2020-04-20

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Sclerocactus wrightiae (Cactaceae): An Evaluation of the Impacts Associated with Cattle Grazing and the Use of Remote Sensing to Assess Cactus Detectability

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A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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ABSTRACT

Sclerocactus wrightiae (Cactaceae): An Evaluation of the Impacts Associated with Cattle Grazing and the Use of Remote Sensing to Assess Cactus Detectability

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The Wright fishhook cactus (*Sclerocactus wrightiae* L.D. Benson) is an endangered cactus species endemic to south-central Utah. Since its listing in 1979 by the U.S. Fish and Wildlife Service, the potential impacts of soil disturbance by cattle have become a central focus of management policies and monitoring efforts. However, little to no empirical data has been collected to substantiate the hypothesis that soil disturbance by cattle has direct or indirect negative effects on Wright fishhook cactus growth or reproduction. Over the years, the Bureau of Land Mangement (BLM) and Capitol Reef National Park (CRNP) have invested significant resources documenting cactus populations including several attributes of individual cacti: GPS location, diameter, number of flowers, fruits, or buds, number of stems, and the presence or absence of a cow track within 15 cm of the cactus. While these efforts have been commendable, due to the defining phenological characteristics of this species (flower and filament color) and its short flowering period (April-May) it remains difficult to study and much basic biological information including a range wide population estimate and defined critical habitat remain unknown. Our research had two primary objectives, 1) evalutate the effects of soil disturbance by cattle on reproduction and diameter of the Wright fishhook cactus (Chapters 1 and 2), and 2) explore the use of drones and GIS to define critical habitat and obtain an accurate range wide population estimate (Chapters 3 and 4). In Chapter 1, we analyzed cactus attribute data collected by the BLM at 30 macro-plots representing different levels of soil related cattle disturbance (high, moderate, and low) from 2011-2017. We found no significant association between level of cattle disturbance and flower density or cactus diameter. We did find a significant negative association between flower frequency and increased disturbance. In Chapter 2, we conducted an experimental study where tracks were simulated within 15 cm of cacti at various levels (Ctrl, 1-Track, 2-Track, 4-Tracks, and 4-Tracks Doubled). No significant association was observed between the number of tracks and response in diameter, flower production, fruit production, or seed set. In Chapter 3, we conducted drone flights over 14 macro-plots at three different altitudes above ground level (10 m, 15 m, and 20 m) and found that while the 10 m flights provided the best remotely sensed survey results, drones are not a suitable replacement for ground censuses. In Chapter 4, we used Resource Selection Function to define critical habitat for the Wright fishhook cactus. Our modeling suggests that geology, elevation, and slope are significant factors in defining cactus habitat. Based on the results of our research we conclude that soil disturbance by cattle may not have a significant influence on Wright fishhook cactus populations or dynamics, and that accurate range wide population estimates may be best obtained through ground surveys within the predicted critical habitat.

Keywords: *Sclerocactus wrightiae*, fishhook cactus, cattle, disturbance, track simulation, drones, high resolution remote sensing, endangered plants, sUAS, critical habitat, RSF.

ACKNOWLEDGEMENTS

A special thanks to my wife Rebecca Bates for her invaluable help and support throughout the research and writing process, and to my father Steven Bates for inspiring me from a young age with a love of the outdoors and a determination to pursue higher education.

I would also like to thank Dr. Anderson for his guidance, support and mentorship throughout my undergraduate and graduate experiences.

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CHAPTER 1

Effects of Cattle Disturbance on Change in Population Densities and Flowering of Wright Fishhook Cactus (*Sclerocactus wrightiae* L.D. Benson)

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ABSTRACT

In 1979, the United States Fish and Wildlife Service listed the Wright fishhook cactus (*Sclerocactus wrightiae* L.D. Benson) as endangered. Since this time, the potential impacts associated with cattle grazing have been a central focus of land management policies and debate. To better understand and monitor the impacts of cattle disturbance on Wright fishhook cactus population trends, the Bureau of Land Management (BLM) established 30 macro-plots (25 m x 50 m). These macro-plots were placed in multiple grazing allotments and located in areas representing different levels of disturbance (high, moderate, and low). Our objective was to evaluate the effects of cattle related soil disturbance on change in population densities (individuals · macro-plot $^{-1}$), flowering plant frequency (%), and flowering density (number of reproductive structures · macro-plot $^{-1}$) of Wright fishhook cactus across seven years (2011-2017). Our analysis suggests that decreased flowering frequency (%) is significantly associated with high cattle disturbance. However, no significant association was observed between level of disturbance and flower density or change in population density. These results indicate that soil disturbance by cattle may not be significantly impacting Wright fishhook cactus populations or contributing to their range-wide population decline.

INTRODUCTION

The Wright fishhook cactus (*Sclerocactus wrightiae* L.D. Benson) is a small, globose cactus endemic to the San Rafael Swell region of south-central Utah (Benson, 1966; Welsh et al., 2003). In October of 1979, the United States Fish and Wildlife Service (USFWS) listed the Wright fishhook cactus as endangered due to its limited range and population size, as well as its popularity for field collection by amateur and professional cactus fanciers (United States Fish and Wildlife Service 1979). Subsequently, impacts associated with cattle grazing were also identified as a primary threat to this species (United States Fish and Wildlife Service 1985, 2005). At the time of listing there were only five known populations, but by 2013 surveys had documented more than 300 additional populations. Consequently, the Wright fishhook cactus currently influences management decisions on more than 280,000 ha of Utah rangelands (United States Fish and Wildlife Service 1979; Spector 2013).

Disturbance of endangered plant species by livestock has been a management concern for several decades (Schemske et al. 1994). Cactaceae in general are thought to be particularly sensitive to disturbance due to their longevity and low recruitment (Godínez–Álvarez et al. 2003). The effects of livestock disturbance have been documented in the literature for a variety of cactus species. For example, increased regeneration of saguaro (*Carnegiea gigantea* (Engelm.) Britton & Rose) was observed to directly correspond with removal of livestock grazing (Pierson et al. 2013). For one threatened pincushion cactus (*Mammillaria dixanthocentron* Backeb. ex Mottram), population growth rate was reduced by cattle disturbance, while the population growth rate of a closely related threatened pincushion cactus species (*Mammillaria hernadezii* Glass & R.A Foster), increased with cattle disturbance. (Ureta and Martorell 2009).

For the Wright fishhook cactus, there are concerns that cattle may impact individual plants both directly (i.e. crushing, up-rooting, burying, or root shear) and indirectly (i.e. soil compaction, secondary host infection, reduced seed production, or reduced diametric growth) (Kass 2001; Clark and Clark 2007; Spector 2013). Wary of these potential impacts, the USFWS, in conjunction with an interagency team, arbitrarily defined disturbance as a cactus having a cow track within 15 cm of any stem. This distance was based on the average diameter of a cow hoof print (10 cm) and the approximate length of the shallow horizontal roots (15 cm) of the Uinta Basin hookless cactus (*Sclerocactus glaucus* (K.Schum) L.D. Benson) (Guthery and Bingham 1996; Spector 2013).

In 2011, a plan for monitoring disturbance was established by an interagency team with input from the USFWS, Capitol Reef National Park (CRNP), and the Bureau of Land Management (BLM). This plan outlined a cattle soil disturbance threshold of 15% for key areas (i.e. groupings of cactus locations in a distinct geographical area). Meaning that no more than 15% of cacti within a key area could have a cow track within 15 cm of any stem. Exceeding this threshold would require re-consultation with the USFWS and a commitment to take protective actions (e.g. fencing or a reduction of grazing permits) (Bureau of Land Management et. al, 2011).

Since the establishment of this plan, CRNP and the BLM, the two primary agencies responsible for managing lands where the Wright fishhook cactus is found, have invested significant resources in documenting cactus attributes: location, diameter, number of stems, number of reproductive structures, and the presence or absence of disturbance (visible tracks within 15 cm) by cattle. From 2011-2013, the BLM conducted surveys for Wright fishhook cacti at 58 sites across its range (representing 8,767 individuals) and found no correlation between disturbance by cattle and population density ($r^2 = 0.0873$) (Bureau of Land Management 2013).

Capitol Reef National Park conducted a study on 352 Wright fishhook cacti from 2013-2016. From the mixed response to disturbance in both cactus diameter and reproduction, they postulated that disturbance by cattle has "indirect negative impacts on population processes as a result of changes to habitat structure and composition" (Hornbeck 2017). The discrepancy found in these results has led to disagreements between the two agencies, and the USFWS on appropriate management policies (pers. comm.).

Our objective was to evaluate the effects of cattle related soil disturbance on change in population densities (individuals · macro-plot $^{-1}$), flowering plant frequency (%), and flowering density (number of reproductive structures · macro-plot $^{-1}$) of Wright fishhook cactus across seven years (2011-2017). We hypothesized that high levels of cattle disturbance would be negatively associated with both 1) change in population density and 2) flowering (frequency and density).

MATERIALS AND METHODS

Study Area

The Wright fishhook cactus is endemic to the San Rafael Swell region of Emery, Sevier, and Wayne counties, Utah (Fig. 1). It occupies habitats ranging from 1,280-2,320 m in elevation and is found on members of the Mancos Shale, Dakota, Morrison, Summerville, and Entrada Formations (Welsh et al. 2003; Spector 2013). The associated climate is hot desert with an average annual precipitation of 15.88 cm (PRISM Climate Group, http://www.prism.oregonstate.edu/explorer/). The soil texture is predominantly characterized as sandy clay loam (Bureau of Land Management, unpublished data). The Wright fishhook cactus grows in areas where there is low vegetative cover. Some of the most common associated native species include: Gardner's saltbush (*Atriplex gardneri* (Moq.) D.Dietr.), shadscale (*Atriplex* *confertifolia* (Torr. & Frém.) Wats.), mat saltbush (*Atriplex corrugata* S. Watson), alkali sacaton (*Sporobolus airoides* (Torr.) Torr.), galleta (*Hilaria jamesii* (Torr.) Benth.), Torrey's ephedra (*Ephedra torreyana* S. Watson), Indian rice grass (*Achnatherum hymenoides* (Roem. & Schult.) Barkworth), prickly pears (*Opuntia* spp.), Russian thistle (*Salsola tragus* L.) and halogeton (*Halogeton glomeratus* (M. Bieb.) C.A. Mey.).

Establishment of Macro-plots

From 2011-2013, the BLM completed censuses and measured disturbance at 58 Wright fishhook cactus population sites across their known habitat. Finding that many of the sites exceeded the 15% cattle soil disturbance threshold outlined by the interagency team, the BLM divided disturbance into three categories: high disturbance (> 50% of individuals with a cow track within 15 cm), moderate disturbance (20-50%), and low disturbance (< 20%). A plan was then established where 30 macro-plots would be designated to monitor the impacts of disturbance intensity on cactus population trends. Sites for macro-plots were selected using several criteria.

The USFWS requested that the top 30% of disturbed sites be included in the monitoring plan (i.e. the 15 most disturbed sites). The top 30% included ten sites in the high disturbance category, and five in the moderate. An additional five moderate and ten low disturbance sites were selected by the BLM for monitoring. Each of these sites had to be reasonably accessible, contain a minimum population of 30 individuals, and needed to be distributed across grazing allotments.

Within each site, a 25 m x 50 m macro-plot was positioned in ArcMap (Esri, Redlands, California) to contain the highest cacti densities. In 2014, these plots were marked on the ground for repeat census (Bureau of Land Management 2015). Key area censuses taken from 2011-2013 were clipped in ArcGIS Pro (Esri, Redlands, California) retrospectively to these plot boundaries. These macro-plots were established on BLM lands ranging from 8.5 km SE of Fremont Junction, Utah (lat 38°63'N, long 111°33'W) to 10 km S of Hanksville, Utah (lat 38°22'N, long 110°42'W).

Data Collection Methods

During each summer field season from 2011-2017, the BLM completed censuses for the Wright fishhook cactus. All 30 permanent macro-plots were to be inventoried on a three-year cycle (i.e. 10 macro-plots per year). However, due to funding and time constraints, the BLM inventoried less than ten sites in some years and more than ten in others. For each cactus found within a plot, the BLM recorded several attributes: coordinate location using GPS, health, number of stems, diameter, flowers per individual, and the presence or absence of a cow track within 15 cm (Bureau of Land Management 2015). Each cactus was then assigned to one of three diametric size classes as previously defined by Ronald Kass (2001): size class 1 (≤ 2.0 cm), size class 2 (2.1 cm-4 cm), and size class 3 (4.1 cm-9 cm). Kass (2001) also had a fourth size class (> 9cm), but in all seven years of surveys only three individuals were found in this size class, therefore for analysis purposes, they were combined with size class 3.

Total density for each macro-plot was calculated in ArcGIS Pro using the recorded GPS locations. Change in population density was calculated by taking the difference between the total density the first year a macro-plot was read and the total density of the last year it was read. The difference between first and last year readings was not uniform for each macro-plot, with a minimum time difference of two years and a maximum of six. The average time difference was 4.6 years.

Flowering plant frequency was evaluated as percent of individuals which had flowers, fruits, or buds when the survey was completed. Flowering density was evaluated as the number of reproductive structures within each macro-plot during census. For the analysis of flowering plant frequency and flower density, only surveys completed during the flowering-fruiting season were included (April 14th-July 14th). These analyses were also only conducted for the flowering size classes (size class 2 and 3). Change in population density for 29 macro-plots (n = 29) and 39 flowering (n = 39) census surveys were included in the analysis (BLM, unpublished data).

Statistical Analyses

Statistical analyses were conducted in R (R Core Team 2018) using packages lme4 (Bates et al., https://github.com/lme4/lme4/), lmerTest (Kuznetsova et al., https://github.com/runehaubo/lmerTestR), and MuMIn (Barton, https://www.rdocumentation.org/packages/MuMIn/versions/1.43.15). Linear mixed-effects regression (lmer) was used to analyze flowering data, while basic ANOVA was used to analyze change in population density. For the flowering data analysis, we formulated a list of seven *a priori* models (Table 1-2). These models contained various combinations of elevation, slope, aspect, and cattle disturbance as fixed effects. Year and site were forced into each model as random effects. Flowering was evaluated as both plant frequency (%) and density (number of reproductive structures · macro-plot $^{-1}$). Flowering plant frequency data (%) were transformed to the logit scale. Model selection based on Akaike's Information Criterion (AICc) was used to determine the best fit model (Burnham and Anderson 2004). Prior to model selection, covariates were examined for multi-collinearity, and the assumptions of normality and homoscedasticity were met. Satterthwaite's approximation for degrees of freedom and the differences of least squares means were used to obtain difference estimates and *p*-values. For the analysis of change in population density, *p*-values were then adjusted using the Tukey method. All analyses were conducted as totals and by individual size classes.

RESULTS

Density

Contrary to part one of our original hypothesis, when ANOVA was used to evaluate the change in Wright fishhook cactus population densities, we found no significant difference between disturbance (trampling) levels ($p<0.98$). This lack of significance was consistent for all size classes. Though differences were not significant, there were some observable patterns. For size class one, population densities appeared to increase with disturbance, for size class 3, population densities appeared to decrease, and for size class 2 there was no observable pattern.

Flowering

For flowering plant frequency, our mixed-model analysis (lmer) and model selection indicated that cattle disturbance plus the forced random effects of year and site was the best fit model for the data and accounted for the majority of the observed variation. However, for flowering density the null model best fit the data, indicating that yearly climatic variation best described observed differences.

In support of part two of our original hypothesis, our mixed model analysis (lmer) found that high levels of cattle disturbance were negatively associated with flowering plant frequency. Macro-plots with low disturbance had 28% more individuals that flowered on average than macro-plots with high disturbance ($p<0.01$). Size class 2 had 24% fewer flowering individuals in high disturbance than in low disturbance sites ($p<0.05$). Moderate to low was also significant for size class 2 with 12% fewer flowering individuals at moderate levels of disturbance ($p<0.05$). However, there was no significant difference for size class 3 in the percent of flowering individuals between high and low disturbance macro-plots ($p<0.44$). When the mixed model analyses were conducted on flower densities, the results indicated no significant association between cattle disturbance and the number of reproductive structures per macro-plot ($p<0.51$). Though negative trends similar to those found for flowering frequency were observable, regardless of size class, the differences were not significant. These results were consistent with the model selection process which indicated that differences were better attributed to yearly climatic variation than to cattle disturbance.

DISCUSSION

Since the drafting of the 1985 recovery plan, cattle have been considered a primary threat to the persistence of the endangered Wright fishhook cactus and a probable cause of their decline (USFWS 1985; Kass 2001; Spector 2013; Hornbeck 2017). From our analysis of change in population density (2011-2017), it is clear that Wright fishhook cactus populations have declined, but that decline was not attributed to the degree of cattle disturbance. Even though our results demonstrated a negative impact associated with cattle traffic on the percent of flowering individuals in size class 2 (the juvenile size class), the lack of significant differences between disturbance levels in flowering plant frequency of size class 3 (mature individuals), flowering density, and change in population densities suggest that soil disturbance by cattle may not be significantly contributing to range-wide population decline.

Soil disturbance by cattle has not always been found to be a detriment for members of Cactaceae. While studying the beehive cactus (*Coryphantha werdermannii* Boed.), a similarly sized, endangered globose cactus species of Mexico, Martorell et al. (2015) found population densities significantly increased with increased livestock disturbance. Several other globose cactus species have exhibited a similar response with higher population densities and growth rates in disturbed areas (Martorell and Peters 2009; Ureta and Martorell 2009; Portilla-Alonso and Martorell 2011; Martorell et al. 2012, 2015).

However, for some members of Cactaceae soil disturbance by cattle has been found to negatively impact populations. While studying *Pediocactus winkleri* K.D. Heil, a threatened cactus species on the San Rafael Swell, Clark et al. (2015) found that disturbance by large ungulates decreased the odds of a cactus flowering. The results of our analysis demonstrated a similar decrease in total flowering plant frequency for Wright fishhook cacti. However, the negative impacts of disturbance on flowering plant frequency were only significant in size class 2. These smaller individuals do not flower as frequently as size class 3 and do not contribute as much to total seed production (Spector, 2013, BLM unpublished data). The observation made of increased recruitment of size class 1 in more disturbed sites may suggest that there is a greater number of individuals transitioning to size class 2 that are still sexually immature and not contributing to flowering plant frequency. The results of our analysis indicate that for the Wright fishhook cactus, land managers may need to look to sources other than livestock disturbance for population decline.

Though underrepresented in the literature, several studies have found that insect herbivory can have substantial impacts on rare plant populations (Ancheta and Heard 2011). One of the reported causes of mortality for the Wright fishhook cactus is the cactus borer beetle (Cerambycidae: *Moneilema semipunctatum* LeConte). Ronald Kass (2000;2001) found that this beetle accounted for 23% of combined mortality in three plots (61 m x 122 m) across seven years

(1993-2000). The two largest size classes (size class 3 and 4) suffered even higher levels of mortality by beetles (44% and 40% respectively). Size class 2 only experienced 16% mortality from beetles, while size class 1 remained untouched (0%; Kass, 2001). Herbivory by lagomorphs and rodents also poses a substantial threat to this species accounting for 13% of total mortality from 2011-2013 at BLM monitoring sites (Bureau of Land Management 2013).

CONCLUSION

Since its listing in 1979, the Wright fishhook cactus has played a significant role in land management decisions on the San Rafael Swell. These decisions were often based on small scale studies, observations, or anecdotal evidence. While the scope of application for this study is limited due to subjective placement of macro-plots and lack of control sites, it does represent the best available science and the most extensive data set for this species. Our analysis indicates that cattle disturbance may not be significantly contributing to the population decline of the Wright fishhook cactus. However, this does not mean that cattle are having no effect. In natural systems, we often do not have the advantage of performing controlled experiments and are forced to rely on correlations or associations we draw from observational studies. While the effects of cattle disturbance on this species are still not fully understood, given the results of the analysis of this dataset, land management agency resources may be better allocated investigating other sources of mortality for the Wright fishhook cactus.

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FIGURES

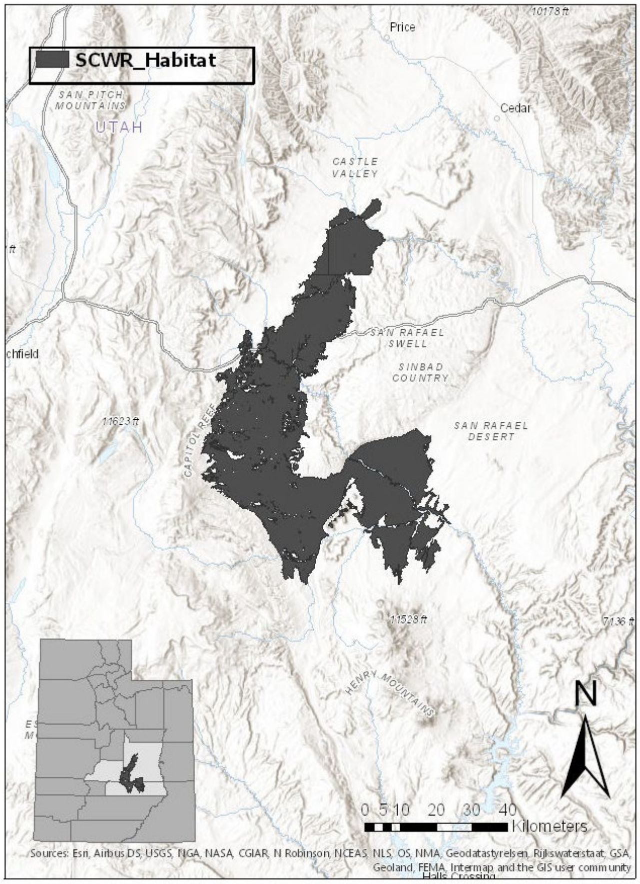

Figure 1-1: Potential distribution for Wright Fishhook Cactus (BLM, unpublished).

Effects of Cattle Tracks in Proximity to the Endangered Wright Fishhook Cactus (*Sclerocactus wrightiae* L.D. Benson)

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ABSTRACT

The Wright fishhook cactus is a small, globose cactus endemic to the San Rafael desert of south-central Utah (Benson, 1966; Welsh et al., 2003). Listed as endangered in 1979 by the United States Fish and Wildlife Service, original threats for this species included mining, OHV use, and illegal collection (USFWS, 1979). However, recent management practices and protections have focused on the potential impacts of cattle on the Wright fishhook cactus, specifically the impact of a cow track within 15 cm of a cactus stem (BLM, 2013; Spector, 2013). While this measurement is based on the root structure of a similar cactus, no empirical evidence has been collected to evaluate the impacts of a cow track in proximity to a Wright Fishhook cactus (Spector, 2013). From 2018-2019, we conducted an experimental study on private land where cattle tracks were simulated at varying levels (Control, 1-Track, 2-Tracks, 4-Tracks, and 4-Tracks Doubled) within 15 cm of 112 Wright fishhook cacti. Over the following months we observed the response of these cacti to the track treatments via diametric measurements, flower production, fruit production, and seed set. We also measured penetration resistance to quantify the level of soil compaction. Though the simulated tracks caused significant soil compaction, no significant association was observed between the number of tracks and response in diameter, flower production, fruit production, or seed set.

INTRODUCTION

Grazing has been shown to impact different ecosystems in a variety of ways. Cattle specifically, have been shown to alter their environments through several herbivory related activities beyond ingestion (i.e. trampling, trailing, bedding, urination, and defecation) (Mazzini et al., 2018). For example, in pastoral settings trampling has been shown to increase soil compaction (Herbin et al., 2011; Rakkar and Blanco-Canqui, 2018). For perennial grasslands, time-controlled grazing can increase vigor of decadent native bunchgrasses through increased light penetration (Menke, 1992). In this same system, cattle dunging has been recorded to increase soil nitrogen content (Dai, 2000), while trampling has been shown to decrease species richness (Ludvíková et al., 2014). In forested ecosystems, removal of sapling Doublas-fir bark (*Pseudotsuga menziesii* (Mirb.) Franco.) by trampling has been found to decrease survival (Eissenstat et al., 1982). While the impacts associated with cattle grazing are universally disputed, in arid landscapes they have been a consistent source of controversy (Brussard et al., 1994; Jones, 2000; Noss, 1994). A current management controversy in arid southern Utah involves soil trampling by cattle in proximity to the endangered Wright fishhook cactus (*Sclerocactus wrightiae* L.D. Benson).

The Wright fishhook cactus is a small, globose cactus endemic to south-central Utah (Benson, 1966; Welsh et al., 2003). In October of 1979, the U.S. Fish and Wildlife Service (USFWS) determined the Wright fishhook cactus to be endangered due to its limited range and population size, as well as its risk of extirpation from local mining, OHV use, and field collection (USFWS, 1979). Since its listing, potential impacts associated with cattle grazing have also been identified as a primary threat to the species (Spector, 2013; USFWS, 2005, 1985).

The potential impacts of livestock related disturbance on endangered plant species has been a management concern for several decades (Schemske et al., 1994). Due to their longevity and low recruitment, Cactaceae in general are thought to be particularly sensitive to disturbance (Godínez–Álvarez et al., 2003). The effects of disturbance associated with livestock have been recorded for a variety of cactus species in the literature. Increased saguaro (*Carnegiea gigantea* (Engelm.) Britton & Rose) regeneration was observed to directly correspond with removal of livestock grazing (Pierson et al., 2013). The beehive cactus (*Coryphantha werdermannii* Boed.) was favored by cattle grazing as populations showed increased recruitment with disturbance (Martorell et al., 2015). For one pincushion cactus (*Mammillaria dixanthocentron* Backeb. ex Mottram), population growth rate was found to be reduced by cattle disturbance, while another pincushion cactus (*Mammillaria hernandezii* Glass & R.A. Foster) experienced increased population growth with increased disturbance (Ureta and Martorell, 2009). This suggests that not only are the effects of disturbance on cacti variable, but even two species of the same genus behave differently under disturbance from grazing (Ureta and Martorell, 2009).

For the Wright fishhook cactus, there are concerns that cattle related soil disturbance (tracks in proximity to a stem) may impact individual plants directly via crushing, burying, or root shear and indirectly via soil compaction, secondary host infection, decreased reproductive effort, or decreased growth rates (Clark and Clark, 2007; Kass, 2001; Spector, 2013). Based on these potential impacts, the USFWS, in conjunction with an interagency team, arbitrarily defined disturbance as a cactus having a cow track within 15 cm of any stem. This distance was determined using the average diameter of a cow hoof print (10 cm) and the approximate length (15 cm) of the shallow horizontal roots of the Uinta Basin hookless cactus (*Sclerocactus glaucus* L.D. Benson) (Guthery and Bingham, 1996; Spector, 2013).

A monitoring plan for Wright fishhook cactus was established in 2011 by an interagency team with input from the USFWS, Capitol Reef National Park (CRNP), and the Bureau of Land Management (BLM). It was determined that only 15% of Wright fishhook cacti in any key area (i.e. groupings of cactus locations in a distinct geographical area) could have a cow track within 15 cm. Exceeding this disturbance threshold would require re-consultation with the USFWS and a commitment to take protective actions: fencing or reduction of grazing permits (BLM et. al, 2011).

Since this determination, CRNP and the BLM, the two land management agencies responsible for public land where Wright fishhook cacti are found, have invested significant resources in finding cactus populations and documenting cactus attributes: diameter, stems, reproductive structures, and the presence or absence of cattle tracks within 15 cm of any stem. From 2011-2013, the BLM conducted surveys for individual Wright fishhook cacti at 58 sites across its range (representing 8,767 individuals) and found no correlation between disturbance and population density (r^2 =.0873) (BLM, 2013). Capitol Reef National Park monitored 352 individual Wright fishhook cacti from 2013-2016. From the mixed response to disturbance in both cactus diameter and reproduction, they postulated that disturbance by cattle has “indirect negative impacts on population processes as a result of changes to habitat structure and composition” (Hornbeck 2017). This discrepancy in results and implications has led to disagreements between the BLM, USFWS, and CPNP on appropriate management practices.

While there are undoubtedly both direct and indirect effects associated with cattle grazing and soil disturbance in arid ecosystems, our objective was to evaluate the effects of a cow stepping within 15 cm of an individual Wright fishhook cactus. Specifically, we examined the effects of simulated, proximal tracks on 1) growth (i.e. change in diameter (cm)), 2) reproduction (number of flowers, fruits, and seeds), and 3) soil compaction. We hypothesized that the presence and number of cow tracks within 15 cm of a cactus would have a significant association with diameter and reproduction and that the tracks would cause significant soil compaction.

MATERIALS AND METHODS

Study Site

The study site is located on 4 ha of private property in the Last Chance desert, approximately 14 km south of Fremont Junction, Utah (lat 38°63'N, long 111°33'W). The climate is arid with a mean annual precipitation of 190 mm (Bureau of Land Mangement, unpublished data). The soil is sandy clay loam in texture and the underlying geology is surficial alluvium. The dominant plant community consists of blue grama (*Bouteloua gracilis* (Kunth) Lag x. Griffiths), four-wing saltbush (*Atriplex canescens* (Pursh) Nutt.), shadscale (*Atriplex confertifolia* (Torr. & Frém.) S. Watson), Russian thistle (*Salsola tragus* L.) and prickly-pears (*Opuntia* sp.).

Trampling Device and Track Simulation

A variety of methods exist for simulating cattle trampling (Abdel-Magid et al., 1987; Dobarro et al., 2013; Striker et al., 2006). Using information from existing methods, we designed a device that expeditiously effectuated the necessary treatments (Figure 1). The device needed to be readily portable and provide the necessary application of force. We constructed this device using steel and it has two primary components: a stabilizing platform and a plunger assembly. The stabilizing platform measures 55 cm x 55 cm and is 32.5 cm tall. It has four central bars that form an octothorpe around a central guide pipe. The guide pipe is 21.6 cm tall and 11.4 cm in diameter. We welded it in place with 6.4 cm exposed above the plane of the stabilizing platform.

The plunger consists of an upper platform measuring 30 cm x 49.5 cm, a flanged pipe fitting measuring 23 cm in diameter, and a PVC pipe 10.2 cm in diameter and 38 cm in height. The plunger assembly slides freely through the guide pipe of the stabilizing platform. We mounted a cow leg with a hoof surface area of 82 cm^2 obtained from a local butcher into the bottom of the plunger (Figure 1). The plunger assembly (including leg) weighs 6.8 kg. To adequately simulate the proper pressure applied by a 400 kg cow while walking, two persons with a combined mass of 200 kg stand simultaneously on the upper platform exerting a total force of 2.5 kg cm^{-2} (245 kPa) (Abdel-Magid et al., 1987; Frame, 1970).

Treatments

In April 2018, we surveyed the study site for Wright fishhook cacti counting a total of 153 individual plants. Nineteen of these cacti were excluded from possible selection due to apparent damage or other visible distress. The remaining 134 cacti were then categorized using three diametric size classes as previously defined by Ronald Kass (2001): size class 1 (≤ 2.0 cm), size class 2 (2.1 cm-4 cm), and size class 3 (4.1 cm-9 cm). Kass (2001) also had a fourth size class (> 9cm), but no size class 4 individuals were located on the study site, therefore only three size classes were represented in the study. We randomly selected individual plants to be included in the study: 50 from size class 3, 50 from size class 2, and 12 from size class 1 (only 12 were located).

Within the designated size classes, cacti were randomly assigned a track treatment. In size classes 2 and 3, ten cacti were randomly selected for each of the five different track treatments: Control, 1-Track, 2-Tracks, 4-Tracks, and 4-Tracks Doubled (two sets of four tracks within each other). For size class 1, six cacti were randomly selected for the control treatment and the other six received the 4-Tracks treatment. We assingned water treatments within the track treatments with half of the cacti within each track treatment receiving no supplemental water (natural precipitation = drought conditions) and the other half received supplemental water (additional water applied to simulate an average wet year).

Prior to implementation of any track treatment, each cactus received 300 ml of water containing 15 ml of Fertilome systemic drench (Voluntary Purchasing Groups, Bonham, Texas) to protect plants for 12 months against insect herbivory and to exterminate any potentially existing stem boring larvae. Since tracks in these soils are only ever apparent in rain softened soils, we applied 1000 ml of water, penetrating to an approximate depth of 5 cm and covering a 15 cm radius around each cactus. This watering was done immediately prior to treatment. Track treatments were effectuated using the trampling device. For each track the cow hoof was placed directly adjacent to the primary cactus stem, then two persons with a combined mass of 200 kg stood simultaneously on the upper platform to create the track. Tracks were positioned ordinally in the four cardinal directions (N, S, E, W) immediately outside of the cactus perimeter, so that the entire track was within 15 cm of the cactus stem. The cow hoof was cleaned regularly between tracks to ensure that soil attachment did not affect the trampling device performance.

Supplemental water treatments were calculated by averaging the quarterly precipitation values from the five wettest years as recorded by the local Rock Springs weather station (Bureau of Land Management, unpublished data). These quarterly values were then divided into months using average monthly percentages (2005-2017) taken from the closest NOAA weather station (National Oceanic and Atmoshperic Administration, Climate Data Center. Precipitation Data, http://www.ncdc.noaa.gov/cdo-web/datasets/GSOM/stations/GHCND:USC00423254/detail). Water was added monthly to the supplemental watered cacti treatment group using drip irrigation so that total precipitation (natural + supplemental) was equal to the calculated monthly mean wet-year values. Supplemental water treatments were added to evaluate whether climatic conditions influenced the effect of cattle tracks in proximity to cacti.

The diameter of each cactus was recorded monthly from April through August of 2018 and again in May of 2019. Measurements were recorded to the nearest half centimeter. The number of flowers was recorded annually in May. Fruits and seeds were collected and counted annually following determination of seed maturity.

Soil Compaction

Soil compaction was measured using a 0.5-inch cone-nose penetrometer (Field Scout SC 900 Soil Compaction Meter, Spectrum Technologies Inc., Plainfield, Illinois). Penetration resistance (PR) measurements were taken within 40 simulated tracks: single track with supplemental water (n=10), single track with no supplemental water (n=10), double track with supplemental water (n=10), and double track without supplemental water (n=10). These measurements were recorded in June and September of 2018 and in June of 2019. Penetrometer sites were selected at random from cacti within the treatment population. An additional 40 control penetrometer sites were also concurrently recorded. These control sites were located 15 cm from their associated treatment site (in the same cardinal direction). Penetration resistance measurements were recorded in kPa at 2.5 cm increments from 0-10 cm (Mulholland and Fullen, 1991).

Analysis

Using the data collected in 2018 and 2019, statistical analyses were performed in R (R-Core Team, 2018) using packages lme4 (Bates et al., https://github.com/lme4/lme4/), lmerTest

(Kuznetsova et al., https://github.com/runehaubo/lmerTestR), MuMIn (Barton, https://www.rdocumentation.org/packages/MuMIn/versions/1.43.15)).), and emmeans (Lenth et al., https://github.com/rvlenth/emmeans). *A priori* model formulation and model selection based on Akaike's Information Criterion (AICc) were used to determine the best fit model for each analysis (Burnham and Anderson, 2004). Prior to model selection the assumptions of normality and homoscedasticity were met.

Due to high precipitation in the fall of 2018, the water treatments implemented in 2018 had no significant effect on reproduction, diameter, or soil compaction. Therefore, these two treatment groups were combined for the purpose of analysis. In 2019, 31% of all study individuals were moderately to extremely damaged by rodents or lagomorphs (i.e. partial to complete removal of above ground tissues). This reduced sample sizes for all reproductive measurements. The sample sizes for fruit and seed count were even further reduced due to ant activity prior to harvest. Diameter sample sizes were only moderately affected by the damage reducing all track treatment group sample sizes by three. Final sample sizes for flower analysis across years were for size class 2: 16 for Control, 16 for 1-Track, 14 for 2-Tracks, 16 for 4-Tracks, and 19 for 4-Tracks Doubled. For size class 3, final sample sizes were: 19 for Control, 18 for 1-Track, 20 for 2-Tracks, 19 for 4-Tracks, and 19 for 4-Tracks Doubled. Only the reproductive size classes (2 and 3) were included in the reproduction analysis. Final sample sizes for fruit and seed analysis across years were for size class 2: 12 for Control, 14 for 1-Track, 13 for 2-Tracks, 14 for 4-Tracks, and 14 for 4-Tracks Doubled. For size class 3, final samples sizes were: 17 for Control, 18 for 1-Track, 19 for 2-Tracks, 15 for 4-Tracks, and 17 for 4-Tracks Doubled.

Diameter measurements were analyzed using both linear modeling (lm) and linear mixed effects regression (lmer). Size class 1 had to be omitted from both analyses due to low sample size. Linear modeling was used to compare the delta change in diameter from 2018-2019. *A priori* models for delta change in diameter contained treatment, size class, and the interaction between treatment and size class. The best fit model was delta change in diameter as a function of treatment. Linear mixed effects regression was used to evaluate the change in diameter from month to month using April 2018 as the baseline. *A priori* models for change in diameter from month to month included: treatment, size class, month, and their interactions as fixed effects. Treatment was forced into each model as a fixed effect, and cactus tag number was forced into every model as a random effect. The top model included treatment, size class, month and cactus tag with no interaction terms.

Reproductive measurements (i.e. number of flowers, fruits, and seeds) were analyzed using linear modeling (lm). Only the reproductive size classes (2 and 3) were included in the reproduction analysis. For reproductive measurements, model selection was only used to determine if year should be included in the model. Reproductive measurements as a function of treatment, size class, year, and the interaction between treatment and size class was found to be the top model.

For the analysis of soil compaction, linear modeling and model selection were used to compare the treatment depth readings to control depth readings across time. Soil compaction between single tracks and double tracks was also analyzed using the difference between treatment depth readings and associated control sites. Our *a priori* models included treatment, depth, month, as well as each of their interactions. The top model for analyzing the difference between the penetration resistance of single tracks and their associated controls, and the penetration resistance of double tracks and their associated controls, contained treatment, depth, month, and the interaction between treatment and month. The top model for comparing treatment readings to control readings across time contained treatment, depth and month, but no interaction terms.

All diameter and reproduction data were analyzed first as a function of all track treatments combined against the control group, then as a function of track groups (1-2 Tracks, 4-8 Tracks) against the control, and finally as a function of individual track treatments (1-Track, 2-Track, 4-Track, and 4-Tracks Doubled) against the control group. When conducting mixed effects regression (lmer), Satterthwaite's approximation for degrees of freedom and the differences of least squares means were used to obtain difference estimates and *p*-values. For linear modeling (lm), *p*-values were adjusted using the Tukey method. For all analyses, significance was evaluated using $p<0.05$.

RESULTS

Diameter

Contrary to our original hypothesis, growth (i.e. change in diameter) was not significantly associated with the number of tracks within 15 cm of a cactus. Our analysis of change in diameter from 2018-2019 found no significant difference between the control group and the treatment groups. This lack of difference was consistent across all three levels of analysis: track treatments combined vs control, track groups vs control, and individual track treatments vs control (Figure 2). Our analysis of change in diameter across months using April 2018 as the baseline, yielded the same results, finding no significant difference between treatments for either size class. However, we observed that month had a significant effect on diameter, with each month being significantly different from each other ($p<0.01$), except for the months of May and June ($p<0.50$; Figures 3-4).

Reproduction

The results relative to reproduction also failed to support our original hypothesis. No significant difference was observed between the treatment groups and the control group for number of flowers, fruits, or seeds in either of the two size classes. This lack of difference was also consistent across all three levels of analysis (Figures 5-7).

Soil Compaction

For soil compaction the results from both analyses supported our original hypothesis. In both versions of the analysis our simulated tracks caused an increase in penetration resistance relative to the control sites. The analysis of raw penetration resistance values through time found that across the 10 cm depth gradient, both simulated single tracks and double tracks (track within a track) caused significant compaction relative to the control sites ($p<0.01$; $p<0.01$). This compaction was higher for the single track treatments than the controls during June 2018 and May 2019, but not during October of 2018 (Figure 8). The compaction for the double track treatments remained greater than the control sites throughout the study period. On average, penetration resistance of double track sites was 191 kPa greater than control sites. Penetration resistance of single track sites was 144 kPa greater than the control sites. This analysis did not find a significant difference in the compaction between single track and double track sites ($p<0.75$).

When compaction was analyzed as the difference between the track sites and the paired control sites, the single track treatment did not appear to cause any compaction with the mean difference between the single track sites and their paired controls remaining near zero. However, the difference between double track sites and their paired controls was significantly greater than the single track sites, increasing the average penetration resistance. The average compaction level of the double track sites did decrease over time. In June, the average compaction was 525 kPa greater than single track sites (p<0.001), by October it was 221 kPa greater (p<0.05), and by May the average was not significantly different than the single track sites (p<0.31*;* Figure 9).

DISCUSSION

For nearly a decade the USFWS, BLM, and CRNP have worked under the assumption that soil disturbance by cattle (a track within 15 cm of a cactus) negatively impacts Wright fishhook cacti (BLM, 2013; Spector, 2013). While this assumption without empirical data was perhaps a necessary caution, our study found no significant impact to reproduction or diameter associated with the number of cattle tracks within 15 cm of a cactus. Therefore, we fail to reject the null hypothesis that cow tracks within 15 cm of a Wright fishhook cactus have no effect on their diameter or reproductive effort (number of flowers, fruits, or seeds). The most meaningful finding of this study was that diametric measurements vary significantly from month to month. If diametric measurements are going to be taken by land managers for the purpose of understanding population dynamics, they need to be taken during the months of May and June. This will keep the measurements consistent and comparable between years.

CONCLUSION

While the results from this study are not conclusive, they did not show a significant relationship between cattle tracks and measured variables. Another replication cycle will be valuable to test the accuracy of our findings. Though some patterns occurred for both diameter and reproduction relative to cattle track disturbance, these findings were not significant. Study replication with increased sample sizes will help to verify our findings and is advisable prior to management application.

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FIGURES

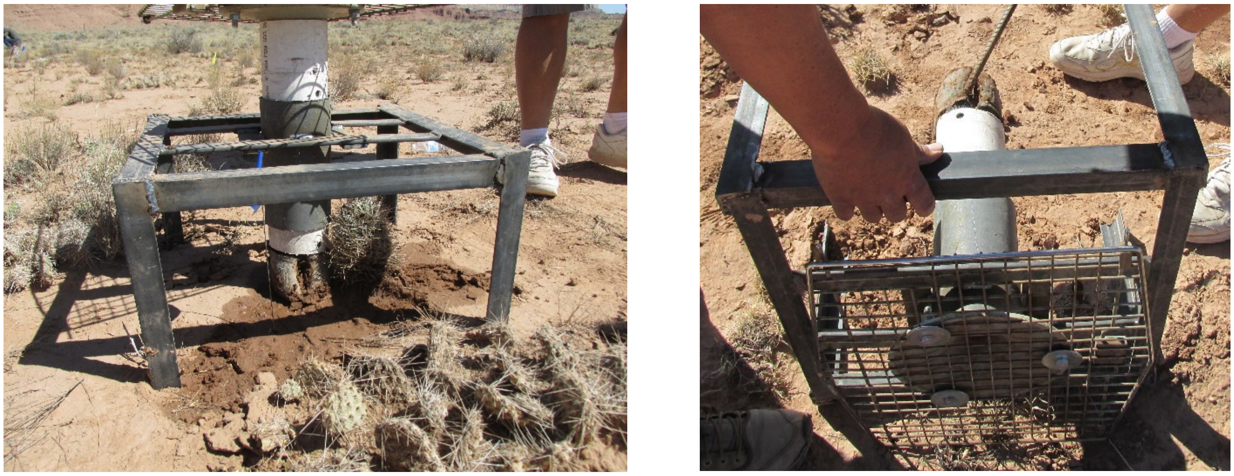

Figure 2-1: Trampling device.

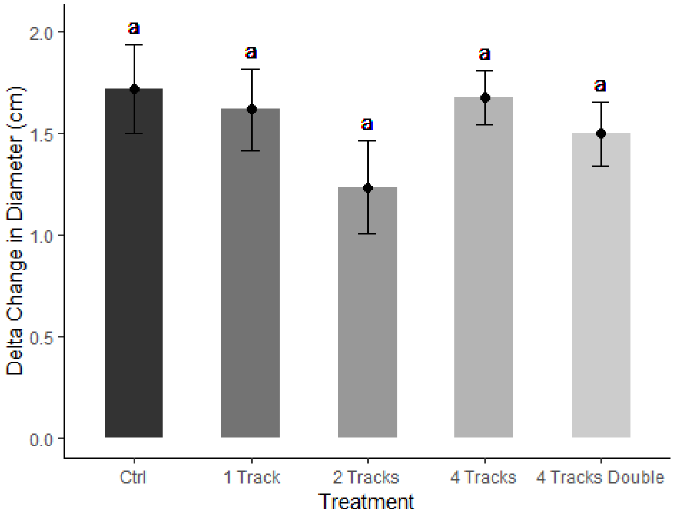

Figure 2-2: Mean delta change in diameter of Wright fishhook cacti ± standard error of the mean by treatment Ctrl vs Track Treatments (2018-2019). Means with common letters do not differ (*p*>0.05).

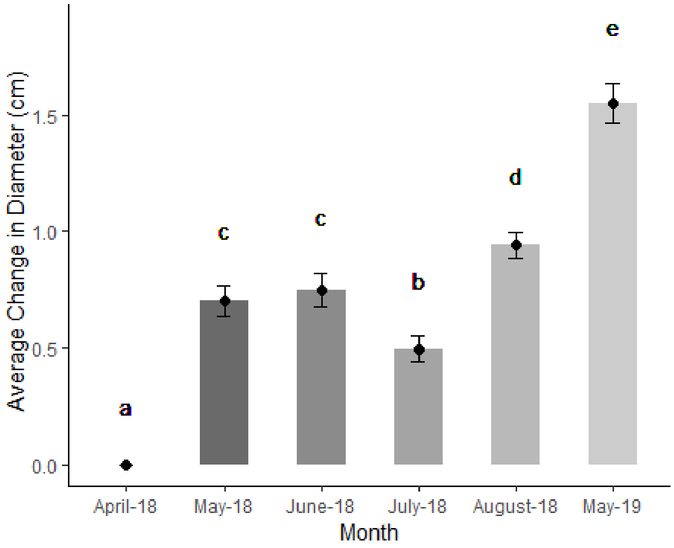

Figure 2-3: Mean delta change in diameter of Wright fishhook cacti ± standard error of the mean across months (2018). Means with common letters do not differ (*p*>0.05).

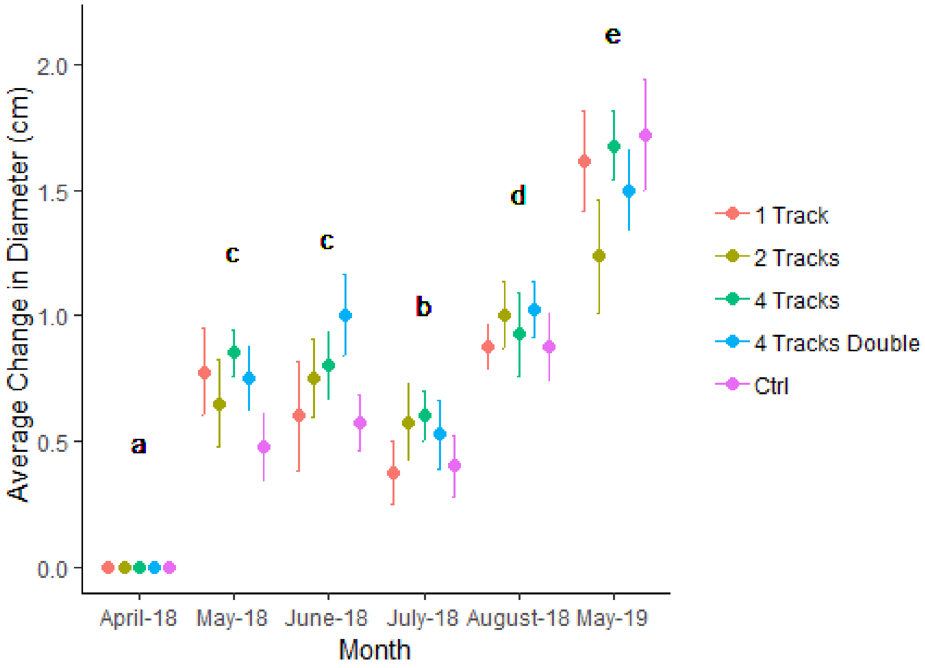

Figure 2-4: Mean delta change in diameter of Wright fishhook cacti ± standard error of the mean by treatment across months (2018). Means with common letters do not differ (*p*>0.05).

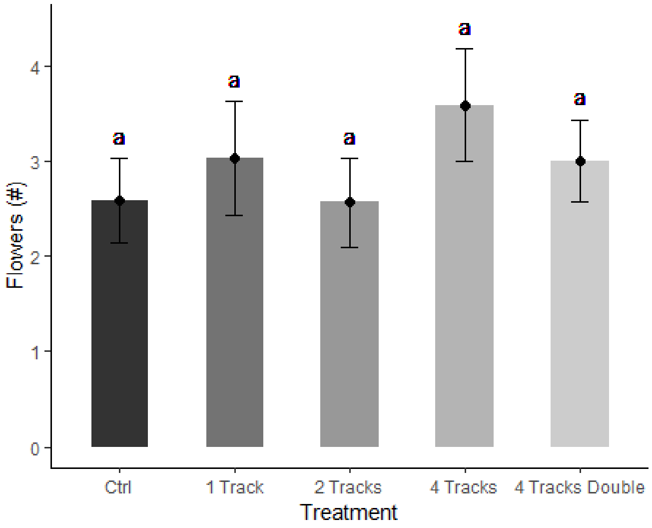

Figure 2-5: Mean number of flowers per Wright fishhook cactus ± standard error of the mean by treatment Ctrl vs Track Treatments. Means with common letters do not differ (p>0.05).

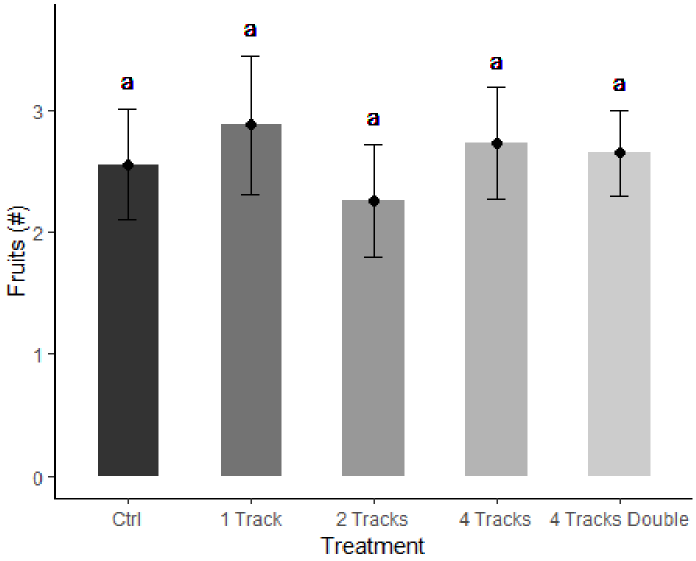

Figure 2-6: Mean number of fruits per Wright fishhook cactus ± standard error of the mean by treatment Ctrl vs Track Treatments. Means with common letters do not differ (p>0.05).

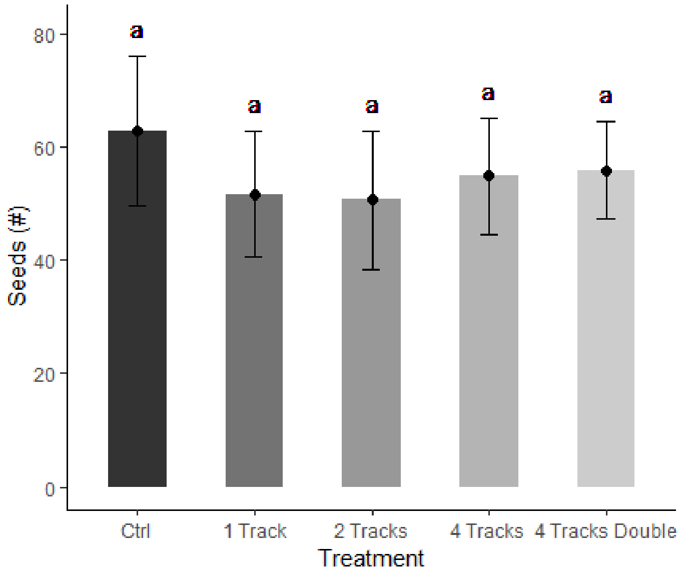

Figure 2-7: Mean number of seeds per Wright fishhook cactus ± standard error of the mean by treatment Ctrl vs Track Treatments. Means with common letters do not differ (*p*>0.05).

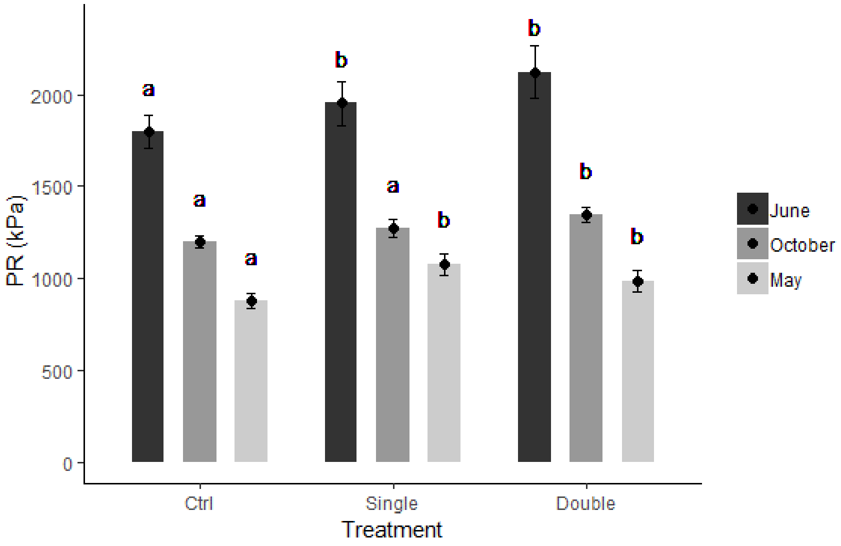

Figure 2-8: Mean penetration resistance (kPa) ± standard error of the mean by compaction treatment. Means with common letters do not differ (*p*>0.05). Letters are only to be compared within months.

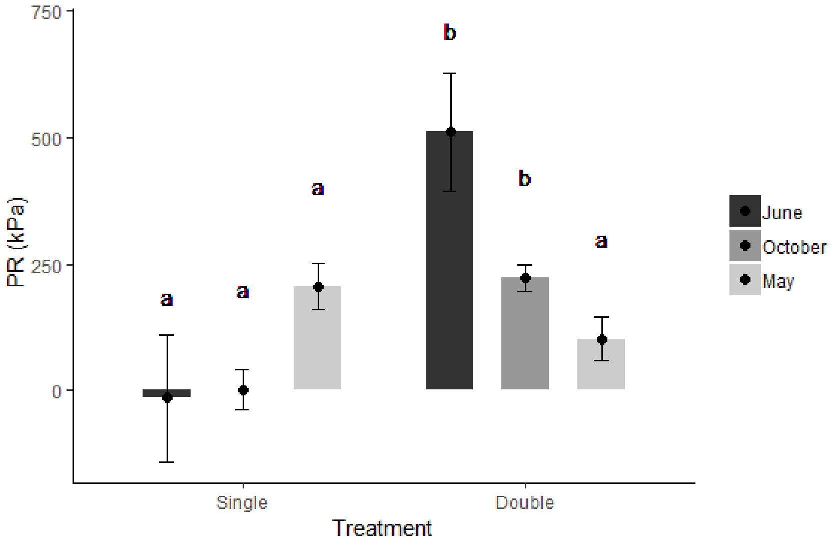

Figure 2-9: Mean difference in penetration resistance (kPa) between control and paired treatment sites ± standard error of the mean. Means with common letters do not differ (*p*>0.05). Letters are only to be compared within months.

CHAPTER 3

A Practical Assessment of Using Drones (sUAS) to Detect and Quantify Wright Fishhook Cactus (*Sclerocactus wrightiae* L.D. Benson) Populations in South-Central Utah, USA

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ABSTRACT

Obtaining accurate population estimates has been an integral part of the listing, recovery, and delisting of species under the U.S. Endangered Species Act (ESA) of 1973. However, obtaining such estimates for many species remains a daunting and labor-intensive task. The use of drones (sUAS) may provide an effective alternative to ground surveys for rare and endangered plants. The objective of our study was to evaluate the effectiveness of using drones (DJI Phantom 4 Pro with a 20 MP camera) to survey for the Wright fishhook cactus (*Sclerocactus wrightiae* L.D. Benson), a small (1-8 cm diameter) endangered species endemic to Utah. We accomplished this by 1) assessing the effectiveness of using drone-based remotely sensed imagery to detect and count individual cacti relative to ground surveys and 2) determining the optimal altitude (10 m, 15 m, or 20 m) for collecting that imagery. Our results demonstrated that the lowest altitude flights (10 m) provided the best detection rates ($p<0.001$) and counts ($p<0.001$). However, drone surveys did not prove an effective replacement for ground surveys for this species. While drone-based remote sensing may have been successfully used in a variety of vegetative surveys for larger species and groups, it is important to acknowledge that these technologies can still have limits in effectively identifying small individual plants.

INTRODUCTION

Since the creation of the U.S. Endangered Species Act (ESA) in 1973, identifying critical habitat for and obtaining accurate population estimates of species has been an integral part of the listing, recovery, and delisting processes [1–3]. Originally, Congress intended that each species listed would have critical habitat designated as part of the listing process [1]. However, when a species is threatened by human take or there is inadequate biological information, a species may be listed as threatened or endangered without the prescribed designation of critical habitat [2,3].

In October of 1979, the U.S. Fish and Wildlife Service (USFWS) listed the Wright fishhook cactus as endangered due to its known limited range and population size (5 known populations), as well as its popularity for field collection by amateur and professional cactus fanciers (i.e. threat from human take) [4]. Although range and population size are mentioned in the original listing, only a small portion of its potential habitat had been surveyed (resulting in only five known populations), and critical habitat was not defined [4,5].

The Wright fishhook cactus is a small, globose cactus endemic to the San Rafael desert of south-central Utah (Figure 1). It is only readily distinguishable from its widespread relative, the small-flower fishhook cactus (*Sclerocactus parviflorus* Clover & Jotter), using flower and filament color. The Wright fishhook cactus has white flowers and magenta filaments as opposed to the pink flowers and green filaments of the small-flower fishhook cactus [6–8]. The range of these two species often overlaps. This presents a challenge for land use agencies because the Wright fishhook cactus only flowers from late April through May, making accurate population estimates and habitat delineation particularly difficult to obtain [8].

Since its listing in 1979, Capitol Reef National Park (CRNP) and the Bureau of Land Management (BLM), the two agencies primarily responsible for managing federal lands where the Wright fishhook cactus is found, have invested significant resources searching for cactus populations and documenting its attributes: location, diameter, stems, reproductive effort, and disturbance by cattle [9,10]. As of 2013, more than 300 Wright fishhook cactus populations had been documented on BLM and CRNP lands, expanding its potential range from only two key areas to more than 90 key areas across 128,000 ha [4,10].

Over the years, population estimates for the Wright fishhook cactus have varied dramatically. Some early surveys estimated a range-wide population as high as 50,000-100,000 individuals [10–12]. These estimates were dismissed by the USFWS in 2005, and a more conservative estimate of 4,500-21,000 individuals was accepted [13,14]. Subsequent surveys have continued to challenge these numbers. In 2013, the BLM reported having documented over 12,000 individual cacti, and concluded that the early estimates of 50,000-100,000 individuals may have been conservative [5]. While these estimates and surveys provide valuable information, they are highly variable and required hundreds of person hours to complete. Surveys and population estimates may be vastly improved by using drone (sUAS or small unmanned aerial system) technologies.

Drones present seemingly endless applications for researchers and land managers. In many ways they represent the frontier of ecological data acquisition. Over the past decade, dozens of articles have been published on the use of drones and object-based image analysis (OBIA) to distinguish plants or plant groups from the surrounding vegetation [15,16]. These studies principally rely on large plants, or groupings of plants, to aid in detection and identification. However, very few studies have explored the possibilities of counting small individual objects or plants [17,18]. At maturity, the Wright fishhook cactus averages 4-8 cm in diameter [6,7]. Detecting and counting plants of this size using drones will test the limits of current technology.

In an effort to improve population estimates and aid in critical habitat designation for the Wright fishhook cactus, our study had two objectives: 1) assess the effectiveness of using drone-based remotely sensed imagery to conduct cactus surveys (i.e. detect and count individual cacti) relative to ground surveys and 2) determine the optimal drone flight altitude for conducting these remote sensing surveys. We hypothesized that drone-based imagery would prove an effective alternative tool to ground surveys, and that the lowest altitude flights (10 m) would provide the best survey results.

MATERIALS AND METHODS

Study Area and Survey Locations

The Wright fishhook cactus is endemic to the San-Rafael Swell region of Emery, Sevier, and Wayne counties, Utah. This cactus occupies habitats ranging from 1,280-2,320 m in elevation and is found on several geologic formations including: Mancos Shale, Dakota, Morrison, Summerville, and Entrada [7,10]. The associated climate is arid desert with an average annual precipitation of 15.88 cm [19]. The Wright fishhook cactus grows in areas with low vegetative cover, where the soils are predominately sandy clay loam in texture. Some of the most common associated plant species include: Gardner's saltbush (*Atriplex gardneri* (Moq.) D.Dietr.), shadscale (*Atriplex confertifolia* (Torr. & Frém.) Wats.), mat saltbush (*Atriplex corrugata* S. Watson), alkali sacaton (*Sporobolus airoides* (Torr.) Torr.), galleta (*Hilaria jamesii* (Torr.) Benth.), Torrey's ephedra (*Ephedra torreyana* S. Watson), Indian rice grass (*Achnatherum hymenoides* (Roem. & Schult.) Barkworth), prickly pears (*Opuntia* sp.), Russian thistle (*Salsola tragus* L.) and halogeton (*Halogeton glomeratus* (M. Bieb.) C.A. Mey.).

From 2011-2012, the BLM selected 15 sites for monitoring livestock disturbance on Wright fishhook cactus population trends. In 2018, 25 m x 50 m paired macro-plots were established at ten of these sites. Cactus populations were inventoried, and GPS locations were recorded for each cactus. In 2019, 15 of these 20 macro-plots were randomly selected for drone surveys (Figure 2). These 15 macro-plots represented eight of the ten paired plot locations, and were widely distributed across cactus habitat on BLM lands ranging from 8.5 km SE of Fremont Junction, Utah (lat 38°63'N, long 111°33'W) to 5 km S of Hanksville, Utah (lat 38°22'N, long 110°42'W).

Mission Planning and Flights

Before conducting flights, we explored the possibilities of using both near infrared (NIR) and Red-Green-Blue (RGB) imagery to detect Wright fishhook cacti. While some species, such as prickly pears (*Opuntia* sp.), presented a distinct reflectance signature in NIR, the signature of Wright fishhook cacti was weak and less effective in distinguishing plants compared to RGB images. Ultimately, survey flights were completed using a DJI Phantom 4 Pro (SZ DJI Technology Co. Ltd. Shenzhen, China) with a standard 20MP RGB camera (f/2.8-f/11, 84° FOV, 20MP).

Each flight was programmed using the Pix4D capture application (Pix4D S.A. Lausanne, Switzerland) on an iPad:6th Gen (Apple, Cupertino, California). The iPad was then interfaced with the drone remote control during the flights. Each macro-plot was surveyed at three different altitudes: 10 m (0.25 cm GSD), 15 m (0.40 cm GSD), and 20 m (0.55 cm GSD) above ground level (Figure 3). Due to the level aspect of the terrain and the relatively small survey areas (1,250 m^2), elevation models were not incorporated into flight planning.

Plots were censused on foot for cacti immediately following the three flights. Each cactus location was marked using a Trimble Juno (Trimble Inc. Sunnyvale, California), and the following attributes were recorded: location (UTM), diameter (cm), number of stems, and any damage or disturbance to the plant. All flights were conducted during the peak flowering period (April 29th-May 14th) so that flowers could be used to aid in both ground censuses and aerial surveys.

Image Processing and Ground Truthing

Flight images were stitched into an orthomosaic using Pix4D (Pix4D S.A. Lausanne, Switzerland). Our original intent was to use object-based image analysis (OBIA) in eCognition (Trimble Inc., Sunnyvale, California) to count the number of cacti in each image. However, after we determined that the software could not define a cactus as an object, we abandoned this method. Since cactus densities are relatively low (an average of 35 individuals per macro-plot), we determined that hand counting individuals from the images would be the best alternative. Remotely sensed images were loaded into ArcGIS Pro (Esri, Redlands, California) and clipped to the macro-plot boundaries. We then overlaid these clipped images with a 1 m^2 grid to ensure a consistent search scale and thorough coverage of the entire image (Figure 3). Potential cacti were marked based on a combination of hue, circular shape, size (approximately 1-8 cm), and visible flowers or buds. Pictures from the 10 m flights, GPS locations, and descriptions of each marked cactus point were then taken to the field and verified on the ground.

Analyses

Cactus counts between the different survey altitudes and ground censuses were compared using two techniques: 1) a validation data matrix adapted from Rominger and Meyer (2019) and 2) mixed effects modeling (glmer and lmer). In all analyses, a total of 14 flights were used for analysis at each flight altitude. One of the original 15 flights was not included due to distortion caused by high winds at the time of the flight.

Validation Matrix

For the validation data matrix, all potential cacti that were marked in the images were labeled "Marked". Each "Marked" cactus that was verified on the ground was labeled "Confirmed". The total number of cacti that were recorded during the ground census was labeled "Actual". Cacti that were not detected during the drone flights but were present on the ground were labeled "Missed". The validation data matrix also included three correction terms: errors of omission (EOO), errors of commission (EOC), and net error. These correction terms were determined using the criteria developed by Rominger and Meyer (2019). Errors of commission were defined as the ratio of cacti confirmed to the number of cacti marked. Errors of omission were defined as the ratio of actual cacti to the number of confirmed cacti. Net error was calculated in Microsoft Excel (2010) by multiplying the error of omission by the error of commission for each macro-plot flight and then taking the average. Correction terms were evaluated independently for each of the different survey altitudes.

Mixed Modeling

Generalized and linear mixed-effects regression (glmer and lmer) were conducted in R [20] (packages: lme4 [21], lmerTest [22], MuMIn [23]) to analyze cactus detection rates (%) and cactus counts (#) relative to flight altitude. Prior to conducting linear mixed-effects regression, each cactus was assigned to one of three diametric size classes as previously defined by Ronald Kass (2001): size class 1 (≤ 2.0 cm), size class 2 (2.1 cm-4 cm), and size class 3 (4.1 cm–9 cm). Count data were transformed using the square root transformation, and detection data were transformed to the logit scale to meet the assumptions of normality and homoscedasticity. Cactus detection rates (%) and cactus counts (#) were modeled individually using equation (1):

$$\text{Rates or Counts} \sim \text{Altitude} + \text{Size Class} + (\text{Altitude} * \text{Size Class}) + (1|\text{Site}), \tag{1}$$

Altitude of drone flight and size class were used as fixed effects while site was incorporated as a random effect to adjust for any variation due to image quality. Satterthwaite's approximation for degrees of freedom and the differences of least squares means were used to obtain difference estimates and *p*-values. Generalized linear mixed effects regression (glmer) was used to conduct logistic regression on the probability of detection relative to cactus diameter (cm). For this analysis, the data were configured into a binomial error structure and the following equation (2) was applied:

$$\text{Detection} \sim \text{Altitude} + \text{Diameter} + (1|\text{ID}) + (1|\text{Site}), \tag{2}$$

Altitude and diameter were included as fixed effects, while cactus ID and site were included as random effects.

RESULTS

Validation Matrix

The first objective of our study was to evaluate the effectiveness of drones in detecting and counting cacti relative to ground censuses. From the fourteen macro-plot locations where flights were conducted, a total of 480 cacti were detected during the ground censuses. From the 10 m flight imagery, a total of 284 objects were marked as cacti, of which 183 were confirmed to be cacti. From the 15 m flight imagery 234 objects were marked as cacti, of which only 89 were confirmed to be cacti. And from the 20 m flight imagery, 185 objects were marked of which 46 were cacti. More than twice as many cacti were detected in the 10 m imagery than in the 15 m imagery and nearly four times as many than in the 20 m (Table 1). A few cacti that were marked in the images were found to be dead, these points were not included in the confirmed category. It was imposible to distinguish live cacti from dead cacti in the remotely sensed images even at the lowest flight altitude.

The 10 m drone flights consistently produced the best results with the least amount of error. However, even at 10 m, 61.9% of all cacti were missed. At 15 m, 81.5% of cacti were missed, and at 20 m, 90.4% of cacti were missed (Table 1). As anticipated, the errors of commission (EOC) decreased as flight altitude increased, while error of omission (EOO) substantially increased as flight altitude increased.

Mixed Models

In support of our original hypothesis, our mixed model analysis of cactus counts and cactus detection rate (%) found that the 10 m drone imagery provided the best survey results (Figure 4-5). An average of three more cacti per macro-plot were counted in the 10 m imagery than in the

15 m ($p<0.001$), and six more than in the 20 m imagery ($p<0.001$). For size class 3, three more cacti were counted in the 10 m than in the 15 m ($p<0.08$), and five more than in the 20 m ($p<0.002$). For size class 2, two more cacti were counted in the 10 m than in the 15 m ($p<0.02$), and three more cacti were counted in the 10 m than in the 20 m ($p<0.001$). For size class 1, three more cacti were counted in the 10 m than in the 20 m ($p<0.08$), but the difference between the 15 m and the 10 m was not significant ($p<0.17$).

Our analysis of cactus detection rate (%) found that on average 17% more cacti were detected in the 10 m imagery than in the 15 m ($p<0.001$) and 31% more than in the 20 m ($p<0.001$). For size class 3, 21% ($p<0.05$) more cacti were detected in the 10 m than in the 15 m imagery and 37% ($p<0.001$) more than in the 20 m. For size class 2, 19% ($p<0.03$) more cacti were detected in the 10 m imagery than in the 15 m, and 44% ($p<0.001$) more cacti were detected in the 10 m than in the 20 m. For size class 1, there was no significant difference between detection rates at the different flight altitudes ($p<0.10$).

When we used logistic regression to analyze the probability of detection as a function of diameter, all factors were found to be significant. When the flight altitude increased from 10 m to 15 m, the log odds probability of detection decreased by 2.66 log units ($p<0.001$). When flight altitude increased from 10 m to 20 m, the log odds probability of detection decreased by 4.46 log units ($p<0.001$). And for every 1 cm increase in diameter, the log odds probability of detection increased by 1.27 log units ($p<0.001$; Figure 6).

DISCUSSION

While drones have been successfully used in a variety of vegetative studies [16,18,25], it is important to acknowledge that these technologies still have limitations. The first objective of our study was to assess the effectiveness of using drones to conduct Wright fishhook cactus surveys relative to ground surveys. Our results demonstrated that even at the highest resolution flights (0.25 cm GSD), detecting cacti remained an arduous task. With each image taking an average of 80 minutes to visually process for cacti, little time was saved compared to ground surveys, which took an average of 90 minutes. If flight times, image preparation, and processing times are incorporated into the time evaluation, the use of drones constituted an overall loss in time relative to ground censuses. Due to the low detection rates and high amounts of error obtained from all altitudes of drone imagery, it appears that drones (i.e. the DJI Phantom 4 Pro with 20 MP camera) are currently not an effective replacement for ground censuses of Wright fishhook cacti.

While the quality of the data collected through drone flights was inferior to ground surveys, there may still be benefits for their use. The counts obtained from the imagery can be multiplied by the net error term (Table 1) to obtain rough population estimates. Thus, if high accuracy count data is not requisite, drones could shift the workload from the short flowering period to other times of the year. Cacti were also discernable in all flight altitudes indicating drones may be of use in finding new populations. For rare and endangered plant species, drones may also reduce human disturbance in these often fragile environments by removing the need to walk among plants [18]. Improvement in image classification software toward high resolution imagery would likely significantly reduce processing time and would increase the practicality of using drones in rare plant surveys.

The second objective of our study was to determine the optimal altitude at which to conduct drone surveys for Wright fishhook cacti. While the 10 m imagery provided significantly better counts and detection rates than the 15 m and 20 m imagery, the gains remained marginal based on scale. To cover the flight areas of 1,250 m^2, drone surveys at 10 m took an average of 13 minutes to complete, while flights at 15 m took only six minutes, and flights at 20 m took only four minutes. The average battery life for the DJI Phantom 4 Pro is about 20 minutes (personal observation). Determining the true optimal flight altitude would largely depend on the size of area to be surveyed, time constraints, and the acceptable level of error. For an area of 1,250 m^2, 10 m was clearly the optimal altitude for conducting drone surveys.

CONCLUSION

In our study, drones did not prove an effective alternative to ground surveys for the endangered Wright fishhook cactus. However, they do provide land managers an alternative for finding new cactus populations, preventing potential disturbance while conducting ground surveys, tracking cactus populations over time, and obtaining rough population estimates. As groups and individuals continue to push the limits of these technologies, improvements will continue to be made. While drones certainly have potential to improve the quality and accuracy of vegetative surveys, they are not ready to replace ground suveys in every situation.

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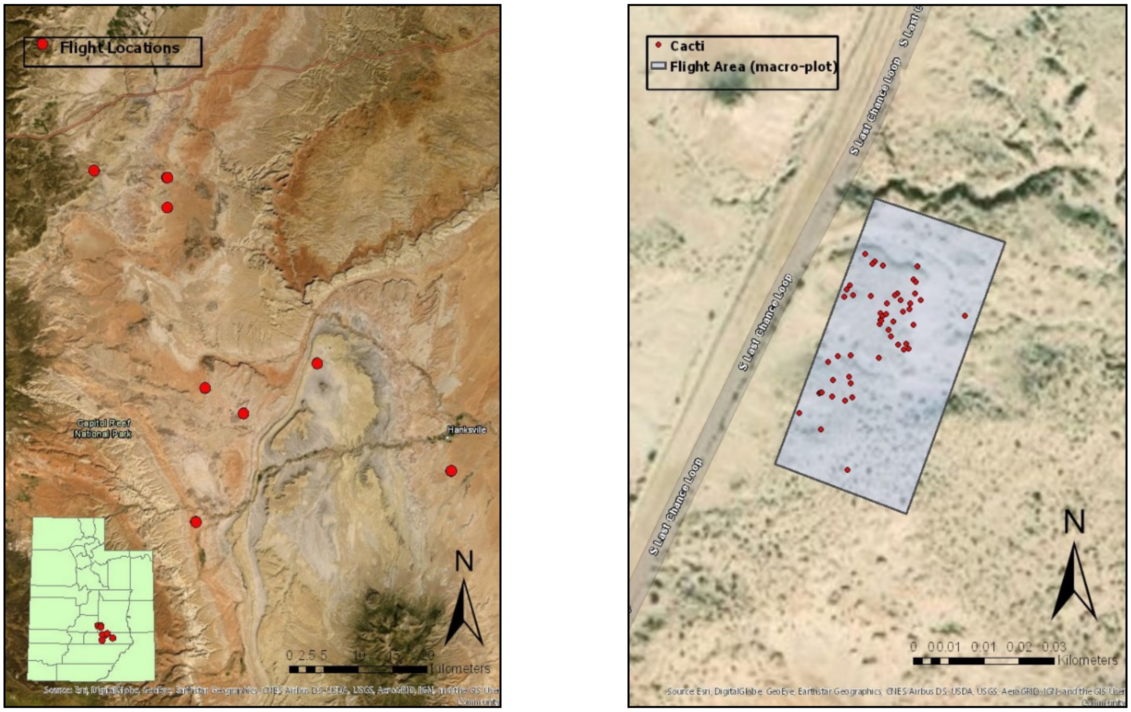
FIGURES

(**a**) (**b**)

Figure 3-1: (a) Example of habitat type where Wright fishhook cacti occur; (b) a mature Wright fishhook cactus in flower.



(**a**) (**b**)

Figure 3-2: (a) Flight locations; (b) enlarged map of one flight area (macro-plot).

(a) (b) (c)

Figure 3-3: Example of 1 m2 search scale at each drone flight altitude. Two size class 3 (>4.1 cm) individuals in flower are contained in each image: (a) 10 m (0.25 cm GSD); (b) 15 m (0.40 cm GSD); (c) 20 m (0.55 GSD).

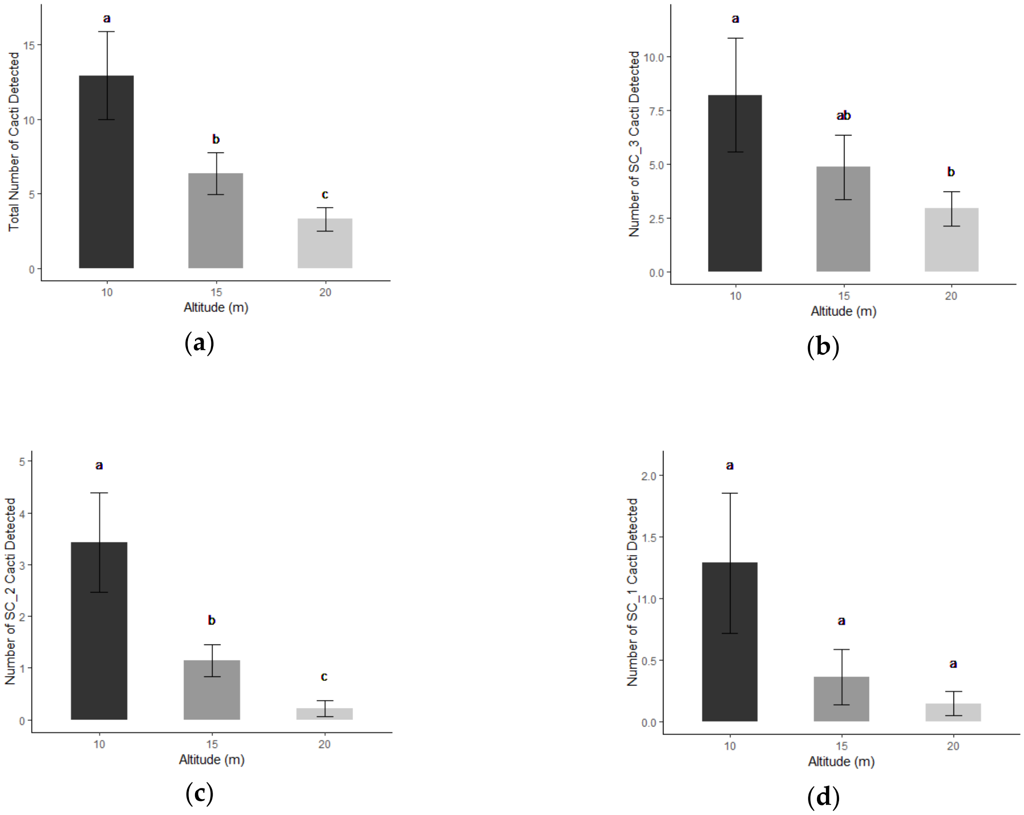


Figure 3-4: Mean number of counted Wright fishhook cacti per flight area (macro-plot) ± standard error of the mean by flight altitude (m). Means with common letters do not differ (*p*>0.05): (a) Total; (b) Size Class 3 cacti; (c) Size Class 2 cacti; (d) Size Class 1 cacti.

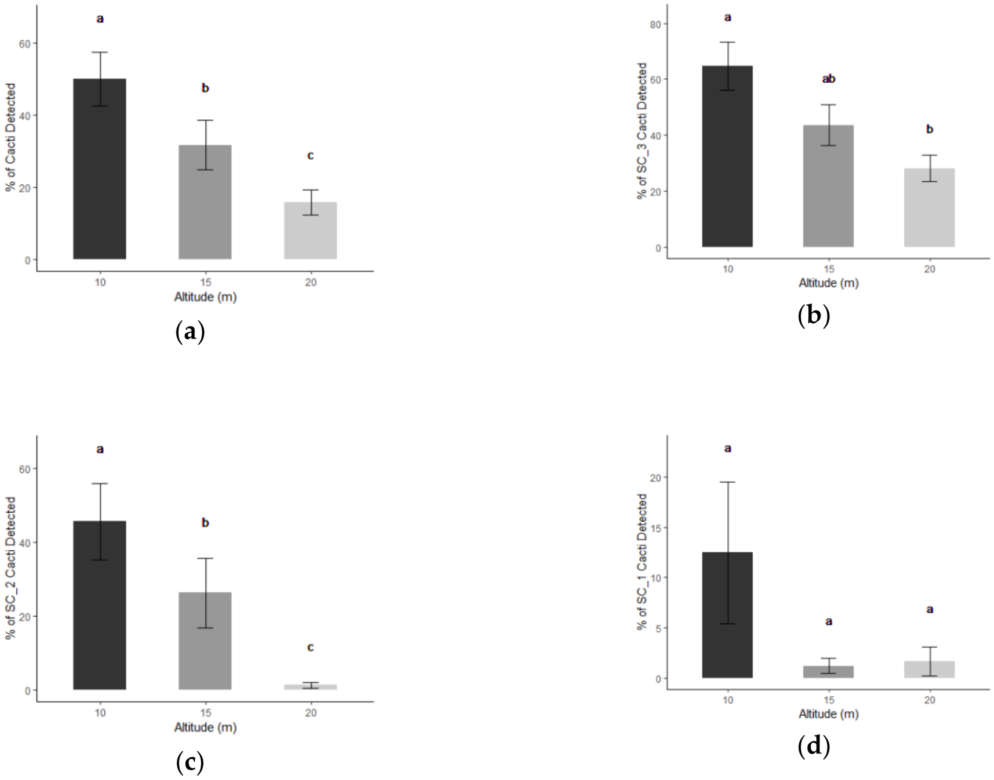


Figure 3-5: Mean percent of detected Wright fishhook cacti (total and by size class) ± standard error of the mean by flight altitude (m). Means with common letters do not differ ($p>0.05$). Means with common letters do not differ ($p>0.05$): (a) Total; (b) Size Class 3 cacti; (c) Size Class 2 cacti; (d) Size Class 1 cacti.

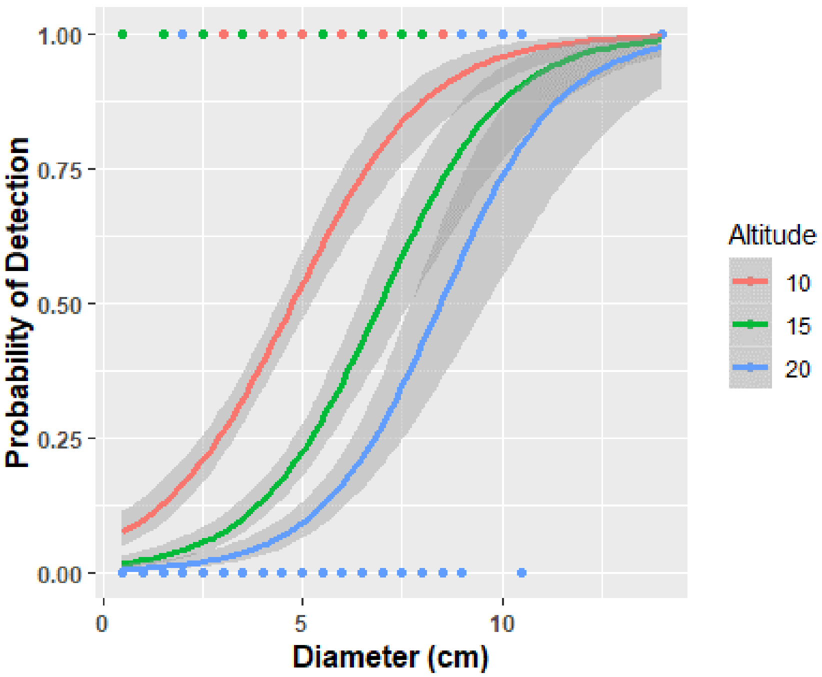


Figure 3-6: Probability of detection of Wright fishhook cacti ± standard error of the mean as a function of flight altitude (m).

TABLES

Table 3-1: Validation data matrix for drone imagery adapted from Rominger and Meyer (2019). Drone imagery was obtained from flights (n=14) conducted at 10, 15, and 20 m AGL. Potential cacti were marked at each of these altitudes and then verified in the field. Results were then compared against ground census surveys. Correction terms are expressed as mean values ± the standard error of the mean.

Drone Imagery	**Total Cactus Counts**				**Percent Confirmed**[1]	**Percent Missed**[2]	**Correction Terms**		
	Marked	Confirmed	Missed	Actual			EOC[3]	EOO[4]	Net Error[5]
10 m	284	183	297	480	64.7	61.9	.647 ± .049	2.81 ± 0.58	1.62 ± .202
15 m	234	89	391	480	41.6	81.5	.416 ± .059	6.18 ± 1.43	2.14 ± .486
20 m	185	46	434	480	26.6	90.4	.266 ± .047	13.71 ± 3.78	2.52 ± .433

[1] Percent Confirmed = (Confirmed/Marked)*100 (calculated as the mean of plot values); [2] Percent Missed = (Missed/Actual)*100 (calculated as mean of plot values); [3] EOC= Error of commission correction term = Percent confirmed/100; [4] EOO= Error of omission correction term = Actual/Confirmed; [5] Net Error Correction Term = EOC * EOO = Actual/Marked (calculated as mean of plot values).

CHAPTER 4

Using Resource Selection Function Analysis and GIS to Model Habitat for the Endangered Wright Fishhook Cactus (*Sclerocactus wrightiae* L.D. Benson)

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Master of Science

ABSTRACT

Identifying critical habitat for rare and endangered species is an integral step in the listing, recovery, and delisting processes [1–3]. However, many species have been listed without the proper designation of critical habitat [3]. Our objective was to create a predictive habitat model for one such species, the Wright fishhook cactus (*Sclerocactus wrightiae* L.D. Benson), using Resource Selection Function analysis and GIS technology. Employing a 10 m DEM, available geologic layers, and logistic regression, we were able to project relative cactus presence probabilities across its anticipated range. These efforts can help land managers focus search efforts in areas where cacti are most likely to occur. Our analysis indicated that geology, slope, and elevation were all significant factors in determining where the Wright fishhook cactus grows.

INTRODUCTION

Under the U.S. Endangered Species Act (ESA) of 1973, identifying critical habitat for species is an integral step in the listing, recovery, and delisting processes [1–3]. Indeed, the original intent of Congress was that each species listed would have critical habitat designated as part of the listing process [3]. However, if a species is thought to be threatened by human take or inadequate biological information exists relative to the species, a species may be listed as threatened or endangered without the mandatory designation of critical habitat [1,2]. Due to these two exceptions, nearly 90% of all listed species had not received a critical habitat designation as of 2001 [4]. Though litigation has pushed to address the backlog of designations, most species remain without defined critical habitat. One such species is the Wright fishhook cactus (*Sclerocactus wrightiae* L.D. Benson).

The Wright fishhook cactus is a small, globose cactus endemic to the San Rafael desert of south-central Utah [5,6]. In October of 1979, the U.S. Fish and Wildlife Service (USFWS) declared this species endangered due to its limited range and population size, as well as its popularity for field collection [7]. Although limited range was a justification for the original listing, only a small portion of its potential habitat had been surveyed (resulting in five known populations), and due to the threat from human take (field collection), critical habitat was not defined [7,8].

Since its listing, the federal agencies responsible for managing public lands where the Wright fishhook cactus is found (the Bureau of Land Management and National Park Service), have invested significant resources searching for cactus populations and documenting cactus attributes: location, diameter, stems, and reproductive effort [9,10]. As of 2013, more than 300 Wright fishhook cactus populations had been documented on federal land [10].

Range-wide population estimates for the Wright fishhook cactus have varied dramatically over the years. Early habitat inventories estimated a range-wide population of 50,000-100,000 individuals and called for an investigation relative to the appropriateness of delisting [10–12]. In 2005, a petition for delisting was denied by the USFWS, and a more conservative estimate of 4,500-21,000 individuals was accepted [13,14]. In 2013, the Bureau of Land Management

(BLM) reported having physically documented over 12,000 individual cacti from 2011-2013, which rendered a range-wide estimate of more than 50,000-100,000 [8]. While these estimates and surveys provide valuable information, they are highly variable and required hundreds of person hours to complete. They also lacked defined habitat for consistent extrapolation of cactus counts. Range-wide population estimates may be greatly improved by defining critical habitat using Geographic Information Systems (GIS) and Resource Selection Functions (RSF) modeling techniques.

Since its debut in the ecological literature, GIS has become a useful tool for mapping, characterizing, and modeling habitats. Some of the earliest work used GIS in combination with land cover data to model resource availability for White-tailed deer (*Odocoileus virginianus* Zimmerman) [15]. Others used the Habitat Suitability Index and GIS to create habitat models for wildlife [16]. As computing technology advanced, ecologists began to use RSF to correlate resource availability with presence and absence data. This presented a more sophisticated way to map habitat selection using statistical probabilities and geospatial data [17,18].

Much like RSF habitat models for wildlife, species distribution models (SDMs) for rare and endangered plants began to emerge in the late 1990's and have been applied to a variety of species [19]. These models can be identical to RSF in their use of GIS and logistic regression (LR) to identify and map potential habitat [20].

Our objective was to create a range-wide habitat model for the endangered Wright fishhook cactus using GIS and LR. We hypothesize that creating an accurate habitat model will improve population estimates and provide vital information relative to the designation of critical habitat.

MATERIALS AND METHODS

Study Area and Map Boundaries

The Wright fishhook cactus is endemic to the San Rafael Swell desert of Emery, Sevier, and Wayne counties, Utah. This cactus occupies habitats ranging from 1,280-2,320 m in elevation and is found on several geologic formations including: Mancos Shale, Dakota, Morrison, Summerville, and the Entrada [6,10].

Map boundaries for our habitat model were provided to us by the BLM. These boundaries were largely based on experience and ground documentation of Wright fishhook cactus populations, small-flower fishhook cactus populations (*Sclerocactus parviflorus* Clover & Jotter), and hybrid zones of the two species.

Habitat Model

From 2011-2018 the BLM recorded GPS coordinates for 12,480 individual Wright Fishhook cacti. These cacti represent all known localities on BLM land. Each cactus point was coded with a 1 for presence, and an equal number of random points were generated and coded with a 0 for absence. Using a 10 m digital elevation model from the Utah AGRC's State Geographic Information Database (SGID) and several geologic layers from the Utah Geological Survey [21–25] in ArcGIS Pro (Esri, Redlands, California), we assigned each point an elevation, slope, aspect, and geology. Geologies were then grouped into one of 14 categories: alluvium, Carmel formation, Cedar Mountain/Dakota formation, Curtis formation, Entrada formation, eolian, Mancos shale, Blue Gate member of the Mancos, Ferron Sandstone member of the Mancos, Tununk member of the Mancos, Morrison formation, Navajo Sandstone, Summerville formation, and Sills, Slumps, and Talus. This was done to ensure model convergence by having representative points in each group. A total number of 23,560 points were included in the analysis. We formulated 11 generalized linear models (glm) containing all combinations of elevation, slope, aspect, and geology. Model selection was completed in R (R-Core Team, 2018) (packages lme4 [27], MuMIn [28]) using Akaike's Information Criterion (AICc) [29]. Coefficients from the best fit model were placed in the LR equation (Eq.1) to obtain estimates for each pixel. Relative probability estimates were divided by quantile and projected across the study area as defined by the BLM.

$$p = \frac{exp(\beta_{\circ} + \beta_1 x_1 + \beta_2 x_2 + \ldots.+\beta_n x_2)}{(1 + exp(\beta_{\circ} + \beta_1 x_1 + \beta_2 x_2 + \ldots.+\beta_n x_2))} \qquad \text{(Eq.1)}$$

RESULTS

Our model selection process found that the top model for cactus presence included geology, elevation, and slope. Aspect dropped out of the top model. Elevation, slope, and all the geologies except for Mancos Shale and Tununk member of the Mancos were significant ($p<0.01$). As elevation and slope increased, probability of cactus presence decreased. The geology formations were ordered by probability (high-low) as follows: alluvium, Mancos Shale, Cedar Mountain/Dakota formation, Curtis formation, eolian, Morrison formation, Navajo Sandstone, Blue Gate member of the Mancos, Tununk member of the Mancos, Entrada formation, Carmel formation, Sills, Slumps, and Talus, Summerville formation, and Ferron Sandstone member of the Mancos.

The geologic quadrangle covering the area around Hanksville, UT, and the Manti quadrangle, show a disproportionate amount of high probability due to the lower resolution of geological surveys completed by the Utah Geological Survey. The map (Figure 1) displays probability in five categories: high, medium-high, medium, medium-low, and low. These five categories are color-coded on a gradient from red to yellow. Red indicates the highest probability of cactus presence and yellow indicates the lowest. Future ground truthing will be necessary to validate the model. Ground truthing and model validation may be accomplished by walking transects from roads to randomly generated points and recording cactus presence or absence (Figure 2).

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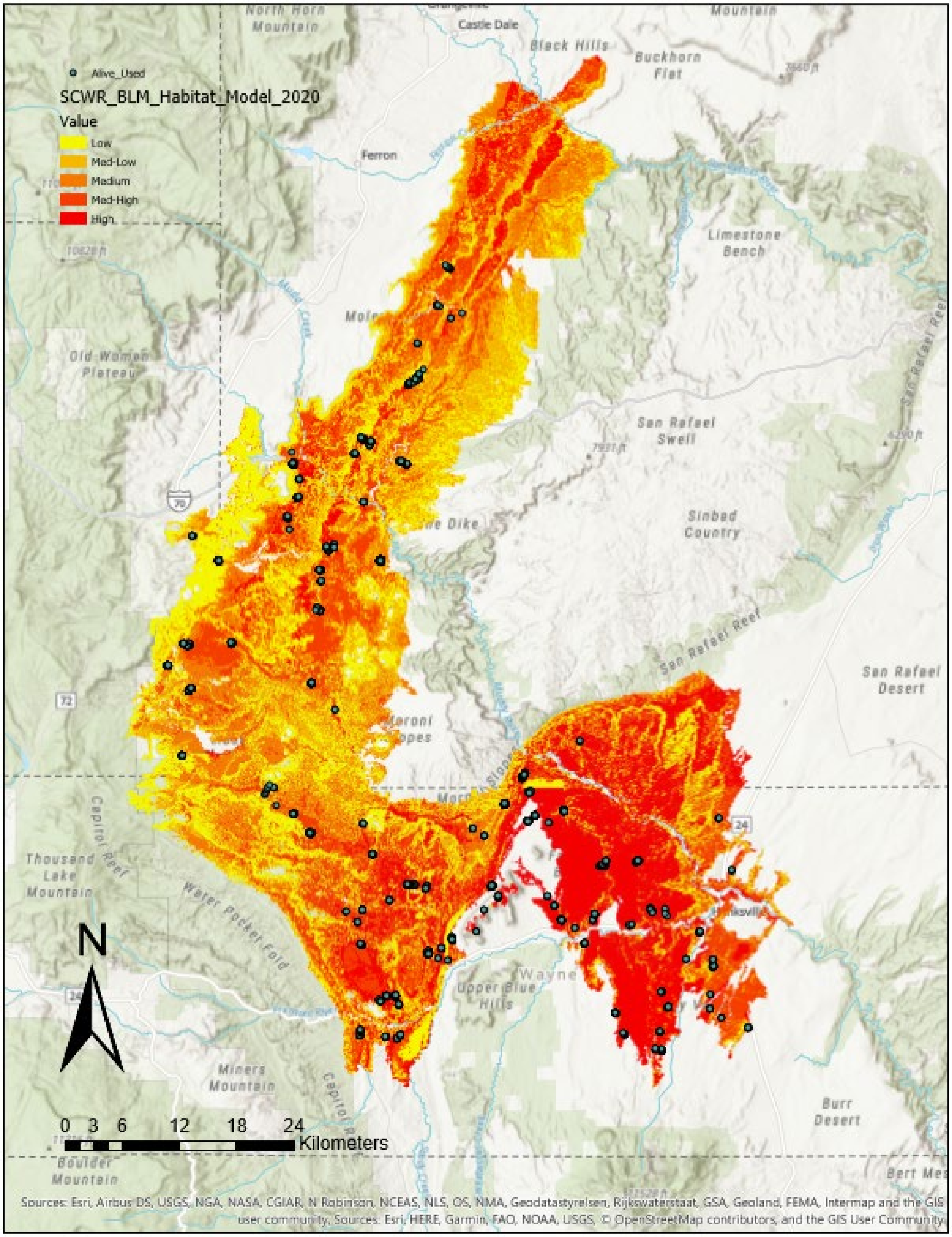
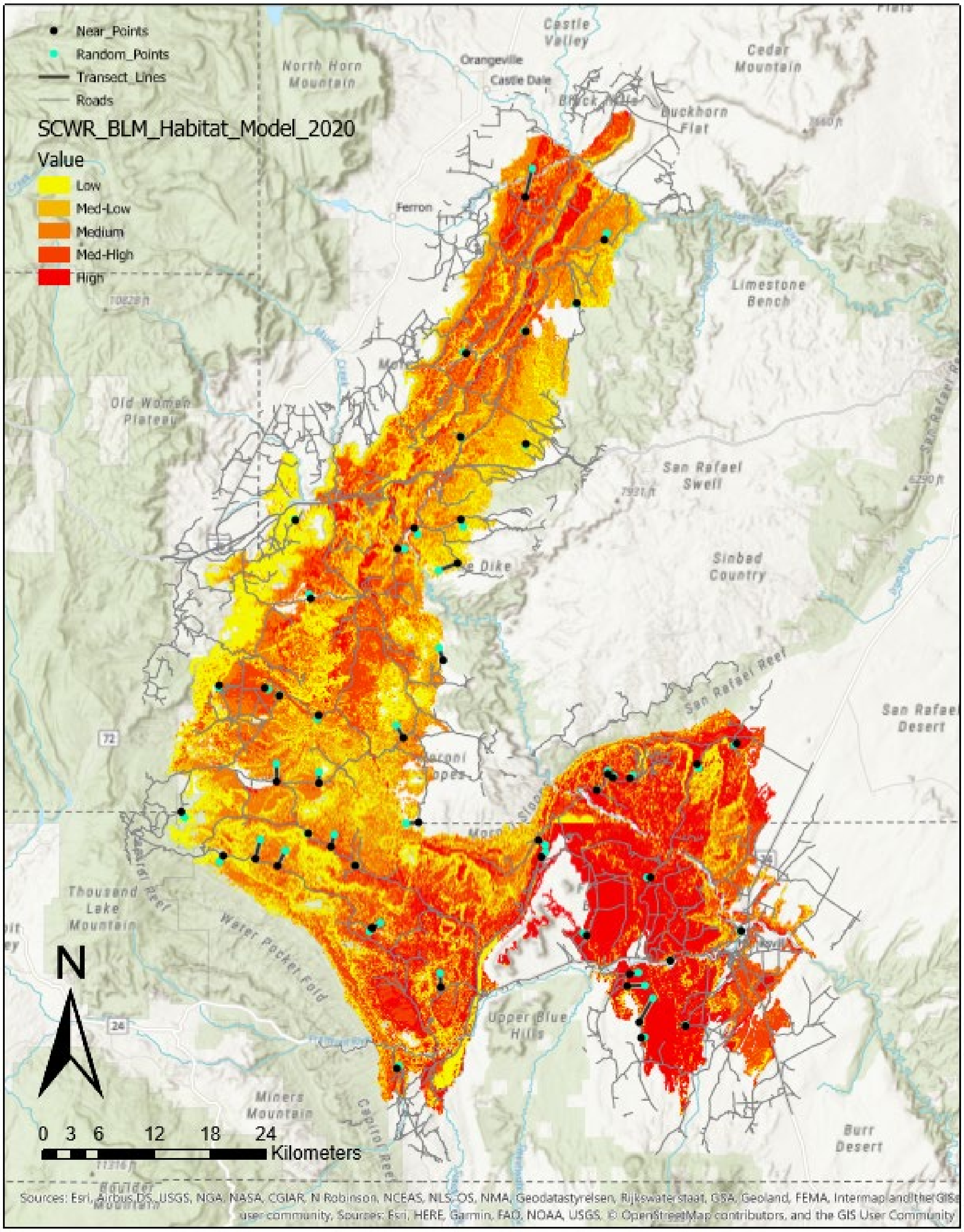
FIGURES



Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

Figure 4-1: Habitat model for Wright fishhook cacti (SCWR). Points represent known cacti locations. Relative presence probability is represented by a color scale from high to low. Red indicates high probability and yellow indicates low.



Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

Figure 4-2: Potential ground truthing and model validation protocol for the Wright fishhook cactus (SCWR) predictive habitat model. Light blue points represent random locations. Black points represent the departure points from the nearest roads (near points). Transects are deliniated by gray lines connecting the random points and the near points.