Project Title: Predict Condor Range to Reduce Development Threats
Final Accomplishment Report

Summary

California condors (*Gymnogyps californianus*) have been listed as critically endangered since the first endangered species list was created in 1967. As the population's growth continues to face challenges, it is imperative that managers reduce all potential threats to the species and foster conditions that promote condor recovery. This study aimed to predict condor range expansion into their historic range to identify habitat necessary to protect from development that can negatively impact condors. We collaborated with Pinnacles National Park (PINN) to collect location data and conduct analyses that provide a basis for these predictions. Condors narrowly evaded extinction during the 1980s when the population reached a low of 22, causing biologists to bring all remaining wild individuals into zoos for captive breeding programs. By the mid-1990s, condors were being released back into the wild from several release sites in CA, naturally forming two flocks in central and southern CA.

Thousands of square miles of currently unoccupied historic condor range separate the two flocks and interactions between the two have been extremely rare. However, PINN detected long-range condor movements in 2015 and 2016 from central to southern CA throughout the historical condor range and beyond, which highlighted a critical need to understand how condors will utilize the landscape as their range expands. Unfortunately, alternative energy development, in the form of wind generators, may proceed within currently unoccupied habitat without considering risks to condors despite the substantial threat it poses to birds. Predicting condor range expansion and identifying hotspots will provide critical information necessary to protect habitat by enabling developers to consider impacts to condors and select alternate sites during compliance processes.

This research built upon data collected regarding historic and current condor locations during Phase 1 of our project. During Phase 2 of the project we estimated core and home range areas of 123 condors that wore GPS units between the years of 2006 – 2017 and identified individual characteristics, management factors, population changes, and environmental variables associated with home ranges. Using the associated factors, we built a tool to predict condor range expansion in suitable habitat in California, then identified likely areas of conflict between predicted range expansion and potential wind energy development. More than 85% of commercially valuable wind was unaffected by predicted home range areas, suggesting there are many alternative sites to develop. We found that <5% of predicted range overlapped with commercially valuable wind, however overlapping areas coincide with the most recent core areas estimated during our study. Protection of endangered California condors is in line with the NPS's mission statement and contributes to overarching recovery goals.

Objectives

1) Analyze historical, current, and new travel (2014-2017) GPS data to create a predictive GIS model to map range expansion over time and travel corridors between current and central CA flocks.

2) Predict when the flocks will merge and expand within and beyond 'historical' range.
3) Create a GIS tool to aid proposed development planning that could pose threats to condors.
4) Use the tool to inform condor recovery planning and management actions.

Methods

1) We estimated annual core and home range areas for 123 condors that wore GPS units between 2006 – 2017 using used 'ctmmweb' (Dong et al., 2018) a web application based on the 'ctmm' package (Fleming and Calabrese, 2019) for R statistical software (R Core Team, 2018). A condor's range was estimated if it had ≥ 6 months cumulative data during a calendar year.
2) We conducted a stepwise model selection of linear mixed-effects models (LMMs) that were fitted using the 'lme4' package in R Studio version 1.1.43 (Bates et al., 2015; R Core Team, 2018) to identify variables associated with home range area. We used the 'lmer' function with a normal distribution, maximum likelihood estimation, and Satterthwaithe degrees of freedom. We used home range area as the response variable and Bird ID as a random variable. We included all other factors as fixed variables (see Table 1 for descriptions).
3) We designed a predictive tool (Figure 2) in Netlogo version 6.1.1 (Wilenksy, 1999) to predict condor range expansion in California. A study by D'Elia et al. (2015) identified habitat suitable for condor occupation and found < 40% was being used by condors at the time of the study. We used this habitat suitability map and the results of our home range analysis to create our predictive tool.
4) We predicted condor range expansion under 4 different scenarios with the origins of predicted home ranges constrained within the most recent (2017) core and home ranges included in our study:
    a. Population demography stays the same (2019 California population).
    b. Each flock has ≥150 individuals with ≥15 breeding pairs).
    c. Maximize breeding pairs, minimize sub-adult condors (70 breeding, 35 adult non-breeding, 10 subadult, 35 juvenile).
    d. Maximize subadult condors, minimize breeding pairs (10 breeding, 35 adult non-breeding, 70 subadult, 35 juvenile).

    We included scenarios c. and d. based on results from our home range analysis, which we explain below.
5) Finally, we identified areas of conflict between predicted condor range expansion and areas of commercially valuable wind in ArcGIS Pro version 2.5.0 (ESRI, 2020). We used a dataset from the National Renewable Energy Lab (NREL) that classifies wind at 50 meters above ground level. Of the 7 wind classes, areas with class ≥ 3 (i.e. high-class winds, with speeds >6.4 m/s) are considered commercially valuable and suitable for wind energy development (Poessel, et al., 2018; NREL, 2015).

Results

We estimated 375 core areas and home ranges (Figure 1) from 123 individuals that wore GPS units between 2006 – 2017. Overall, we analyzed 105 adult-breeding, 160 adult non-breeding, 87 subadult, and 23 juvenile condor GPS years. The sample is representative of the entire California population, including both sexes (59 females, 64 males), and both rearing methods (108 captive-bred, 15 wild-hatch). The median number of home ranges estimated per individual was 2 (range: 1 – 11). Factors that significantly effect home range area are: age group, time spent in the wild, age of managing agency, maximum slope, maximum NDVI, distance to water, and road density (Table 2).

The mean home range area for all condors is 5,154 ± 181 km^2 (range = 7.76 – 20,716 km^2), however age group did have significant effects on home range area. Subadults use the largest home ranges (mean = 6339 ± 289 km^2), followed by juveniles (mean = 5628 ± 501 km^2), adult non-breeding (mean = 5157 ± 208 km^2), and adult breeding condors using the smallest (mean = 4348 ± 251 km^2, Figure 2). The mean home range areas of subadults, non-breeding adults, and breeding adults were all significantly different from each other, but the mean home range area of juveniles was no significantly different from any other age group (Figure 3). Factors that positively effect home range area are: age of managing agency, mean NDVI, and mean road density. Factors that negatively affect home range size are: time spent in the wild, mean maximum slope, and mean distance to water.

We predicted condor range expansion in California under four scenarios:

a. Population demography stays the same (2019 California population).
b. Each flock has ≥ 150 individuals with ≥15 breeding pairs.
c. Maximize breeding pairs, minimize sub-adult condors.
d. Maximize subadult condors, minimize breeding pairs.

We predicted condor range expansion under scenario b. as those are the population requirements for de-listing, in addition to populations being self-sustaining. While we cannot simulate a self-sustaining population in our predictive tool, we can predict condor home ranges for that number of individuals within a population. We predicted scenarios c. and d. as we found breeding and subadult condors have the smallest and largest home ranges, respectively, and hypothesized larger proportions of those age group within a population would have the largest effect on whether condor range would expand.

We found that central and southern California ranges overlapped in all scenarios. We intersected the predicted ranges with commercially valuable wind and found <5% of predicted condor range for all scenarios was affected (Figure 4). We also found that >85% of commercially valuable wind was unaffected by predicted condor range under all scenarios.

Interpretation and Management Recommendations

The results from our study indicate that home range sizes change based on the biological needs of different life stages and knowledge of available resources. Breeding adults have the smallest mean home range areas, while subadults have the largest. Subadults, adult non-breeding, and adult breeding condors all had significantly different mean annual home range areas from each other, but juvenile condors did not have significantly different annual home range sizes from any age group. Other studies of vultures and eagles also report smaller home ranges for breeding individuals than other age groups (Margalida et al., 2016; Moss, et al, 2014; Reading et al., 2019). This pattern is attributed to different fitness priorities—subadults seek to improve chances of survival by exploring the landscape looking for optimal resources, whereas breeders focus on reproduction and constrain movements around their nests (Kendall et al., 2014; Margalida et al., 2016; Reading et al., 2019).

Information sharing may influence home range area. Condors are social and communally roost and forage; an adaptation seen in many vulture species and hypothesized to aid in and generate information sharing (Bijleveld et al., 2010; Dermody et al., 2011; Harel et al., 2017). Though a few condors that were captured in 1987— when all remaining individuals were brought into captivity to save the species—have since been released, condors were reintroduced to a novel landscape absent of conspecifics. We found that annual home range areas grow as managing agencies mature and age. Less experienced condors added to the population each year can follow more experienced and knowledgeable individuals from communal roosting sites and learn about the surrounding landscape, eventually exploring further than the known areas. However, following an individual to a novel site is risky; therefore, there may be a minimum critical number of condors that consistently use a new area before it is deemed safe and incorporated into core areas (Cortes-Avizanda et al., 2014).

In all our predictions, we found that <5% of condor range overlapped with areas that generate commercially valuable wind. Unfortunately, the overlapping area coincides with estimated core areas of the southern California flock in 2017. Poessel et al. (2018), found that condors in southern California regularly flew near commercially valuable wind and flew within the rotor-swept zone of wind turbines 39% of the time. Condors also use these high-wind areas most frequently in the morning and evening and during winter, i.e. when thermals are weakest (Poessel et al., 2018). It is also recommended that turbines, “be placed a certain distance (e.g., 100 m) away from ridgelines with strong orographic updrafts to reduce collision risk with soaring birds” (Poessel et al., 2018). However, we found >85% of commercially valuable wind was unaffected by condor range expansion, suggesting there are many alternative areas for wind energy development.

Products and presentations

We created a predictive tool that will be provided to PINN and other California Condor Recovery Program agencies.

We have also presented this research through poster and oral presentations:

- Natural Resource Ecology Lab Soup & Science Seminar Series, November 2019
- California Condor Annual Field Team Meeting, September 2019
- Front Range Student Ecology Symposium, February 2018
- International Colloquium on Ecosystem Science, November 2017
- California Condor Annual Field Team Meeting, September 2017
- Front Range Student Ecology Symposium, February 2020
- California Condor Annual Field Team Meeting, September 2020 (upcoming)

References

Bates, D., M. Maechler, B. Bolker, and S. Walker. 2015. Fitting Linear Mixed-Effects Models Using lme4. Journal of Statistical Software, 67(1), 1-48. doi:10.18637/jss.v067.i01.

Bijleveld, A.I., Egas, M., van Gils, J.A., Piersma, T., 2010. Beyond the information centre hypothesis: communal roosting for information on food, predators, travel companions and mates? Oikos 119, 277–285. https://doi.org/10.1111/j.1600-0706.2009.17892.x

D'Elia, J., Haig, S. M., Johnson, M., Marcot, B. G., and Young, R. 2015. Activity-specific ecological niche models for planning reintroductions of California condors (Gymnogyps californianus). Biological Conservation 184: 90–99 https://doi.org/10.1016/j.biocon.2015.01.002

Dermody, B.J., Tanner, C.J., Jackson, A.L., 2011. The Evolutionary Pathway to Obligate Scavenging in Gyps Vultures. PLoS ONE 6, e24635. https://doi.org/10.1371/journal.pone.0024635

Dong, X., C.H. Fleming, M.J. Noonan, and J.M. Calabrese. 2018. ctmmweb: A Shiny web app for the ctmm movement analysis package. https://github.com/ctmm-initiative/ctmmweb

ESRI. 2020. ArcGIS Pro: Release 2.5.0. Redlands, California: Environmental Systems Research Institute.

Fleming, C. H. and J. M. Calabrese. 2019. ctmm: Continuous-Time Movement Modeling. R package version 0.5.5. https://CRAN.R-project.org/package=ctmm

Harel, R., Spiegel, O., Getz, W.M., Nathan, R., 2017. Social foraging and individual consistency in following behaviour: testing the information centre hypothesis in free-ranging vultures. Proc. R. Soc. B 284, 20162654. https://doi.org/10.1098/rspb.2016.2654

Kendall, C.J., Virani, M.Z., Hopcraft, J.G.C., Bildstein, K.L., Rubenstein, D.I., 2014. African Vultures Don't Follow Migratory Herds: Scavenger Habitat Use Is Not Mediated by Prey Abundance. PLoS ONE 9, e83470. https://doi.org/10.1371/journal.pone.0083470

Margalida, A., Pérez-García, J.M., Afonso, I., Moreno-Opo, R., 2016. Spatial and temporal movements in Pyrenean bearded vultures (Gypaetus barbatus): Integrating movement ecology into conservation practice. Sci Rep 6, 35746. https://doi.org/10.1038/srep35746

Moss, E.H.R., Hipkiss, T., Ecke, F., Dettki, H., Sandström, P., Bloom, P.H., Kidd, J.W., Thomas, S.E., Hörnfeldt, B., 2014. Home-Range Size and Examples of Post-Nesting Movements for Adult Golden Eagles (*Aquila chrysaetos*) in Boreal Sweden. Journal of Raptor Research 48, 93–105. https://doi.org/10.3356/JRR-13-00044.1

NREL (National Renewable Energy Laboratory). 2015. Geospatial Data Science: Wind Data National Renewable Energy Laboratory, U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Washington, DC, USA. https://www.nrel.gov/gis/data-wind.html

Poessel, S. A., Brandt, J., Mendenhall, L., Braham, M. A., Lanzone, M. J., McGann, A. J., & Katzner, T. E. 2018. Flight response to spatial and temporal correlates informs risk from wind turbines to the California Condor. The Condor, 120(2): 330–342. https://doi.org/10.1650/CONDOR-17-100.1

R Core Team (2018). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Reading, R.P., Bradley, J., Hancock, P., Garbett, R., Selebatso, M., Maude, G., 2019. Home-range size and movement patterns of Hooded Vultures *Necrosyrtes monachus* in southern Africa. Ostrich 90, 73–77. https://doi.org/10.2989/00306525.2018.1537314

Wilensky, U. 1999. NetLogo. http://ccl.northwestern.edu/netlogo/. Center for Connected Learning and Computer-0Based Modeling, Northwestern University. Evanston, IL.

Table 1. Variables considered in model selection, organized by category

Variable	Description
Individual characteristics	
Age group	Categorical - 4 levels: adult breeding, adult non-breeding, subadult, juvenile. Adult breeding: ≥6 years of age and breeding, adult non-breeding: ≥6 years of age and not breeding, subadult: ≥3 years old and ≤5 years of age, juvenile: ≤2 years of age. *One female individual was 5 years of age and breeding and was included in adult breeding category
Sex	Categorical - 2 levels: male, female
Time spent in wild	How long an individual has been in the wild from release/wild hatch to end of GPS year
Management characteristics	
Rearing method	Categorical - 2 levels: Wild-hatch, captive-bred and release. Wild hatch includes individuals that were hatched in the wild from captive-laid eggs.
Flock	Categorical - 2 levels: Central CA (condors managed by PINN/VWS), Southern CA (condors managed by USFWS)
Age of managing agency	Age of managing agency at the end of the GPS year
Population factors	
Population size	Number of individuals per flock at end of GPS year
Adult breeding to subadult ratio	Ratio of breeding adult individuals to subadult individuals per flock per GPS year
Soaring conditions and climate	
Thermal updraft velocity	Annual mean velocity of rising air (m/s)
Thermal height	Annual mean thermal height (m)
Wind speed	Categorical - Horizontal wind power class at 50 m above the ground
Winter severity	Mean minimum winter temperature (^{o}C x 100)
Terrain	
Cliffs	Maximum slope within a 1 km2 neighborhood (degrees)
Terrain ruggedness	Ratio of a 3-dimensional surface area to planar surface area
Landscape productivity	
Landscape productivity	Average Maximum Normalized Difference Vegetation Index (NDVI)
Distance to water	Euclidean distance to the nearest freshwater
Vegetation characteristics	
Canopy cover	Median canopy cover (%)
Canopy height	Categorical - 5 levels: Bare or very low vegetation (<0.5m), low vegetation (0.5-1m), medium vegetation (1-5m), tall vegetation (>5m), other/non-habitat.
Land cover type	Categorical - 10 levels: Non-habitat, perennial ice and snow, developed, bare rock/sand/clay, deciduous forest, evergreen forest, mixed forest, shrubland, grassland/herbaceous/pasture, row crops
Human disturbance	
Road density	Meters of road/km^2
Human density	Humans/km^2

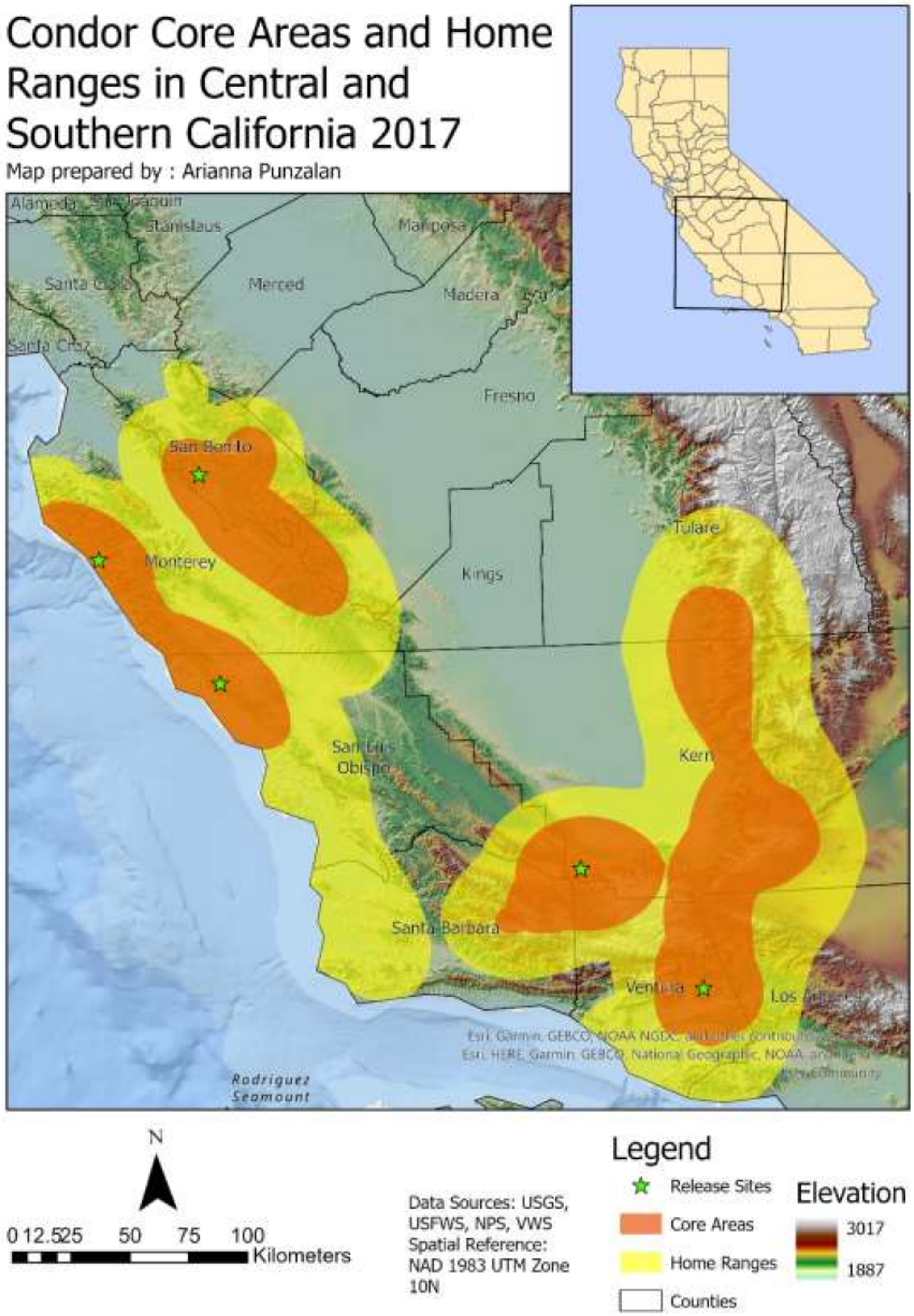

Figure 1. Estimated core and home range areas of condors in California during 2017.

Table 2. Coefficients of significant predictors included in top model. Marginal R^2 value represents variation explained by fixed effects. Conditional R^2 is the variation explained by both fixed effects and random effects Bird ID).

	Beta Estimate	Std. Error	Degrees Freedom	t - value	Pr (>|t|)
Adult Breeding (Intercept)	-16301.65662	6172.673	271.6186	-2.64094	0.008746
Adult Non-breeding	809.1718345	263.4531	364.759	3.071407	0.00229
Juvenile	1280.218238	563.5564	359.6616	2.271677	0.023696
Subadult	1991.274799	377.8327	371.0209	5.270255	2.32E-07
Time Spent in the Wild	-109.5391614	34.11336	154.3224	-3.21103	0.00161
Age of Managing Program	195.0115068	29.8262	196.7377	6.538261	5.24E-10
Maximum Slope	-347.9939376	57.702	365.2557	-6.03088	4.00E-09
Maximum NDVI	130.0706451	36.68741	226.9953	3.545375	0.000476
Distance to Water	-135.8813247	30.76175	373.1018	-4.41722	1.31E-05
Road Density	4.192764194	0.585192	374.9631	7.164767	4.16E-12
Marginal R^2: 0.65			**Conditional R^2**: 0.74		

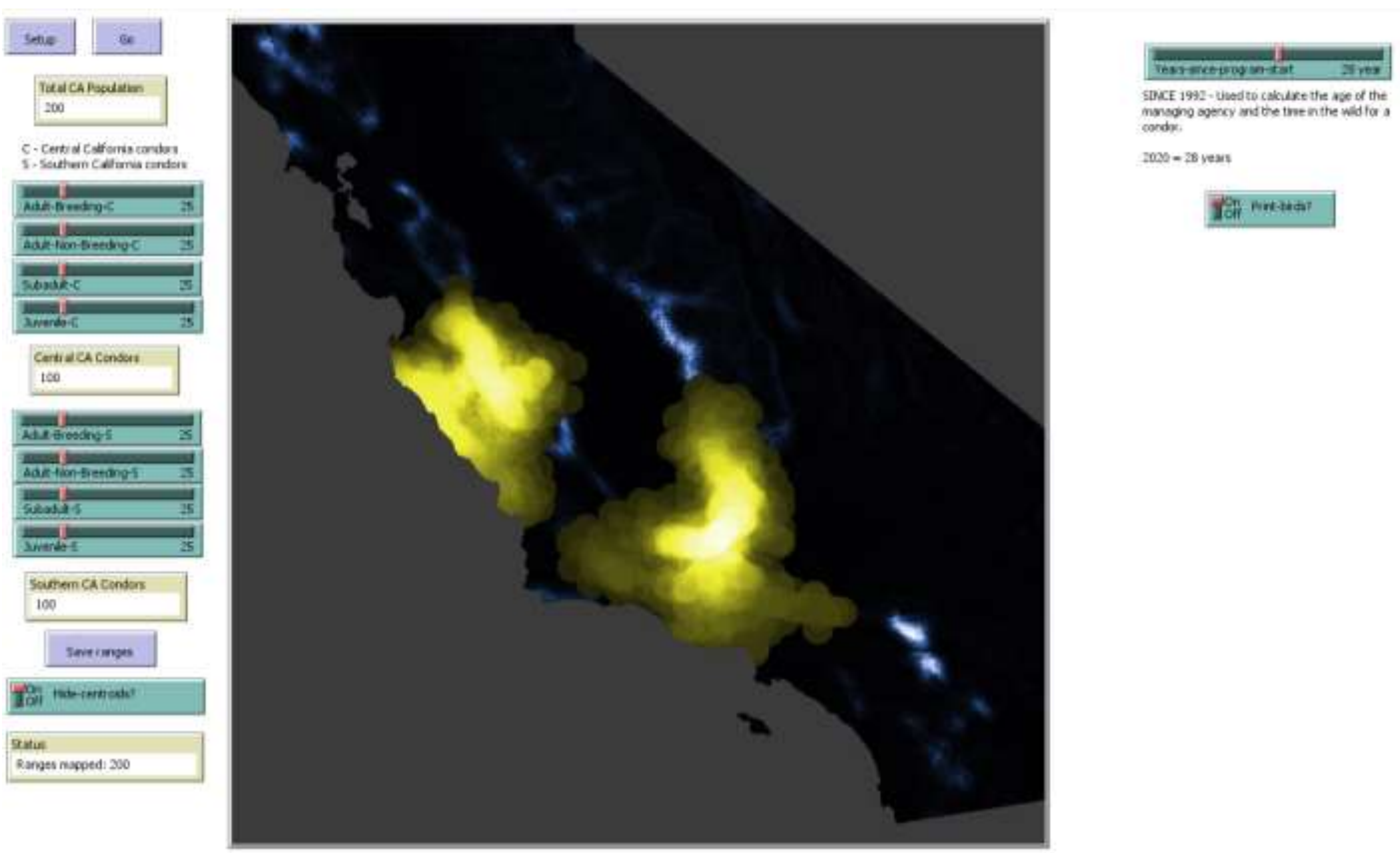

Figure 2. User interface of predictive model with example of predicted ranges. Habitat suitability map in central and southern California in black and white. Lighter areas have higher suitability values (D'Elia et al., 2015). The yellow gradient represents overlapping predicted condor home ranges.

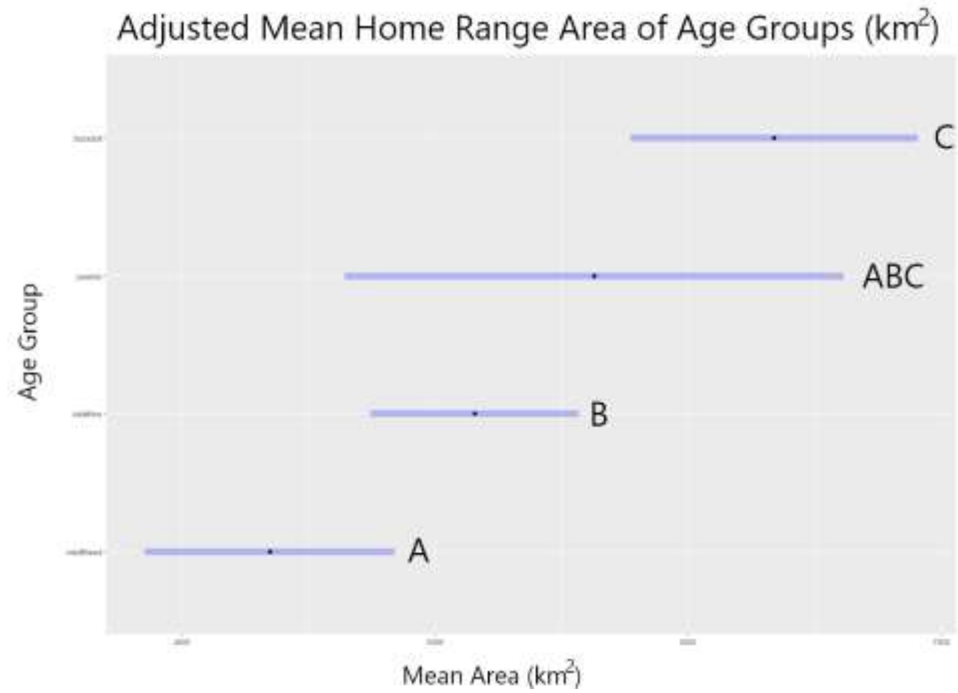

Figure 3. Compact letter display of pairwise comparisons of mean home range sizes of different age groups. Age groups with the same letter are not significantly different from each other.

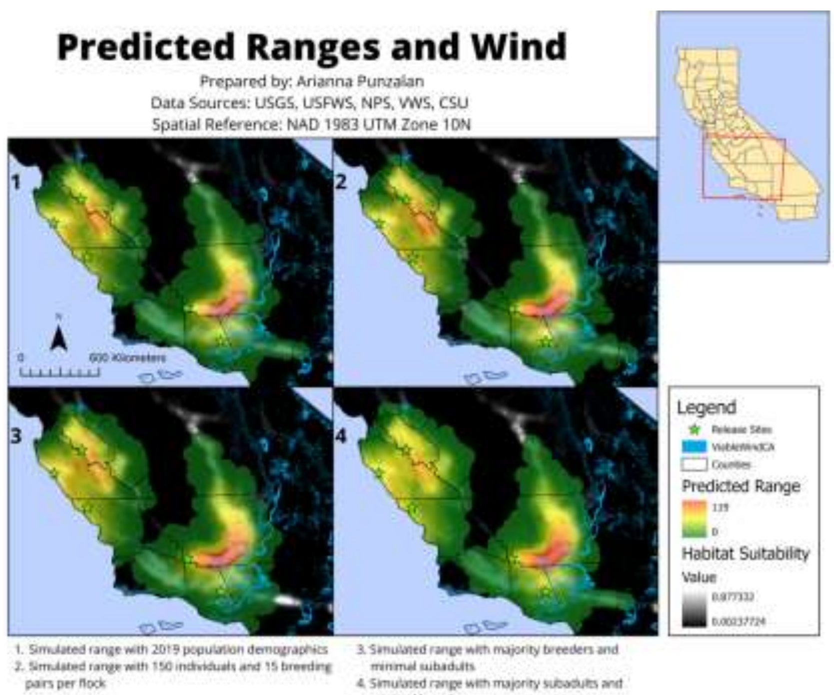

Figure 4. Predicted condor ranges and commercially valuable wind. Predicted range values represent number of overlapping individual home ranges.