Strategic Habitat Selection for Reintroduction of Endangered Species

Angel Gantzia (angel_g@mit.edu)
Sasha Lioutikova (lioutik@mit.edu)

15.093 Optimization Methods
December 8, 2023

1 Problem Overview

In the World Wildlife Fund Living Planet Report of 2022 [1], a sobering analysis reveals that global biodiversity is facing unprecedented threats, with numerous animal species edging perilously close to extinction. This decline in biodiversity, notably due to human-induced habitat destruction and climate change, necessitates innovative conservation strategies. Thus, to counter this trend, we will use optimization techniques to aid the successful reintroduction of species by evaluating the suitability of potential release sites within U.S. National Parks. This approach aims to promote natural population growth and enhance conservation efforts for the endangered species in question.

In our focused case study, we examine the reintroduction of the Thick-billed parrot to the United States. This medium-sized parrot was once native to the southwest United States, one of the few exotic birds to have been native to the country. However, largely due to illegal hunting, there has been a local extinction of the parrot. The species is now native to Mexico, with its estimated wild population in 2018 being just 1700 parrots. Past failed reintroduction attempts to the United States in the '80s had been hindered by high predation and poor release strategies. Since 2005, the Arizona Game and Fish department has also worked with counterparts in Mexico on further reintroduction attempts, with little success. [2]

Utilizing optimization techniques, we aim to enhance the likelihood of success by selecting habitats that offer natural protections against predators and support the bird's behaviors and biological requirements and preferences, providing a stronger foundation for their survival and population growth. This approach will involve binary decision variables for site selection, where the selected site must offer a favorable climate, minimal predatory risks, and ample food supply for the Thick-billed parrot. We will compare the performance of the U.S. National Parks with the parrot's current habitat, the Sierra Madre Occidental in Mexico, and with the previous attempted relocation site, the Madrean Sky Islands in southeastern Arizona.

2 Data

This study requires environmental data on potential release sites (U.S. National Parks) and data on the biology and preferences of the Thick-billed parrot to assess compatibility between the bird and the potential release sites. Important location information includes climate (temperature, seasonality), land cover (biome), and flora and fauna distribution; important species data similarly includes environmental requirements (temperature, biome), diet, and potential predators. All of these data streams coalesce to help determine the most viable release sites, ensuring the best possible outcome for the reintroduction initiative. This information, however, is not readily-available in datasets online, and requires extensive manual data collection and scraping. The process of collecting data and formatting it such that it is applicable to optimization formulation proved to be a challenging task.

2.1 U.S. National Park Data

Much of the flora and fauna data of U.S. National Parks is sourced from the Kaggle dataset *Biodiversity in National Parks* [3]. The files in this dataset describe the area and species occurrence (both flora and fauna) in 56 of the 63 U.S. National Parks; more specific information is available in the datasets is described in Table 1 below.

The species dataset was extensively preprocessed to be suitable for optimization modeling. In particular, the final dataframe had one row per park with one-hot encodings of species occurrences, i.e. each column corresponded to a species (e.g. moose) and each entry was 1 if that species occurred in that park, and 0 if it did not.

The parks dataset was enhanced with additional information, including the parks' minimum and maximum elevation, with data scraped from Wikipedia [4]. Park-specific monthly temperature data – specifically average minimum, mean, and maximum temperatures – was scraped from each park's individual Wikipedia page [5] when available, and from nearby weather stations on timeanddate.com

[1] World Wildlife Fund, *Living Planet Report 2022* [2]

[2] Wikipedia, *Thick-billed parrot* [16]

[3] National Park Service, *Biodiversity in National Parks* [5]

[4] Wikipedia, *List of national parks of the United States by elevation* [9]

[5] Wikipedia, *List of national parks of the United States* [8] (For example: *Acadia National Park* [10])

(a) `parks.csv`: Relevant Information

Column	Description	Example
Park Name	Official park name	Acadia
Acres	Size of park in acres	47390
Latitude	Latitude of centroid of park	44.35
Longitude	Longitude of centroid of park	-68.21

(b) `species.csv`: Relevant Information

Column	Description	Example
Park Name	Park in which species occurs	Acadia
Scientific Name	Scientific species name	Alces alces
Common Names	Usual common name(s) for species	Moose
Occurrence	Species presence in park	Present
Abundance	Commonality of sightings	Rare

Table 1: Relevant Information about Datasets

when not available on Wikipedia. Each park's biome information (e.g. desert, grassland, forest) was also researched online via Wikipedia and other sources.

After all data collection and preprocessing, for each park, we have information on flora and fauna occurrence, temperatures, biome, elevations, and area.

2.2 Sierra Madre Occidental and Madrean Sky Islands Data

The two baseline locations – Sierra Madre Occidental in Mexico and the Madrean Sky Islands in Arizona – did not have any readily available datasets online with respect to their geographic, climactic, and species distribution information.

Sierra Madre Occidental's species, biome, and elevation data was scraped from various Wikipedia pages [6] [7] [8] [9] , and its temperature was scraped from timeanddate.com [10].

The Madrean Sky Islands' species data was similarly scraped from the Arizona Wildlife Conservation Strategy website [11], with its biome and elevation data scraped from Wikipedia [12] and its temperature data scraped from timeanddate.com [13].

2.3 Thick-billed parrot Data

Information for the Thick-billed parrot was gathered from various sources, including Wikipedia [14], animalia.bio [15], and parrots.org [16]. The Thick-billed parrot lives in temperate deciduous and coniferous forests at elevations of 1200-3600 meters, and mainly feeds on seeds from various pine species, including Mexican white pine, Douglas fir, Apache pine, Chihuahua pine, and yellow pine. The primary predatory threats to these parrots include raptors, such as the Red-tailed hawk, Apache goshawk, and Peregrine falcon, as well as the Ring-tailed cat. Its preferred temperatures are assumed to be the temperatures in its current location, the Sierra Madre Occidental, which range from 39° F to 86° F.

3 Modeling Methods

While the interactions between a species and its environment are complex, we aim to model how suitable a potential habitat is to house the Thick-billed parrot based on biological and ecological necessities, preferences, and behaviors as best we can with the available data described in Section 2. Below, we walk through the optimization formulation.

[6] Wikipedia, *Sierra Madre Occidental* [14]
[7] Wikipedia, *Sierra Madre Occidental pike-oak forests* [15]
[8] Wikipedia, *Category:Flora of the Sierra Madre Occidental* [12]
[9] Wikipedia, *Category:Fauna of the Sierra Madre Occidental* [11]
[10] Time and Date, *Climate & Weather Averages in Sierra Madre Oriental, Mexico* [7]
[11] Arizona Game and Fish Department, *Madrean Woodlands* [3]
[12] Wikipedia, *Madrean Sky Islands* [13]
[13] Time and Date, Climate & Weather Averages in Paradise, Arizona, USA [6]
[14] Wikipedia, *Thick-billed parrot* [16]
[15] Animalia, *Thick-Billed Parrot* [1]
[16] Lurie, A., & Snyder, N. (2001). Thick-billed Parrots [4]

3.1 Matrices

For the purposes of modeling, define the following data matrices:

- B $\in$ (#sites, 1) where $B_p = 1$ if site p contains the relevant biome, temperate forests;
- TMin $\in$ (#sites, 1) where $TMin_p$ = minimum temperature at site p;
- TMax $\in$ (#sites, 1) where $TMax_p$ = maximum temperature at site p;
- T $\in$ (#sites, #months) where $T_{p,m}$ = average temperature of month m at site p;
- EMin $\in$ (#sites, 1) where $EMin_p$ = minimum elevation at site p;
- EMax $\in$ (#sites, 1) where $EMax_p$ = maximum elevation at site p;
- F $\in$ (#sites, #foods) where $F_{p,i} = 1$ if food item i appears at site p, with more important food items occurring first;
- P $\in$ (#sites, #predators) where $P_{p,j} = 1$ if predator j appears at site p, with more important predators occurring first;
- A $\in$ (#sites, 1) where A_p = area of site p in acres.

Here, we include the Sierra Madre Occidental and the Madrean Sky Islands in the potential release sites, so we have $56 + 2 = 58$ potential release sites.

3.2 Decision Variables

The primary decision variable for this problem is a binary variable that describes whether or not park p is chosen as the selected release site for the Thick-billed parrot:

$$z_p = \begin{cases} 1 & \text{if site } p \text{ is selected,} \\ 0 & \text{otherwise.} \end{cases}$$

This is thus a binary optimization problem.

3.3 Constraints

The hard constraints will model ecological and biological necessities for the Thick-billed parrot's survival, and will support modeling assumptions (e.g. only one release site) and linking constraints (i.e. care about constraints only for park chosen).

One Release Site

For simplicity, we consider only one release site:

$$\sum_{p=1}^{58} z_p = 1$$

i.e. only one z_p may equal 1.

Biome Suitability

The Thick-billed parrot lives in temperate deciduous and coniferous forests; thus, the release site must also contain temperate deciduous and coniferous forests:

$$z_p \leq B_p \quad \forall p = 1, ..., 58$$

If $B_p = 0$, then z_p must equal 0, i.e. if site p does not contain a temperate forest, then it may not be chosen as a release site.

Temperature Extremes

The temperatures at the site must not be too extreme (cold/hot) for the Thick-billed parrot. We model this by requiring the park to not achieve a lower temperature than the minimum temperature in its current environment, and to not achieve a higher temperature than the maximum temperature in its current environment, with a small (10%) cushion on either side of the minimum/maximum tolerated temperatures. Recall from Section 2 that the parrot's assumed temperature range is 39°F to 86°F:

$$\text{Min}_p \geq 39 \cdot 0.9 \cdot z_p \quad \forall p = 1, ..., 58$$

$$z_p \cdot \text{Max}_p \leq 86 \cdot 1.1 \quad \forall p = 1, ..., 58$$

If $z_p = 1$ (site p is chosen), then the minimum temperature of the site must be greater than $39 \cdot 0.9$; if $z_p = 0$, the minimum temperature of the site is unconstrained (we assume nonnegative minimum temperatures here). Similarly, if $z_p = 1$ (site p is chosen), then the maximum temperature of the site must be less than than $86 \cdot 1.1$; if $z_p = 0$, the maximum temperature of the site is unconstrained ($0 \leq 86 \cdot 1.1$).

Elevation Range

Recall from Section 2 that the Thick-billed parrot lives at elevations from 1200 to 3600 meters. We require that the site contains at least some of this range of elevations:

$$z_p \cdot (\min\{3900, \text{EMax}_p\} - \max\{1200, \text{EMin}_p\}) \geq 0 \quad \forall p = 1, ..., 58$$

This constraint calculates the size of the intersection of the ranges of elevations of the site and of the Thick-billed parrot, and requires that it is greater than or equal to 0. For example, if the park has a range of elevations [2000, 4000], then the intersection between $[2000, 4000]$ and $[1200, 3900]$ is $[2000, 3900] = [\max\{1200, 4000\}, \min\{3900, 4000\}]$, the size of which is $3900 - 2000 = 1900$. Again we multiply by z_p to make this constraint obsolete if site p is not chosen ($0 \geq 0$).

Food Availability Constraint

The release site must have enough food items that the parrot is known to feed on, including conifer, pine, fir, spruce, bark, willow, pinion pine, oak, juniper, agave, cherry, and invertebrates. We require that at least 3 food items occur in the release site:

$$\sum_{i=1}^{\#\text{important foods}} F_{p,i} \geq 3 \cdot z_p \quad \forall p = 1, ..., 58$$

Predator Scarcity Constraint

The release site must also have low predatory threat to the parrot. Recall from Section 2 that the parrot's main predatory threats include the Red-tailed hawk, Apache goshawk, Peregrine falcon, and Ring-tailed cat. We require that at most 3 of these high-level threats occur in the release site:

$$z_p \cdot \sum_{j=1}^{\#\text{important predators}} P_{p,j} \leq 3 \quad \forall p = 1, ..., 58$$

3.4 Objective Function

The objective of this formulation is to maximize suitability of the environment to the Thick-billed parrot. To model this, we similarly use food/predator occurrences, temperatures, area, and elevations of the potential release sites.

Factors that contribute positively to suitability are food occurrence and area. We reward release sites with more food items. We also reward release sites with larger area in comparison to the bird's current location, the Sierra Madre Occidental.

Factors that contribute negatively to suitability are predator occurrence and temperature deviation. We penalize the objective by the number of predators that occur in the park, and penalize deviation of the release site's average monthly temperatures from the monthly average temperatures realized in the

Sierra Madre Occidental. This will account both for general temperature range, and for seasonality of temperature throughout the months. Note that because these subparts of the objective function (food items, area, predators, temperature) are not in the same units, we scale each subpart to be comparable to every other subpart in terms of importance to survival.

$$\begin{aligned}
\max \sum_{p \in \text{parks}} z_p \cdot \sum_{f \in \text{foods}} F_{p,f} \; - & \qquad \text{food items } (+) \\
\sum_{p \in \text{parks}} z_p \cdot \sum_{t \in \text{threats}} P_{p,t} \; - & \qquad \text{threats } (-) \\
\sum_{p \in \text{parks}} z_p \cdot \sum_{m \in \text{months}} |T_{\text{Sierra},m} - T_{p,m}|/86 \; + & \qquad \text{temperature deviation } (-) \\
\sum_{p \in \text{parks}} z_p \cdot (A_p - A_{\text{Sierra}})/A_{\text{Sierra}} & \qquad \text{area } (+)
\end{aligned}$$

4 Results and Implications

This modeling formulation identifies Yellowstone National Park as the most suitable release site for the Thick-billed parrot with an objective value of 2.12. The Sierra Madre Occidental and Madrean Sky Islands had objective values of -8 and -15 respectively due to their larger imbalances of food sources and predators. Tables 2 and 3 below contain Yellowstone's important characteristics, and how they compare to the Sierra Madre Occidental's (the Thick-billed parrot's current environment) and the Madrean Sky Islands (the previously-attempted release site for the Thick-billed parrot).

Aspect	**Yellowstone**	**Sierra Madre Occidental**	**Madrean Sky Islands**
Food (#important)	23 (8)	18 (10)	12 (8)
Predators (#important)	19 (2)	26 (4)	25 (3)
Biome	Temperate Forests	Temperate Forests	Temperate Forests
Elevation Range (ft)	5250 – 11350	3900 – 10860	1500 – 7250
Area (acres)	2,219,790	55,030,368	2,000,000
Temperature Range (°F)	39 – 94	39 – 86	38 – 93

Table 2: Comparison of Yellowstone, Sierra Madre Occidental, and Madrean Sky Islands

Location	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Yellowstone	47	52	57	62	68	74	79	77	74	66	55	47
Sierra Madre Occidental	55	59	62	67	69	69	67	67	65	62	59	56
Madrean Sky Islands	49	52	58	64	72	81	80	78	75	67	57	49

Table 3: Average Daily Temperatures (°F)

Out of the three locations, Yellowstone houses the greatest number of potential food sources for the parrot (23), including 8 of the 12 particularly important food sources for the parrot. Yellowstone also includes fewer potential predators than the other two locations (19), including only 2 of the 4 current known predators to the parrots. They all contain the correct biome (as is required by our model). Yellowstone has a slightly higher elevation than the Sierra Madre Occidental, and a significantly higher range than the Madrean Sky Islands, though all sites contain appropriate elevation ranges for the parrot (3900 – 12800 ft). The temperature ranges of all sites are similar, as seen in Table 2, but Yellowstone better matches the seasonal temperatures of Sierra Madre Occidental, as seen in Table 3.

Many of the other National Park locations achieved high objective functions due to the high ratio of food items to potential predators (e.g. Hawaii Volcanoes with 28 food items and 2 potential predators; Great Smoky Mountains with 37 food items and 29 predators), but were infeasible in the optimization formulation due to either biome incompatibility (e.g. tropical rain forests, deserts) or due to temperature- or elevation- range incompatibility.

While we cannot, as MBAn students with no expertise in ecology or zoology, officially recommend that the Thick-billed parrot be reintroduced to Yellowstone National Park, this analysis provides a warm-start for discussions concerning the reintroduction of the Thick-billed parrot by analyzing factors of the habitat that are important to the survival and thriving of the parrot. True comparison to the baseline sites would require a carefully-monitored reintroduction to the chosen location(s). This modeling approach can also be applied to other species with different food, predator, temperature, and elevation requirements and preferences, and can ultimately be instrumental in guiding decision makers by recommending optimal (or various feasible) proposed reintroduction sites, enabling species experts to make decisions that are not only informed by quantitative data but also by their qualitative understanding of the species.

5 Limitations

An important limitation of the modeling is the binary nature of the existence of predators and food sources. In a perfect world, these two would be quantified. Furthermore, this model largely relies on the manual collection of data from various sources on each release site and on the Thick-billed parrot itself. This process is tedious and time-consuming, and provides opportunity for inaccurate measurements to sneak into the modeling data, thus rendering the model less useful. This modeling approach is also limited by our knowledge of the environment in U.S. National Parks and of the requirements and preferences of the Thick-billed parrot; perhaps some of our included factors should be weighed more than others, or we are missing vital factors important to its survival. Collaboration with experts in the Thick-billed parrot and in the ecology of U.S. National Parks can help inform which habitat factors are most important and further hone the optimization model.

References

[1] Animalia. Thick-billed parrot, 2023. Available at animalia.bio.

[2] World Wildlife Fund. Living planet report 2022. 2022. Available at wwflpr.org.

[3] Arizona Game and Fish Department. Madrean woodlands, 2023. Available at awcs.azgfd.com.

[4] Snyder N. Lurie, A. Thick-billed parrots, 2001. Available at parrots.org.

[5] National Park Service. Biodiversity in national parks, 2017. Retrieved 11/15/2023 from Kaggle.com.

[6] Time and Date. Climate weather averages in paradise, arizona, usa, 2023. Available at timeanddate.com.

[7] Time and Date. Climate weather averages in sierra madre oriental, mexico, 2023. Available at timeanddate.com.

[8] Wikipedia. List of national parks of the united states, 2022. Available at Wikipedia.com.

[9] Wikipedia. List of national parks of the united states by elevation, 2022. Available at Wikipedia.com.

[10] Wikipedia. Acadia national park, 2023. Available at Wikipedia.com.

[11] Wikipedia. Category:fauna of the sierra madre occidental, 2023. Available at Wikipedia.com.

[12] Wikipedia. Category:flora of the sierra madre occidental, 2023. Available at Wikipedia.com.

[13] Wikipedia. Madrean sky islands, 2023. Available at Wikipedia.com.

[14] Wikipedia. Sierra madre occidental, 2023. Available at Wikipedia.com.

[15] Wikipedia. Sierra madre occidental pike-oak forests, 2023. Available at Wikipedia.com.

[16] Wikipedia. Thick-billed parrot, 2023. Available at Wikipedia.com.