THE INFLUENCE OF VISITORS, HABITAT, AND METHODOLOGY ON MEXICAN SPOTTED OWL (*STRIX OCCIDENTALIS LUCIDA*) OCCUPANCY AND DETECTION IN A REMOTE CANYON ENVIRONMENT.

by

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DEDICATION

For my best bud.

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ABSTRACT

National Parks across America play an important role in protecting natural resources and providing access to recreation for visitors. However, these goals may come into conflict as visitation rates rise. Grand Canyon National Park in Northern Arizona is one of the most highly visited parks in the United States, with over 6 million visitors a year. Backcountry hiking and camping are popular activities in the park, and many highly visited hiking trails and campgrounds overlap with known breeding areas of a threatened species, Mexican Spotted Owl. In this thesis, I explore the intersection of recreation and wildlife conservation at this popular park through the lens of long-term occupancy of a threatened species. My aims are to (1) assess the potential impact of visitor use on long-term occupancy (2001 to 2021) of Mexican Spotted Owls at the Grand Canyon, and (2) evaluate the potential for autonomous recording units (ARUs) to complement current survey protocols. To assess long-term occupancy, I ran a multi-season occupancy model using 20-years of call-back survey data conducted in protected activity centers (PACs), along with measures of visitor use and habitat characteristics. To assess the use of ARUs, I ran a single-season occupancy model using three years of data, which was collected using autonomous recording units in PACs from 2019 to 2021. I found that visitor use in the Grand Canyon had no effect on owl occupancy, which remained stable across PACs over the 20-year study period. Owl occupancy remained high across the 20-year survey period and was strongly informed by habitat characteristics. Specifically, Mexican Spotted Owls occupied PACs with higher proportions of mixed shrubland habitat and

Supai formation. Conversely, owl occupancy decreased in PACs with more pinyon-juniper woodland habitat and Redwall Limestone. Assessing the use of ARUs as a complement to current protocol, ARUs were found to be a useful tool for supplementing traditional call-back surveys, particularly at PACs with extremely limited access. In particular, ARUs detected Mexican Spotted Owls with high probability early in the breeding season prior to the official call-back survey period, which allows managers to extend their monitoring period. In highly remote PACs, ARUs were more suitable than call-backs because they could collect more data with less effort. Incorporating this method into Spotted Owl survey protocol may be essential for improving monitoring of under-sampled locations, which is a critical component for assessing long-term trends for this species across its range.

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LIST OF ABBREVIATIONS

ARU	Autonomous Recording Unit
BLED	Band Limited Energy Detector
NPS	National Park Service
PAC	Protected Activity Center

CHAPTER ONE: MEXICAN SPOTTED OWL LONG-TERM OCCUPANCY IN A HIGHLY VISITED NATIONAL PARK

Abstract

National Parks across the United States provide extensive recreational opportunities to visitors and protect critical habitat for wildlife species. Balancing the impact of the growing number of visitors on wildlife is an important mission of parks. Long-term monitoring programs are conducted in parks to ensure that wildlife populations are not being negatively impacted by increased visitation. These programs also contribute information about wildlife that can be scaled up to help predict the possible consequences to the species outside of park boundaries. Grand Canyon National Park in Northern Arizona sees over 6 million visitors per year. Over a quarter million of those visitors traverse the inner canyon, which is occupied by several threatened and endangered species. One threatened population of interest, Mexican Spotted Owl (*Strix occidentalis lucida*), occurs in fragmented patches of rocky canyons across the Southwestern United States, including the Grand Canyon. Since 2001, National Park Service biologists have monitored the population of Mexican Spotted Owls in known breeding areas in the inner canyon during the breeding season using territorial call-back surveys. From this 20-year data set, I developed a multi-season occupancy model to evaluate long-term demography of this species at the park. I assessed the potential effects of increased visitor rates and a suite of habitat characteristics on occupancy, while also accounting for detection. The number of overnight visitors camping in the backcountry

fluctuated spatially in the park. However, there was no apparent effect of visitors on occupancy of owls, even in highly visited areas. There was lower occupancy of Mexican Spotted Owls in pinyon-juniper woodland habitat, primarily consisting of Utah juniper (*Juniperus osteosperma*) and Colorado pinyon (*Pinus edulis*), and higher occupancy in mixed shrub habitat, indicating owls may have occupied cover types that have higher capacity to support a relevant prey population. Overall, Mexican Spotted Owl occupancy increased slightly over the last two decades. These results suggest that Grand Canyon National Park is balancing the trade-offs between protecting Mexican Spotted Owl habitat while providing backcountry recreation opportunities for visitors.

Introduction

Grand Canyon National Park in Northern Arizona is one of the most popular National Parks in the United States. Visitation to the park has increased from two million visitors per year to over six million visitors from 1970 to 2018 (National Park Service IRMA: Annual Park Recreation Visits). Overnight camping in the backcountry of the Grand Canyon has increased as well, with a record 350,000 campers in 2018 (National Park Service IRMA: Overnight Stays). The period of highest visitation, March to October, overlaps with the breeding season of multiple raptor species in the canyon, including federally threatened Mexican Spotted Owls (*Strix occidentalis lucida*). This subspecies of Spotted Owl occupies old growth forests and rocky canyons across the desert southwest (U.S. Fish and Wildlife Service, 2012) and were first recognized as breeders in the Grand Canyon in 2001 (Willey & Ward, 2003). Like other Spotted Owl subspecies, Mexican Spotted Owls are threatened by a loss of suitable habitat, which may be attributable to timber harvest, land development, and wildfires (U.S. Fish and Wildlife Service, 2012). In addition to pressures imposed by habitat loss, these owls are also sensitive to disturbance (Delaney et al., 1999; Swarthout & Steidl, 2001; Swarthout & Steidl, 2003).

In general, human disturbance is classified as either consumptive (i.e., hunting or fishing) or non-consumptive, where the species experiences changes to their behavior or demography as a result of human activity (Blanc et al., 2006). While there is considerable research into the effects of consumptive activities on the management of wildlife populations (Simard et al., 2013; Wilson et al. 2016; Harborne et al., 2018), more work could be done to explore the effects of non-consumptive activities on wildlife. Of the studies that have explored this, many focus on responses in animal behavior (Swarthout & Steidl, 2001; Longshore et al., 2013; Selman et al., 2013). Assessing behavioral responses of wildlife can be an informative way to learn about temporary impacts to a species. For example, Spotted Owls studied in Capitol Reef, Canyonlands, and Zion National Parks in Southern Utah, spent less time handling prey and exhibiting maintenance behaviors, and increased the number of contact calls transmitted between mates when hikers were present (Swarthout & Steidl, 2001; Swarthout & Steidl, 2003). Equally as important to assessing behavioral responses in wildlife is assessing the long-term effects of disturbance on demography, which may provide important clues about concerning trends in a population. There is little knowledge about the potential impacts of sustained visitor presence on long-term occupancy of Spotted Owls across their range, despite a long history of monitoring programs across National Parks since these owls were listed as threatened in 1993 (U.S. Fish and Wildlife Service, 2012). Continued occupancy in breeding areas year after year (i.e., persistence) may suggest minimal disturbance to individuals (Lombardi et al., 2018), while decreased use with high rates of recreation through time would be an obvious concern. Previous reports called for further research into how off-trail recreation impacts owl occupancy (Bowden et al., 2015). However, to date the potential impacts of visitor presence on long-term Spotted Owl occupancy in breeding areas has not been assessed in the Grand Canyon.

In addition to the potential effect of park visitors, the availability of suitable habitat may also influence Spotted Owl occupancy in Grand Canyon National Park. Most studies that assess Spotted Owl habitat use have occurred in forested areas (Ganey & Balda, 1994; Seamans & Gutiérrez, 1995; May et al., 2004). Mature, old-growth forest, high canopy cover, and steep slopes are all associated with Spotted Owl nest and roost sites in forested areas (May et al., 2004; U.S. Fish and Wildlife Service, 2012). Less is known about their preferences in canyon environments. Spotted Owls home ranges along the Colorado Plateau in Utah included desert scrub or pinyon-juniper woodland habitat (found at 17 and 42% of plots across home ranges respectively) and canyons lined with very steep cliffs (Willey & van Riper III, 2015). Focusing specifically on Zion National Park in southern Utah, Spotted Owls occupy narrow canyons, typically with a source of water (Rinkevich & Gutierrez, 1996). At the Grand Canyon, Mexican Spotted Owls choose nests and perching locations (roosts) in relatively narrow side-canyon draws containing Redwall Limestone and Muav Limestone cliffs (Bowden et al., 2015). Their home ranges in general contain pinyon-juniper (*Juniperus osteosperma* and *Pinus edulis*) vegetation (Bowden et al., 2015), similar to the findings by Willey and van Riper (2015) in Utah.

My aim was to assess the potential impact of landcover types and park visitor-use on occupancy of Mexican Spotted Owls at Grand Canyon National Park using data collected over the last two decades. I used a multi-season approach to jointly model occupancy and detection probabilities in protected activity centers (PACs) within the park, monitored from 2001-2021. PACs are management units that encompass a minimum of 242 hectares (600 acres) around an identified Spotted Owl nest or roost location. Owls were not limited by the PAC boundaries, but the side-canyon draws that encapsulated most PACs provided ample topographic barriers separating one PAC from another. Thus, PACs essentially served as a proxy for a nesting owl breeding areas and were the units at which I extracted site level covariates. I made two primary predictions:

(1) that increased visitor use in PACs would have a negative effect on Spotted Owl occupancy, and (2) habitat characteristics, such as vegetation classes and topographic features, would have a positive effect on owl occupancy.

Methods

Study Site

Grand Canyon National Park encompasses 4,931 km^2 (493,059 ha) of public land in Northern Arizona, managed by the National Park Service (NPS). The park is approximately 200 km east of Las Vegas, Nevada, and 100 km northwest of Flagstaff, Arizona. The climate is dry, with low humidity and an average of 31 cm of precipitation annually over the course of this study (Lawrimore et al., 2016). The canyon changes by over 2,000 m in elevation from the lowest point at Lake Mead, Nevada (375 m) to the North Rim (2,682 m), and as a result it supports a variety of habitat types (Huisinga et al., 2006; Kearsley et al., 2015). The North and South Rims of the park are predominantly pine/oak and mixed-conifer forests, with pinyon-juniper woodlands along the canyon rim (Kearsley et al., 2015). The inner canyon is characterized by steep rocky cliffs, desert scrub vegetation, and side-canyon riparian systems with perennial and ephemeral water sources (Huisinga et al., 2006). These side-canyon draws are where most Mexican Spotted Owl PACs have been identified.

Data Collection

The NPS delineated a total of 54 Mexican Spotted Owl PACs in Grand Canyon National Park from 2001 to 2021 following U.S. Fish and Wildlife Service Mexican Spotted Owl survey protocol. Because of difficult access and limited staff, only a subset of PACs are surveyed each year (range: 0 – 32 yrs.), with the objective of surveying all PACs within a five-year period. Surveys were conducted between March 1st and August 31st using call-back methods (Forsman et al., 1984), where surveyors mimic the call of a Spotted Owl to elicit a response. Common hoots used by surveyors include four-note hoots and contact calls, which make up a large proportion of Spotted Owl vocalizations (Ganey, 1990). Surveyors hooted from stations spaced 400 to 800 m apart across the PAC, every 60 to 90 seconds for 15 minutes, followed by a five-minute listening period (U.S. Fish and Wildlife Service, 2012). Additionally, surveys were conducted using alternative passive methods such as a parabolic dish, a device used from the rim of the canyon to amplify the sounds coming from the inner canyon below, and more recently, autonomous recording units (ARUs), which record sound, including owl hoots. However, these data were excluded from this analysis because they were passively collected, whereas call-back data were actively elicited from owls, and were therefore not directly comparable (i.e., would need an integrated approach to be used in the same model). Auditory or visual observations of either a single or a pair of Spotted Owls on a call-back survey were treated as a single owl detection for the purposes of this analysis.

Factors Affecting Occupancy and Detection

I evaluated the potential effect of the following factors on Mexican Spotted Owl occupancy: vegetation classes, backcountry visitation, canyon geometry, PAC area, and day of the year (Table 1.1). Factors that could have affected detection rate included the day of the year the survey took place (to account for phenology in the breeding season), and PAC area (the area of the owl PAC, measured in km^2), supplied by the National Park Service (NPS, personal communication).

Vegetation classes were characterized by the Grand Canyon National Park-Grand Canyon Parashant National Monument vegetation classification and mapping project (Kearsley et al., 2015). Only the most dominant vegetation classes distributed across all Spotted Owl PACs were included in the analysis. These included: Blackbrush (*Coleogyne* *ramosissima*), mixed shrubland (e.g., Q*uercus turbinella*, *Arctostaphylos sp.*, *Cercocarpus intricatus*, and *Artemisia tridentata*), and pinyon-juniper woodland (e.g., Utah Juniper (*Juniperus osteosperma*) and Colorado Pinyon (*Pinus edulis*)). I predicted that owl occupancy would increase with an increase in the proportion of vegetation within a PAC, likely because more vegetation would support more abundant prey communities.

Backcountry visitation data were supplied by the backcountry division of Grand Canyon National Park (Sullivan, personal communication). The total number of overnight visitors were collected monthly for each of 92 use-areas in the park. These range in accessibility from very remote areas that typically receive lower visitation, to those closer to developed areas, which typically receive higher visitation (Fig. 1.1). Spotted Owl PACs typically fell completely within one use-area. I therefore defined visitor use as the number of overnight visitors from the use-area associated with each PAC. In cases where PAC boundaries overlapped more than one use-area, I used visitor statistics from the use-area that contained most of the PAC. I assessed monthly variation in visitor use during the Mexican Spotted Owl breeding period, as well as among the years. Overall, there was low variability at either the monthly or yearly levels, which was likely related to NPS permit limitations that restrict the number of overnight visitors in each use area of the canyon. Thus, averaged the number of visitors for each use area across years (range: 0 – 1215 visitors).

Typically, PAC boundaries mirror the topography of the side-canyon draw that it contains, which means smaller PACs often have more narrow canyons and larger PACs have more broad canyons. I defined canyon geometry as the narrowness of the tributary side canyon containing the PAC. I used Google Earth to measure the angle of opening between two sheer slabs of Redwall Limestone that form the walls of these side-canyon draws. Redwall Limestone is one of the preferred habitat types for Mexican Spotted Owl nesting and roosting in the Grand Canyon (Bowden et al., 2015), likely related to the high number of caves and overhangs this rock formation supports (Babcock et al., 1974). In the case where the side-canyon containing a PAC had two distinct draws, the larger of the two was used.

Statistical Analysis

I used a multi-season occupancy model to estimate occupancy for each PAC during each breeding season, while accounting for imperfect detection (Kéry & Schaub, 2012). I originally considered a dynamic model that partitioned occupancy into colonization and persistence parameters following methods described by MacKenzie et al. (2003) and Kéry & Schaub (2012). However, the high number of missing values during some years for several PACs, and very low values of colonization impeded convergence. Therefore, I simplified the multi-season occupancy model to only include occupancy. Occupancy was conditional on detection and was related to pinyon-juniper woodlands, Blackbrush, and mixed shrub habitat, which were included as fixed effects. Probability of detection was related to the day of the year and PAC area, which were also included as fixed effects. I included year as a random intercept in the observation and detection sub-models to account for repeated measures in sampling, and annual variance unaccounted for by predictor variables. Prior to analysis, I examined potential multicollinearity concerns using Spearman’s correlation analysis and removed one variable of a pair if |r| > 0.6. All predictor variables were centered at the means and divided by one standard deviation to allow for comparison.

Priors for the yearly random intercepts were distributed as ~Normal (0, σ^2) and their standard deviations were given Student-t priors (distributed as ~t (0, 2.5, 7) (Gelman et al., 2008). Priors for fixed effects were distributed as Normal ~ (0, 10), with a slightly tight variance to provide some level of regularization. Priors for the mean response (either occupancy or detection probability) were distributed as a Beta ~ (4,4) that were centered around zero and linked to the intercept of the sub models as: intercept = log (mean/1 – mean). I assessed model fit using the deviance of the observed data from the data predicted by the model, which I plotted at the PAC and season level (Cruz et al., 2019) and used it to calculate a Bayesian p-value, which is a measure of how much the data simulated by the model deviates from the observed data, with values closer to 0.5 suggesting good fit (Gelmen, 2013; McElreath, 2019).

Models were fit in R v4.1.2 (R Core Team, 2021), and package *jagsUI* (Kellner, 2021). I ran five chains of 70,000 iterations, burned the first 10,000 and thinned every five. All chains converged for all models with no divergent transitions, and all r-hat values were below the set limit of 1.02 (Gelman & Rubin, 1992; McElreath, 2019). The model fit well to the data (Bayesian p-value of 0.64). Deviance between observed and predicted data was relatively consistent across the study period. Exceptions include 2008 to 2010 when no surveys occurred, and during 2011, 2020 and 2021 where deviance values possibly reflect low sampling efforts (Appendix A, Fig. 1).

Results

Survey effort across the study period was highly variable (Fig. 1.2), with lowest effort from 2008 to 2010 when no PACs were surveyed, and highest in 2013 when 32 PACs were surveyed (mean: 10 PACs per year). In the five years leading up to the conclusion of this study, 29 PACs were surveyed within a five-year time frame. However, nearly half of the PACs (44%) were surveyed less than four times across the 20-year study using call-back surveys. This is most likely because of their remote nature and difficult access. Mexican Spotted Owls were detected in 57% of call-back surveys. Most PACs (84.9%) had at least one Spotted Owl detected over the course of the study period.

The probability of occupancy of Mexican Spotted Owls across all PACs over the 20-year survey period was high (mean: 0.78, 90% CI: 0.26 – 0.99), increasing slightly over the course of the study period (Fig. 1.3). There were nine PACs that had so few surveys that occupancy probability could not be estimated. The number of overnight visitors and canyon geometry had no effect on Mexican Spotted Owl occupancy probability (Fig. 1.4). However, vegetation composition of the PAC was important. Pinyon-juniper woodland had a strong negative effect on occupancy probability (mean: -0.65, 90% CI: -1.53 – 0.05), while mixed shrub habitat had a strong positive effect (mean: 0.99, 90% CI: -0.16 – 2.51) (Fig. 1.5). Thus, the chances of a PAC being occupied by Mexican Spotted Owls increased nearly three times when at least 60% of the PAC was covered in mixed shrubs, and the chances decreased by nearly three times when at least 60% of the PAC was covered in Pinyon-Juniper habitat. Blackbrush trended towards having a positive but weak and more uncertain effect on occupancy (mean: 0.51; 90% CI: – 0.19 to 1.63).

Mean detection probability of Spotted Owl was relatively high (mean: 0.57, 90% CI: 0.35 – 0.76). Like I did with occupancy probability, I also assessed differences in detection probability at the PAC levels. Detection was mostly consistent across the study period and was generally high, ranging between 0.43 and 0.71. Detection probability could also not be estimated for nine PACs because of low or no surveys. Neither PAC area nor day of the year were important predictors of detection probability (Fig. 1.4).

Discussion

National Parks have a responsibility to protect biodiversity while also facilitating opportunities for recreation. Evaluating how population dynamics of threatened wildlife are impacted by anthropogenic stressors in National Parks is important for understanding long-term impacts to threatened species over time in these highly visited landscapes. I used a 20-year dataset comprising call-back surveys from 54 Mexican Spotted Owl PACs to assess the impact of habitat and visitation on the occupancy probability of owls occupying these locations over multiple decades. Despite the spatial variability in the number of overnight visitors to the backcountry in one of the most popular National Parks in the country, visitor presence had no apparent effect on Spotted Owl occupancy in PACs. Owls were more likely to occupy PACs with a high proportion of mixed shrubland habitat. Interestingly, I found that Spotted Owls avoided occupying PACs with higher proportions of pinyon-juniper woodlands, which contradicts previous research. Overall, of the predictors included in this study, habitat was the biggest predictor of occupancy.

Shrublands are scattered across the geologic formations and elevations below and above the rim of the Grand Canyon (Kearsley et al., 2015). These shrub habitats are likely to be used by small mammal communities for cover and food (Parmenter & MacMahon, 1983). Desert woodrats (*Neotoma lepida*) and white-footed mice (*Peromyscus leucopus*) are common prey species widely distributed across the southwestern United States (Stones & Hayward, 1968; Bedford & Hoekstra, 2015). These species comprise 92% of Mexican Spotted Owl diet by biomass in the Grand Canyon (Willey, 2013). The observed relationship between shrubland habitat and owl occupancy, may be attributed to an owl's dependency on small mammals for food (Ganey 1992; Block et al., 2005; Willey, 2013), and mammals' dependency on shrub habitat (Stamp & Ohmart, 1979). There may be additional habitat characteristics that may impact Spotted Owl occupancy. For example, like other desert environments, the Grand Canyon has ephemeral sources of water that create riparian systems (Huisinga et al., 2006). In a similar landscape nearby, Zion National Park, Spotted Owls were linked to areas with a source of water (Rinkevich & Gutierrez, 1996). There has been links between rodent density and riparian woodlands in the desert (Stamp & Ohmart, 1979). If this is the case at Grand Canyon, then riparian systems are likely to be a feature that influences where a Spotted Owl chooses to occupy as well. Unfortunately, at the Grand Canyon information about ephemeral water sources within owl PACs was lacking and was therefore unable to be incorporated into the model.

Visitors to the backcountry did not appear to negatively impact long-term occupancy of owls in historic PACs in Grand Canyon National Park, even in areas with very high visitor use. One potential reason may be related to the vertical separation between where visitors camp on the canyon floor, and where Spotted Owls nest and roost, which is often high up on canyon walls. Spotted Owl home ranges include primarily cliffs and ledges in Redwall Limestone, Muav Limestone, as well as the Supai Group (Bowden et al., 2015). These geologic layers can tower over 200 m above the canyon floor. Spotted Owls in other highly visited National Parks across the canyonlands in Utah experienced minimal negative effects to the presence of hikers (Swarthout & Steidl, 2003). Occupancy for other owl species also appear to be minimally affected by human disturbance. For example, Great Gray Owl occupancy (*Strix nebulosa*) in

Yosemite National Park was mainly driven by prey availability instead of the indirect effects of recreational activities and development (defined as the linear meters of hiking trails, roadways, campgrounds, and the presence of fire rings) (van Riper III et al., 2013). Despite this, future research should continue to investigate how additional anthropogenic disturbance factors such as rock climbing and helicopter overflights, affect population dynamics of threatened wildlife in recreation areas.

Neither day of the year nor size of the PAC were related to detection probability of Mexican Spotted Owls in Grand Canyon National Park. While Spotted Owls may be the most vocal early in the breeding season (Ganey, 1990), callback surveys appear to elicit responses throughout the breeding season. Care should still be taken when using this method, as call-back surveys may also elicit responses from sympatric and predatory species, such as Great Horned Owls (*Bubo virginianus*), which may affect calling behavior of Spotted Owl. Barred Owls (*Strix varia*), a known Spotted Owl predator, affect detection of Northern Spotted Owls (Olson et al., 2005). Protocols require stopping call-back surveys if a potential competitor or predatory owl calls rather than a Mexican Spotted Owl. An additional safeguard could include relying on alternative survey methods, such as passive acoustic recorders at sites where non-desired calls are being elicited by call-back surveys.

Overall, occupancy of Mexican Spotted Owl PACs was high across two decades of monitoring at Grand Canyon National Park. Unfortunately, survey efforts were highly variable over the sampling period. There were at least six PACs that showed a particularly high variance suggesting that increased sampling of these PACs should be prioritized in the future. While Grand Canyon National Park has been monitoring

Mexican Spotted Owls for over 20 years, call-back surveys have not been conducted in a consistent manner. This may be a direct reflection of the remoteness, inaccessibility, and hazardous nature of the terrain, which hindered consistent monitoring of some PACs. Using the call-back method alone to reach the prescribed objective of surveying all 54 PACs over five years, is really challenging with allocated resources. I recommend the focus be placed in the next few years on surveying PACs that have been minimally surveyed so far, and that therefore have high uncertainty around their occupancy estimates. This could be achieved with the incorporation of complementary survey methods, such as autonomous recording units that may be more time efficient (Darras et al., 2019).

Contrary to my expectations, Mexican Spotted Owl occupancy appears to be minimally affected by disturbance from visitors at Grand Canyon National Park. However, these results tell us nothing about additional facets of demography that may be affected by visitation, such as breeding success. Without additional information about individual owls, and more information about their nesting behaviors, there are still unanswered questions about whether owls are being successful and persisting at historic PACs, or if other individuals are replacing pairs with a high turnover rate. While Spotted Owls do appear to have stable occupancy at historic PACs, there are still unanswered questions about the population in this region. For example, these owls are seemingly choosing to occupy the canyon habitat repeatedly, despite appropriate forest habitat nearby (U.S. Fish and Wildlife Service, 2012). This may indicate that the population is still be too small to expand beyond the apparent preferred habitat into the less preferred habitat. Like Grand Canyon, other National Parks across the country aim to provide access to outdoor recreation and to conserve wildlife. This study suggests that demonstrates that accomplishing both goals is possible. Park Service units should continue to support long-term monitoring programs for threatened and endangered species to track the effect of rising visitation rates, as well as other threats that may arise.

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Tables

Table 1.1 Predictor variables included in a multi-season occupancy model estimating Mexican Spotted Owl occupancy while accounting for imperfect detection at Grand Canyon National Park from 2001 – 2021. Shaded area indicates variables associated with occupancy probability, and the unshaded area indicates variables linked to the probability of detection.

Predictor	Level	Description	Source	Prediction
Blackbrush (%)	Site	Percent of Spotted Owl PAC classified as Blackbrush vegetation.	Kearsley et al., 2015	Blackbrush (%) will increase with Spotted Owl occupancy.
Visitors	Site	The number of overnight backcountry campers averaged at the PAC level from 2010– 2019.	Sullivan, 2021	As the number of visitors camping in a PAC increases, Spotted Owl occupancy will decrease.
Canyon Geometry	Site	Angle measuring the narrowness of the tributary side canyon.	Measured in ArcMap 10.8	As canyon geometry increases, Spotted Owl occupancy will decrease.
Mixed Shrub (%)	Site	Percent of PAC classified as mixed shrubland vegetation.	Kearsley et al., 2015	Mixed Shrub (%) will increase with Spotted Owl occupancy.
Pinyon– juniper (%)	Site	Percent of PAC classified as pinyon– juniper vegetation.	Kearsley et al., 2015	Pinyon– juniper (%) will increase with Spotted Owl occupancy.
PAC Area	Site	PAC area (km^2).	National Park Service, 2014	As PAC area increases, Spotted Owl detection will decrease.
Day of Year	Survey	The day the survey took place.	National Park Service, 2021 and Field data	As the day of the year increases, Spotted Owl detection will decrease.

Figures

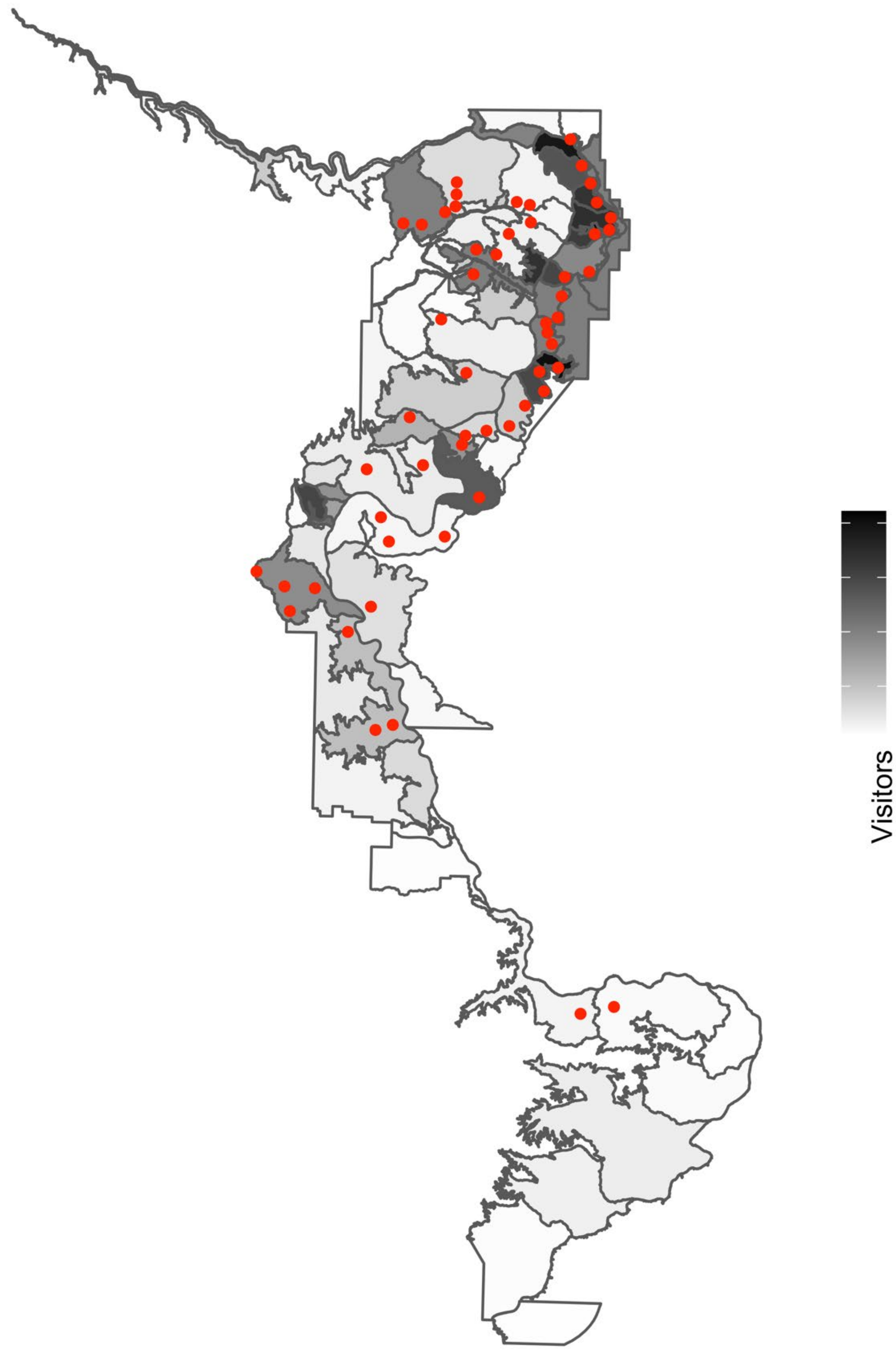

Figure 1.1 Visitor use-areas across Grand Canyon National Park, Arizona, with Mexican Spotted Owl PAC centroids indicated in red (NPS, personal communication). The number of visitors (shown here as the average number of people) camping in a use-area over the course of this study (2001 – 2021) increases with darkening of the grayscale.

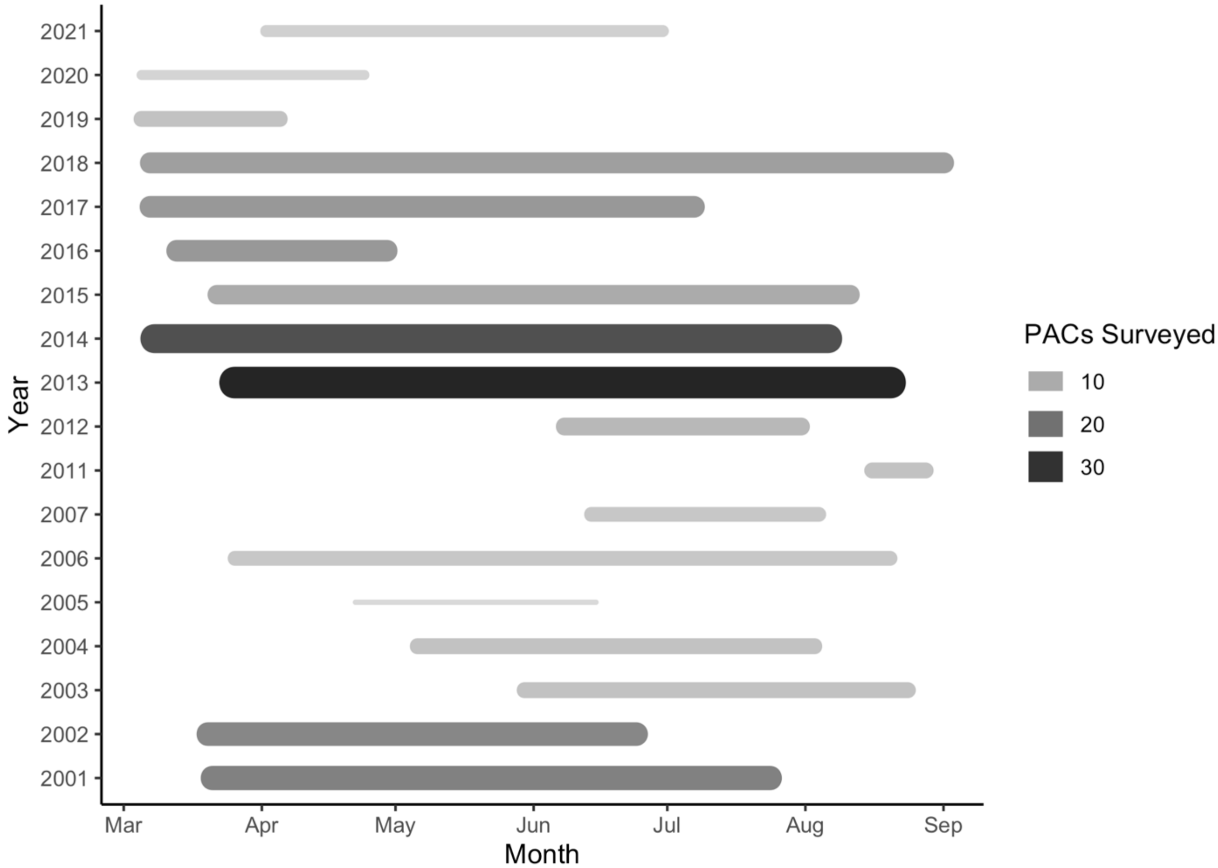

Figure 1.2 The number of Mexican Spotted Owl PACs monitored each year (y axis) during the breeding season (x axis) at Grand Canyon National Park. Line thickness and color intensity represent the number of PACs, and line length indicates the span of surveys by month. To be included on this plot, a PAC had to be visited at least 1 time. No PACs were monitored using call-back surveys from 2008 – 2010.

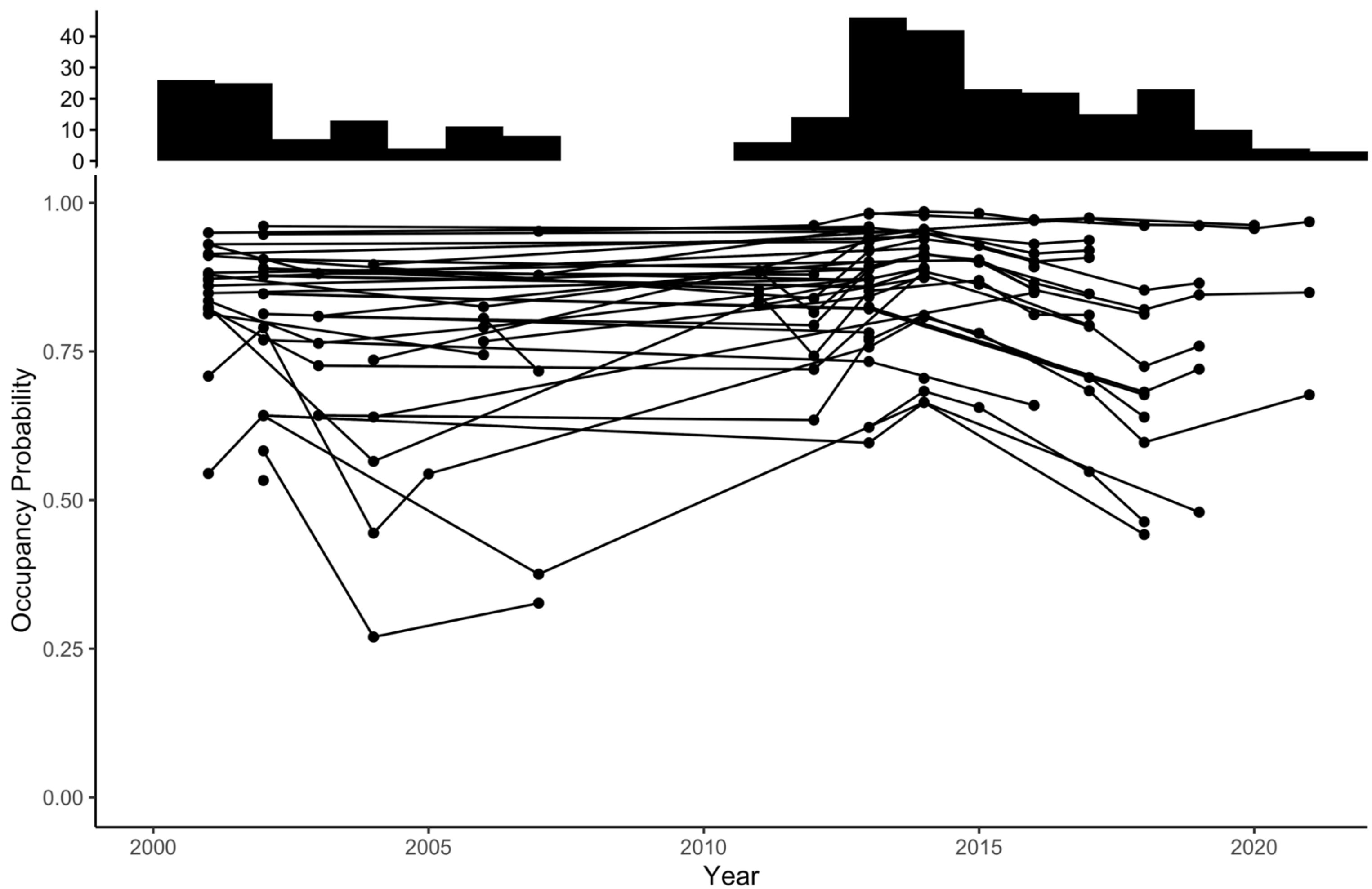

Figure 1.3 Estimated mean probability of occupancy by Mexican Spotted Owls for each PAC (by name: see Appendix 1) from 2001 – 2021 derived from a multi-season occupancy model in Grand Canyon National Park see methods for details). Points indicate mean estimates from years when a PAC was surveyed, while lines help delineate the trajectory of each PAC through time. The histogram displays survey effort.

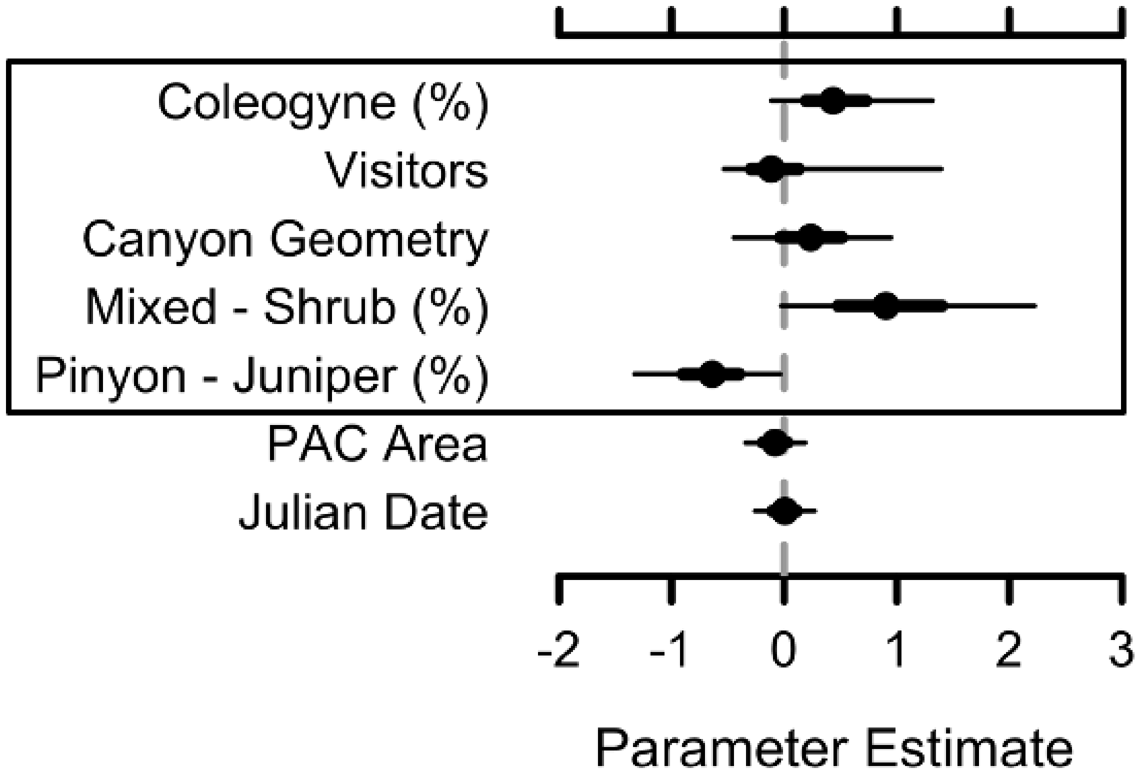

Figure 1.4 Estimated coefficients for predictors included in the occupancy and detection sub models for Mexican Spotted Owls in Grand Canyon National Park (2001 – 2021). Credible intervals of 50 % (bold line) and 90 % (thin line) are reported for each coefficient. Predictors within the box are linked to occupancy probability and those outside the box are linked to detection probability.

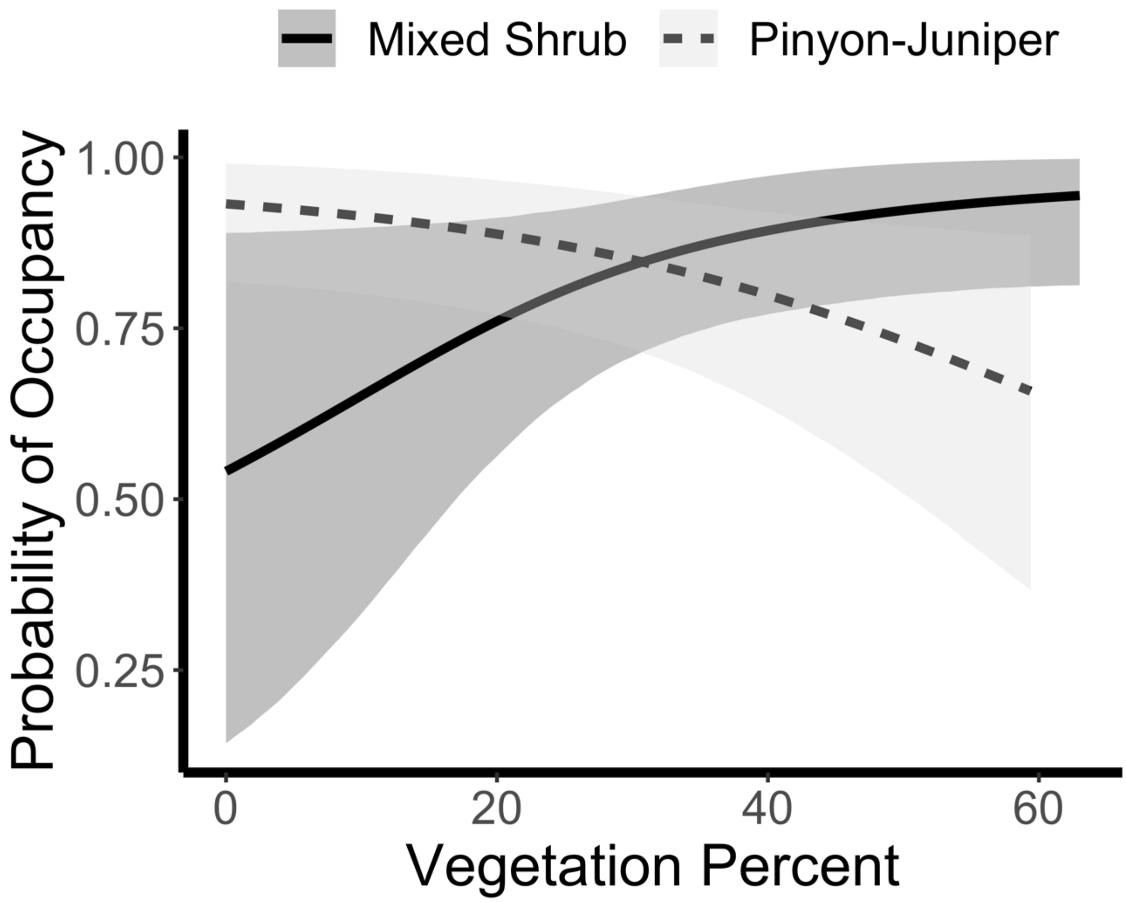

Figure 1.5 Marginal effect plots depicting probability of occupancy of Mexican Spotted Owls in Grand Canyon National Park with changing percent of pinyon-juniper woodland and mixed shrub in a PAC. Estimates derived from a multi-season occupancy model using call-back surveys of Mexican Spotted Owls at 53 PACs monitored from 2001-2021. Shaded areas represent the 90% credible intervals.

CHAPTER TWO: AUTONOMOUS RECORDING UNITS, A COMPLEMENTARY TOOL TO MONITOR OWL OCCUPANCY IN REMOTE CANYON HABITAT

Abstract

Long-term monitoring programs play an important role in wildlife conservation. Many monitoring efforts rely on well-established approaches which may be outdated or less efficient. Shifting towards more technologically advanced techniques is challenging because of concerns over the continuity of data. However, recent advances in statistical modeling now afford the opportunity to combine standard survey methods with newer approaches which may be cheaper and more efficient. Autonomous recording units (ARUs) are passive recording devices used to detect vocal wildlife such as whales, bats, and owls. These devices increase the quality and quantity of data collected, reduce personnel costs, and minimize disturbance to species. They may be especially useful in remote settings where repeat access to sites is difficult, such as the setting of this study, Grand Canyon National Park. The Grand Canyon poses many challenges to surveying for wildlife in the backcountry, including extreme temperatures, unpredictable weather, and limited access to sites. One threatened species at the park, Mexican Spotted Owls (*Strix occidentalis lucida*), occur in isolated locations that are very difficult to repeatedly visit. To increase the number of owl surveys conducted each year in this remote landscape, biologists have begun using ARUs to supplement in-person call-back surveys. I aimed to (1) assess the potential of ARUs as a complementary method to commonly used call-back surveys for estimating occupancy of owl

protected activity centers (PACs), as well as (2) assess how habitat features, weather conditions, and survey protocols influenced detection and occupancy probability for this method. I used ARU data from 2019 to 2021 to evaluate the probability of Spotted Owl occupancy and detection at 15 PACs in the park. I viewed these estimates alongside estimates produced from a previously analyzed multi-season occupancy model that relied on in-person call-back surveys. Geologic features of an owl PAC were the most important predictors of occupancy in the single-season model. Survey protocol, specifically the deployment date and number of ARUs deployed, influenced detection probability more than weather conditions, with detection being higher later in the breeding period and higher when more ARUs were recording. Finally, estimates of occupancy using ARU data were similar to estimates derived from call-back data when there were detections of Spotted Owls at PACs. Overall, ARU surveys were more time efficient, and captured early season activity, which made them ideal for extending the survey period. These results demonstrate that ARUs can be incorporated into long-term monitoring programs to increase sampling efforts, although they are not a full replacement for well-established and well-tested methodology.

Introduction

Long-term monitoring programs are fundamental for tracking changes to local populations over time (Murphy & Weiss, 1988; Hafner & Fasola, 1997). In some systems, conducting surveys is extremely time consuming or physically laborious, which can limit the data that is collected. Expanding monitoring programs to incorporate emerging technologies designed to be more efficient may relieve some of these challenges. Resistance to changing methodology is common for fear that it will disrupt the continuity of data collection and result in an inability to compare historical data to new data (Pelton & van Manen, 1996). However, the recent development of statistical models that can incorporate multiple data types have alleviated some of these concerns (Jiménez et al., 2016).

Passively recording sounds produced by wildlife using autonomous recording units (ARUs), is a modern data collection technique used to monitor vocal species such as birds, bats, and amphibians (Johnson et al., 2002; Acevedo & Villanueva-Rivera, 2006). While first mentioned in the literature in 1997, there has been a rise in the number of publications mentioning ARUs over the last 10 years (Abrahams, 2018; Darras et al., 2019). These devices are useful because they can be deployed for weeks at a time increasing the quantity of data collected (Hobson et al., 2002), potentially improving the chances of detecting a species if it is present at the site (Colbert et al., 2015; Thompson et al., 2017), while also minimizing deleterious effects to the target species from more invasive survey methods (Rognan et al., 2012). Acoustic monitors can also provide a better overall picture of the natural soundscape of an area, potentially capturing information about the full community of species present (Celis-Murillo et al., 2009). This may reveal complex interactions among species that are hard to observe during in person visits (Wood et al., 2019). Acoustic recorders also reduce the number of surveyors needed, which may decrease cost and minimize variability associated with multiple observers (Borker et al., 2015; Darras et al., 2019). These devices have been used to assess trends in Wild Turkey (*Meleagris gallopavo*) behavior (Colbert et al., 2015), determine inter-sex variation in the calling patterns of owl species (Dale et al., 2022), and evaluate the detection probability of bird species during the breeding season (Thompson et al., 2017). They have also become a popular method to assess the presence/absence of cryptic species (Rognan et al., 2012; Clément et al., 2021), and more recently to assess their distribution and occupancy (Stiffler et al., 2018; Balantic & Donovan, 2019; Jahn et al., 2022). Acoustic monitors may be especially useful in remote locations with limited access (Darras et al., 2019), where repeat visits to sites can be a challenge. In this study, I use ARUs to monitor occupancy of a threatened species, Mexican Spotted Owl (*Strix occidentalis lucida*) in highly remote landscape at Grand Canyon National Park.

Mexican Spotted Owls are a federally threatened species found across the desert southwest. The most common technique to detect Spotted Owls in the Grand Canyon are call-back surveys, in which a call (by either a surveyor or playback device) is used to imitate owl hooting vocalizations to solicit a vocal response from the bird (Miller, 1930; U.S. Fish and Wildlife Service, 2012). Call-back surveys are effective because they elicit territorial responses from owls, especially during the breeding period (Forsman, 1983). However, they also disturb owls during a sensitive time in their annual cycle (U.S. Fish and Wildlife, 2012). An additional concern is that call backs may encourage an owl away from its territory and towards the surveyor (Laiolo, 2010), potentially obscuring results about true territory locations. Call-back surveys are costly and time consuming as they require multiple visits, including potentially overnight stays, to be able to reliably estimate occupancy (U.S. Fish and Wildlife Service, 2012). Finally, they can also be hazardous to conduct, as traversing challenging terrain at night to survey for a nocturnal species increases risks for surveyors.

There have been 54 Spotted Owl Protected Activity Centers (PACs) identified at the park since surveys began in 1998. PACs are highly remote and must be accessed by either backpacking, boating down the Colorado River, or in some cases, rappelling from the rim of the canyon. Those PACs accessible by foot are at least 5 km away from the closest developed area and take multiple days to survey; those accessible by river are between 80 to 330 river km from the boat launch point in Lee's Ferry, Arizona; and finally, those accessible by rappelling into the canyon require specialized technical climbing skills to survey. Overall, travel time between sites is substantial regardless of access method, meaning that it is only typically feasible to survey a maximum of one site per night using call-back methods. The U.S Fish and Wildlife Service recommends four complete surveys to assess occupancy status (U.S. Fish and Wildlife Service, 2012), which requires considerable time and resources for Mexican Spotted Owls in Grand Canyon National Park.

I aimed to assess the potential of ARUs as a complementary tool to call-back surveys, with the overall intention of optimizing monitoring efforts. I also aimed to understand how landcover, topography, weather conditions, and survey protocols influenced estimates of occupancy and detection probability using ARU data alone. To do so, I deployed ARUs in PACs at the Grand Canyon to supplement ongoing call-back surveys during the Spotted Owl breeding season between 2019 and 2021. I predicted that owls would avoid pinyon-juniper woodland and occupy mixed shrub habitat (based on results from chapter 1). I also predicted that owls would have occupy PACs with more Supai Group and Redwall Limestone. Additionally, I predicted that the probability of owl detection would decrease across the breeding season and with an increase in wind and rain and would increase as the number of acoustic monitors used in a PAC increased. Finally, I predicted that incorporating ARUs into monitoring protocol would increase survey effort and improve the repeat sampling rate.

Methods

Study Site

This study took place at Grand Canyon National Park, which spans 4,931 km^2 (493,059 ha) in Northern Arizona, USA. The climate is dry, with low precipitation, most of which accumulates during the summer monsoon season. There is > 2,000 m of elevation change at the park, from the lowest point at Lake Mead, NV (375 m) to the North Rim of the canyon (2,682 m). The North and South Rims of the park are pine-oak and mixed-conifer forests, characterized by Ponderosa Pine (*Pinus ponderosa*), and Gambel Oak (*Quercus gambelii*), with pinyon-juniper woodland, (mainly Utah Juniper (*Juniperus osteosperma*) and Colorado Pinyon (*Pinus edulis*)), extending from the canyon edge to the upper portion of the inner canyon. Below the rim, the inner canyon exhibits steep cliffs, slopes, and plateaus with desert-scrub vegetation, and tributary side-canyons with perennial and ephemeral riparian systems (Huisinga et al. 2006).

Data Collection

From 2019 to 2021 I placed autonomous recording units (8GB AGPTEK U3 USB stick MP3 players) in 15 Mexican Spotted Owl PACs below the rim of the Grand Canyon to passively detect owls throughout the breeding season (range: 7 Feb. – 1 Aug.). I used consumer-level MP3 players instead of commercial ARUs (for example, *Wildlife Acoustics* SM4 Song Meters or SwiftOne ARUs by *Cornell Lab of Ornithology*), because of their affordability (~$30 USD per unit) and light weight; the latter is especially beneficial when working in remote sites that require long distance backpacking to access and transport units and batteries. The mp3 player ARUs used were structurally modified (Pic. 2.1) to increase battery power and expose the microphone to increase acoustic receptivity (Mark Szydlo, personal communication). I deployed and retrieved these devices by foot in 10 PACs, and via boat along the Colorado River in five PACs. Units were placed 1 to 2 m above the ground (Abrahams, 2018) on rock ledges, typically under rock overhangs to protect the units from the elements. Between one and six ARUs (most commonly two) were placed ~ 400 m apart in each PAC and recorded for up to 26 days (mean: 20 days).

The area of acoustic coverage for some individual ARUs overlapped depending on the topography of the site, which led to a lack of independence between units. Thus, I created a nightly detection history for each PAC. At least one detection of a Mexican Spotted Owl by any ARU in a PAC qualified as a detection point for that night of the survey. Acoustic data were collected 24 h a day in WAV format and split into diurnal and nocturnal file segment using the program AudioSplit v 1.9 (McClimans, 2020). Nocturnal data captured between 1900 and 0600 were subsequently processed in Raven Pro v1.6 (K Lisa Yang Center for Conservation Bioacoustics at the Cornell Lab of Ornithology, 2021). I used a band-limited energy detector ("BLED"), a feature in Raven Pro, to automate the process of searching through the acoustic data for Mexican Spotted Owl calls. A BLED uses input parameters specified by the user to automatically flag events in the acoustic data that meet the specifications and presents the results on a spectrogram (Charif et al., 2010). The BLED was designed to search for Mexican Spotted Owl four-note hoots between 200 and 750 Hz and with individual notes between 0.192 – 1.024 s in duration, with a minimum separation of 0.256 s (parameters were developed by Mark Szydlo, personal communication). This BLED also frequently captured Spotted Owl barking hoots, which have similar cadence and frequency. Mexican Spotted Owls also emit whistle contact calls that are generally higher in frequency and were typically not captured by this detector. Specifically searching for four-note calls only might have led to under-detection of owls, but this type of vocalization predominates in the breeding season (Ganey, 1990). Results of the automatic detector were manually reviewed to sort out false positive results. These included frogs, wind, insects, and additional owl species, which were excluded from the final occupancy analysis. Of the positive detections, owl hooting sessions were recorded by owl sex, and were considered individual bouts of calling when there was a hooting session that was separated by at least one hour from the previous hooting session by one individual owl.

Predictor Variables

In the occupancy model I included the variables deemed important from my first chapter's analysis (the proportions of pinyon-juniper and mixed shrub vegetation), as well as two variables that represent geologic formations (the proportions of Redwall Limestone and Supai Group) in PACs. I was unable to explore these variables in chapter 1 because their inclusion would have overfit the data. The full occupancy model included year as a random intercept, and the percent cover of pinyon-juniper woodland, mixed shrub, Redwall Limestone and Supai Group in each PAC, as fixed effects (Table 2.1). I acquired vegetation data from Kearsley et al. (2015), and geologic formation data were acquired from the NPS Geologic Resources Inventory Project (National Park Service, 2013). The potential variables influencing detection that I investigated were day of year, average daily precipitation (mm), maximum daily wind speed (m/s), and survey effort, defined as the number of ARUs operating at the PAC each night. Daily weather data were obtained from the nearby weather station at the Grand Canyon National Park Airport

(Menne et al., 2012), located ~12 km from the rim of the canyon (Latitude: 35.94581 N, Longitude: -112.1554 W). I evaluated predictor variables for multicollinearity using pairwise Spearman's correlation analysis. When $|r| > 0.6$, one predictor of the pair was discarded from the analysis. I anticipated that moon phase would also affect calling behavior of owls, and ultimately detectability, given that Spotted Owls hoot more often when the moon is in its last quarter and new moon phases (Ganey, 1990). However, this variable correlated with day of the year. Given that I was more interested in observing seasonal changes in detection across the breeding period, and to see how this variable compared to detection using call-back data, I decided to keep day of the year in the model and eliminate moon phase. The remaining predictors were scaled by centering them at their means and dividing by one standard deviation.

Occupancy Analysis

I modeled the three years (2019 – 2021) of presence/absence data using a single-season occupancy model that included year as a random intercept. I assumed PACs were closed within each breeding season, and I treated unique PAC/year combinations as individual sites. The hierarchical model included sub models for occupancy and observed detections. Latent occupancy for each PAC each year was modeled as a Bernoulli process linked to the probability of occupancy. The probability of occupancy was in turn examined in relation to Redwall Limestone (%), Supai Group (%), pinyon-juniper woodland (%), and mixed shrub vegetation (%) as fixed effects and year as a random intercept (distributed as ~Normal $(0, \sigma^2)$, with standard deviations, σ, given Student-t priors, ~t (0, 2.5, 7) (Gelman et al., 2008)). Observed detections were also modeled as a Bernoulli process dependent on the probability of detection and latent occupancy. The probability of detection was examined in relation to the day of year, survey effort, average daily precipitation (mm), and maximum daily wind speed (m/s), as fixed effects. Priors for all coefficients were distributed as ~Normal (0, 10), and priors for mean occupancy and detection probability were distributed as ~Beta (4,4) centered around 0.5, where the mean probabilities were linked to the model intercepts as: *intercept = log (mean/1 – mean)*.

The occupancy analysis was conducted in R v 4.1.2 (R Core Team, 2021) using the package *jagsUI* (Kellner, 2021) in a Bayesian framework following (Kéry and Schaub, 2012). I ran five chains of 510,000 iterations, thinning by five and burning the first 10,000 iterations. Model fit was assessed by measuring the deviance of the actual data from the data predicted by the model summarized at the PAC level (Cruz et al., 2019), and by calculating a Bayesian p-value, which describes how the observed data compares to data simulated by the model, with values closer to 0.5 suggesting reasonable fit (Gelmen, 2013; McElreath, 2019). The occupancy model had good fit overall (Bayesian p-value = 0.51). However, some PACs had large deviances including, Matkat Canyon and Indian Hollow, indicating that there is more uncertainty around the estimates at those sites (Appendix B).

<u>Method Assessment</u>

I evaluated the potential for ARUs to be used as a complementary technique by comparing estimates of occupancy and detection to estimates derived from call-back survey data. These data were previously analyzed using a multi-season model approach in chapter 1, which used 20 years of call-back surveys conducted at 54 PACs in the canyon. To do this, I visually inspected occupancy estimates for five PACs that were monitored using both techniques by plotting the individual PAC mean estimates together. I also assessed temporal differences in detection during the breeding season by plotting predicted marginal effects for detection probability estimated by each method, across day of the year. Additionally, I made a general comparison of which survey methods would be the most effective at PACs with different access methods. I also looked at the total number of PACs that were surveyed at least three times in a season, which has been recommend as the minimum to estimate occupancy when detection of a species is high (Field et al., 2005; Mackenzie & Royle, 2005). Additionally, I made a general comparison of which survey methods would be the most effective at PACs with different access methods.

Results

Occupancy Analysis

I collected > 9,500 h of ARU data from 58 recorders in 15 Mexican Spotted Owl PACs from (2019 = 9 PACs, 2020 = 4 PACs, 2021 = 8 PACs). There was a high number of false positive results from the band limited energy detector used the automatically detect Spotted Owl calls in RavenPro. There were 173 individual detections of Spotted Owls total (individual meaning a hooting session that was separated by at least one hour from the previous hooting session by one individual owl). 23% of nights had at least one Mexican Spotted Owl detection and 53 % of PACs had at least one detection over the survey period. Mean occupancy probability overall across all PACs was 0.49 (90% CI: 0.013 – 0.93), and mean detection probability was 0.38 (90% CI: 0.11 – 0.80). Mean occupancy was highest in 2020 (0.62). Mean detection probability was also higher in 2020 (0.61), compared to 2019 and 2021 (0.28 and 0.38, respectively). Of the six PACs surveyed in 2 years of the study, occupancy probability decreased over time at four PACs, and remained unchanged over the study period in 2 years. Detection probability decreased over time for all but one of the six PACs surveyed with ARUs in more than 1 year.

The probability of owl occupancy increased with increasing Supai Group in a PAC (Mean: 1.67; 90% CI: 0.25 to 3.31) and decreased as the percent of Redwall Limestone in a PAC increased (Mean: -1.91; 90% CI: -3.95 to -0.19) (Fig. 2.1a). Neither pinyon-juniper woodland nor mixed shrub habitats influenced owl occupancy (Mean: 0.73 and -0.17 respectively; Fig. 2.2). The probability of owl detection decreased later in the breeding season (Mean: -0.85; 90% CI: -1.16 to -0.55; Fig. 2.1b) and increased as the number of acoustic monitors deployed increased (Mean: 0.79; 90% CI: 0.39 to 1.22; Fig. 2.1c). While I did have three complete ARU failures from the onset of deployment, my survey effort was primarily impacted by ARUs that started recording when deployed but ultimately stopped recording prematurely. There were 13 ARUs that recorded for less than 10 days, and of those, two ARUs recorded for less than 5 days.

Assessment of ARUs

The probability of owl detection across the breeding period varied depending on the survey technique used. Call-back surveys led to consistent detection probability across the survey period (Mar. 1 – Aug. 31). Acoustic monitors yielded a high detection probability early in the breeding season and declined across the breeding period (Fig. 2.1b). For the five PACs that were surveyed using both methods from 2019 – 2021, acoustic monitors underestimated occupancy probability in 60% of PACs. Of those PACs where occupancy probability was underestimated using ARUs, two PACs (Manzanita and Horn Creek) had no Spotted Owl detections using either method, and one PAC, Cottonwood, had owl detections using both methods. However, at sites where Spotted Owls were detected, ARUs were able to match the estimates from the multi-season model, which relied on two decades of call-back survey data (Fig. 2.3). Acoustic monitors were able to collect on average 20 days of data with each ARU, which is significantly more data than what is typical for call-back surveys. I also looked at the number of times a PAC was surveyed to my set minimum requirement of 3 repeat surveys per PAC. From 2001 to 2021, only 14 PACs were surveyed to this minimum requirement; that number increased to 23 PACs surveyed to protocol when only 3 years of ARU data were added to the data set. Acoustic monitors were also able to reach the minimum requirement of three repeat surveys per PAC per season more easily with only 2 visits to the site, (one visit to deploy ARUs and one visit to retrieve them), which led to less days in the field per site than call-back surveys. For example, in 2019 there were 8 PACs surveyed using ARUs in 18 field days, and that same year there were 6 PACs surveyed with call-back surveys in 23 field days. Overall, most PACs across the canyon were best accessed by backpacking, however there were still a significant number of PACs that were best accessed via the river, or technical rappelling (Fig. 2.4).

Discussion

The development of new technology and advanced statistical methods now allows multiple survey techniques to be incorporated into wildlife monitoring programs (Jiménez et al., 2016; Garland et al., 2020). Autonomous recording units are increasingly being incorporated into long-term monitoring programs to study population dynamics of vocal species (Bombaci & Pejchar, 2019; Garland et al., 2020; Jahn et al., 2022). I used three years of ARU data at 15 Mexican Spotted Owl PACs in a single-season occupancy model to assess the potential use of this method as a complement to standard call-back surveys. I found detection probability was higher earlier in the breeding season when using ARUs, prior to the start of the official call-back survey period. This makes ARUs ideal for extending the survey period while minimizing disturbance to owls early in the breeding period when they are particularly sensitive (U.S. Fish and Wildlife Service, 2012). Occupancy estimates were similar for two PACs that had a high number of detections using both ARUs and call-back surveys. However, PACs with no detections, or a low number of detections, likely required more years of data to estimate occupancy reliably using ARUs. I demonstrated that a combination of ARUs and traditional call-back surveys increased survey effort for owls in remote settings.

Through this analysis, I found that Mexican Spotted Owl occupancy was affected by rock formations, specifically Supai and Redwall Limestone. Supai, a rock formation found in the upper region of the canyon, was related to increased occupancy probability. This formation has conglomerate layers made up of limestones, sandstones, and mudstones (McKee, 1975), which form ledges that may be ideal for roosting owls. It is also close to the rim of the canyon and nearby forest, where owls likely forage (Bowden, 2008). This layer also supports vegetation and may provide enough appropriate habitat to host a prey community, potentially providing owls with more foraging habitat. Contradicting previous research, model results also revealed that Redwall Limestone was associated with decreased owl occupancy probability. This formation is associated with Spotted Owls home ranges (Bowden et al., 2015). However, an increase in the proportion of this layer within PAC boundaries, rather than just its presence, may not be advantageous for nesting owls. A greater amount may afford Spotted Owl predators or competitors, such as sympatric Great Horned Owls, the opportunity to nest nearby. While Great Horned Owls are commonly observed in the canyon, and within Spotted Owl PACs, this postulation has not been specifically researched. Since I looked at these variables proportionally, it is also possible that an increase in the percent cover of Redwall just indicates that there is less of the other rock formations in the PAC. As results revealed, other rock formations (specifically the proportion of Supai Group) were deemed important.

For ARUs, the highest probability of detection was in February, prior to the official start of the call-back survey period on March 1st. As the season progressed, the probability of detection by ARUs declined, while call-back detection probability remained consistently high. Barred Owls (*Strix varia*) were also found to have a higher detection probability earlier in the breeding season which declined as the season progressed when surveyed passively with ARUs (Clément et al., 2019). The decline in detection of Mexican Spotted Owls using ARUs was potentially related to owls becoming less territorial later in the breeding season when they no longer need to staunchly defend a territory (Ganey, 1990). There may be other biological reasons why hooting would decline later in the season. For example, in the fall when young are dispersing from nests and some species of owls migrate, there may be a decrease in vocal activity (Ganey, 1990). It is clear from these results that call-back surveys can elicit a response from the birds, even when they are less naturally vocal. While it is possible that call-back surveys would be able to match the high ARU estimates early in the season, conducting a call-back survey prior to March 1st is considered harassment to the owls and is therefore not permitted (U.S. Fish and Wildlife Service, 2012). This makes ARUs a great choice for conducting surveys earlier in the season, and it even may be a valuable tool for collecting data during the non-breeding season. Finally, detection probably increased with the number of ARUs operating. This effect can be attributed to the limitations in recording distance for each individual device. Although the number of ARUs used to survey a PAC was meant to increase with the size of the PAC and provide complete coverage, ARU failure at some stations led to some PACs being under-surveyed, and consequently owls were likely under detected. Neither precipitation nor wind speed had any effect on owl detection, as is has in other studies (Colbourne & Digby, 2016; Jahn et al., 2022). For this study, the environmental data included in the analysis may not have been an accurate representation of the weather conditions experienced at each individual ARU since the weather station was over 12 km from the rim of the canyon, and even further from many of the owl PACs. This may explain why this variable did not show up as a strong predictor of detection probability.

The Grand Canyon, like other remote landscapes, poses a multitude of challenges to conducting surveys. It has not always been possible to achieve the target of surveying all Mexican Spotted Owls PACs at the Grand Canyon every five years using call-back surveys alone. Additionally, expanding survey efforts beyond PACs would provide more information about the distribution and abundance of owls at the Grand Canyon, but efforts to do so have been minimal because of the challenging nature of visiting remote locations multiple times. I found ARUs to be an efficient method for data collection, particularly at remote PACs. While traditional call-back surveys require a surveyor to undergo at least 40 hours of supervised training (U.S. Fish and Wildlife Service, 2012), ARUs don't require any training or prior experience to deploy in the field (Darras et al., 2019). At PACs that require specific skills to access, such as those at the Grand Canyon that require technical rappelling, this ease of use is especially important. For example, in 2019, ARUs were given to volunteers to deploy in a highly remote PAC that had only been surveyed one time in 20 years. In the same year, ARUs were deployed and retrieved during a mission on the Colorado River, as an addition to other wildlife work occurring in nearby areas. Both deployment and retrieval of the ARUs on that river trip took only a few hours to complete; however, to conduct call-back surveys in these same PACs would have required overnight stays, three repeat visits, and technical skills. These efforts nearly doubled the total number of PACs surveyed "to protocol" (at least 3 repeat visits) that season.

For Barred Owls, detection probability was estimated be as likely as high as 90 % when using a combined approach of call-back surveys and ARU surveys (Clément et al., 2021). This approach has also been tested to assess occupancy in other vocal species and with other survey methods. For example, wolf detectability in Canada was highest when using a combined approach of ARUs and cameras (Garland et al., 2020), and another study of wolves in Spain showed that the estimation of reproductive state was more accurate at sites with low detection and high occupancy when a combination of sampling techniques was used (Jiménez et al., 2016). Conducting surveys following a protocol that utilizes only one method may lead to inefficiencies, especially when sites are hard to access, as they are at the Grand Canyon. By complementing call-back surveys with ARUs in rugged and remote landscapes, I demonstrated that more sites could be surveyed more completely each year. I recommend deploying ARUs early in the breeding season to capture early season owl presence, as well as prioritizing ARUs at sites that are more difficult to access.

Despite the benefits of ARUs, I acknowledge that call-back surveys and ARUs are not completely interchangeable. While ARUs can increase the amounts of data collected, there are limitations for their use. For example, they only capture acoustic information (Darras et al., 2019), whereas in-person surveys can collect information about specific nest or roost locations of focal species (U.S. Fish and Wildlife Service, 2012). Call-back surveys continue to be the most suitable method for sites that can be easily revisited, or when identifying nest location is of priority. Developing a two-method approach that maximizes survey effort and detection rates is likely to result in the most accurate estimates of occupancy probability (Rognan et al., 2012). Future research should highlight how the use of multiple survey methods coupled with multi-method, multi-season occupancy models can help long-term monitoring programs to improve their sampling goals and inference, thereby providing improved guidance to aid in the ongoing conservation of species in remote landscapes.

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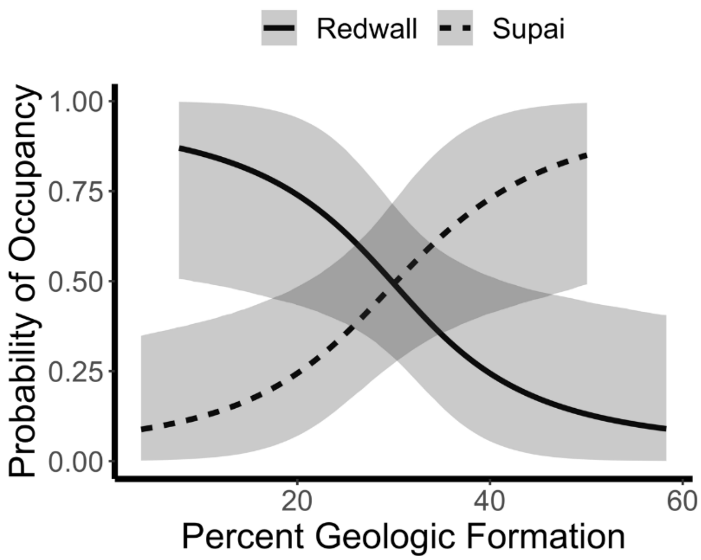
Tables

Table 2.1 Fixed effects occurring at the site and survey levels included in final model describing Mexican Spotted Owl occupancy and detection using ARUs at Grand Canyon National Park from 2019 – 2021. Shaded area indicates predictors of occupancy, and the unshaded area indicates predictors of detection.

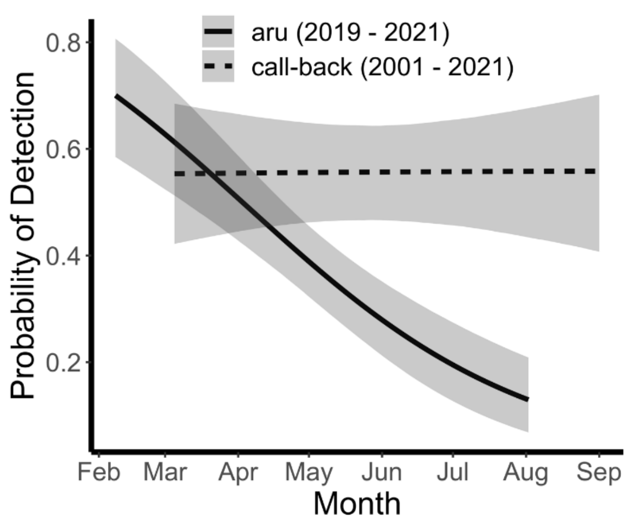
Predictor	Level	Description	Source	Prediction
Mixed Shrub (%)	Site	Percent of PAC classified as mixed shrubland vegetation.	Kearsley et al., 2015	Mixed shrub (%) will increase with Spotted Owl occupancy.
Pinyon-Juniper (%)	Site	Percent of PAC classified as pinyon-juniper woodland vegetation.	Kearsley et al., 2015	Pinyon-juniper (%) will increase with Spotted Owl occupancy.
Redwall Limestone (%)	Site	Percent of Redwall Limestone in the owl PAC.	National Park Service, 2013	Spotted Owl occupancy will increase with increase in Redwall Limestone (%).
Supai Group (%)	Site	Percent of Supai Group in the owl PAC.	National Park Service, 2013	Spotted Owl occupancy will increase with increase in Supai Group (%).
Precipitation	Survey	Average daily precipitation (mm).	Menne et al., 2012	Detection will decrease with increased precipitation.
Max Wind	Survey	Maximum daily wind speed (m/s) sustained for 5 seconds.	Menne et al., 2012	Detection will decrease with increased wind speed.
Day of Year	Survey	The day of the year the survey took place.	Field data	As day of the year increases, Spotted Owl detection will decrease.
Effort	Survey	The number of ARUs operating each day of the survey period.	Field data	As effort increases, Spotted Owl detection will increase.

Figures

2.1a



2.1b



2.1c

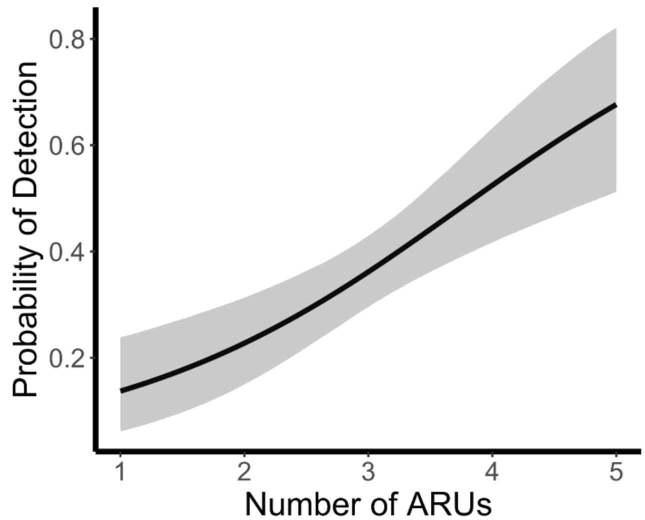


Figure 2.1 Marginal effect plots depicting the predicted probability of occupancy of Mexican Spotted Owls with changes in 2.1a) the percent of geologic formations in a PAC, and the probability of detection with changes in 2.1b) the day of the year using ARUs (solid line) and call-back methods (dashed line), and 2.1c) the number of ARUs deployed in a PAC. All other fixed effects were held at their mean values. Shaded areas represent the 90% credible intervals.

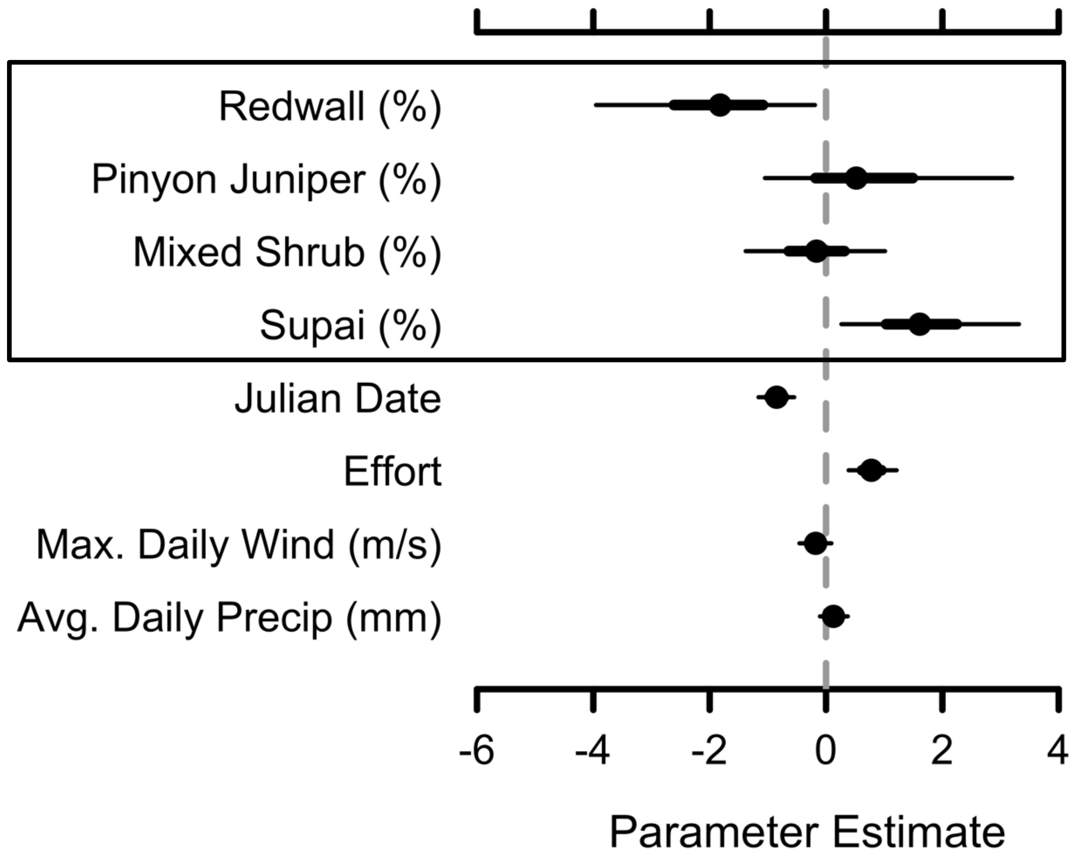


Figure 2.2 Parameter estimates for the fixed effects included in the occupancy (effects in the black box) and detection (effects outside the black box) sub models. Credible intervals of 50% (thick line) and 90% (thin line) are reported for each parameter.

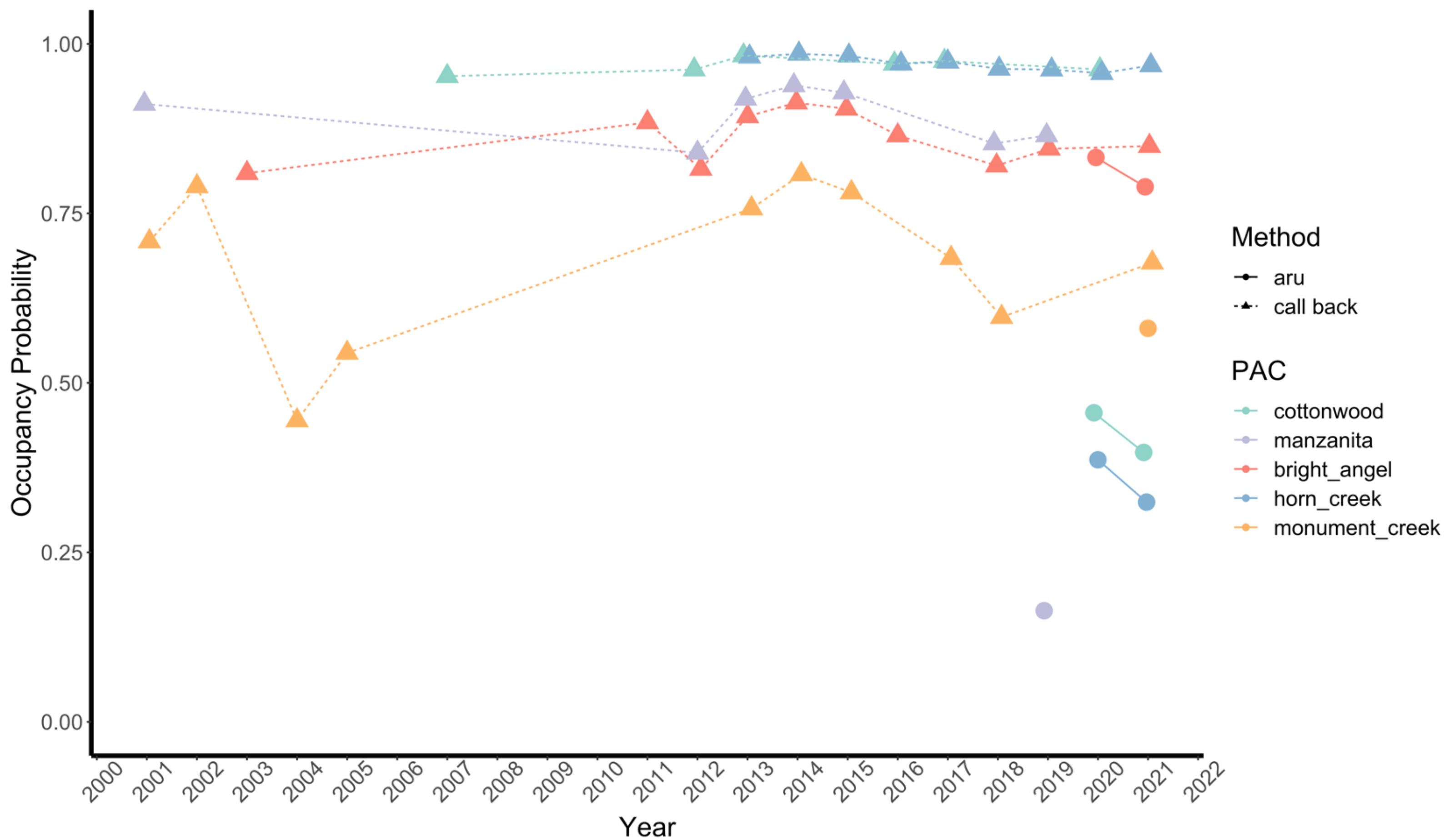


Figure 2.3 Occupancy probability estimated from ARU survey data (circles) and call-back survey data (triangles) for sites that were surveyed using both methods. Call-back occupancy estimates were derived from a 20-year multi-season occupancy model, while the ARU estimates were derived from a single-season occupancy model on three years of ARU data.

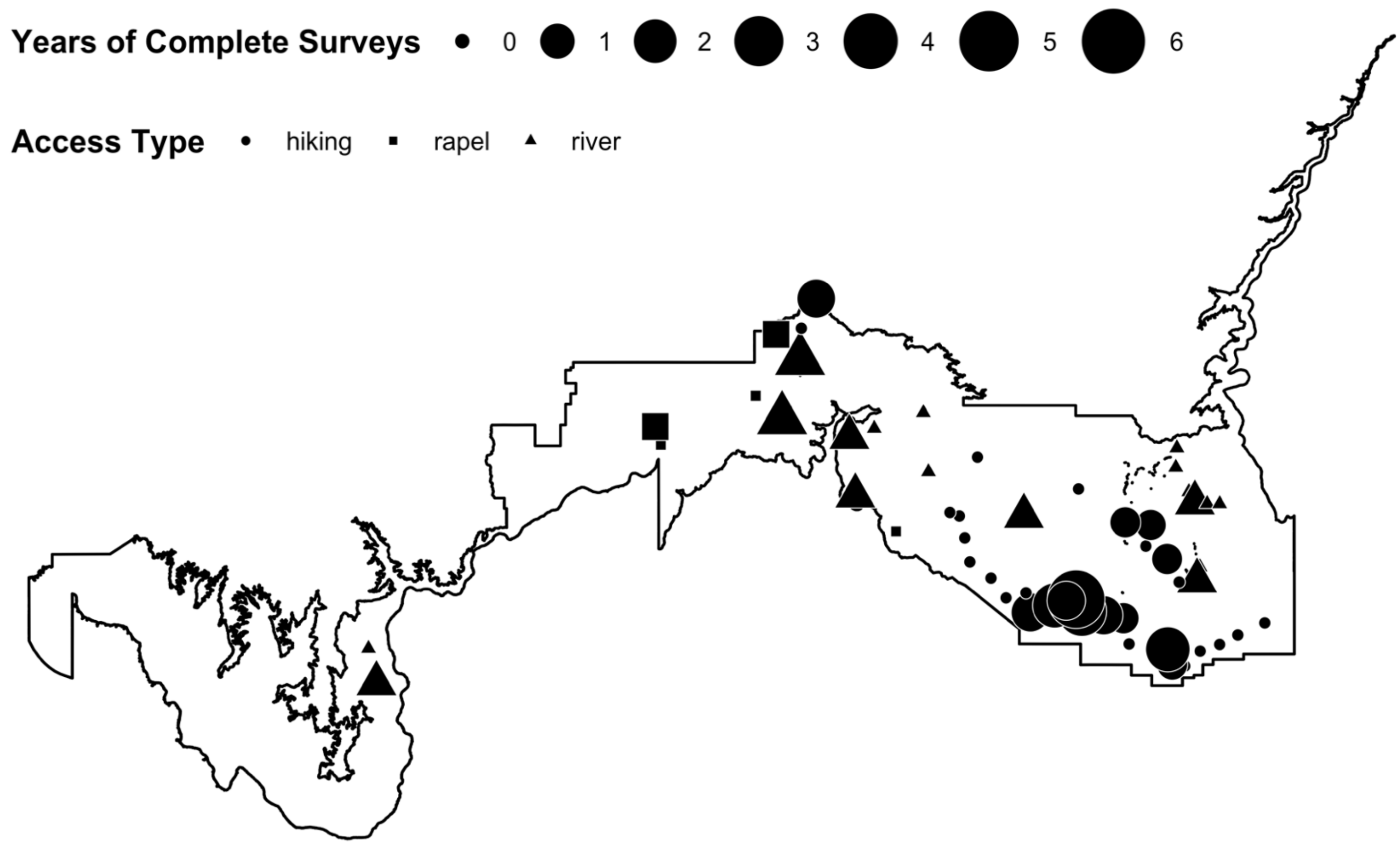


Figure 2.4 Spatial plot of access of PACs across the canyon. Size of the point represents the number of years where complete surveys took place. Surveys were considered complete when at least 3 surveys took place in one year at the PAC. Shape indicates the access type

Pictures

Picture 2.1 Photo depicting the structural modifications made to 8GB AGPTEK mp3 players. Design was created by Mark Szydlo (personal communication). Holes were drilled over the microphone to increase acoustic receptivity, and modifications were made to the battery coils to allow the device to be powered by two D cell batteries, which allowed the devices to stay powered for over 21 days.

APPENDIX A

Deviance Estimated Using a Multi-Season Occupancy Model

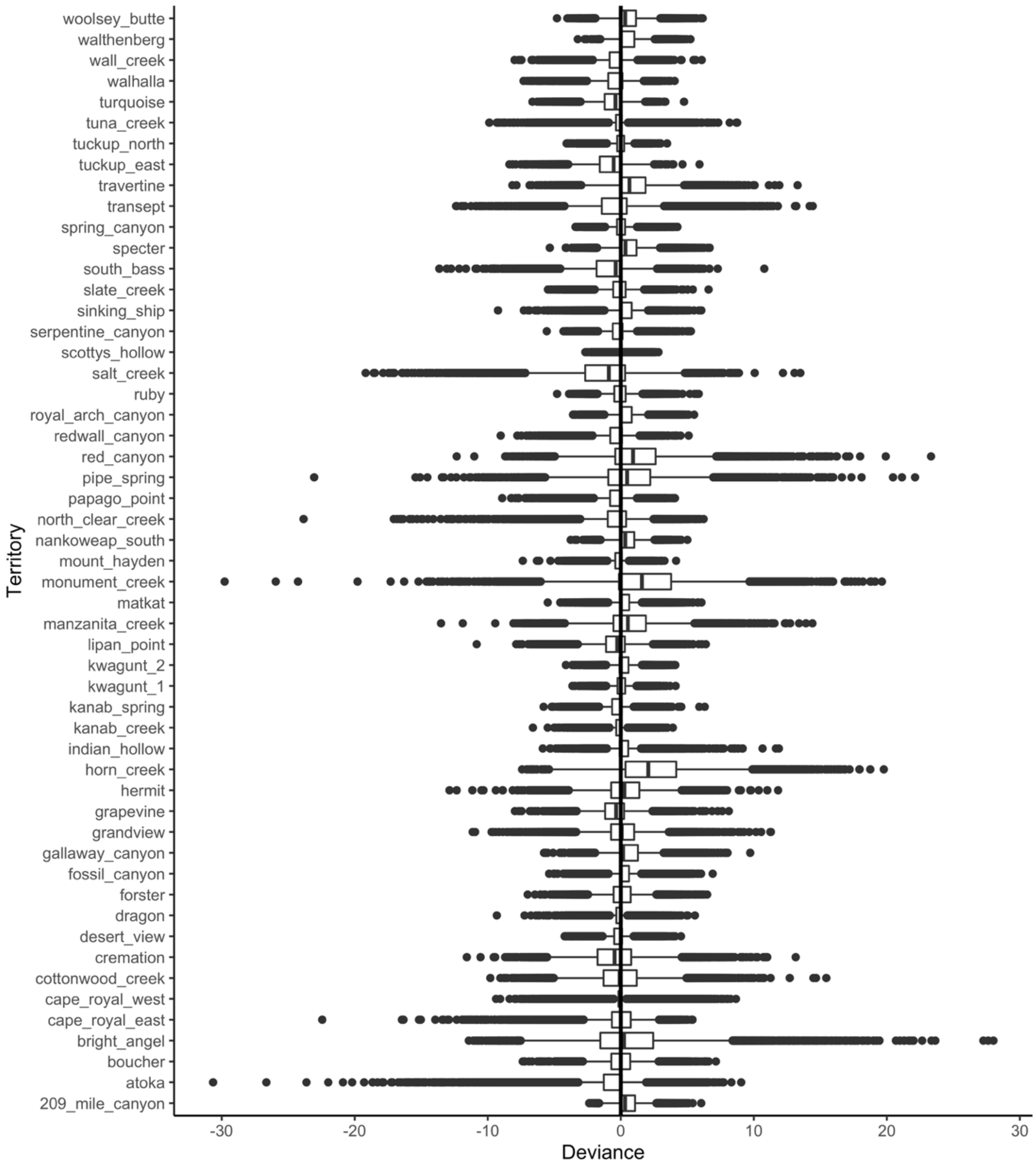


Figure A.1 Deviance estimates calculated by comparing differences between the observed data at each PAC (protected activity center) from the data predicted by a multi-season occupancy model of Mexican Spotted Owls surveyed using call-back surveys at Grand Canyon National Park from 2001-2021.

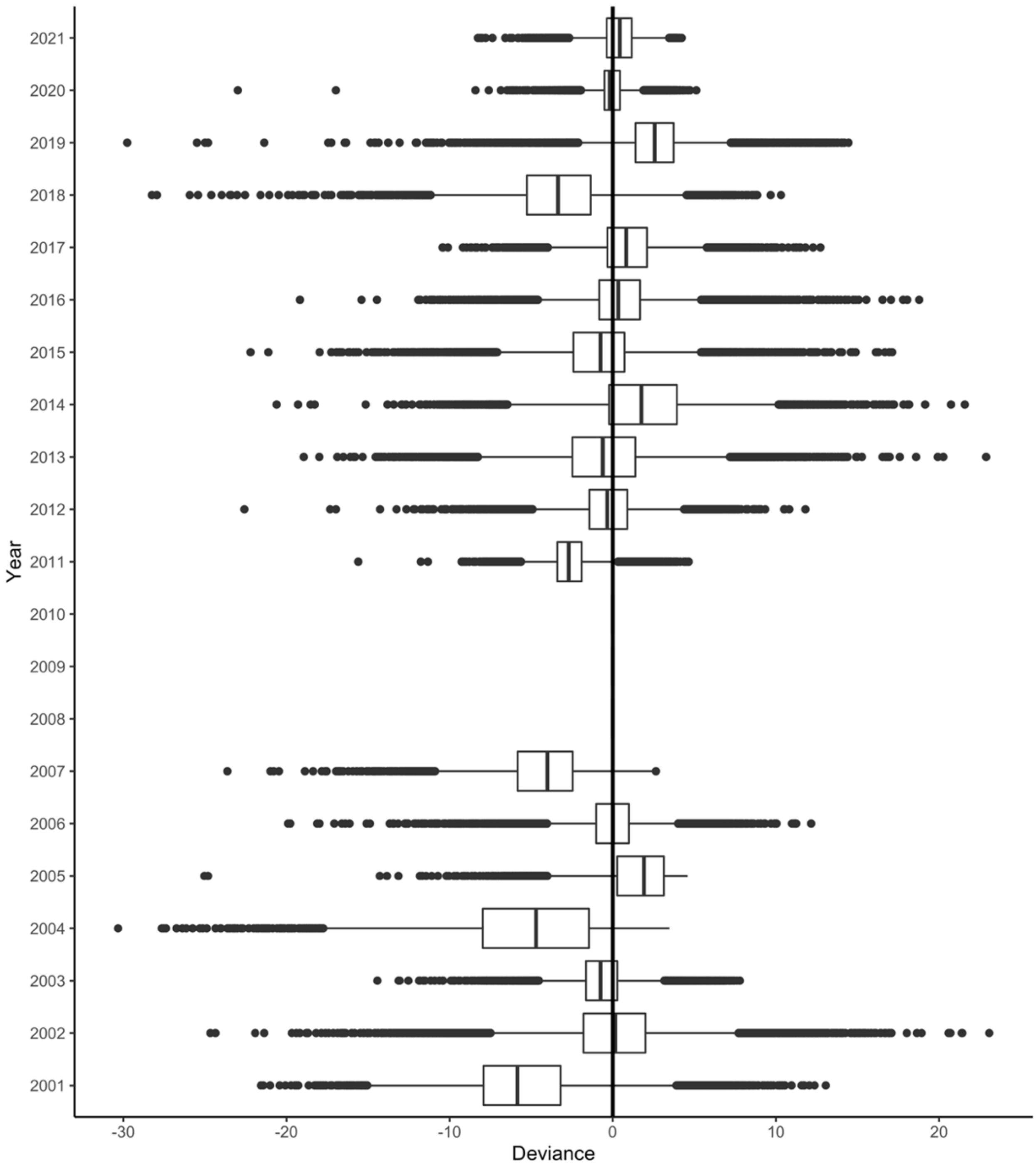


Figure A.2 Deviance estimates calculated by comparing annual differences between the observed data and the data predicted by a multi-season occupancy model of Mexican Spotted Owls surveyed using call-back surveys at Grand Canyon National Park from 2001-2021. No deviance was calculated for years 2008 to 2010 because no call-back surveys were conducted during those years.

APPENDIX B

Protected Activity Center (PAC) Deviance Estimated Using a Single-Season Occupancy Model

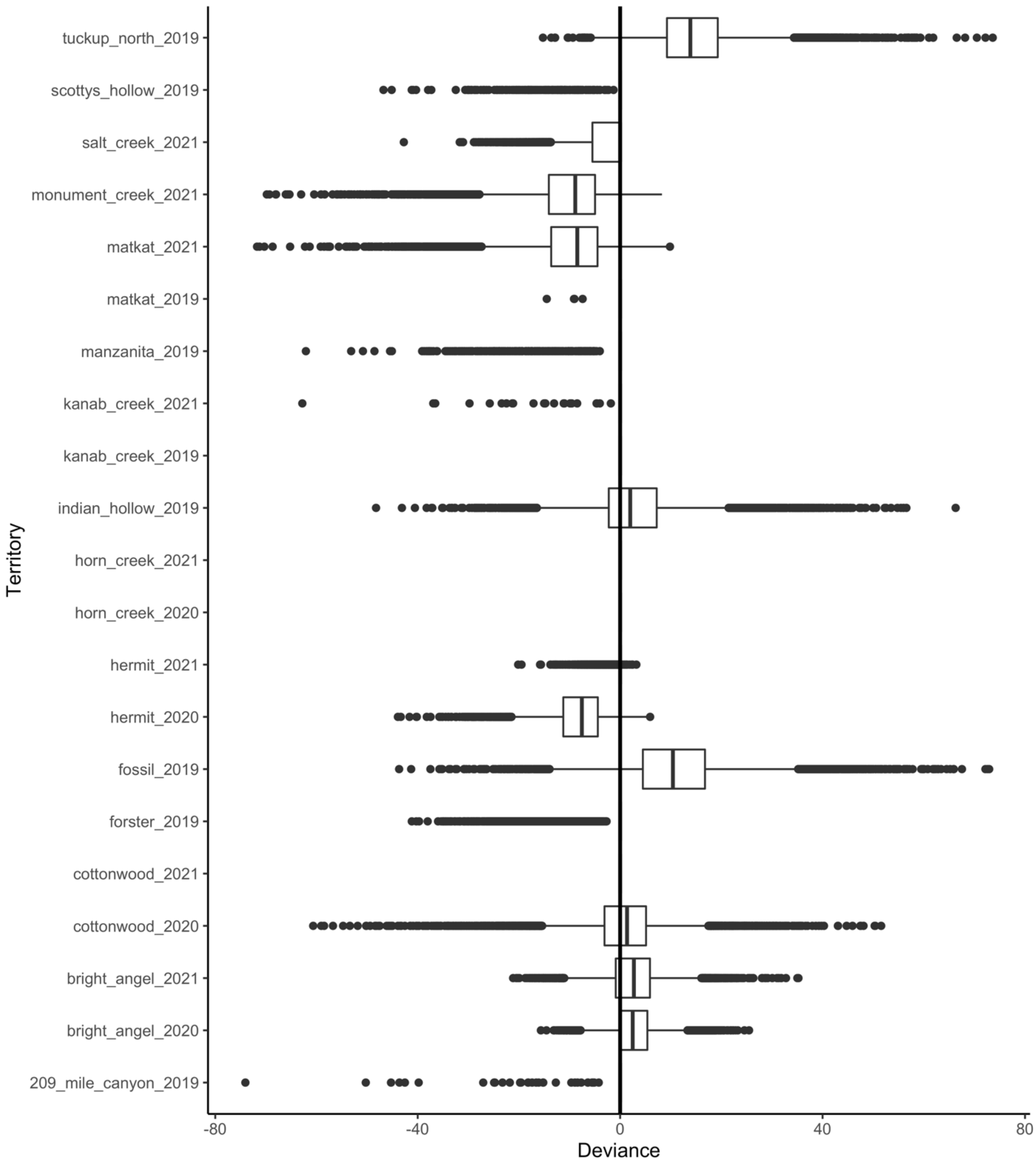


Figure B.1 Deviance estimates calculated by comparing differences among PACs (protected activity centers) between the observed data and that predicted by a single-season occupancy model of Mexican Spotted Owls surveyed using ARU surveys at Grand Canyon National Park from 2019-2021.