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# How to Predict Nesting Sites?

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## Abstract

How to predict nesting sites? Usually, all we know is the past nesting sites, and the fact that the birds select a site which is optimal for them (in some reasonable sense), but we do not know the exact objective function describing this optimality. In this paper, we propose a way to make predictions in such a situation.

## 1 Formulation of the Biological Problem

We observe nesting sites for a certain bird species. Our goals (see, e.g., [4, 8]) are:

- to analyze which criteria are important for selecting nesting sites, and
- to come up with formulas that would enable us to predict nesting sites.

## 2 Reformulating the Problem in Precise Terms

**General description.** Let  $v_1, \dots, v_n$  be parameters that may influence the selection of the nesting site: e.g., elevation, hydrology, vegetation level, etc. For each geographic location  $\vec{x}$ , we record the values of all these variables  $v_1(\vec{x}), \dots, v_n(\vec{x})$ .

**Main assumption.** We assume that the birds select a nesting site based on the values of (some of) these quantities. Namely, a bird tries to maximize the value of some objective function  $F(v_1, \dots, v_n)$  depending on these values.

**Simplifying assumption.** Let us start with the simplest case, when the objective function is linear, i.e., when

$$F(v_1, \dots, v_n) = \sum_{i=1}^n w_i \cdot v_i \quad (1)$$

for some weights  $w_i$ .

We assume that each year, each of the observed nesting sites  $\vec{x}_j$  has the largest possible value of this objective function among all locations within the corresponding *Voronoi cell*  $C_j$  (see, e.g., [2, 3, 5] and references therein) – i.e., among all locations  $\vec{x}$  which are closer to  $\vec{x}_j$  than to any other nesting location.

Under this assumption, we would like to find the weights  $w_1, \dots, w_n$  that best explain the observed nesting sites.

### 3 Analysis of the Problem

The fact that on the cell  $C_j$ , the linear function (1) attains its largest value at the site  $\vec{x}_j$ , means that

$$\sum_{i=1}^n w_i \cdot v_i(\vec{x}_j) \geq \sum_{i=1}^n w_i \cdot v_i(\vec{x}) \text{ for all } \vec{x} \in C_j.$$

In other words, we should have

$$\vec{w} \cdot \vec{a}(\vec{x}) \stackrel{\text{def}}{=} \sum_{i=1}^n w_i \cdot a_i(\vec{x}) \geq 0, \quad (2)$$

where we denoted  $\vec{w} = (w_1, \dots, w_n)$ ,  $\vec{a}(\vec{x}) = (a_1(\vec{x}), \dots, a_n(\vec{x}))$ , and  $a_i(\vec{x}) \stackrel{\text{def}}{=} v_i(\vec{x}_j) - v_i(\vec{x})$ .

Similarly, we should have  $w \cdot (-a(\vec{x})) \leq 0$  for all  $\vec{x}$ .

### 4 How Can We Solve This Problem?

**This can be reduced to a known problem.** From the mathematical viewpoint, this problem is similar to a *linear discriminant analysis* (see, e.g., [1, 6, 7]), when:

- we have two sets  $A$  and  $B$  and
- we need to select a hyperplane that separates them, i.e., a vector  $\vec{w}$  for which  $\vec{w} \cdot \vec{a} \geq 0$  for all  $a \in A$  and  $\vec{w} \cdot \vec{b} \leq 0$  for all  $b \in B$ .

In our case:

- $A$  is the set of all the vectors  $\vec{a}(\vec{x})$ , and

- $B$  is the set of all the vectors  $-\vec{a}(\vec{x})$ .

**How to solve our problem.** The standard way of solving this problem is to compute the mean  $\vec{\mu}$  of all the vectors  $\vec{a} \in A$ , the covariance matrix  $\Sigma$ , and then to take  $\vec{w} = \Sigma^{-1}\vec{\mu}$ . So, in our case, we should do the following:

- compute all the vectors  $\vec{a}(x)$  with components  $a_i(\vec{x}) = v_i(\vec{x}_j) - v_i(\vec{x})$ , where  $\vec{x} \in C_j$ ; let  $N$  be the total number of such vectors;

- compute the average  $\vec{\mu} = \frac{1}{N} \cdot \sum_{\vec{x}} \vec{a}(\vec{x})$  of these vectors;

- compute the corresponding covariance matrix  $\Sigma$  with components

$$\Sigma_{ik} = \frac{1}{N} \cdot \sum_{\vec{x}} (a_i(\vec{x}) - \mu_i) \cdot (a_k(\vec{x}) - \mu_k); \quad (4)$$

- compute the desired weights as  $\vec{w} = \Sigma^{-1}\vec{\mu}$ , i.e., as a solution to a linear system  $\Sigma\vec{w} = \vec{\mu}$ .

## 5 Auxiliary Question: How Can We Gauge the Quality of the Resulting Prediction

To gauge the quality of the resulting prediction, for each cell  $C_j$ , we compute the location  $\vec{c}_j$  at which the weighted combination  $\vec{w} \cdot \vec{v}(\vec{x})$  attains its maximum. The mean square distance between these predicted nesting sites  $\vec{c}_j$  and the actual nesting sites  $\vec{x}_j$  can serve as a natural measure of prediction accuracy.

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