Appendix B. Detailed description of environmental predictor variables

Soaring Conditions and Climate

Thermal Height and Thermal Updraft Velocity

Condors are a large soaring bird, dependent upon rising air to move around the landscape and find food (Koford, 1953). Atmospheric conditions are rarely accounted for in habitat selection or niche models for soaring birds, but there have been recent advances in integrating atmospheric data with raptor soaring patterns (Mandel et al., 2008; Bohrer et al., 2012; Rivers et al. 2014). Monthly thermal height (i.e., the upper limit of thermal activity) and thermal updraft velocities (W*) were derived from the National Oceanic and Atmospheric Administration's (NOAA's) Rapid Update Cycle (RUC) Sounding Forecast (*http://ruc.noaa.gov/*) data from April 2007-April 2009. Thermal updraft velocities were calculated as $W^* = [(g/T_o)\ Q_s\ D]^{1/3}$, where D is the boundary layer depth (or thermal depth), Q_s is the surface heating, and (g/T_o) is a known buoyancy constant obtained by dividing the earth's gravitational acceleration (g) by the average temperature (T_o)). Monthly averages for thermal height and thermal updraft velocities were converted to annual averages for the analysis. The original data was available in 12 km^2 pixels, which we resampled to 1km^2 pixels using the RESAMPLE tool and the BILINEAR technique. We then used the FOCAL STATISTICS tool to summarize MEAN values within 10 km of each cell. We used a 10 km circular radius and ignored NoData values in our FOCAL STATISTICS calculation.

Wind Speed

Horizontal wind speeds are a potentially negative factor for soaring birds over flat terrain because they can rip apart thermals, but potentially a positive factor for soaring birds in rugged terrain where they can provide slope lift. High resolution average annual wind resource potential at 50 m above the ground was downloaded for California and the Pacific Northwest from the National Renewable Energy Lab. Both datasets had a 2.5 km^2 resolution and were resampled with the RESAMPLE tool to 1 km^2 grids using the MAJORITY resampling technique. The California and Pacific Northwest grids were then combined into a single grid using the MOSAIC TO NEW RASTER tool. Wind resource potential (i.e., power class) is a categorical variable and is an indicator of likely wind strength, with a higher wind power class representing higher wind resource levels (Table B1).

Table B1. Wind power classes used to characterize the National Renewable Energy Lab's average annual wind resource potential at 50 m above the ground for California condor (*Gymnogyps californianus*) ecological niche models

Power Class	Category	Wind Power Density (Watt/m^2)	Wind Speed (m/s)
1	Poor	0-200	0-5.6
2	Marginal	200-300	5.6-6.4
3	Fair	300-400	6.4-7.0
4	Good	400-500	7.0-7.5
5	Excellent	500-600	7.5-8.0
6	Outstanding	600-800	8.0-8.8
7	Superb	>800	>8.8

Winter Severity

Because of their long nesting periods (Koford, 1953), we hypothesized that nesting birds might be constrained by winter severity. Average minimum temperature (a proxy for winter severity) was obtained from the PRISM (Parameter-elevation Regressions on Independent Slopes Model) Climate Group (2004). PRISM data are spatially gridded average monthly and annual minimum temperatures for the climatological period 1971-2000. Data, which were originally 400 m^2 resolution, were resampled to a 1 km^2 grid using the RESAMPLE tool with the BILINEAR resampling technique.

Terrain

Condors use cliffs and mountainous terrain for nesting and roosting (Koford, 1953; Snyder et al., 1986). In addition, mountainous terrain can also create rising air for soaring condors, as winds are deflected off cliffs and steep slopes (i.e., slope lift). We obtained a 100 m^2 resolution Digital Elevation Model (DEMs) from the National Atlas (*http://nationalatlas.gov/mld/elev100.html*) to derive cliff and terrain ruggedness layers.

Cliffs

Cliffs were identified by calculating slope from the 100m^2 DEM using the SLOPE tool with the output set to DEGREES. We then resampled the slope layer to 1 km^2 pixels using the AGGREGATE tool, specifying a cell factor of 10 with an aggregation technique of MAX. This returned the maximum slope (from the 100 m resolution map) within 1 km^2 cells for the entire study area.

Terrain Ruggedness

To calculate terrain ruggedness, we first resampled the 100 m^2 DEM to 1 km^2 pixels using the AGGREGATE tool, specifying a cell factor of 10 and an aggregation technique of MEAN. We then calculated a Surface Area Raster using DEM Surface Tools (Jenness, 2004) for ArcGIS 10. Elevation units were in meters and output units were km^2. Flat terrain returned a value of 1, whereas more rugged terrain (i.e., high surface area) had higher values. We then used

the FOCAL STATISTICS tool to summarize MEAN values within 10 km circular radius of each cell and ignored NoData values.

Landscape Productivity

Maximum NDVI

Direct measures of scavenger food availability are difficult to obtain because they are dependent upon numerous factors, including number of animals, differential mortality rates, competition from other scavengers, and rates of decomposition. Furthermore, current food availability in southern California may not be a good indicator of high quality habitat as ungulate densities, ranching practices, and livestock numbers have experienced drastic changes over the last half-century. To provide an indirect measure of terrestrial food availability we used an index of net primary productivity (maximum Normalized Difference Vegetation Index (NDVI) during the growing season). NDVI is a satellite-derived measure that can be used as an indicator of relative plant biomass or greenness and has been shown to be positively correlated with ungulate densities at landscape scales (Pettorelli et al., 2009; 2011).

We obtained Conterminous United States AVHRR Remote Sensing Phenology Metrics - Maximum Normalized Difference Vegetation Index (MaxNDVI) layers for the years 2006 through 2010 from the USGS/EROS website (*http://phenology.cr.usgs.gov/*). All areas classified as water (VALUE=255) were reclassified to "NoData." In addition, the 2010 MAXN layer contained zero values, which are defined as areas "where MAXN could not be detected due to insufficient change in time-series NDVI or insufficient input data." These areas were also reclassified to NoData. Mean cell values were calculated over the five year period using Cell Statistics in Spatial Analyst, ignoring all NoData cells. The resulting floating point grid was converted to an integer grid using standard rules for rounding. We then used the FOCAL STATISTICS tool to summarize MEAN values within 10 km of each cell. We used a 10 km circular radius and ignored NoData values in our FOCAL STATISTICS calculation.

To evaluate whether maxNDVI was correlated with ungulate densities in our study area we obtained mule deer (*Odocoileus hemionus*) and elk (*Cervus canadensis*) density estimates, by game management unit, from State wildlife agencies for the same five year period for which we had maxNDVI data (2006-2010) [note: deer density estimates were not available for Washington State, so those game management units were excluded from the analysis]. Average maxNDVI values were then calculated within State game management units using ZONAL STATISTICS and we evaluated the correlation between average maxNDVI and average deer and elk densities. Maximum NDVI had a significant positive (logarithmic) relationship to deer densities ($r^2 = 0.50$, $p < 0.0001$) and elk densities ($r^2 = 0.12$, $p = 0.0003$) (Figs. B1 & B2).

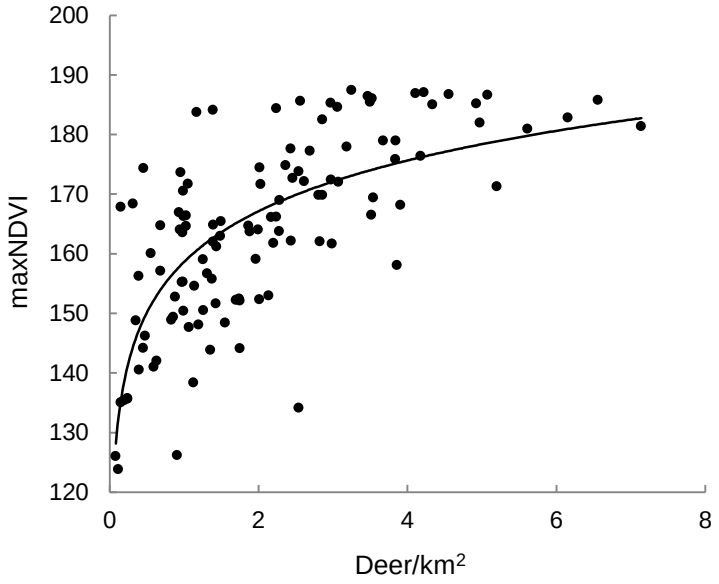

Figure B1. Relationship between maximum NDVI and deer density, by game management unit in California and Oregon ($r^2 = 0.50$, $p < 0.0001$).

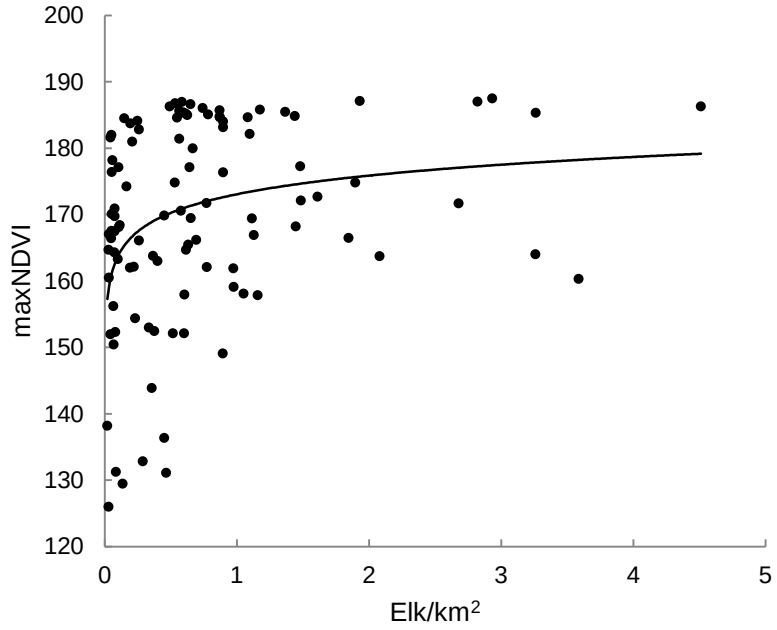

Figure B2. Relationship between maximum NDVI and elk density in California, Oregon, and Washington ($r^2 = 0.12$, $p = 0.0003$).

Distance to Water

Condors appear to be attracted to areas of water for bathing (Koford, 1953). They may also use rivers and waterways for navigation, as they appear to follow rivers during long distance movements (Arizona Condor Review Team, 2002). Therefore we included a distance to water (streams, rivers, lakes, and reservoirs) metric derived from the 1:2,000,000 scale Streams and Waterbodies of the United States data layer in the National Atlas of the United States (*http://www.nationalatlas.gov*). For waterbodies (polygon features), the following Feature attributes were selected: "Lake", and "Reservoir." For streams and rivers (linear features) the following Feature attributes were selected: "Shoreline", "Stream", "Left Bank" and "Right Bank." Euclidean distances were calculated for each of these features with an output pixel size of 1km^2. The grids were then merged using the MOSAIC TO NEW RASTER tool, with a Mosaic Operator of MINIMUM (the output cell value of overlapping areas is the minimum value (i.e., distance) of the overlapping cells).

Vegetation Characteristics

Observational data suggest that condors tend to forage in relatively open areas with limited canopy cover and low vegetation height (Snyder and Snyder, 2000). Vegetation characteristics were derived from the 2006 National Land Cover Database (NLCD) (*http://www.mrlc.gov/nlcd2006.php*) and LANDFIRE data (*http://landfire.cr.usgs.gov*). Specifically, we derived canopy cover and dominant land cover type from the NLCD and canopy height from LANDFIRE.

Canopy Cover

Percent canopy cover was obtained from the 2006 NLCD (*http://www.mrlc.gov/nlcd2006.php*) at a resolution of 30 m^2. We resampled this grid to 1 km^2 using BILINEAR resampling.

Canopy Height

Canopy height was derived from LANDFIRE data (*http://landfire.cr.usgs.gov*). The 30 m^2 grid was reclassified according to Table B2. The reclassified grid was then resampled using MAJORITY resampling to obtain a 1 km^2 grid.

Table B2. Reclassification table used to group LANDFIRE categories into vegetation heights for California condor (*Gymnogyps californianus*) ecological niche models.

Category Description	LANDFIRE Values	New Value
Bare or very low vegetation (<0.5m)	31, 66, 67, 75, 76, 81, 100, 101, 104	1
Low vegetation (0.5-1m)	102, 105	2
Medium vegetation (1-5m)	106, 108, 103	3
Tall vegetation (>5m)	107, 109, 110, 111, 112	4
Other/non-habitat	11, 14-25, 32, 60-65, 80, 82-85, 95	0

Landcover

Landcover from the 2006 NLCD (*http://www.mrlc.gov/nlcd2006.php*) for the coterminous U.S. in 30 m^2 pixels was reclassified to aggregate classes that had similar vegetation structure (Table B3). The reclassified raster was then resampled to 1 km^2 pixels using MAJORITY resampling (i.e., the most common land cover type within the 1 km^2 pixel was assigned to the entire pixel).

Human Disturbance

Condors suffer from a variety of human-induced mortality factors, including lead poisoning, collisions with overhead powerlines, and ingestion of microtrash (Rideout et al., 2012). Although a spatial map of the intensity of each of these factors is not available at the temporal and spatial-scales of our analysis, surrogate measures of these stressors, via spatial layers of human population density and road density (a measure of human access), were available.

Table B3. Reclassification table used to aggregate National Landcover Types for use in California condor (*Gymnogyps californianus*) ecological niche models.

Value	Landcover Type	New Value	Aggregated Land Cover Type
11	Water	11	Non-habitat
12	Perennial ice and snow	12	Perennial ice and snow
21	Low intensity residential	21	Developed
22	High intensity residential	21	Developed
23	Commercial/industrial	21	Developed
24	Developed high intensity	21	Developed
31	Bare rock/sand/clay	31	Bare rock/sand/clay
41	Deciduous forest	41	Deciduous forest
42	Evergreen forest	42	Evergreen forest
43	Mixed forest	43	Mixed forest
52	Shrubland	52	Shrubland
71	Grassland/herbaceous	71	Grassland/herbaceous/pasture
81	Pasture/hay	71	Grassland/herbaceous/pasture
82	Row crops	82	Row crops
90	Woody wetlands	11	Non-habitat
95	Emergent herbaceous wetlands	11	Non-habitat

Human Population Density

We downloaded Tiger/Line files (shapefiles) containing the 2010 Census Population and Housing Unit Counts--Block Data for CA, OR and WA (separately) from *http://www.census.gov/geo/maps-data/data/tiger-data.html*. These files were combined into a single file using the MERGE tool. We calculated the area of all block polygons in km^2, and then calculated the population density (in people/km^2) for each block. We converted the merged polygon layer to a raster using the POLYGON TO RASTER tool. We specified the "Value

field" as the population density, the "Cell assignment type" as MAXIMUM_AREA, and the "Cellsize" as 100m. We resampled the raster to a resolution of 1 km^2 using the AGGREGATE tool, specifying the cell factor as 10 and aggregation technique as MEAN. We then used the FOCAL STATISTICS tool to summarize MEAN values within 10 km of each cell. We used a 10 km circular radius and ignored NoData values in our FOCAL STATISTICS calculation.

Road Density

We downloaded the "Road density (length in meters/sq. kilometer) for the contiguous U.S." layer from Data Basin (http://databasin.org/datasets). This raster layer required minimal processing as it was already at a resolution of 1 km^2. We used the FOCAL STATISTICS tool to summarize MEAN values within 10 km of each cell. We used a 10 km circular radius and ignored NoData values in our FOCAL STATISTICS calculation.

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