundance (see vegetation changes, below). All of the above studies found that the grasshopper species composition changed with grazing. Grazing effects are more fully discussed in chapter V.1.

Grasshoppers that compete with the pest species might be encouraged by management to reduce the pests' abundance. This option would be useful if the competitor emerges earlier than the pest, so that survival of the pest species' nymphs is reduced. In addition, it would be particularly useful if the earlier emerging competitor cannot survive later into the season, when the pest would otherwise be most abundant; this scenario would allow the vegetation to regrow after consumption by the competitor.

An example is provided by the nonpest early-season grasshopper *Melanoplus confusus* and the pest late-season grasshopper, *M. sanguinipes*, in the Palouse prairie of western Montana (Belovsky 1990 unpubl). As fourth- and fifth-instar nymphs and adults, *M. confusus* dramatically reduces the survival of *M. sanguinipes* in experimental populations by competing for food plants (fig. VII.15–2). The *M. confusus* adults quickly die off in early July, and the vegetation regrows because rains in most years permit continued growth. The negative effect of *M. confusus* on *M. sanguinipes* is illustrated by *M. sanguinipes* being able to reach the same densities in the experimental mixed populations as in experimental pure populations, when *M. sanguinipes* are placed in the experiments after *M. confusus* dies off (fig. VII.15–2). Unfortunately, under natural conditions, *M. confusus* populations are generally too low to achieve this effect.

Encouraging *M. confusus*.—A straightforward means by which a manager might increase *M. confusus* numbers is not apparent.

Manipulating Plant Species.—The relative abundance of different plant species might be manipulated to reduce the abundance of those species that are more important to the pest grasshoppers than they are to livestock. While grasshoppers and livestock consume many of the same plant species and thereby compete, grasshoppers do not consume identical sets of food plants. A good example of this manipulation might be to reduce the abundance of annual grasses and forbs and to increase the abundance of perennial grasses and shrubs. Many pest grasshoppers, especially in the spurthroated group (Melanoplines), seem to thrive with the annuals, and livestock are capable of foraging on the perennials. But changing vegetative composition can also modify cover and plant abundance.

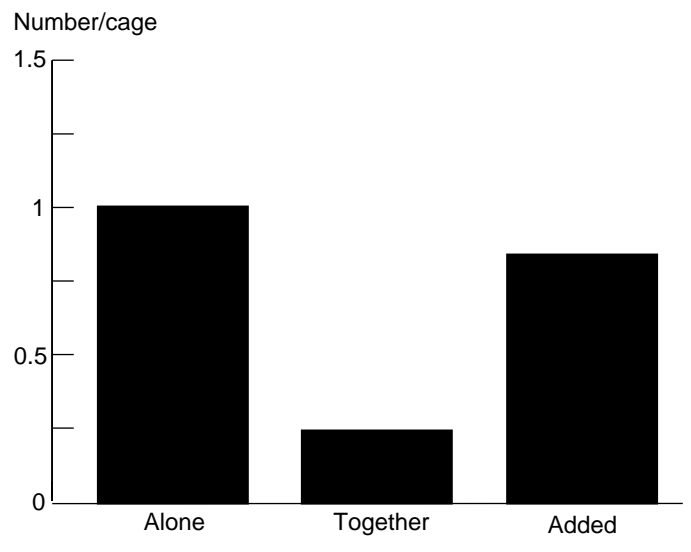


Figure VII.15–2—The densities attained by *Melanoplus sanguinipes* in experimental field populations (cages) when by itself (Alone), when with *M. confusus* (Together), and when it is added after *M. confusus* dies off later in the summer (Added).

Therefore, habitat manipulations that modify the relative abundances of plants need to be weighed against changes in these other factors and how they affect both pest and livestock.

Changing Grasshopper Thermal Cover

Vegetation provides more than food—it also provides thermal cover for grasshoppers. Grasshoppers are able to consume a greater quantity of food when they are in favorable thermal conditions. Under favorable conditions, a grasshopper can process more food through its digestive tract and has more time to consume foods. Greater food consumption leads not only to greater immediate losses of forage resources on rangelands but also to larger grasshopper populations by increasing the grasshoppers' survival and reproduction.

Thick vegetative cover for a grasshopper may lead to a thermal environment that is cooler than optimal, reducing grasshopper survival and reproduction. The same effect can be caused when there is too little vegetative cover for a grasshopper and the environment is warmer than optimal. Therefore, land managers might

manipulate vegetative cover to diminish grasshopper feeding, and thereby, their survival and reproduction.

Possible Methods for Habitat Manipulation

We have presented a series of ecological processes that habitat management might be able to exploit to reduce pest grasshoppers. However, methods are required to modify the habitat and thereby change the ecological processes.

A number of methods have been investigated without reference to how they changed ecological processes. It has been demonstrated that the use of herbicides on rangelands has little effect on grasshoppers, while furrowing, scalping, and interseeding grazing lands can reduce grasshopper numbers dramatically (Hewitt and Rees 1974). Researchers are not sure if furrowing, scalping, and interseeding change predation cover, thermal cover, plant composition, or all of these factors.

One method that has been investigated at least partially from the perspective of ecological processes operating on pest grasshoppers is fire on rangelands. It primarily operates to change the composition of the vegetation and, thereby, grasshopper food abundance. However, fire can produce different outcomes on pest grasshoppers. Under some conditions, fire enhances grasshopper numbers and in others, decreases them. For example, intense fires destroy sagebrush/native bunchgrasses, enhancing annual plants, which are favored by pest grasshoppers. On the other hand, "cool" fires enhance the abundance of native bunchgrasses and, thereby, decrease pest grasshoppers. Likewise, livestock grazing can be used to manipulate vegetation composition, but as with fire, different grazing intensities result in different outcomes.

Reseeding areas with crested wheatgrass after native bunchgrasses have been destroyed can reduce pest grasshopper abundance but not to the extent that native bunchgrasses can. Therefore, methods for restoring native rangelands may have considerable potential for grasshopper pest management.

A greater variety of these methods needs to be investigated in a range of different habitats. However, these methods may require greater than normal monitoring by managers. For example, grazing and fire both require the manager to assess intensity carefully, and doing that can be difficult as weather conditions dramatically change the vegetation from year to year.

For example, management by grazing might require the manager to manipulate stocking rates much more than ranchers traditionally have undertaken, or in ways that do not maximize the rancher's income. In addition, habitat manipulations must be evaluated in terms of their impacts on wildlife, recreation activities, and the maintenance and restoration of native vegetation. Habitat manipulations have not been adequately investigated as a viable pest-management strategy for grasshoppers, but manipulations may have great potential to reduce grasshopper-caused damage with fewer negative impacts on the environment.

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VII.16 Grasshoppers—Plus and Minus: The Grasshopper Problem on a Regional Basis and a Look at Beneficial Effects of Grasshoppers

G. E. Belovsky, A. Joern, and J. Lockwood

Introduction

From an environmental perspective, grasshopper control in rangelands of the Western United States poses several unique and difficult problems compared to the control of many other insect pests.

- When scientists or land managers speak of grasshoppers, they are not referring to a single pest species but to a group of insects that contains more than 400 species, with as many as 30 to 40 species found in any given area. Some of these species cause economic damage, but most do not; however, current control methods influence all (Lockwood 1993a and b, Carruthers and Onsager 1993).
- None of these insects has been introduced to the West by humans. All are natural elements of a complex ecological system that is highly productive for livestock and wildlife. Therefore, grasshoppers are an important consideration in conservation planning (Lockwood 1993a and b, Carruthers and Onsager 1993).
- While managers often consider rangelands to be uniform grasslands, rangelands can refer to mountain meadows, savannas, forested parklands and shrublands, and steppe grasslands. Rangelands vary dramatically in plant species composition; the amount, frequency, and annual distribution of precipitation; and forage production.

Seeking or expecting a single control strategy for pest grasshoppers may be fruitless. Grasshoppers form a diverse group of species that inhabit a diverse group of habitats. Advocating the elimination or dramatic reduction in grasshopper numbers, even if this action were biologically and economically feasible, could be destructive to the very ecological system whose production we are trying to maintain and exploit (Lockwood 1993a and b, Mitchell and Pfadt 1974). Consequently, control may not be a desirable goal. Management may be the more appropriate perspective.

Grasshopper management should attempt to minimize competition for forage between grasshoppers, livestock, and wildlife in cases when most rangeland production is

needed for livestock and wildlife. Of course, all forage that grasshoppers eat cannot be consumed by livestock and wildlife. Grasshoppers have an important role in the ecological processes that make U.S. rangelands so productive. Shifting the management viewpoint from elimination to suppression is a difficult undertaking but places grasshopper management within the larger context of sustainable ecosystem management and the preservation of biodiversity.

Given past concern over grasshopper damage to rangeland production, one would think that the scientific ability to address the central issues would be much more extensive than it is. Most efforts have focused on control, and perhaps in some cases eradication, of grasshoppers. With the development of commercially produced synthetic pesticides in the 1930's, this focus led to a predominance of studies intended to produce better insecticides and means of application. Such a focus also replaced investigating grasshopper biology in ways that might form a basis for alternate approaches.

An integrated pest management approach must be founded upon the biology of the pest species. The Grasshopper Integrated Pest Management Project has helped provide us with more information on grasshopper control and biology. Project-funded investigators have identified many important questions that a pest manager must consider. Considering such questions is the critical first step in fostering the development of management strategies for particular rangeland locations in the future.

Grasshopper Management Over the Variety of Rangelands

One simple observation from grasshopper studies illustrates the enormous task posed by grasshopper management over the range of species and habitats found in the Western United States. In the southern rangelands, increased precipitation and possibly cooler temperatures appear to increase grasshopper numbers. In northern rangelands, the opposite conditions (warm and dry) appear to increase grasshopper numbers (Capinera and Horton 1989). This comparison covers an immense region and glosses over the variability in vegetation among different areas. There also are other ecological factors that lead to variation in grasshopper numbers and

species composition (Joern and Gaines 1990). Furthermore, we have little idea of what particular mechanisms are driving the above patterns (including changes in plant production, plant nutritional value, grasshopper developmental rate, predation rate, fungal infection rate, and more), because the weather variables are no more than correlates with grasshopper numbers (Joern and Gaines 1990).

To illustrate further the problems arising from the diversity of rangeland habitats, there are two other major differences that emerge in comparisons of southern and northern rangelands. In the South, warm-season grasses dominate, and the smaller bodied, slantfaced (Gomphocerinae) grasshoppers are most abundant. In northern areas, cool-season grasses dominate, and the larger bodied, spurthroated (Melanoplinae) and bandwinged (Oedopodinae) grasshoppers are most abundant. Warm-season grasses generally are less nutritious for grasshoppers than cool-season grasses. Slantfaced grasshoppers that dominate in areas with warm-season grasses are better at feeding on these plants. Therefore, the weather correlates observed over the rangelands of the Western United States are further complicated by major changes in vegetation and grasshopper species composition.

The above points illustrate the need to better define the environmental conditions that affect grasshoppers in different regions and the ways that grasshopper populations function. Furthermore, some evidence suggests that rapid, human-induced climate changes could make identifying regional patterns worth little to managers. Climate changes may produce new patterns rather than simple latitudinal displacements of existing patterns (southern rangelands may not simply move northward). Similarly, other human-induced changes in the environment (changes in the abundances of native plant species and introductions of exotic plants and animals) could disrupt observed patterns. Therefore, people need to understand the different processes creating the patterns observed in different western U.S. rangelands. By doing so, managers can anticipate and plan responses to the changing environments, policies and values that will confront us in the future.

The Ecological Role of Grasshoppers

Grasshoppers play an important role in the functioning of rangeland ecosystems (Mitchell and Pfadt 1974). First, results from a variety of studies reveal that grasshoppers typically consume at least 10 percent of available plant biomass. Second, grasshoppers often harvest more plant biomass than they consume, influencing the availability and distribution of litter in the environment. This consumption and harvesting could be deemed negative from the perspective of available plant biomass for livestock production. But such “harvesting” processes can serve important functions for the cycling of nutrients.

Microbes can break down the feces produced by grasshoppers more easily than those produced by larger herbivores, such as cattle or sheep. Grasshopper-generated fecal nutrients are therefore more available for plant production. Also grasshoppers have a shorter lifespan and generally decompose where they die. The nutrients in their bodies return more rapidly to the soil for plant use than do nutrients found in the bodies of livestock. Even when grasshoppers create litter, they are enhancing plant production because increased litter increases the water retention of soils and reduces summer soil temperatures. These phenomena, in turn, enhance plant production by making more water and nutrients available in the semi-arid and arid conditions of the West. In total, grasshoppers may exert a positive influence on rangeland plant production.

Grasshoppers selectively feed on different plant species and, consequently, influence the plant species composition of the ecosystem. Sometimes, the grasshoppers harvest plants that livestock prefer. In other instances, grasshoppers consume plants that are poisonous or competitively reduce the abundance of plants preferred by livestock. The selective consumption of different plant species by grasshoppers can change the nutrient cycling dynamics in a rangeland. This change happens because the total nutrient content and decomposition rate of the litter depend on the plant species composing the litter (Pastor et al. 1987). Therefore, selective consumption of certain plant species can have a positive or negative effect on primary production for livestock by changing plant species abundances and nutrient cycling.

Grasshoppers are a major food source for other species that inhabit rangelands, especially spiders, reptiles, birds, and small mammals. Consequently, grasshoppers support other biological components of the ecosystem and influence their ability to affect ecosystem functioning. Again, grasshoppers can positively or negatively influence the biological composition of ecosystems and their productivity for livestock.

With the increasing emphasis placed upon ecosystem management by Federal and State agencies, grasshoppers in the rangelands of the Western United States must be considered in terms of their beneficial actions, not just in terms of their potential to reduce the abundance of forage for livestock. Consequently, pest management cannot be considered in isolation from larger ecological issues. This is especially true when the pest is a natural, coevolved component of the ecosystem, as grasshoppers are in western rangelands. Land managers must explicitly acknowledge that in most years, in most places, most grasshopper species do not harm the rangeland resource; rather they may benefit the resource.

Grasshoppers as a Range-Management Tool

Considering the important role grasshoppers serve in ecosystems, these insects deserve consideration as a tool land managers could employ to enhance rangeland productivity for livestock. First, nutrient cycling must be maintained to preserve or enhance rangeland production, and grasshoppers may aid in this goal. Second, the selective foraging of grasshoppers on different plant species might increase the abundance of plants that are more palatable and beneficial to livestock. Therefore, the negative effects of grasshoppers on forage availability for livestock must be compared against their positive effects on maintaining or enhancing rangelands.

Perhaps the greatest potential of grasshoppers as a management tool may be to alleviate the growing problem of weed control (Lockwood 1993a). For example, it appears that the grasshopper *Hesperotettix viridis* may control the abundance and spread of snakeweed (*Gutierrezia* spp.), rabbitbrush (*Chrysothamnus* spp.), ragweed (*Ambrosia* spp.), and locoweeds (*Astragalus* spp.). The grasshopper *Melanoplus occidentalis* may

reduce the abundance of prickly pear cacti. Even more important, grasshoppers may prevent or retard the spread of exotic weeds, as with feeding by *Aeoloplides turnbulli* and *Melanoplus lakinus* on Russian thistle (*Salsola iberica*). Scientists need to investigate more fully the potential benefit of weed control through grasshopper feeding. This area of research could become especially important with the difficult problem of controlling the spread of exotic weeds on rangelands. Weeds compete with native flora, and livestock find many weeds especially unpalatable.

Grasshoppers and Conservation

Clearly grasshoppers can provide many benefits that the public frequently has overlooked for the conservation of rangelands. In addition, there is growing social and political concern for the protection of biodiversity. Concern increases because of unrecognized benefits provided by many species and their important role in maintaining healthy ecosystems, and because these species are an important part of our cultural history and they are esthetically pleasing (Wilson 1989). Finally, there is a growing view in U.S. society that people have an ethical obligation to ensure the continued existence of all species and the ecosystems that they inhabit. The view is that each species has the same evolutionary value as the human species, and ecosystems have the same value as human society (Kellert and Wilson 1993).

Grasshoppers usually are abundant enough to be exempt from threats of extinction. Nonetheless, at least one species of grasshopper that was a very abundant pest appears to have become extinct, the Rocky Mountain locust (*Melanoplus spretus*). This species did not die out from control efforts but probably from habitat destruction caused by agriculture and livestock grazing (Lockwood and DeBrey 1990).

Not many years ago, the loss of the Rocky Mountain locust was considered a benefit. Today, many view this loss with apprehension. Few people would wish a return to the state where this species destroyed croplands, but the public can no longer experience, even on a small scale, the swarms that darkened the skies and stopped transcontinental railroads as told as part of America's national heritage and folklore. More importantly, the loss

of the Rocky Mountain locust means that an important element of the Nation's pristine rangelands has been lost, and the loss exemplifies the general assault upon natural environments, especially rangelands, by human actions.

For example, exotic plant species have almost entirely replaced the native annual grasslands of California. Only remnants of tallgrass prairie remain, and the introduction of exotic plants threatens most other western rangelands. What will happen to the native grasshoppers that inhabit these ecosystems? Several species of monkey grasshoppers in native desert grasslands are considered threatened and may eventually be listed for protection under the Endangered Species Act.

The decline of grasshoppers also affects other species, especially those that consume them. Recently, the U.S. Fish and Wildlife Service announced that western rangeland birds have dramatically declined in abundance over the last decade, with the numbers of some species decreasing by as much as 70 percent. Many of these birds feed on grasshoppers as adults, and almost all rely heavily on grasshoppers to provision their nestlings. Therefore, the control of grasshoppers must be considered in a broader conservation perspective than forage production for livestock, protection of threatened grasshopper species, and the maintenance of the ecosystem functions provided by grasshoppers. Grasshopper reduction also might harm declining or threatened species that depend on these insects as food (Belovsky 1993).

Conservation concerns are becoming more pronounced in formulating management plans because of legal and social mandates. Therefore, the scope and scale of grasshopper control programs will no doubt become more restricted in the future and will require consideration of far more than the short-term economic costs of grasshopper consumption of livestock forage.

Questions for the Future

One certainty for the future is that grasshopper management will be changing. There will be little "business as usual."

- The methods of grasshopper control will change as society becomes more concerned with environmental degradation and the protection of all native species. Therefore, new and innovative control methods that are environmentally sound will need to be found and used.
- Grasshoppers, as native components of rangelands, will no longer be considered solely as pests to be suppressed or eradicated, but as important elements for the functioning of our natural ecosystems. Furthermore, society is beginning to view all species that are part of our native biodiversity as having esthetic value, as providing a reflection of our national heritage that deserves some level of protection, and as requiring protection from an ethical perspective. The short-term economic costs/benefits of pest control to livestock production will become less important in decisionmaking and more subject to review by society.
- The general patterns of grasshopper abundance in different regions will change if humans change the global climate as projected by many scientists. Therefore, managers must act in places and ways previously unanticipated. The result is that pest managers need to adopt a broader perspective of their role, become more flexible in their actions, and view the changing environment as an exciting challenge, rather than a hindrance.

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