Quantifying Turbine-Level Risk to Golden Eagles Using a High-Fidelity Updraft Model and a Stochastic Behavioral Model

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Risk to Eagles from Wind Power Plants

Eagles are protected species under:

- Bald and Golden Eagle Protection Act
- Migratory Bird Treaty Act.

Eagles face increased risk of turbine collision:

- Obligate soaring birds and reliance on updrafts
- Low-altitude flapping flight during hunting
- Overlap between wind resource and eagle habitat.

Golden Eagles at Top of the World wind power plant near Casper, Wyoming

Problem Statement

Existing tools to estimate risk to eagles are:

- Not generalizable across wind power plants
- Based on simplified atmospheric conditions
- Do not quantify explicit eagle behavior
- Requires prohibitive localized sampling.

Need a predictive eagle behavior model that exploits:

- High-fidelity atmospheric modeling
- Modern machine learning and probabilistic tools
- Extensive eagle telemetry and fatality data
- Increasing knowledge and literature in eagle biology.

Research Objective

Goal: Construct, implement, and validate an **eagle behavior model** that is:

- **Predictive**: Simulates eagle path given a set of atmospheric and eagle-centric conditions
- **Probabilistic**: Quantifies uncertainties to produce stochastic eagle risk maps
- **Generalizable**: Predicts eagle behavior across wind power plants and eagle species
- **Microscale**: Generates turbine-level eagle tracks and presence/risk maps.

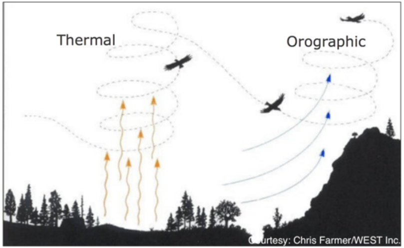
Intended model usage:

- Guide future wind power plant siting and smart curtailment strategies
- Design tailored curtailment strategies for existing wind power plants
- Implement real-time eagle path prediction and turbine control

Major Factors Affecting Eagle Behavior

Measurable factors:

- Orographic updraft (deflected by terrain features)
- Thermal updraft (caused by differential heating of ground)
- Ground cover (sagebrush/grass/forests/paved)
- Season and time of the day
- Prey distribution
- Vicinity to nest



Unmeasurable factors:

- Eagle activity (hunting/perching/migrating/following others)
- Eagle-to-eagle interaction.

Current State-of-the-Art in Turbine-Level Eagle Presence Mapping

- **The fluid-flow model**: Simulate eagle tracks based on fluid-flow principle of minimizing energy expenditure given a field of hydraulic conductivity[1,2]:

$$\underbrace{q_s}_{\text{Flux velocity}} = \underbrace{K}_{\text{Ease of movement}} \times \underbrace{\delta h/\delta s}_{\text{Directional energy gradient}} \tag{1}$$

- Conductivity K is chosen to be a parameterized orographic updraft estimate w_o computed using wind speed (v), wind direction (α), terrain slope (θ), and terrain aspect (β) as[2]:

$$w_o = v \sin(\theta) \cos(\alpha - \beta) \tag{2}$$

- Idea is analogous to:
  - Darcy's law in flow through porous medium
  - Fourier's law in heat conduction
  - Ohm's law in electrical networks
  - Fick's law in diffusion theory.

[1] Brandes and Ombalski, "Modeling Raptor Migration Pathways Using a Fluid-Flow Analogy," The Journal of Raptor Research (2004).
[2] Bohrer et al., "Estimating Updraft Velocity Components Over Large Spatial Scales: Contrasting Migration Strategies of Golden Eagles and Turkey Vultures," Ecology Letters (2012).

The Fluid-Flow Model: Proposed Extensions

The proposed extensions include:

- Stochastic eagle flight path generation (eagles initiated from same point take different paths)
- Spatiotemporal variation in atmospheric conditions (2 km$\times$2 km, hourly)
- Uncertainty in atmospheric conditions (simulating eagles for several instances of time/day/year)
- Variation in eagle entry point in the domain (initiating large number of eagles far from turbines)
- Seasonal variation in atmospheric conditions and migratory behavior (spring vs. fall migration)
- Producing turbine-level eagle tracks and presence maps (50-m resolution).

Using only the publicly available data sets:

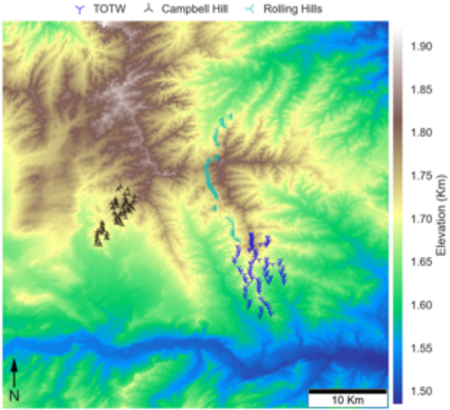
- National Renewable Energy Laboratory's (NREL) Wind Integration National Dataset (WIND) Toolkit[1] for atmospheric variables
- National Aeronautics and Space Administration's (NASA's) Shuttle Radar Topography Mission (SRTM) data set for topographical data

[1] Draxl et al., "The Wind Integration National Dataset (WIND) Toolkit," Applied Energy (2015).

Application to Top of the World Wind Power Plant

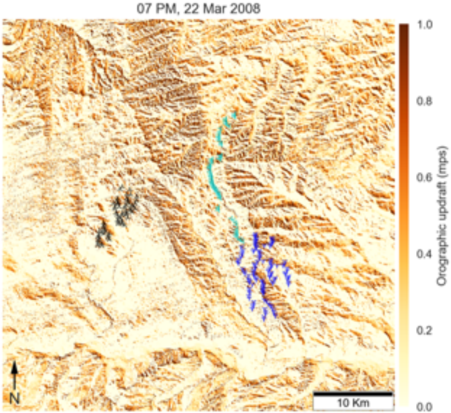
50-km by 50-km domain with 50-m resolution (extracted from NASA's SRTM data set)

- History of eagle fatalities
- Fatality and telemetry data available.

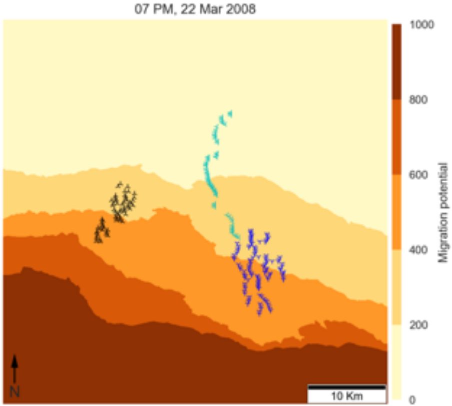


Northerly Migration in Spring

Focusing solely on migratory eagles relying on orographic updrafts!



Orographic updraft w_o computed using wind conditions at 100-m AGL

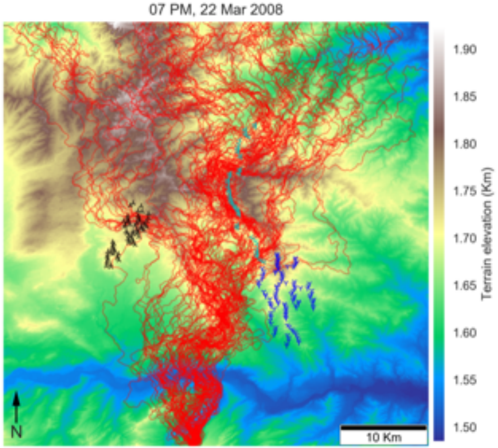


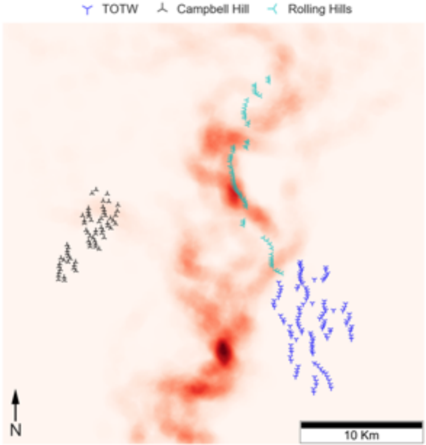
Energy h represents the migration intent (eagle moves from high to low values)

Stochastic Presence Map for a Given Entry Point

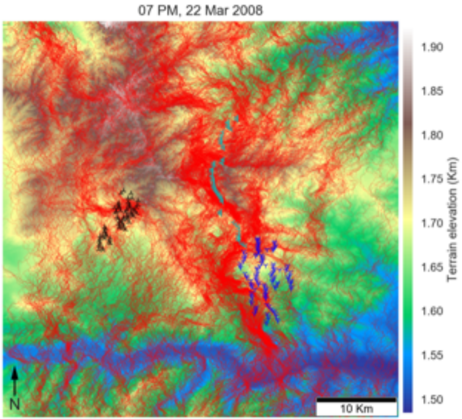
100 virtual eagles initiated from the middle of southern boundary. At each step:

- Eagles are provided with a set of probabilities associated with the eight moves.
- Eagles remember the last two moves when making a decision about the next move.

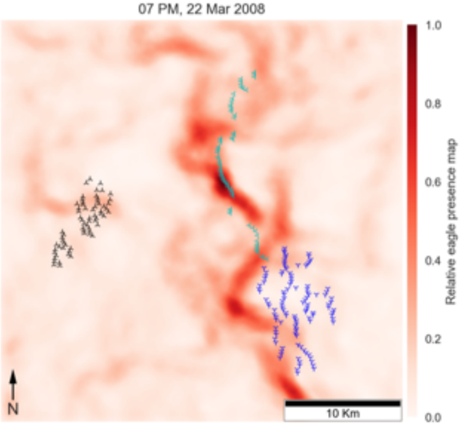




Stochastic Presence Map Irrespective of Entry Point



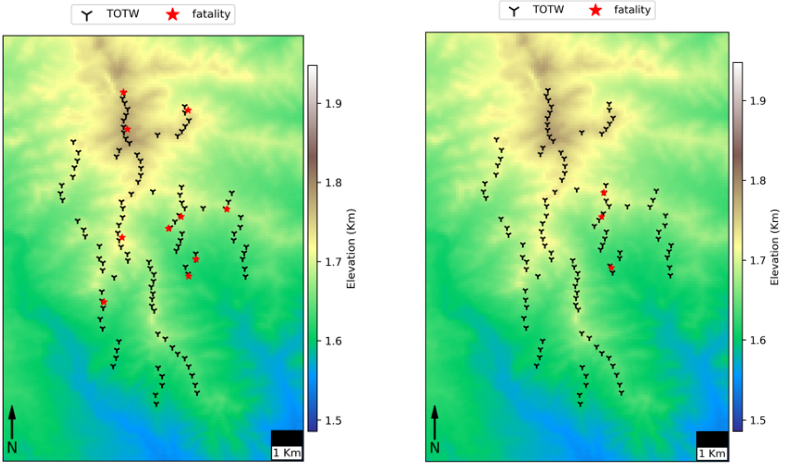
900 virtual eagles initiated equally distanced from southern boundary



Presence map irrespective of entry point at the southern boundary

Observed Golden Eagle Fatalities at Top of the World

Spring vs. fall (data for 2014–2019): More fatalities in spring than fall!



Spring

Fall

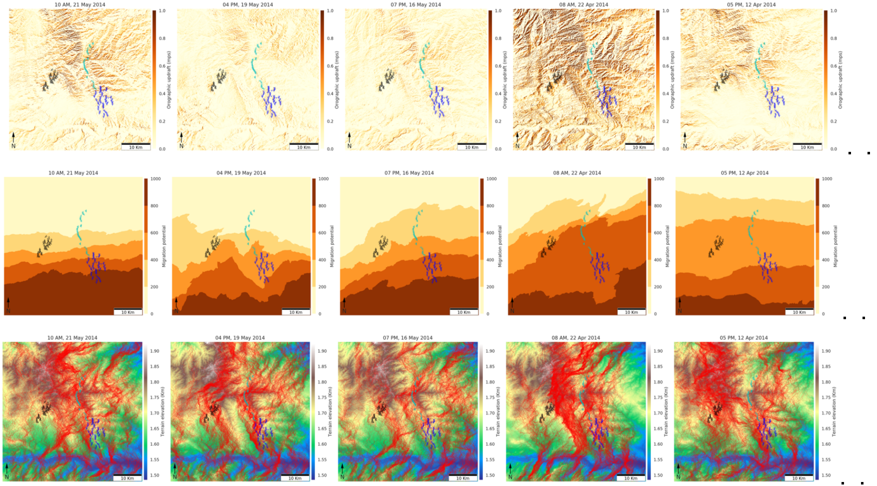
Seasonal Eagle Presence Map for Spring

100 randomly selected atmospheric conditions for time frame: 6 a.m.–8 p.m., March–May, 2007–2014

Updraft:

Energy:

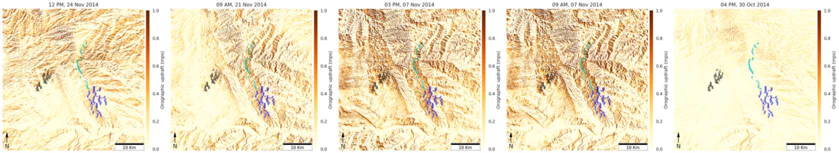
Tracks:



Seasonal Eagle Presence Map for Fall

100 randomly selected atmospheric conditions for time frame: 6 a.m.–8 p.m., Sept–Nov, 2007–2014

Updraft:



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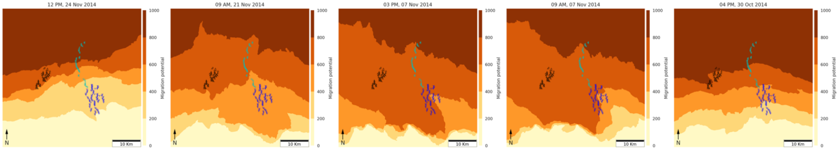
Energy:



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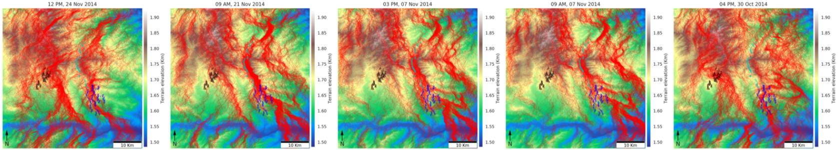
Tracks:



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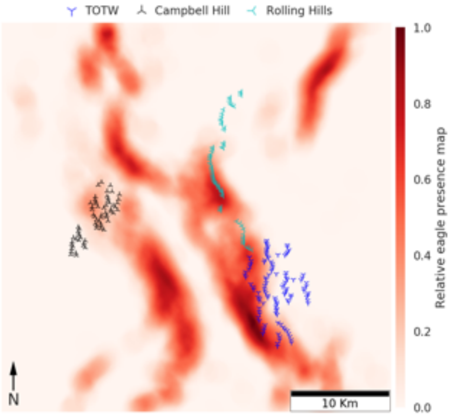
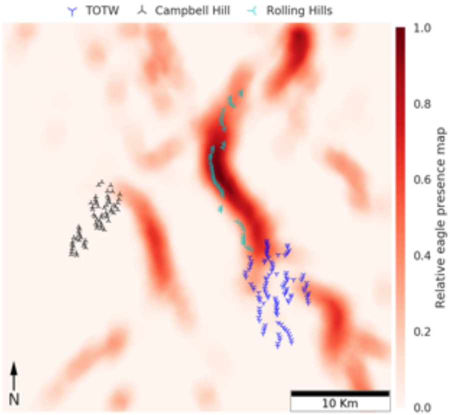
Summarized Seasonal Presence Map: Spring vs. Fall



Spring



Fall

More eagle presence in spring than fall at Top of the World!

Summary and next steps

Summary so far:

- Incorporated uncertainty in wind conditions, eagle decision making, and entry point into the domain
- Implemented the model at 50-m resolution to ensure turbine-level presence mapping
- Employed high-performance computing to ensure scalable simulation of thousands of virtual eagles
- Model employs only the publicly available data, ensuring broader appeal of the predictive tool.

Next steps:

- Exploiting high-fidelity atmospheric modeling data to further refine the model output (in progress)
- Inclusion of thermal updrafts into eagle decision making (in progress)
- Transition between the use of thermal vs orographic updrafts depending on eagle intent
- Use of eagle telemetry data to extend the model for other factors affecting eagle behavior.

Thank you

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