Ecological Niche Modeling: niche theory and the estimation of ecological niches

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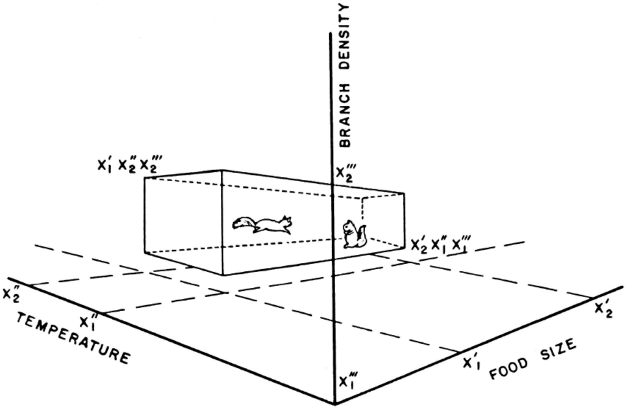
The concept of ecological niche

Three aspects of the ecological niche:

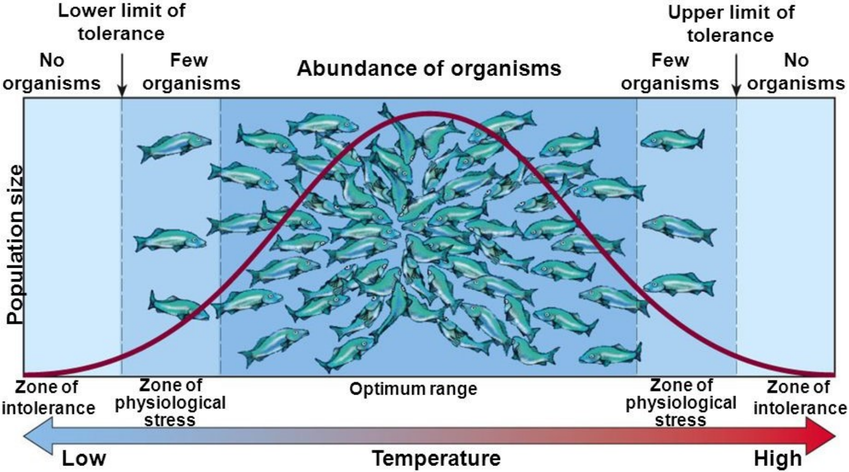
1. **Habitat niche**: Joseph Grinnell (1928) thought of a niche in terms of the space or habitat that a species occupies.
2. **Trophic niche**: Charles Elton (1927) was the first who used the term niche as the "functional status of an organism in its community", emphasizing the importance of energy relations.
3. **Multidimensional or hypervolume niche**: George Evelyn Hutchinson (1957) suggested that a niche could be visualized as a multidimensional set or hypervolume. Within this, the environment permits an individual species to survive indefinitely.

The niche as a hypervolume



Hutchinson, 1973. An Introd. to Population Ecology. Ch.5 What's the niche?

The niche as a response curve and its relation to fitness



The niche as a response curve and its relation to fitness

$$N_F = \{\boldsymbol{x} \in E | \Lambda(\boldsymbol{x}) \geq \lambda_{min}\}, \qquad (1)$$

where

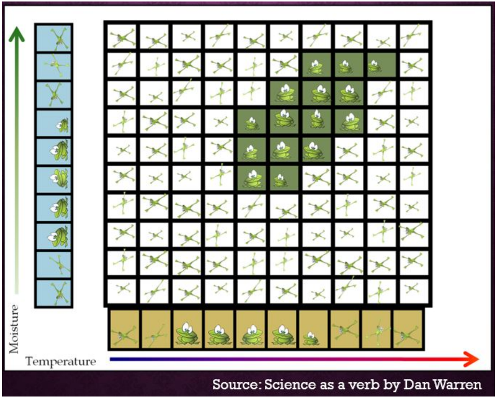
- $E \subseteq \mathbb{R}^d$ is a multidimensional space whose axes are defined by environmental variables relevant to the species of interest,
- the function $\Lambda(\boldsymbol{x})$ relates each environmental combination, $\boldsymbol{x} \in E$ to fitness:

$$\Lambda : E \longrightarrow \mathbb{R},$$

- λ_{min} is the threshold above which the **fitness** is high enough to support a population, therefore, it defines the border of the niche.

Tolerance ranges measured in the lab

- The individuals of a species are expected to evolve physiological adaptations to local environmental conditions.
- Thus, physiological experiments can provide approximations of a species' tolerance to environmental gradients.



Ecological niche modeling approaches

Johnathan M. Chase & Mathew A. Leibold, 2003

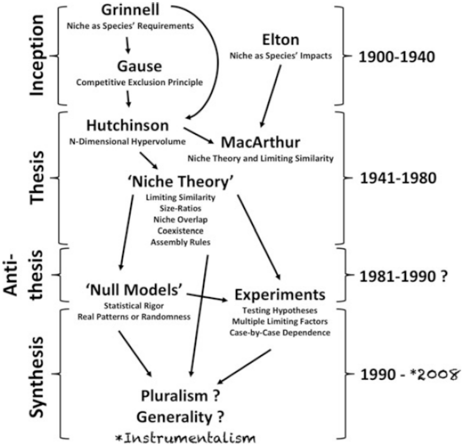
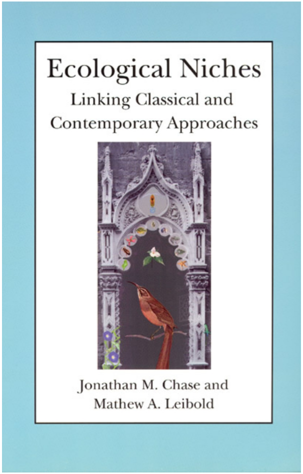


Fig. 1 Evolution of the Niche Concept (Chase and Leibold 2003, redrawn with *addition)

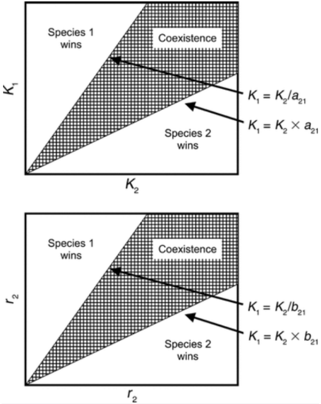
Kineman & Wessman, 2020. Relational systems ecology.



Ecological niche modeling approaches

Johnathan M. Chase & Mathew A. Leibold, 2003

- They proposed to separate the niche of a species into two fundamental units:
- The requirement component of the niche denotes the minimum or maximum level of a particular factor that allows a species to persist in a given habitat.
- The impact component of a species' niche denotes the influence of the species on the niche factor of interest.



Leibold & McPeek, 2006. Ecology.

Ecological niche modeling approaches

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B

Phil. Trans. R. Soc. B (2010) **365**, 3469–3483
doi:10.1098/rstb.2010.0034

Modelling the ecological niche from functional traits

Michael Kearney[1,*], Stephen J. Simpson[2], David Raubenheimer[3] and Brian Helmuth[4]

3474 M. Kearney *et al.* *Modelling the ecological niche*

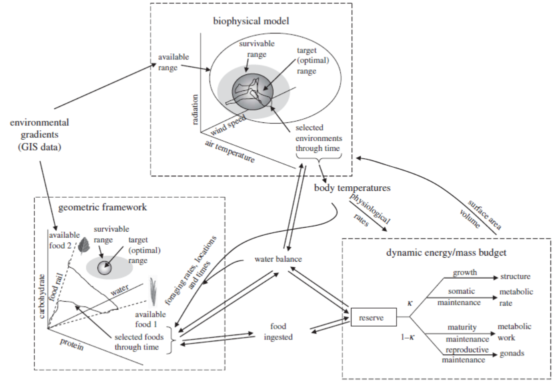


Figure 2. A functional trait-based model of the niche derived by integrating a biophysical model and a nutritional state-space

Ecological niche modeling approaches

Journal of Animal Ecology 2011, **80**, 595–602 doi: 10.1111/j.1365-2656.2011.01806.x

Comparing isotopic niche widths among and within communities: SIBER – Stable Isotope Bayesian Ellipses in R

Andrew L. Jackson[1]*, Richard Inger[2], Andrew C. Parnell[3] and Stuart Bearhop[2]

598 *A. L. Jackson* et al.

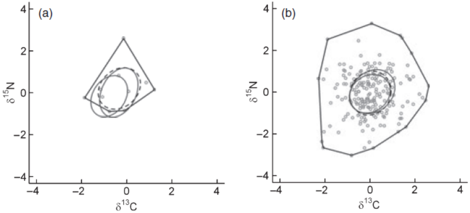


Fig. 2. Samples drawn from the same population (open circles) and their respective convex hulls (solid black lines), frequentist standard ellipses (dotted black lines) and two posterior estimates of the Bayesian standard ellipses (solid grey lines) for (a) $n = 10$ and (b) $n = 200$. The true population standard ellipse for both examples is a circle with radius = 1.

Ecological niche modeling approaches

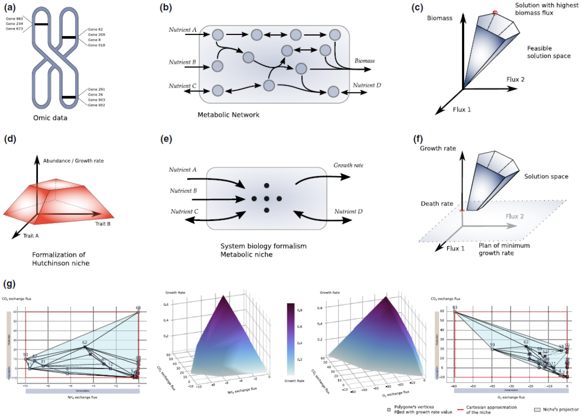
DOI: 10.1111/ele.13954

LETTER

ECOLOGY LETTERS cnrs WILEY

Contribution of genome-scale metabolic modelling to niche theory

Antoine Régimbeau[1] | Marko Budinich[1] | Abdelhalim Larhlimi[1] |
Juan José Pierella Karlusich[2] | Olivier Aumont[3] | Laurent Memery[4] |
Chris Bowler[2,5] | Damien Eveillard[1,5]



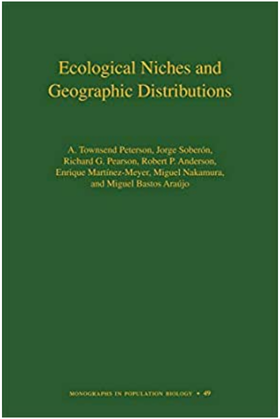
Ecological niche modeling approaches

A. Townsend Peterson, Jorge Soberón, *et al*, 2011

Fundamental niche of a species:

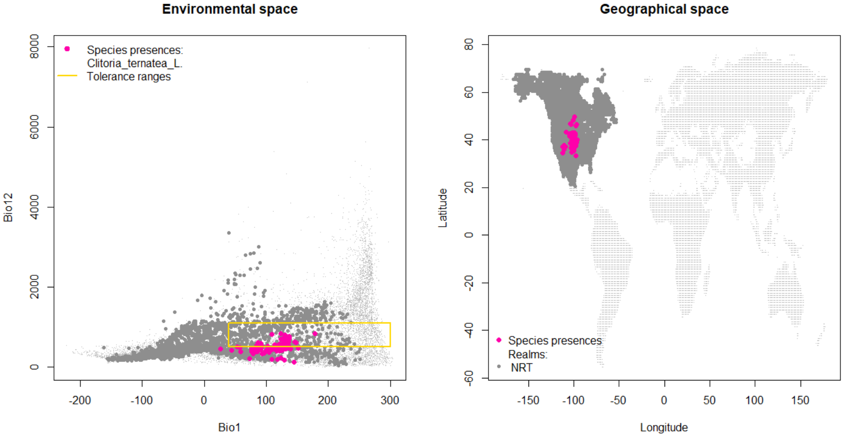
> *"The set of environmental combinations that lead to a positive growth rate for a population of the species under study; leading, at the same time, to the survival of the species"*

Major contribution: BAM diagram

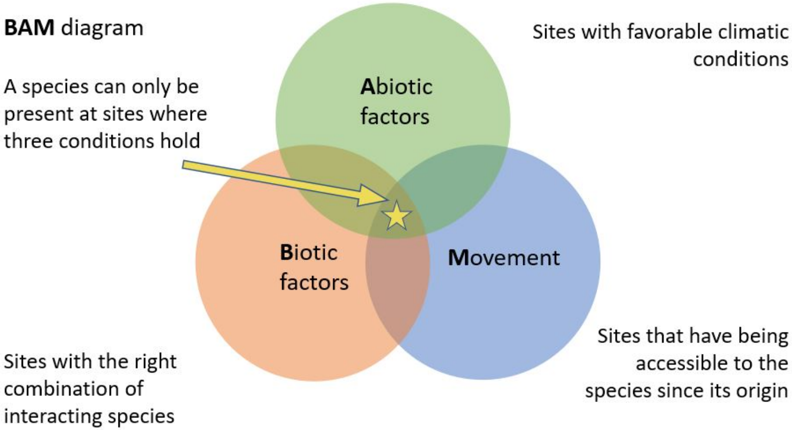


Hutchinson's duality (Colwell & Rangel, 2009)

$$G \longleftrightarrow E\,(t; G)$$
$$(x, y) \longleftrightarrow (e_1, e_2)$$



Factors that limit the geographic range of a species



Note: there are different possible configurations of the BAM diagram.

Presence data

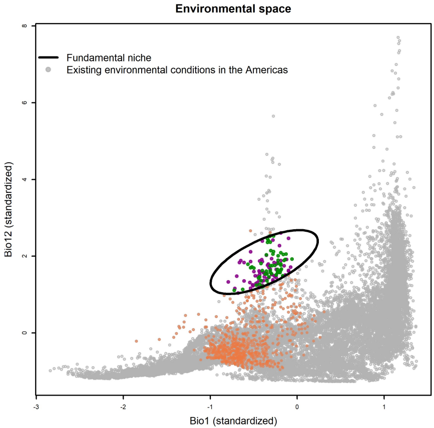
- Surrogate data to estimate niches.
- Obtained from G-space, but the $\boldsymbol{N}_f$ is an object defined in E-space,
- Come from the realized niche, this is, the intersection $A \cap B \cap C$.

Longitude	Latitude	Temperature	Precipitation
x_1	y_1	t_1	p_1
x_2	y_2	t_2	p_2
...	...	...	...
x_n	y_n	t_n	p_n

Relationship between three niche concepts

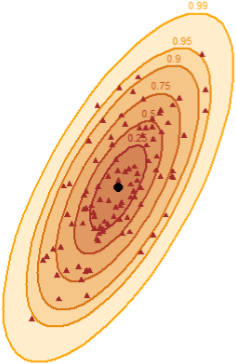
$\boldsymbol{N}_R(t;G) \subseteq \boldsymbol{N}^*(t;G) \subset \boldsymbol{N}_F$

- $\boldsymbol{N}^*(t;G) = N_F \cap E(t;G)$ is the existing niche, a discrete subset of the fundamental niche
- $\boldsymbol{N}_R(t;G)$ is the realized niche, includes dispersal limitations and biotic interactions
- Presence data come from the realized niche!



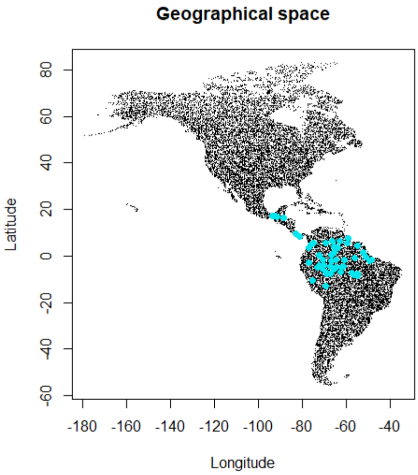
A biologically realistic shape for $\boldsymbol{N}_f$

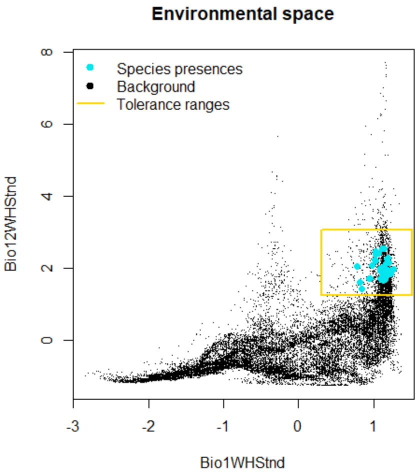
- Main hypothesis: If we have observed the species in two different environmental combinations, then the species should be able to survive in intermediate environmental conditions.
- Implication: The $\boldsymbol{N}_f$ is a convex set in E-space. For instance, an ellipsoid in multivariate space. Remember, Hutchinson assumed a rectangle!



$$f_1(\boldsymbol{x}_i \mid \boldsymbol{\mu}, \Sigma) = (2\pi)^{-d/2} |\Sigma|^{-1/2} \exp[-\frac{1}{2}(\boldsymbol{x}_i - \boldsymbol{\mu})^T \Sigma^{-1} (\boldsymbol{x}_i - \boldsymbol{\mu})]$$

Model 1: combining the information contained in both presence and physiological data





Model 1: Formulation

Suppose that the data consists of n independent occurrences of the species of interest. Let $D = \{\boldsymbol{x}_1, \ldots, \boldsymbol{x}_n\}$ be the set of environmental combinations where the species has been observed, where $\boldsymbol{x}_i$ is a vector of length d:

$$\mathcal{L}\left(\boldsymbol{\mu}, \Sigma | D\right) \propto \prod_{i=1}^{n} \frac{\exp\left[-\frac{1}{2}(\boldsymbol{x}_i - \boldsymbol{\mu})'\Sigma^{-1}(\boldsymbol{x}_i - \boldsymbol{\mu})\right]}{\sum_{\boldsymbol{y} \in E(t;G)} \exp\left[-\frac{1}{2}(\boldsymbol{y} - \boldsymbol{\mu})'\Sigma^{-1}(\boldsymbol{y} - \boldsymbol{\mu})\right]}$$

Parameters of interest: $\boldsymbol{\mu}$ and Σ^{-1}.
Adding *a priori* information given by the tolerance ranges.

$$f(\boldsymbol{\mu}, \Sigma | D, E\left(t; G\right)) \propto \mathcal{L}(\boldsymbol{\mu}, \Sigma | D) g_1(\boldsymbol{\mu}) g_2(\Sigma).$$

Bayesian approach: Specifying the *a priori* distributions

- $\boldsymbol{\mu} \sim N(\boldsymbol{\mu}_0, \Sigma_0)$

$$g_1(\boldsymbol{\mu}) = (2\pi)^{-d/2} |\Sigma_0|^{-1/2} \exp[-\frac{1}{2}(\boldsymbol{\mu} - \boldsymbol{\mu}_0)^T \Sigma_0^{-1}(\boldsymbol{\mu} - \boldsymbol{\mu}_0)]$$

- $\boldsymbol{A} = \Sigma^{-1} \sim Wishart(\alpha, \boldsymbol{W})$

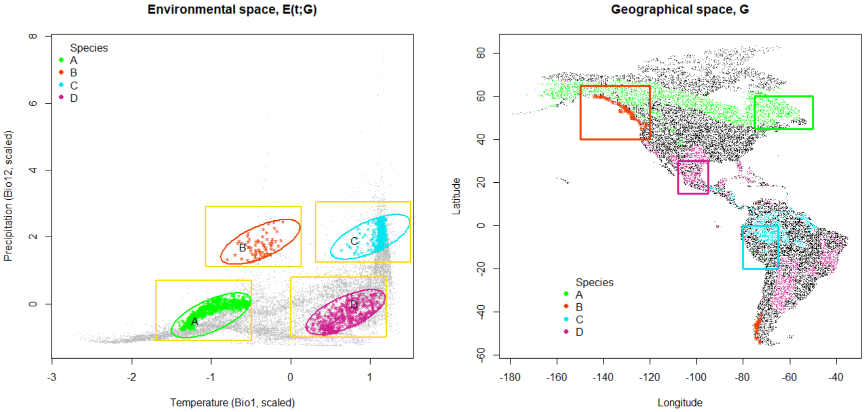
$$g_2(\boldsymbol{A}) = \frac{|\boldsymbol{A}|^{(\alpha-d-1)/2} \, exp[-\frac{1}{2} tr(\boldsymbol{A}\boldsymbol{W}^{-1})]}{2^{\alpha d/2} \pi^{d(d-1)/4} \prod_{i=1}^{d} \Gamma(\frac{\alpha+1-i}{2})}$$

Estimating the mean and variance from the range of a sample, (x_{min}, x_{max}) (Hozo *et al.* 2005):

- $\hat{\boldsymbol{\mu}}_{0,i} = \bar{x}_i \approx \frac{x_{min}+2m+x_{max}}{4}$, where m is the median of sample.
- There is no information regarding the covariances, therefore, we only specify the diagonal of the matrix (using Chebyshev's inequality):

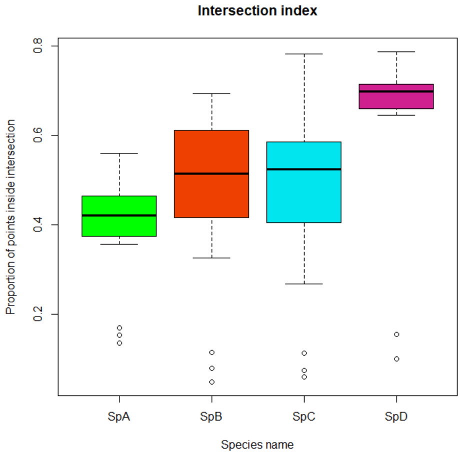
$$\hat{\Sigma}_{0,i} = \frac{x_{max} - x_{min}}{6}.$$

Assessing the model through virtual species



Jiménez *et al*, 2019. On the problem of modeling a fundamental niche from occurrence data. Ecological Modelling 397, 74-83

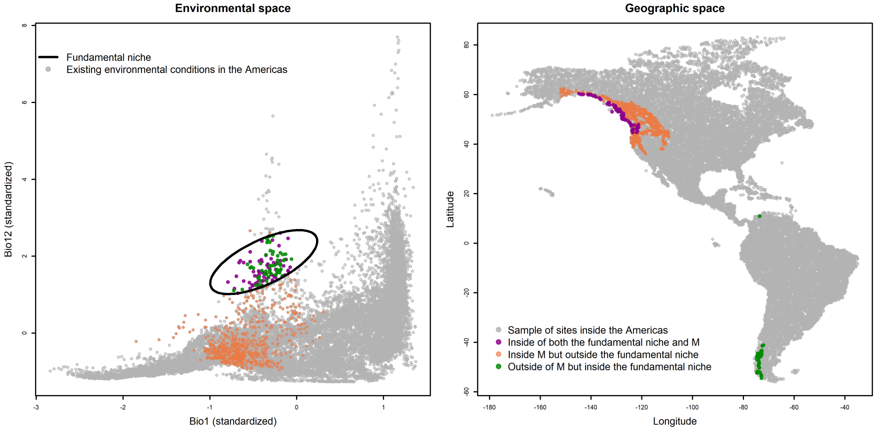
Summary of the results for the virtual species: Overlap between virtual species and results of the model



Jiménez *et al*, 2019. On the problem of modeling a fundamental niche from occurrence data. Ecological Modelling 397, 74-83

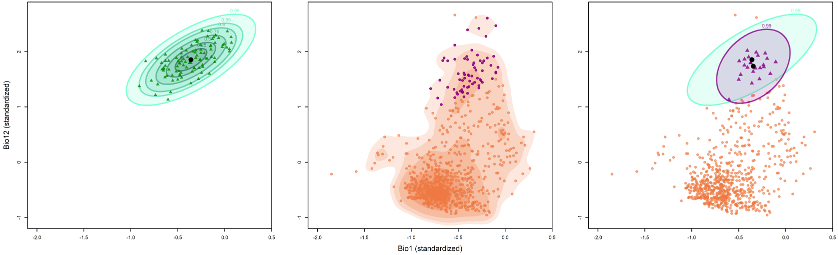
Model 2: Explicit consideration of the shape of M

An implicit assumption of Model 1 is that all the environmental combinations in E-space can be observed. However, we know that $E(t; G)$ has an intricate shape and that not all the environmental combinations exist in G-space.



Two-stage sampling

The random process under which an environmental combination is observed can be described as the result of a two-stage sampling.



Jiménez & Soberón. Estimating the fundamental niche: accounting for the uneven availability of existing climates in the accessible area. *In Prep.*

Model 2: Formulation

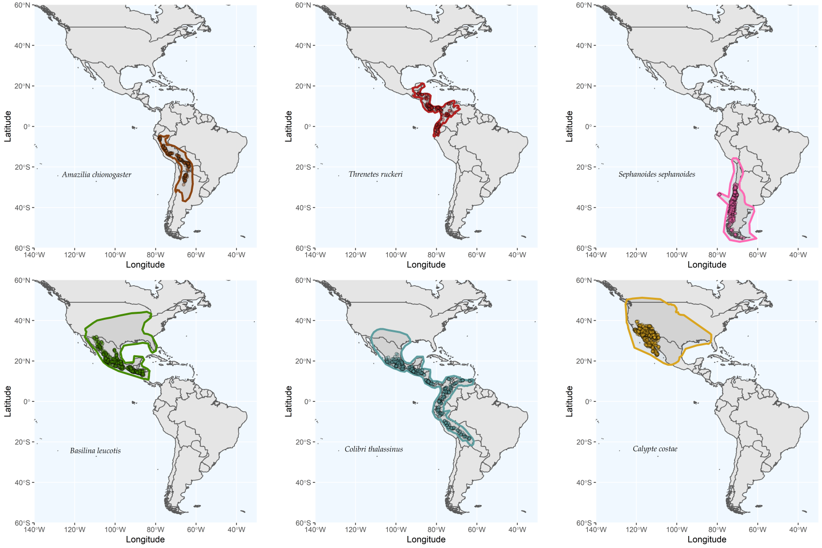
We modify the likelihood to include explicitly the non-uniform properties of the sampling E-space, $E\,(t; G)$.

$$\mathcal{L}\,(\boldsymbol{\mu}, \Sigma | D) \propto \prod_{i=1}^{n} \frac{w(\boldsymbol{x}_i) f_1(\boldsymbol{x}_i; \boldsymbol{\mu}, \Sigma)}{E[w(\boldsymbol{X})]}$$

where

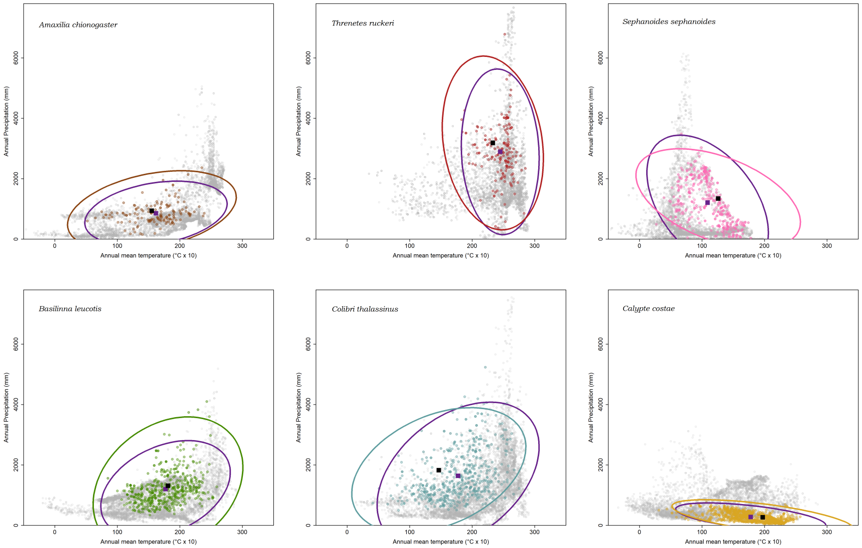
- $w(\boldsymbol{X})$ is a weight function defined by the distribution of environmental combinations that are accessible to the species, which we estimate with a kernel method,
- $E[w(\boldsymbol{X})] = \int w(\boldsymbol{x}) f(\boldsymbol{x}; \boldsymbol{\mu}, \Sigma) dx$,
- $f_1(\cdot; \boldsymbol{\mu}, \Sigma)$ is a multivariate normal distribution.

Worked example: Hummingbirds

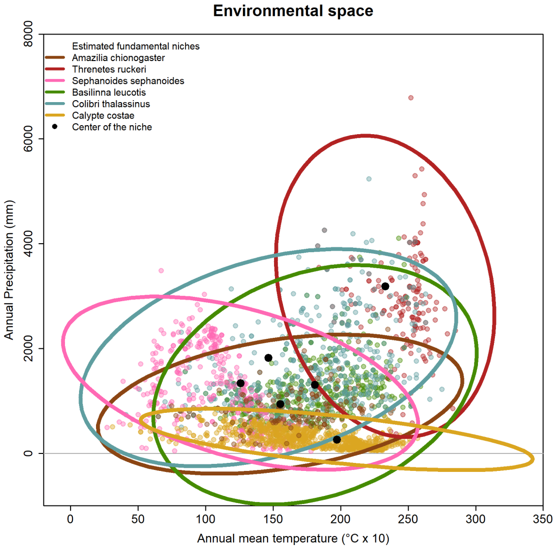


Cooper & Soberón (2017). Global Ecology and Biogeography, 27(1), 156-165.

Worked example: Hummingbirds

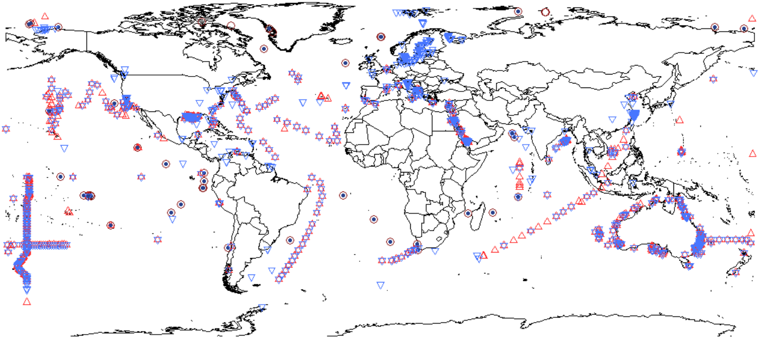


Worked example: Hummingbirds

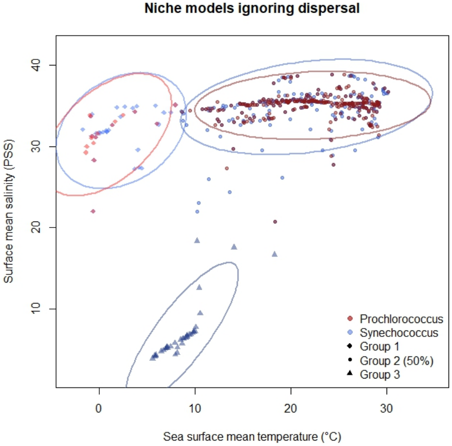


Modeling niches of plankton species

- Prochlorococcus (red) and Synechococcus (blue).
- Combining TARA OCEANS and GBIF data (or other data sources).
- What are the relevant environmental variables to model their niches?



Modeling niches of plankton species



Conclusions

Key aspects of niche modeling approaches:

- The type of variables used to define the niche space.
- How to define the relationship between the data used in the model and fitness.
- The type of constraints included in the model to determine the border of the niche.
- The assumptions about the shape of the response curve to environmental gradients.
- How to assign a suitability value and how to measure niche size.

¡Gracias!

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