Changes in Bald Eagle Nesting Distribution and Nest-site Selection in Kentucky during 1986–2019

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Abstract - Kentucky's breeding *Haliaeetus leucocephalus* (Bald Eagle) population began recovering in 1986, with a single nest, and has since expanded from the state's western portion to the central and eastern regions. We used aerial survey data to describe the spatiotemporal distribution of Bald Eagle nests in Kentucky, to examine changes in nest-site selection relative to natural and anthropogenic features, and to create a nesting-habitat suitability model. Our results highlight increased nesting near developed areas in recent years. Although nests in these areas productively contribute to populations, we note some considerations of increased risks associated with nesting in developed areas. We also provide predictions of available nesting areas and data to direct the future monitoring and management of Bald Eagles in Kentucky.

Introduction

In recent decades, *Haliaeetus leucocephalus* (L.) (Bald Eagle) populations in the eastern United States have recovered from historically low levels and extirpation in some states (Buehler 2020, Smith et al. 2016, Zehnder 2012). Recent estimates indicate a tremendous increase in overall population size from when the species was removed from the United States Fish and Wildlife Service endangered species list in 2007 (USFWS 2007, 2020). However, current updates on local populations can be useful to inform local management and monitoring.

Due to past declines and conservation concerns, the Kentucky Department of Fish and Wildlife Resources (KDFWR) lists the Bald Eagle as a species of greatest conservation need in Kentucky's State Wildlife Action Plan (KDFWR 2013). Thus, KDFWR monitored the nesting population in Kentucky annually via aerial and ground surveys, documenting a steady increase in nest numbers from 1986 to 2019 (Slankard 2019). Kentucky's nesting Bald Eagle population started with a single nest in 1986 and then grew at a rapid pace, especially from 2007 to 2019. In fact, the number of occupied Bald Eagle territories jumped 390% from 48 in 2007 to 187 in 2019.

Bald Eagle nest-site selection is influenced by factors such as local habitat, human activity, and prey availability (Smith et al. 2017). The most important factor influencing nest-site selection is the presence of a suitable nest tree, with Bald

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Eagles preferring to nest in large, mature trees taller than the average height of the surrounding forest canopy (McEwan and Hirth 1979). In the midwestern US, nests are seldom built on manufactured structures such as electrical transmission towers (Zehnder 2012).

Human disturbance may also influence nest-site selection and, in some cases, affect nest success (USFWS 2007). Bald Eagles tend to prefer nesting in areas where development and human activity are low (Smith et al. 2017, Zehnder 2012), or select a site buffered from disturbance by stands of vegetation (Andrew and Mosher 1982). However, there doesn't appear to be a relationship between nesting success and proximity to human development (Andrew and Mosher 1982, Peterson 1986, Smith et al. 2017). Food availability is another important site-selection factor (Letto et al. 2015). The diet of Bald Eagles is composed mostly of fish and waterfowl (Peterson 1986), making open waterbodies important foraging locations (Andrew and Mosher 1982). Previous studies have found that most Bald Eagles nest within 3 km of coastlines, lakes, rivers, or wetlands (Zehnder 2012). Other important factors in nest selection include the size of the waterbodies, which influences the number of pairs in an area (Smith et al. 2017), and the availability of suitable perch sites for spotting prey (Zehnder 2012).

Due to a high concentration of suitable habitat, the majority of eagle nests in Kentucky were located in the western portion of the state from 1986 to 2005. However, in recent years, Bald Eagle nests in central and eastern Kentucky have become increasingly common. Although nest numbers and broad-scale (national-level) nesting distribution for Bald Eagles have been well studied (USFWS 2009), factors influencing nesting distribution at a finer scale require more exploration in the northeastern United States. Studies from other regions have described local and landscape habitat selection for nesting Bald Eagles in Texas, Louisiana, Maine, and Indiana (Livingston et al. 1990, Saalfeld and Conway 2010, Smith et al. 2017, Zehnder 2012), but the habitat for this species varies considerably across its range. This study was prompted by the need to quantify changes in nest-site selection over time and the spatial distribution of the growing population of Bald Eagles in Kentucky.

For this study, we had 3 objectives. First, we aimed to describe the spatial distribution of Bald Eagle nests in Kentucky over time. Second, we tested whether nest-site selection relative to natural and anthropogenic features changed throughout the recovery of this species in Kentucky. Finally, we created a spatial model predicting suitable Bald Eagle nesting habitat in Kentucky. Although we do not directly predict eagle population growth, the data from this study can be used to qualitatively predict where future growth might occur. Taken together, these objectives allowed us to summarize lessons learned from 34 years of monitoring Bald Eagle nests in Kentucky and suggest future approaches for these efforts. The Bald Eagle is one of the most successful endangered species recoveries in North America. Analyses such as these help biologists to understand the processes behind recovery and population growth in hopes of replicating conservation success in other species.

Methods

To monitor Kentucky's nesting Bald Eagle population, KDFWR conducted annual aerial (helicopter) surveys of nests (west of Frankfort, KY) in March from 1986 to 2019. Nests that could not be covered during the aerial survey (east of Frankfort, KY) were checked in late winter or early spring by boat and ground. KDFWR made efforts to document as many nests as possible statewide; in general, checking 95–100% of known nests during each survey. Areas with suitable habitat (based on biologist opinion) that lacked nesting records and locations where nesting activity was suspected due to reports from the public were also included in the aerial and ground surveys as time permitted. Through early nesting-season monitoring, KDFWR biologists recorded GPS coordinates for each nest and determined the status of each nesting territory as "occupied" or "unoccupied". KDFWR biologists deemed a territory "occupied" if it contained a nest that Bald Eagles recently built or maintained, adult eagles were seen at a nest, or there was evidence of reproduction (incubation, eggs, or chicks observed) during the breeding season (Slankard 2019).

To describe the spatial distribution of nests over time, we created maps of the locations over 4 periods, each of 7 or 9 years (1986–1994, 1995–2003, 2004–2012, 2013–2019). These periods were selected arbitrarily to divide the total time period into 4 groups while shortening the most recent period so that future survey data could be added. Within each time period, we plotted coordinates of nests first recorded as occupied. We also calculated a kernel density estimate for each period to better show the probability of nest occurrence and how it changed over time (Fig. 1).

To test if land cover at newly established nest sites changed over time, we extracted land-cover proportions from buffers centered on nests. We included each nest site in our dataset only once for the year it was first occupied. We created 2 buffers around each nest: one representing the immediate nest area (500-m radius) and the other representing the territory area (3000-m radius). We selected these spatial scales based on previous studies of Bald Eagles in the eastern United States, including satellite telemetry data from a nesting eagle in Kentucky (Buehler 2020, Buehler et al. 1994, Slankard et al. 2021, Watts et al. 1994, Zehnder 2012). To calculate the proportion of each land-cover class, we intersected the buffers with the National Land Cover Database (NLCD), a Landsat-imagery-based, 30 m x 30 m resolution land-cover classification for the conterminous United States (Homer et al. 2020). Land-cover classes occurring in Kentucky included water, developed, barren, forest, shrubland, herbaceous, planted/cultivated, and wetlands. Seven versions of the NLCD are available and correspond to imagery from 2001, 2004, 2006, 2008, 2011, 2013, and 2016. We made buffer intersections for each nest site with the most recent NLCD data year (Table 1). Nest sites first occupied prior to 2001 were not included in this analysis.

We used separate ANOVAs for 5 land-cover classes for the 500-m and 3000-m buffers to test for trends in the change in land cover over time. We excluded 3 land-cover classes (barren, shrubland, and herbaceous) because they had low percent-cover values (third quartile of all observations < 1%). We log-transformed

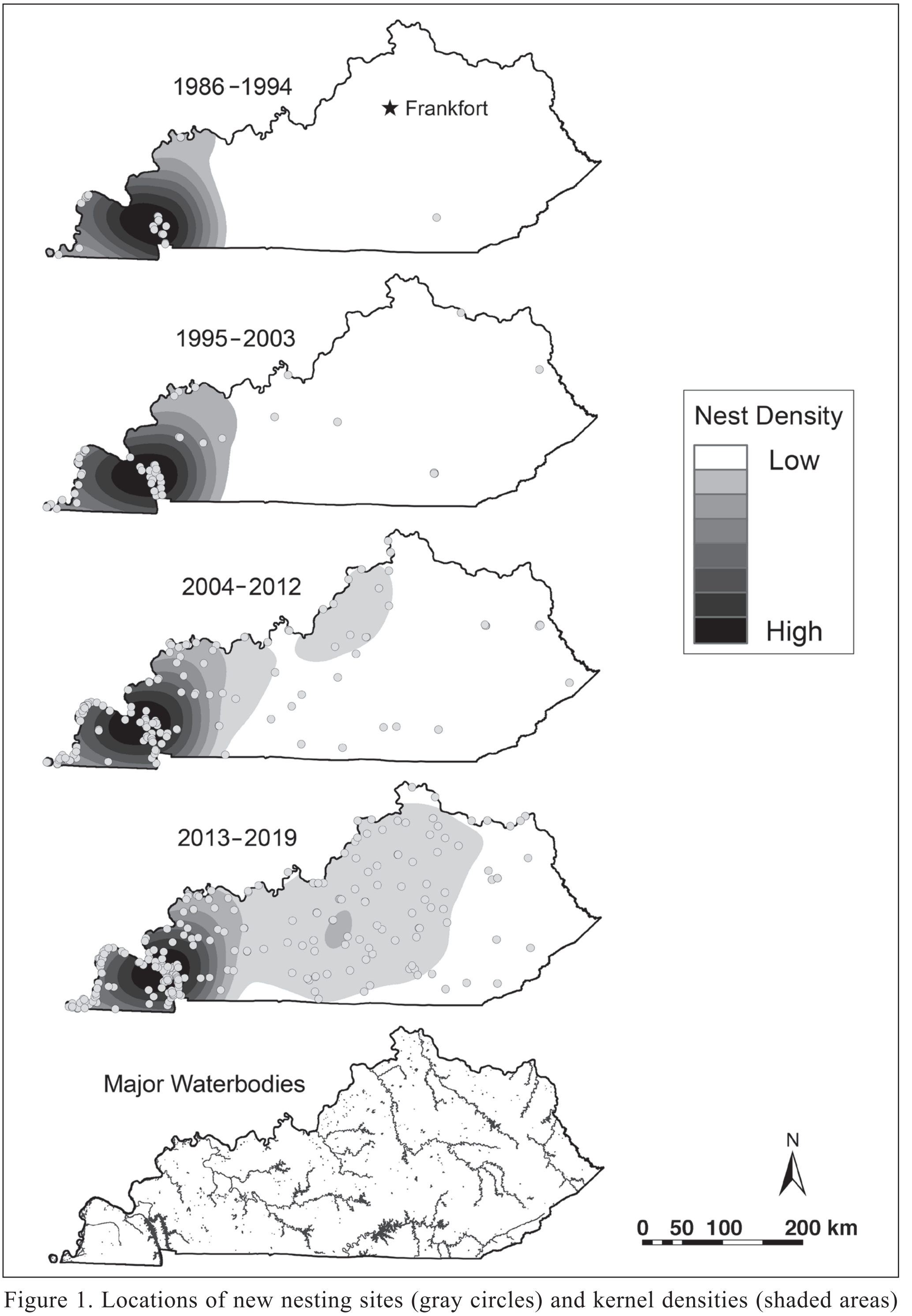

Figure 1. Locations of new nesting sites (gray circles) and kernel densities (shaded areas) of Bald Eagles during 4 time periods (1986–1994, 1995–2003, 2004–2012, 2013–2019) and the distribution of lakes and rivers in Kentucky.

the response variables, percent cover of each land class, after assessing normality with Shapiro–Wilk tests. We treated NLCD year as a factor. We conducted an orthogonal contrast to test for a sequential trend across the NLCD years.

We calculated the proximity of Bald Eagle nest sites to landscape features by measuring the linear distance between the nest locations and each feature. Features included lakes (both natural lakes and reservoirs), streams (using separate values for great rivers, large rivers, medium rivers, small rivers, and all rivers combined), dams, wetlands, development (using separate values for open, high, medium, low, and all development combined), primary and secondary roads, electric power transmission lines (hereafter, powerlines), and cell towers. We extracted data for lakes and streams from a layer created by the Southeast Aquatic Resources Partnership (SARP; Sheldon and Anderson 2013). We utilized dam-location data from the US Army Corps of Engineers (USACE 2021). We extracted data for wetlands and developed lands from the 2016 NLCD layer. We extracted the roads layer, which included primary and secondary roads, from US Census 2021 TIGER/Line files (US Census 2021). We obtained cell tower and powerline data from a US Department of Homeland Security database, which includes nationwide infrastructure features (DHS 2020). We performed all spatial analyses using ArcMap v.10.3.1 (ESRI 2014). We conducted linear regression analysis with each environmental value as a separate response variable and the year a nest was first occupied as the predictor. We assessed statistical significance in our linear models using an alpha of 0.05. We report effect sizes as beta coefficients and standard errors as well as unadjusted R^2 values. We performed all statistical analyses using Program R v. 4.0.4 (R Core Team 2021).

To model potential nesting habitats throughout Kentucky, we created a species distribution model (SDM) using Maxent v.3.4.1 (Phillips et al. 2004). SDM algorithms estimate the relationship between species occurrences (localities) and environmental variables to predict species distributions in space and time (Franklin 2010). These methods can offer insights into habitat suitability. We chose this method because of the nature of the data collected (presence-only) and because of Maxent's high-ranking performance compared to other methods (Elith et al. 2006).

Table 1. National Land Cover Dataset (NLCD) years and the number of nests first occupied during the corresponding range of years.

NLCD Year	Nest year range	Years in range	No. of nests
Pre-NLCD	1986–2000	15	69
2001	2001–2003	3	24
2004	2004–2005	2	18
2006	2006–2007	2	24
2008	2008–2010	3	70
2011	2011–2012	2	48
2013	2013–2015	3	102
2016	2016–2019	5	163

Many of our environmental variables are based on land-cover data extracted from the 2016 NLCD. As such, we chose not to include nest-site data obtained before its creation in our SDM, narrowing our localities to nests occupied from 2017 to 2019. We further limited our samples to their most recent year of occupancy, leaving a single sample per location from 2017 to 2019 for a total of 260 occupied localities for our analysis.

Using the 'Euclidean Distance' tool in ArcMap, we created distance-from variables for each land feature used in our proximity analysis. We made 1 additional variable by combining all water features. We also extracted forested land-cover features from the NLCD to create a distance-from-forest variable. Likewise, we used forested land features in combination with data extracted from the USGS Protected Areas Database (Gergely and McKerrow 2013) to create a distance-from-protected-forests variable. We also included the NLCD as a categorical variable in Maxent for a total of 19 variables used in our analysis.

To prevent multicollinearity in our models, we used the 'Band Collection Statistics' tool in ArcMap to calculate a correlation matrix for our environmental raster data. We subsetted data that had a correlation coefficient ≥ 0.70 into separate bins. We used each subset to develop separate models that we evaluated for variable selection. Following Yiwen et al. (2016), we used a stepwise removal approach wherein all other variables were included with each sub-set. We ran each model using 5-fold cross-validation and jackknife testing and evaluated variables by their averaged percent contribution. After each iteration, we removed the variable with the lowest average contribution. We continued this process until variables met our predetermined stopping criterion, which was (i) the percent contribution for each variable was equal to or greater than 1 (Li et al. 2020), and (ii) the correlation of variables was below a correlation coefficient of 0.70. We evaluated each sub-set for spatial bias by geographically isolating calibration and evaluation data (Radosavljevic and Anderson 2014). For our assessment, we spatially isolated the westernmost 70% of localities for model calibration and used the remaining easternmost localities for model evaluation. If a variable did not fit both calibration and evaluation data, limiting the model's transferability, we removed it from further use.

We used the final variable selection to create a model that used 10-fold cross-validation. We evaluated each replication by omission rate and its receiver operating characteristics (ROC). We selected a replicate with a low omission rate relative to others and the highest possible area under the curve (AUC) value while maintaining a relatively low difference between the training AUC and test AUC to represent the final habitat suitability prediction. We used Maxent's logistic output to create a feature in ArcMap that gave the probability of suitability for each 30 m x 30 m pixel across the study region. Because Bald Eagles in Kentucky nest almost exclusively in trees, we then extracted each pixel that fell within land cover classed as forested (deciduous forests, mixed forests, evergreen forests, and woody wetlands) within the NLCD. Then we used a color ramp to make a map that displayed habitat suitability across Kentucky.

Results

Between 1986 and 2019, the nesting population of Bald Eagles in Kentucky grew exponentially. Although eagles continued to construct nests in western Kentucky, the proportion of nests in central and eastern Kentucky increased over time (Fig. 1).

Forest was the dominant land-cover type across all years within 500-m (31–37%) and 3000-m (32–38%) buffers (Fig. 2). Planted/cultivated, water, and wetland land-cover types also had relatively high proportions across years in 500-m (13–28%) and 3000-m (8–31%) buffers. The land-cover composition of nest-site buffers (500-m radius) for newly occupied nests showed increasing trends for developed and planted/cultivated cover over time. Still, none of the land-cover classes changed significantly (Table 2). At the 3000-m scale, forest and wetland

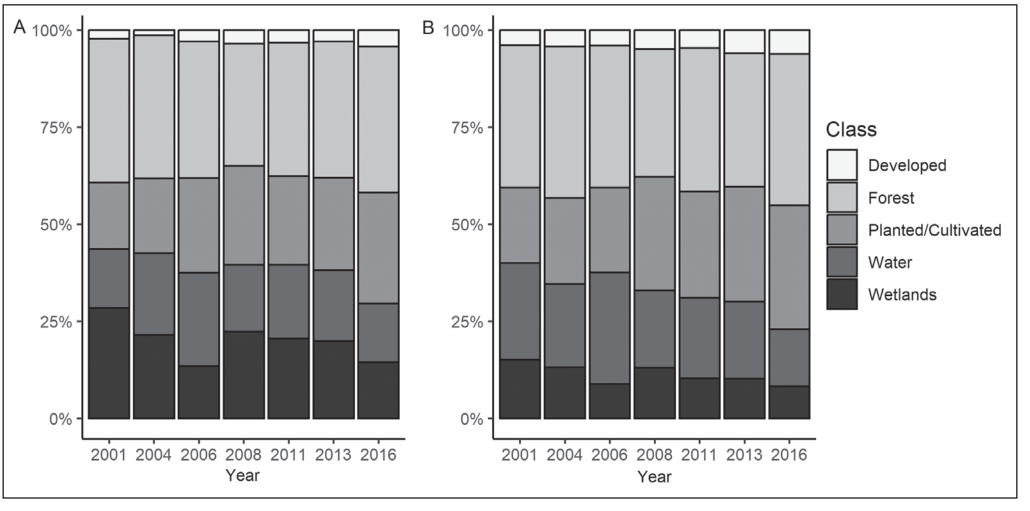

Figure 2. Mean percent land cover in (a) 500-m and (b) 3000-m buffers for all nests first occupied between the NLCD year and the year prior to the next NLCD year. Sample sizes correspond to the "No. of nests" in Table 1.

Table 2. Statistics from post-ANOVA linear contrasts for trend of land cover change for nest sites first occupied from 2001-2019 at 500-m and 3000-m radius buffers. * indicates statistically significant *P*-value.

Buffer	Land-cover category	Beta	SE	*t*-statistic	*P*-value
500 m	Developed	1.50	0.89	1.69	0.091
	Forest	0.19	1.31	0.01	0.885
	Planted/Cultivated	2.57	1.44	1.79	0.075
	Water	-0.56	1.25	-0.45	0.653
	Wetlands	-2.05	1.47	-1.40	0.163
3000 m	Developed	1.38	0.52	2.64	0.008*
	Forest	0.00	1.05	-0.001	0.999
	Planted/Cultivated	3.30	1.17	2.83	0.005*
	Water	-3.06	1.01	-3.03	0.003*
	Wetlands	-1.95	1.20	-1.63	0.104

cover classes did not change over time, but changes occurred for other classes. Although the developed cover class had a consistently low proportion across time, there was a trend for increased percent developed land cover over time within territories of newly occupied nests. Planted/cultivated land cover also increased in proportion over time. In contrast, there was a strong negative trend for the percent water cover within 3000-m of new nests over time.

Proximity analysis indicated that Bald Eagle nest locations over time were further from lakes, great rivers, and wetlands (Table 3). Over time, nest locations were nearer to large rivers, small rivers, all values of developed land classes, roads, and cell towers. For all of these landscape variables, the trends are clearly significant. There was no trend over time in the proximity of nests to medium rivers, dams, and powerlines.

Maxent accurately predicted habitat suitability for Bald Eagles with an AUC of 0.926 for training and 0.931 for test data (Fig. 3). Our model found that proximity to waterbodies was the most relevant factor for predicting suitable habitat for eagle nest construction, with distance from lakes (45% contribution) and distance from rivers (21.5% contribution) being the highest contributing variables. Qualitative assessment using jackknife testing revealed that generality in variables depicting distance from waterbodies (i.e., all water combined) resulted in overestimating the importance of Bald Eagle nests being located near water and, as such, resulted in models that predicted high probability near any waterbody regardless of size. However, spatial filtering of nest localities showed that generality in waterbody variables created more transferable models across the study region. In contrast, models created using specific SARP-classed rivers resulted in models that overfit

Table 3. Regression statistics for simple linear regressions of nest site proximity to landscape features from 1986-2019. Indented landscape features were nested within broader landscape variables. * indicates statistically significant *P*-value.

Landscape feature	Beta	SE	*F*-statistic	*P*-value	R^2
Lakes	200.39	40.14	24.93	<0.001*	0.047
All Rivers	-133.64	32.80	16.60	<0.001*	0.031
Great Rivers	1132.10	222.59	25.87	<0.001*	0.049
Large Rivers	-1646.99	330.78	24.79	<0.001*	0.047
Medium Rivers	-97.41	59.88	2.65	0.104	0.005
Small Rivers	-183.78	79.83	5.30	0.022*	0.010
Dams	-116.40	120.90	0.92	0.336	0.001
Wetlands	16.47	7.16	5.28	0.021*	0.010
All Developed	-7.40	2.54	8.51	0.004*	0.016
High Developed	-26.28	11.80	4.96	0.026*	0.009
Medium Developed	-31.46	7.65	16.91	<0.001*	0.032
Low Developed	-22.15	4.51	24.09	<0.001*	0.046
Open Developed	-7.01	2.67	6.90	0.009*	0.013
Roads	-35.50	11.48	9.56	0.002*	0.018
Powerlines	-18.40	18.75	0.96	0.327	0.001
Cellular Towers	-62.46	24.41	6.55	0.011*	0.012

larger rivers and lakes. We observed that great, large, and small rivers became less important to eagle nest construction as distributions move east and trend toward medium rivers. Models created using the 2 intermediate variables, distance from lakes and distance from rivers, resulted in predictions that accurately fit the current distribution of eagle nests and were transferable between calibration and evaluation data when spatially isolating localities.

Jackknife testing for the distance-from-forest variable also showed a high contribution to model gain in our preliminary models. When we implemented distance from protected forests, we found a slightly higher probability of suitable habitat within protected forests throughout the state. Variables depicting distance from development contributed little to model gain. Distance from wetlands was second only to distance from water in overall model contribution. However, models created with this variable resulted in overfitting that skewed habitat-suitability predictions to the western portion of Kentucky. We observed a similar pattern in the NLCD variable, showing a higher probability of suitable habitat associated with wetland types and open-water areas. Nonetheless, because the NLCD contains data not found in other variables, we chose to include it in our final model. The remaining variables, distance from roads, distance from powerlines, and distance from cellular towers, contributed little to model performance.

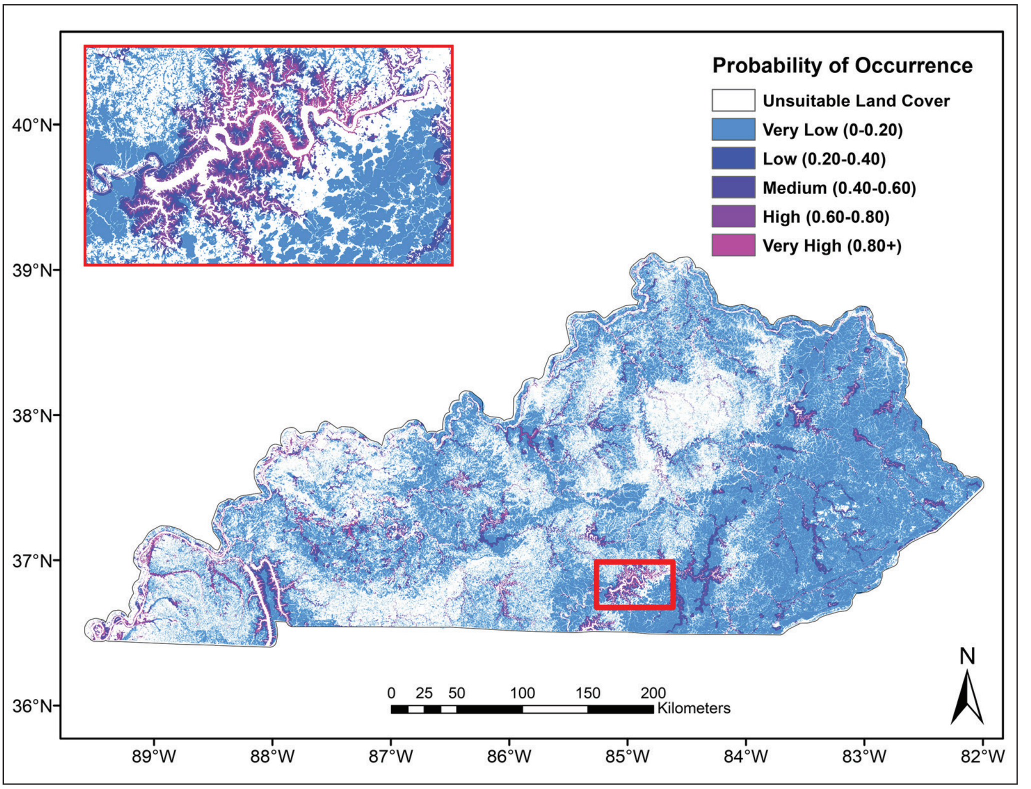

Figure 3. Maxent habitat suitability for Bald Eagle nests in Kentucky. Map inset shows the distribution of habitat suitability of Lake Cumberland, KY, with the inner polygon of unsuitable open water that is colored white.

Discussion

Over 34 years of population recovery in Kentucky, the nesting distribution of Bald Eagles expanded eastward, although nests continued to increase in western Kentucky. During the same timeframe, the proportion of developed and planted/cultivated land covers increased within 3000-m territory buffers, while the proportion of water within those buffers decreased. Central and eastern Kentucky have fewer wetlands, lakes, and large rivers than western Kentucky. Given that Bald Eagles strongly associate with these habitats for foraging (Smith et al. 2017, Zehnder 2012), our findings suggest that Bald Eagles started nesting in areas with more large waterbodies and gradually expanded the population over time into areas with fewer and more widespread waterbodies.

Although there is a pattern of less water cover over time within territory buffers, the proportion of water in the nest area buffer did not change, which likely reflects the selection of rivers or lakes for nesting sites. This finding suggests that at the scale of the nest site (i.e., 500-m radius immediately surrounding the nest), newer Bald Eagle nests share land-cover composition with nests first occupied 2 decades before. However, at the territory scale (3000-m radius buffer), recent nests are more likely to have more developed and planted/cultivated land cover and less water cover. Regardless, it is clear that Bald Eagles continue to select nest sites and territories with a high proportion of water, especially relative to the total statewide cover of water (2%). The increase in planted/cultivated land cover probably represents new nests, in perhaps more marginal habitat, in western and central Kentucky since row-crop agriculture is widespread in these regions and less common in eastern Kentucky.

Another interesting finding that is evident graphically but we did not explore statistically is that a greater proportion of land cover consists of wetlands at the 500-m buffer scale than at the 3000-m scale. Statewide cover of wetlands is very low (2%), whereas the average proportion of wetlands per NLCD year within 500 m of nest sites varied from 17% to 27%. Although the correlation of wetland and water land-cover types within both buffers tended to be very low, it is possible there was some degree of spatial autocorrelation of wetlands and other large water bodies that would explain this pattern. Nonetheless, because fish and waterfowl are important components of the diet of Bald Eagles, it is possible that wetlands represent areas with high prey availability and thus influence nest-site selection (Smith et al. 2017).

Our proximity analysis showed that nests were found closer to certain landscape features over time, including all rivers combined, large rivers, small rivers, all classes of developed land cover, roads, and cellular towers. There are very few cases of nesting on electrical transmission towers, and none were observed on cellular towers in Kentucky, so we assume the pattern for cellular towers is related to eagles nesting closer to developed areas and/or an increased density of towers. One limitation of our approach is that we used only the most recently available landscape-feature data for the proximity analysis.

In general, our proximity analysis was complementary to our findings of changes in land-cover composition within nest buffers. We found change over time in the proximity of Bald Eagle nests to several landscape features. Over time, newly constructed nests were increasingly located farther from lakes, wetlands, and great rivers. Since these landscape features are associated with foraging (Smith et al. 2017, Zehnder 2012), it makes sense that Bald Eagles would claim territories near them first. Habitat selection in raptors is influenced by prey availability, human disturbance, interspecies interactions (e.g., predators, colonial nesting waterbirds), nest-tree availability, and the presence of intraspecific competitors (Cody 1985). In a recovering population, high-quality sites should be occupied first (Treinys et al. 2015). Since Bald Eagles are territorial, long-lived, and have high site fidelity, nesting territories tend to remain occupied once established (Jenkins and Jackman 1993). Thus, selection for smaller rivers and areas near developed land over time may reflect patterns of intraspecific competition and selection of lower-quality sites as populations grow and the highest-quality sites become occupied.

Our SDM predicted high probabilities of suitable habitat in forested areas near waterbodies, particularly within 2000–3000 m of the shore. Proximity to water, both lakes and rivers, were the highest contributors to our SDM. Similar to other studies, Bald Eagle nests in Kentucky occur in high numbers along river banks (Winder and Watkins 2020). Probabilities were generally high around lakes and were highest near coves and source waters, where lakes are narrower. Computationally, this may be due to forested areas near water having strong probabilities of suitability. Compared to linear shorelines, narrow portions of lakes have more forested land cover in close proximity to water. Thus, Maxent interpreted these areas as more suitable. However, Bald Eagles may locate nests near coves and source waters to avoid disturbance since these areas are further from the main channel and usually support less boating activity. Likewise, shallower water and high potential for suitable perch trees in these areas may also offer better foraging opportunities (Kaltenecker et al. 1998, Zehnder 2012). Models by Letto et al. (2015) suggest that food resources were more important than other modeled habitat characteristics in determining nesting activity. We considered food resources in our proximity analysis by including dams, since these represent a hotspot of foraging opportunity (Kaltenecker et al. 1998, Slankard et al. 2022). However, we found no relationship and can only make general inferences in relation to foraging habitat based on the availability of land-cover types.

One drawback of our habitat-suitability model is poor prediction of nests in isolated trees within open fields or small patches of trees separating rivers and cropland. Due to the resolution of the data used in this model (30 m x 30 m), these individual or small isolated patches of trees are misclassified as the dominant land-cover type within the area. However, nests in these locations are often more easily spotted and reported by the public. Since Bald Eagles usually nest in larger, older trees, including a canopy layer to estimate tree height and forest age would likely improve our model's performance. However, this data is not yet available across the state of Kentucky. Further, our study showed that the landscape setting of newly established Bald Eagle nests changed over time. Thus, the modeling effort may need to be repeated every 10–15 years, if monitoring continues, to ensure it accurately predicts nesting habitat.

The spatial analyses we conducted provide quantitative support for patterns of change observed in Bald Eagle nesting distribution and allow us to better understand how Bald Eagles interact with developed landscapes. Along these lines, observations from monitoring further support that Bald Eagles in Kentucky are increasingly nesting near developed residential (i.e., urban and suburban) areas. In fact, in the past decade, KDFWR recorded 9 nests within 200 m of residential homes. Despite the increasing trend over time (2001: 3.8%, 2016: 6.0%), the developed cover within territory buffers was still low relative to other cover classes and less than developed cover statewide (7.4%). We surmise Bald Eagles in Kentucky choose to nest near developed areas with suitable undeveloped foraging habitat, sometimes choosing a nest tree near developed areas due to limited options in mature nest-tree availability. Some older studies indicate Bald Eagles avoid human activity (Andrew and Mosher 1982). However, those findings likely represent an earlier era of Bald Eagle recovery, when undeveloped habitat was largely unoccupied and thus readily available. Guinn (2013) suggested generational habituation as a mechanism for change in Bald Eagle nest distribution, allowing for the expansion of the population into areas near human activity that were once considered suboptimal nesting habitats. In other locations, Bald Eagles have been nesting in developed areas earlier than observed in Kentucky. For example, in Kansas, Bald Eagles began nesting near urban environments early in their recovery, with 4 of the first 11 nests on the Kansas River located near developed land cover in major cities (Winder and Watkins 2020). Florida is another example where Bald Eagles have nested in developed areas for decades (Bohall Wood et al. 1989). In both these states, Bald Eagles likely used developed areas because of the presence of mature trees for nesting. The differences in timing of increased urban Bald Eagle nest observations in developed areas may be attributable to varying population densities, habitat availability, and perhaps disturbance tolerance of these regional populations.

Nests sites in developed areas can be productive contributors to the nesting population. Bald Eagle nests in Florida located in suburban areas (>50% intensive human use) had similar occupancy and productivity as nests in rural areas (<5% intensive human use) (Millsap et al. 2004). Watts (2006) found that Bald Eagles breeding in urban areas were at least as productive as other pairs in the population. However, nest sites in developed areas may also present a higher risk of human-related disturbance, which may, at times, impede productivity at particular sites. (USFWS 2007). Nesting in developed areas may also present survival-related risks to Bald Eagles, such as exposure to anticoagulant rodenticides and other contaminants and increased risk of vehicle collisions or powerline electrocutions (Niedringhaus et al. 2021). More study may be needed to understand the effects of developed areas on Bald Eagle habitat quality.

The Bald Eagle is protected by the Bald and Golden Eagle Protection Act, which prohibits the taking of eagles or disturbance of their nests without permitted authorization. The National Bald Eagle Management Guidelines help landowners and land managers avoid disturbing Bald Eagles by recommending buffers (e.g., 100 m and 200 m) around known nests for potentially disturbing activities (USFWS 2007). However, to implement these guidelines, nest locations need to be known. Our model may be useful for pre-development environmental consultation with state agencies and the US Fish and Wildlife Service to help determine if surveys for Bald Eagle nests are needed at a site for mitigation planning. If Bald Eagles continue to increase, we expect more nests will be found near developed areas. This growth is likely to result in an increase in incidental-take permit applications for potentially disturbing activities near nests and eagle nest-related consultation with state agencies and the US Fish and Wildlife Service. More research is needed to determine how to avoid disturbance at Bald Eagle nest sites near developed areas, especially as the species shows growing resilience to human activity. Mitigation to minimize disturbance around nests may be important to maintain the population in certain locales where a significant number of nests occur near developed areas.

Despite a successful recovery, the Bald Eagle continues to uphold conservation interests. Our model may be useful for conservation planning, as it shows where large areas of habitat exist for the species and where unprotected areas could be prioritized for land acquisition by conservation entities. Our SDM predicts highly suitable habitat in woody wetlands, which are generally bottomland hardwood forests in Kentucky. Bottomland hardwood forests are in dire need of conservation in this region (King et al. 2006), and restoration activities would undoubtedly benefit Bald Eagles. Protected forested areas such as state parks, Wildlife Management Areas, and the Land Between the Lakes National Recreation Area had considerably higher probabilities than other sites within the study region. Kentucky has very few natural lakes, instead having many large reservoirs created by flood-control dams managed by the US Army Corps of Engineers. These constructed reservoirs have probably resulted in more Bald Eagle habitat in central and eastern Kentucky than was present historically. The higher probability of suitable habitat near protected forests is probably attributable partly to many nests occurring near these reservoirs. However, due to their protected nature and management as wildlife areas, forests surrounding Kentucky's lakes provide undisturbed areas that probably make them more desirable to Bald Eagles.

Spatial modeling will direct future surveys to areas where eagles may be nesting but have not already been discovered or may establish new nests in the future (Peterson 1986). This insight allows for more efficient surveys and expenditure of monitoring funds. As demonstrated by past declines, the Bald Eagle is an important species to monitor as an environmental indicator. More efficient monitoring will help ensure the health of this once-imperiled species and serve as a check on ecosystem health (Bowerman et al. 2002). Recent disease concerns due to the highly pathogenic avian influenza virus may also spur the need for increased monitoring to ensure Bald Eagle declines do not recur (Nemeth et al. 2023).

Our study does not predict future population sizes, but our results provide predictions of sites that Bald Eagles could occupy in the future. In March 2022, we conducted an aerial survey of eastern Kentucky for the first time. We searched many areas identified by the model, and while the habitat in most areas did appear suitable, occupied nests were still sparse. While Bald Eagle populations at or near carrying capacity have been reported for other regions in the US (Baldwin et al. 2012, Watts and Byrd 2008), we think there is still suitable, unoccupied habitat in eastern Kentucky that may support the continued growth of the population.

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