Climate Envelopes for Species Distribution Models

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Also: Bob O'Hara (Bik-F Frankfurt), Barbara Anderson (Landcare Research, Otago, NZ) and Ralf Ohlemüller (University of Otago, NZ)

What is a climate envelope?

Scottish Natural Heritage:

> *"the range of climatic conditions within which a species can survive."*

Expressed as a function between response and climate variable(s).

Suitable climatic range can be thought of as part of the species' **ecological niche**.

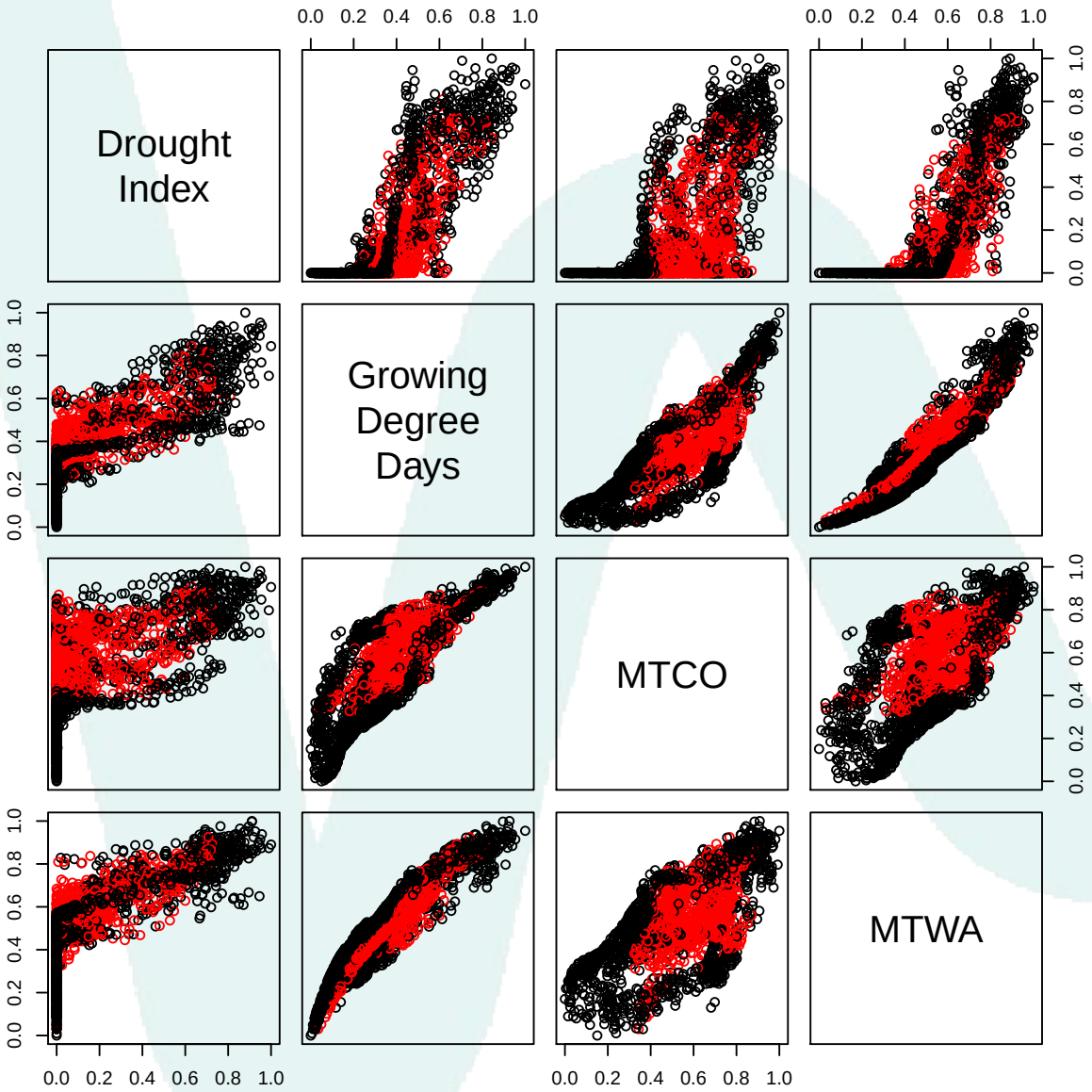
Outline

1. Climate envelopes — issues
   - Occupancy models
2. Simple parametric form allowing for plateau
   - Multivariable extension — “warped cone”
3. Illustration — European vascular plants
   - Northern; central; southern
4. Add external information — priors

1. Climate Envelopes

- Regression: data on climate variables and species distribution (presence/absence)
- Analysis on **current/past** relationships with climate — occupancy models
  - “Climatic niche”
- Predict future responses of species’ distributions to climate change
- **BUT:** difficult; confounding effects of location, scale etc; poor “design”

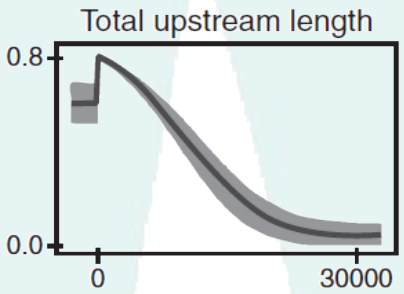
Poor Experimental Design



Envelopes — Concerns

- Differences between **realised** and **fundamental** niches
- Issues with dispersal, connectivity
  - View as “bioclimatic suitability”?
- Biotic effects
- Currently popular: splines with few knots/DoF (new: Gaussian Processes - GRaF in R)
- Multiple regression problem

Example Envelopes



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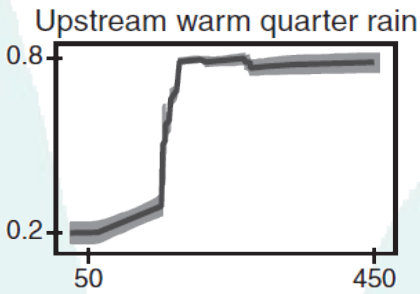

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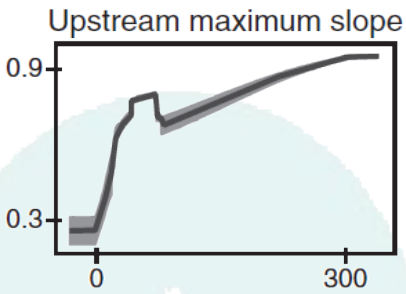

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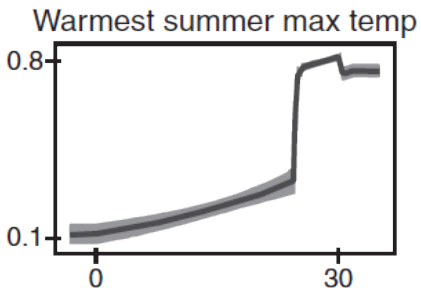

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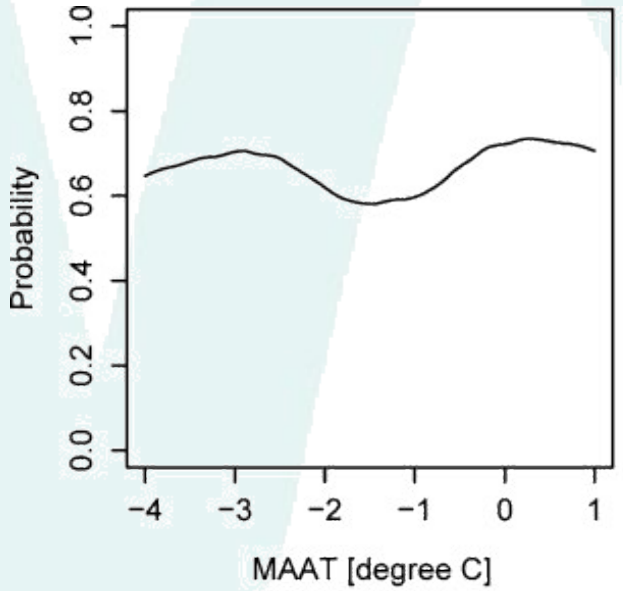


Ideal

Considerations for “ideal” envelope:

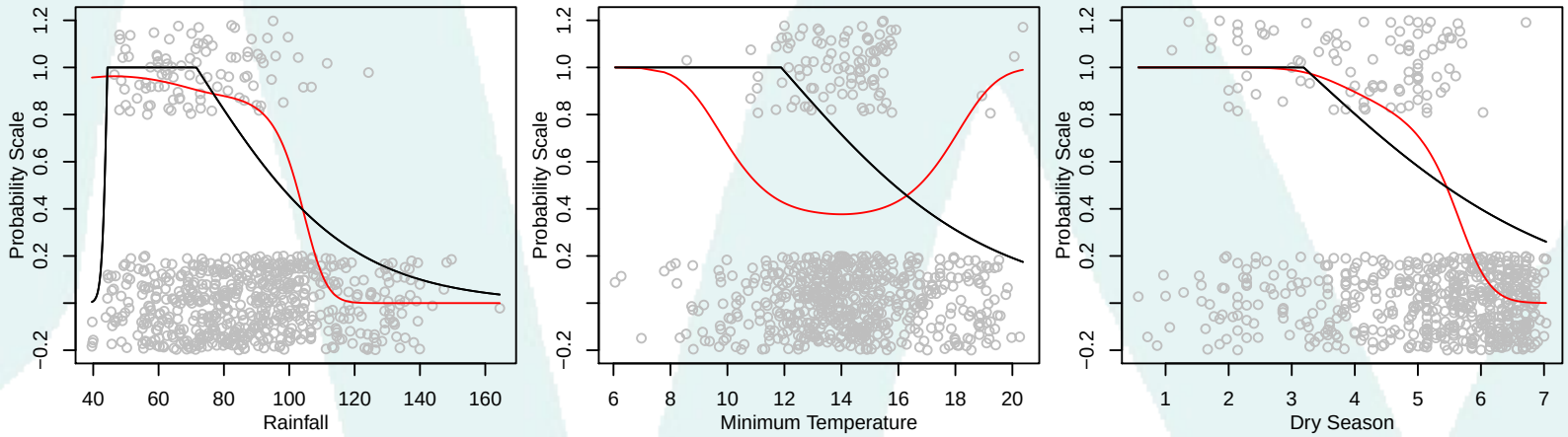
- **Simple** but **realistic**
- Unimodal/monotonic allowing for “plateau”
- Ability to use external information
  - e.g. biophysical understanding
- Parametric vs non-parametric
- Account for conditional responses from climate variables — multivariable surface?

Spline Envelopes

- Splines (via GAM) — non-parametric
- Using (e.g.) GCV to select spline smoothing is poor
- Set spline DoF/knots low or constrain parameters of basis functions
- Splines have large uncertainty at margins

GAMs Need Thought

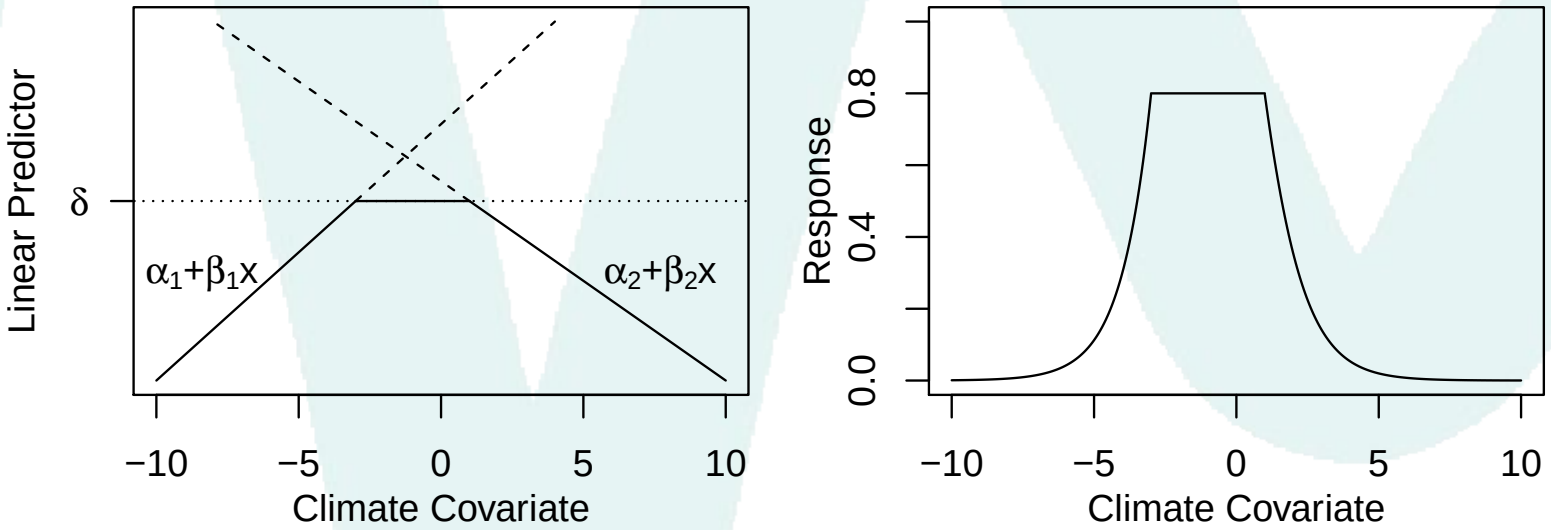
Fischer's lovebirds in Tanzania:



- red lines: Spline curves from GAM
- black lines: Parametric alternative

2. Simple Parametric Envelope

- Start simple — one covariate
- **Observation**: straight lines on logit scale are curved on probability scale



Univariate Envelope

- Consider piecewise linear form for envelope:

$$f(x) = \begin{cases} \alpha_1 + \beta_1 x & x < -\alpha_1/\beta_1 \\ \delta & -\alpha_1/\beta_1 < x < \alpha_2/\beta_2 \\ \alpha_2 + \beta_2 x & x > \alpha_2/\beta_2 \end{cases}$$

  for intercepts α_1, α_2, slopes $\beta_1 > 0, \beta_2 < 0$

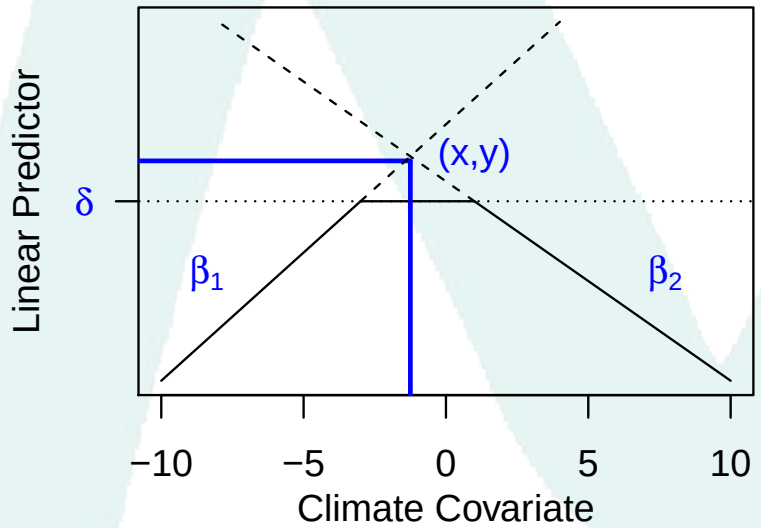
- Alternative view:

$$f(x) = \min\{\alpha_1 + \beta_1 x, \delta, \alpha_2 + \beta_2 x\}$$

- Get "plateau" if δ below intersection

Implementation in WinBUGS

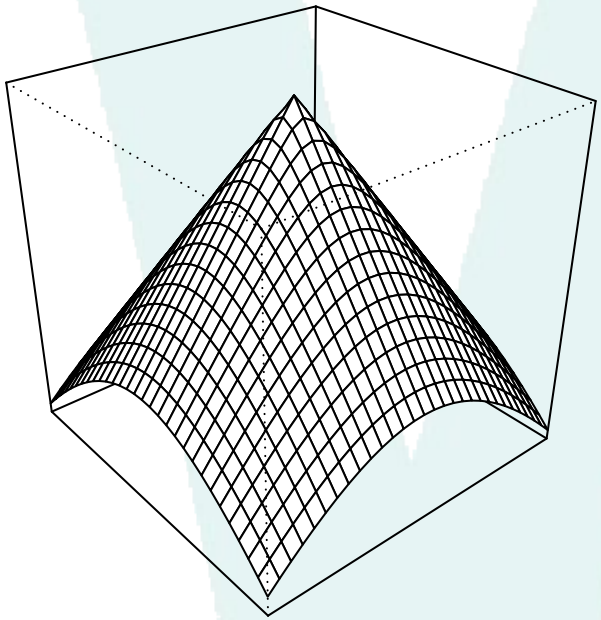
- Parameterisation is key
- Using $\alpha_1, \alpha_2, \beta_1, \beta_2$ gives poor convergence
- **Solution**: model *slopes* and *intersection point* ("*apex*")

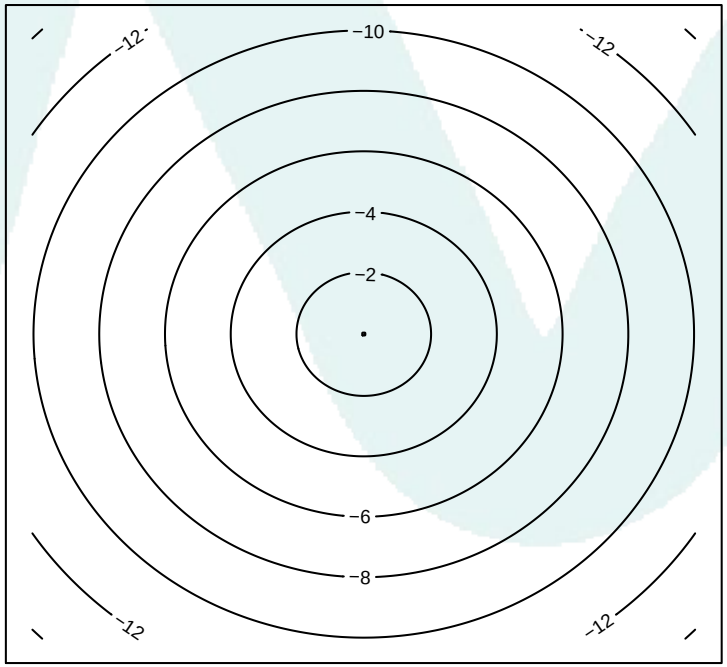


- Scale covariates to [0,1] and allow apex to lie in [-1,2]

Multivariable Envelope

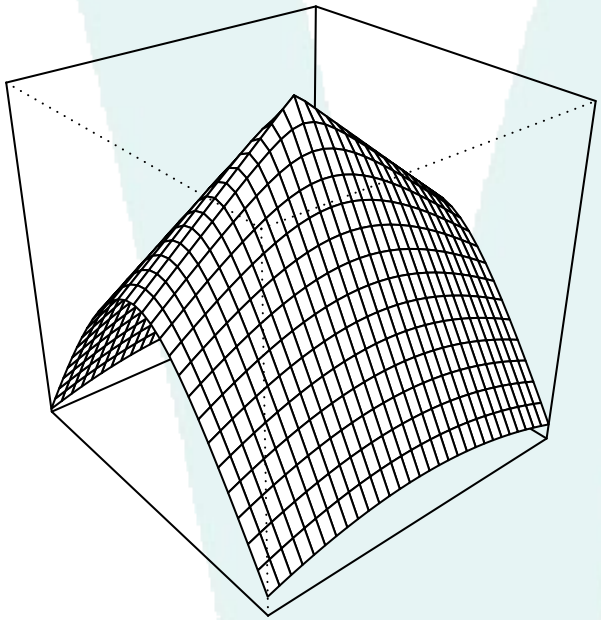
- Extension to consider multiple climate variables simultaneously
- Start with standard cone (equal slopes)

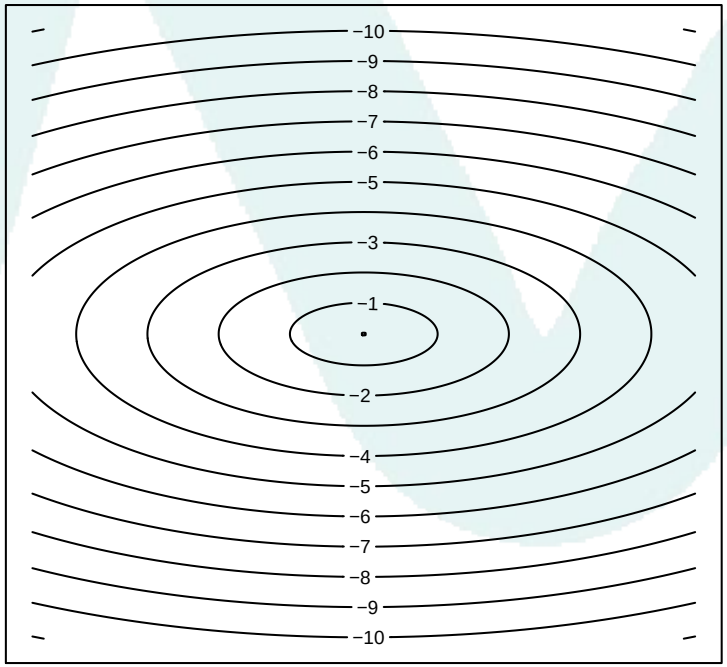




Multivariable Envelope

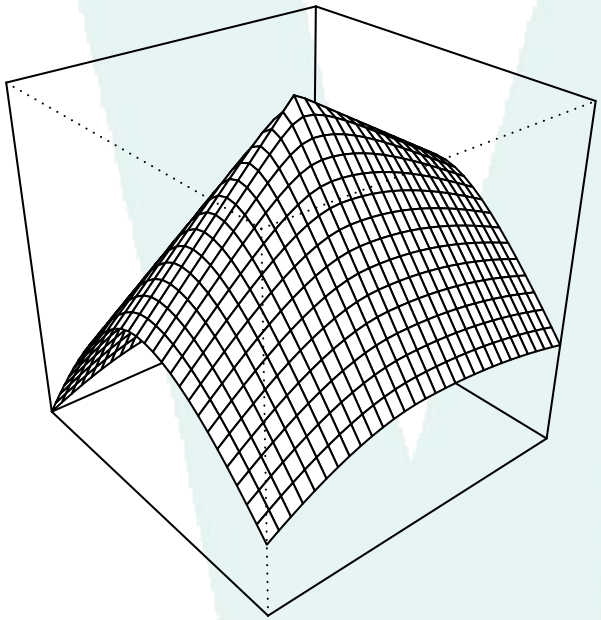
- Extension to consider multiple climate variables simultaneously
- Different slopes for each variable

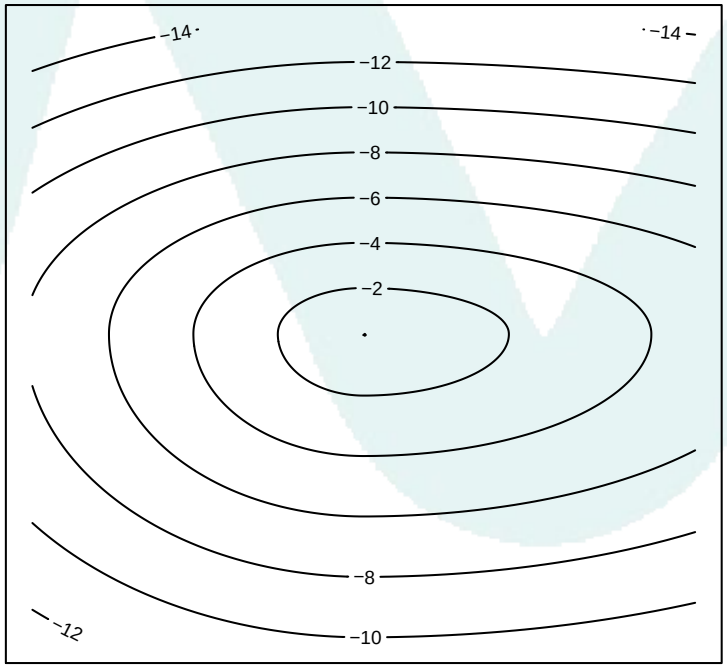




Multivariable Envelope

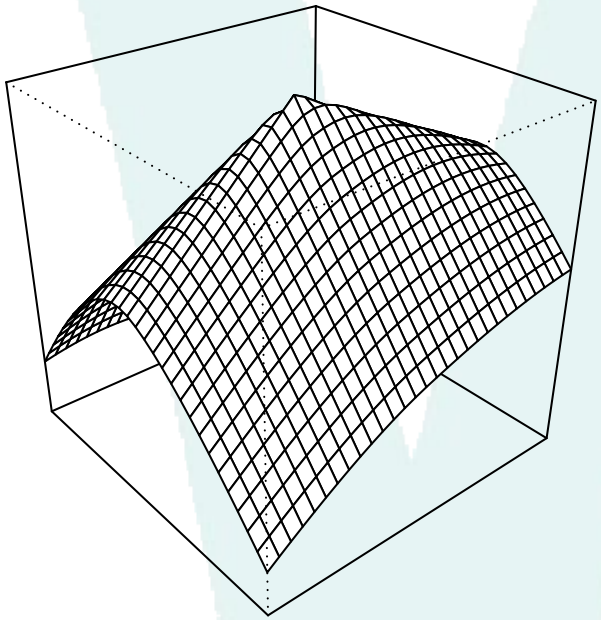
- Extension to consider multiple climate variables simultaneously
- Different slopes either side of apex

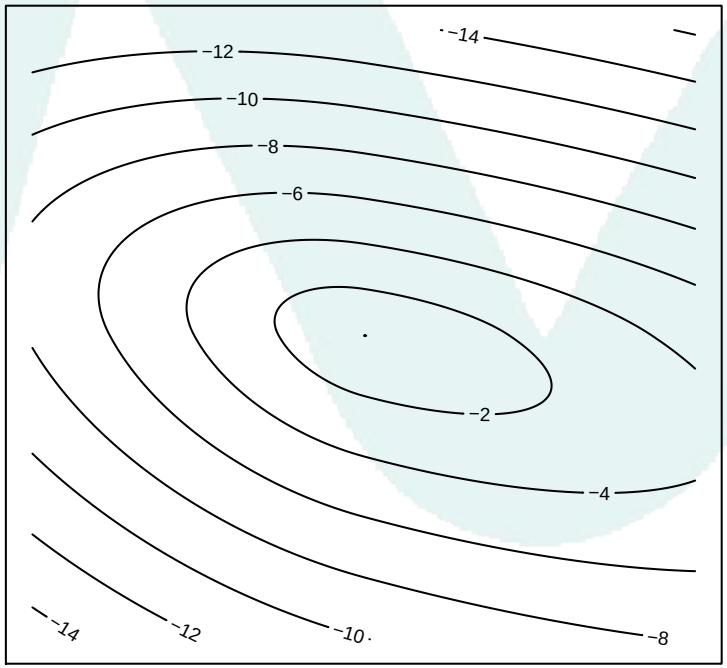




Multivariable Envelope

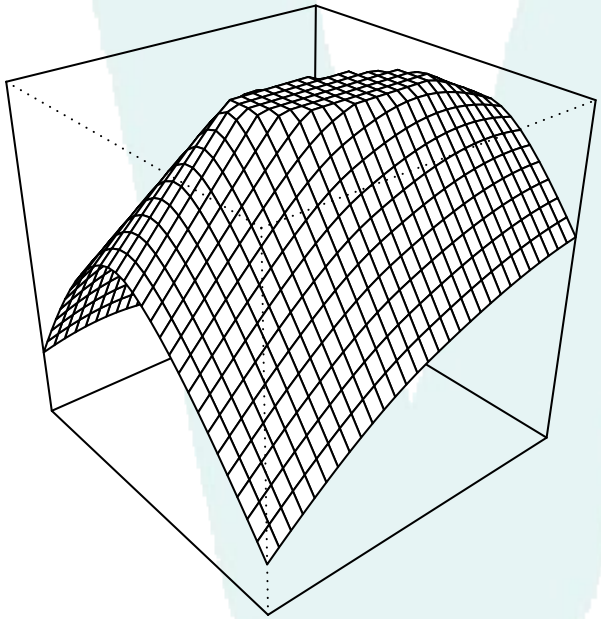
- Extension to consider multiple climate variables simultaneously
- Apply interaction term (warp diagonally)

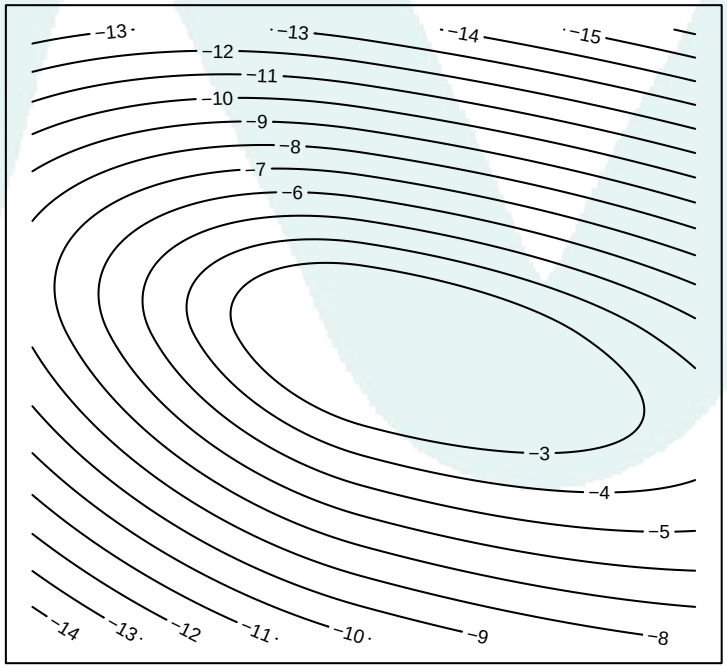




Multivariable Envelope

- Extension to consider multiple climate variables simultaneously
- Finally, top-slice cone to give **plateau envelope**





Multivariable Envelope

- Cartesian equation for plateau envelope in M dimensions, for apex a and covariates x:

$$(z - a_z)^2 = \sum_{i=1}^{M} \beta_{i,1} (x_i - a_{x_i})^2 I[x_i < a_{x_i}] + \beta_{i,2} (x_i - a_{x_i})^2 I[x_i \geq a_{x_i}] + \sum_{i>j} \gamma_{i,j} (x_i - a_{x_i})(x_j - a_{x_j})$$

- Also $\beta_{i,1}, \beta_{i,2} > 0 \quad \forall i$
- Plateau if apex height $a_z > \delta$
- Top-slicing enforced by $z = \min(z, \delta)$

Implementation in WinBUGS

- As in univariate case, model *slopes* and *apex*
- Still able to use max/mins in code to implement change-points
- Identifiability — apex is function of other parameters for monotonic envelope
- Constraints on interaction terms to ensure no $\sqrt{-1}$?

$$\gamma_{1,2} \in \left[-\frac{2\sqrt{\beta_1 \beta_2}}{M-1}, \frac{2\sqrt{\beta_1 \beta_2}}{M-1} \right].$$

Implementation in INLA

- Not possible in R-INLA?
- Solution: calculate envelope for fixed parameters, add to INLA model as offset
- Optimise over envelope parameters using `optim()`
- (Effectively ML/MAP estimates for envelope, then marginalising rest of model)
- Note: works with GLM, GAM etc too

3. European Vascular Plants

- Data from *Atlas Florae Europaeae*
  - Distribution of Vascular Plants in Europe
  - Data on $\frac{1}{2}^\circ$ grid
- Climate variables chosen:
  - Drought index
  - Growing degree days (w.r.t. 5°C)
  - Mean temperature of coldest month (°C)
  - Mean temperature of warmest month (°C)
- From Ohlemüller *et al*., *Global change Biology*, 2006
- Current climate data based on 1931-1960

Model

- Binomial GLM, presence/absence response
- Climate covariate(s)
- Term for spatial correlation, iCAR in WinBUGS

Climate Projections

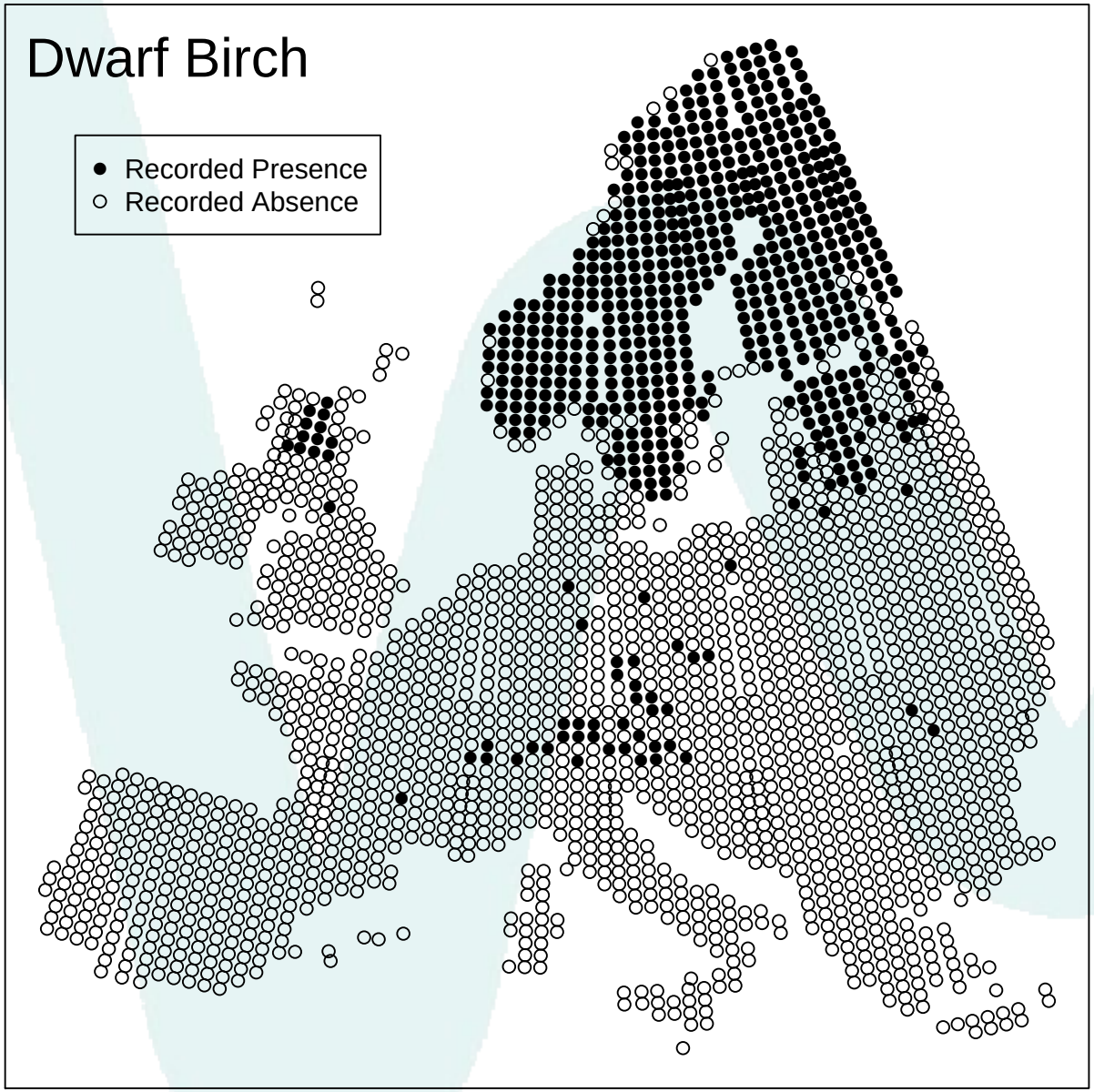
- Future climate projections from HadCM3 GCM (“average”)
  - Average of 2030–2060 (“2045”)
  - Average of 2080–2110 (“2095”)
- Two emission scenarios:
- **B1**: low emissions
- **A1FI** : high (fossil fuel) emissions

Climate Projections

Concentrate on three species:

- *Betula nana* - Dwarf Birch (Abedul)
  - Northern, e.g. Scandinavia, Baltic states, Scotland
- *Fagus sylvatica* - Common Beech (Haya)
  - Central, e.g. from Northern Spain to Southern UK, Sweden
- *Quercus coccifera* - Kermes Oak (Chaparro, Roble)
  - Southern, e.g. Southern Spain/Portugal and Greece

Betula nana - Dwarf Birch



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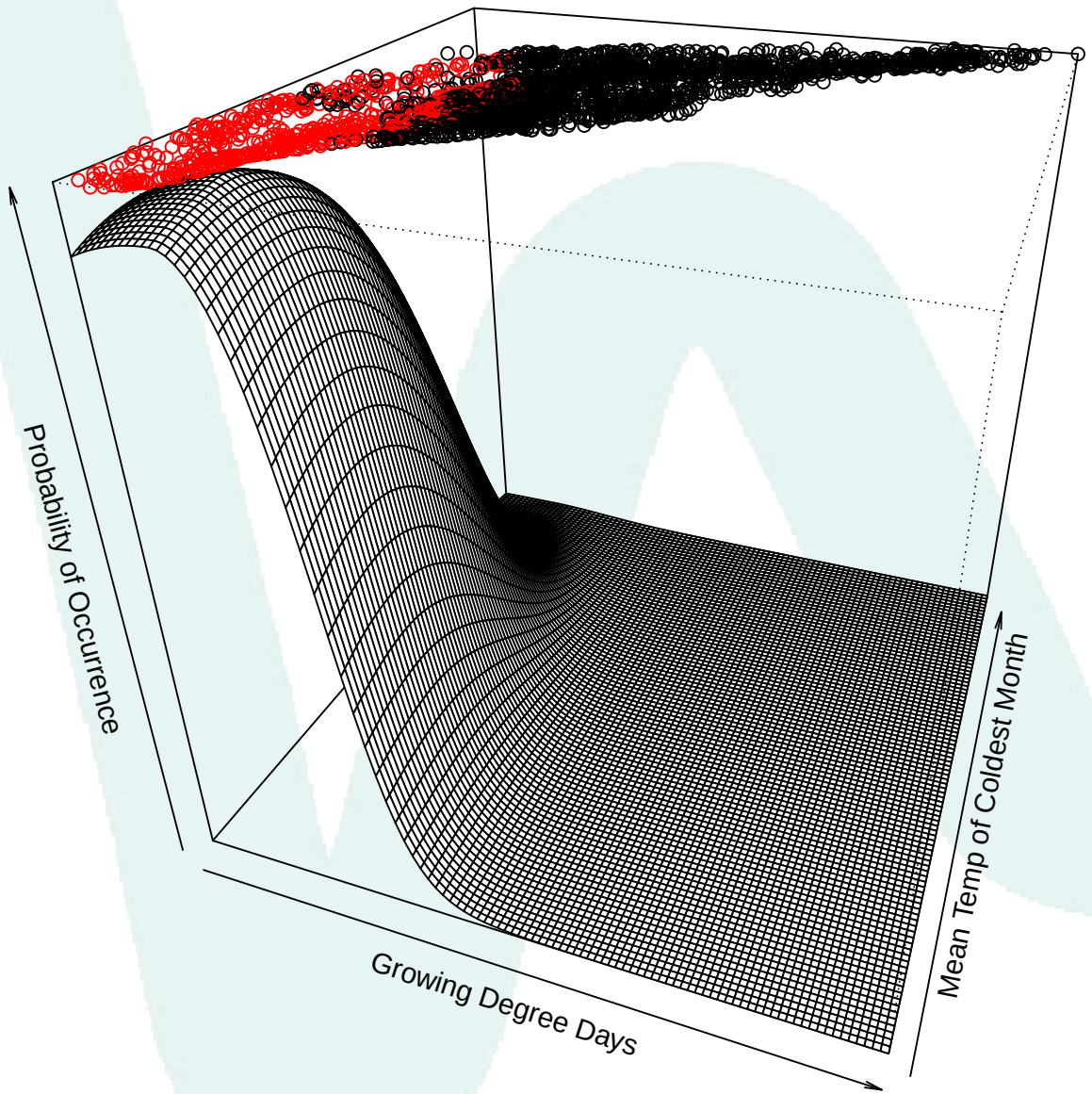

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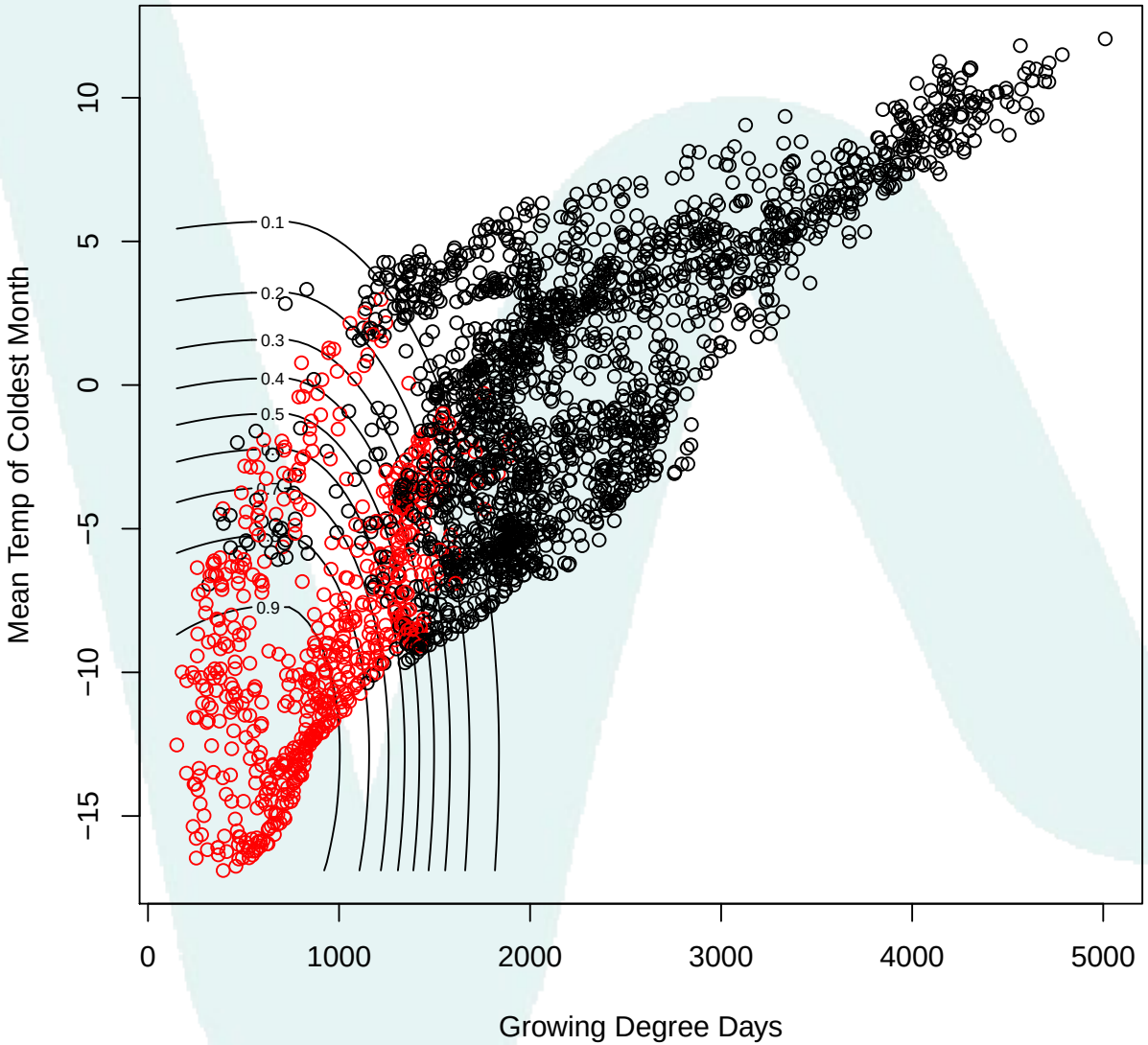

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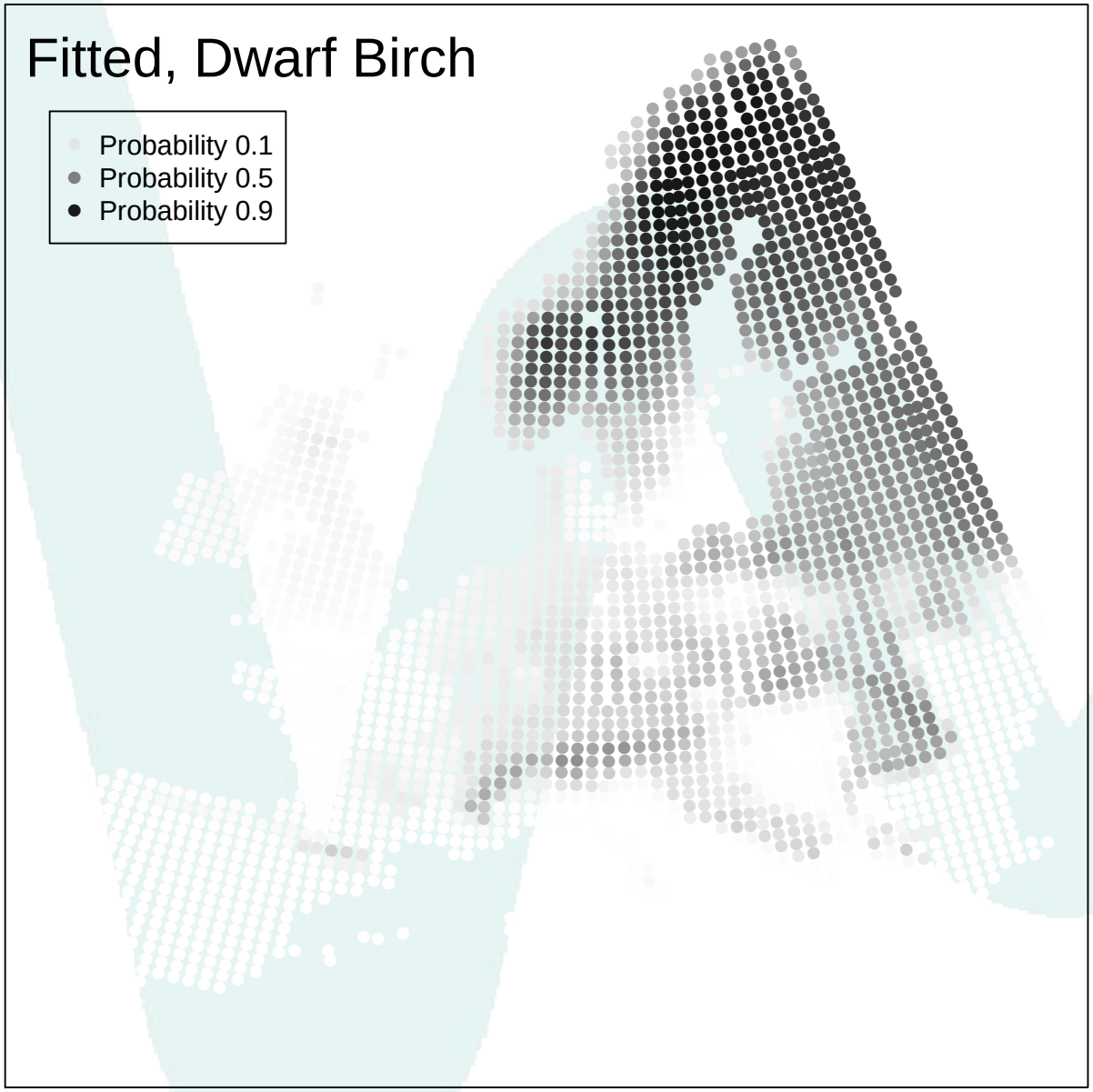

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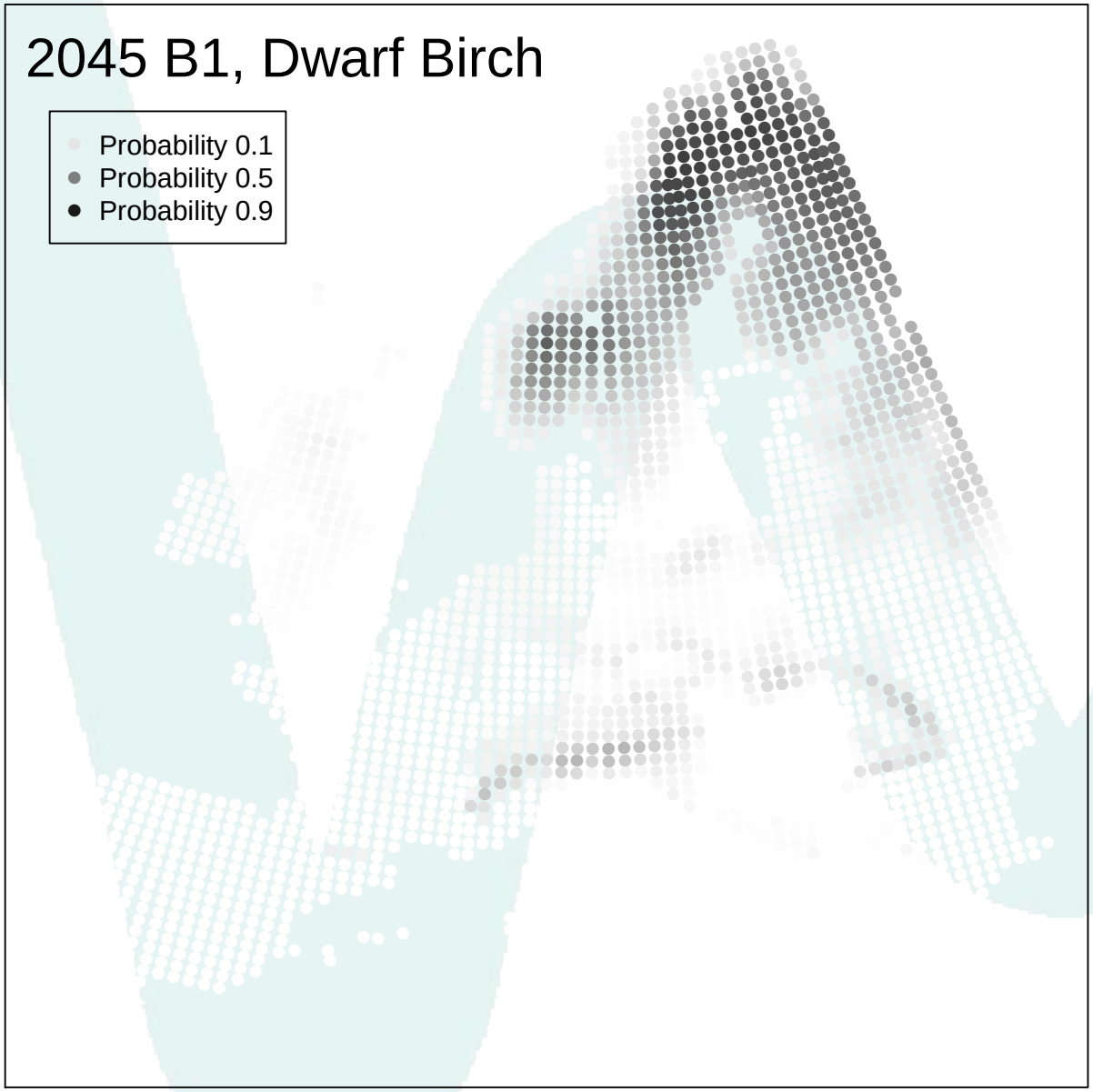

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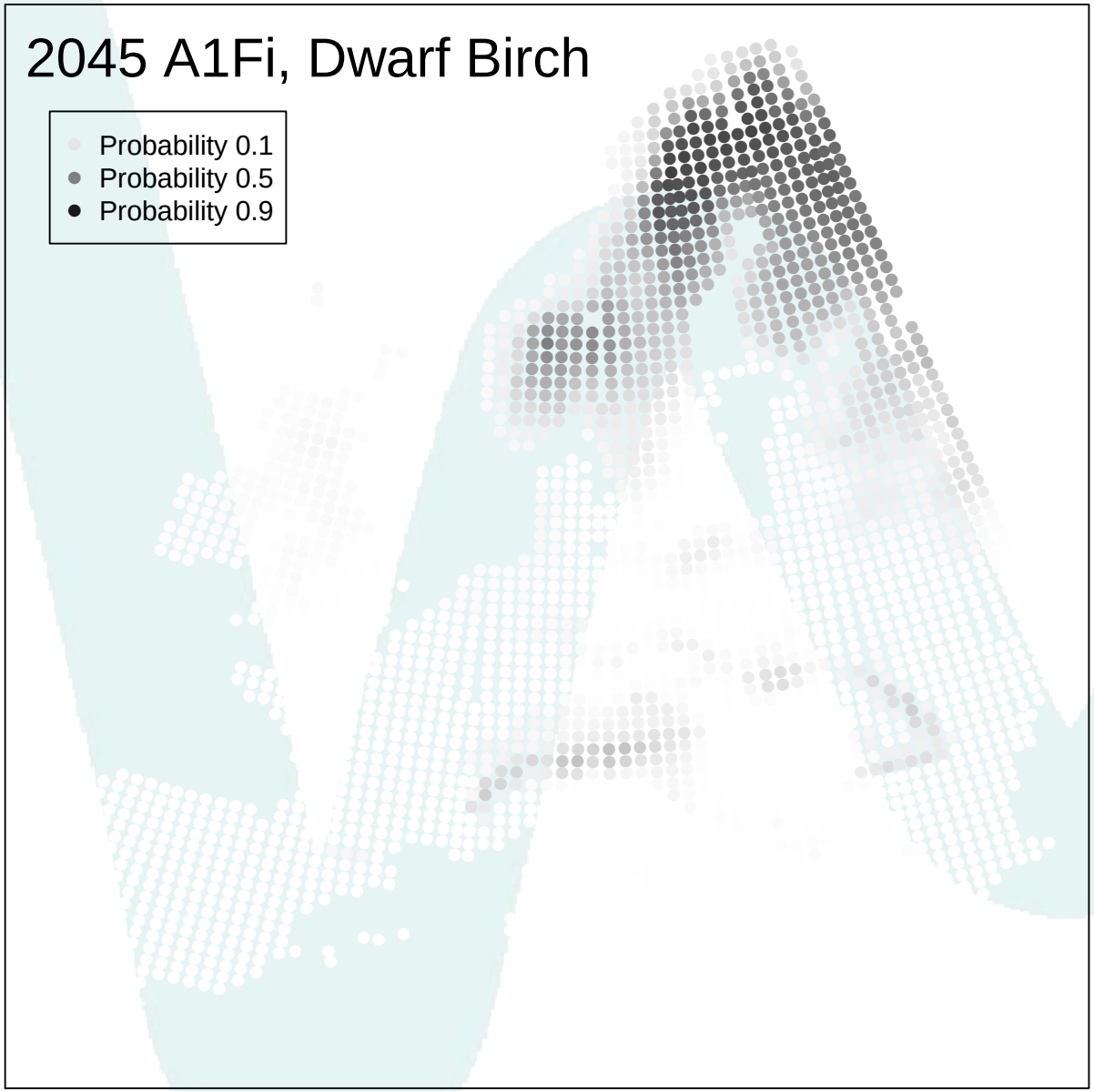

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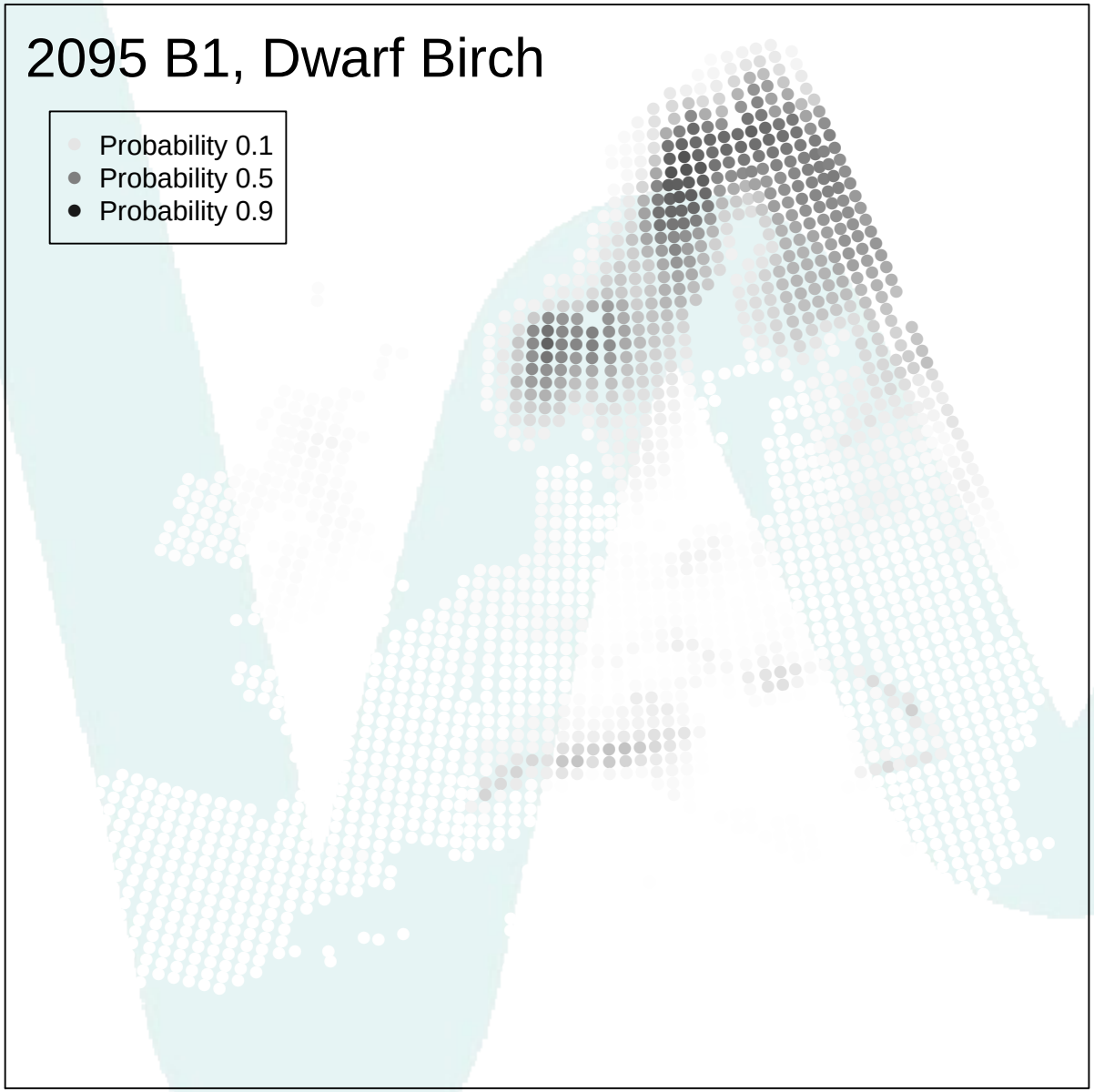

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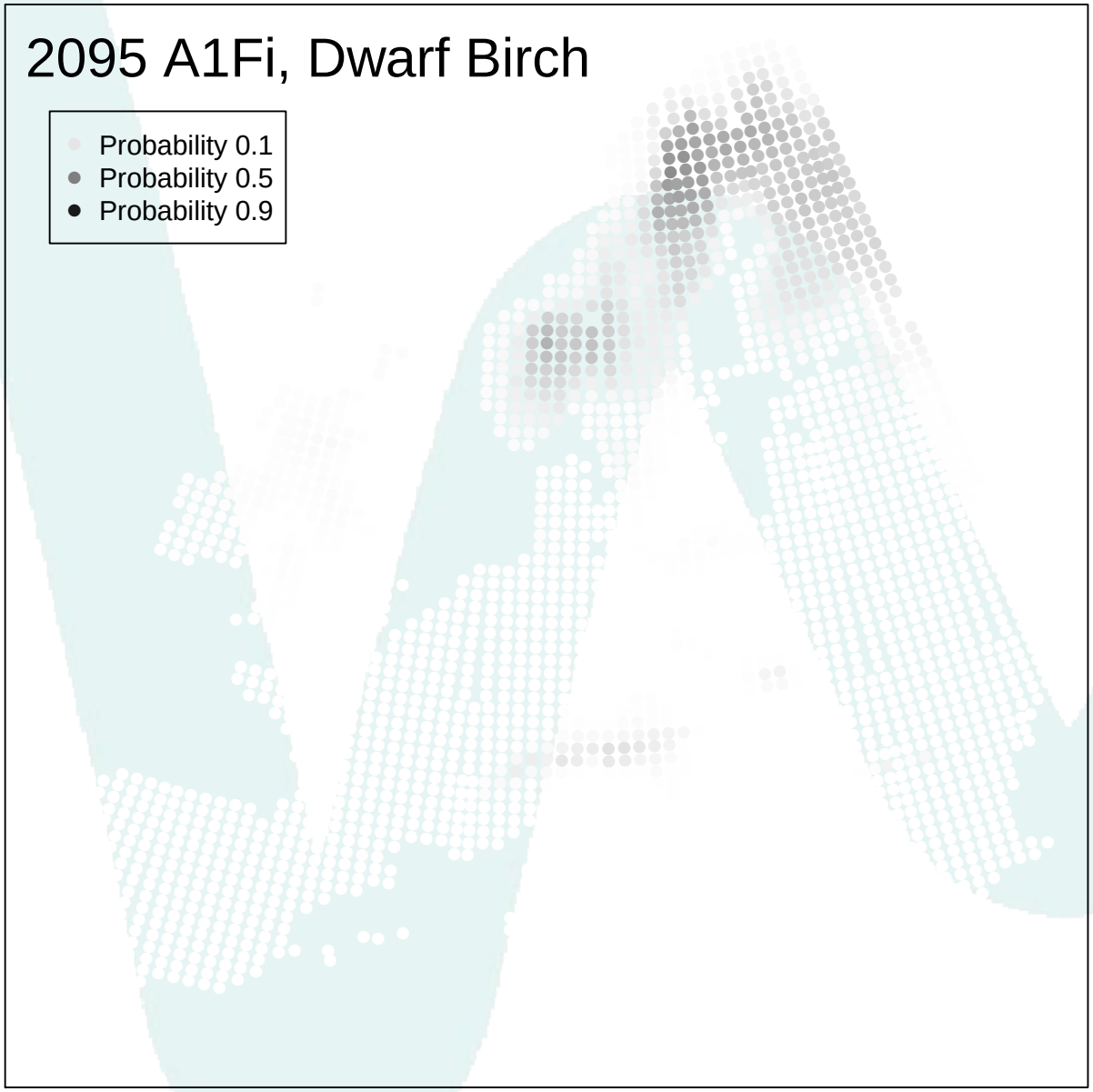
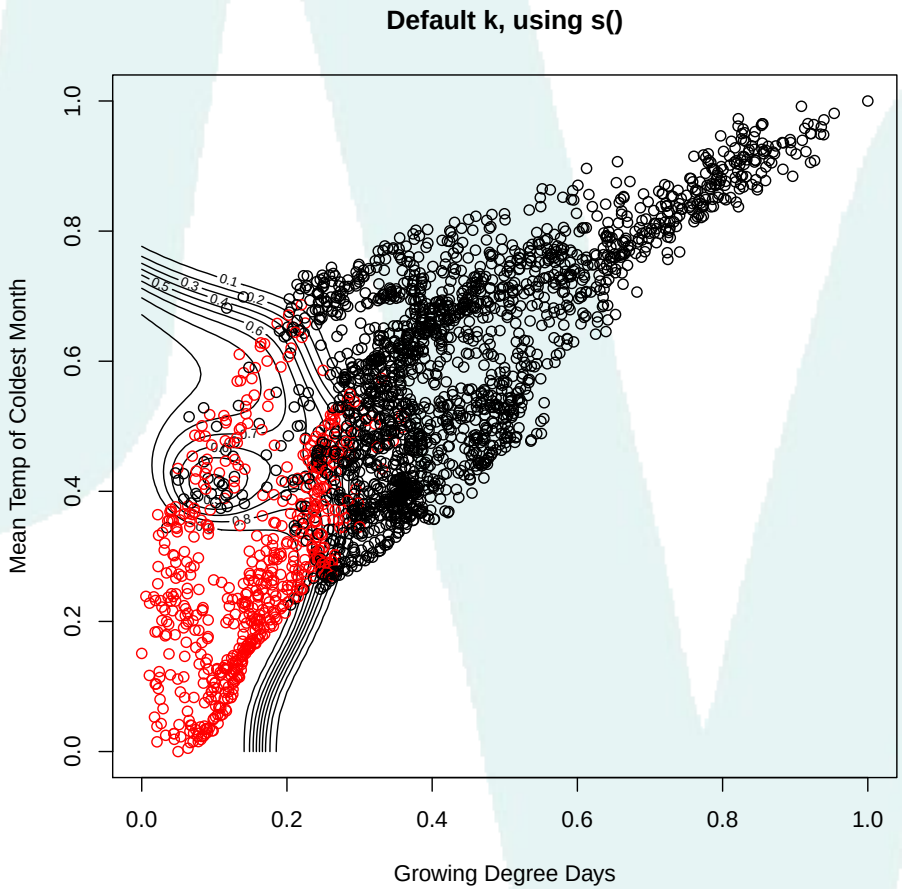
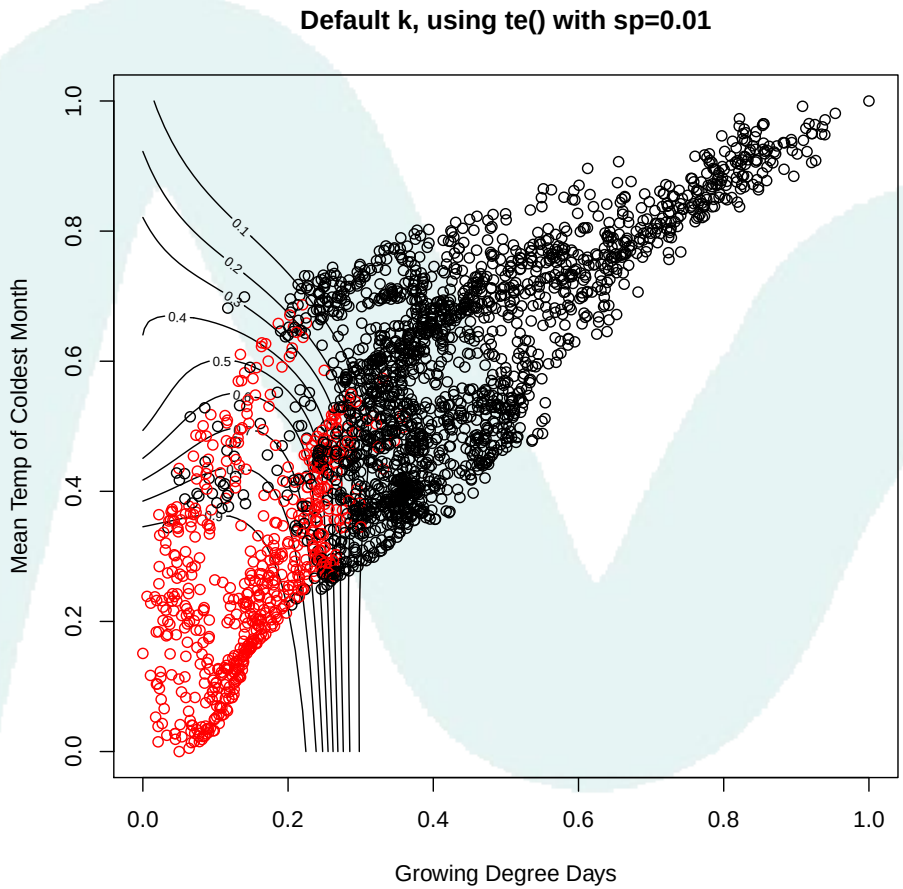


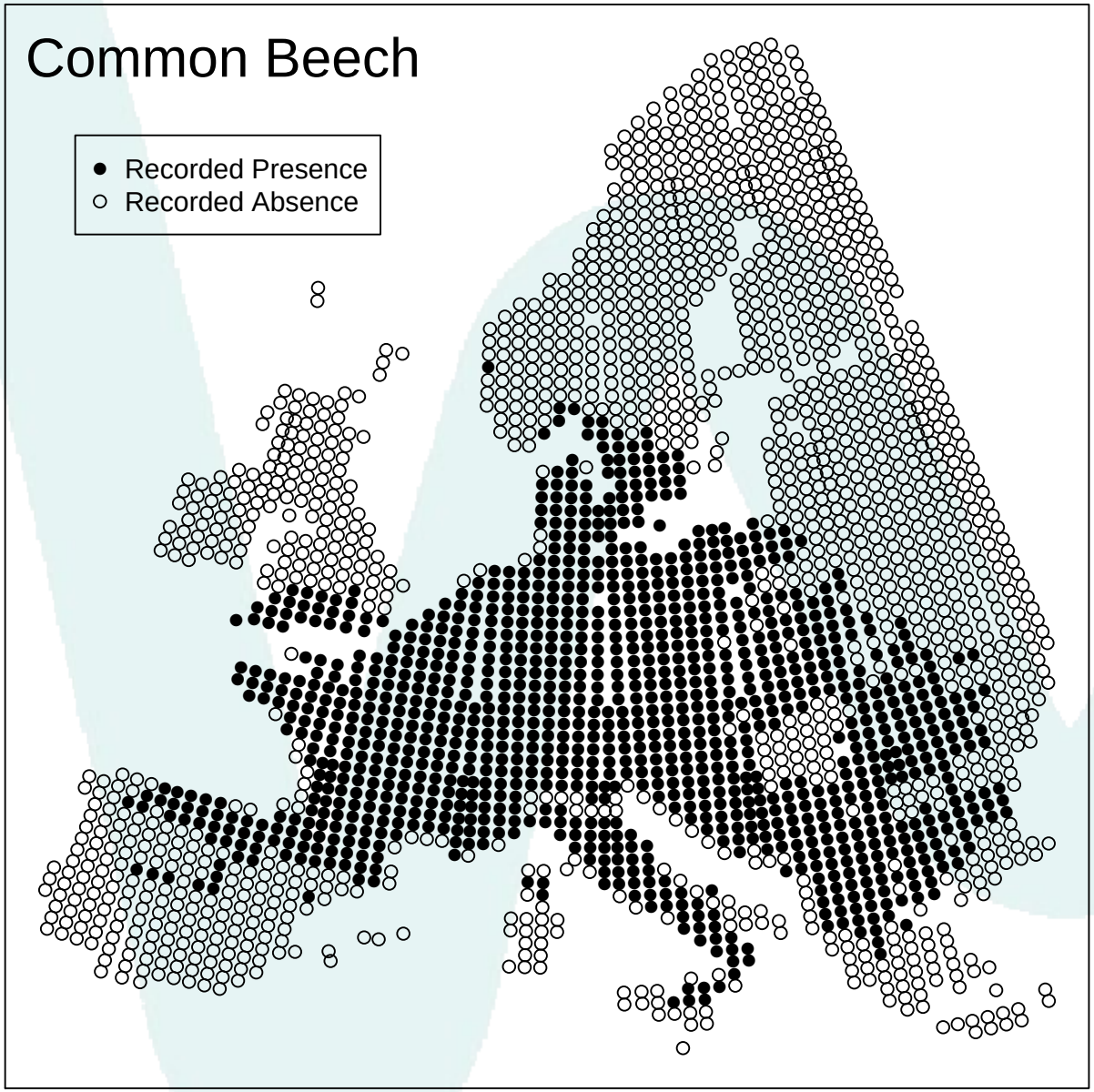
Betula nana - Dwarf Birch

Splines? How to choose knots/smoothing?





Fagus sylvatica - Common Beech



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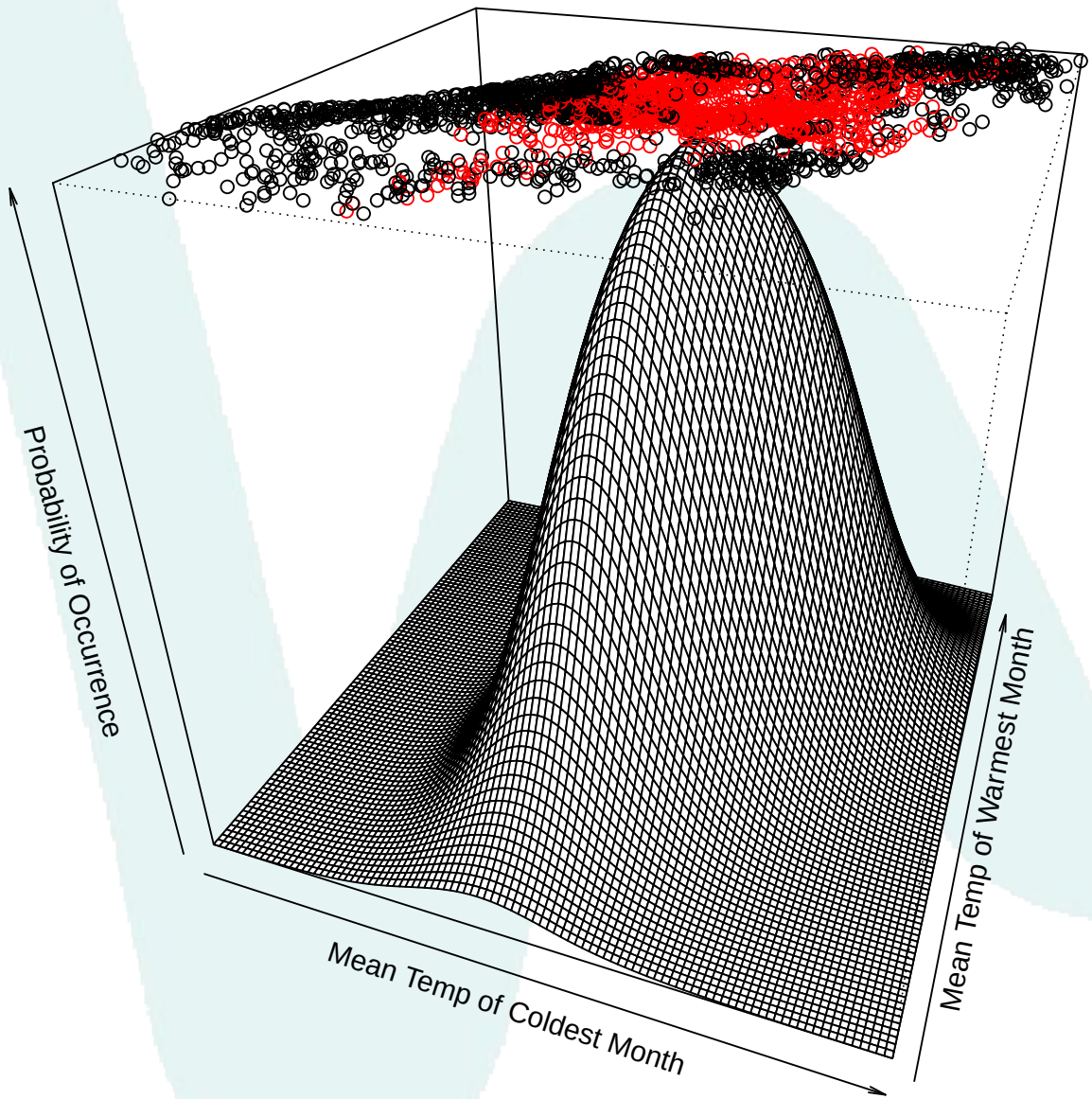

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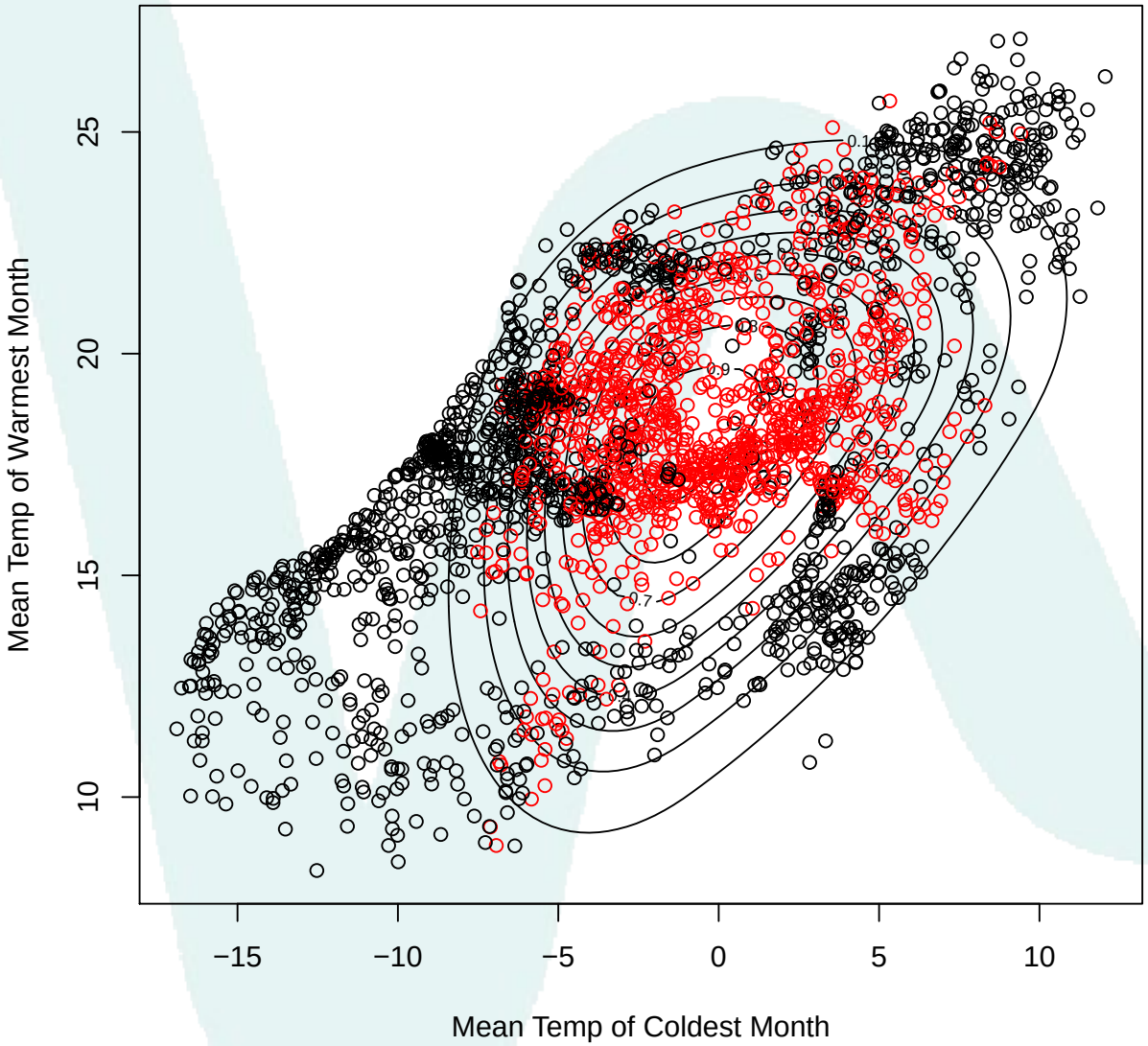

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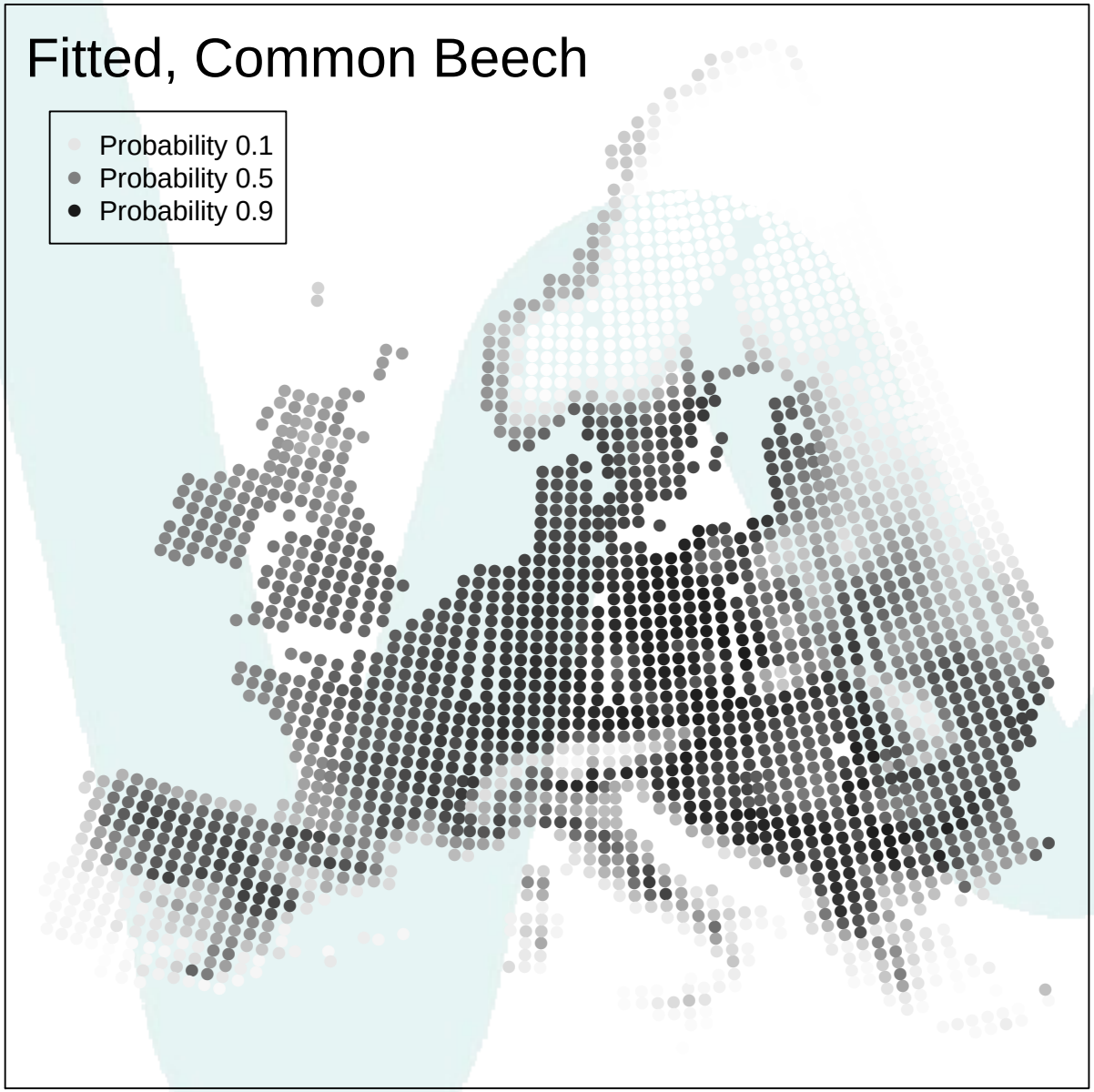

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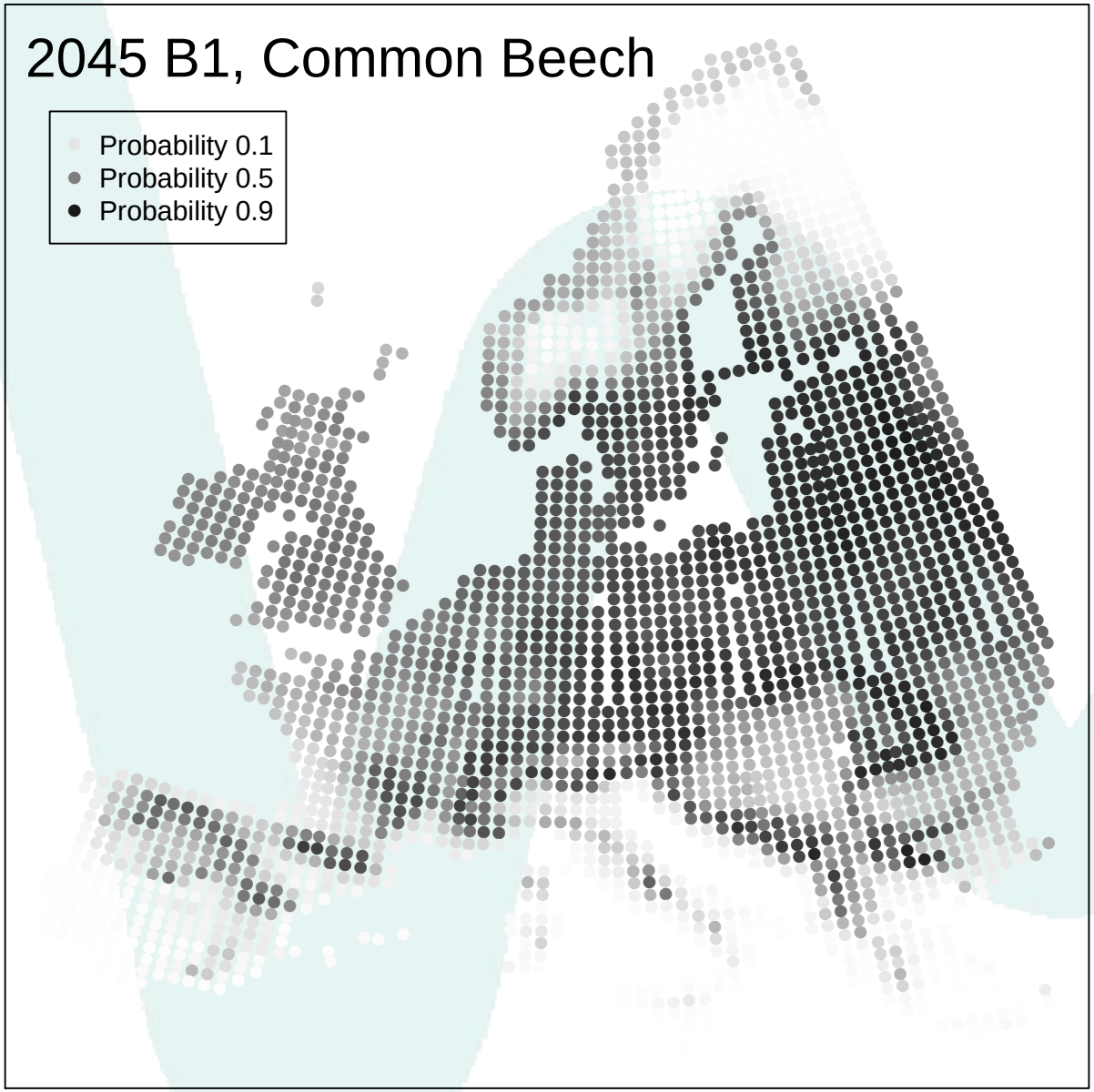

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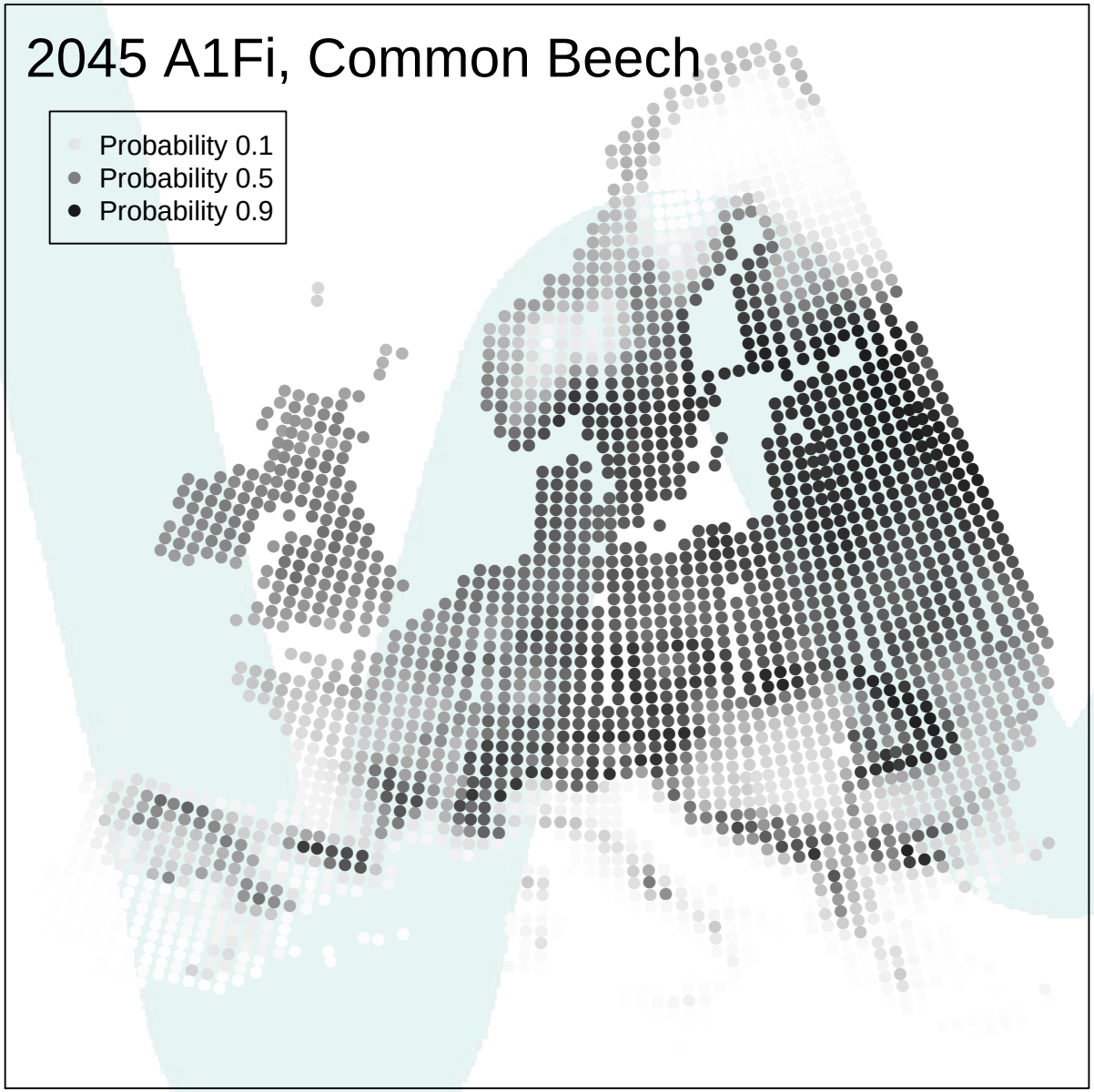

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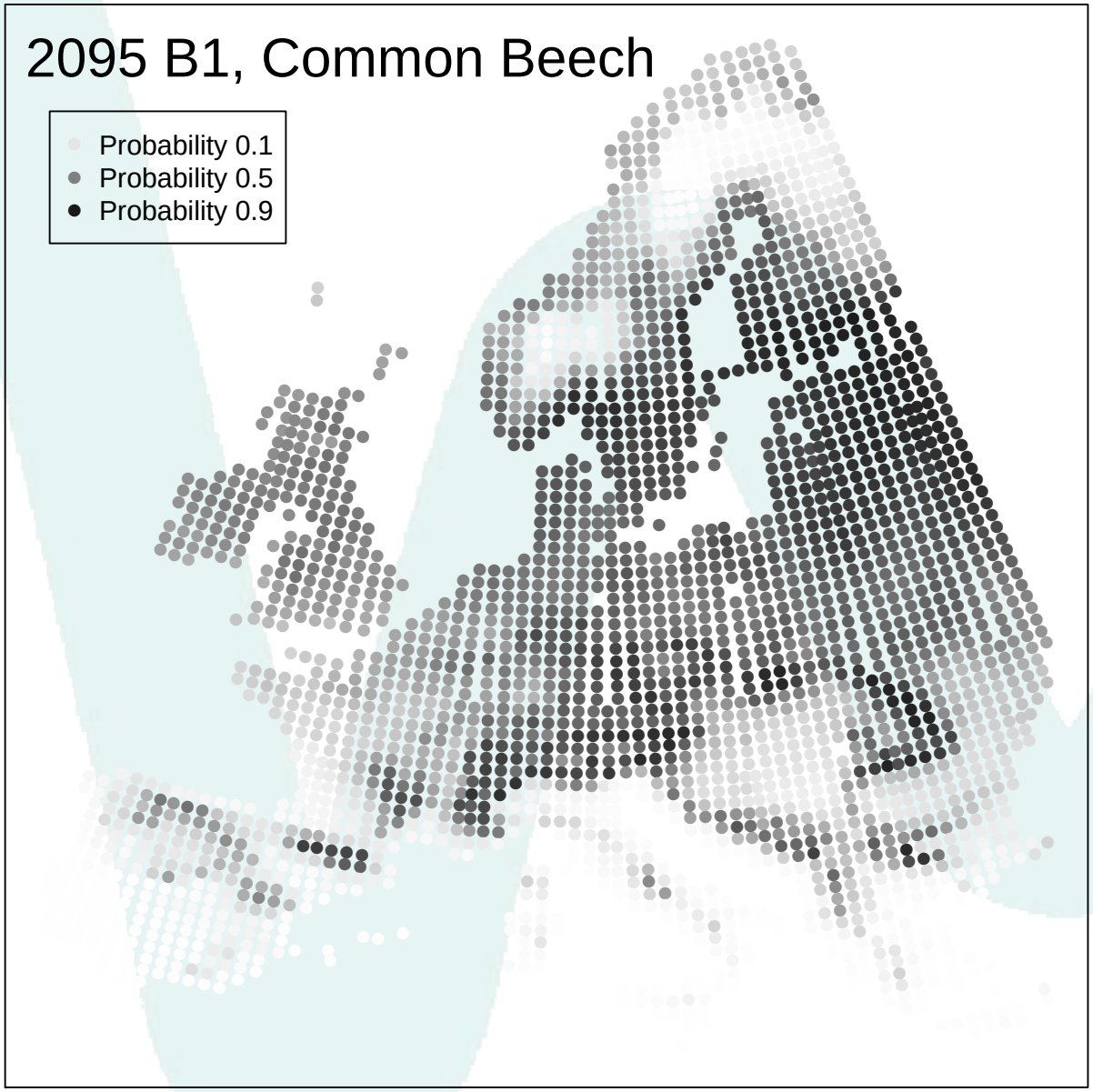

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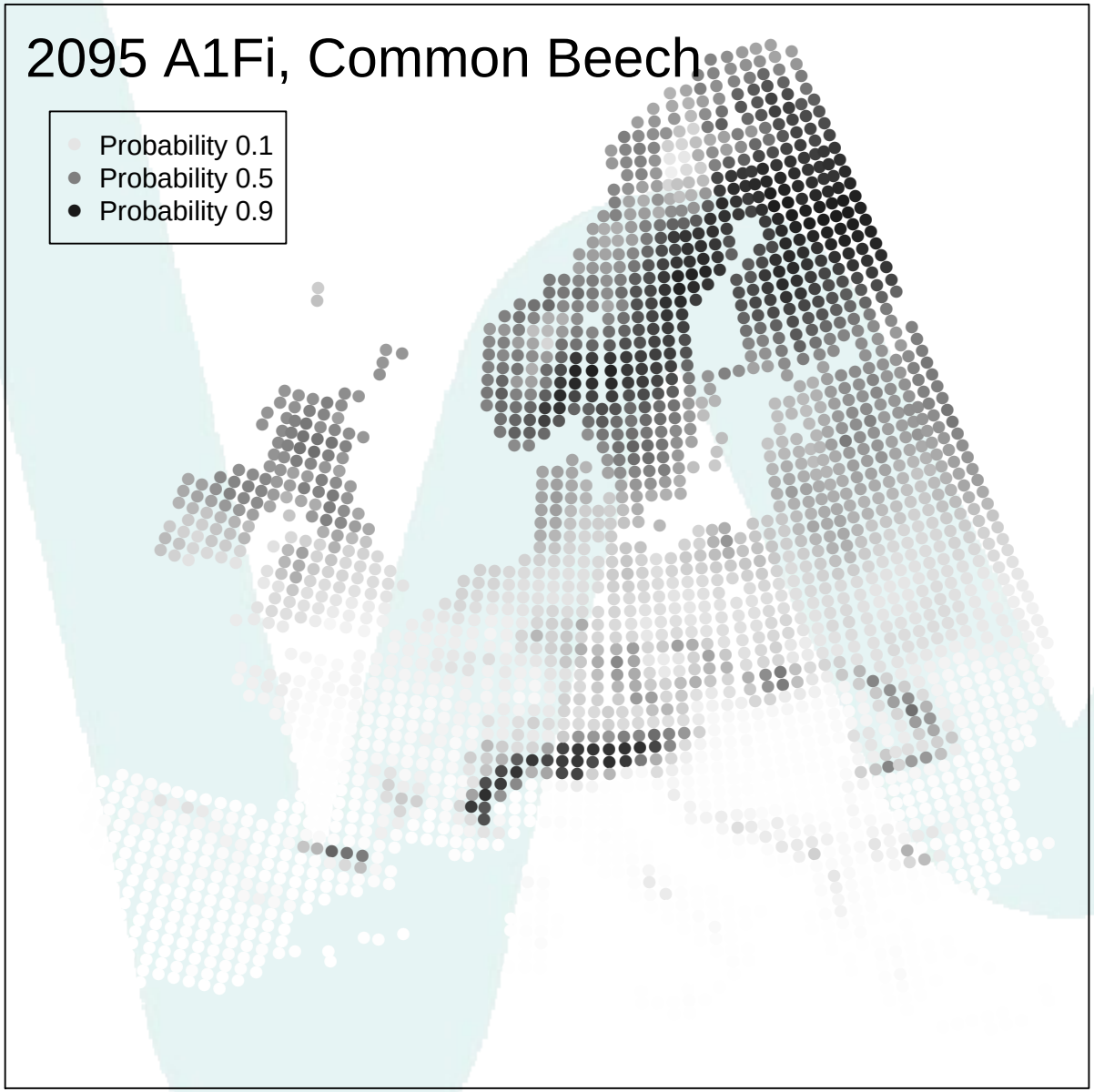
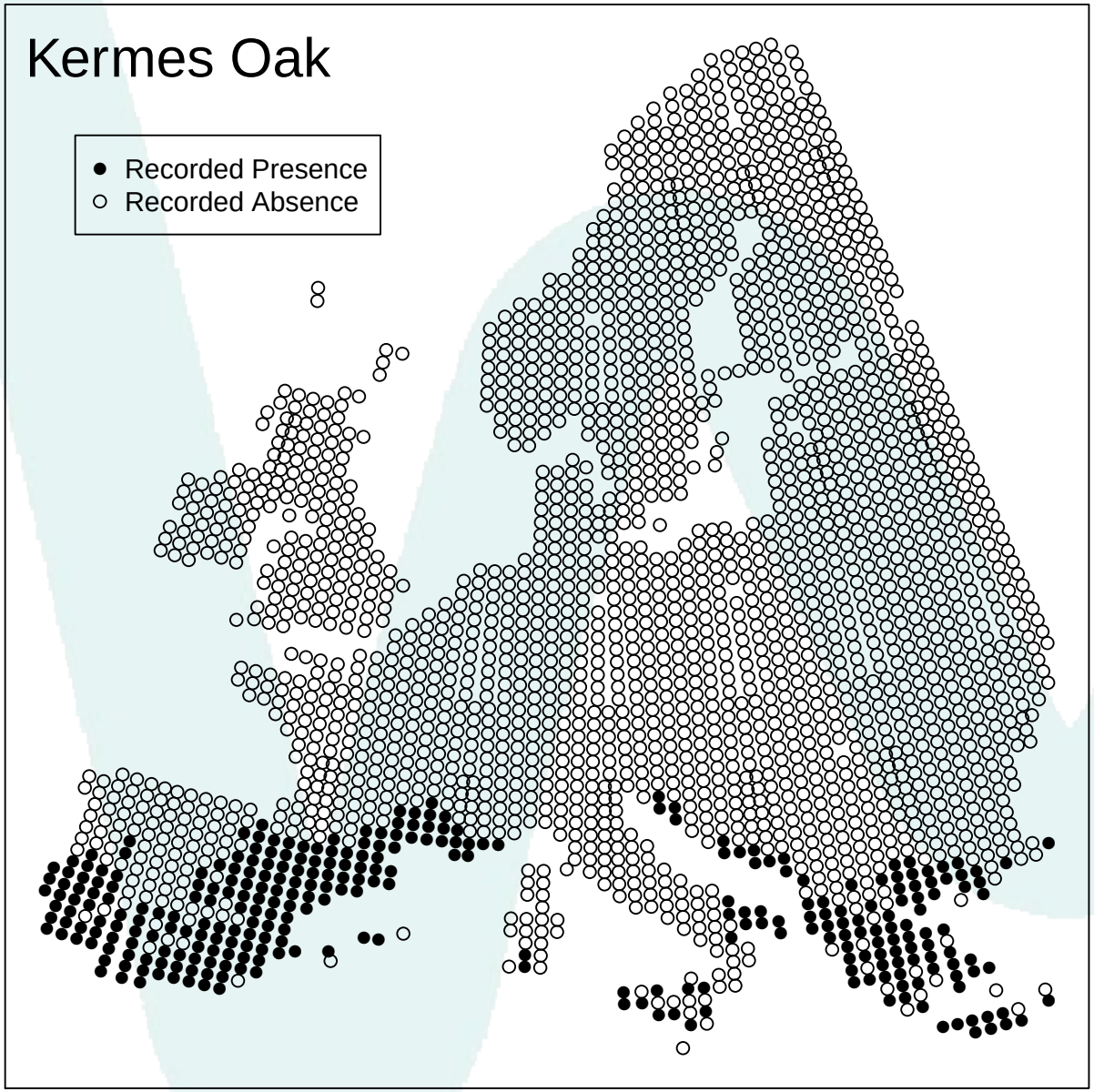


Quercus coccifera - Kermes Oak



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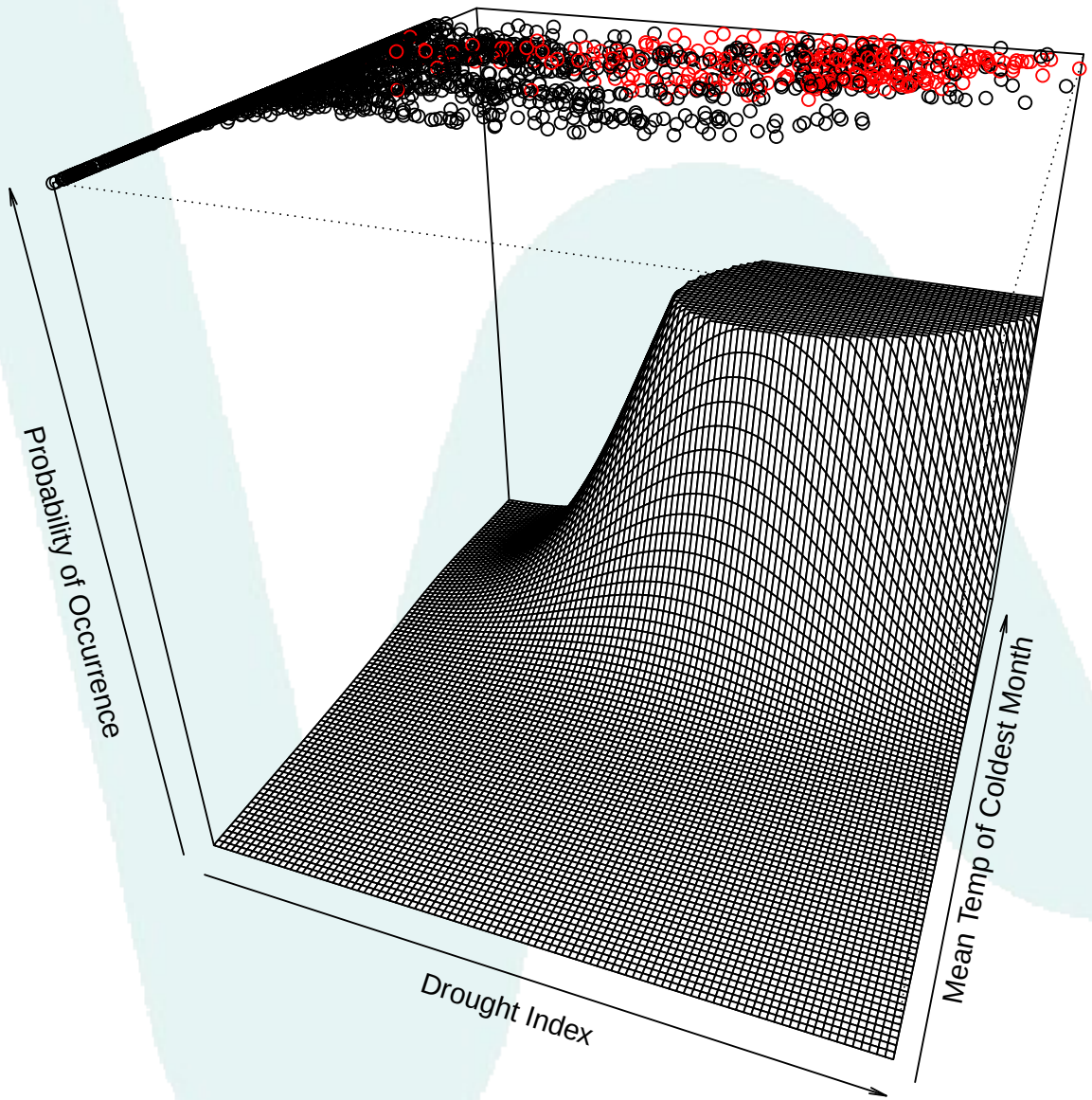

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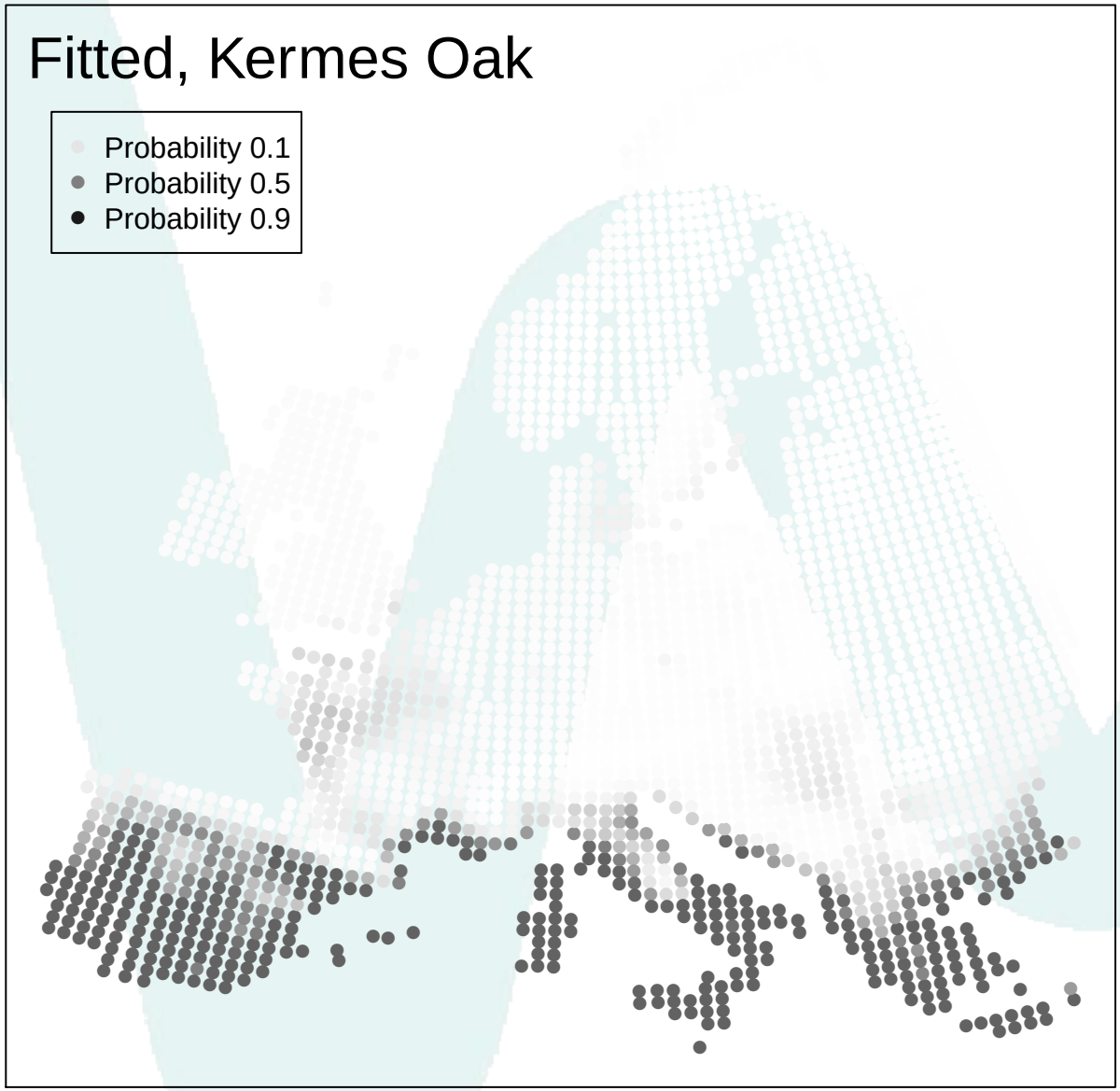

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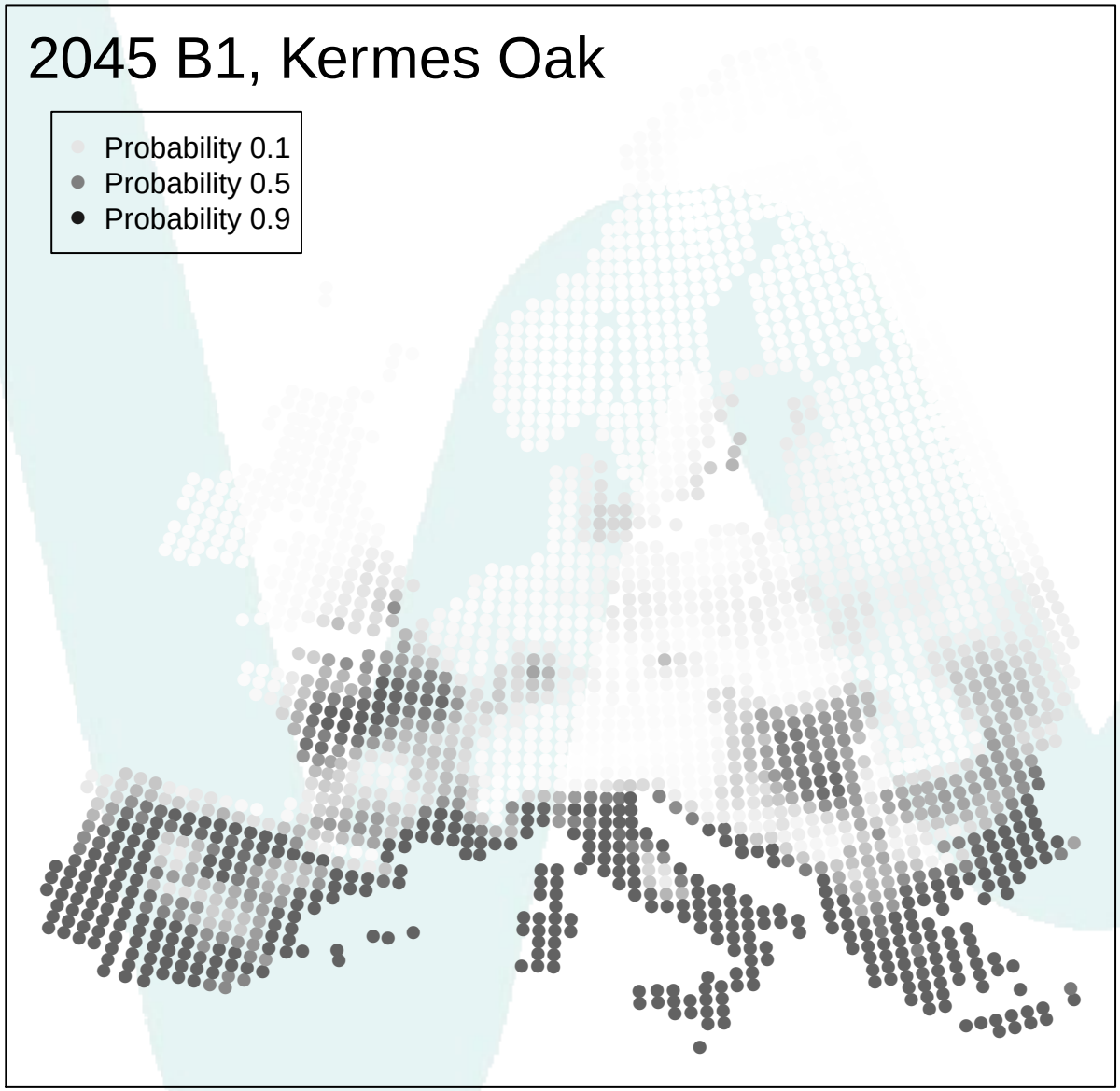

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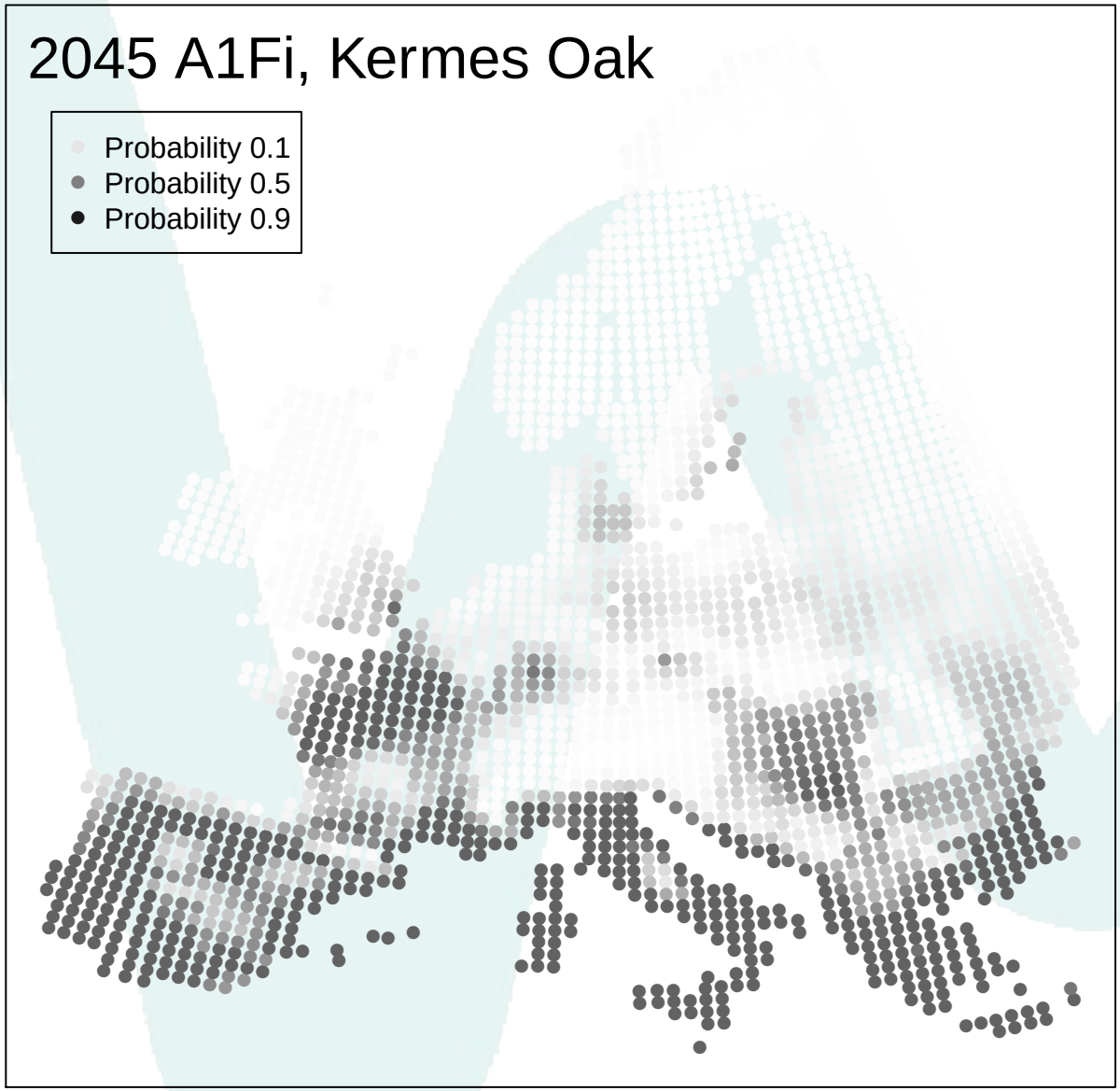

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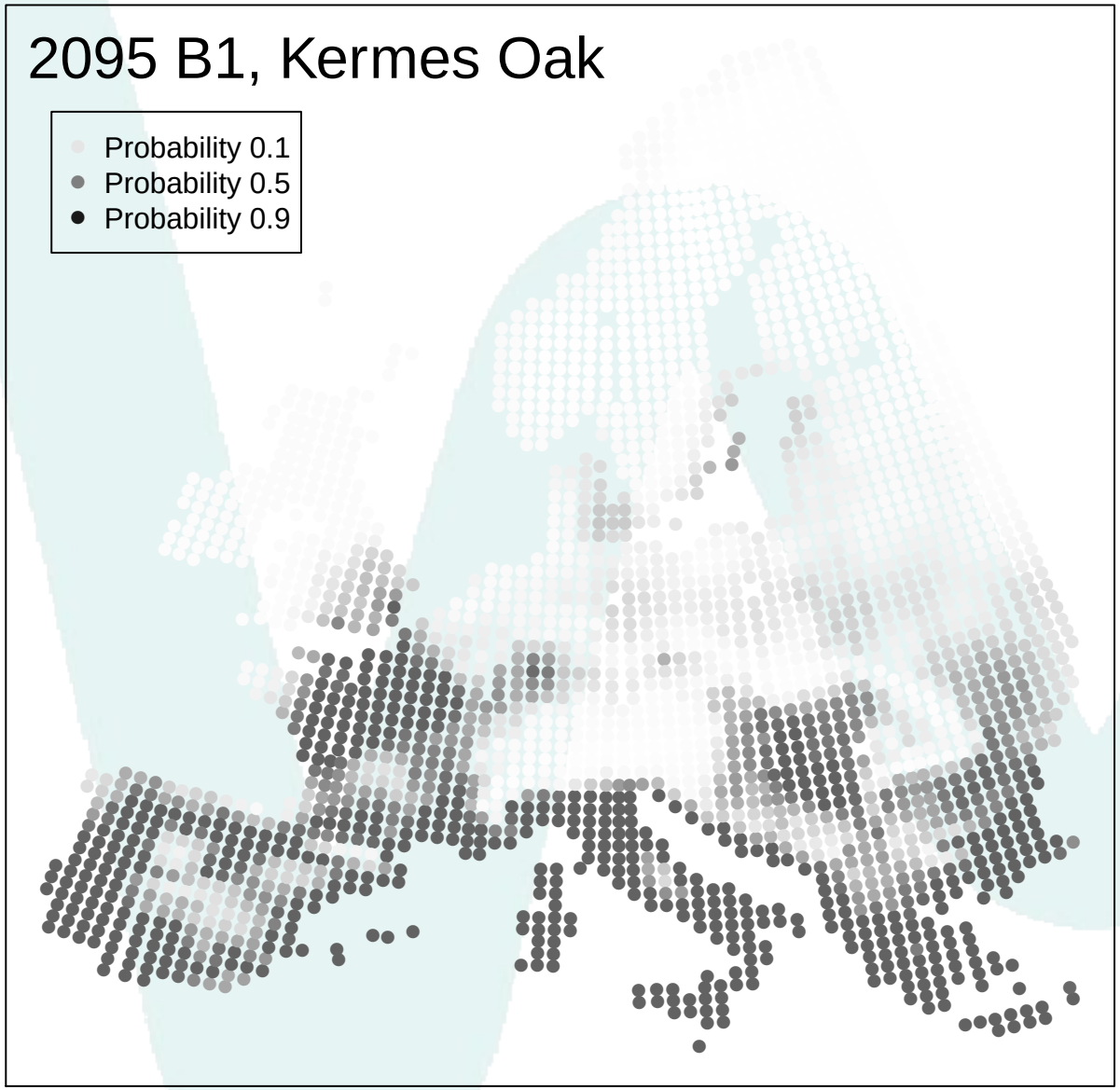

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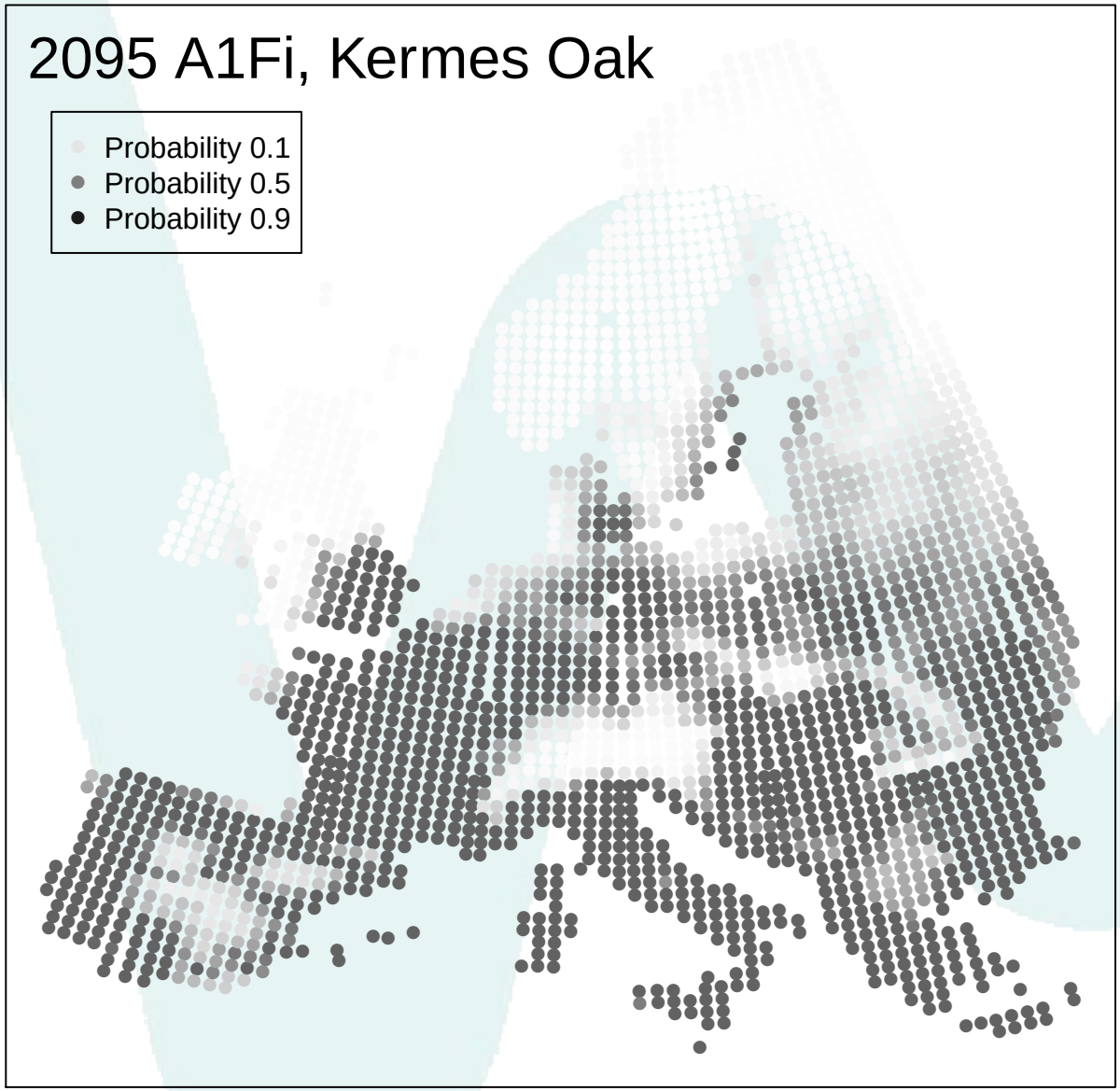


Fagus sylvatica - Common Beech

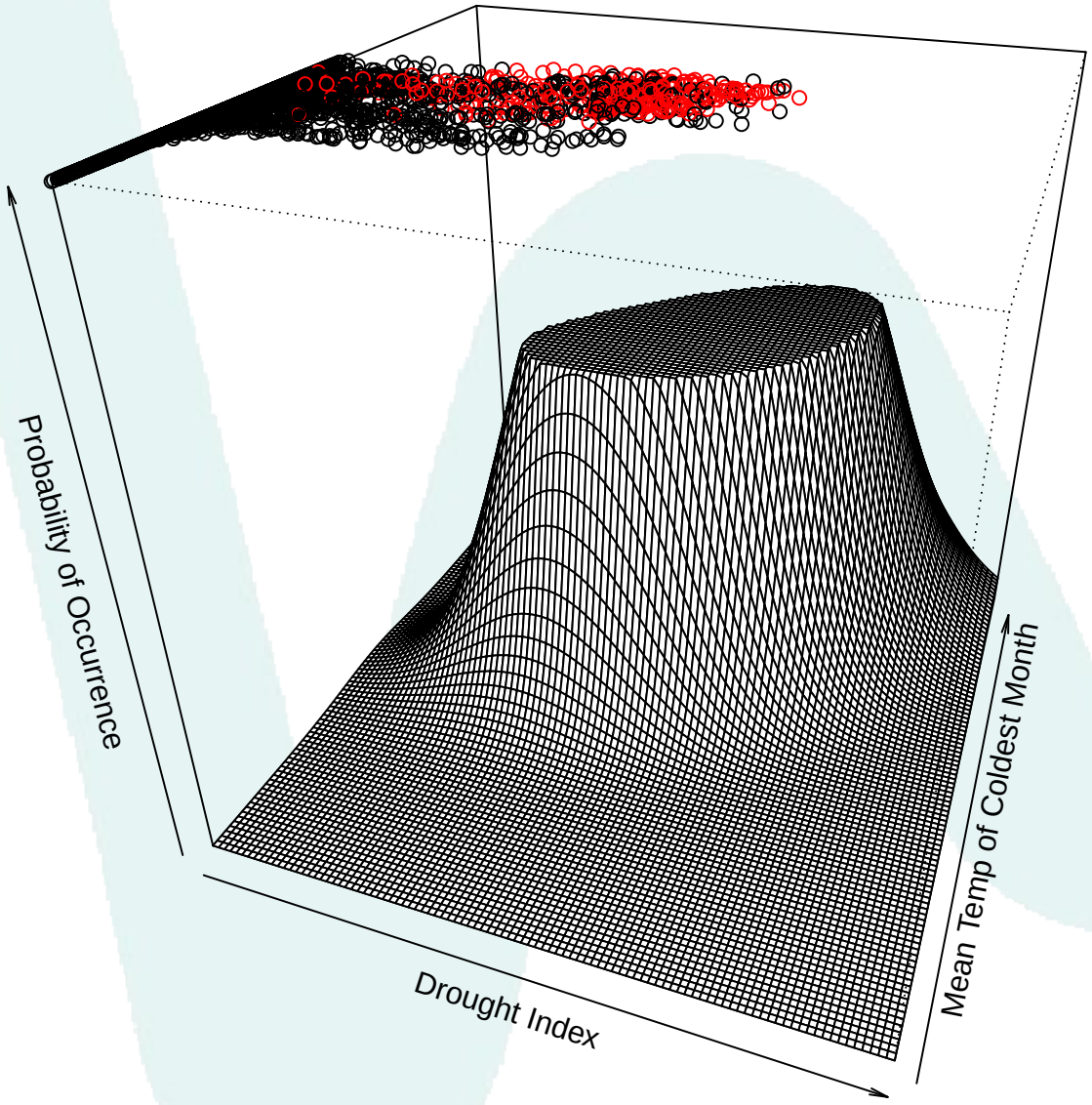
- Not limited to two variables. . .
- Consider *Fagus sylvatica* again
- Drought index and temperature variables (MTCO and MTWA)
- Plot Drought and MTWA; allow MTCO to vary

Fagus sylvatica - Common Beech

4. Using External Information

- Kermes Oak on Southern edge of Europe
- No information for “upper” end of climate envelope
- Modelled plateau just assumes upper ends are “similar” to lower ends

Quercus coccifera - Kermes Oak



Using External Information

- If available, can use information from
  - Biophysical understanding of species
  - Occurrences of species in other continents
- GBIF Backbone Taxonomy data set is worldwide
  - Quality/integrity not as good as *Atlas Florae Europaeae*
  - Shows Kermes Oak found in north Africa and parts of Middle East
  - GBIF Secretariat (2013)

Using External Information

- In *Atlas Florae Europaeae* maximum MTCO is around 12°C
- In GBIF 2% of presences occur where MTCO greater than 13°C
- This suggests the cone passes through $(13.0, \text{logit}\{0.02\})$ on MTCO axis

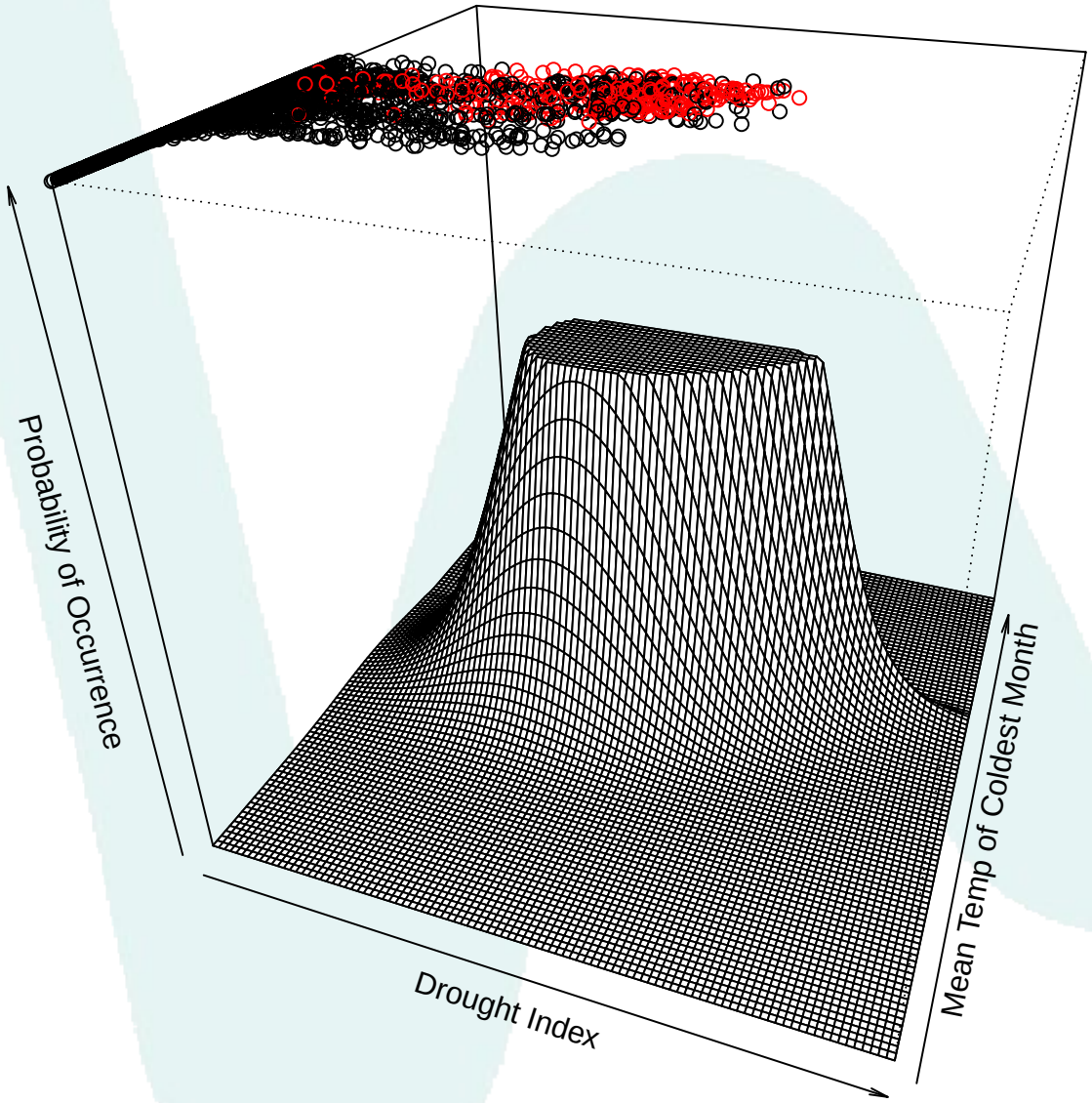
Using External Information

- Since there is a straight line between that point and apex, can work out slope:

$$\beta_{2,2} = \frac{a_z - \text{logit}\{0.02\}}{a_{x_2} - 13}$$

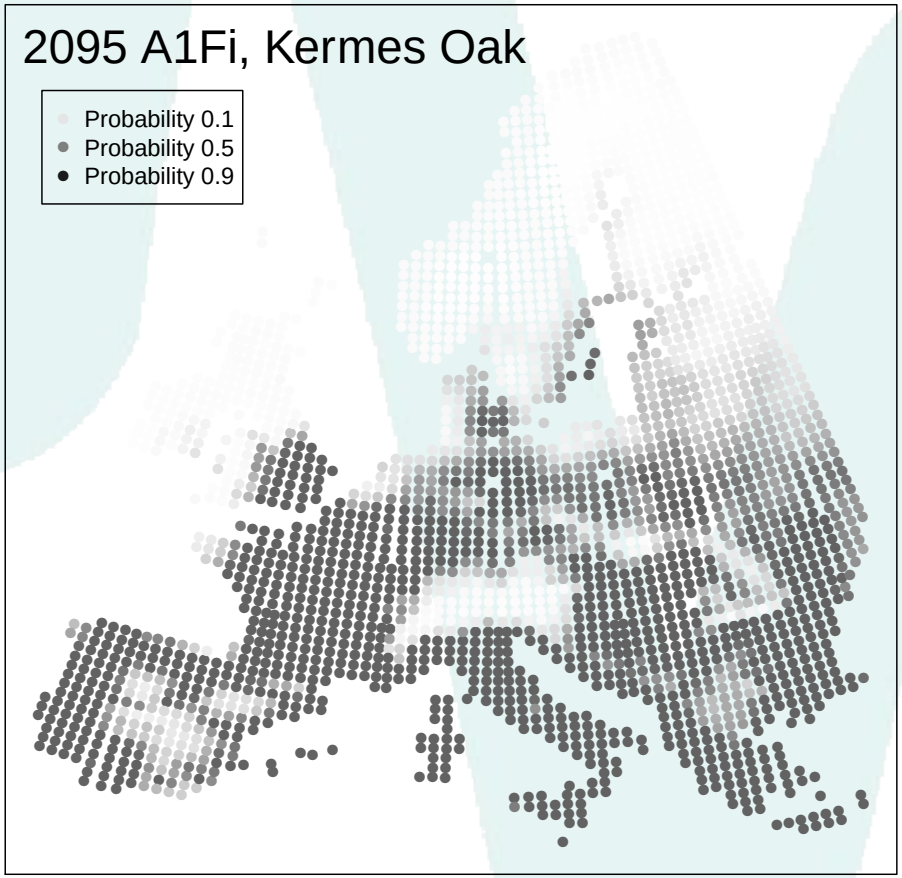
- Can do similar calculations for e.g. apex, or use a prior rather than a fixed value

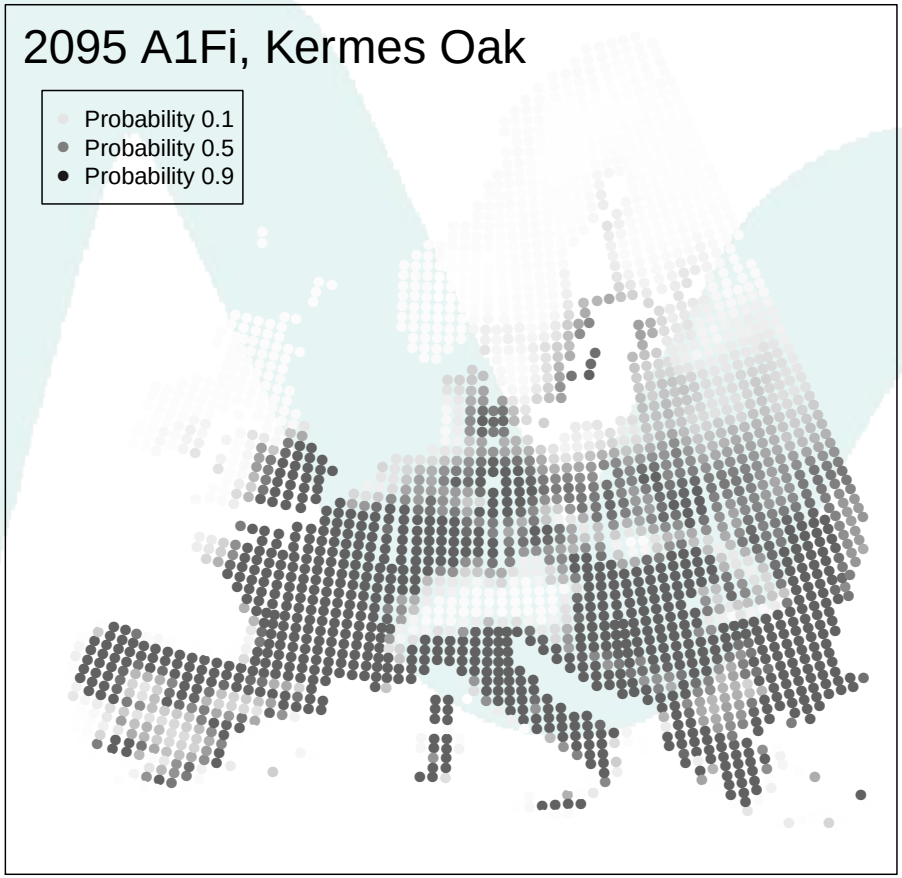
Quercus coccifera - Kermes Oak



Quercus coccifera - Kermes Oak

With and without external information, respectively.





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