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Ground Ingredients: Analysis of Lead Exposure in the California Condor's (*Gymnogyps Californianus*) Ground Foraging Habitat

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**Ground Ingredients: Analysis of Lead Exposure in the California
Condor's (*Gymnogyps Californianus*) Ground Foraging Habitat**

Evan Michael McWreath

**Thesis submitted
to the Eberly College of Arts and Sciences
at West Virginia University**

in partial fulfillment of the requirement for the degree of

**Master of Arts in
Geography**

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ABSTRACT

Ground Ingredients: Analysis of Lead Exposure in the California Condor's (*Gymnogyps Californianus*) Ground Foraging Habitat

Evan Michael McWreath

The California Condor (*Gymnogyps californianus*) is a critically endangered species that reached its nadir in 1987 with a population of 27 birds in the wild. Intensive management efforts have been implemented to aid the condors' recovery, however, anthropogenic factors, like use of lead ammunition, continue to cause fatalities in this vulnerable population. Lead toxicosis, which is responsible for approximately 40% of all condor deaths since 1992, is one of the most significant threats to condors. In birds lead poisoning leads to neurological dysfunction, reproductive impairment, immune suppression, gastrointestinal disturbance, anemia, and ultimately increased vulnerability to predation, starvation, and infection. For this research I investigate the relationship between lead exposure and condor ground foraging ecology. I analyzed a subset of data from a GPS telemetry dataset of condors in southern and central California, focusing on ground foraging locations, sites where condors are most likely to ingest lead from spent ammunition while scavenging carrion. Using these data from December 2013-2017, I explored the differences between condors with high and low blood lead concentration readings (BLC) to determine the relationships between the birds' BLCs and spatial patterns in their ground foraging. I found that the best predictor of BLC in condors was how the land that they are foraging on was managed. Non-managed lands provided the best model of BLC, indicating that policy enforcement is a major component of the issue of lead exposure in condors. My research can be used to target areas of high risk of lead exposure, where increased management efforts (lead-free food provisions, policy enforcement, and educational outreach) should be focused.

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Introduction

The California Condor (*Gymnogyps californianus*) (hereafter condor) is the largest flying bird in North America and has been historically present throughout the west coast and the south central and eastern parts of the United States and Mexico (Cade, 2007). As an obligate carrion-feeder, condors traditionally fed on the carcasses of large mammalian wildlife (Snyder and Snyder, 2000). However, since human population expansion has resulted in a decrease in the availability of many terrestrial and marine mammals, condors have adapted to rely on agricultural animals as a primary food source (Emslie, 1987; Chamberlain et al., 2005). Currently, introduced pigs, livestock, and newly rebounded wildlife populations of deer, elk, and marine animals act as the most important natural food sources for the new condor population, and consumption of smaller animals, down to the size of ground squirrels and rabbits, has been observed (Chamberlain et al., 2005; Walters et al., 2010; Cade 2005). Satellite telemetry data from California and Arizona-released birds shows that condors travel more than 100km a day in search of these food sources (Fry, 2003). Because condors cover these vast distances, they are exposed to a number of environmental risks that have contributed to their status as critically endangered.

Condors reached their nadir in 1987 when the global population dropped to 27 individuals and all of the remaining birds were pulled into captivity (USFWS, 2018). In 1992, wild and captive bred condors were released and the wild populations in California, Mexico, Arizona, and Utah were reestablished (Snyder and Snyder, 2000). Since then, the condor population has begun to recover with 488 birds reported in 2018 and 312 are in the wild (USFWS Condor Recovery Program 2018 Report). Despite the increase in the wild population, condors are still dependent on humans for capturing, testing, treating, and provisioning food

(Walters et al., 2010). These management efforts have not come without monetary cost. In 2007, the USFWS estimated the cost over the last 20 years of the recovery program to be between \$35 and \$40 million, with an annual cost of around \$2 million (USFWS, 2017). The U.S. Fish and Wildlife Service (USFWS) identifies that the goal of the California Condor Recovery Plan is to establish a self-sustaining population (Myatt, 2017). Despite the success of improving the numbers of wild birds, there is a need for continued research focused on understanding the environmental risks that are inhibiting the condor's recovery to a self-sustaining population. As the condor population began its recovery, researchers sought to identify the causes of the population decline (Emslie, 1987; Wiemeyer et al., 1988, Snyder and Snyder 1989; Cade, 2007; Mee et al., 2007; Rideout et al., 2012). These studies concluded that anthropogenic factors reduced the quality of the condors' environment. Factors contributing to the population decline include intentional killings, collisions with power lines, electrocutions, Dichlorodiphenyldichloroethylene (DDE)-induced eggshell thinning, disturbances of nest sites, food scarcity, and ingestion of harmful materials such as microtrash or lead from spent ammunition (Mee et al., 2007; Green et al., 2008; Rideout et al., 2012; Burnett et al., 2013; Finkelstein et al. 2014). Once lead poisoning from spent ammunition was identified as a primary cause of the population decline (Snyder and Snyder, 2000), many policies were implemented to decrease its use, yet the condor is still currently red listed as a critically endangered species by the International Union for Conservation of Nature (BirdLife International, 2018).

The state of California has attempted to reduce lead in the environment by enacting policies that will completely phase out the use of lead ammunition within the condor's habitat and ultimately in the entire state of California (California Department of Fish and Wildlife, 2016). Walter et al. discussed the significance of the Ridley-Tree Condor Preservation Act

passed as part of the state legislation in 2007, which restricted the use of lead ammunition for big-game hunting within the range of the condor. And in the following two years the California game commission adopted these restrictions for all other hunting zones (2010). Nearly a decade after California took such measures, lead toxicity due to spent ammunition still presents a significant concern for the condor as well as many other species (Bakker et al., 2017).

Recognizing this, the state of California is currently implementing procedures to adopt requirements that will ban the use of lead ammunition entirely by July 1st, 2019 (California Department of Fish and Wildlife, 2016). Despite these efforts, ongoing population effects from lead exposure indicates that relying on policy alone is unlikely to resolve this problem.

Lead toxicosis is one of the most significant threats to the condor population as it has caused 40% of the reported condor deaths since 1992 (USFWS, 2018). Lead is most commonly ingested while the birds are on the ground feeding on wild carrion killed by lead ammunition (Cade, 2007; Walters et al., 2010; Rideout, 2012). In birds, lead poisoning negatively affects all of the body systems and causes a myriad of cellular and organ-level dysfunction (Fisher et al., 2006). Sub-lethal toxic effects can lead to physiological, behavioral, and biochemical changes in birds, which can lead to neurological dysfunction, reproductive impairment, immune suppression, gastrointestinal disturbance, anemia, and increased vulnerability to predation, starvation, and infection (Fisher et al., 2006; Kendall, 1995). Finkelstein et al. found that the wild condor population is chronically exposed to lead and nearly 50% of birds sampled between 1997 and 2010 needed treatment for some level of lead poisoning (2010). Compared to other birds, condors also have a delayed sexual maturity and very low rates of reproduction, as they do not typically reproduce successfully until the age of 8 and only reproduce 0.25 to 0.37 young per breeding age female per year (Meretsky et al., 2000; Cade, 2007). The effects of lead toxicosis in

condors and other species indicates the need for controlling and eliminating sources of lead entering the environment. To decrease lead exposure in condors, researchers must first understand how human and environmental conditions influence the distribution of lead throughout the landscape.

One of the primary research challenges for condor conservation is interpreting the spatio-temporal dynamics of condor exposure to environmental hazards, like lead. Technological advances involving the use of radio telemetry and geographical positioning systems (GPS) units have allowed researchers to conduct assessments of how undisturbed organisms interact with their environment in fine detail (Cooke et al., 2004). The increase in quantity and quality of information produced by these devices gives researchers the ability to conduct spatial analyses more accurately. While these advances have allowed for more advanced exploration of the condors' exposure to many risks, analyses still primarily focus on exposure to risks during flight rather than while on the ground (Meretsky and Snyder, 1992; Hunt et al., 2008; Kelly et al., 2014; Poessel et al, 2018). Previous researchers have discussed the landscape characteristics that could potentially contribute to lead exposure such as land use, land ownership, and land management (Kelly et al., 2014; Poessel et al., 2017). Until recently, most spatial studies did not explore the risks that condors encounter on the ground while feeding or resting, but with the advancement of tracking devices such as the CTT-1070 GPS units, researchers now have the ability to differentiate ground foraging points (Hall et al., forthcoming 2019) from other telemetry point data. In this type of analysis, ground foraging points are defined as points when the condor is on the ground, during the day, away from roosting and nesting sites, and presumably feeding. The ability to record these ground foraging points is important because they represent the locations that condors are likely to be foraging for food, where they are at the

greatest risk of consuming lead. Due to the complexity and quality of data required, few studies have attempted to review lead exposure measurements within the condors' range, and those that have did not focus solely on ground locations. In order to understand the significance of the spatio-temporal dynamics of lead exposure in the condors' habitat, it is necessary to review the previous studies that have combined spatial data produced by tracking devices with lead exposure indicators.

Since condors were first equipped with patagial tracking devices in the early 2000s, few studies have analyzed the specific spatial components of lead exposure (Hunt et al. 2006, Finkelstein et al., 2010; Kelly et al., 2014; Poessel, 2017). Hunt et al. examined movement patterns of condors in the Arizona and Utah population on a case-by-case basis and found birds with high blood lead concentrations (BLC) are more frequently present in deer hunting areas than birds with low BLCs (2006). A few years later, Finkelstein et al. greatly enhanced the understanding of chronic lead exposure in the California population of condors by applying isotopic feather sequential analytics to identify a highly precise and accurate measure of the condors' day-to-day lead exposure for up to a 4-month span (2010). Of the 7 individual condor case studies, 1 condor had been fitted with a solar powered GPS satellite transmitter prior to capture which revealed evidence of a lead exposure event. However, since the tracking device only collected data at one hour intervals and condors have the ability to cover a large distance in that time, the exact location of the lead exposure was unable to be determined. Since then, continued analysis of sequential feather segments has been done, but this research has not been completed with the higher resolution CTT-1070 GPS units (Finkelstein et al., 2010). Kelly et al. reviewed the spatial temporal patterns that existed in the California population during a study from 1997 to 2011 to identify demographic factors, home range, feeding behaviors, and

environmental conditions that could contribute to increased BLCs (2014). By using the size of the size of a condors monthly home range and distance from food provisioning locations as explanatory variables for BLCs, Kelly et al. found a statistically significant indirect relationship between these variables and BLCs. In 2017, Poessel et al. reviewed the impact of increased BLCs on flight behavior and found that flight behaviors do not change with elevated BLCs. They indicate that one possible explanation for this is that condors are effective at masking their illness and attempt to hide weakness since condors have a strong social-hierarchy where vulnerability could put them at a disadvantage.

Defining the exact location of a specific lead exposure event is still not possible using only BLCs and current GPS telemetry data, but these data can provide an estimated time frame of exposure. This is because once a bird has ingested lead, BLCs increase over several days and slowly decrease over a period of 2 to 3 weeks because the half-life of lead in the bloodstream, approximately 13 days (McKinney, 2000; Fry and Maurer, 2003; Johnson et al., 2007; Green, 2008; Finkelstein et al., 2014).

Previous studies have evaluated the spatial component of potential lead exposure events using telemetry and GPS units in conjunction with bioindicators like blood samples. However, these studies indicate the need to refine the spatial analysis of lead exposure, which is why I chose to focus on ground foraging points and home range of ground foraging points specifically. This investigation emphasizes ground foraging patterns and locations which enhances the focus on lead exposure, as the primary opportunity for a condor to be exposed to lead is during feeding. Research also tells us that understanding condor response to lead poisoning at specific measurements (ie. $\mu\text{g/dL}$) is difficult due to the strong social hierarchy present amongst condors

that drives them to likely hide a potential illness rather than reveal weakness (Poessel et al., 2017).

The goal of this study is to better understand the factors that affect a condor's likelihood of exposure to lead through foraging. I used a non-experimental quantitative research design to examine the factors that affect BLC measured in condors and how ground foraging patterns are associated with BLCs. My objectives for this study were to (1) determine the relationship between BLC and ground foraging patterns, (2) determine the association between landscape characteristics and BLC in condors, and (3) model the blood lead concentration of condors based on their ground foraging patterns and the characteristics of the landscapes where they forage.

Methods

Study Area

I focused on data from condors in the California population that were outfitted with a CTT-1070 GPS unit, a GPS for mobile communications (GPS-GSM) telemetry system attached to the bird's patagium (Rivers et al., 20140). These condors are found in three areas in throughout California; southern California, Big Sur Condor sanctuary, and Pinnacles National Park areas (Figure 1). The approximate range of the area covered by condors in this study is nearly 7,000 km² which spans from the north coast of Los Angeles to the Sierra Nevada. This population's habitat interacts with various types of human dominated landscapes, including several large cities, road networks, agricultural lands, and gas wells. Land cover types in this area range from open grasslands and agricultural fields to coniferous and deciduous forest, while the most dominant land cover types used for foraging are Coastal Grasslands, Dry Chaparral, Pasture, and Riparian (Hall et al., forthcoming 2019). Condors are released at six sites: Bitter Creek National Wildlife Refuge, Hopper Mountain National Wildlife Refuge, Lion Canyon, and

Castle Crag in southern California and Pinnacles National Monument and Ventana Wildlife Society's Big Sur Condor Sanctuary in central California (Figure 1). The areas throughout this region are managed by private agencies or local, state, or federal governments. One managed area of interest is the Tejon ranch hunting reserve, which is a 240,000-acre private entity that has forbidden the use of lead ammunition on their hunting lands since 2008 and hosts a major portion of the ground foraging locations for the condor (Hill, 2009).

Blood Collection and Analysis

BLCs in condors were measured semi-annually and recorded by US Fish and Wildlife biologists. Birds were baited and captured with walk-in trapping pens at the six release sites. Once captured, biologists from the United States Fish and Wildlife Service (USFWS) restrained the birds to draw blood from the medial metatarsal vein and place the blood samples in tubes with a dipotassium ethylenediaminetetraacetic acid (K₂-EDTA) additive (Poessel et al., 2017).

These samples were analyzed to obtain the lead concentration in the certified commercial laboratory at the California Animal Health and Food Safety Laboratory, University of California, Davis using graphite furnace atomic absorption spectrometry on a PinAAcle 900z (PerkinElmer, Waltham, MA, USA). The certified commercial laboratory's method allows for a detection limit of approximately 5 µg/dL, therefore, any level below this detection limit is considered as a value of 0 (Poessel et al., 2017). The threshold at which a condor begins to show physiological symptoms of lead poisoning was determined to be 20 µg/dL in a study by Finkelstien et al. in 2012, however, the actual level at which a condor begins to suffer from these symptoms is not well understood. Previous research has not been able to identify specific BLCs at which condors show different physiological symptoms of lead toxicosis (ranges from 20-60µg/dL), and there is significant variance in the tolerance threshold of each bird based on their genetics, life history,

and history of exposure (Kramer and Redig, 1997; Franson, 2011). Therefore, we separated these birds into two groups based on their BLCs for analysis so we were better able to compare all of the birds, including those with BLCs that fall within the range of uncertainty. For this reason, I used the level at which condors were hospitalized by the USFWS (35 μ g/dL) to separate condors into 2 distinct groups for comparison. The “high exposure” group includes individuals with elevated BLCs greater than or equal to 35 μ g/dL, and the “low exposure” group includes individuals with BLCs below the 35 μ g/dL threshold.

Ground Foraging Point Data Collection

The CTT-1070 GPS units transmit data every 30 seconds or every 15 minutes, however, all 30 sec data was subsampled at 15min intervals for equal comparison. The collection of this data has been ongoing since the summer of 2013, but this study focuses on a time frame between December 2013 and December 2017.

I began processing this data by filtering out all observations that were inadequate data based on unit error and triangulation (Figure 2). The criteria for the FIX variable selects points that had at least 3 satellites used in the definition of the true location of the condor with precision (Katzner et al., 2012). I also evaluated horizontal and vertical dilution of precision and only included points less than 10m. Some birds in captivity are equipped with these units for research purposes and some data is recorded for wild birds being held and treated for lead toxicosis. In order to only include condors that were in the wild, I filtered the points that were assigned a deployment value of wild excluding the condors that were sent to the hospital for chelation therapy, were held in captivity, or otherwise temporarily not ranging freely as wild animals.

To identify the points that were associated with ground foraging, we isolated the points that were on the ground, were not accelerating, were recorded during the day, and were not at

known nesting locations. First, any points that recorded a speed above 3 knots were removed (Katzner et al. 2012). I calculated altitude above ground level (AGL) for each point based on that point's altitude reading and elevation from a 30-m resolution digital elevation model using ArcGIS v.10.5 ((Environmental Systems Research Institute, Redlands, CA, USA,USGS 2015, Hall et al., forthcoming 2019). Points that were not within 50m of the ground were also removed (Katzner et al., 2012), which is the standard value used to account for the accuracy of the 30-m resolution of the DEM. To remove the roosting and perching points from the remaining ground points, I eliminated the points between the first and last flight event of the day and all points within 1 km of known nesting sites (Hall et al., forthcoming 2019; Figure 2).

Exposure Windows

A period of 4 weeks prior to a BLC measurement was used to identify the presumed time frame of an exposure event, which accounts for the biological processes that occur during absorption and disposal from the bloodstream (Kelly et al., 2014; Poessel et al., 2017). For this study, the time frame, termed the condor's "exposure window," defines all of the ground foraging points that occurred during the 4-week period prior to the collection of BLC samples. I connected ground foraging points to BLCs by pairing each ground foraging point location collected during the exposure window with the recorded BLC of the individual bird. If ground foraging points for an individual bird were not recorded throughout the entire exposure window, they were excluded (Figure 2). Over the four year period that this data was collected, multiple exposure windows were included for some birds. In order to evaluate these as independent samples, exposure windows were only included in this study if they were greater than or equal to 2 months apart for the same individual condor (Kelly et al., 2014).

Objectives

(1) Association Between BLC and Ground Foraging Patterns

Ground Foraging Pattern Data Collection

Number of ground foraging points, the home range of ground foraging points, and average distance to feeding provisions from those foraging points were the foraging parameters used to determine how ground foraging patterns impact BLC in condors. The number of ground points within each exposure window was used to represent the number of times that a condor lands on the ground, presumably to feed, when they have the potential to be exposed to lead.

The United States Fish and Wildlife Service (USFWS) provided supplementary food provisions approximately every 3 days to maintain lead-free food sources for the wild condor population (Kelly et al., 2014). I measured average distance to feeding provisions from ground foraging points during each exposure window to evaluate how the reliance on this lead-free food source influences BLCs. In order to assess these distances, I used tools included in the geoprocessing packages from ESRI's ArcGIS v.10.5 (Environmental Systems Research Institute, Redlands, CA, USA). Specifically, I used the proximity tool to calculate the distance from each ground foraging point to the nearest food provision. After I made these calculations, I averaged the distances for each exposure window.

I also assessed the home range of ground foraging points during exposure windows to determine if the size of the area that condors forage on the ground in affects exposure to lead. I estimated home range using methods from Braham et al., 2015. I used 95% isopleths to estimate overall monthly ground foraging home range sizes. Table 1 defines all of the variables used in the analysis of the ground foraging pattern data.

Data Analysis

I used binomial logistic regression (Fox and Weisberg, 2018; R Core Team, 2018; The jamovi project, 2019) to answer the question of how condor ground foraging patterns, including number of ground foraging points, average distance to feeding provisions from ground foraging points, and home range of ground foraging points, are associated with increased exposure to lead. This allowed us to assess whether these ground foraging patterns could explain the variation in BLCs. All non-normal data was transformed using the logarithmic transformation to meet model assumptions.

(2) Association Between Landscape Characteristics and BLC

Landscape Data Collection

To evaluate the relationships between BLCs and human and environmental landscape characteristics, I extracted landscape characteristics for each point and calculated usage summarizations. I made observations regarding the ground foraging points' specific landscape characteristics using ArcGIS v.10.5 (Environmental Systems Research Institute, Redlands, CA, USA) extract by point tool. This allowed us to extract the characteristics from the land management, land cover, and hunting zones from the shapefiles to each of the ground foraging points. Table 1 defines all of the variables used in the analysis of landscapes.

The areas throughout this region are managed by private agencies or local, state, or federal governments. Management refers to the protection of lands, through assumed enforcement of policy, to preserve the biological diversity, and natural, recreational, and cultural uses of the land. Policies banning the use of lead in condor territory have been implemented in California, but monitoring lead use and enforcement of these restrictions is more difficult on non-managed lands owned by private entities. One managed area of interest is the Tejon Ranch

hunting reserve, which is a 240,000-acre private entity that has prohibited the use of lead ammunition on their hunting lands since 2008 and hosts a major portion of the ground foraging locations for the condor (Kunkel, 2013). I used the California Protected Areas Database to denote the land management component of the human landscape characteristics, which defines the spatial boundaries and management of lands throughout the state.

The California Department of Fish and Wildlife provides hunting zone boundaries in a GIS compatible format (California Department of Fish and Wildlife, 2016). I used this dataset because the big game hunting with lead ammunition has been identified as a major cause for lead poisoning in condors (Hunt, 2006). There are 5 hunting zones used throughout the condors' ground foraging habitat, which include D8, D9, D10, D13, and North Zone A. I recorded the hunting zone that each ground foraging point fell within to compare between the hunting zones, which all vary in size, landscape, management, and use.

The United States Geological Survey (USGS) Gap Analysis Program (GAP) also provides a land cover dataset that includes detailed vegetation and land use patterns for the continental United States (USGS, 2016). The data set incorporates the Ecological System classification system developed by NatureServe to represent natural and semi-natural land cover. In order to be able to generalize our findings, I used the least detailed land cover classifications, which included 8 land cover types. I used this land cover dataset to identify components of the condor's habitat that have hazardous qualities in terms of risk to lead exposure.

Standardization for Comparison

I collected landscape descriptors for each ground foraging point by extracting the attributes of the features that the ground foraging point lays within. However, since each exposure window contains various numbers of ground foraging points, I standardized these

variables by dividing the number of ground foraging points in each landscape by the total number of ground foraging points within the exposure window to establish a percentage. In doing so, I established a percentage of ground foraging points on each landscape classification during an exposure window that I used for comparison.

Data Analysis

I used binomial logistic regression (Fox and Weisberg, 2018; R Core Team, 2018; The jamovi project, 2019) to answer the question of how the landscape characteristics of condor ground foraging – use of lands managed by different governments, hunting zones, and land covers – were associated with BLC groups. Since a standardization for comparison was used within each landscape characteristic category (land management, land cover, and hunting zone), the variables within these categories violated the covariance assumption of the logistic regression test (i.e. %Land management = % on Federal + %NGO +%State + %Local + %Non-Managed). For this reason, I modeled each variable with at least 1% of ground points individually to determine its relationship with the BLC group. I evaluated normality using the Shapiro Wilk W test, and transformed all non-normal data using the logarithmic transformation to meet model assumptions.

(3) Modeling BLC based on Ground Foraging Patterns and Landscape Characteristics

I used the variables that showed the most statistically significant relationship with BLC group in our previous binomial logistic regressions to model BLC group (Fox and Weisberg, 2018; R Core Team, 2018; The jamovi project, 2019). Then, I used the variables that were significantly related to BLC, fit BLC as a continuous variable, and used a standard least squares regression to determine how well they modeled BLC (JMP, 2019). All non-normal data was transformed using the logarithmic transformation to make data distributions more symmetrical.

Results

There were 37 birds equipped with GPS units for this study from December 2013-December 2017. During this time, over 1.5 million locations were documented. After poor quality GPS data and selected ground points associated with flight and nesting behaviors were processed out, 208,503 ground points remained for use in this study. These remaining points for the 37 birds only had 55 instances where there was an associated BLC for the length of the entire exposure window. These 55 exposure windows account for 9,013 ground foraging points recorded for 23 birds, thus some birds had multiple exposure windows throughout the years of observation. The BLC measures for the 55 exposure windows (23 condors) sampled ranged from 0 $\mu\text{g/dL}$ to 540 $\mu\text{g/dL}$, and I retained the 540 $\mu\text{g/dL}$ reading for the logisrtic regressions (when BLCs were grouped), despite it being an extreme outlier. I then removed it for the standard least squares linear regression. I found a median value of 22 $\mu\text{g/dL}$ and a mean value of 40.67 $\mu\text{g/dL}$ (SE = 9.96). The total number of ground foraging points collected during exposure windows ranged from 40 to 422 points. The mean number of ground foraging points during the exposure window per bird was 163.87 with a median of 137 (SE = 13.33).

Objectives

(1) Association Between BLC and Ground Foraging Patterns

There were no statistically significant correlations between BLC group and other independent variables using the binomial logistic regression model (Table 2).

(2) Association Between Landscape Characteristics and BLC

I found that the majority of all ground foraging points (57.05%; $n = 5,142$) were found on non-managed land, and the remaining ground points were found on federally managed lands (23.43%; $n = 2112$), lands managed by non-governmental organizations (19.14% ; $n = 1751$),

and lands managed by local and state governments <1% (n = 8). Since only 1 of 55 exposure windows were identified as using lands managed by the state and by local government, I excluded these management types from analysis. There was a statistically significant association between BLC group and proportion of ground foraging points on lands managed by the Federal government ($p = 0.046$, $z = -1.99$), where birds that had more ground foraging points on Federal lands had a higher probability of being in the low BLC group. There was also a statistically significant association between BLC group and proportion of ground foraging points on unmanaged lands ($p = 0.005$, $z = 2.82$), where a larger proportion of ground foraging points on unmanaged lands increased the probability of a bird being in the high BLC group. There were no other statistically significant relationships between BLC group and the other landscape characteristics. The results of the binomial logistic regression for the non-government organizations lands are found in table 5.

I found that 57.42% of all ground foraging points (n = 5,175) were found on hunting zone D10 (Table 6), 26.52% (n = 2,390) were on D13 (Table 7), 8.93% (n = 805) were on zone D9, 4.8% (n = 432) were found on zone D8, 1.88% (n = 169) were found on zone A (south Unit 110), and 0.75% (n = 68) were found on zone D11. Zones D8, D9, D11, and A were excluded from analysis because there were too few samples (<37%). There were no statistically significant associations between BLC group and number of ground foraging points within each hunting zone. The results of the binomial logistic regression for the remaining hunting zones are found in tables 6 and 7.

Condors in this study used 5 of the 8 land classifications. The largest percentage of ground foraging points were found on the rangeland (n = 5,446, 60.42%), followed by forestlands (n = 1,798, 19.95%), urban or built up lands (n = 803, 8.91%), water (n = 718, 7.97%),

and agricultural lands ($n = 249$, 2.76%). None of the land covers showed a statistically significant association with BLC group. The results of the binomial logistic regression for the each land cover are found in tables 8-12.

(3) Modeling BLC based on Ground Foraging Patterns and Landscape Characteristics

Using the three most significant independent variables from our previous binomial logistic regressions, we modeled the BLC groups. This model indicated that 16-24% of the variance in BLC groups was explained by these three significant or nearly significant variables ($p = 0.026$; Table 13). From that model, I determined that non-managed lands was the best explanatory variable ($p=0.05$) for BLC grouping and the variations in BLC as a continuous variable (Table 13).

I then used that result to fit BLC as a continuous variable and run a bivariate regression model. I excluded two samples ($BLC = 540\mu\text{g/dL}$ and $130\mu\text{g/dL}$) because they were extreme outliers that lay greater than 4 standard deviations from the mean BLC value. The trend for non-managed lands was best described with as cubic ($r^2=0.54$; Figure 4) rather than linear ($r^2=.32$) (Table 13).

Discussion

This study isolates ground foraging locations to address the dynamics of lead exposure in condors. The findings of this study focused on the primary source of lead exposure in condors, which is the consumption of contaminated animal remains on the ground (Hunt et al. 2008, Hall et al. 2019). Ground foraging patterns were based on the number, location, and range of the ground foraging points collected. The average distance of ground foraging points from lead-free feeding provisions was nearly statistically significant, meaning the importance and effectiveness

of providing these lead-free provisions for condors should be analyzed further to assess the condor's reliance on human intervention to avoid lead poisoning. The findings on the ground foraging proximity to feeding provisions agrees with the study by Kelly et al. (2014). However, in contrast to Kelly et al.'s findings on home range analysis and BLC levels, I found that the association between the size of the home range of ground foraging points and BLCs was not statistically significant. Despite the home range of ground foraging points is more specific to lead exposure than the standard home range used by Kelly et al. and other studies, these findings do not indicate that home range size of ground foraging points are significant to the understanding BLC (2014). This brings into question whether the landscape characteristics of the home range of the ground foraging points influence the likelihood of exposure more than just the size of the range. I found significant or nearly significant relationships between BLCs and average distance to feeding provisions from ground foraging points and proportions of ground foraging points on non-managed and federally managed lands.

Condor Ground Foraging Patterns

Average distance to feeding provisions showed a nearly significant association with BLC, where birds that foraged further from feeding provisions tended to be in the high exposure group compared to those that foraged closer to the provisions. These birds that forage further from the food provisions are considered more independent and "wild" than those that are more reliant on human intervention (Kelly et al., 2014). This presents a major problem to condor recovery because independence and natural ground foraging abilities are required for a self-sustaining population, but the most independent and "wild" population of condors is more likely to have higher BLCs than those that remain dependent on humans.

Land Management and Condor Conservation

The average proportion of ground foraging points on federal managed lands (23.43%) was directly associated with BLC, indicating that federal managed lands could be considered a “safe zone” for condors. This is likely due to the federal government’s substantial resources and investments into managing land in the condor range to help this critically endangered species recover. However, since condors forage more frequently on the ground on non-managed lands (57.05%), these management efforts are not capturing the population as a whole.

Condors in the high exposure group had a larger proportion of ground foraging points on non-managed lands compared to that of the low exposure group. Also, when I modeled BLC as a continuous and categorical (BLC groups) variable, non-managed lands was the best explanatory variable for BLC grouping and the variations in BLC (Table 5). I also found that a cubic function modeled BLC as a continuous variable much better than a linear fit (Figure 4). This shows that when a condor has either a high or low frequency of ground foraging points on non-managed lands, their BLC is easier to estimate than those birds that have a mixed number of ground foraging points on non-managed and federal lands. Since condors, which are free ranging in the wild, often forage on non-managed and managed lands, this presents great challenges for the future expansion of condors.

Without enforcement of policies that ban lead, like the Ridley Tree Act of 2008, these non-managed lands leave condors vulnerable to the unregulated hunting practices of private landowners, putting them at greater risk of consuming lead in this environment. Educating private landowners, particularly those involved with hunting, about the dangers of lead in the environment, the alternative ammunition available, and the importance of condors and other scavengers in the environment is a vital part of conserving this species. The NGO Tejon Ranch,

for instance, is a hunting reserve within the condor's range that began enforcing a no lead ammunition policy in 2008 following the introduction of the Ridley Tree Act in California. Their adherence to the lead ban is believed to be important to the condors' recovery and survival because the largest concentration of condor ground foraging points out of the entire range is found on Tejon Ranch. Since Tejon Ranch accounts for nearly all of the lands managed by non-governmental organization used by condors and they enforce a lead ban, I anticipated that lead exposure events would be less likely to occur on NGO managed lands in my study. However, my results did not indicate a statistically significant relationship between proportion of ground foraging points on NGO managed lands and BLC.

These findings, which help determine where condors are most likely being exposed to lead through ground foraging, can be used to improve the application of current management strategies and develop new strategies by providing target areas for intervention. Also, the non-managed lands model of BLCs in condors can be used to make predictions about condors that may need an additional medical evaluation given the characteristics of their previous ground locations. As the condor population continues to recover and grow, the importance of remote monitoring of these birds increases due to our need to prioritize which birds will receive help as financial support and resources are limited. The results of my study can be used to enhance our ability to monitor these birds remotely and also gives us insight into the areas that need additional or enhanced regulation on lead ammunition. Identifying these non-managed lands as the main lead exposure locations for condors should also help shape the management strategies used in these areas. A statewide ban began phasing out lead ammunition in California in 2016 with the goal of completely eliminating it by July of 2019, however, the use of lead has been banned for big game hunting in the condor range since the Ridley Tree Act was enacted in 2008.

These findings, and those of many others, show that condors are still being exposed to lead at an alarming rate in southern California despite the ban being in place for over a decade. This shows that policy alone has not been effective at eliminating lead in the environment. With the understanding that hunting on these private lands is less regulated than on Federal and non-governmental organization lands, I believe that focusing resources on educating the hunting community in these areas about the dangers of using lead ammunition and the alternative type of ammunition available will likely be more effective than relying on regulation of policy alone.

Limitations and Future Studies

This study shows the value of isolating ground foraging points and observing the landscape characteristics of these specific ground foraging locations when studying lead exposure in condors. The sample size was limited by the specificity of only using those ground foraging points that fell within the 4 week window prior to collection of blood for each bird, however, the mean and median BLCs for the condors in this study still fell within the range of other larger scale studies by Finkelstein et al. (2012) and Kelly et al. (2014). Despite the long duration of this study (4 years) and the large number of GPS data points collected over that time period, this sample size was limited by the frequency of blood samples collected because the bi-annual blood samples only represent approximately 10% of a condor's yearly lead exposure history (Finkelstein et al., 2012.) Additionally, analysis of these spatial components is limited by the time between data collection (15 minutes) when the bird's behavior and location is unknown.

Future studies in this area should focus on improving the understanding and remote identification of ground foraging behavior so we can continue to focus on specifically the ground foraging points (when lead exposure is most likely to occur) in the analysis rather than including flight, nesting, and perching points as well. Increasing the frequency and quantity of ground

foraging points collected for analysis to increase the sample size and accuracy of the ground foraging information is another important next step. Also, combining the ground foraging points with feather sequential analysis rather than blood collection would reduce the exposure window from 30 days down to 5 days, increasing the specificity of our data. Feather sequential analysis also provides a more accurate and longer lead exposure history (~4 months) than BLCs, which would provide information on a much larger proportion of the bird's life and would allow for the accumulation of more ground foraging points to improve our understanding of the magnitude and duration of lead poisoning events (Finkelstein et al., 2012). Lastly, comparing a home range analysis of ground foraging points between managed and non-managed lands would improve our understanding of how the landscape characteristics of an individual bird's range can be used to understand potential exposure to lead. All of these adjustments would allow for increased monitoring, accuracy, and remote predictive ability, which could help us eliminate lead exposure in the California condor.

Although humans have played a vital role in saving condors from extinction, they are also the primary cause of their decline due to anthropogenic factors like the use of lead ammunition and irresponsible hunting practices (Finkelstein et al., 2012). We must first improve our understanding of where condors are being exposed to lead while foraging on the ground in order to improve our management strategies and enforcement of policy on lead ammunition. Only then will we be able to eliminate lead as a road block to achieving a self-sustaining condor population in the wild.

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Tables

Table 1. Definition of variables used in the ground foraging pattern data and landscape collection.

Variable Name	Definition
BLC	Blood Lead Concentration
BLC Group	High Exposure = 35.0 µg/dL and above Low Exposure = 34.9 µg/dL and below
Number of Ground Foraging Points	Total number of ground foraging data points collected for an individual bird within a single exposure window
Average Distance to Feeding Provisions	Distance to the nearest safe food source provided by the USFWS
Home Range of Ground Foraging Points	Total area covered during ground foraging
Non-Managed Lands	Private land not listed in the U.S. Protected Areas Database
Federally Managed Lands	Federal land listed in the U.S. Protected Areas Database
State and Local Lands	Areas managed by state and local governments
Non-Governmental Managed Lands	Lands managed by non-governmental organizations (i.e. Tejon Ranch)
Hunting Zones	Specific areas defined for hunting by the state of California
Land Covers	Ecological classification system of the area as defined by the U.S. Geological Survey

Table 2: Binomial logistic regression statistics for association between BLC group and average distance to feeding provisions, ground foraging home range size, and number of ground points.

Model Coefficients					
	Predictor	Estimate	SE	Z	p
	Intercept	-7.2415	4.2051	-1.722	0.085
	Average Distance to Feeding Provisions (km)	0.0458	0.0249	1.837	0.066
	Log[Ground Foraging Home Range Analysis (ha)]	0.3063	0.3879	0.790	0.430
	Log[Total Number of Ground Points]	0.1407	0.5337	0.264	0.792

Note. Estimates represent the log odds of "Exposure Group = High" vs. "Exposure Group = Low"

Table 3: Binomial logistic regression statistics for association between BLC group and proportion of ground foraging points on non-managed lands during an exposure window.

Model Coefficients

Predictor	Estimate	SE	Z	p
Intercept	4.02	1.21	3.32	< .001
Non-Managed Lands	-5.16	1.83	-2.82	0.005

Note. Estimates represent the log odds of "Exposure Group = Low" vs. "Exposure Group = High"

Table 4: Binomial logistic regression statistics for association between BLC group and proportion of ground foraging points on federally managed lands during an exposure window.

Model Coefficients

Predictor	Estimate	SE	Z	p
Intercept	2.106	0.662	3.18	0.001
Log[Federal]	0.579	0.291	1.99	0.046

Note. Estimates represent the log odds of "Exposure Group = Low" vs. "Exposure Group = High"

Table 5. Binomial logistic regression statistics for association between BLC group and proportion of ground foraging points on lands managed by Non-Governmental Organizations during an exposure window.

Model Coefficients

Predictor	Estimate	SE	Z	p
Intercept	0.990	0.312	3.173	0.002
Non-Governmental Organization	-2.655	20.418	-0.130	0.897

Note. Estimates represent the log odds of "Exposure Group = Low" vs. "Exposure Group = High"

Table 6. Binomial logistic regression statistics for association between BLC group and proportion of ground foraging points on Hunting Zone D10 during an exposure window.

Model Coefficients				
Predictor	Estimate	SE	Z	p
Intercept	0.817	0.632	1.293	0.196
Hunting Zone D10	0.288	0.987	0.292	0.770

Note. Estimates represent the log odds of "Exposure Group = Low" vs. "Exposure Group = High"

Table 7. Binomial logistic regression statistics for association between BLC group and proportion of ground foraging points on Hunting Zone D13 during an exposure window.

Model Coefficients				
Predictor	Estimate	SE	Z	p
Intercept	0.653	0.449	1.454	0.146
Hunting Zone D13	1.317	1.420	0.927	0.354

Note. Estimates represent the log odds of "Exposure Group = Low" vs. "Exposure Group = High"

Table 8. Binomial logistic regression statistics for association between BLC group and proportion of ground foraging on Rangeland during an exposure window.

Model Coefficients				
Predictor	Estimate	SE	Z	p
Intercept	0.246	0.931	0.265	0.791
Rangeland	1.238	1.509	0.820	0.412

Note. Estimates represent the log odds of "Exposure Group = Low" vs. "Exposure Group = High"

Table 9. Binomial logistic regression statistics for association between BLC group and proportion of ground foraging points on Forest Land during an exposure window.

Model Coefficients				
Predictor	Estimate	SE	Z	p
Intercept	1.61	0.552	2.92	0.003
Forest land	-2.96	2.022	-1.46	0.143

Note. Estimates represent the log odds of "Exposure Group = Low" vs. "Exposure Group = High"

Table 10. Binomial logistic regression statistics for association between BLC group and proportion of ground foraging points on Urban or built-up land during an exposure window.

Model Coefficients				
Predictor	Estimate	SE	Z	p
Intercept	1.22	0.434	2.810	0.005
Urban or built-up	-2.53	3.142	-0.806	0.420

Note. Estimates represent the log odds of "Exposure Group = Low" vs. "Exposure Group = High"

Table 11. Binomial logistic regression statistics for association between BLC group and proportion of ground foraging points on Water during an exposure window.

Model Coefficients				
Predictor	Estimate	SE	Z	p
Intercept	0.427	0.423	1.01	0.313
Water	8.326	5.228	1.59	0.111

Note. Estimates represent the log odds of "Exposure Group = Low" vs. "Exposure Group = High"

Table 12. Binomial logistic regression statistics for association between BLC group and proportion of ground foraging points on Agricultural land during an exposure window.

Model Coefficients

Predictor	Estimate	SE	Z	p
Intercept	1.03	0.371	2.774	0.006
Agriculture	-1.65	7.320	-0.226	0.821

Note. Estimates represent the log odds of "Exposure Group = Low" vs. "Exposure Group = High"

Table 13: Binomial logistic regression statistics for association between BLC group and the three most significant variables (proportion of ground foraging points on federally managed lands and non-managed lands and average distance to feeding provisions from ground foraging points during an exposure window).

Model Coefficients				
Predictor	Estimate	SE	Z	p
Intercept	3.249	1.535	2.117	0.034
Average Distance to Feeding Provisions	1.87e-5	3.68e-5	0.509	0.611
Non-Managed Lands	-4.718	2.404	-1.963	0.050
Log[Federal]	0.270	0.433	0.625	0.532

Note. Estimates represent the log odds of "Exposure Group = Low" vs. "Exposure Group = High"

Figures

Figure 1. Map of Condor Ground Foraging Points for the California Population. Global positioning system (GPS) locations ($n = 9,013$) during the 1-month period before blood collection of 37 California condors tracked in southern California, USA, December 2013–December 2017, and the locations of Bitter Creek and Hopper Mountain National Wildlife Refuges (NWR).

Figure 2. Data Filtration for the California Condor Ground Foraging Patterns. Procedures for filtering data to exclude poor quality GPS data, altitudes greater than 50 meters, velocities greater than 3 Knots, points collected a night (prior to first flight or after last flight of the day), and points within 1 km of known nesting sites, leaving only the presumed California condor ground foraging points for further analysis.

Figure 3. Criteria for Establishing Ground Foraging Points of the California Condor.
Description of the criteria for establishing California condor ground foraging points to be included in an exposure window.

Figure 4. Model Comparison Between Linear and Cubic Regressions for Blood Lead Concentration (BLC) in California Condor. The graph shows the comparison between the linear (blue) and cubic (green) fits used to model BLC (as a continuous variable) using the proportion of California condor ground foraging points on non-managed lands. The cubic fit ($r^2=0.54$) indicates a better fit than linear ($r^2=.32$). Note that blood lead concentrations 540 and $130\mu\text{g/dL}$ were excluded as they were extreme outliers.