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Quantifying off-highway vehicle impacts on density and survival of a threatened dune-endemic plant

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ABSTRACT

Off-highway vehicle (OHV) recreation impacts species and ecosystems around the world, and is particularly prevalent in the United States. Our study examines the impact of OHVs on one of several species restricted within the United States to the Algodones Dunes, California. This dune system attracts many OHV enthusiasts annually, and interest in determining the impact of OHVs on *Astragalus magdalenae* var. *peirsonii* (Peirson's milk-vetch) has motivated multiple investigations. Several of these investigations have arrived at seemingly contradictory conclusions. Our study objectives were to quantify the degree by which *A. m.* var. *peirsonii* densities differed between high- and low-OHV use areas and determine whether OHV impact was a plausible factor for affecting plant density. Density estimate comparisons indicated 4 to 5 times fewer plants occupied a study area open to OHVs relative to two nearby study areas legally closed to OHVs. A manipulative mark-resight experiment compared the survival probabilities of control plants to those purposefully struck by OHVs and found that, for plants with canopy diameters of < 50 cm, OHV impact reduced survival by 33%. Density estimates from one of the study areas recently closed to OHVs were surprisingly large, which may suggest that periodic closure of occupied habitat during favorably wet years would assist in ensuring *A. m.* var. *peirsonii* productivity and thereby persistence. An improved understanding of this phenomenon may indicate a dunes-wide management strategy that would allow OHV activity to coexist with *A. m.* var. *peirsonii*.

Key words: mark recapture; distance sampling; Astragalus magdalenae var. peirsonii; Peirson's milk-vetch; OHV; off-road vehicle

INTRODUCTION

Off-highway vehicle (OHV) activity impacts species and their environments in a variety of places around the world (Kutiel et al., 1999; Rickard et al., 1994; Moss and McPhee, 2006). The United States is currently experiencing rapid growth in OHV recreation. Off-highway vehicle (OVH) usage increased by 42% between 1999 and 2004 (51 million United States participants in 2004 [Cordell 2005]) while the amount of public land available for OHV recreation has decreased. California's usage exhibits a similar pattern, where OHV registration numbers have increased by 108% between 1985 and 2002 while the amount of desert available to OHV recreationists has diminished by 48% (California State Department of Parks and Recreation, 2002). The impact of these vehicles on ecologically sensitive areas has become an issue for several non-profit organizations (Cordell 2005); in particular, attention has been focused on the Algodones Dunes, the largest sand dune system in the United States, which supports several endemic species and attracts over 1.4 million OHV enthusiasts annually (BLM, 2003). Concern regarding the impacts of OHVs on 16 species considered endemic to this dune system resulted in a petition and lawsuit to list them under the Endangered Species Act (Center for Biological Diversity v. Norton et al., No. 05 CV 1988 BEN [BLM]). Currently only one species has received federal coverage: *Astragalus magdalenae* var. *peirsonii* (Peirson's milk-vetch).

A. m. var. *peirsonii*, listed federally as a threatened species (U. S. Fish and Wildlife Service [USFWS], 1998) under the Endangered Species Act of 1973 (ESA), is restricted within the United States to the Algodones Dunes, Imperial County, California. The USFWS identified the primary threat to the species as "…destruction of individuals and dune habitat from OHV use and the recreational development associated with it" (USFWS, 1998). Portions of the dunes have been closed to OHV activity since 2000 as the result of a lawsuit filed by the Sierra Club,

Center for Biological Diversity, and Public Employees for Environmental Responsibility (BLM, 2000a). These OHV closures likely will remain in place until this lawsuit is resolved among the environmental groups, OHV community, BLM, and USFWS. Since 1998 the USFWS has received two ESA petitions to "delist" or remove the species from the List of Threatened and Endangered Species (Hubbard et al., 2001; Hubbard, 2005). A 90-day finding and 12-month finding were published on the 2001 petition (USFWS, 2003 and 2004, respectively). A 90-day finding has been published on the 2005 petition (USFWS, 2005) and a status review has been initiated.

The delisting petitions claimed that human (i.e., OHV) activities do not pose a significant threat to *A. m.* var. *peirsonii* (Hubbard et al., 2001, Hubbard, 2005). Hubbard (2005) cited results from surveys performed by the BLM (Willoughby, 2005a, b), Phillips et al. (2001), and Phillips and Kennedy (2002, 2005) as support. Following previous years' efforts BLM surveyed *A. m.* var. *peirsonii* habitat in the springs of 2004 and 2005 in an effort to estimate the number of *A. m.* var. *peirsonii* within the dune system as well as the number of *A. m.* var. *peirsonii* exhibiting OHV damage. Only 0.3% of plants in 2004 (Willoughby, 2005a) and 0.44% of plants in 2005 (Willoughby, 2005b) exhibited apparent OHV damage. The spring 2005 dunes-wide BLM population estimate for *A. m.* var. *peirsonii* population was 1.8 million plants (Willoughby, 2005b). A separate survey effort (Phillips et al., 2001) reported little apparent difference in *A. m.* var. *peirsonii* density between management areas that were open or closed to OHV activity, though the survey of the closed area was conducted by helicopter while the open area was surveyed on the ground. Phillips and Kennedy (2002) found no relationship between OHV use levels and survival, and during the winter of 2004-2005 they tallied 77 922 plants in areas open to OHVs (Phillips and Kennedy, 2005). They stated that "OHVs may damage or kill some plants, but by far most mortality is the result of natural causes, usually inability to survive the

96 hot, dry summer season." These results, taken together, were interpreted by Phillips and
97 Kennedy to indicate that OHVs do not pose a serious threat to the species.
98 In contrast, other studies of dunes and arid habitats have found that OHVs alter plant
99 communities. Off-highway vehicles compact substrates (Iverson et al., 1981; Kutiel et al., 1999,
100 2000), alter plant species richness and diversity (Kutiel et al., 1999, 2000), and decrease
101 vegetation cover (Lathrop, 1983; Anders and Leatherman, 1987; Rickard et al., 1994). Previous
102 studies conducted in the Algodones Dunes reflect similar findings. Lukenbach and Bury (1983)
103 performed a paired plots study (n = 6 pairs) and reported substantial differences in vegetation
104 cover between open and closed areas. ECOS (1990) found differences in reproductive output
105 and the number of *A. m.* var. *peirsonii* individuals between open and closed areas. McGrann et
106 al. (2005) conducted a paired-plots study (n = 42 pairs) along the North Algodones Dunes
107 Wilderness (Wilderness) closure boundary and the boundaries of temporary closures (Bureau of
108 Land Management, 2000a; see Fig. 1 in McGrann et al., 2005) and found larger numbers of *A. m.*
109 var. *peirsonii* in the temporary closures and Wilderness than in the open areas. The level of
110 inference in these studies was limited to either the margins of open and closed areas or the study
111 plots themselves, as no probability-based sampling design was used. Also, population densities
112 across entire areas of interest were never estimated.
113 We designed a two-part study to help resolve the above controversy, as well as provide
114 management information. We first designed a descriptive study to test the assertion that OHVs
115 pose a threat to *A. m.* var *peirsonii* that allowed us to make inferences to defined portions of a
116 management area, an aspect lacking in other studies. We hypothesized that if OHVs posed a
117 threat to one or more of the life history phases of *A. m.* var. *peirsonii* or its habitat, we would
118 observe a reduction in *A. m.* var. *peirsonii* densities in areas open to OHV activity compared to

119 closed areas. We assessed seed pod numbers on a subset of plants to translate plant density into
120 reproductive output differences between study areas.
121 If vehicles damaged few plants, we would predict that our observational study would
122 detect no difference in plant density between OHV-open and OHV-closed areas. Previous
123 surveys reported low numbers of standing plants showing evidence of OHV impact during
124 limited survey periods (Phillips and Kennedy, 2003; Willoughby, 2005a, b) and Phillips and
125 Kennedy (2003) anecdotally reported that "seedlings pop back up after being run over." The
126 second aspect of the study assessed the direct impact of OHVs on *A. m.* var *peirsonii* through an
127 experimental manipulation. We hypothesized that survival probabilities were lower for plants
128 that were driven over compared to control plants. If plant densities differed between areas open
129 and closed to OHVs, and it was found that OHV impact affected the probability of plant survival,
130 OHV impact would serve as one mechanistic explanation for reduced *A. m.* var. *peirsonii* density
131 in OHV-open areas.
132 Our objectives were to quantify the degree by which *A. m.* var. *peirsonii* densities
133 differed between high- and low-OHV use areas and determine whether OHV impact was a
134 plausible mechanistic cause of observed differences in plant density.
135
136 METHODS
137 **Study Area and Species Information**
138 The Algodones Dunes system is 65 km by 5 - 10 km and extends northwest to southeast
139 from within Imperial County, California, to Baja California, México. The central portion of the
140 dune system is dominated by large transverse dunes reaching 90 m in height. The western edge
141 of the dunes is dominated by northwest-curving ridges of coalesced barchan dunes (Norris and
142 Norris, 1961). Winter temperatures are mild (averaging 23º C) while summers temperatures

often surpass 45º C (California Data Exchange Center [CDEC], 2005). Rainfall averages 6.4 cm/yr; however, 12.4 cm of rain fell from 1 October 2004 to 1 June 2005 at the Cahuilla Remote Area Weather Station located in the Gecko Management Area (CDEC, 2005; Willoughby, 2005a, Fig. 1). This quantity of rain probably led to a dunes-wide abundance of *A. m.* var. *peirsonii* resulting in high counts during that year (Willoughby, 2005b).

Astragalus m. var. *peirsonii* require from 3 to 9 months of post-germination growth before flowering (Phillips and Kennedy, 2005; Porter, 2005). Although this species is perennial, both seedling and adult plants may experience high annual mortality (Phillips and Kennedy, 2003; Porter, 2005). For instance, seedlings germinating in February 2004 failed to produce seed pods or survive through the summer (Porter, 2005; Willoughby, 2005a). Once pods mature and desiccate they separate easily from the parent plant and are available for wind dispersal (JDG, pers. obs.). Each pod may contain up to 16 seeds (Barneby, 1964).

This *Astragalus* is primarily found in the western half of the dune system (Willoughby, 2005a) in "bowls at the bottom of southeast-facing slipfaces and on the gentle NW-facing slopes that run SE from the bowls" (cited in BLM, 2003; also see Phillips et al., 2001; Phillips and Kennedy, 2002, 2003). These vegetated portions of dune are the areas that generally support *A. m.* var. *peirsonii* and its associated psammophytic scrub biota.

Study Site Selection

The dunes are divided into eight resource Management Areas (BLM, 2003). *Astragalus m.* var. *peirsonii* occur at varying densities in seven of the eight Management Areas. We conducted our study in the Gecko Management Area (GMA; 8,590 ha, Fig. 1), a Management Area that supported the third highest density of *A. m.* var. *peirsonii* in the Dunes in 2004 and the fourth highest density in 2005 (Willoughby, 2005a, b, respectively). Many off-road enthusiasts visit the GMA annually. Of the eight Management Areas the BLM has designated only the

GMA and one other Management Area as "intensive" use in their multiple-use classification (BLM, 2003). Campsites in the GMA are situated along Gecko Road, which extends several kilometers along the western edge of the dunes (Fig. 1). We selected the Gecko Management Area as the location for our study based on logistics, its moderate-to-high densities of *A. m.* var. *peirsonii*, and its designation as an intensive use area.

The three study areas (A, B, and C) were delineated within portions of the GMA (Fig. 1). Each study area was 229 ha in size. We conducted the descriptive portion of the study in all three areas and the manipulative experiment in area C. Areas A and C were located within disjunct OHV closures, though before 2000 these areas had been open to and used by OHV recreationists. Area B, continuously open to and used by OHV recreationists, lies between study areas A and C. Closures established in 2000 are marked with carsonite posts placed approximately every 75 m along the closure boundaries. The boundaries were permeable to OHVs and we observed some OHV usage within these closures.

Our study areas are in close geographic proximity and physiographically similar. Study area positions and sizes were determined by closure locations and OHV usage pattern data (1998 BLM aerial overflight transects; see Map 24 in BLM, 2000b). Study areas B and C were placed along the 1998 overflight transects; study area B lay within an area with high track density while area C had few tracks recorded. We extended the eastern border of B to the point where there was an observed decline in the number of vehicle tracks according to the overflight transects. Based on field observations, we initially assumed that areas A and C received at least 75% less vehicular impact than area B. To verify this assumption we quantified vehicular track density in the three study areas by performing a GIS analysis of digital aerial photographs taken of our study areas April 2005.

We limited our sampling to the northwest-facing slopes of dune bowls. We define a dune "bowl" as the area encompassed by the slipface of a coalesced barchan dune and the associated windward dune slope. To randomly select dune bowls in which to conduct plant sampling, we placed parallel GIS-derived "navigation transects" at 200 m intervals (with random initial transect placement, Fig. 2) perpendicular to dune faces within each study area. We subdivided these navigation transects into 700m (± 100m) segments. Segments along the same navigation transect were equal in length. Study areas each contained 6 to 7 navigation transects of 15 to 16 segments in total. We sampled segments in a random order within each study area. To select dune bowls, we navigated to selected segments using GPS units, and traveled along the segment until we reached a suitable dune bowl within 100 m of the segment (Fig. 3). Suitable bowls were those with a northwesterly slope distance of at least 50 m from the bottom of the bowl and had a vertical rise of at least 2 m. Once a bowl was sampled for plants, observers traveled 200 m further along the navigation transect before searching for the next bowl or until reaching the end of the navigational transect. We sampled 58 dune bowls along 27 segments.

Field work occurred from 28 February to 2 June 2005. Daily high temperatures in March and April ranged from 21 - 32º C and from 27- 43º C in May. Cumulative rainfall totaled 11.5 cm between 1 October 2004 and the start of our study. An additional 0.9 cm fell during our study period (CDEC, 2005).

Plant Density Estimation:

The area of inference for our density estimation was the northwest-facing slope of dune bowls. We expected total numbers of plants to increase with distance from the bottom of the dune bowl due to the increase in area of the northwestern face. Therefore, we sampled from the base of the dune upwards to sample parallel to the direction of this gradient (Buckland et al., 2001). We used a 135 º orientation of sampling transects to standardize our sampling method

214 across all dune bowls. Our goal was to reduce the variance of samples within study areas to
215 allow comparison between study areas. As a consequence, our inference may be limited if the
216 milk-vetch sampled along the 135º transect did not provide a representative sample of the milk-
217 vetch within a dune bowl. We examined this potential bias by performing two line transects
218 within a subset of dune bowls (n = 17): one at 135º and the other at a random angle between 90º
219 and 180º. We randomized the order in which each transect type was performed. We estimated
220 densities for each subset of data, pooled across dune bowls.

221 At each dune bowl, one observer remained at the bottom and recorded a start point of the
222 sample line transect using a Trimble GeoXT Global Positioning System (GPS) unit (Trimble
223 Navigation Limited, Sunnyvale, California, USA). The second observer scaled the northwest-
224 facing dune slope at an angle of 135º up to 100 m from the first observer, or to the lip of the dune
225 bowl, whichever was encountered first. The lip was defined as the location at which an observer
226 at the top of the bowl disappeared from the view of the observer at the base of the bowl. The
227 first observer marked the second observer's position using an Impulse 200 laser rangefinder with
228 a MapStar digital compass module (Laser Technology Inc., Centennial, Colorado, USA). The
229 GPS recorded the second observer's location as a GPS position offset. The second observer
230 walked in a straight line back to the first observer, creating the line transect with their footprints
231 in the sand. The two observers then performed distance sampling along the line transect. One
232 observer searched for *A. m.* var. *peirsonii* and used the rangefinder to determine the distance of
233 the plant(s) from the line transect. The second observer recorded the information into the GPS
234 unit's data dictionary and ensured that all plants within 3 m of the transect line were detected
235 (i.e., the probability of detection along the line [$g(0)$] = 1).

236 We recorded the position, size class, and the size of each *A. m.* var. *peirsonii* cluster
237 observed. Plant size classes were based on the apparent reproductive differences between size

classes: Plants with canopy widths ≥ 50 cm (large plants) appeared to bear a disproportionately greater number of seed pods than plants with canopy widths <50 cm (small plants). We examined the validity of this distinction during the course of the survival experiment (described below). Plants were sampled as clusters, or loose aggregations of individuals, which varied from one to 112 individuals. The laser rangefinder and GPS unit were used to record the location of each plant or cluster's center point as defined by the observer. Observers determined cluster size by counting individual plants and using the rangefinder's telescopic eyepiece (up to 4× magnification) as needed.

Survival Experiment

We conducted an experiment to quantify OHV impact on the survival of individual *A. m.* var. *peirsonii* plants. We selected plants from every second dune bowl sampled in Area C. Two dune bowls were excluded for treatment because our vehicles could not be safely operated within them. After performing distance sampling within a dune bowl, we selected a subset of recorded plants for inclusion in the experiment using a systematic random sample based on the sequence of plant-cluster detection. The randomized selection included up to 16 small (<50 cm width) and 8 large (> 50 cm width) plants in each bowl. No more than half of the plants within a size class in a bowl were selected as treatment (impacted) plants. Impact levels were randomly assigned to selected plants. Half of the selected plants of each size class served as controls. A quarter were selected to receive one vehicular pass (plant directly struck by two vehicle wheels), and the remaining quarter received 3 passes.

Plants were marked with 2 10-cm translucent plastic zip-ties. We placed one tie around a branch in the upper foliage and the other around the stem/root juncture. Each tie was marked with one, two, or three black spots to aide individual plant identification during revisits. The ties were used as markers because they are lightweight, unlikely to draw the attention of people to

the plant, and durable. We recorded the number of permanent ink marks placed on an individual's plastic tags. We temporarily flagged treatment and control plants to inform the field crew member operating the OHV of the treatment level of target plants at a distance and the location of control plants.

Treatments occurred when individuals were first detected and marked, between 1 March and 22 March 2005. Plants were struck with either a Honda Foreman or Honda Ranger four-wheel drive utility quad. Vehicular speed at impact varied from 8 to 25 kph. The vehicles weighed between 240 and 250 kg and had all-terrain tires inflated between 0.4 and 0.8 kg/cm^2. The observer not performing treatments ensured that plants were struck by a front and back tire. All treatment and control plants were revisited 24-25 March (between 2 and 25 days post-treatment), 20-22 April, and again 31 May – 2 June 2005.

Prior to treatment all plants were measured, size classes assigned, and numbers of immature green-colored seed pods tallied. We avoided counting desiccated pods as they were more likely than green pods to have been counted at a previous revisit, and we did not determine individual plant seed pod numbers outside of Area C. Seed pod numbers were assessed to verify the reproductive difference between our two plant size classes as well as to predict the difference in seed pod production between our three study areas. We report the number of green seed pods on control plants during subsequent revisits to assess the reproductive output for large and small plants. This procedure potentially produced an index of reproductive output instead of a true count of seed pod production, as individual green or desiccated pods may have remained on plants for time periods greater or less than one month, in which case individual pods would have either been missed or counted during more than one revisit. We excluded plants that received an OHV treatment, died during the study, or were not found during any rechecking period from the seed-pod analysis.

Data Analysis

We estimated the density of small and large *A. m.* var. *peirsonii* along the northwest-facing slopes of dune bowls using program Distance 5.0 (Thomas et al., 2005). We assumed that: 1) all plants on the transect line were detected with certainty; 2) plants were detected at their initial location; 3) measurements were exact; and 4) detections were statistically independent. The two size classes were analyzed separately. For each size class, we examined the fit (compared Akaike's Information Criterion values with small sample size adjustment [AIC_c]; Hurvich and Tsai [1989]) of initial detection functions to data from all distances, and used the "best" function to determine the detection distance beyond which data were truncated (Buckland et al., 2001). Initial curve fits were used for determining truncation distances, after which the truncated data were used to estimate plant densities. We compared the fit of the key functions and expansion terms suggested on page 47 of Buckland et al. (2001) and which appear in Table 1.

Six detection curves were fit according to the stratification of two size classes and three study areas. Detection curves were allowed to rise and fall to fit the data (i.e., weakly monotonically non-increasing). We determined whether the same detection function utilized across study areas was adequate to describe the distance data, or if separate detection functions were needed per study area by comparing AIC_c values of model fits. We compared the density estimates between strata within each size class by using the variance and approximate degrees of freedom provided by program Distance to calculate an approximate *t*-statistic ($\alpha = 0.05$, Buckland et al., 2001). The significance level of α was adjusted according to a stepwise Bonferroni procedure (Holm, 1979). We used the same analysis technique to compare large and small plant densities between fixed and random-angle transects.

For the mark-resight experiment analysis, we used Cormack-Jolly Seber (CJS; Lebreton et al., 1992) models in Program MARK (Version 4.2; White and Burnham, 1999) to estimate detection and monthly survival probabilities and to examine the effects of treatment and other covariates on survival probability. Plants that were not found or found dead were coded as zeros. Apparent survival probability (ϕ_i) was defined as the probability that a plant alive at time i survived until time $i + 1$. Detection probability (p_i) was defined as the probability that a plant alive at time i was encountered at sampling period i. The assumptions for CJS methods (Pollock et al., 1990; Williams et al., 2002) are: 1) every marked organism present in the population at sampling period i has the same probability p_i of being recaptured or resighted; 2) every marked organism present in the population immediately following the sampling in period i has the same probability of survival until sampling period i+1; 3) marks are neither lost nor overlooked, and are recorded correctly; 4) sampling periods are instantaneous and recaptured organisms are released immediately; 5) all emigration from the sampled area is permanent; and 6) the fate of each organism with respect to capture and survival probability is independent of the fate of any other marked organism.

There were four groups of interest based on plant size category and treatment status: large treatment, large control, small treatment, and small control. Due to field logistic constraints, we were failed to mark sufficient numbers of treatment plants to provide separate estimates for both treatment levels (one or three OHV passes). We therefore analyzed the two levels as a single treatment level.

We developed a candidate set of thirteen a priori models to examine the importance of the treatment on both the apparent survival probability (ϕ) and the probability of detection (p) based on our experience and the literature. Survival was modeled as varying by time (ϕ_t) and

size (ϕ_s). Most observed plant mortality in the dunes occurs during the summer months (Willoughby, 2005a) and maximum daily temperatures during our study period were highest in May. Porter (2005) found that although adult plants (> 1 yr) exhibited high levels of annual mortality, mortality was much higher for seedlings (< 1 yr). Porter additionally found that adult plants possess longer taproots than seedlings. Therefore we modeled survival probability as varying by plant size as well as time. To understand how survival probability was affected by OHV treatment (ϕ_{trt}), we modeled survival as dependent on size and time alone (ϕ_{s+t}), size and time with treatment ($\phi_{s+t+trt}$), size and the interaction of treatment with time ($\phi_{s+t*trt}$), and time and the interaction of treatment and size ($\phi_{t+s*trt}$). We included these final two survival expressions with interaction terms to account for the possibilities that treatment effects may not manifest until post-treatment time periods and that the treatment may have impacted large plants to a different degree than small plants. We do not present results for a model with full survival covariate interactions ($\phi_{t*s*trt}$) due to estimation convergence failures.

We suspected that the probability of detection would be constant across plants ($p.$) or vary by plant size (p_s) or treatment (p_{trt}). A constant detection probability would result from either $p = 1$ or all plants being equally likely to be detected under all conditions. However, sand accumulation may have decreased the probability of detection. Small plants would be more likely buried than large plants, and treatment plants (occasionally flattened against the substrate or reduced in mass by the vehicle) may have been more likely to have been buried than control plants. We assumed that the probability of detection was constant across time. We used AIC_c values to compare competing models.

The delta method (Cooch and White, 2005) was used to calculate the variance around the cumulative survival probability values (survival over the length of the study) for each size and

355 treatment category using model-average survival values and associated covariance matrices.
356 This procedure allowed us to examine the cumulative impact of the treatment on survival of *A.*
357 *m.* var. *peirsonii* for large and small plants.
358
359 RESULTS
360 **Density**
361 We detected 2,901 (2,653 small and 248 large) *A. m.* var. *peirsonii* individuals and
362 clusters totaling 6,751 small plants and 268 large plants. We met all four distance sampling
363 assumptions in this study. One crew member guarded the line against missed detections.
364 Because our species of interest was a plant, we avoided issues of target movement. The GPS
365 equipment used was precise enough that we could return to individual plants post-distance
366 sampling for use in the mark-resight portion of the study. We believe that cluster sampling
367 detections were statistically independent as we used "cluster" as the object of inference, we
368 utilized a size-biased regression method in cluster size estimation, and we estimated variance
369 empirically (Buckland et al., 2001).
370 The maximum distance plants were detected from the line was 107 m and 102 m for
371 small and large plants respectively. We truncated detection distances to 35 m for small plants
372 and 40 m for large plants. With these truncation distances, 2,125 small plant clusters and 195
373 large plant clusters were used in our analyses.
374 Detection functions were independently generated for each stratum (six strata: two size
375 classes and three study areas; Fig. 4). Within each size class we determined whether detection
376 functions varied among study areas or performed well pooled across the study areas (Buckland et
377 al. 2001). We found that detection functions for small plants varied by strata ($AIC_{c\ \text{strata}} = 14$

409.84 < $AIC_{c\ \text{pooled}}$ = 14 415.65) while detection function for large plants performed well pooled across strata ($AIC_{c\ \text{strata}}$ = 1350.72 > $AIC_{c\ \text{pooled}}$ = 1347.84; Table 1).

The Kolmogorov-Smirnov and Cramer-von Mises family tests indicated no lack of fit for detection curves for data from either size class or any study area (lowest $P = 0.12$). We estimated small plant density in study area A by using the hazard-rate + cosine model (Table 1). The decision was arbitrary as the hazard-rate + simple polynomial model performed almost as well ($\Delta AIC_c = 0.16$) and produced a density estimate that differed by < 1% from the selected model and had an identical coefficient of variance (CV). The half-normal + cosine model was used for small plants in areas B and C. For large plants we used the half-normal + cosine model for density estimation, although the half-normal + hermite polynomial model produced an identical detection curve.

Density estimates of detections were adjusted according to estimated expected cluster sizes. We used a cluster size-biased regression method within each study area to estimate the expected cluster size at $g(0)$ when regression equations were significant ($P < 0.15$); otherwise, we used the average cluster size of all detections to estimate the expected cluster size. A relatively large P-value threshold was used to minimize type II error, the failure to adjust the expected cluster size by a real but statistically non-significant bias. The ln(cluster size) was regressed against the detection function ($\hat{g}(x)$). Regression corrections were necessary for small plants in areas A and B only (Table 2).

The density of small and large *A. m.* var. *peirsonii* along northwestern-facing slopes of dune bowls was 4 to 5 times greater in areas A and C than in B (Table 3). The differences are statistically significant between areas A and B as well as areas B and C for both size classes. For small plants, areas A and C did not differ ($df_{approx} = 61.12$, $t = 0.470$, $P = 0.3273$) while areas A and B ($df_{approx} = 47.41$, $t = 4.092$, $P < 0.0001$) and areas C and B ($df_{approx} = 29.90$, $t = 3.223$, $P <$

0.0016) did. For large plants, areas A and C did not differ (df_{approx} = 36.54, t = 0.368, P = 0.3574) while areas A and B (df_{approx} = 32.90, t = 2.359, P = 0.0123) and areas C and B (df_{approx} = 27.59, t = 2.054, P = 0.0247) did. The ratio of large to small plant density was similar for each area: Area A = 0.031, B = 0.038, and C = 0.042. Vehicle track density, as analyzed from digital aerial photographs, indicated that OHV tracks were 10 times more prevalent in study area B than in either study areas A or C.

Transect Bias Exploration:

The density estimate comparison between the 135º and random transects required that we process the distance data in a similar manner as for the strata comparisons performed above. Data were pooled according to transect bearing type (135º vs. random). We truncated distance data for large and small plants by 35 and 40 m respectively, and detection functions were generated independently for transects of each bearing type. Detection functions did not vary between bearing type strata for each size class but differed by size class. The same set of detection functions were examined for these strata as listed in Table 1.

The Kolmogorov-Smirnov and Cramer-von Mises family tests indicated no lack of fit for detection curves for data from either size class or any study area (lowest P = 0.14). We used a hazard-rate + cosine model for small plants and a half-normal + cosine model for large plants. Model selection for both size classes indicated that alternate models performed similarly to those selected (hazard-rate + simple polynomial model for small plants and uniform + cosine model for large plants), with differences no greater than 4% and 3 % in density estimates or CVs, respectively. Additionally, for large plants the half-normal hermite polynomial model performed identically to the half-normal + cosine model.

A marginally significant difference in density was found between 135º vs. random transects for small plants (n = 17, t = 1.474, df_{approx} = 52, P = 0.0738), while no significant

426 difference was found for large plants (n = 17, t = 0.0901, df_{approx} = 22, P = 0.1863; Fig. 5). The
427 ratio of densities for 135º transects to random transects was 1.6:1 for small and 1.7:1 for large
428 plants.

429 **Survival**

430 During March 2005 we individually marked 147 *A. m.* var. *peirsonii* individuals in nine
431 dune bowls (plant categories: 56 small treatment, 57 small control, 15 large treatment, 19 large
432 control). We removed two additional plants (one large treatment and one small treatment) from
433 the analysis, because they were mistaken as dead and later confirmed to be living.

434 We assessed the first two CJS assumptions by performing goodness-of-fit tests using
435 TEST2 and TEST3 of program RELEASE (Burnham et al., 1987) within Program MARK and
436 detected no significant departures of the data from the assumptions of the CJS model (TEST2 +
437 TEST3 X^2 = 0.7231, P = 0.6966). Therefore we did not adjust for data over-dispersion.
438 However, our sparse data may have limited the ability of the program to detect assumption
439 violations. We are confident that individual plants were not overlooked due to tag loss
440 (assumption 3). At each plant resighting we recorded the distance (error) the GPS unit claimed
441 we were from the target; of the 484 resightings, the average error was 0.60 m (95% CI ± 0.04
442 m). We met the fourth assumption of instantaneous sampling because the plants were resighted
443 every month over a period of 2-3 days. The fifth assumption was met imperfectly because sand
444 accumulation could remove a plant (temporary emigration) from the study area. Therefore the
445 nuisance parameter *(p)* was modeled according to factors hypothesized to influence missed
446 detections (treatment level and plant size class). The final assumption, independence of
447 individual detection and fate, was met for detection. We navigated to individually marked plants
448 using a GPS unit, and plant tags were difficult to detect until we were close to target plants. Our
449 plant selection method (random systematic sampling of plant locations recorded during the

450 distance sampling effort) was designed to meet the assumptions for plant fate as well, because
451 we selected non-neighboring plants. This limited exposure to similar microclimate influences
452 and placed treatment and control plants at equal risk of being struck by OHVs that failed to stay
453 outside of the closure boundaries.

454 We knew the fates of 75 control plants over all time periods. We were unable to find one
455 control plant during its final revisit. Therefore, for all models including p_{trt}, we fixed p for
456 control plants to 1 and estimated p only for treatment plants. Detection modeled as varying by
457 treatment and size (p_{trt+s}) or size alone (p_s) did not perform as well (less parsimonious) as
458 models varying by treatment (p_{trt}). The model-averaged estimate of p for small treatment plants
459 was 0.971 (SE = 0.018) and for large treatment plants 0.965 (SE = 0.025).

460 The "best" model ($\phi_{t+s+trt} p_{trt}$; $\Delta AIC_c = 0.000$, $\omega = 0.373$) performed similarly ($\Delta AIC_c <$
461 2) to models in which modeled survival probability included interaction terms between treatment
462 and time ($\phi_{s+t*trt} p_{trt}$; $\Delta AIC_c = 1.603$, $\omega = 0.167$) or treatment and plant size ($\phi_{t+s*trt} p_{trt}$; ΔAIC_c
463 $= 1.716$, $\omega = 0.158$; Table 4). These models were also reasonably close to a model in which p
464 was modeled as varying by plant size and treatment ($\phi_{t+s+trt} p_{trt+s}$; $\Delta AIC_c = 1.912$, $\omega = 0.142$).

465 Survival probability was mostly affected by treatment, as there was no support for models
466 lacking a treatment component. The top model had more than 100 times the support than those
467 that did not include treatment ($\phi_{t+s} p_{trt}$; $\Delta AIC_c = 10.141$, $\omega = 0.002$). Models incorporating a
468 treatment effect on survival had overwhelming cumulative support ($\omega_{cumulative} = 0.997$).

469 Model-averaged estimates of survival were lower for treatment plants than control plants
470 (Fig. 6). Plant survival appears to have been relatively constant between March and April but
471 declined during the final time period (May). The cumulative survival from March through May
472 was lower for large and small treatment plants than control plants, although the 95% confidence

intervals overlapped for large plants (Fig. 7). Large and small treatment plants experienced an estimated 16% and 33% respective reduction in survival relative to the control plants.

Reproductive Potential

Large control plants produced on average 251.4 seed pods per plant (SE = 36.80, n = 19), while small plants produced on average 20.8 seed pods per plant (SE = 4.28, n = 59). Large plants bore 75.6% of the pods noted on the plant over the duration of the study in March, but only 2.1% in May. Small plants had a small proportion (2.6%) of their seed pods present in March, while most appeared in April (71.4%). Ninety-four percent of large control plants and 46% of small control plants produced seed pods between March and 1 June.

DISCUSSION

Our evidence suggests that OHV activities were associated with the observed four- to five-fold difference in *A. m.* var. *peirsonii* density between the OHV-open and -closed study areas. The proportional difference in density of *A. m.* var. *peirsonii* in the OHV-open vs. -closed study areas is similar between plant size classes. The aerial overflight results verified our assumption that our study areas within the closures received less OHV use than our OHV-open study area. The experimental results further indicate that direct OHV impact decreases the survival probability of *A. m.* var. *peirsonii*, which mechanistically provides at least a partial explanation for the differences in density estimates between study areas open and closed to OHVs. We cannot estimate the magnitude by which *A. m.* var. *peirsonii* is being depressed dunes-wide in areas open to OHVs, as our results may not be extrapolated beyond the dune bowls in the three study areas (Yoccoz et al., 2001). However, within the limits of our study areas, the results of this study indicate that OHVs substantially impact *A. m.* var. *peirsonii.*

496 The magnitude of the difference in plant density between our OHV-open study area
497 compared to the two OHV-closed study areas suggests that fewer *A. m.* var. *peirsonii* seed pods
498 were produced in the open study area. Assuming seed pod production per plant was similar for
499 all three study areas (seed pod numbers were counted only in area C), plants in study area B
500 would have produced roughly 1/5 the number of pods as those in study areas A or C. An
501 accurate assessment of the impact of OHVs on regional *A. m.* var. *peirsonii* reproductive output
502 would require similar comparisons to be made over the extent of the species' range.
503 The delisting petitions contend that monitoring studies demonstrate *A. m.* var. *peirsonii* to
504 be "abundant and thriving," and at least as abundant in areas open to OHV activity as closed
505 (Hubbard et al., 2001; Hubbard, 2005). The BLM springtime population estimates in 2004 and
506 2005 were 286 374 (95% CI = 141 800 to 430 974) and 1 831 076 (95% CI = 1 688 259 to 1 973
507 893) standing plants, respectively (Willoughby, 2005a, b). Willoughby (2005a, b) reported that
508 plant density estimates were similar in management areas open and closed to OHVs.
509 We are concerned that previous estimates do not provide sufficient information to assess
510 the status of this species. Virtually all standing plants that germinated in February 2004 failed to
511 reproduce before succumbing to the summer conditions of the dunes (Porter, 2005; Willoughby,
512 2005a). Our results suggest that OHVs may be responsible for some degree of population
513 depression within the dunes. Knowledge of OHV effects on *A. m.* var. *peirsonii* reproductive
514 output and seed-bank dynamics dunes-wide is likely needed to assess species status, which
515 standing-plant estimates do not provide when interpreted in the absence of other information.
516 Large plant abundance likely influences the quantity of seeds produced dunes-wide. The
517 BLM recorded *A. m.* var. *peirsonii* in age categories ($<$ or $\geq$ 1 yr) based on the examination of
518 basal leaf or branch scars (BLM, 2003). We did not use BLM's age categorization because it
519 was impractical to check plants for basal leaf and branch scars during distance sampling, basal

520 scars were not always detectable in large plants with relatively thick and woody basal stems, and
521 plant size was related to reproductive output in another dune endemic milk-vetch species,
522 *Astragalus lentiginosus* var. *micans* (Pavlik and Barbour, 1988). Our categorization likely
523 approximates the one made by BLM, although it is probable that some *A. m.* var. *peirsonii*,
524 which germinated in fall 2004, achieved our large size class criterion by March 2005. The
525 approximation appears supported as we estimated large plants comprising between 3 and 4% of
526 the plant densities in each of the three areas sampled, close to the 2.25% estimated by
527 Willoughby (2005b) for the entire Gecko Management Area.
528 If our assumptions were valid that individual seed pods mature within a month and that
529 seed pod production by size class did not vary substantially between study areas, large plants on
530 average produced 12× the number of seed pods as small plants, and would have accounted for
531 roughly 31% of seed pod production in our three study areas in 2005. This level of seed pod
532 production suggests that large plants are important contributors to the seed bank. Of the 286 374
533 plants estimated to occur in the dunes in 2004, approximately only 16 324 (5.7%) flowered, of
534 which 9,775 were > 1 yr (Willoughby, 2005a). If the reproductive output ratio between large
535 and small plants remained constant between years and throughout the dunes, 95% of the
536 reproductive output would have come from the large (>1 yr) plants. In 2005 when many plants
537 reached a flowering stage, > 1 yr old plants comprised only 1.6% of the estimated 1.37 million
538 flowering plants, yet may have contributed roughly 20% of all seed pods. In addition, our data
539 indicate that large and small plants produce seed pods at different times, with the small plants
540 reproducing later in the spring when temperatures may be less conducive for seed production.
541 More information on the conditions necessary to promote recruitment of large plants and
542 reproduction of small (< 1 yr) plants is needed to determine the long-term contributions of each
543 size class to the seed bank. Although an overall reduction in large plant numbers would not

greatly affect the apparent population size, it would likely disproportionately affect the dunes-wide quantity of seeds produced.

Differences exist between our descriptive study results and the results of other investigations, which found low percentages of *A. m.* var. *peirsonii* plants with OHV damage (Willoughby, 2005a, b; Phillips and Kennedy, 2003). An explanation for this discrepancy is that BLM, Phillips, and Kennedy were examining damage to standing plants, whereas arguably our density estimates reflect collective OHV impacts on abiotic conditions and life history phases. Off-highway vehicles may have affected soil compaction (Kutiel et al., 1999, 2000), decreased soil moisture (Kutiel et al., 1999), or directly impacted seed germination and germinant survival. Seeds and plants impacted by OHVs may not have been available for sampling at the time of BLM's 2004 and 2005 surveys.

Our mark-resight results suggest that OHV impacts reduce small plant survival. Survival of treatment plants was estimated to be lower over all time intervals than for control plants, suggesting that the effects of treatment persisted beyond the single treatment event. Our estimates may represent a low level of impact, as plants in certain areas may be exposed on average to more vehicle strikes than we subjected treatment individuals to. Survival for small treatment plants was cumulatively reduced by 33% over the 3-month period relative to small control plants. Off-highway vehicles may therefore cause short- and long-term damage to *A. m.* var. *peirsonii* following impact. The survival of large plants was not as greatly affected by OHV impact, and the ratios of large to small plants in all three study areas were similar. These two findings suggest that the low density of large plants in the open areas is a consequence of fewer small plants being available for recruitment to the larger size class rather than a direct reduction in large-plant densities by OHVs.

Previous efforts to estimate *A. m.* var. *peirsonii* population parameters via random sampling techniques (WESTEC, 1977; BLM, 2000b, 2001; Willoughby, 2005a, 2005b, 2005c) were not designed to clarify management-related issues, such as quantifying the impact of OHV activity on *A. m.* var. *peirsonii* distribution or density. Studies that examined the indirect impact of OHVs on *A. m.* var. *peirsonii* without estimating population parameters such as Lukenbach and Bury (1983), ECOS (1990), and McGrann et al. (2005) limited their investigations to the margins of open and closed areas. Other studies attempted to obtain meaningful population estimates in the absence of spatial sampling methodology. Phillips et al. (2001) and Phillips and Kennedy (2002, 2003) state that "statistical sampling methods were not included" in their investigations of *A. m.* var. *peirsonii* population size and visible OHV damage, limiting their inference to the sites at which they collected data. Our descriptive study was the first to employ a sampling framework designed to simultaneously derive population estimates for specified areas and address management questions about the direct impact of OHVs on *A. m.* var. *peirsonii*, as well as correct our count data by a probability of detection (Lancia, 1994; Yoccoz, 2001; Pollock et al., 2002). However, results from our descriptive study indicate improvements that would benefit our line transect sampling protocol.

We utilized fixed 135º transects for density estimation to minimize sample variance between transects. The density estimates for random angles were lower than for 135º angles for both plant size classes, and the *P*-value for small plant density estimate comparison approached statistical significance ($P = 0.074$). Our failure to detect a density estimation bias may therefore represent a Type II error. It is likely that plants were not evenly distributed between 90º and 180º. There may have been a gradient of plants that was greatest along the 135º angle. Although this bias does not affect the inference of a difference in plant density between study areas, such a gradient would lead to a high-biased estimate of plant density within the bowl. A randomization

591 of line transects start and end points within bowls would avoid the risk of producing biased
592 estimates within the dune bowls. Alternatively, the area of inference could be expanded from
593 dune bowls to the entire study area if transects were substantially longer and randomly
594 distributed, similar to the efforts of Willoughby (2005a, b, c).

595 **Monitoring and Management**

596 Long-term OHV impacts in the Algodones dunes may result in depressed *A. m.* var.
597 *peirsonii* seed production through the ongoing removal of standing plants and suppression of
598 seedlings recruitment to the 1+ year age class. The dunes have been a popular destination for
599 off-road enthusiasts for over half a century (WESTEC, 1977). We were pleased to find that plant
600 density in study area A was greater than in study area B and similar to study area C, even though
601 study area A is located within 1 km of campgrounds along Gecko Road and has only been
602 closed to OHVs since 2000. If these data indicate a true rebounding of the population in study
603 area A, either little seed depletion occurred before 2000 or the large germination event in 2001
604 (Phillips et al., 2001) enabled the newly-protected reproducing plants to replenish the seed bank.
605 The markedly above-average rainfall winter 2004-2005 likely enabled another generation to
606 contribute sizably to the seed bank within this closure. Unfortunately the degree by which plant
607 densities have changed within study area A since 2000 is unknown. The study area A closure
608 encircles a region in which a previous report (BLM, 2000b) found high abundance class values
609 of *A. m.* var. *peirsonii* density in 1998. Although we find it counter-intuitive to imagine that *A.*
610 *m.* var. *peirsonii* density in an area so close to an OHV staging area has remained constant
611 following the implementation of the year 2000 closures, no hard data exists to demonstrate
612 otherwise. A future lifting of the closures may offer the opportunity to determine the degree by
613 which the closures enhance *A. m.* var. *peirsonii* density and therefore inform managers of closure
614 efficacy.

Robust population estimates of *A. m.* var. *peirsonii* were first obtained in 2004 and 2005 when the BLM sampled the entire dunes with hundreds of 25m-wide belt transects, each many kilometers in length, as described in BLM (2003). Transects were several kilometers in length to ensure that each transect passes through sufficient numbers of *A. m.* var. *peirsonii* aggregations to minimize between-transect variance (Elzinga et al., 1998; BLM, 2003). The BLM may be able to improve monitoring efficiency (i.e., lower the effort required to obtain target confidence intervals) by replacing belt transects with line transects. Shorter or fewer transects would be necessary to estimate plant densities within target confidence intervals during low-density years when fewer plants are likely to fall within belt transects. We would suggest for years of high plant density that distance-sampling observers only search for small plants within 20 m or less of the transect line, as such a restriction would have improved the efficiency of our own data collection efforts. If line transects improved sampling efficiency relative to belt transects, the BLM may be able to stratify their survey effort by regional OHV use patterns or landscape morphology to investigate management-related issues while still obtaining population estimates.

Conclusions

Our results indicated that OHVs were a probable cause of *A. m.* var. *peirsonii* density depression in study area B. Our mark-resight experiment verified that vehicles are capable of decreasing *A. m.* var. *peirsonii* survival through direct impact. However, we do not know whether direct vehicular impacts on standing plants or indirect vehicular-related effects (e.g., loss of soil moisture, vehicular-related changes in dune morphology) are responsible for the low *A. m.* var. *peirsonii* density in area B. Neither the extent of seed bank depletion in areas of continual OHV activity nor the size of the seed bank is known. A shift in monitoring priorities from strictly standing-plant population estimates towards understanding seed-bank dynamics and

638 plant life history (through tracking individuals over time) would more rapidly increase our
639 knowledge of the status of this species.
640
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Table 1. Detection curve performance by *A. m.* var. *peirsonii* size class and study area in the Algodones Dunes, California, 2005. Small plant data required the use of a separate detection function for each study area. A single detection function adequately fit large plant data across all three study areas. Models used in analyses are indicated by $\Delta AIC_c = 0$. Where ties occurred, we used the half-normal key term with cosine expansion. The number of parameters used in a model is indicated by k.

		Small Plants						Large Plants	
Detection Curve		Area A		Area B		Area C		Areas Pooled	
Key Term	Expansion Term	ΔAIC_c	k	ΔAIC_c	k	ΔAIC_c	k	ΔAIC_c	k
uniform	cosine	13.91	5	5.09	1	26.67	2	1.53	3
uniform	simple polynomial	31.60	5	6.53	2	26.10	2	6.32	6
half-normal	cosine	6.61	5	0.00	4	0.00	5	0.00	3
half-normal	hermite polynomial	49.19	1	6.64	1	35.13	1	0.00	3
hazard rate	cosine	0.00	3	2.64	3	32.92	2	4.70	6
hazard rate	simple polynomial	0.16	6	2.99	2	15.40	6	4.70	6

Table 2. Expected cluster size estimated based on a regression of the natural log of cluster size on the detection probability *g* (x). Linear regression components are presented for density estimations and plant size class. An asterix indicates that the regression equation was used to determine the mean performed by study area and cluster size ($p < 0.15$). Otherwise, an average of cluster size regardless of distance from the transect line was used to determine mean cluster size.

Study area	Correlation	Slope	Intercept	Df	*P*	Mean cluster size	SE
Small plants							
Area A	-0.129	-0.334	0.504	851	0.0001	2.072 *	0.125
Area B	-0.084	-0.225	0.515	284	0.0772	2.140 *	0.188
Area C	0.001	0.002	0.357	984	0.5094	2.258	0.170
Large plants							
Area A	0.054	0.026	0.008	73	0.6763	1.040	0.228
Area B	No clusters reported						
Area C	-0.009	-0.010	0.112	93	0.4649	1.179	0.560

Table 3. Density estimates for large and small *A. m.* var *peirsonii* for three study areas within the Algodones dunes. The number of observations within a stratum is *n* ; ESW is the effective strip width of line transects, in meters. The reported ratio is a comparison of the density of plants between study areas (e.g., A:C, B:A, C:B).

Study area	Transects	*n*	Density	SE	Lower CI	Upper CI	*df*	ESW	Ratio
Small plants									
A	17	853	460.86	86.517	316.43	671.21	40.50	10.85	Area A to C = 1.1:1
B	21	286	91.61	25.677	52.15	160.93	27.86	14.63	Area B to A = 1:5.0
C	20	986	403.2	94.658	250.84	648.11	27.78	15.91	Area C to B = 4.4:1
Large plants									
A	17	75	14.33	3.969	8.13	25.255	20.28	21.58	Area A to C = 1:1.2
B	21	25	3.49	2.312	1.00	12.185	22.13	19.77	Area B to A = 1:4.1
C	20	95	17.03	6.174	8.21	35.323	21.63	18.95	Area C to B = 4.9:1

Table 4. Rankings of *A. m.* var. *peirsonii* Cormack-Jolly-Seber models[a] using Akaike's Information Criterion with sample size correction (AIC_c) to examine factors affecting survival and detection[b,c] of *A. m.* var. *peirsonii* and detection[b,c] in a manipulative experiment in Algodones Dunes, California (March - June 2005).

Model	AIC_c	ΔAIC_c	ω	Likelihood	k	Deviance
$\phi_{t+s+trt} p_{trt}$	265.891	0.000	0.373	1.000	6	14.641
$\phi_{s+t*trt} p_{trt}$	267.494	1.603	0.167	0.449	8	12.094
$\phi_{t+s*trt} p_{trt}$	267.606	1.716	0.158	0.424	7	14.287
$\phi_{t+s+trt} p_{trt+s}$	267.821	1.931	0.142	0.381	7	14.502
$\phi_{t+s*trt} p_{trt+s}$	269.334	3.444	0.067	0.179	9	11.844
$\phi_{s+t*trt} p_{trt+s}$	269.431	3.541	0.064	0.170	8	14.032
$\phi_{t+s+trt} p_{s}$	272.321	6.431	0.015	0.040	7	19.002
$\phi_{t+s+trt} p_{s}$	274.364	8.474	0.005	0.015	8	18.965
$\phi_{s+t*trt} p_{s}$	274.673	8.783	0.005	0.012	9	17.184
$\phi_{t+s} p_{trt}$	276.031	10.141	0.002	0.006	5	26.841
$\phi_{t+s} p_{trt+s}$	277.729	11.838	0.001	0.003	6	26.479
$\phi_{t+s} p_{s}$	285.411	19.521	0.000	0.000	6	34.162
$\phi_{.} p_{.}$	287.978	22.087	0.000	0.000	2	44.907

[a] t = time, s = plant size (small or large), trt = treatment, c = control,

[b] Survival and detection were modeled as constant (.) or as a function of time (survival only), plant size, or treatment effect. The ΔAIC_c values are the differences in AIC_c values standardized to the model with the lowest AIC_c. The AIC weights (ω) are the Akaike weights associated with each model and a measure of the relative explanatory ability of each model. The model likelihood (ω_i / ω_{best}), number of parameters (k), and deviance (difference in -2log[Likelihood] of the current model and -2log[Likelihood] of the saturated model) is given for each model.

[c] For models in which the probability of detection varied by treatment (p_{trt}), values were only estimated for plants that received OHV treatment (see text). The probabilty of detection for control plants was fixed to 1.

Fig. 1. Location of study sites A, B, and C in the Gecko Management Area portion of the Algodones Dunes, Imperial County, California. Study areas A and C were located within areas temporarily closed to OHVs (BLM 2000a) while study area B was in an area open to OHV activity and near the Roadrunner Campground, a popular OHV staging area at the south end of Gecko Road. Local rainfall information was obtained from the Remote Area Weather Station located at the BLM Cahuilla Ranger Station.

Fig. 2. Navigation transects within the three study areas, used for dune bowl selection. These transects were systematically placed 200 m apart with random initial transect placement. Navigation transects were oriented perpendicular to local dune bowl slip-faces.

Fig. 3. Navigation transects were broken into segments, whose start and endpoints from study area A are shown here. We traveled along randomly-selected navigation transect segments using 4-wheel drive utility quads. We sampled *A. m.* var. *peirsonii* within the dune bowls within 100m from either side of a selected navigation transect segment.

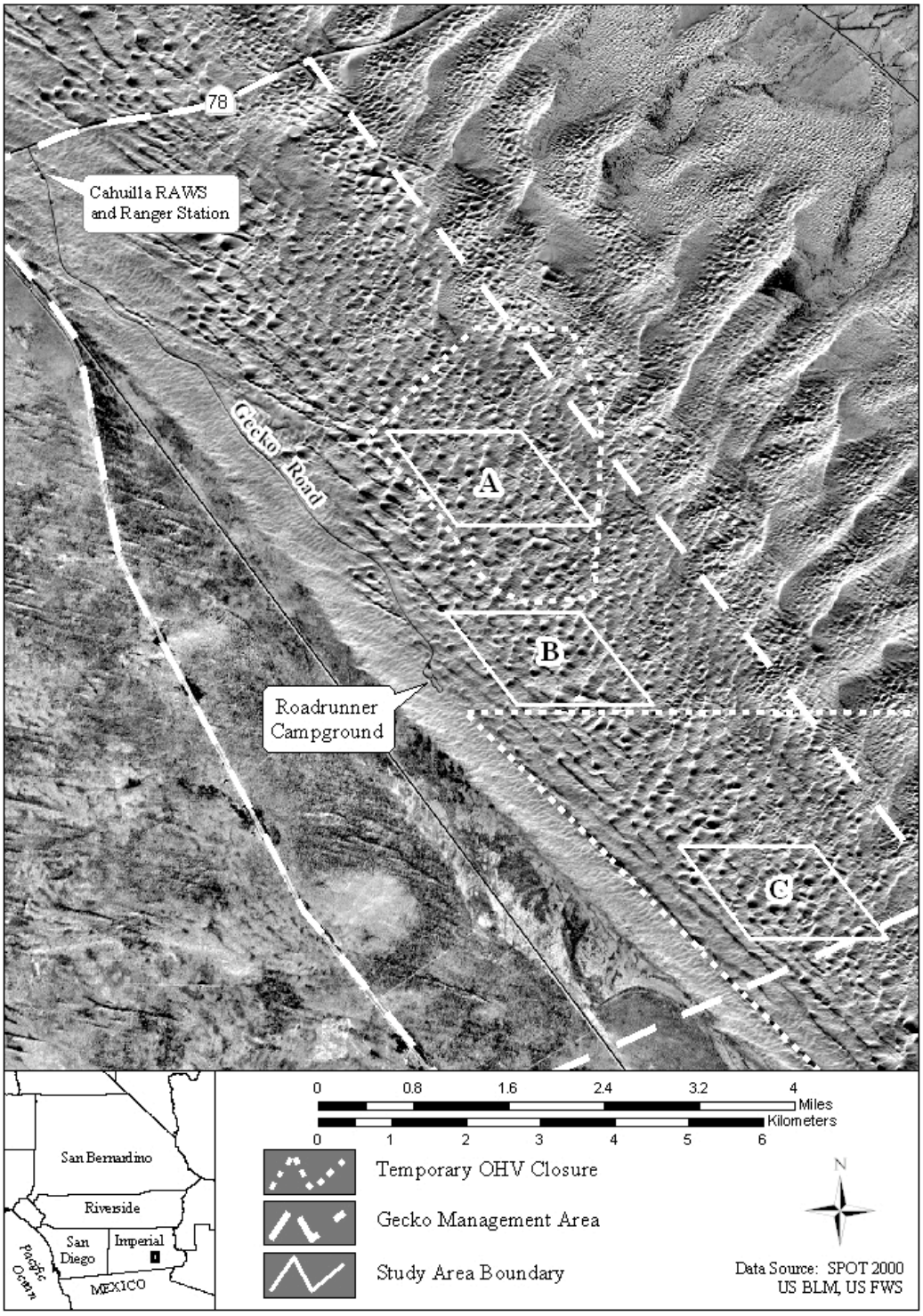
Fig. 4. Detection function ($\hat{g}$[x]) fits for *A. m.* var. *peirsonii* distance sampling data, presented for large and small plants in study areas A, B, and C. The detection function for each category depicts the probability of detecting a plant given its distance from the transect line. The same detection function models (curves) were fit to each data subset (histograms) presented; the "best" (minimum AIC_c value) key function and expansion term are stated for each category. Detection functions were used to calculate plant density (Table 3).

Fig. 5. A comparison of density estimates with 95% CIs for large and small *A. m.* var. *peirsonii*

taken along sampling transects oriented along 135º or random (between 90º and 180º) bearings from the bottom of 17 dune bowls. No significant difference in density was found between the two bearing types.

Fig. 6. Model-averaged survival probability (ϕ) estimates with associated 95% CIs for treatment and control (dashed and solid lines, respectively) *A. m.* var. *perisonii*. Treatment plants were purposefully struck one or three times by an OHV; control plants were not. Plants were selected and treatment plants impacted during March, the first recheck of plants occurred at the end of March. One hundred and eleven small plants and 36 large plants, each approximately evenly divided into control and treatment groups, were included in the experiment.

Fig. 7. Cumulative survival probability (ϕ) values with associated 95% CIs for each *A. m.* var. *peirsonii* size and treatment category. Values were calculated using the delta method (Cooch and White 2005) to examine model-averaged survival values and associated covariance matrix. There was no overlap of the 95% CIs for small treatment and control plants.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Cahuilla RAWS
and Ranger Station
Gecko Road
A
B
C
Roadrunner
Campground
San Bernardino
Riverside
San
Diego
Imperial
MEXICO
Pacific
Ocean
0 0.8 1.6 2.4 3.2 4
Miles
0 1 2 3 4 5 6
Kilometers
Temporary OHV Closure
Gecko Management Area
Study Area Boundary
N
Data Source: SPOT 2000
US BLM, US FWS

Figure 1

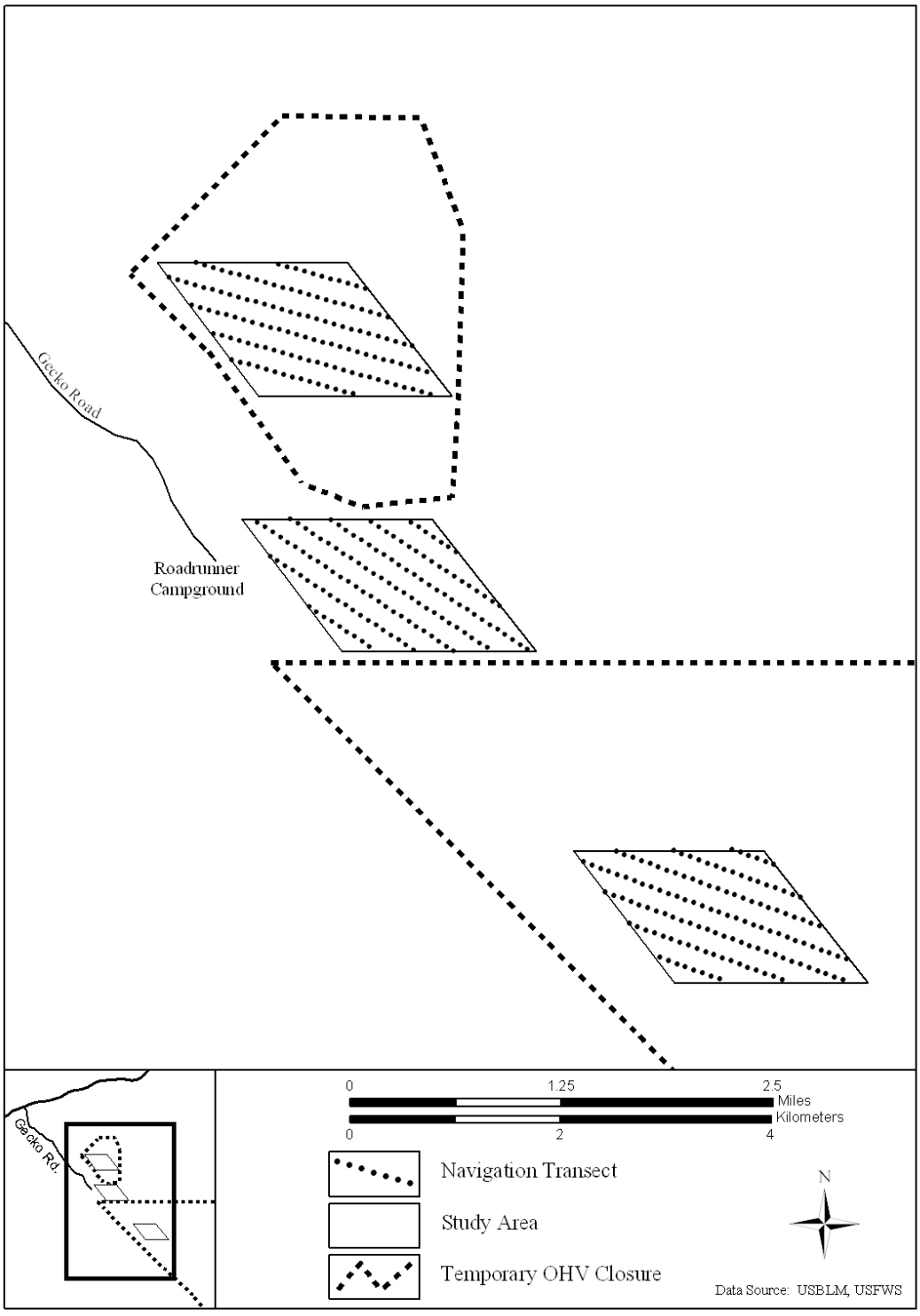
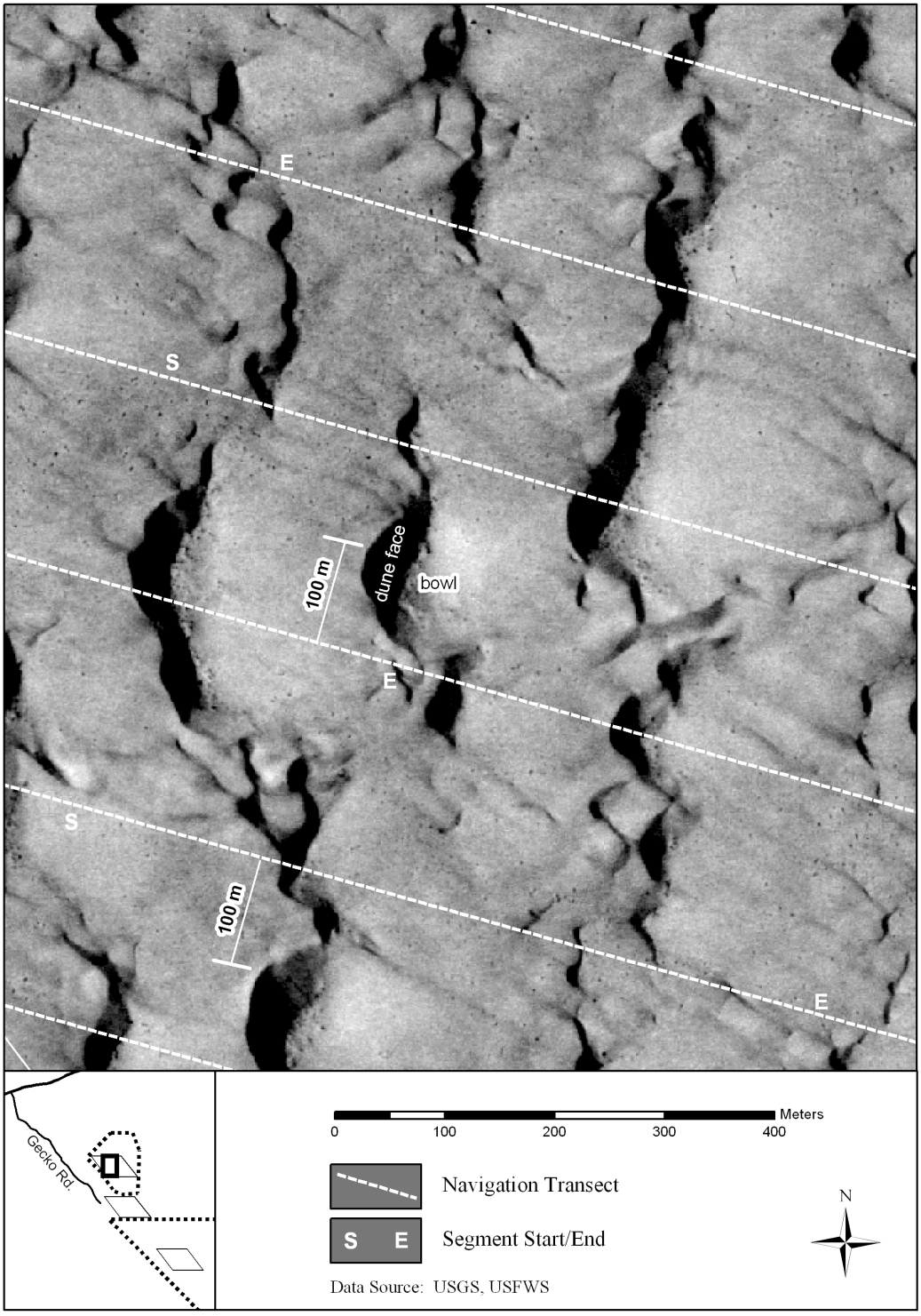

Gecko Road
Roadrunner
Campground
Gecko Rd.
0
1.25
2.5
Miles
Kilometers
0
2
4
Navigation Transect
Study Area
Temporary OHV Closure
N
Data Source: USBLM, USFWS

Figure 2


E
S
dune face
bowl
100 m
E
S
100 m
E
Gecko Rd
Meters
0
100
200
300
400
Navigation Transect
S E
Segment Start/End
Data Source: USGS, USFWS
N

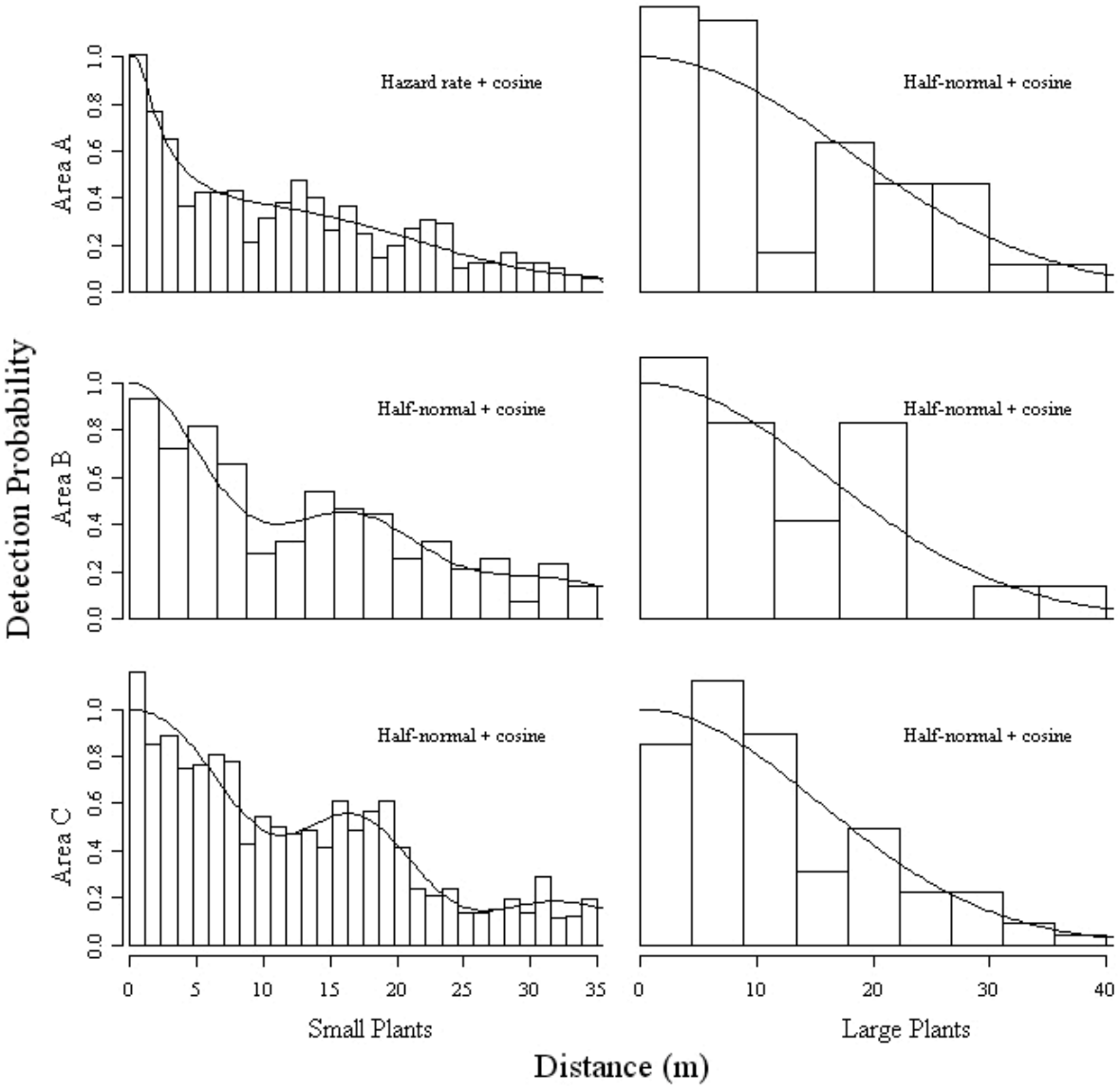

Detection Probability
Area A
Area B
Area C
Hazard rate + cosine
Half-normal + cosine
Half-normal + cosine
Half-normal + cosine
Half-normal + cosine
Half-normal + cosine
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
25
30
35
0
10
20
30
40
Small Plants
Large Plants
Distance (m)

Figure 4

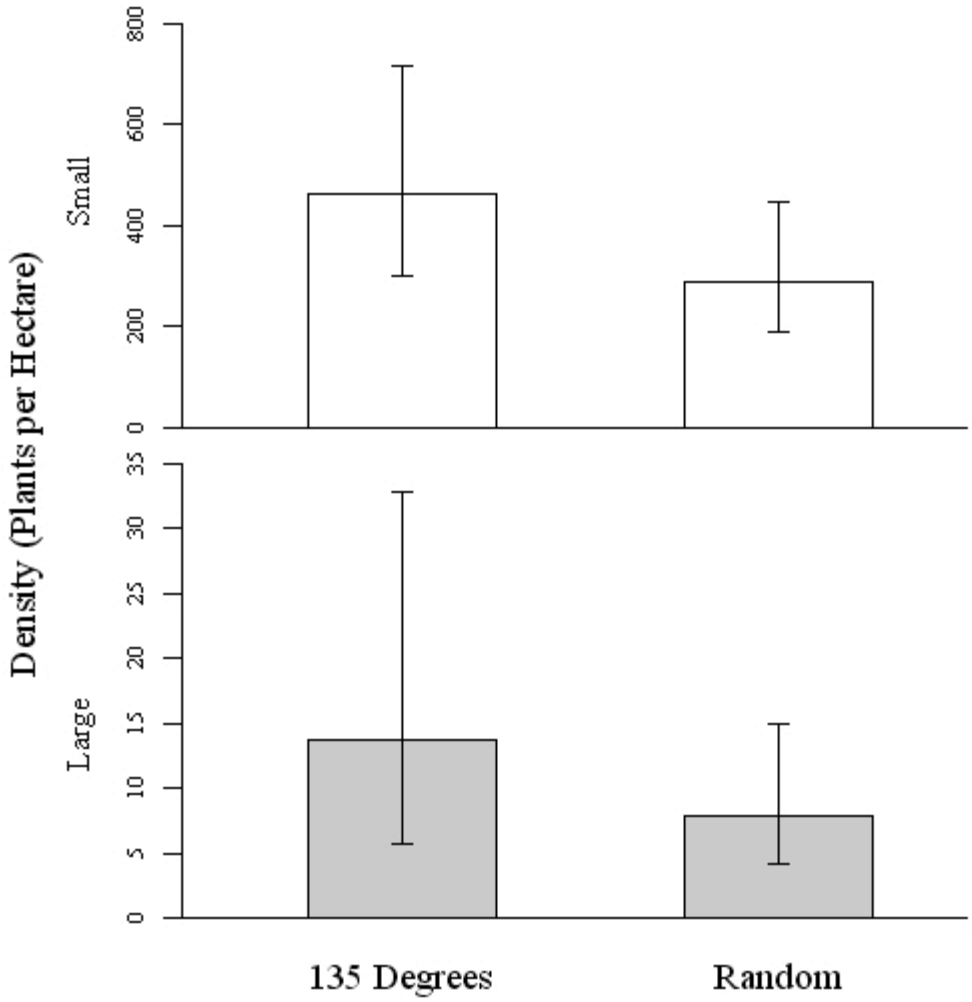

Density (Plants per Hectare)
Small
0
200
400
600
800
Large
0
5
10
15
20
25
30
35
135 Degrees
Random

Figure 5

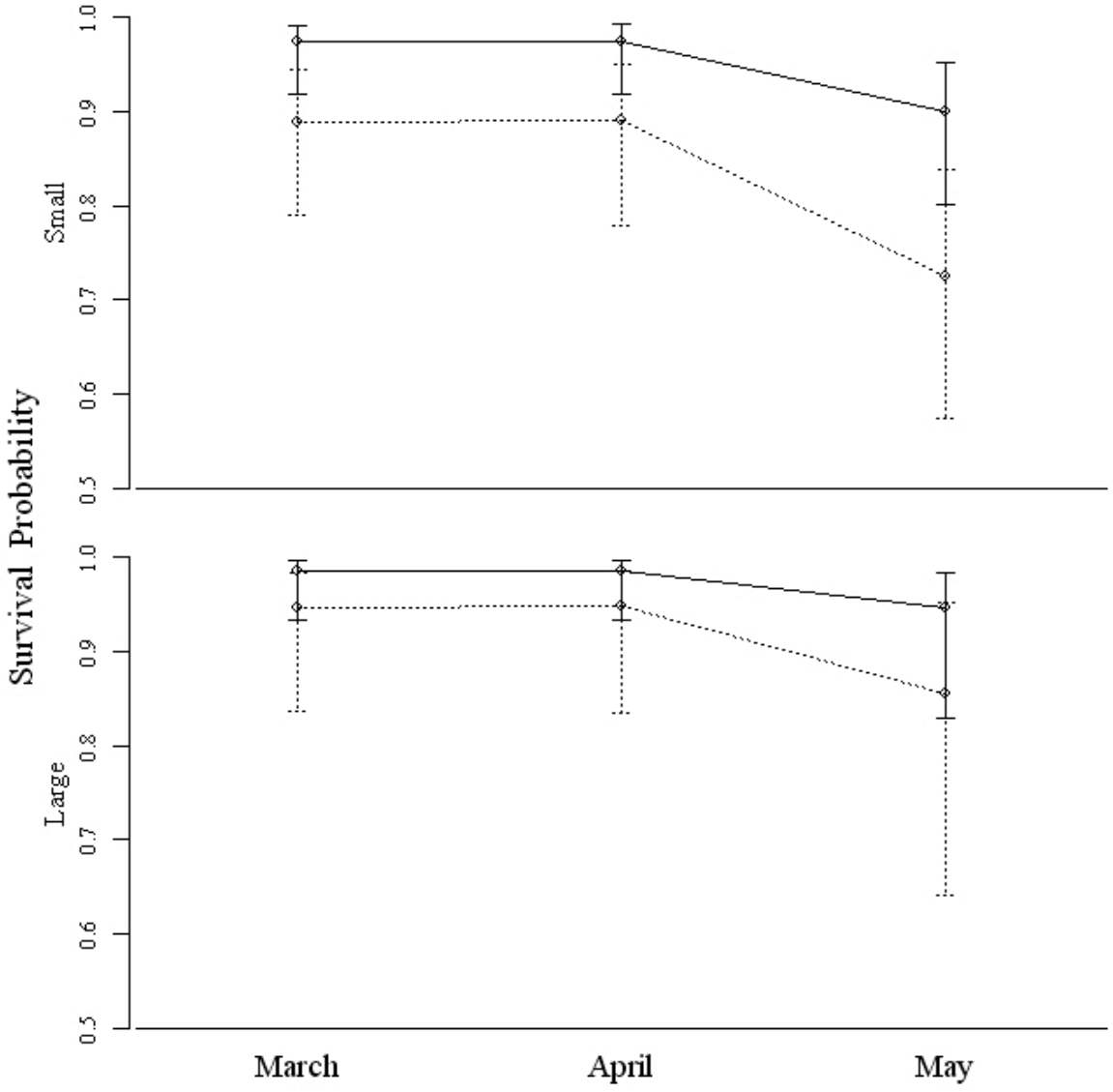

Survival Probability
Small
Large
1.0
0.9
0.8
0.7
0.6
0.5
March
April
May

Figure 6

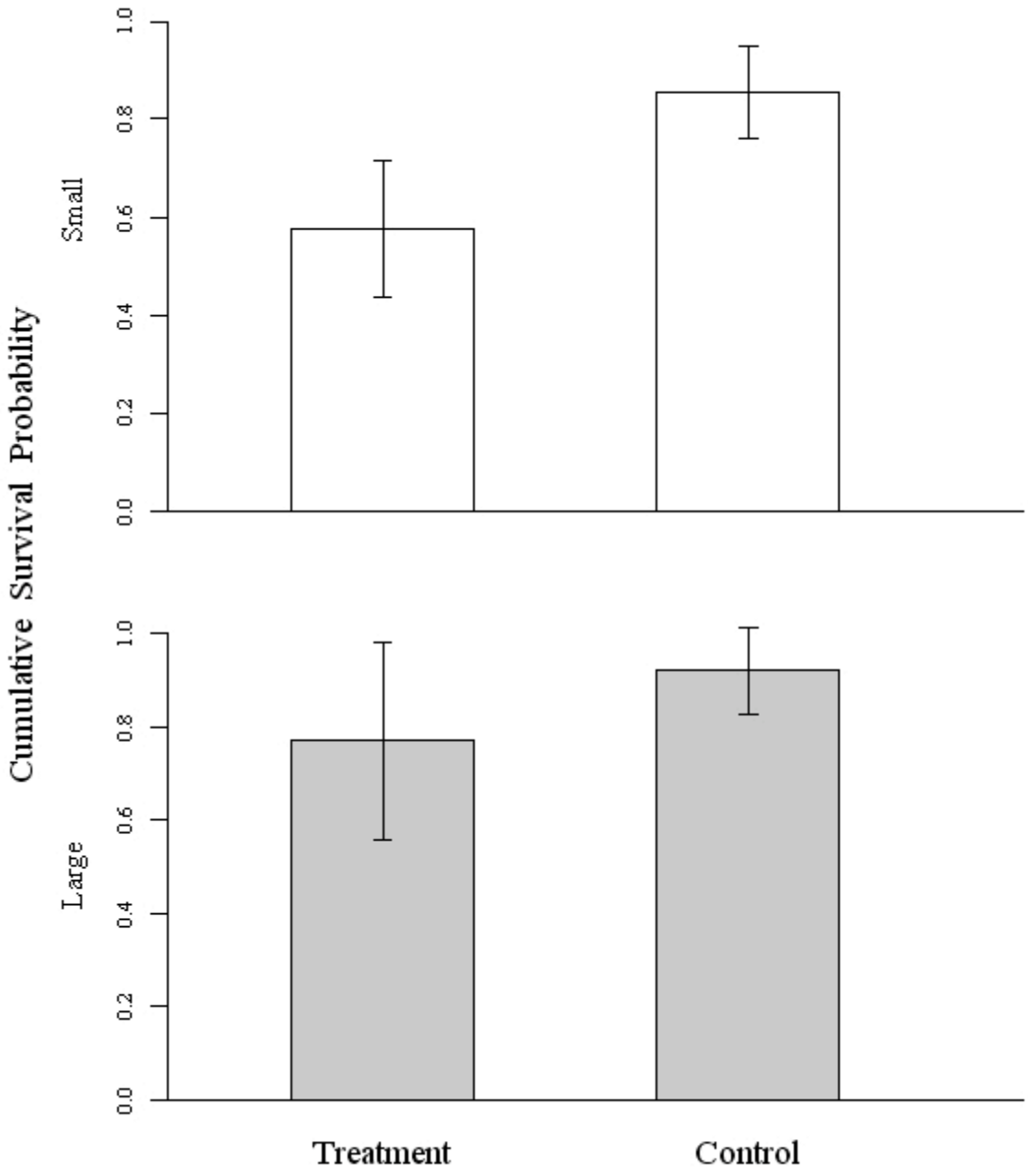

Cumulative Survival Probability
Small
Large
0.0
0.2
0.4
0.6
0.8
1.0
Treatment
Control

Figure 7