# Assess risk of individual turbines to Golden Eagles

Task 3

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## Summary

Wind power production is an important part of international strategies to reduce greenhouse gases and combat climate change. Nonetheless, there are costs to wildlife, especially eagles and bats, from wind turbines. Golden Eagles are a federally protected species; therefore, when a wind facility is predicted to "take" Golden Eagles during normal operation, the facility is often legally required to attempt to avoid that take. If avoiding take is not possible, minimizing take is the next step. Minimizing take can be achieved by micro-siting wind turbines to avoid high risk areas. I applied existing models of predicted risk to low-flying Golden Eagles from wind energy, Golden Eagle habitat suitability, and wind turbine suitability to wind turbine locations at the Bluestone Wind Project. Of the 33 turbines, 24% (n = 8) were originally sited in high risk areas. Models suggest that each of those turbines could be micro-sited, i.e., relocated to a spot within 500 feet of the original location, to reduce predicted risk to Golden Eagles.


## Introduction

Wind power is an important part of international strategies to reduce carbon emissions to combat climate change (American Wind Energy Association [AWEA]). As such, it has expanded considerably over the last two decades. However, this expansion has come at a cost to wildlife, especially eagles and bats (Smallwood and Thelander 2008, Tabassum-Abbasi et al. 2014). To minimize the effects of wind energy on eagles, and because both Bald and Golden Eagles are federally protected under the Bald and Golden Eagle Protection Act (BGEPA), the United States Fish and Wildlife Service (USFWS) introduced strategies outlined in an Eagle Permit Rule (USFWS 2009 and USFWS 2016*a*) and an Eagle Conservation Plan Guidance (ECPG; USFWS 2013). These frameworks provide wind energy companies the ability to obtain a permit to incidentally "take" (in this case, incidentally cause the mortality or injury of) eagles west of the 100$^{th}$ meridian. The 2016 revision of the Rule allowed for the establishment of an Eagle Management Unit (EMU; a geographic area "where permitted take is regulated to meet the population objective") delineated by the Mississippi and Atlantic Flyways for take of Golden Eagles east of the 100$^{th}$ meridian. The 2016 revision also modified the BGEPA to "maintaining the persistence of local populations."

The USFWS conducted analyses and reviews of nationwide Golden Eagle population trends and causes of mortality (Katzner et al. 2012, Millsap et al. 2013, USFWS 2016*b*) and determined that the existing level of unpermitted take (estimated at 10%) was the maximum that the species could incur without declining. Thus, permitting additional take in any EMU was not compatible with the USFWS objective of increasing or sustaining populations at current levels. The USFWS, therefore, instituted a policy of "no net loss" for the species. The ECPG describes steps that a developer might follow to meet the "no net loss" rules. Step 1 is to predict and avoid take. Step 2 is to minimize take and step 3 is to offset take.

Take can be avoided by reducing the number of turbines or through macro-siting to avoid siting projects in high risk areas (Smallwood and Karas 2009, Katzner et al. 2012*a*, Miller et al. 2014). Because the Bluestone Wind Project is at a later stage of development, macro-siting is not a viable option to avoid take. However, minimizing take may remain a viable option for some turbines. Take can be minimized in several ways including use of flight diverters, removing attractants, curtailment, and turbine micro-siting (Smallwood and Karas 2009, de Lucas et al. 2012, Katzner et al. 2012*a*, USFWS 2013, Miller et al. 2014, Allison et al. 2017). In this report, I focus on micro-siting of turbines as a potential method to minimize take.

## Methods

Miller et al. (2014) developed regional models to predict risk to low-flying Golden Eagles from wind turbines in three topographically distinct regions of Pennsylvania, the Ridge and Valley, the Allegheny Mountains and the Allegheny Plateau (Appendix A). Risk was predicted by creating separate spatial resource selection models for wind turbines and for low-flying Golden Eagles. The two models were over-laid to understand where resource selection of both eagles and turbines intersected.

The risk models were built using proposed and existing wind turbine locations, telemetry data from migrating Golden Eagles during spring, and topography. A more detailed description of the techniques used are provided in that manuscript, which is attached here.

Here, I applied the model from the nearest region of Pennsylvania, the Allegheny Plateau, to the Bluestone Wind Project (BWP). BWP is situated 9 km (5.6 miles) from the model area on the New York border (Fig. 1). Importantly, topography, wind energy development, and flight paths of Golden Eagles are consistent from the modeled area through this part of southern New York, making the model applicable to BWP.

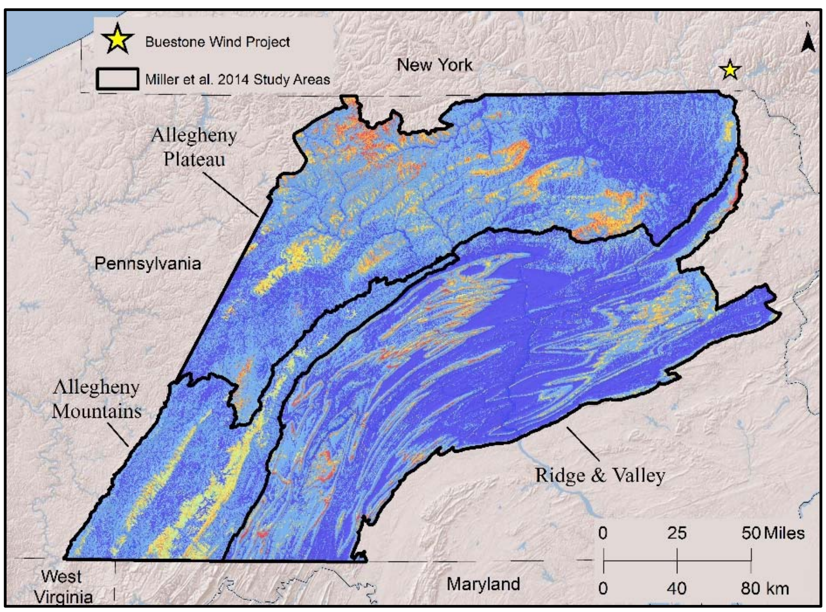


Figure 1. Location of Bluestone Wind Project in relation to models from Miller et al. 2014.

The 2014 models focused on spring migration. Additional modeling in the Ridge and Valley in Pennsylvania and Virginia across seasons (spring and fall migration and winter), showed that eagles used a wider variety of areas for low-altitude flight in winter than spring and they used a more restricted area in spring than during fall migration (Miller 2015). Regardless of region and season, migrating Golden Eagles consistently selected to travel along ridges (Miller et al. 2014, Miller 2015) and lower flight altitudes were associated with summits and cliffs (Katzner et al. 2012*a*).

The models were extended to a 40 km region surrounding the BWP using the same model in Miller et al. (2014). I extracted the latitude and longitude for wind turbine locations in the project from the FAA (FAA Archived Cases, Wind Turbines East, https://oeaaa.faa.gov/oeaaa/) and plotted those locations in ArcGIS 10.3. I extracted the underlying risk class, wind turbine suitability class, and Golden Eagle habitat suitability class. Risk level was classified based on risk class from the model, eagle habitat suitability and turbine suitability (see Table 1, Appendix A). I then examined and summarized each turbine's risk class. Because some turbines were sited in risk class 3, I broke down class 3 into 3 sub-classes that better represent risk based only on eagle habitat suitability (Table 1).

Table 1. Classification of risk to Golden Eagles from wind turbines based on eagle habitat suitability and turbine suitability. Modified from Miller et al. 2014.

| Level of Risk | Risk Class[a] | Eagle Habitat Suitability Class | Turbine Suitability Class |
|---|---|---|---|
| Low | 1 | poor | poor |
| Low | 2 | poor | fair - excellent |
| Moderate* | 3a | fair | poor |
| High* | 3b | good | poor |
| Extreme* | 3c | excellent | poor |
| Moderate | 4 | fair | fair - excellent |
| High | 5 | good | fair - excellent |
| Extreme | 6 | excellent | fair - excellent |

[a]Classes based on Golden Eagle and wind energy resource selection.

*Risk class 3 - variable risk - from Miller et al. 2014 was broken down into 3 classes to better represent risk.

When risk class was predicted to be high for a given wind turbine, I identified locations where a turbine could be moved to reduce risk within a 500 foot buffer, said to be the farthest a turbine can be moved at this stage of development (T. Salo, Delaware-Otsego Audubon Society, pers. comm.). Because risk extends from the base of the turbine out to the tips of the blades, to better visualize risk, I buffered each existing and potential new turbine location by 246 feet (492 foot diameter), which is the maximum reach of the turbine rotors used in the project (Bluestone Wind, LLC). I plotted all "risky" turbines and the associated buffers on the Golden Eagle habitat suitability map, the risk map, and a topographic map. I illustrated where a turbine could be moved to reduce the risk of the turbine to low-flying Golden Eagles.

## Results

Models predicted that Golden Eagles selected habitat along slopes and near ridgetops (Fig. 2). Areas suitable for wind turbines were restricted to ridge lines and it appeared that models accurately predicted, in most cases, where developers would choose to put turbines. Ridge lines were also usually the areas of highest risk, with variable risk extending down slopes.

I analyzed the risk for 33 turbine locations in BWP. I found that 8 (24%) turbines were located in high risk areas, 18 (55%) turbines were located in moderate risk areas and 7 (21%) were located in low risk areas (Fig. 3). No turbines were located in extreme risk areas.

Because risk models reasonably predicted good locations for turbines, I felt confidence in suggesting alternative locations that would provide similar wind resources but less modeled risk to eagles. All turbines that were located in high risk areas could be moved within 500 feet to lower risk areas (Figures 4-11; Table 2).

## Conclusions

Minimizing take can reduce a company's predicted take and thus reduce the amount of compensatory mitigation needed to offset take. Micro-siting of turbines is an important mechanism for minimizing take. The assessment of BWP turbines showed that nearly one-quarter of the turbines were located in high risk areas. All of those turbines could be micro-sited, i.e., moved <500 feet from the current location, to reduce predicted risk. Moreover, although this model is unlikely to be as accurate as those that wind developers use, some of the suggested turbine moves actually resulted in a predicted increase in suitability for wind turbines in conjunction with lower risk to eagles.

Table 2. List of wind turbines in the Bluestone Wind Project with high predicted risk to Golden Eagles. Original location is the location provided to me. Proposed location is a location within 500 feet of the original location where predicted risk to Golden Eagles is lower. Risk class, Golden Eagle habitat suitability and wind power suitability were based on models from Miller et al. 2014. Latitude and longitude are in North American Datum 1983.

| | Original Location | | | | | | Proposed Location | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Name | Latitude | Longitude | Risk Class | | Golden Eagle Habitat Suitability | Wind Power Suitability | Latitude | Longitude | Risk Class | | Golden Eagle Habitat Suitability | Wind Power Suitability |
| T13 | 42.104610 | -75.530202 | High | 3b | Good | Poor | 42.105442 | -75.529977 | Low | 2 | Poor | Moderate |
| T22 | 42.104965 | -75.498934 | High | 5 | Good | Moderate | 42.104241 | -75.497815 | Moderate | 4 | Poor | Good |
| T23 | 42.113698 | -75.512253 | High | 3b | Good | Poor | 42.113458 | -75.511434 | Low | 2 | Poor | Moderate |
| T25 | 42.088098 | -75.468844 | High | 3b | Good | Poor | 42.087550 | -75.467978 | Moderate | 4 | Poor | Moderate |
| T27 | 42.113460 | -75.453467 | High | 3b | Good | Poor | 42.113648 | -75.452229 | Low | 2 | Poor | Good |
| T31 | 42.103124 | -75.456848 | High | 5 | Good | Moderate | 42.102485 | -75.457787 | Moderate | 4 | Poor | Good |
| T32 | 42.117601 | -75.452985 | High | 3b | Good | Poor | 42.117138 | -75.452269 | Moderate | 4 | Poor | Moderate |
| T40 | 42.095313 | -75.452485 | High | 5 | Good | Moderate | 42.095684 | -75.451758 | Moderate | 4 | Poor | Moderate |

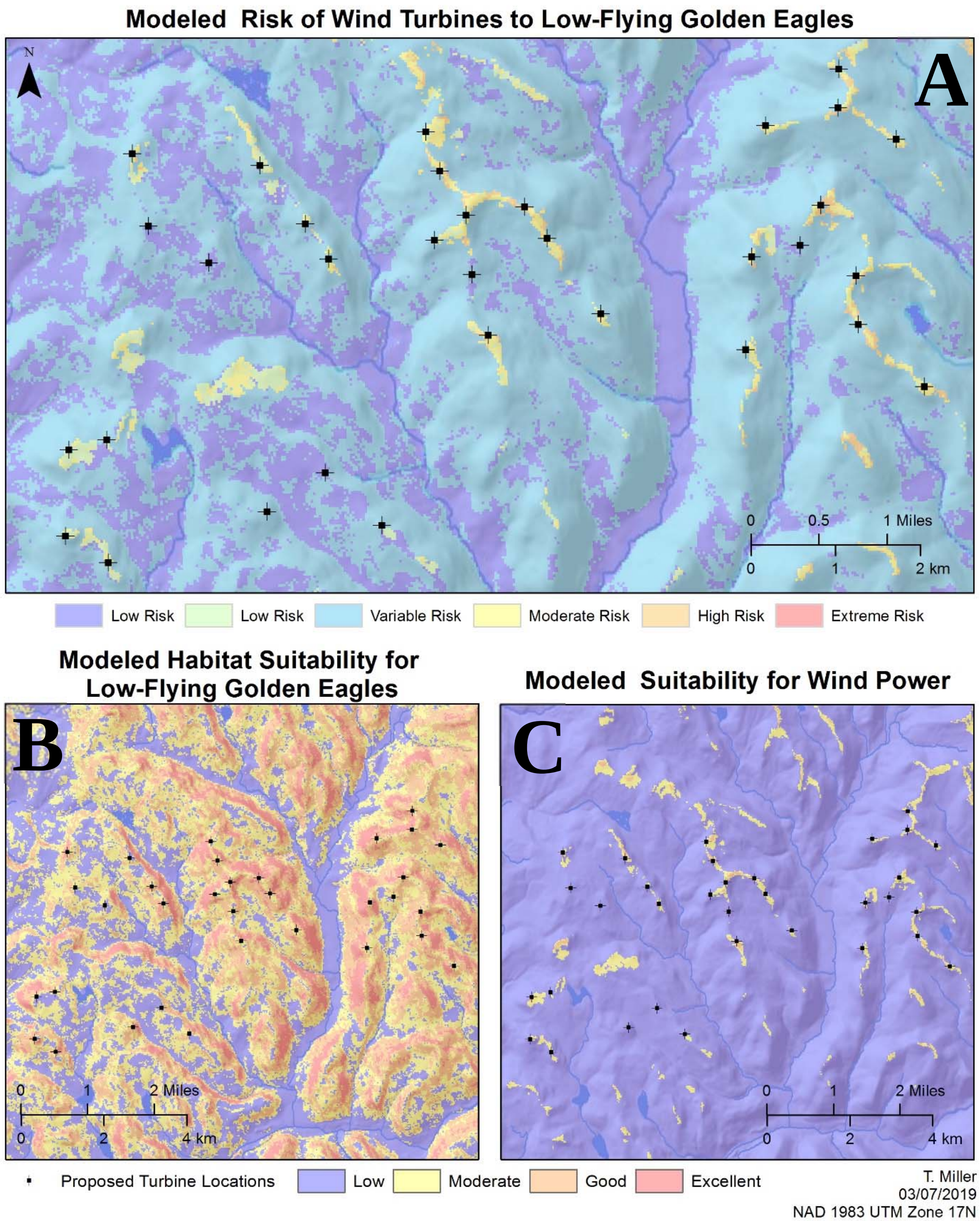


Figure 2. Wind turbine locations (FAA Archived Cases, Wind Turbines East) for the Bluestone Wind Project and (A) modeled risk to Golden Eagles, (B) habitat suitability based on resource selection of low-flying Golden Eagles, (C) modeled suitability for wind energy based on resource selection of wind turbines. Models were based on Miller et al. 2014.

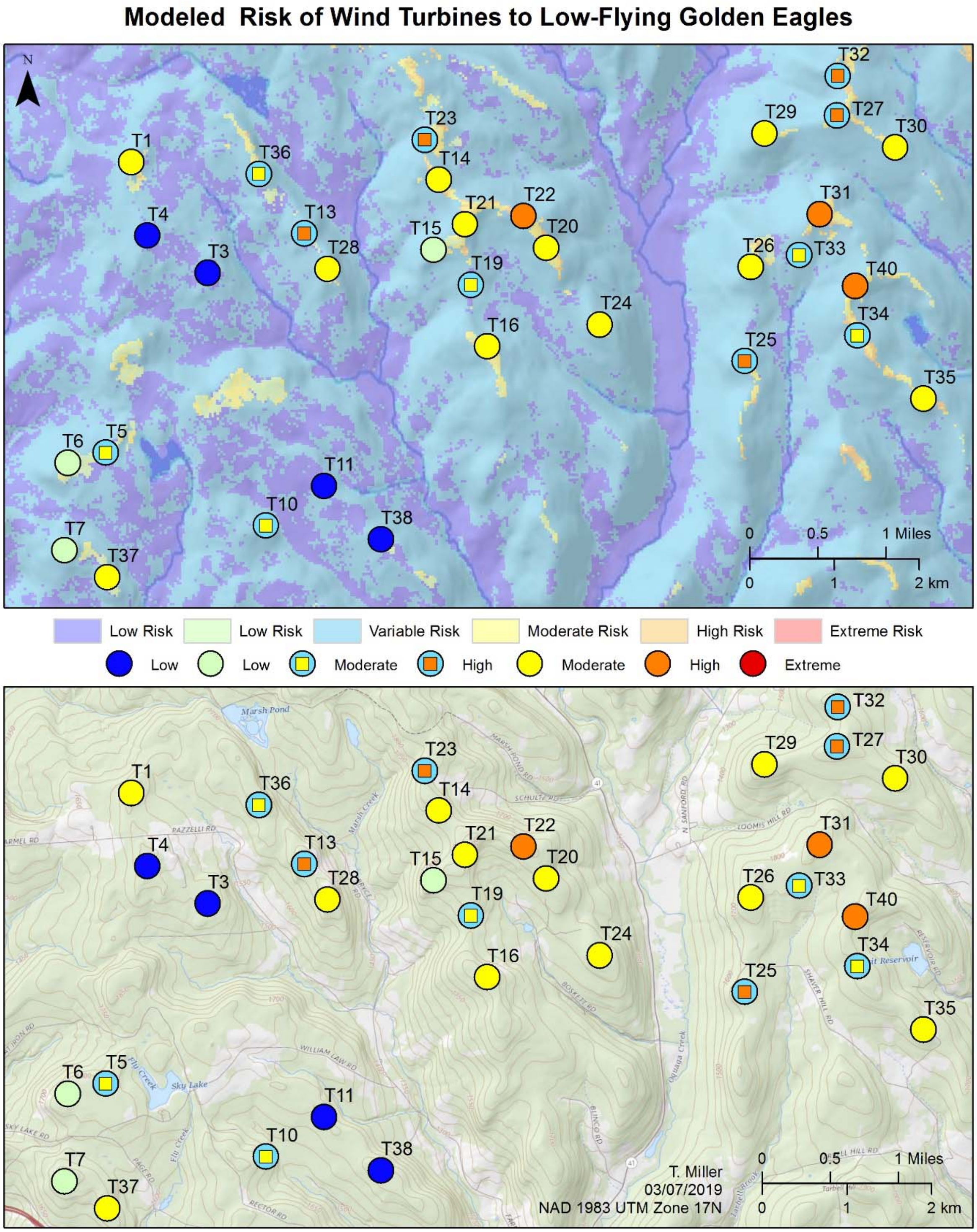


Figure 3. Risk classification of wind turbines in the Bluestone Wind Project and (A) modeled risk and (B) topography.

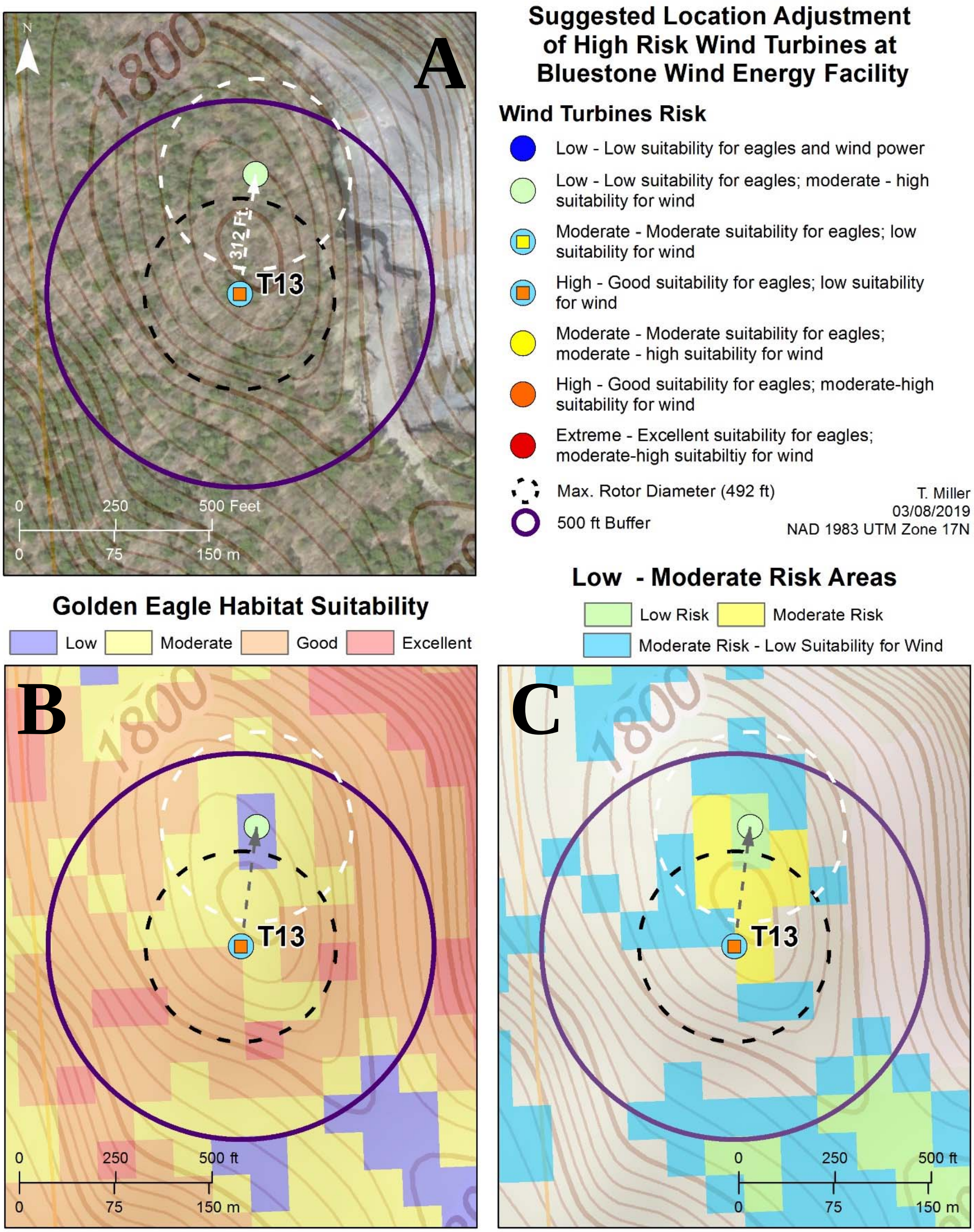


Figure 4. Location of T13 and proposed location adjustment in relation to (A) land cover, (B) habitat suitability for low-flying Golden Eagles, and (C) risk to Golden Eagles from wind turbines.

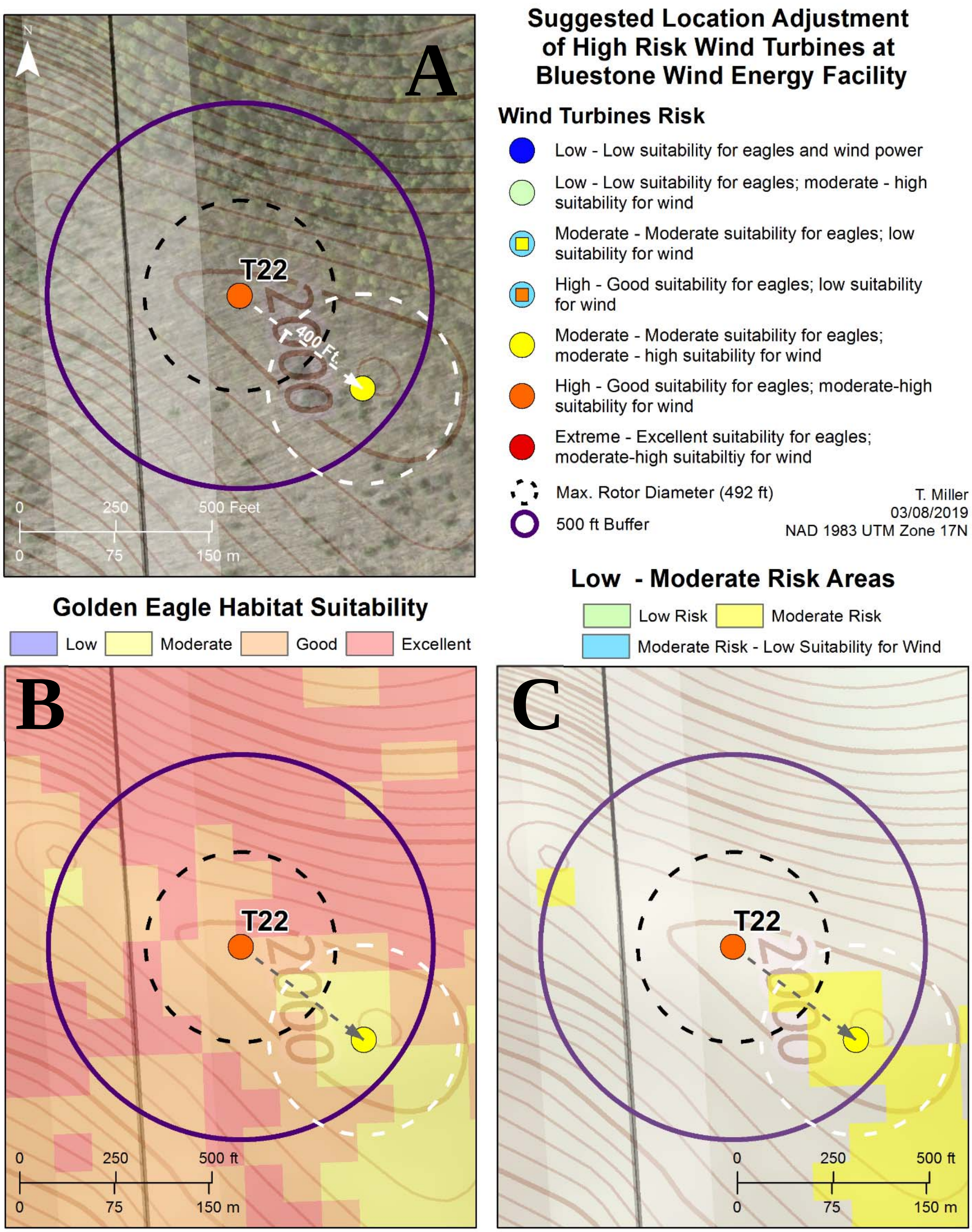


Figure 5. Location of T22 and proposed location adjustment in relation to (A) land cover, (B) habitat suitability for low-flying Golden Eagles, and (C) risk to Golden Eagles from wind turbines.

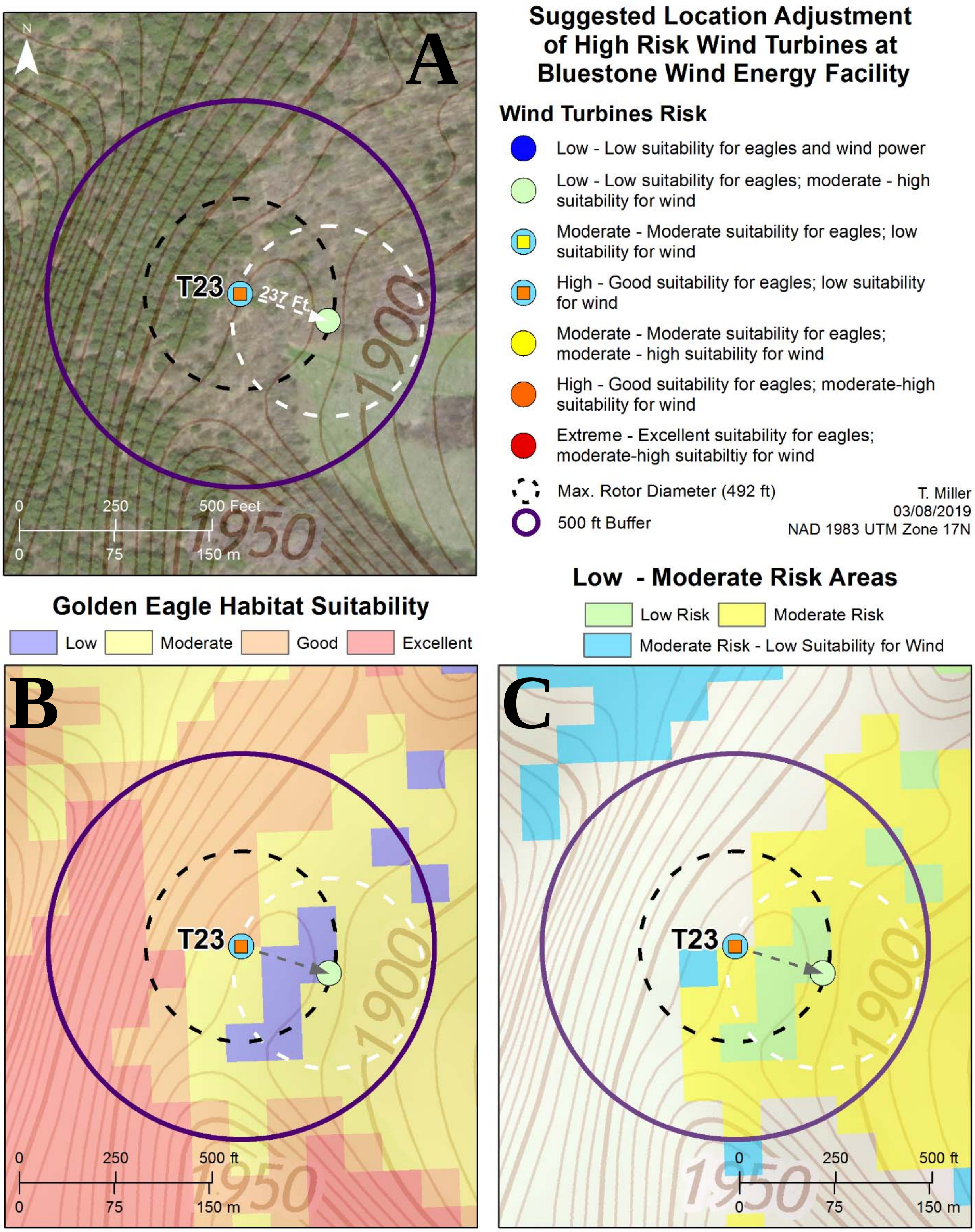


Figure 6. Location of T23 and proposed location adjustment in relation to (A) land cover, (B) habitat suitability for low-flying Golden Eagles, and (C) risk to Golden Eagles from wind turbines.

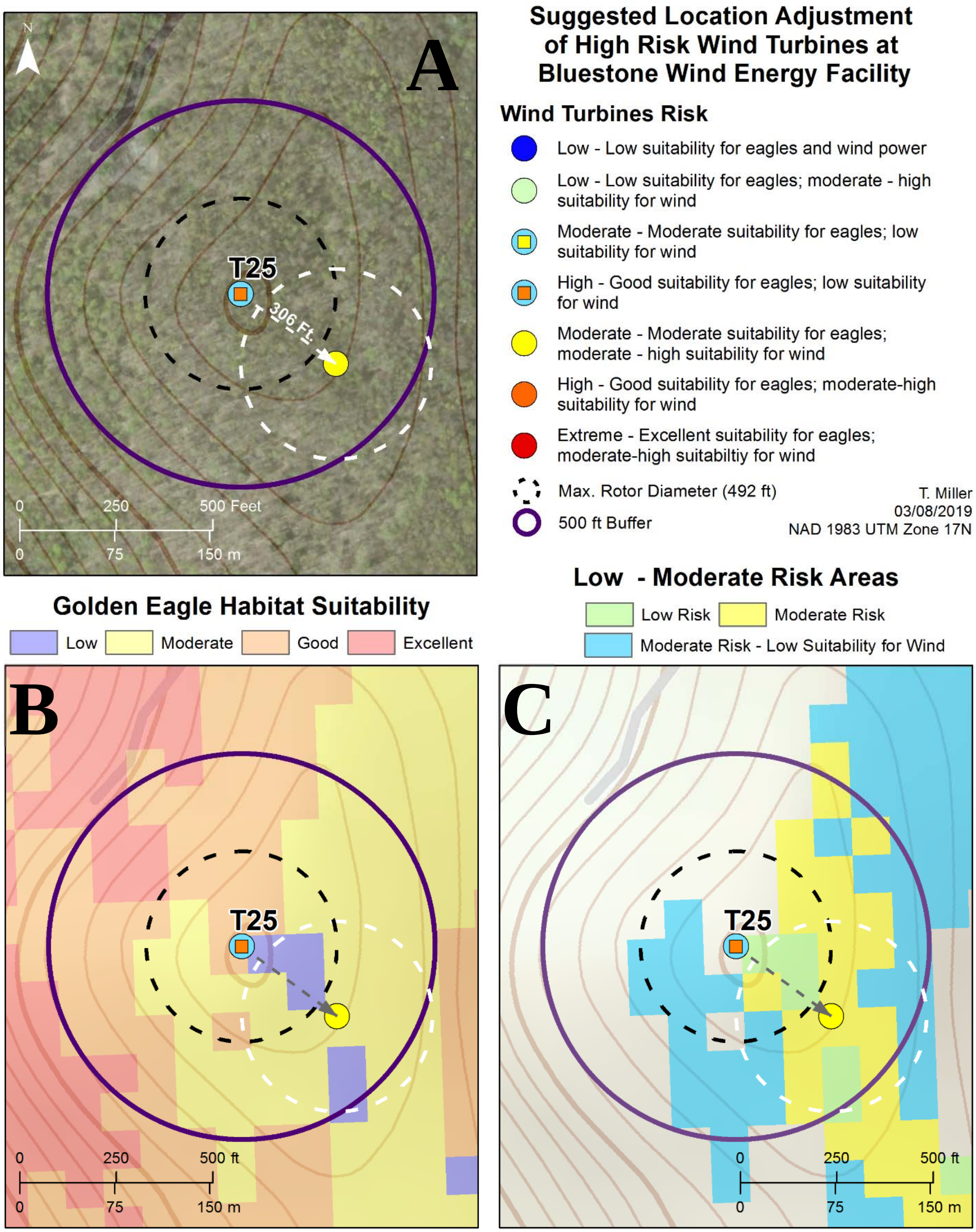


Figure 7. Location of T25 and proposed location adjustment in relation to (A) land cover, (B) habitat suitability for low-flying Golden Eagles, and (C) risk to Golden Eagles from wind turbines.

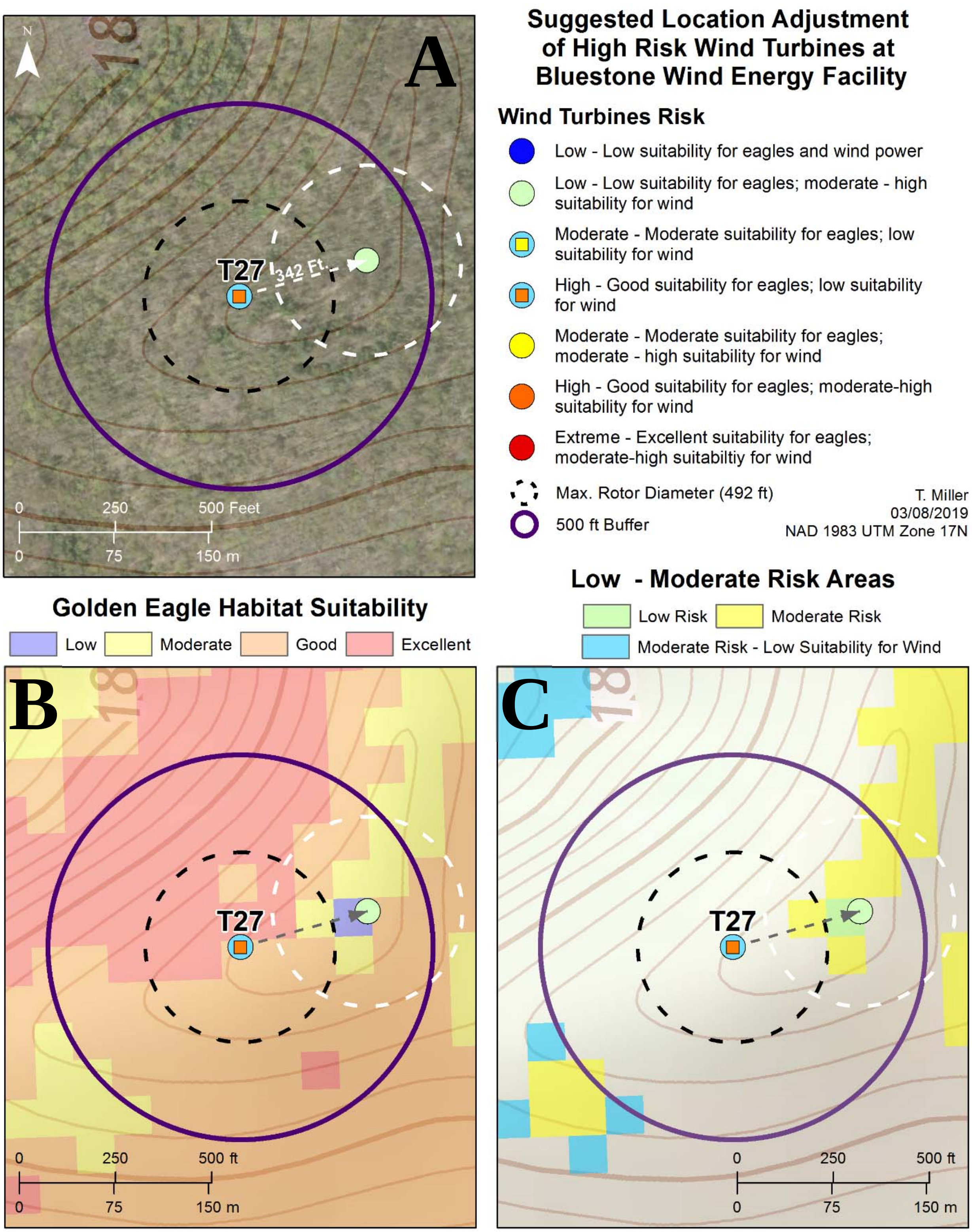


Figure 8. Location of T27 and proposed location adjustment in relation to (A) land cover, (B) habitat suitability for low-flying Golden Eagles, and (C) risk to Golden Eagles from wind turbines.

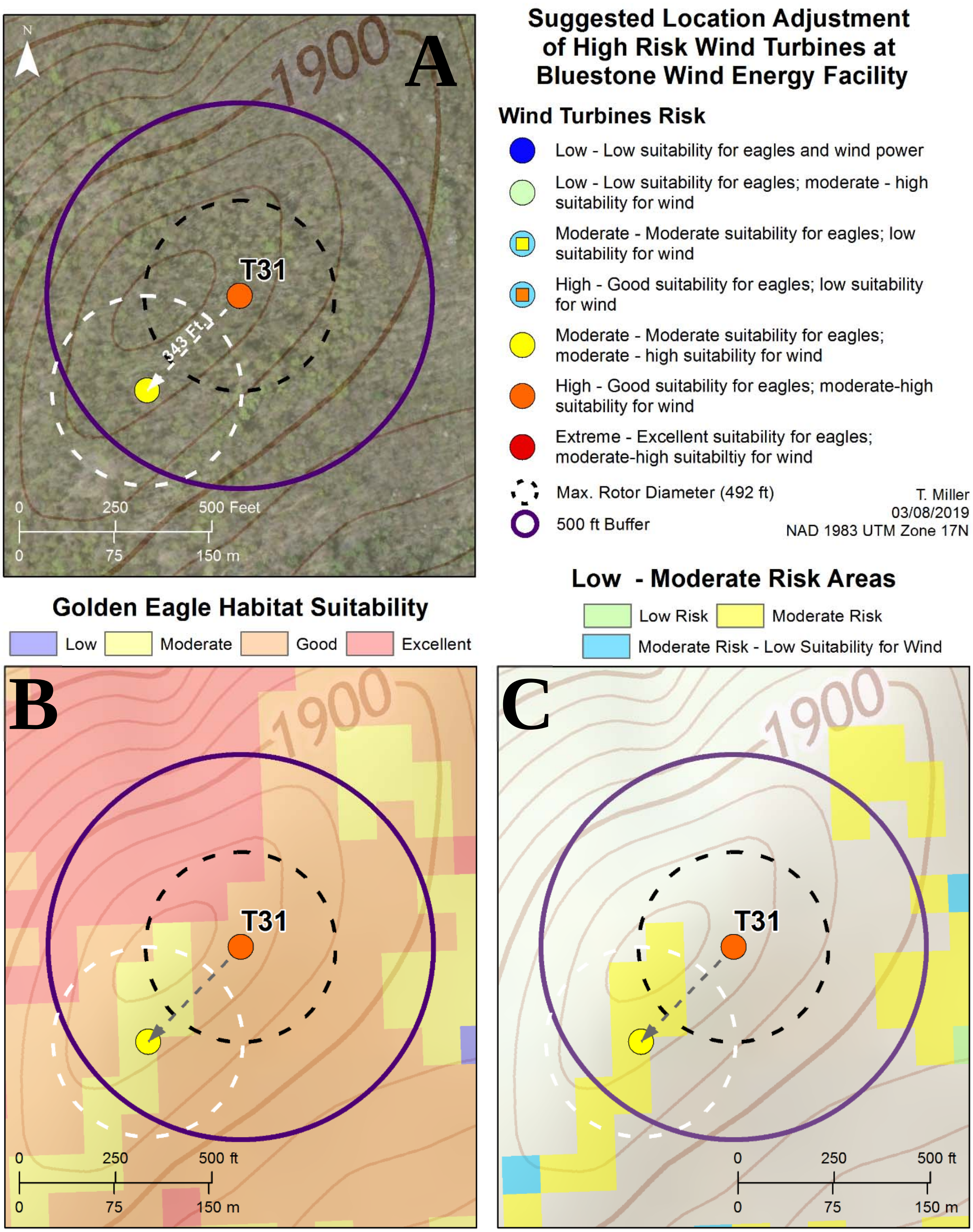


Figure 9. Location of T31 and proposed location adjustment in relation to (A) land cover, (B) habitat suitability for low-flying Golden Eagles, and (C) risk to Golden Eagles from wind turbines.

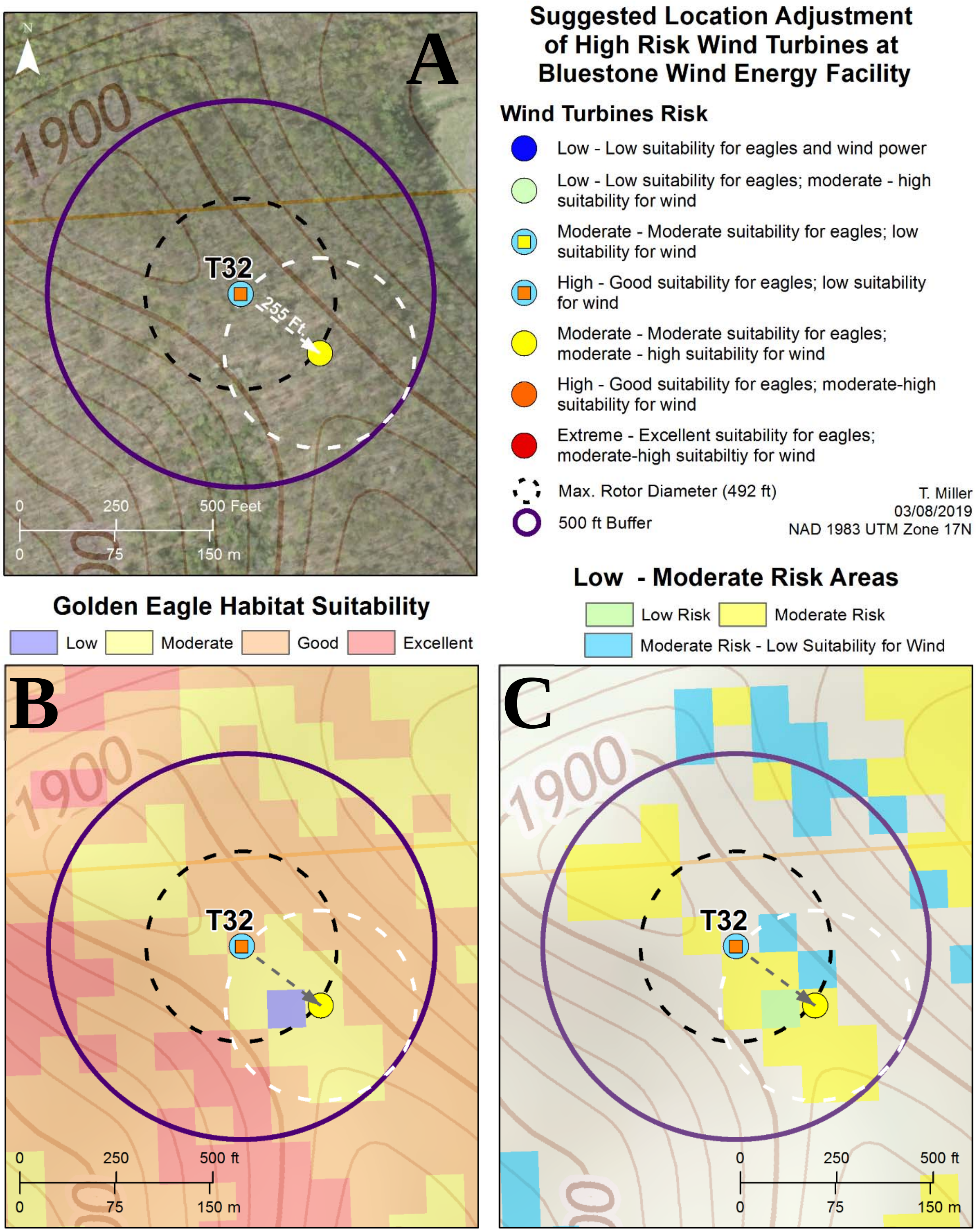


Figure 10. Location of T32 and proposed location adjustment in relation to (A) land cover, (B) habitat suitability for low-flying Golden Eagles, and (C) risk to Golden Eagles from wind turbines.

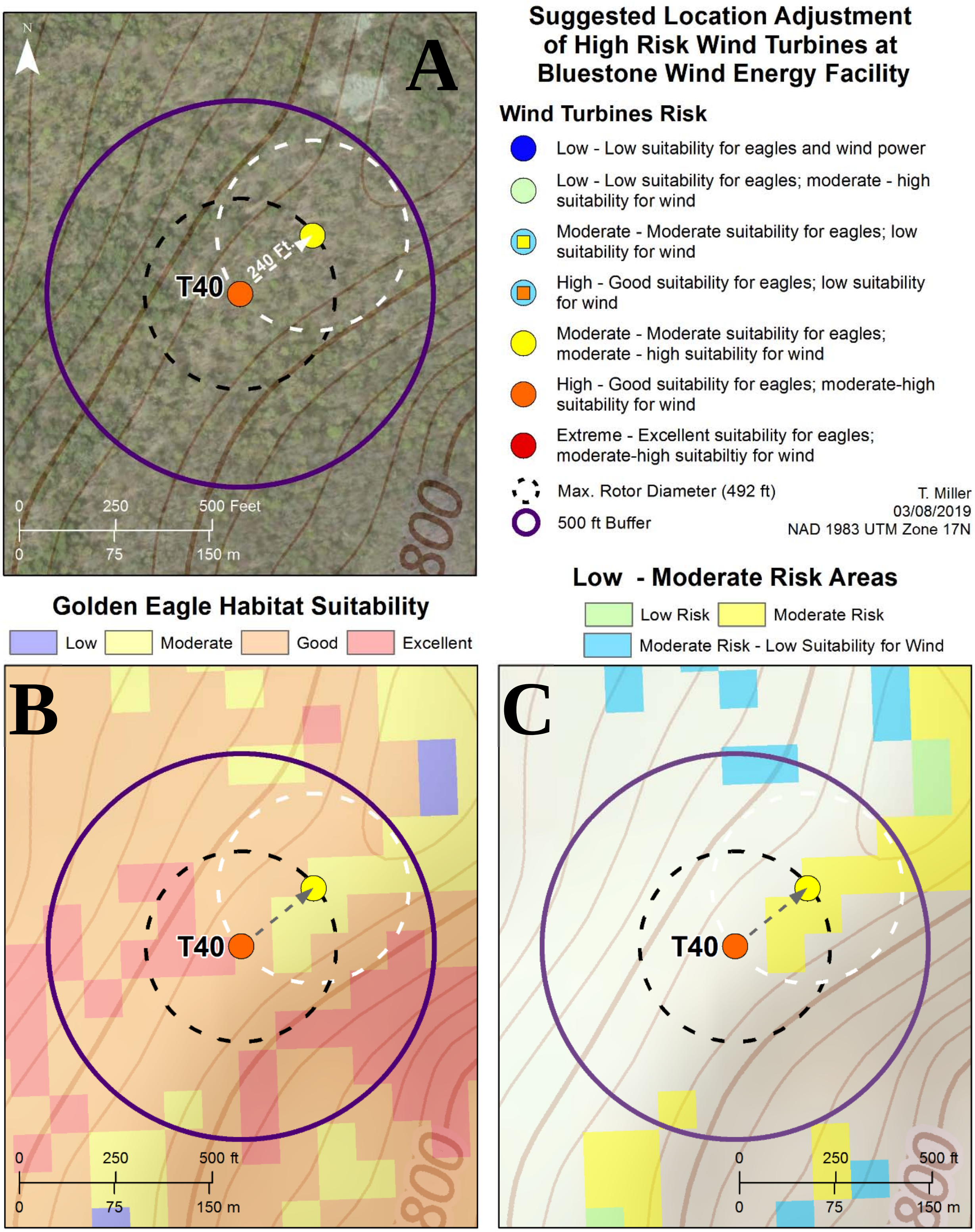


Figure 11. Location of T40 and proposed location adjustment in relation to (A) land cover, (B) habitat suitability for low-flying Golden Eagles, and (C) risk to Golden Eagles from wind turbines.

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Conservation Biology

Appendix A. Miller et al. 2014

Contributed Paper

# Assessing Risk to Birds from Industrial Wind Energy Development via Paired Resource Selection Models

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**Abstract:** *When wildlife habitat overlaps with industrial development animals may be harmed. Because wildlife and people select resources to maximize biological fitness and economic return, respectively, we estimated risk, the probability of eagles encountering and being affected by turbines, by overlaying models of resource selection for each entity. This conceptual framework can be applied across multiple spatial scales to understand and mitigate impacts of industry on wildlife. We estimated risk to Golden Eagles* (Aquila chrysaetos) *from wind energy development in 3 topographically distinct regions of the central Appalachian Mountains of Pennsylvania (United States) based on models of resource selection of wind facilities* (n = *43) and of northbound migrating eagles* (n = *30). Risk to eagles from wind energy was greatest in the Ridge and Valley region; all 24 eagles that passed through that region used the highest risk landscapes at least once during low altitude flight. In contrast, only half of the birds that entered the Allegheny Plateau region used highest risk landscapes and none did in the Allegheny Mountains. Likewise, in the Allegheny Mountains, the majority of wind turbines (56%) were situated in poor eagle habitat; thus, risk to eagles is lower there than in the Ridge and Valley, where only 1% of turbines are in poor eagle habitat. Risk within individual facilities was extremely variable; on average, facilities had 11% (SD 23; range = 0–100%) of turbines in highest risk landscapes and 26% (SD 30; range = 0–85%) of turbines in the lowest risk landscapes. Our results provide a mechanism for relocating high-risk turbines, and they show the feasibility of this novel and highly adaptable framework for managing risk of harm to wildlife from industrial development.*

**Keywords:** birds, Golden Eagle, habitat modeling, risk assessment, spatial ecology, wind energy development

Evaluación del Riesgo para las Aves por el Desarrollo de Energía Eólica Industrial Mediante Modelos de Selección de Recursos Pareados.

**Resumen:** *Cuando el hábitat de la fauna silvestre se traslapa con el desarrollo industrial, los animales pueden resultar afectados. Como la fauna silvestre y la gente seleccionan recursos para maximizar la aptitud biológica y el reingreso económico, respectivamente; estimamos el riesgo y la probabilidad de que las águilas entren en contacto y sean afectadas por las turbinas al sobreponer modelos de la selección de recursos para cada entidad. Este marco de trabajo conceptual puede aplicarse en múltiples escalas espaciales para entender y mitigar los impactos de la industria sobre la fauna silvestre. Estimamos el riesgo para el águila dorada*

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(Aquila chrysaetos) *a partir del desarrollo de energía eólica en tres regiones distintas topográficamente de la parte central de las montañas Apalaches en Pennsylvania (E.U.A) basándonos en modelos de selección de recursos de las instalaciones eólicas (*n = *43) y de las águilas que migraban hacia el norte (*n = *30). El riesgo para las águilas fue mayor en las zonas de la Cresta y del Valle; las 24 águilas que pasaron por esa región usaron los paisajes con alto riesgo por lo menos una vez durante el vuelo de poca altitud. En contraste, sólo la mitad de las aves que entraron a la región de la Meseta Allegheny usaron paisajes de alto riesgo y ninguna los usó en las montañas Allegheny. Así mismo, en las montañas Allegheny, la mayoría de las turbinas eólicas (56%) estaban situadas en un hábitat pobre para las águilas; por esto el riesgo para las águilas es más bajo aquí que en el Risco y el Valle, donde solamente el 1% de las turbinas se encuentran en un hábitat pobre para las águilas. El riesgo dentro de las instalaciones individuales fue extremadamente variable: en promedio, las instalaciones tuvieron un 11% (SD 23; rango = 0 - 100%) de las turbinas en paisajes de alto riesgo y un 26% (SD 30; rango = 0 - 85%) de las turbinas en los paisajes con riesgo más bajo. Nuestros resultados proporcionan un mecanismo para reubicar a las turbinas de alto riesgo y muestran la factibilidad de este marco de trabajo novedoso y altamente adaptable para manejar el riesgo de dañar a la fauna silvestre con el desarrollo industrial.*

**Palabras Clave:** Águila dorada, aves, desarrollo de energía eólica, ecología espacial, estudio de riesgo, modelado de hábitat

## Introduction

Economic development creates complex problems when juxtaposed against wildlife conservation. Conservation biology seeks to understand and manage threats to species, populations, and ecosystems that can be brought on by development (e.g., Durner et al. 2003; Sawyer et al. 2006; Harju et al. 2011). Biologists traditionally focus exclusively on ecological solutions to these problems. However, advancements in conservation are likely most effective when they focus on solutions that consider the needs of both species and industries. A holistic perspective recognizes that although species select resources to improve their survival and fitness, industries also select resources that are important for their economic bottom line and, thus, survival. In this context, risk, the probability of a negative outcome for eagles and for developers can be visualized by overlaying spatially explicit models of wildlife and industrial resource selection. The resultant model can be used to adjust industrial enterprises so that they pose less of a threat to wildlife.

Wind power generation is one of the fastest growing sources of alternative energy (Wiser & Bolinger 2009). When industrialized, however, wind power has both direct and indirect effects on wildlife; thus, it is one of the most controversial sources of so-called green energy. The direct effects of turbines on wildlife are well documented and come mainly in the form of mortality through blade strikes of birds and bats (Hunt et al. 1999). However, risk extends beyond mortality and includes a suite of relevant indirect effects (Drewitt & Langston 2006). Habitat loss may be a substantial problem especially when intact core habitats are fragmented by infrastructure, pads, and roads (Osborn et al. 2000; Kuvlesky et al. 2007). Displacement, where birds avoid turbines, may have fitness repercussions, for example, when birds are pushed away from preferred movement pathways and incur increased energetic costs (Chamberlain et al. 2006; Band et al. 2007). Overall, indirect effects may be more important to demography, but more difficult to quantify, than direct mortality (Kuvlesky et al. 2007).

Neither direct nor indirect effects on birds are equally distributed spatially or temporally within or among species or wind facilities (e.g., Barrios & Rodriguez 2004; De Lucas et al. 2008; Ferrer et al. 2012). For example, the Altamont Pass Wind Resource Area in California kills thousands of federally protected birds annually, including approximately 67 Golden Eagles (*Aquila chrysaetos*) and >1000 other raptors per year (Smallwood & Thelander 2008). Conversely, other sites in California and elsewhere cause few mortalities (Erickson et al. 2001; Drewitt & Langston 2006; Johnson et al. 2008). Likewise, within a given facility, certain individual turbines are often responsible for a disproportionate number of mortalities (Osborn et al. 2000; Kuvlesky et al. 2007; May et al. 2011). Finally, individuals or populations of some species, especially eagles, other raptors, and bats, are among the most at risk (Hunt et al. 1999; Chamberlain et al. 2006; Fielding et al. 2006). These site-specific negative impacts all stem from a lack of understanding of resource selection overlap and the challenges of considering potential negative effects on wildlife and species of conservation concern (Smallwood & Thelander 2008; Bevanger et al. 2010; Ferrer et al. 2012).

The central Appalachian Mountains of eastern North America are an important migratory corridor where large numbers of raptors concentrate (Newton 2008) along long narrow ridges that provide subsidized lift (Reichmann 1978; Kerlinger 1989; Lanzone et al. 2012). This region is also important for wind energy development because of the presence of high-quality wind resources similarly associated with the topography (National Renewable Energy Laboratory [NREL], http://www.nrel.gov/gis/data_wind.html/). Pennsylvania can support an installed wind generation capacity of 3307 MW; the majority of suitable sites for development are located within this critically important avian migratory corridor (NREL 2011). With a current installed capacity of only 883 MW at 19 locations, there is potential for substantial negative turbine-wildlife interactions as additional facilities are installed. Furthermore, an increase in the number of wind power facilities in preferred migratory habitat could result in cumulatively higher energetic costs during migration if the presence of turbines causes birds to alter their flight paths and use of subsidized lift (Drewitt & Langston 2006).

We developed a spatial model-based framework as a tool to solve problems stemming from conflicting industrial and ecological goals. We apply this framework by building models of resource selection for actively migrating Golden Eagles and for wind energy facilities in central Pennsylvania (U.S.A.); testing hypotheses related to resource selection by eagles and wind developers; and overlaying those models to assess risk. We predicted that these models would identify regional differences in resource selection by eagles and by energy developers and that these differences would be driven by variation in topography. We applied our models and show how they can be used to guide site selection at a regional scale, to identify high-risk facilities, and to modify siting of individual turbines at a local scale. This framework can be applied not only to eagles and the wind industry, but also more broadly in other settings with different species and industries.

## Methods

### Study Species and Area

Golden Eagles are at high risk for collision with wind turbines (Hunt et al. 1999; Smallwood & Thelander 2008). In eastern North America, the small Golden Eagle population breeds in Canada and migrates through and winters in the U.S. Appalachian Mountains (Fig. 1) (Katzner et al. 2012*a*). We focused our risk assessment in central Pennsylvania, where both eagle migration and wind energy development are coincident. We divided the study area into 3 topographically distinct regions, the Allegheny Mountains, the Ridge and Valley, and the Allegheny Plateau, which were primarily delineated along boundaries of physiographic provinces (Fig. 1) (Bailey 1993).

### Telemetry

We captured 30 Golden Eagles on their wintering grounds in Virginia and West Virginia with cannon or rocket nets from 2009 to 2012. We took traditional morphometric measurements (e.g., weight, wing chord) and estimated age on the basis of molt limits (Jollie 1947; Bloom & Clark 2001). Each bird was banded and outfitted with a 95 g CTT-1100 telemetry unit (1.9–2.8% of the body mass; Cellular Tracking Technologies, Somerset, PA, U.S.A.) that collected GPS-derived location, altitude, heading, and speed at 30- to 60-second intervals. Data were transmitted once daily over the Global System for Mobile Communications (GSM) network. We used Teflon ribbon (Bally Ribbon Mills, Bally, PA, U.S.A.) to attach telemetry units in a backpack style (Fuller et al. 2005). We classified data points as in-flight or perched and used only in-flight data for our analysis. We assigned elevation of the underlying ground to each point using the 10 m national elevation data set of the U.S. Geological Service. Elevation was subtracted from the altitude above sea level reported by the GPS to give approximate altitude above ground level (AGL). Vertical accuracy of the GPS is within 22.5 m (Lanzone et al. 2012).

We used only in-flight data points that were <150 m AGL to model resource selection mainly because modern day turbines are <150 m tall. We, therefore, assumed that birds flying <150 m AGL were at relatively higher risk of encountering and being affected by wind turbines than higher flying birds. Additionally, birds flying at low altitudes should respond similarly to topography (Kerlinger 1989; Katzner et al. 2012*b*).

### Wind Turbine Data

We obtained locations of wind turbines from the public online Federal Aviation Administration (FAA) obstructions database available from https://oeaaa.faa.gov/oeaaa/external/searchAction.jsp/action=showSearchArchivesForm. Data were examined for accuracy and duplicate turbines and meteorological towers were removed. Locations of existing facility data were validated by comparison with high resolution Google Earth imagery (W. Seirer, personal communication).

### Explanatory Variables

We selected 9 environmental variables that may influence low altitude eagle flight and turbine placement (Supporting Information). We derived 4 variables from a 30-m digital elevation model (Gesch et al. 2002): mean elevation, mean slope, mean eastness, and mean northness, where the mean of each variable was calculated as the average of all pixels within 100 m of that cell. To understand the effect of topographic position, we created continuous variables from 3 categorical topographic positions—steep slopes, side slopes, and summits (ELU, ecological land units) (Anderson et al. 2006)—by calculating a separate Euclidean distance grid to each. Because available wind is important to turbines and to eagles, we also included a variable describing wind conditions (NREL). These data classify available wind at 50 m AGL into 7 classes, where

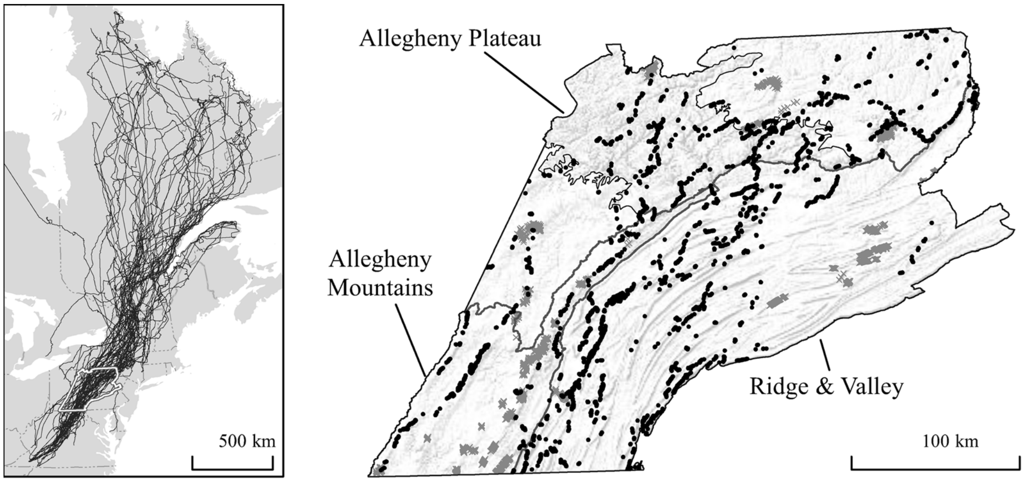


*Figure 1. Map on the right shows migratory tracks of Golden Eagles (n = 47) (white outline, migratory bottleneck in the study area in the central Appalachian Mountains, U.S.A., 2007–2012). Map on the left study area with Golden Eagle telemetry locations (dots) and proposed or existing wind turbine locations 2001–2010 (Xs) (black lines, physiographic province boundaries; dark gray lines, modeled regions. Data sources: physiographic boundaries, USDA Forest Service, Washington, D.C.; wind turbine locations, Federal Aviation Administration; background data, ESRI, Redlands, California.*

class 3 and above are suitable for wind energy development. We extracted and combined classes 3–7 and calculated a continuous Euclidean distance grid to those cells and used the distance to class 3 and above winds as our variable of interest. Finally, to estimate the potential for orographic lift, which is a lift mechanism used by low-flying migratory eagles, we calculated updraft potential ($w_o$) (Brandes & Ombalski 2004) for each of the 8 cardinal directions with a standard wind speed ($v$) of 10 m/s:

$$w_o = v \times \sin(\theta) \times (\cos(\alpha - \beta)), \quad (1)$$

where $\theta$ is the slope angle, $\alpha$ is the wind direction, and $\beta$ is the terrain aspect; all angles are in radians. We combined the 8 resultant raster layers into one by selecting the maximum potential updraft value among the 8 cardinal directions. We standardized all raster data sets by dividing the mean and subtracting the standard deviation.

**Modeling Resource Selection**

We modeled resource selection of eagles and siting of wind turbines by relating locational data to underlying topographic variables that potentially influence fine scale movement of wind across the landscape, which is important to both eagles and wind power generation. In each region, we employed a use-available design for eagles to generate resource selection functions (RSF) that estimate the relative probability of use based on known use locations and the resources available throughout the study area (Manly 2002). Because wind turbines are stationary, we employed a used or unused design to generate resource selection probability functions (RSPF), which estimate the actual probability of use based on known use locations and known unused locations that were selected at random (Manly 2002).

For eagles, we generated random points along directed correlated random walks (dCRW) (CRW Simulator II, Hawth's Tools (Beyer 2004)) to represent available habitat. For wind turbines, we used FAA database locations of turbines for the used data and generated random points that did not overlap with used locations. Detailed descriptions of the methods for generating random locations are included in Supporting Information.

We separated our data into training and test data; 75% of the points were used to create the models and 25% of the points were used to validate the models. We separated the data by randomly selecting 25% of the used eagle points and 25% of both the used and unused turbine points; the random selections were stratified among individuals and facilities.

We calculated a correlation matrix for all variables in each region for eagles and turbines with the training data. We removed variables with a Pearson correlation >0.5. We used logistic generalized estimating equations with an independence correlation structure (GEE, geepack) (Højsgaard et al. 2005) (R version 2.13) (R Development Core Team 2011) to determine resource selection. We calculated full models with the remaining uncorrelated variables and two-way interactions between each variable. We defined repeated measures within both data sets using individual eagle and individual wind facility. We used backwards stepwise selection, where terms remained in the model when $p < 0.05$. From the final model generated by the GEE, we created spatially

**Table 1. Classification of risk of migrating Golden Eagles encountering and being affected by wind turbines.**

| *Level of risk* | *Risk class*[a] | *Eagle resource selection class* | *Turbine resource selection class* |
|---|---|---|---|
| Low | 1 | poor | poor |
| Low | 2 | poor | fair—excellent |
| Moderate—extreme | 3 | fair—excellent | poor |
| Moderate | 4 | fair | fair—excellent |
| High | 5 | good | fair—excellent |
| Extreme | 6 | excellent | fair—excellent |

[a] *Classes based on Golden Eagle and wind energy resource selection.*

explicit RSF models for eagles and RSPF models for turbines (ArcInfo 10, ESRI, Redlands, CA, USA) (Manly 2002).

To account for model uncertainty, we reclassified the continuous turbine and eagle models into 4 bins representing poor, fair, good, and excellent habitat. We reclassified the eagle models and used the training data as a guide for breakpoints. We broke the RSF values for the training data into 4 classes, where class 1 contained 10% of the training points, class 2 contained the next 15%, class 3 contained 25%, and class 4 contained the remaining 45% of the training points. We then used these values to reclassify the spatial RSF models into the 4 bins. Because the RSPF turbine models are constrained between 0 and 1, we used equal breaks at 0.25, 0.5, and 0.75 to reclassify the spatial RSPF models into 4 bins.

We validated all models with existing accuracy assessment methods (DeLeo 1993; Fielding & Bell 1997; Johnson et al. 2006). We fully describe the methods and results of the model validation in Supporting Information.

### Assessing Risk

We created risk models for each region by overlaying the eagle and turbine models. We categorized risk of negative interactions into 6 classes of increasing resource selection by eagles, where classes 1–2 are low risk, class 3 is moderate—high risk, class 4 is moderate risk, class 5 is high risk, and class 6 is extreme risk (Table 1).

## Results

We tracked 30 birds, 29 of which crossed more than one topographically distinct region. Fourteen eagles migrated through the Allegheny Mountains region, 18 the Allegheny Plateau, and 24 the Ridge and Valley (Fig. 1). We obtained 37,386 telemetry points during spring migration from 2009 to 2012; of these, 26,681 were in-flight. In the Allegheny Mountains region we used 586 migratory flight points <150 m AGL. There were 1481 similar points in the Allegheny Plateau region, and 2279 in the Ridge and Valley.

There were 43 wind facilities in the study area, 19 in operation and 24 proposed. We modeled 20 facilities with 473 turbines in the Allegheny Mountains, 9 facilities and 383 turbines in the Allegheny Plateau, and 14 facilities and 298 turbines in the Ridge and Valley.

### Resource Selection by Low-Flying Eagles

Eagles selected areas with higher updraft potential in all regions (Table 2). Additional factors influencing movements varied by region. In both the Allegheny Plateau and Ridge and Valley, selection was for higher elevations and south-facing slopes. The final models in the Allegheny Plateau and the Allegheny Mountains contained interactions. In the Allegheny Plateau region updrafts became increasingly important as distance from high quality wind resources increased. In the Allegheny Mountains the interactions showed that eagles selected areas with higher updraft potential along west facing slopes and preferred either northwest slopes or southeast slopes over other orientations.

### Resource Selection for Siting of Wind Turbines

Turbine placement varied with region. In the Allegheny Mountains, placement was in high elevation areas with low updraft potential and westerly aspects (Table 2). Turbine placement in the Allegheny Plateau was much more complicated because there were several interaction terms in the final model. These indicate that placement was associated with high elevation summits with low updraft potential and westerly aspects. In the Ridge and Valley, developers selected high elevation summits away from side slopes in areas with lower updraft potential and southeasterly aspects.

### Risk of Negative Interactions

The intersection of good eagle and wind-power resources occurred along slope edges and narrow ridgetops (Table 2). Risk of negative interactions varied by region and was lowest in the Allegheny Mountains and highest in the Ridge and Valley. The land area suitable for development of wind energy was relatively small (16.4% in Allegheny Mountains, 13.4% in Allegheny Plateau, and 9.1% in Ridge and Valley) (Fig. 2). Conversely, land area suitable for eagle migration was considerably larger (65.4% in Allegheny Mountains, 68.7% in Allegheny Plateau, and 48.4% in Ridge and Valley). However, the global models we created for eagles included all wind directions. The amount of eagle habitat on any given day depends on the specific set of weather conditions on that day; thus, the amount of available habitat is constrained by those conditions.

**Table 2. Results of logistic generalized estimating equation model of resource selection functions of low-altitude flight of Golden Eagles during spring migration and of siting of industrial wind turbines in 3 regions of Pennsylvania, U.S.A.**

| | *Golden Eagles* | | | *Wind energy facilities* | | |
|---|---|---|---|---|---|---|
| *Explanatory variable*[a] | *Allegheny Mountains* $\beta$ *(SE), p*[b] | *Allegheny Plateau* $\beta$ *(SE), p* | *Ridge & Valley* $\beta$ *(SE), p* | *Allegheny Mountains* $\beta$ *(SE), p* | *Allegheny Plateau* $\beta$ *(SE), p* | *Ridge & Valley* $\beta$ *(SE), p* |
| Intercept | −2.36 (0.44), <0.001 | −2.2 (0.35), <0.001 | −3.28 (0.17), <0.001 | −4.42 (0.59), <0.001 | −4.24 (1.05), <0.001 | −4.46 (0.63), <0.001 |
| Elevation | | 0.58 (0.22), 0.009 | 0.9 (0.12), <0.001 | 3.02 (0.62), <0.001 | 2.71 (0.65), <0.001 | 2.05 (0.49), <0.001 |
| Northness | −0.19 (0.14), 0.165 | −0.25 (0.10), 0.016 | −0.22 (0.10), 0.024 | | | −0.83 (0.25), <0.001 |
| Eastness | −0.14 (0.14), 0.330 | | | −0.35 (0.12), 0.004 | 0.45 (0.25), 0.07 | 0.51 (0.23), 0.024 |
| Updraft | 0.62 (0.09), <0.001 | 0.80 (0.08), <0.001 | 0.51 (0.05), <0.001 | 0.07 (0.32), 0.838 | 0.09 (0.38), 0.821 | 0.07 (0.25), 0.791 |
| Wind | | −0.11 (0.21), 0.591 | | | | |
| Side slope | | | | | | 2.76 (0.64), <0.001 |
| Summit | | | | | −2.01 (1.03), 0.05 | −2.62 (0.78), <0.001 |
| Elevation * northness | | | | | | 0.52 (0.14), <0.001 |
| Elevation * eastness | | | | | −0.37 (0.14), 0.007 | |
| Elevation * updraft | | | | −1.01 (0.17), <0.001 | −0.82 (0.33), 0.013 | −1.11 (0.32), <0.001 |
| Elevation * summit | | | | | 2.02 (0.94), 0.031 | |
| Northness * eastness | −0.31 (0.12), 0.011 | | | | | |
| Eastness * updraft | −0.27 (0.09), 0.003 | | | | | |
| Eastness * summit | | | | | −0.50 (0.15), 0.001 | |
| Updraft * wind | | 0.21 (0.11), 0.048 | | | | |
| Updraft * side Slope | | | | | | 1.94 (0.49), <0.001 |
| Updraft * summit | | | | | 2.10 (0.66), 0.002 | |
| | | | Estimated scale parameters | | | |
| Intercept | 0.99 (0.37) | 1.02 (0.90) | 1.03 (1.21) | 0.64 (1.09) | 0.77 (1.73) | 0.50 (0.97) |

[a] *Variable descriptions and sources are listed in Table 1. Variables shown are those included in the final model.*
[b] *Model coefficient estimates of standardized variables.*

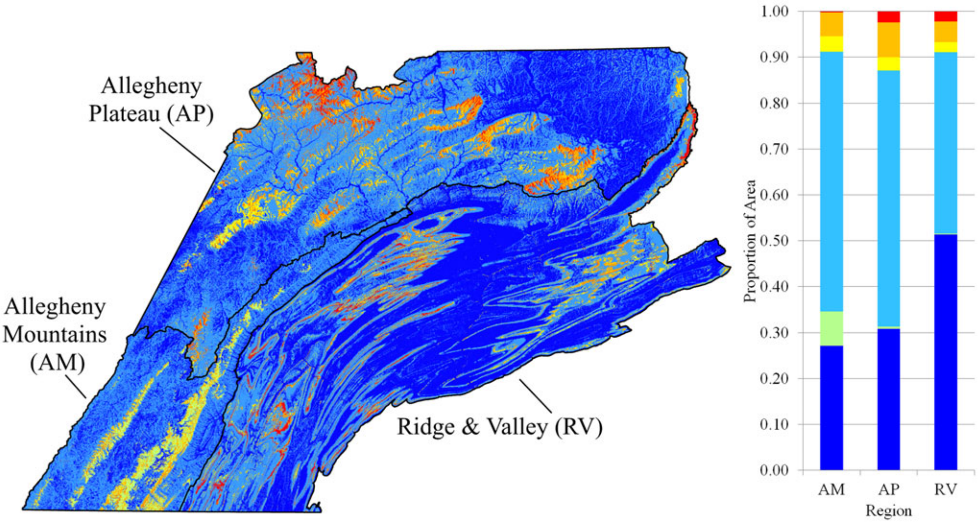


*Figure 2. Risk of Golden Eagles encountering and being affected by wind turbines during spring migration in 3 regions of central Pennsylvania, U.S.A. (dark blue, low risk, low value for eagles and turbines; green, low risk, poor eagle habitat and fair—excellent turbine site; light blue, moderate—extreme risk, fair—excellent eagle habitat and poor turbine site; yellow, moderate risk, fair eagle habitat and fair—excellent turbine site; orange, high risk, good eagle habitat and fair—excellent turbine site; red, extreme risk, excellent eagle habitat and fair—excellent turbine site; AM, Allegheny Mountains; AP, Allegheny Plateau; RV, Ridge and Valley). Graph shows proportion of area within each risk class per region.*

Resource selection by eagles and for wind power overlapped. Nevertheless, the amount of overlap in land area of good eagle habitat and good wind turbine sites was relatively constrained in all 3 regions (risk class 4–6; Allegheny Mountains = 8.8% of total area, Allegheny Plateau = 12.9%, Ridge and Valley = 8.9%). Although 7.5% of the total area of the Allegheny Mountains could be developed with little risk to migratory eagles, only 0.2% of the Ridge and Valley, and 0.5% of the Allegheny Plateau could be similarly developed.

There was spatial variation in risk within each region (Fig. 2). This was most evident in the Ridge and Valley, where the greatest risk occurred along the north-south oriented ridges in the western part of the region; lower risk occurred along northeast-southwest oriented ridges.

Comparison of turbine data and eagle data to the risk model showed the relative risk at each location. Risk from turbines to eagles was higher in the Ridge and Valley and Allegheny Plateau, where most individual eagles used and turbines were sited in the high and extreme risk areas (Table 3, Fig. 2). Overall, 96.6% ($n$ = 29) of the birds we tracked used extreme risk areas (class 6) at least once during the course of migration. Within the Ridge and Valley, 91.7% ($n$ = 22) of birds used high-risk areas (class 5) at least once during migration, and all birds ($n$ = 24) used extreme risk areas (class 6). On the Allegheny Plateau, 61.1% ($n$ = 11) of the individual birds used both high and extreme risk areas at least once. Conversely, in the Allegheny Mountains, only 42.9% ($n$ = 6) of birds used high-risk areas and none used extreme risk areas.

Turbine data showed similar regional patterns. In the Allegheny Plateau, 49.1% ($n$ = 188) of turbines were sited in high-risk areas, and all facilities ($n$ = 9) had at least one turbine in a high-risk area (Table 3). In addition, 23.5% ($n$ = 90) of turbines in 88.9% ($n$ = 8) of the facilities were sited in extreme risk areas. In the Ridge and Valley, 86.7% ($n$ = 8) of the facilities had at least one turbine in high-risk areas, and 52.2% ($n$ = 156) of all turbines were in this risk class. Half as many turbines occurred in extreme risk areas in this region (25.5%, $n$ = 76; 50.0%, $n$ = 7) of the facilities had at least one turbine in the extreme risk class. In contrast, within the Allegheny Mountains region only 18.8% ($n$ = 89) of the turbines from 85.0% ($n$ = 17) of facilities were in high-risk areas and no facilities or turbines occurred in extreme risk areas.

## Discussion

Our models of low-flying Golden Eagles and wind turbines allowed us to estimate, for the first time over a broad geographic scale, risk of negative interactions between wildlife and energy development. This is important because mechanisms are sorely needed to characterize risk to biodiversity in resource extraction processes. Because we modeled overall resource selection rather than specific effects (e.g., collision), our approach provides a context for evaluating both direct and indirect effects at multiple spatial scales. Consequently, our models showed the effectiveness of a comparative

**Table 3. Occurrence and percentage of telemetry points, individual birds, turbines, and wind facilities in each modeled risk class in each region.**

| | Region | n | Risk class[a] 1 | | 2 | | 3 | | 4 | | 5 | | 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Telemetry Points | Allegheny Mts. | 586 | 67 | (11.4) | 14 | (2.4) | 430 | (73.4) | 20 | (3.4) | 55 | (9.4) | - | (0) |
| | Allegheny Plateau | 1481 | 147 | (9.9) | 8 | (0.5) | 1174 | (79.4) | 25 | (1.7) | 98 | (6.6) | 27 | (1.8) |
| | Ridge & Valley | 2279 | 205 | (9.0) | 1 | (0) | 1584 | (69.5) | 25 | (1.1) | 167 | (7.3) | 296 | (13) |
| Birds | Allegheny Mts. | 14 | 14 | (100) | 7 | (50) | 14 | (100) | 5 | (35.7) | 6 | (42.9) | - | (0) |
| | Allegheny Plateau | 18 | 16 | (88.9) | 5 | (27.8) | 18 | (100) | 8 | (44.4) | 11 | (61.1) | 11 | (61.1) |
| | Ridge & Valley | 24 | 20 | (83.3) | 1 | (4.2) | 24 | (100) | 9 | (37.5) | 22 | (91.7) | 24 | (100) |
| Turbines | Allegheny Mts. | 473 | 10 | (2.1) | 265 | (56.0) | 24 | (5.1) | 85 | (18.0) | 89 | (18.8) | - | (0) |
| | Allegheny Plateau | 383 | 13 | (3.4) | 19 | (5.0) | 25 | (6.5) | 48 | (12.5) | 188 | (49.1) | 90 | (23.5) |
| | Ridge & Valley | 298 | 1 | (0.3) | 3 | (1.0) | 18 | (6) | 45 | (14.8) | 156 | (52.3) | 76 | (25.5) |
| Facilities | Allegheny Mts. | 20 | 7 | (35.0) | 20 | (100) | 9 | (45.0) | 18 | (90.0) | 17 | (85.0) | - | (0) |
| | Allegheny Plateau | 9 | 2 | (22.2) | 2 | (22.2) | 6 | (66.7) | 5 | (55.6) | 9 | (100) | 8 | (88.9) |
| | Ridge & Valley | 14 | 1 | (7.1) | 1 | (7.1) | 10 | (71.4) | 10 | (71.4) | 13 | (92.8) | 7 | (50.0) |

[a] *Risk: 1, low risk (low value to eagles and turbines); 2, low risk (poor eagle habitat, fair—excellent turbine site); 3, moderate—extreme risk (fair—excellent eagle habitat, poor turbine site); 4, moderate risk (fair eagle habitat, fair—excellent turbine site); 5, high risk (good eagle habitat, fair—excellent turbine site); 6, extreme risk (excellent eagle habitat, fair—excellent turbine site). Values are occurrences and percentage of total.*

approach to identifying eagle-safe avenues for wind energy development. They would also be useful at a site level—to prevent and mitigate negative energy-wildlife interactions—or at a regional level—to identify broadly where energy development poses relatively high and low risk to wildlife.

### Resource Selection by Low-Flying Eagles

Eagles and other soaring birds minimize the energetic costs of migration by seeking out updrafts to subsidize flight (Katzner et al. 2012*b*). Our models showed that low-flying eagles consistently selected areas of high updraft potential. When in these areas, eagles are likely using orographic lift—updrafts created when horizontally moving wind is deflected by terrain—to subsidize flight (Kerlinger 1989; Duerr et al. 2012; Lanzone et al. 2012). South-facing slopes, which deflect south winds and generate springtime thermals, were associated with low altitude flight in all regions except the Allegheny Mountains. However, because eagles select resources based on the weather conditions they experience when flying, other topographic resources also are important for migration. In a variable meteorological environment the location of the best lift, and thus the location of the greatest risk, depends on the shape and roughness of the terrain (Reichmann 1978).

### Selecting Sites for Wind Turbines

To optimize energy production in the Appalachian Mountains, turbine placement tends to be at higher elevations, where wind flow is smooth and unobstructed. However, all models of turbine placement were highly complex with multiple interaction terms; thus, siting turbines may be driven by a suite of characteristics. Our results suggest that distance to good wind resources as described by NREL was not associated with turbine placement. This may be a result of the fine scale at which we modeled turbine placement and the relatively large scale of the public wind resource data. Indeed, commercial developers always place meteorological towers at sites prior to development to hone fine scale turbine placement.

The high accuracy of our models suggests that in lieu of proprietary wind data that developers are unlikely to share, topography is a useful proxy to estimate turbine placement. Nevertheless, models that include such proprietary data would almost certainly be even more useful to developers to understand the risk to eagles at a specific facility.

### Regional Risk to Eagles

Our models suggest that wind developments in the Allegheny Mountains would, on average, pose lower risk to eagles during spring migration than developments in other regions. Furthermore, the limited resource overlap there suggests lower regional risk and greater opportunities for mitigation by moving high-risk turbines short distances. In contrast, overlap was higher in the Allegheny Plateau and the Ridge and Valley, and there were fewer low-risk options for development. The Ridge and Valley is of particular interest because although it is mainly composed of 2 primary landform types—long, linear ridges, and valleys—there is great within-region variability in risk. Our model results implied that turbines along the north-south ridges pose greater risk to spring migratory eagles than turbines along the northeast-southwest oriented ridges. This is likely because spring migrants move almost directly north along these ridges until they reach the Allegheny Plateau, where their migration proceeds north-northeast. Our model does not

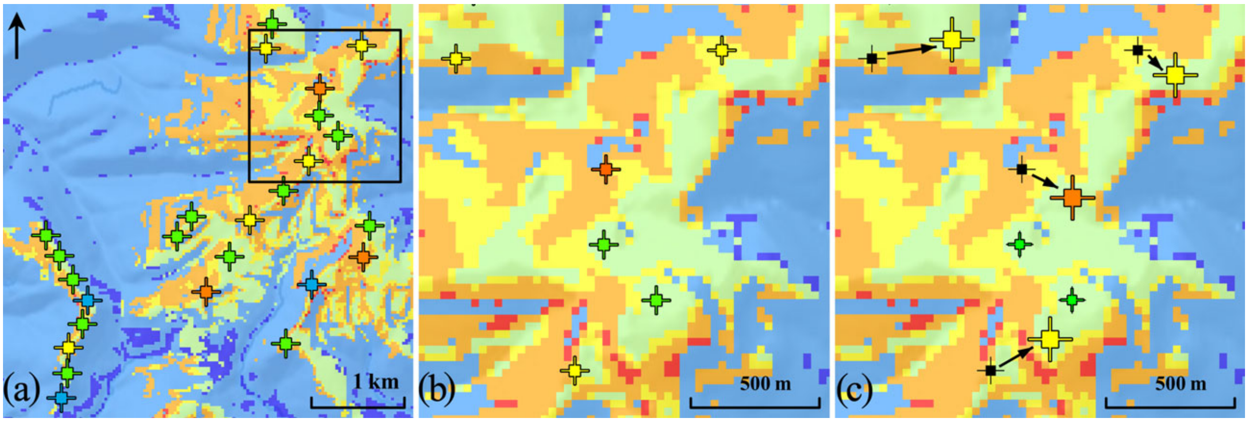


*Figure 3. For a wind-energy facility in southwestern Pennsylvania, U.S.A. (a) location of all turbines in the facility and the associated risk of Golden Eagles encountering and being affected by each, (b) a detailed view of turbines and risk model, (c) application of the model to reduce risk by moving turbines to low-risk areas that still have potential for wind energy development, where enlarged symbols show proposed locations in adjacent low-risk areas (color of turbine symbols and underlying layer corresponds to risk class: dark blue, low risk, low value for eagles and turbines; green, low risk, poor eagle habitat and fair—excellent turbine site; light blue, moderate—extreme risk, fair—excellent eagle habitat and poor turbine site; yellow, moderate risk, fair eagle habitat and fair—excellent turbine site; orange, high risk, good eagle habitat and fair—excellent turbine site; red, extreme risk, excellent eagle habitat and fair—excellent turbine site; black symbols, original proposed locations of wind turbines).*

consider southbound autumn migration when prevailing synoptic weather patterns push eagles to eastern ridges (Kerlinger 1989), and our model may therefore underestimate risk to birds on these ridges during autumn.

The implication of our findings is that we can reduce the risk of negative wind-wildlife interactions by broadly avoiding development where good quality habitat for eagles and good resources for wind turbines overlap. While application of tools such as these is of critical importance for protection of natural resources, the existing frameworks for this process are limited in scope and broad utility (Braunisch et al. 2011). Although our data are from wind energy developments and evaluate risk to one species (Golden Eagles), the conceptual framework we developed can be broadly applied to evaluate risk from any development process to any species or suite of species and to suggest avenues for minimization of that risk.

### Site Level Prediction and Minimization of Risk

Preconstruction model assessments can reduce risk if they are used to guide siting of individual high-risk turbines into adjacent yet lower risk areas. Moreover, post-construction mitigation is also possible by shutting down particularly high-risk turbines during periods when eagles occur with highest frequency (in this region migration generally occurs from late Feb to mid-Apr and late Oct to early Dec). We provide an example of such risk prevention in the Allegheny Mountain region (Fig. 3a), where 32% ($n = 8$) of the proposed turbines are relatively high risk (i.e., they fall in risk classes 4 and 5). The center string has 6 out of 13 turbines in high-risk zones (Fig. 3a). By overlaying the risk model and the turbines, our model identified adjacent lower risk turbine locations predicted to minimally alter energy generation potential (Fig. 3c) and to lower risk to migrating Golden Eagles.

### Implications for Management and Development

Spatial comparison of competing resource selection models is a conceptual way to understand risk across multiple spatial scales. This ecologically based approach is flexible because it allows the use of other types of predictive resource selection models, including wind tunnel simulations (De Lucas et al. 2012). Moreover, it allows biologists and energy developers to visualize and quantify overlaps in resource selection among competing groups and to identify mechanisms to reduce competitive interactions and thus risk to wildlife and to industry. Risk abatement that balances competing ecological and industrial goals is an important step toward safer development of all types of energy and economic growth and it may allow developers to analyze economic viability of projects. As is the case for any development, once a wind plant is built it is economically impractical to decommission problem turbines even if wildlife mortality is high (Smallwood & Karas 2009). Thus, effective prediction of direct and indirect effects is critical. Furthermore, in the case of wind energy, there are few mandatory state-level guidelines for compensatory mitigation. It is, therefore, important to encourage industry compliance with voluntary wildlife guidelines through economically viable tools. An important next step for application of our models would be development of very high-resolution models based on finer-scale elevation data and industrial-quality, proprietary wind maps, and siting plans for individual sites. This would allow developers and land managers to make the best possible and most scientifically informed decisions about turbine placement.

An ultimate goal to minimize risk to wildlife and industry would be to combine models for all high-risk species throughout the annual cycle in conjunction with a suite of energy development activities including oil and gas development, pipeline, road, or electric transmission line placement. Such a framework would allow parameterization of the long-term sustainability of human actions across a broad spatial and temporal scale and quantitative characterization of the true impacts of economically essential activities on biodiversity.

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## Supporting Information

Detailed information on the methods and results of model assessment (Appendix S1) are available online. The authors are solely responsible for the content and functionality of materials. Queries (other than absence of the material) should be directed to the corresponding author.

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