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# The Biology, Ecology, and Management of the Migratory Grasshopper, *Melanoplus sanguinipes* (Fab.)

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## Keywords

Rangeland, suppression treatments, economic species, flight, outbreaks, economic threshold, population dynamics.

## Abstract

Grasshoppers have caused significant damage to crops of farmers and rangeland forage of ranchers throughout history. Populations of grasshoppers can build and explode with exponential growth under the right climatic factors and habitat. *Melanoplus sanguinipes* is the most economic species of grasshopper in the United States. The migratory flight capabilities is very similar to true locusts. This species as been known to travel distances of over 500 miles. Millions of dollars in damage occurs to crops and rangeland annually in the United States due to this species and other economic grasshopper species. The life history of this species and timing of control measures are critical in the suppression of populations to safeguard crops and rangeland. Various techniques are employed to survey, detect and treat grasshoppers. One of the

most cost effective methods of treatment is to use Reduced Agent-Area treatments versus blanket coverage treatments.

# INTRODUCTION

Grasshoppers have been a major concern to farmers and ranchers since the Western U.S. was first settled in the 1800's. Review of historical literature (19) reported that great swarms of the Rocky Mountain locust, *Melanoplus spretus* caused complete destruction to all vegetation in Kansas during 1874-1877. No other insect has ever occupied larger public attention in North America, or was more injurious, than the locust, as it brought ruin and destruction to thousands of farmers in the west (113). Riley (113) was quoted to say, "Knowledge is power in protecting our crops against the ravages of a tiny insect."

There are 620 species of grasshoppers in the United States (2), 400 species of which are in the 17 Western States (104). Of the grasshopper species in the United States, 239 species are of the genus *Melanoplus* (2). This review will cover the biology, ecology and management of one of the most economic pest species of grasshoppers, *Melanoplus sanguinipes* (23, 103).

The Migratory grasshopper *Melanoplus sanguinipes,* represents the most commonly known grasshopper in North America. This species is in the Order: Orthoptera; Family: Acrididae subfamily Melanoplinae. This subfamily is a most diverse grasshopper group, with hundreds of species inhabiting many grasslands and forested ecoregions, from high mountain meadows to low valleys, from alpine to deserts. Extensive mass flights and swarms of *Melanoplus sanguinipes* were documented in the summers of 1938, 1939 and 1940 (99).

Grasshopper populations are influenced by weather patterns, soil characteristics and plant diversity (37, 38,134). In the northern states, long warm autumns, followed by warm, dry springs contribute to the building up of grasshopper populations to economic levels. In the southern areas, spring and summer moisture are a variable in building up of populations (12). *Melanoplus sanguinipes* has been known to periodically engage in some spectacular long distance mass migrations which can have an economic impact to rangeland and crops. These observations have been made since the early 1900's, which appears to be associated with unusual environmental conditions (98, 99, 101, 102).

Grasshopper damage can appear as round to ragged holes in the leaves of vegetation. This damage extends in from the leaf margins and between the veins of the plant. The damaged vegetation is consumed or damaged as a result of clipping the vegetation. Grasshoppers prefer young green growth on plants, grasses and annual flowers; in years when outbreaks occur, grasshoppers will spread out and chew nearly anything.

Hundreds of articles regarding this species of grasshopper have been documented regarding the biology, ecology and various management strategies for control. This review introduces some of the major literature and some of the significant features of this species' biology and ecology. This is not a complete review of this species, as that is beyond the scope of this document. Instead, this review synthesizes and critiques only a portion of the literature available. In conclusion, I identify some areas which could be researched further to aid in understanding this pest species and its management.

# SAMPLING METHODOLOGY

Generally, there is not a standard method to sample grasshopper densities and all methods produce varied results (61). Various methods have been used to estimate grasshopper density (88); sweep net sampling is most commonly used (39). Some authors argue the need for standardized techniques, i.e. how much of an arc the sweep covers, how many steps between sweeps, the diameter of the sweep nets etc. (58,85,86).

When using a sweep net sampling method, one should take into account the activity level of the species and should survey accordingly (133). High and fast sweep sampling is suitable for more active and adult grasshopper species, using low and slow sweeping motions are good for slow moving species and nymphs. A combination of both these methods of sweep sampling will obtain the best results (36). Sweeps using a low and fast method can provide suitable results for adult grasshoppers also (11). To estimate population size, a strategy of subsampling an area is necessary to ensure adequate coverage of the survey site (40).

Grasshopper surveys conducted by USDA, APHIS throughout the 17 Western States use a visual method and a modified transect to estimate grasshopper densities (8, 88). At each sampling point, surveyors count grasshoppers from 18 visually estimated 0.093-$m^2$ (1-$ft^2$) areas. The total number of grasshoppers counted is then divided by two to yield the number of grasshoppers per 0.84 $m^2$ (1 $yd^2$) (30).

Gardiner & Hill (40) found that open quadrat and transect methods provided fairly accurate and quick estimates of nymphal and adult grasshopper abundance in UK grasslands, providing that the same surveyor undertakes the monitoring. These authors' arguments for this method is not always feasible when surveys must cover large areas, hundreds of miles apart, and different surveyors are not always available to survey the same locations. Some researchers argue that other methods for estimating grasshopper densities should be used. This is due to estimation differences between surveyors and the lack of discipline to exclude personal bias (61, 63, 88). Due to the low cost and relative speed of gathering data assessments, sweep sampling remains a viable method for gathering data on populations (39, 61,133).

This method provides fairly accurate estimates of grasshopper densities (24, 61). Collecting species data using a sweep net remains cost effective compared to using other methods (e.g., quadrat sampling, ring estimations, night trapping and visual estimations) (63, 82). Some variations in sweep sampling can under estimate the early instars in taller vegetation (36, 39,133,134). Sweep sampling provides the means in which to obtain accurate estimates of species level data and continues to be a cost effective technique (24, 61).

The time of day and season can have an effect on the sampling results. Barnes (5) suggests surveys should begin as early as February - March in Arizona. Fisher et al. (34) suggest surveys in Arizona for *M. sanguinipes*, be conducted the first part of April. Elsewhere in the Western States surveys usually begin in early May.

# SPECIES IDENTIFICATION

## *Taxonomic Review*

*Melanoplus sanguinipes* is in the Order: Orthoptera; Family: Acrididae subfamily Melanoplinae. The tribe is Melanoplini (Orthoptera Species File (Version 5.0)). This species was first described by Johan Christian Fabricius 1798 in his classic work, *Supplementum Entomologiae Systematicae*. There are three subspecies of *Melanoplus sanguinipes*: 1.) *Melanoplus sanguinipes atlanis* (Riley, 1875) 2.) *Melanoplus sanguinipes defectus* (Scudder, 1897) and 3.) *Melanoplus sanguinipes sanguinipes* (Fabricius, 1798).

In a study of the insects of Kansas it was described that *Melanoplus atlanis* was closely related to *Melanoplus spretus*, the Rocky Mountain locust (19). In 1955, taxonomists considered *M. spretus* an extreme gregarious phase of *M. sanguinipes* (99). Some authors speculate that *M. sanguinipes* is actually the solitary phase of the extinct species *M. spretus* (Walsh) and awaiting the right climatic conditions to reveal itself (94). Faure (25) studied overcrowded *M. sanguinipes* and observed changes in morphology and color, which led him to this conclusion also. One study documented behavioral changes under crowded conditions; for example, females producing more eggs, nymphal stages having more robust bodies overall, and females mating with older males (112).

## *Identification Based on Morphological Characteristics*

Melanopline species can be identified from other grasshoppers by the prosterum. The prosternal tubercle (spine) **is** located between the 1st pair of legs (fig 2). This structure gives this group of grasshoppers the (Spur-throated) name.  All species in subfamily Melanoplinae possess this structure.

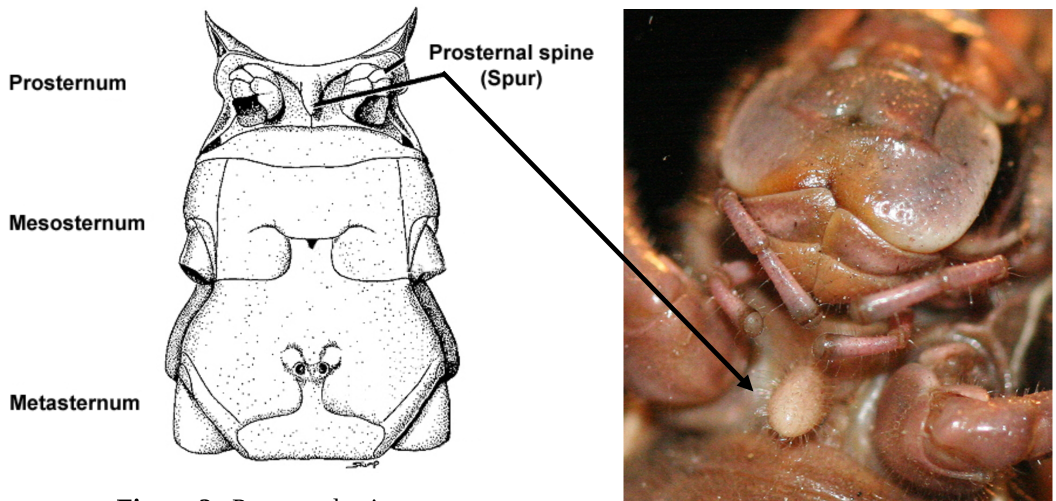


**Figure 2.** Prosternal spine.
http://idtools.org/id/grasshoppers/about_morphology.php

*Melanoplus sanguinipes* are medium-sized grasshoppers. They are easily identified by the shape of the cercus which is wide at the base and bluntly narrows at the tip (fig.3), and the subgenital plate, which is notched (Fig. 3). As a comparison, *Melanoplus spretus* had a similarly notched subgenital plate (fig. 4).

**Figure 3.** Notched subgenital plate at end of male abdomen. Migratory Grasshopper (Male). Image courtesy of Kerry S. Matz. http://bugguide.net/node/view/324940/bgimage

**Figure 4.** Notched subgenital plate of *Melanoplus spretus*. Source: D. Otte (97)

Adult males range from 20-26mm in body length, while females are slightly larger, 20-29mm in body length (103). The hind tibia color varies, including red (4, 13, 14, 59, 103) glaucous (44, 59, 103) orange (42), and deep pink (43).

Other color variations observed in adults was either a prominent orange stripe located between the ventro-external carina and the ventral carina on the external surface of the hind femur, or lacking the stripe (13, 16, 17). A reduced compound eye was found to be a morphological mutation in a non-diapausing strain of *M. sanguinipes* (15, 16). This reduced-eye mutant was shown to be a unique morphological characteristic, a reduction of 40% from normal eye size. This is not a taxonomic feature to be used in identification. The following is a brief summary of a few nymphal characteristics according to Pfadt (103). Nymphs are identifiable by their color patterns (103):

1. Compound eye with many light spots, narrow brown bar across middle.

2. Narrow pale yellow crescent on gena below eye and continuing on pronotal lobe to principal sulcus.
3. Hind femur with dorsal black stripe cut in middle by light bar; a light bar on each end.
4. Hind tibia of first instar fuscous with pale basal ring; hind tibia of other instars pale blue green or reddish without pale ring.
5. General color of body tan or gray, few light green.

## DISTRIBUTION AND HABITAT

*Melanoplus sanguinipes* is widely distributed in North America and Canada (Fig.1). This species of grasshopper has been found in several habitats, including mixed grass prairies, desert prairies, mountain meadows, disturbed lands, rangelands and croplands throughout the United States and Canada (103, 104). Host plants include a variety of forbs and grasses. The migratory grasshopper is known to be a generalist feeder (31). A variety of crops are reported to have been damaged from this species. The crops include corn, soybean, alfalfa, winter wheat, barley, oats, sugar beets and a variety of garden vegetables. This species can feed, depending on availability of plant species, on either a mixed herbivorous or a forbivorous diet.

**Figure 1.** Geographic distribution of the migratory grasshopper. Source: D. Otte (97)

Weeds which have been introduced or that are invasive provide a nutritious and steady supply of food for this species. Tillage of sandy soils in cropland settings result in wind-blown drifts that provide favorable conditions for oviposition. Over grazing of rangeland by livestock reduces grass cover and can lead to the invasion of weeds and grasshoppers (87, 131). Abandoned cropland that rapidly converts to weeds can be an area which can harbor dense populations of the migratory grasshopper as well as a variety of other cohorts and allies. All of these sources of outbreaks make the migratory grasshopper a prime candidate for integrated pest management.

## *Population Dynamics*

Population dynamics of the migratory grasshopper have been study by researchers throughout North America. Results indicate that weather and availability of food plants are the most influential factors affecting population growth of this species and other grasshoppers (9, 56, 66, 79, 80-84, 98). The migratory grasshopper will feed on a large variety of plants; there are, however, a limited number that are particularly favorable for this species' survival, growth, and reproduction (10, 103).

Under normal conditions *M. sanguinipes* is found in densities of 0.1 to 3 grasshoppers /$yd^2$, in all types of grassland habitats (103). During seasons of outbreaks, the migratory grasshopper is present in of densities of 20 - 80 young adults/$yd^2$. These densities will exhaust the forage, inducing grasshoppers to take flight and migrate to more favorable locations (1, 6, 7, 45-47, 103).

Large populations can develop on disturbed cultivated land, weedy rangelands, in fields with stubble of small grains, and along roadsides. A noneconomic population of three adults/$yd^2$, with favorable conditions, can reproduce exponentially so that the following season the population may reach an outbreak density of 30 or more adults/$yd^2$ (20, 103).

The economic injury level (EIL) (123) is the level of a pest population at which the cost of controlling the pests becomes equal to the damage a pest population will cause economically on an area. It is important to manage the pest population before the EIL is reached. The economic threshold of 8 grasshoppers/$yd^2$ is normally used to initiate steps to implement control measures (20, 41).

The economic threshold is dependent on benefits and costs. Some authors argue that a discrete-choice threshold is appropriate for rangeland control of grasshoppers (125). The goal of a grasshopper integrated pest management plan is to improve upon the discrete-choice threshold. This would mean that the economic threshold should vary, depending on the amount and value of forage saved vs. the cost of saving the forage from grasshopper destruction. Economic justification for treatment will depend on many variables: rangeland productivity, livestock prices, cost of alternative sources for forage, accessibility, effectiveness, and of course timing of treatments to control grasshopper populations (20, 41, 127-129).

In northeastern South Dakota, a study conducted from 1934 to 1936 revealed gradual increases in densities of the migratory grasshopper during a period of a severe outbreak. During the spring of 1937, surveys revealed severe infestations of young nymphs estimated at 80 gh/$yd^2$. The adults spread from these hatching sites and traveled throughout the area. During September and October, there was usually warm weather, which allowed the females to oviposit over an extended period of time. Estimates from egg surveys revealed as many as 8,000 eggs/yd$^2$. This demonstrates the reproductive potential of *Melanoplus sanguinipes,* which in 1938, resulted in an enormous outbreak that led to mass migratory flights. Due to the migrations which occurred in 1938, the outbreak expanded the acreage of coverage and continued through 1940 (99).

Normal activity of the migratory grasshopper occurs during the day and becomes inactive at night. Most immatures and adults rest horizontally on the ground during the night. However, there are some individuals which will climb vegetation and rest vertically. In this position, the head is up and is usually 8 to 24 inches above the ground depending on height of vegetation. In the morning, as the sun rises and begins to warm them, they adjust their positions to receive the full benefit of the warming rays. The individuals will continue to bask either on the ground or on vegetation. The usual behavior is to orient a side perpendicular to the sun's rays. Then the grasshopper will expose the abdomen by lowering the hind leg. Basking may last approximately two to three hours before they become active, start walking about and feeding. Grasshopper have been observed to mate and oviposit later in the day (3, 92, 103). As soil temperatures rise, individuals will climb vegetation to help thermo-regulate. When temperatures began to decline in late afternoon, grasshoppers will bask for a second time and then become active, pottering, feeding, mating, and ovipositing, before taking their nighttime positions (92, 98, 99, 117).

# DEVELOPMENT

## *Life Cycle Overview*

Grasshoppers have three life stages – egg, nymph, and adult. The female will lay a cluster of eggs in the soil, referred to as a pod. Under ideal conditions, a female can lay as many as 20 pods and 400 eggs during her lifespan (103). Eggs hatch in the early spring and develop into nymphs. The immatures undergo all nymphal stages in about 35 days when the days are long and warm. There are 5 instar stages of development for *Melanoplus sanguinipes*. Older nymphs, 3rd to 5th instars, have been reported to migrate up to 10 miles; usually this distance is less than 5 miles. Nymphs or adults can travel together in groups referred to as bands. These bands can move at a rate of around 0.1 mile per hour. Adults are highly migratory before reproduction.

Females will deposit eggs in grasses and forbs found on rangeland. In crop areas eggs are deposited usually at the base of alfalfa and wheat stubble. The egg pods are curved in a banana shape, approximately one inch long and 1/8th of inch in diameter. Pfadt (103) reported that in the late 1930's hatches reached densities of 1,500 - 8,000 nymphs/$yd^2$.

Emergence of adults will begin the first portion of early summer and continue for three or four weeks depending on weather. The first adults to emerge have the highest rate of fecundity. During this time of the summer, there is generally an abundance of green food plants to provide nourishment necessary for rapid egg production. In general, the first eggs laid will usually experience more favorable soil moisture and have a longer time to reach an advanced developmental stage before entering diapause (103).

*Melanoplus sanguinipes* appears to have a relatively long life span. In field and laboratory tests, it has been reported that survivors have lived as long as 188 days (106). This species is normally univoltine over most of North America. However, bivoltine species have been reported particularly in the southern states (22, 34, 50). Shotwell (117) reported that in 1936, the first hatching occurred from April 20th to May 15th and adults appeared by June 1st. Then by August, a 2nd generation of *M. mexicanus* occurred in Iowa, Nebraska and Kansas. There have been reports of bivoltine species as far north as Saskatchewan, Canada. In caged field studies, a second generation was also observed in the field (106). Some authors believe that the southern bivoltine populations belong to two subspecies, *Melanoplus sanguinipes vulturnus* Gurney & Brooks, or *defectus* Scudder (42, 43). These morphological characteristics are distinguishable from the typical northern subspecies (107). *Melanoplus sanguinipes* has been reported to lay both diapause and non-diapause eggs, a trait that has been documented to occur in other acridids (21,111, 120). The potential for at least two generations per year probably exists for all populations of this species, although the growing season in northern locations prevents a second generation. Multiple generations of *M. sanguinipes* have been reported in Arizona (5, 34).

### *Oviposition*

Most grassland species will oviposit several eggs clustered within what is known as a pod. The egg pod is deposited about 2 cm below the soil surface or plant litter on the soil surface. Females will extend their abdomens into moist soil and deposit a pod of eggs. Pickford et al. (108) was the first to demonstrate that there was an oviposition stimulant produced from the male accessary gland of the migratory grasshopper, *Melanoplus sanguinipes*. An attempt to purify and characterize this oviposition-stimulating protein (OSP) was conducted by Sieminska et.al (119). This study demonstrated that there is a viscous secretion associated with the spermatophore transfer, the spermatheca, and the egg-pod froth of mated females, confirming the transfer of

MsOSP from male to female during copulation. This protein stimulates the oviposition in females (119).

The egg pod may contain several eggs. *M. sanguinipes* from an Idaho study was less selective in terms of the distribution of egg pods among different ground cover types (29). Pods are curved, one inch long and one-eighth inch in diameter. The top half of the pod, containing dried froth, is oriented vertically in the soil and the bottom half, containing the eggs, is oriented diagonally (103). It was shown in laboratory studies that long-lived females can deposit up to 20 egg pods and 400 eggs (103). The fecundity in nature does not reach this extreme.

### *Egg & Nymphal Development*

The migratory grasshopper is an early-hatching species (44, 103) developing on rangeland about 7-10 days after *Aulocara elliotti* begins to hatch (31, 103). Several environmental factors, such as soil temperature and moisture, affect the exact timing and the duration of hatching. Hatching begins first along the sandy soils of open southern slopes. These fields, pastures and rangeland usually have little cover of vegetation. Hatching can be shortened to 3 weeks when the following variables are present: uniform soil, vegetation and high temperatures. Hatching can be delayed or slowed when eggs are in heavy clay loam soils and tall vegetation that shades the ground (103), along with below-normal temperatures, extending hatching by six weeks.

Developmental thresholds and degree-day requirements for most grasshopper species in North America is largely unknown. Even with the economic importance grasshoppers are to crops and rangeland, not much information is available concerning thresholds (34, 104). Estimates for total degree-day requirements for development from egg to adult have been experimentally controlled and determined for *Melanoplus sanguinipes* (11, 57). Complete embryonic development of eggs requires 527 degree-days above the threshold of 50°F for the soil temperature (11, 103). When conditions are favorable, 80 percent of development occurs during the summer when the eggs are laid and 20 percent will emerge the following spring.

Incubation of eggs begins immediately after females oviposit in the soil. The embryo, at first a tiny disc of cells laying on the ventral side of the yolk surface and at the posterior end of the eggs, grows rapidly, receiving nourishment from the nutrient stores in the yolk. In seven days the embryo of *Melanoplus sanguinipes*, if held at an incubation temperature of 30.5C, reaches Stage 19 or 50% of development. Many other species of rangeland grasshoppers go into diapause at this stage of development. *Melanoplus sanguinipes* will continue to develop up to 15 days (stage 24 or 80% of development) before going into diapause (28, 104).

In the warmer areas of the southwest, the migratory grasshopper produces a smaller (less numerous) second to third generation each year (5, 11, 51, 57, 74, 75, 103, 116, 121, 122). The majority of eggs from the first generation will enter diapause and hatch the following year. The duration of embryonic development and stage of embryonic diapause are influenced by the climatic variables of the area of habitat (11, 52, 26, 28, 118). Grasshoppers from warmer environments will begin diapause at early stages of embryonic development, while species from cooler environments diapause at later developmental stages (32).

### *Diapause*

The migratory grasshopper has a very wide geographic range over which diapause characteristics vary greatly. Embryonic diapause in species from Alaska was shown to be obligate. Fielding (27) showed that even though the diapause was obligate it could not be averted by cold temperatures of pre-diapause embryos. *M. sanguinipes* in more southern latitudes exhibit facultative diapause (28) and respond to the changing photoperiods. A positive change results in an increase in non-diapause egg production and a negative shift results in an increase in diapause egg production (21). Dean (21) found that developmental time was faster under short-day photoperiod, than long-day photoperiods (62). Body size tended to be larger under long-day photoperiods than short-day photoperiods (21, 68, 69). Facultative diapause enables bivoltinism to be a viable strategy (27) and to be controlled by changing photoperiods (21). All these traits affect fitness by determining voltinism, time of hatching, and length of time available for growth and reproduction (26, 27).

During a 12 year period *M. sanguinipes* was bred to produce a non-diapausing strain during winter months in Canada (107). This study showed that six to seven generations could be produced in a single year. This demonstrates this species' ability to adapt to almost any environment.

## BEHAVIOR

### *Migration*

Adults have been reported to fly as far as 30 miles in a day. Swarming will occur on clear days when temperatures approach $80^0$F and winds are gentle and intermittent. Flight usually begins in the late morning, during the middle of the day, and then they feed and rest in the afternoon. The longest migrations recorded were in 1938; swarms traveled from northeastern South Dakota to the southwestern corner of Saskatchewan, a distance of 575 miles (99, 103). Migratory prolonged flight has been shown to decrease reproductive potential in some species of insects. However, in a study of populations of *M. sanguinipes* from Arizona, it was shown that there were no effects of flight on oviposition, and that oviposition was enhanced in females that flew for several hours (68, 69).

These authors suggest that selective pressure for rapid and successful colonization has resulted in this enhanced migratory behavior of the Arizona population, as compared to other populations of the migratory grasshopper. This enhanced behavior is very similar to true locusts. Higham & Haskell (49) found in *Locusta* and *Schistocerca sp*., that the effects of overcrowded conditions were shown to accelerate the production of oocytes and the flight of individuals when they became mature. Due to the flight characteristics exhibited by this species, much research has been done on flight propensity and flight duration (68, 69, 71, 72, 110).

Reduction in stored fuel supplies can be greatly reduced during long-distance flights. This can decrease the reproductive capacity of long distance fliers (110). Flight duration influences the types of fuel utilized. For short flights, carbohydrates are the primary fuel for most insects (110). Relatively little carbohydrates are stored as glycogen in tissues; most of it resides as a ready store of energy in the hemolymph as disaccharide trehalose, which is easily taken up by flight muscles (109). Energy for long flights is metabolized from lipids instead carbohydrates. Lipase activity is readily present in flight muscles (109, 114). This physiological ability is similar to the other locusts, *Locusta migratoria* (110) *Schistocerca gregaria,* (114). An analysis of a neuropeptide hormones isolated from corpora cardiaca (18) of *Melanoplus sanguinipes* revealed similarities with the two locust species previously mentioned. This adipokinetic hormone sequence data adds *M. sanguinipes* to the Lom-AKH-I group with these two locust species. This again reveals the unique characteristics that *Melanoplus sanguinipes* has in common with true locust species (124).

*Melanoplus sanguinipes* has shown the ability after long flight activity an enhanced capacity for reproduction by influencing the timing of oogenesis and yolk deposition, thus increasing the number of eggs produced and the fitness of offspring (68-72, 108).

## FEEDING ECOLOGY

### *Economic Importance*

The United States has about 770 million acres of rangelands. The federal government manages 43 % of the rangeland in the United States (126). State and local governments manage the remainder. The two federal agencies that manage rangeland are the Bureau of Land Management (BLM) 258 million acres and the Forest Service, which administers approximately 191 million acres of National Forest Systems.

Rangeland vegetation is grouped or associated with plants that may approximate the climax vegetation of the ecosystem. There are 11 rangeland cover type or regions in the United States. Each cover type is made up of vegetation types that may be the predominant vegetation within a given locale. Within these 11 cover types there are 176 vegetation types that make up the rangeland ecosystems of the United States (115). Rangeland supports a wide variety of native and nonnative grasses, grass–like plants, forbs, or shrubs that provide forage for wildlife and livestock. The potential vegetation is predominantly grasses, grass-like plants, forbs, or shrubs, including land revegetated naturally or artificially that is managed like native vegetation. Rangeland includes natural grasslands, savannas, shrublands, most deserts, tundra, alpine communities, coastal marshes, and wet meadows that are less than 10% stocked with forest trees of any size (115).

## *Rangeland*

The wide range of diet and the ability to fly large distances truly nominates this species as one of the top economic grasshopper pests of North America (23, 119). Much research has gone into the diet of this species and the economic effects on rangeland in the United States and Canada (31, 105). Millions of acres are damaged each season due to this species and other economic species of grasshoppers (132). A conservative estimate for the average value of rangeland forage loss to grasshoppers in the West each year is about $400 million (48). To help protect rangeland resources, suppression treatments for outbreak populations are conducted by private, state and federal governments each season.

*Melanoplus sanguinipes* was found to feed on 27 different forb species and 5 grass species in a study on short-grass rangelands in Arizona (78). This species is considered to be a mixed feeder or polyphagous (9, 100, 103). The variety of plant species fed upon increases when second and third generations emerge later in summer and fall. This increases the of variety list of species feed upon (78). In a heavily grazed, sparse grass grazing allotment, about 70 percent of the forage was eaten by an average of about 15 grasshoppers per $yard^2$ in comparison to the same density, a moderately grazed, fairly good grass allotment, which was consumed or wasted only by 20 percent (77, 93).

The kind of food consumed determines the volume eaten and the number of times feeding occurs (93). The amount of food grasshoppers eat depends upon the temperature. Apparently more food is required to care for the increased metabolic activities under high temperature conditions (60). Nymphs and adults feed readily on alfalfa, but if it is the only source of nutrients it becomes unsuitable for survival and development of this species (5,100). Adults from 1st generations develop largely on forbs, such as fillaree *(Erodium cicutarium)* and tansy mustard *(Descurainia obtusa)*, a close relative of hedge mustard, which is a preferred food plant and very favorable to their development. (5, 77, 78, 80).

## *Crop Damage*

The migratory grasshopper can cause great damage to cultivated crops. This species prefers habitats with a variety of host plants, including both grasses and forbs. As a result, they prefer cropland settings with nearby undisturbed areas such as roadside ditches, crop borders, abandoned cropland, and over-grazed pastures or rangeland. Field crop problems usually do not arise from neighboring well-managed rangeland or pasture. Grasshoppers primarily damage corn, soybeans, alfalfa, and wheat but during years of high populations, they will damage almost any crop, tree, shrub, and garden.

The primary injury caused by grasshoppers is defoliation and direct feeding on pods and seeds. As they feed they consume and clip foliage (73, 125). Grasshoppers can cause direct crop losses by feeding on ripening grain. With favorable weather conditions, grasshoppers can hatch and mature two to four weeks earlier than normal (90). Early hatching can threaten establishment of corn, sugar beets, or other crops planted in early spring (82). The primary damage to alfalfa is through defoliation; during years of high infestations, grasshoppers will also feed on stems and crowns. This feeding damage can cause the crowns of the plants not to recover, especially when damage occurs just after harvest. Early planted wheat is more vulnerable to injury than later plantings, because the plants emerge while adult grasshoppers are still actively feeding (33, 55, 76). Newly emerged wheat can be severely damaged by grasshopper feeding. Grasshoppers can seriously damage maturing grains as they clip the stems, causing the heads to fall to the ground.

## MANAGEMENT STRATEGIES

### *Cultural Control*

There have been a variety of methods employed over the years to control populations of grasshoppers. The principal cultural methods used to control grasshoppers have included: early seeding of crops, crop rotation, trap strips and tillage. These are all methods which have been used to control grasshoppers in an agricultural setting. Each has a measure of effectiveness. These methods merely involve proper timing and good management strategies all within normal operations necessary in the production of a crops. These cultural control methods are effective if implemented before an outbreak of grasshoppers is apparent, and are a preventive approach to grasshopper control.

In general, tillage is not a very practical method to reduce populations of grasshoppers. However, there are some authors that list this method as a possible cause of extinction of *Melanoplus spretus* (65). This method seems plausible when placed in the context of swarms of locusts which occurred in the late 1870's. Why was only *Melanoplus spretus* susceptible to this method? There may have been some effect on the egg pods in the soil. Tilling these areas will expose the eggs to pathogens, predators and weather conditions. Tillage has no effect on developed grasshoppers already feeding on crops and forage. This method is not considered a productive management tool to control grasshopper populations. Tillage of millions of acres of rangeland is not practical, environmentally acceptable, and would create more problems than the populations of grasshoppers themselves due to the disturbance of soil and invasive weeds. This method seems to have been a convenient solution for the demise of *Melanoplus spretus*. Over the last 146 years there has not been a repeat of another species of grasshoppers going extinct or controlled using this method. There may be localized control or micro-scale control but for management of populations this is not the correct tool for the job at hand. This leaves room for the argument raised by Otte 2002 (94) that *Melanoplus spretus* may not be extinct after all.

## *Biological Control*

Disease-causing micro-organisms have been investigated as potential biological control agents of grasshoppers for many years. Probably the most well-known case has been the parasite *Nosema locustae,* a pathogen that was selected in the early 1960's for development as a microbial control agent for use in long-term suppression of grasshoppers (89). *Nosema locustae* is the only registered microbial agent that is commercially available for control of rangeland grasshoppers. Fungal pathogens that control grasshoppers are slow acting and will not produce results to be of benefit to crops or rangeland already being fed upon. There are some biopesticides for use on grasshoppers, (i.e. Green Guard and Green Muscle) in use in Australia and Africa with good results, but as yet are not labeled for use in the USA. These employ the use of *Metarhizium anisopliae* var. *acridium*. These isolates are very specific to locusts and grasshoppers.

### *Chemical Control*

The first chemical control in the U.S. for grasshopper populations took place in 1885 with the use of bran and arsenic-based baits. Poison baits that grasshoppers would eat were commonly used from 1900-1940's. Arsenic-based baits were used until 1943, when sodium fluosilicate became popular (35). A variety of methods were used to apply the chemicals used historically. Hand spreaders, dusters, and eventually the use of aircraft was incorporated to apply chemicals aerially.

Today, there is a variety of nozzle types for ultra-low volume applications. These can be applied by aerial or by ground using ATVs, UTVs and other vehicles. Liquid formulations and baits have been formulated in a variety ways. Application methodologies have been developed such as Reduced Agent-Area Treatments (RAAT's). RAATs are a method of integrated pest management (IPM) for rangeland grasshoppers in which the rate of insecticide is reduced from levels recommended by the label and untreated swaths are alternated with treated swaths.

During the mid to late 80's, rangeland treated for grasshopper outbreaks was estimated to be >8 million ha, with 5 million liters of insecticide (primarily Malathion) being used for treatments in the western US, at a cost of over $75 million (67).

There are a variety of chemicals registered for control of grasshoppers feeding on crops, pastures and rangeland. These chemicals can be applied by aerial applications or with ground equipment, e.g. ATV's, UTV's, tractors or truck mounted spray equipment. Navigation systems with GPS tracking help to document precise treatment areas. The type of application will depend on field size and on the size of infestations. There are various methods of coverage e.g. blanket or full coverage, RAAT's at 40%, 50% or even 60% coverage. These management options for grasshopper control have developed due to the demand to protect crop and rangeland forage from grasshopper damage.

Effective pest management of rangeland grasshoppers requires not only accurate estimation of overall grasshopper densities, but more specific data about species composition and age distribution (133). *Melanoplus sanguinipes* is highly sensitive to the use of carbaryl in bait formulations, both as adults and nymphs (91). One can expect to get mortality from 70% - 85% from use carbaryl baits for management of this species.

Diflubenzuron is a chemical that has received a label for grasshopper control since the 1987 APHIS Federal Environmental Impact Statement. It is classified as an insect growth regulator that affects the formation and/or deposition of chitin in an insect's exoskeleton. An insect larva/nymph exposed to diflubenzuron is unable to successfully molt and thus dies. It is normally applied by air for grasshopper suppression on rangeland, but it can also be applied using ground equipment (129, 131).

Diflubenzuron was first registered as a pesticide in the U.S. in 1976. The active ingredient is *N*-[(4-Chlorophenyl) carbamoyl]-2, 6-difluorobenzamide. Diflubenzuron is considered an insect growth regulator (IGR) because of its effects on the endocuticle (131), and specifically interferes with the deposition of chitin, which renders nymphs unable to complete the molt process. This results in mortality. The registered trademark for diflubenzuron formulations used for locust and grasshopper control is Dimilin®. Jech et al. (54) showed that treatments using (1.0% (AI)/kg at 2.2 kg/ha) controlled grasshopper populations in the year of treatment and also the following season. Mortality after 28 days using this product has been shown to reach 90% - 97%.

Timing is critical for use of this product for control of grasshoppers. The use during early instars will increase the efficacy of the treatments allowing the chemical interference with chitin development. Thus, it increases mortality among immature grasshoppers. Responding quickly to outbreaks and using diflubenzuron along with RAAT treatment methodology can reduce populations greatly, along with the cost of chemical treatments associated with a treatment program (67).

## CONCLUSIONS

Land managers of county, state and federal agencies will continue to find it necessary to manage, suppress and protect the forage provided on rangeland throughout the Western United States. There will be a need for research into the complexity of the rangeland ecosystem. The complexity of grasshopper management due to the variety of species, developmental stages, biology, feeding habits etc. will be a challenge into the future to try to predict outbreaks of grasshoppers.

*Melanoplus sanguinipes* will undoubtly be researched with more advanced modeling, sensors and computerized equipment. This species will maintain its status as the most economic grasshopper species in the U.S. This fact will not change unless there is an introduction, invasion/migration of one of the locust species such as the Central American locust *Schistocerca piceifrons*. The future may yet unveil the idea posed by Otte in 2002; a comeback of *Melanoplus spretus*. Speculating on emergence due to climatic changes in the environment that is more conducive to

*M. sanguinipes* in a gregarious phase may be more realistic than a comeback of *M. spretus* (64). The future will only hold the truth that grasshopper management will continue as long as there are species which damage and destroy rangeland forage and crops of the U.S.

## RESEARCH NEEDS

The complexity of the rangeland ecosystem is illustrated from the lack of information regarding several aspects of rangeland ecology. For example, Gardiner & Hill (40) suggested research was needed into the efficiency of the open quadrat and transect methods at a range of survey sites with differing vegetation types and varying grasshopper densities. There is a lack of knowledge regarding specific information on a variety of species' biology dealing with grasshopper population dynamics.

In the last 142 years since the outbreak of *Melanoplus spretus*, there has been a vast amount of literature on the biology, ecology and control of rangeland grasshoppers and particularly

*Melanoplus sanguinipes* in the U.S. There are vast amounts of technical reports from the United States Department of Agriculture and, Animal and Plant Health Inspection Service (USDA, APHIS) which have not been used in publications outside of agency use. Presently, there is an effort to digitize this data to make it available to public, academia and other interested parties. Even though there is a great wealth of information on grasshopper biology, much is unclear or unknown.

For example, in 2011, Otte published 80 new species of *Melanoplus* (95) from the U.S. and Hill (53) described and published his findings on a new species of *Melanoplus* from Tennessee. In 2013, three new species of mites not known to occur in the U.S. were discovered parasitizing *Melanoplus gladstoni* and *Anabrus simplex* in Northern Arizona (personal observation). These were sent to the national acarologist in Florida for identification and mounting.

New chemical formulations, advanced techniques of delivery for treatments and use of unmanned aircraft equipment with hyperspectral imaging sensors are being investigated as possible tools for future use. The management of rangeland and crops from economic species of Orthoptera is a global challenge. There are management techniques and strategies that have been proven to be efficient in the U.S. which may not have been used elsewhere in the world due to a lack of knowledge base. There are efforts underway presently to develop better land management practices that will account for the complexity between agricultural activities and ecological systems.

The is a need for effective and efficient biopesticides that can be used in the management of grasshopper populations to replace the present insecticides which EPA may no longer deem safe to use in the environment due to policy changes, etc. There is need for research into chemicals, which have a proven effectiveness in other countries but have not been registered in the U.S. There is a great need for exchange of ideas, knowledge, science, methodologies and management techniques to be exchanged on a global basis. The risk for greater pests such as true locusts becomes greater as there is an increase in global trade and markets. The risk in shifting ranges or distributions of grasshopper species due to climate change may become a reality, thus producing new problems to overcome.

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