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Insecticidal Management of Rangeland Grasshoppers Using a Remotely Piloted Aerial Application System

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Abstract: Grasshoppers are integral parts of rangeland ecosystems but also have the potential to reach population densities high enough (outbreaks) to cause serious economic damage from forage loss and affect adjacent crops. The objective of this study was to investigate the efficacy of treating grasshopper population hotspots with a liquid insecticide using a remotely piloted aerial application system (RPAAS), as opposed to fixed-wing aircraft, which is the most common method currently in use. A liquid insecticide, Sevin XLR PLUS (containing carbaryl), was applied on replicated 4.05-hectare (10-acre) plots with an RPAAS on a ranch in New Mexico. Our results demonstrated that Sevin XLR PLUS significantly suppressed grasshopper populations over a 14-day period (normalized population reduction was 79.11 ± 8.35% SEM) and quite rapidly (mostly by day 3) compared to untreated controls. These results are comparable to those achieved with fixed-wing aircraft. The RPAAS covered the whole test area in a single flight in approximately 5 min, making these population hotspot treatment applications relatively rapid, potentially more cost-effective, and more targeted in comparison to fixed-wing aircraft. Before adoption as an application method option, further research is recommended on using an RPAAS to cover larger areas in combination with using diflubenzuron-based insecticides, which are often preferred.

Keywords: rangeland grasshoppers; *Mormon crickets*; UAV; UAS; RPAS; RPAAS; Sevin XLR PLUS

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Citation: Martin, D.E.; Rodriguez, R.; Woller, D.A.; Reuter, K.C.; Black, L.R.; Latheef, M.A.; Taylor, M.; López Colón, K.M. Insecticidal Management of Rangeland Grasshoppers Using a Remotely Piloted Aerial Application System. *Drones* **2022**, *6*, 239. https://doi.org/10.3390/drones6090239

Academic Editor: Barbara Bollard

Received: 27 July 2022
Accepted: 1 September 2022
Published: 5 September 2022

1. Introduction

There are over 400 species of native grasshoppers (Orthoptera: Acrididae) in the 17 western United States [1]. About two dozen of these species, associated with rangeland ecosystems, are considered to be pests by land managers due to the propensity of their populations to periodically reach outbreak levels [2]. Outbreaking grasshoppers voraciously devour rangeland forage and nearby crops, with significant forage destruction often starting with the 3rd nymphal instar (the species average the 5th before becoming adults) [3]. Areas with concentrated population densities are often referred to as "population hotspots" [4], are typically relatively small in area, and tend to largely be composed of nymphs that have yet to disperse more widely.

Cattle consume about 1.5–2.5% of their body weight in forage per day, so pound for pound, a grasshopper will eat 12–20 times as much plant material as a steer and can cause serious economic damage to the cattle industry, especially during drought when forage is already scarce [5–7]. Grasshoppers annually consume >20% of rangeland forage in the western United States at an estimated loss of $1.25 billion per year in forage [3,5]. Furthermore, grasshopper populations can migrate to neighboring crop lands, causing significant damage to corn, soybean, and wheat [8]. The cyclical nature of grasshopper outbreaks not only reduces livestock forage but can also result in soil erosion and disruption of rangeland nutrient cycles, resulting in overall interference with rangeland ecosystems [3,9,10].

Insecticides are the primary treatments for suppressing grasshopper populations and most often applied on rangelands using fixed-wing aircraft, particularly under the United States Department of Agriculture (USDA) Animal and Plant Health Inspection Service (APHIS) Rangeland Grasshopper and Mormon Cricket Suppression Program. Fixed-wing aircraft have been the default program of choice for treatments due to their ability to cover large areas in a single flight, the ability to treat enormous areas in a relatively short period of time, and because, historically, these types of aircraft have been the only aerial option available. However, recently, the use of remotely piloted aerial (or aircraft) application systems (RPAASs) in small farm operations and site-specific management of crop pests in difficult terrains not easily accessible to fixed-wing aircraft have received increased attention around the globe [11,12]. An RPAAS has the potential to occupy this niche because of its ability to fly at low altitudes, can hover closer to plant canopy at different heights and ground speed with more precision and safety, and has the ability to be deployed relatively rapidly [13,14]. The RPAAS is remotely controlled and flies autonomously using preprogrammed flight paths.

In the United States at least, RPAASs are not yet used in grasshopper management programs due mainly to a lack of studies demonstrating their utility for treating population hotspots. To date, no research report exists describing the use of RPAASs to treat hotspots of rangeland grasshoppers in the United States.

Thus, the objective of this study was, using an RPAAS, to evaluate the efficacy of treating a grasshopper population hotspot with the liquid insecticide, Sevin XLR PLUS (containing the active ingredient carbaryl, an acetylcholinesterase inhibitor, which is effective against all grasshopper life stages).

2. Materials and Methods

2.1. RPAAS

The RPAAS used for the study was a six-rotor Precision Vision 35 (Leading Edge Aerial Technologies, New Smyrna Beach, FL, USA). It was equipped with four Turbo TeeJet XR110-01 nozzles (two on each side of the aircraft) mounted to spray booms. The spray system was set to 262 kPa (38 psi) and measured with an inline pressure gauge (4FLR1, Grainger, Lake Forest, IL, USA) to achieve a total system flowrate of 1.84 L/min (0.49 GPM). In order to achieve an application rate of 1.17 L/ha (16 fl. oz./acre) over 4.05 ha (10 acres), the RPAAS was flown at 9.83 m/s (22 mph) at an altitude of 3.05 m (10 ft). Treatments with Sevin XLR PLUS required a single flight to cover each 4.05-hectare (10-acre) plot, without completely depleting the battery, and each of the four treatments was completed within approximately five minutes of the total flight time. The plots were approximately square, 201 m by 201 m (660 ft $\times$ 660 ft) but fluctuated with other boundaries such as fence lines and high voltage electrical wires.

2.2. Spray Swath and Spray Droplet Spectra Measurements

Twenty-six water sensitive cards (20301-1N, Spraying Systems Co., Wheaton, IL, USA) were placed in a line perpendicular to the flight path, approximately 0.91 m (3 ft) apart, to capture the spray deposition (Figure 1). The RPAAS was flown at a speed of 8.94 m/s (20 mph). The cards were scanned with a laser bed scanner (Perfection 1240U, Epson, Suaw, Nagano, Japan) and swath analysis was performed using DropletScan (WRK of Arkansas, Lonoke, AR, USA; WRK of Oklahoma, Stillwater, OK, USA; and Devore Systems, Inc. Manhattan, KS, USA). The cards were scanned in at 600 dpi and the software was used to determine the coefficient of variation (CV) for both a simulated racetrack and a back-and-forth spray pattern. Since the RPAAS was operated in a racetrack pattern where the RPAAS follows the waypoints and the left side of the aircraft overlaps the right side of the aircraft, that simulated pattern was used to determine the effective swath. The CV for multiple effective swaths was determined using DropletScan and the swath width with the lowest CV was chosen for the study.

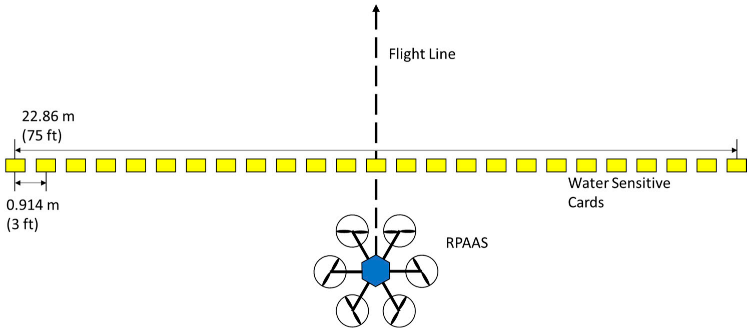

Figure 1. Layout of water sensitive cards and flight line during spray deposition measurements.

Spray droplet spectra measured were $D_{v0.5,}$ the percent area coverage, the number of drops per cm^2, and the application rate (L/ha). The $D_{v0.5}$ is the droplet diameter (µm) where 50% of the spray volume is contained in droplets smaller than this value. The $D_{v0.5}$ is commonly known as the volume median diameter (VMD). Proc Univariate analysis [15] was conducted to determine the normality of the data. A goodness-of-fit test (Anderson-Darling) determined data normality. The test for the location (μ_0 = 0) was conducted to determine if the mean values of the parameter estimates were different from zero. If significant, it means that the standard deviation is reasonably small for the *t*-distribution to not overlap 0.

2.3. Field Trials

A randomized plot design with two treatments and eight plots was established on rangeland habitat near Estancia, New Mexico, with each rectangular plot measuring approximately 4.05 ha (10 acres) (Figure 2). The two treatments consisted of: (1) an untreated control and (2) an insecticide, Sevin XLR PLUS (by NovaSource, the active ingredient is 44.1% carbaryl), sprayed at a total volumetric rate of 2.34 L/ha (32 fl. oz./acre: 1.17 L/ha (16 fl. oz./acre) of Sevin XLR PLUS diluted in 1.17 L/ha (16 fl. oz./acre of water)), which is the maximum program rate. Additionally, in accordance with the label, SEVIN XLR PLUS was applied using a 50% reduced agent and area treatment (RAAT) integrated pest management (IPM) strategy in which a swath of equal width to the preferred swath width (in this case, the effective swath width) is skipped to decrease costs and potential environmental impacts [16]. Due to their relatively small size, the 4.05-hectare (10-acre) plots treated with Sevin XLR PLUS were separated by 0.16 km (0.1 mile) extra spacing to minimize drift effects. Meteorological data were collected from a fixed weather station (Vantage Pro2, Davis Instruments, Hayward, CA, USA) at a height of 2 m located within 1.93 km (1.2 miles) of the plots. For field studies measuring deposition on target sites, meteorological data such as wind speed and wind direction should be collected in accordance with the ASAE S561.1 protocols. The meteorological data collected in this study were in conformity with ASAE protocols [17].

Two types of grasshopper population density estimation methods were performed using established protocols similar to previous studies [16,18,19] on the day before treatment (pre-count) and 3, 7, 10, and 14 days after treatment. Method one was visual estimation using 40 × 0.10 m^2 (0.12 yd^2) aluminum rings to estimate grasshoppers/m^2, with a slight modification in which the rings were set up in four stacked rows of 10 (all spaced 4.6 m (15.09 ft) apart) due to the small plot size. Method two consisted of high-fast (50) and low-slow (50) sweep netting performed around the perimeter of the ring site to determine grasshopper species composition (Table 1). Population density estimations for the untreated control plots were performed each time the treated plots were assessed.

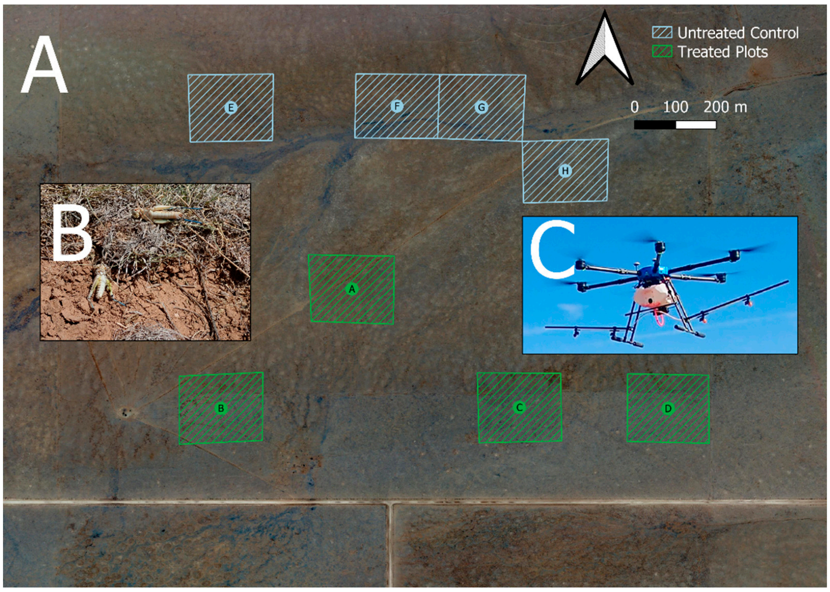

Figure 2. Experimental plots on rangeland habitat near Estancia, New Mexico. (**A**) Map of treatment plots. (**B**) Grasshoppers feeding in plot. (**C**) Precision Vision 35 RPAAS in flight.

Table 1. Species comparison of percent population composition (from sweep sampling) between treated and untreated plots before treatments began (pre-count) and overall percent life stage presence of the same versus day 14. The species shown that are not represented in the pre-count composition did appear in low numbers for one or both treatments sometime during the 14 days. White boxes correspond with 0%. Species are organized in alphabetical order by genus, then species name [20].

	Pre-Count % Population Composition from Sweeps (100% total per column)			
	Treated Plots		**Untreated Control Plots**	
Species	**Instars 1-5/6**	**Adults**	**Instars 1-5/6**	**Adults**
Acrolophitus hirtipes (Say, 1825)	0.0%	0.0%	0.0%	0.0%
Aeoloplides turnbulli (Thomas, 1872)	0.0%	0.0%	0.0%	0.0%
Ageneotettix deorum (Scudder, 1876)	9.5%	0.0%	6.6%	0.0%
Amphitornus coloradus (Thomas, 1873)	0.6%	0.0%	0.5%	0.0%
Aulocara elliotti (Thomas, 1870)	23.1%	31.0%	24.6%	59.3%
Aulocara femoratum Scudder, 1899	12.1%	0.0%	24.6%	0.0%
Cordillacris crenulata (Bruner, 1889)	39.3%	2.4%	22.3%	2.4%
Cordillacris occipitalis (Thomas, 1873)	0.3%	0.0%	0.0%	0.0%
Eritettix simplex (Scudder, 1869)	0.6%	8.3%	0.0%	5.7%
Hadrotettix trifasciatus (Say, 1825)	0.3%	0.0%	0.9%	0.0%
Heliaula rufa (Scudder, 1899)	1.2%	0.0%	1.9%	0.0%
Melanoplus occidentalis (Thomas, 1872)	3.8%	17.9%	9.0%	8.9%
Melanoplus packardii Scudder, 1878	0.0%	0.0%	0.0%	0.0%
Melanoplus regalis (Dodge, 1876)	0.3%	0.0%	0.5%	0.0%
Melanoplus sanguinipes (Fabricius, 1798)	0.0%	0.0%	0.5%	0.0%
Metator pardalinus (Saussure, 1884)	9.0%	0.0%	8.5%	0.0%
Psoloessa delicatula (Scudder, 1876)	0.0%	39.9%	0.0%	23.6%
Xanthippus corallipes (Haldeman, 1852)	0.0%	0.6%	0.0%	0.0%
	Pre-Count Overall % Life Stage Presence (100% total)			
	67.3%	**32.8%**	**62.2%**	**37.9%**
	Day 14 Overall % Life Stage Presence (100% Total)			
	6.3%	**93.8%**	**12.2%**	**87.8%**

Two types of results were reported using the visual estimation data: standard average percent population density reduction and the standard error of the mean (SEM), and normalized population reduction (P_R), which factors in population density reductions in both treated and untreated plots caused by the treatment and natural causes using the equation:

$$P_R = 1 - \frac{T_a C_b}{T_b C_a} \quad (1)$$

where T_a is the final total population density of the treated plots, T_b is the initial total of the treated plots, C_a is the final total of the untreated control plots, and C_b is the initial total of the untreated control plots [21]. SEM was also calculated for this value based on independent and random error propagation [22] using the equation:

$$\Delta P_R = \sqrt{\left[\frac{C_b}{T_b C_a}\Delta T_a\right]^2 + \left[\frac{T_a C_b}{T_b^2 C_a}\Delta T_b\right]^2 + \left[\frac{T_a C_b}{T_b C_a^2}\Delta C_a\right]^2 + \left[\frac{T_a}{T_b C_a}\Delta C_b\right]^2} \quad (2)$$

A repeated measures analysis of variance (ANOVA) was used to measure: (1) the significance of the treatment, (2) time after treatment, and (3) the interactions of these two variables. Statistical analyses were performed using R statistical packages [23].

3. Results

3.1. Spray Deposition Analysis

The effective swath width of the treatment was 12.19 m (40 ft) (Figure 3) with an average application rate of 2.75 L/ha (37.63 fl. oz./acre). Following a 50% RAAT IPM strategy, a 24.38 m (80 ft) swath was used for treatments, with an average treated swath application rate of 1.38 L/ha (18.82 fl. oz./acre). The RPAAS speed was increased to 9.83 m/s (22 mph). Table 2 shows the distribution statistics for the spray droplet spectra data. The $D_{v0.5}$ and the number of drops per cm^2 conformed to a normal distribution, while the application rate and percent area coverage showed significant deviation from normality. The test for location (μ_0 = 0) indicates that the standard deviation of the data is reasonably small for the t-distribution to not overlap 0.

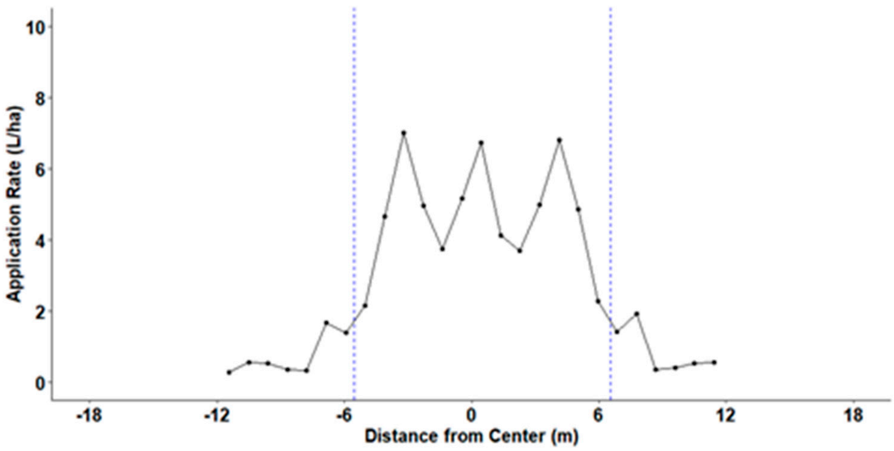

Figure 3. Application rate of tank mixture S across swath. Dashed blue lines indicate effective swath width.

Table 2. Distribution statistics of spray droplet spectra images captured on water-sensitive paper samplers deployed during swath width calibration.

Parameter Estimates	Mean ± SEM	Goodness-of-Fit Test (Anderson-Darling)	P > A-Sq	Location: $\mu_0 = 0$ t-Statistic
$D_{v0.5}$ (μm)	173.5 ± 8.33	0.507	0.19	20.81 *
droplet density (#/cm^2)	52.18 ± 4.01	0.602	0.11	13.00 *
application rate (L/ha)	2.75 ± 0.45	1.167	0.005 *	6.10 *
area coverage (%)	0.98 ± 0.14	1.10	0.01 *	6.77 *

* Indicates significance at $p < 0.05$.

3.2. Field Bioassay

Treatments with Sevin XLR PLUS were conducted on 5 June 2020. Meteorological data for all treatments are contained in Table 3.

Table 3. Average meteorological data collected during treatments.

Plot	Treatment	Wind Direction	Wind Velocity (m/s)	Temperature (°C)	Relative Humidity (%)
A	Sevin XLR PLUS	SE	1.10	21.0	32.4
B	Sevin XLR PLUS	SE	2.03	21.0	34.5
C	Sevin XLR PLUS	SSE	0.38	29.5	26.0
D	Sevin XLR PLUS	S	0.47	30.0	26.0

In terms of average percent population density reduction, the grasshopper populations were reduced by 84.78 ± 4.88% SEM (Figure 4) and 26.7 ± 6.62% SEM by day 14 in the treated and untreated plots, respectively. Normalized population reduction was 79.11 ± 8.35% SEM. Grasshopper populations in plots treated with Sevin XLR PLUS were significantly reduced by the first observation point on day three (Figures 2B and 4). Additional population reduction across time after treatment was observed (Figure 4) but was not significant (Table 4).

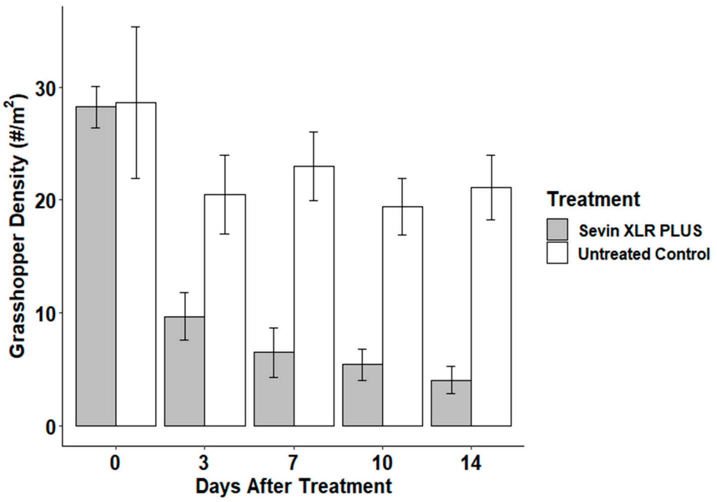

Figure 4. Effects of Sevin XLR PLUS treatment on grasshopper density and mean ± SEM across the trial period.

Table 4. Results of repeated measures analysis of variance (ANOVA) of treatment of grasshoppers with Sevin XLR PLUS. Grey shading indicates factor(s) with $p < 0.05$.

Source of Variation	df	Sum of Squares	Mean Square	F	$P > F$
treatment	1	660.8	660.8	13.693	0.001
time	3	24.9	8.3	0.172	0.914
treatment: time	3	16.4	5.5	0.113	0.952
residuals	24	1158.1	48.3		

4. Discussion

Our objective was to evaluate the efficacy of treating a grasshopper population with a liquid insecticide via an RPAAS and then informally compare the results with those of similar treatments made via fixed-wing aircraft based on our collective experience and knowledge. We would describe the observed efficacy as successful in the sense that grasshopper populations, when accounting for reduction in untreated control plots, were reduced by 79.11 ± 8.35% SEM. This is very close to what is typically expected for APHIS program treatments, which is 80 to 95% population reduction [19]. Our lower-end results can probably be attributed to the arid conditions, lower levels of rangeland forage observed during the study in that region of New Mexico, and a mobile, rapidly aging population (Table 1 and field observations).

Based on our results, our collective knowledge of how the APHIS program works, and our experience with the RPAAS during this study and previous experimentation, we think an RPAAS could potentially be used to treat population hotspots more rapidly, as well as enable more targeted applications of liquid insecticides, compared to fixed-wing aircraft. For example, grasshopper egg pods are often deposited in the soil of open rangeland areas, but also along margins. Soon after hatching, grasshopper nymphs tend to remain congregated in their hatching areas (population hotspots) for some time before dispersal to neighboring sites. Therefore, because RPAASs are relatively portable, the potential exists to shorten the average length of time between the identification of a hotspot and a treatment. Plus, our application time was relatively rapid, taking about five minutes of total flight time to treat each 4.05-hectare (10-acre) plot. Combined, such abilities could potentially be more cost-effective and enable more targeted applications than fixed-wing aircraft, thereby preserving more rangeland forage since a grasshopper's dispersal abilities are often correlated with age.

5. Conclusions

By the grasshopper population density reduction standards of the APHIS program, our results indicate that an RPAAS can be used effectively for this purpose. Despite this, more research is needed before stakeholders adopt the technology, specifically using plots of larger areas and incorporating insecticides containing the active ingredient diflubenzuron. The reasons for this are that the APHIS program often treats significantly larger areas annually (sometimes in the millions of hectares) and most often using diflubenzuron-based insecticides. Our current study had planned to use the latter, but the populations were aging more rapidly than expected (Table 1), hence the shift to Sevin XLR PLUS.

Author Contributions: Conceptualization, D.A.W., R.R. and D.E.M.; methodology, R.R., D.E.M., D.A.W., K.C.R. and L.R.B.; formal analysis, R.R., D.A.W., D.E.M. and M.A.L.; investigation, R.R., D.E.M., D.A.W., K.C.R., L.R.B., M.T. and K.M.L.C.; resources, D.A.W., R.R., D.E.M., K.C.R. and L.R.B.; writing—original draft preparation, D.A.W., R.R., D.E.M. and M.A.L.; writing—review and editing, R.R., D.E.M., M.A.L., D.A.W., K.C.R., L.R.B., M.T. and K.M.L.C.; visualization, D.A.W., R.R., D.E.M. and M.A.L.; supervision, D.A.W., R.R. and D.E.M.; project administration, D.A.W., R.R. and D.E.M.; funding acquisition, R.R. and D.A.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by an interagency agreement with USDA-APHIS-Plant Protection and Quarantine (PPQ): 20-8130-0893. It may not necessarily express APHIS's views.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are publicly available at the following repository zenodo.org/record/6473635 (DOI: 10.5821/zenodo.6473635).

Acknowledgments: We thank the following for contributing to this work: Bill and Lisa Gardner of Gardner Ranch for the rangeland to work on, Daryl Hill (USDA-APHIS-PPQ-Aircraft and Equipment Operations) for possessing the aerial insecticide applicator's permit and assisting with the experiments, Aaron Carlson (USDA-APHIS-PPQ-AEO) for assisting with the experiments, Waleska Ramirez, Shawn Carson, Melinda Sullivan, Bill Wesela, Kai Carraher, Jim Warren (USDA-APHIS-PPQ) for enabling the study, TC&F LLC for their timely assistance with acquiring Sevin XLR PLUS, the City of Moriarty, NM for providing us quality water, and Travis C. Hitchner (USDA-APHIS-PPQ-S&T-IMMDL (Phoenix Station)) for an early review of our manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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