The Quaternary biogeographic history of bryophytes: a window into their ability to face global change

Doctoral thesis defense

Alice Ledent, June 2019

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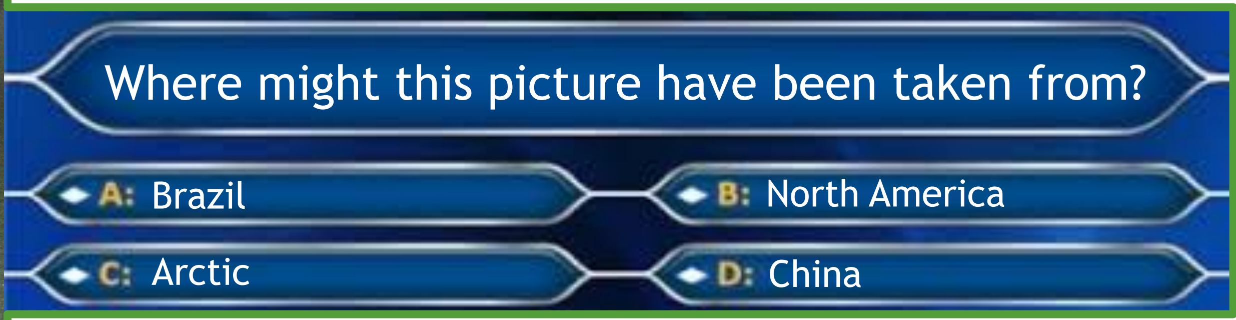
Doctoral thesis defense

Alice Ledent, June 2019

Introduction



Introduction

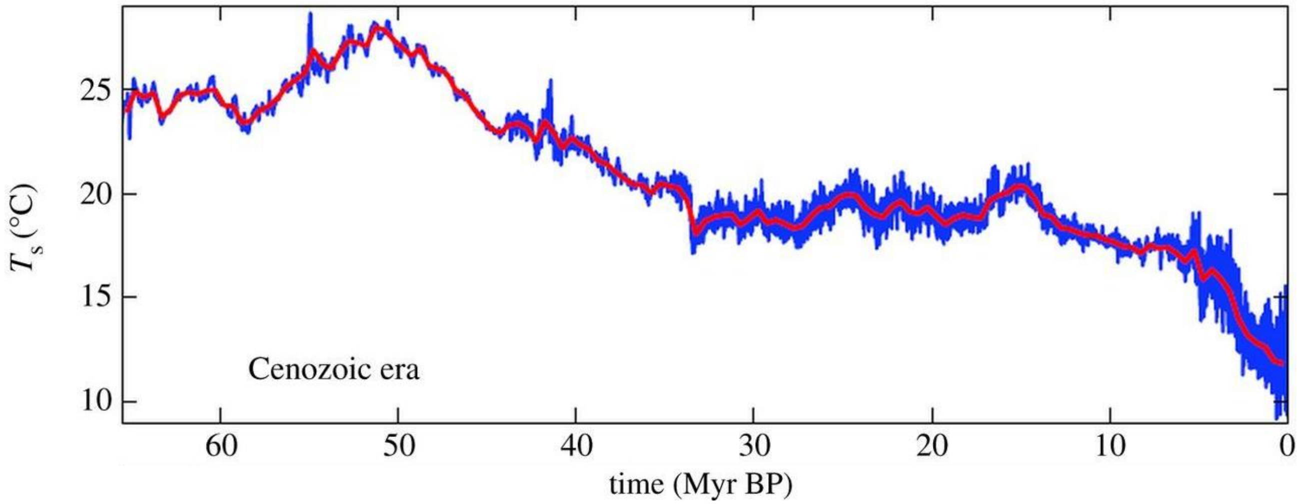
Where might this picture have been taken from?

- A: Brazil
- B: North America
- C: Arctic
- D: China

Introduction

- Climate changes impact the distribution of species

Hansen *et al.*, 2013



Surface temperature estimate for the past 65.5 Myrs

Introduction

- Climate changes impact the distribution of species
  - Quaternary period = high amplitude climatic oscillations
    - 2.4 Myrs ago – present
    - Glacial/interglacial periods

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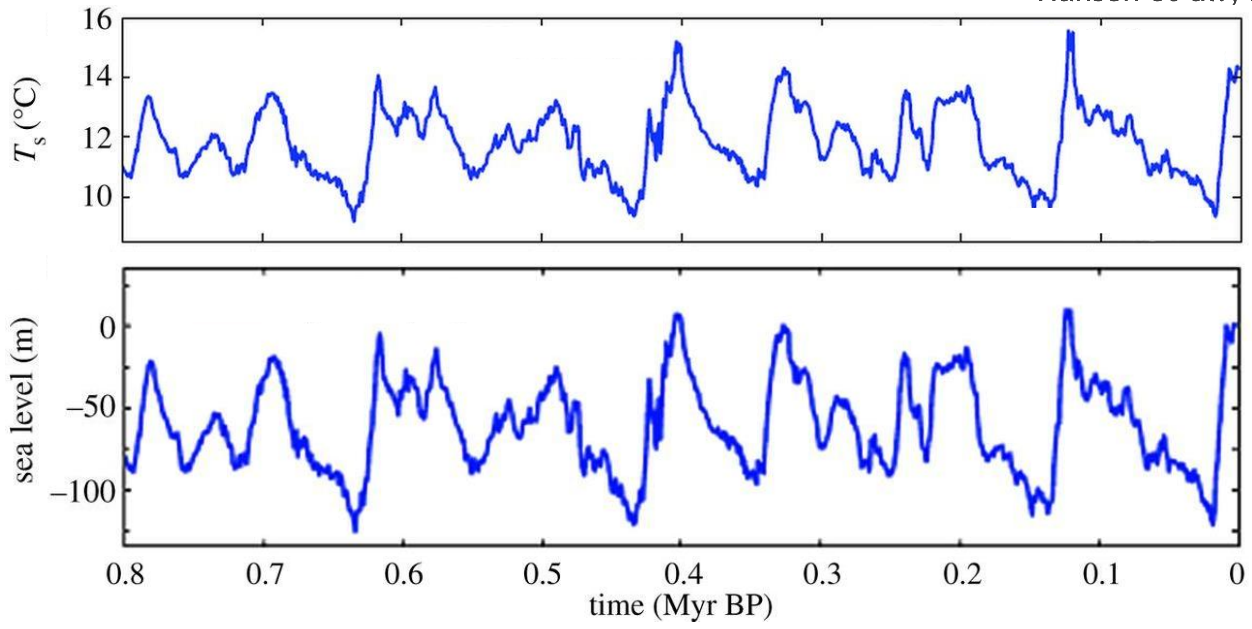
  - Quaternary period = high amplitude climatic oscillations
    - 2.4 Myrs ago – present
    - Glacial/interglacial periods
    - Temperatures and Ice-sheets extent fluctuations

Hansen *et al.*, 2013

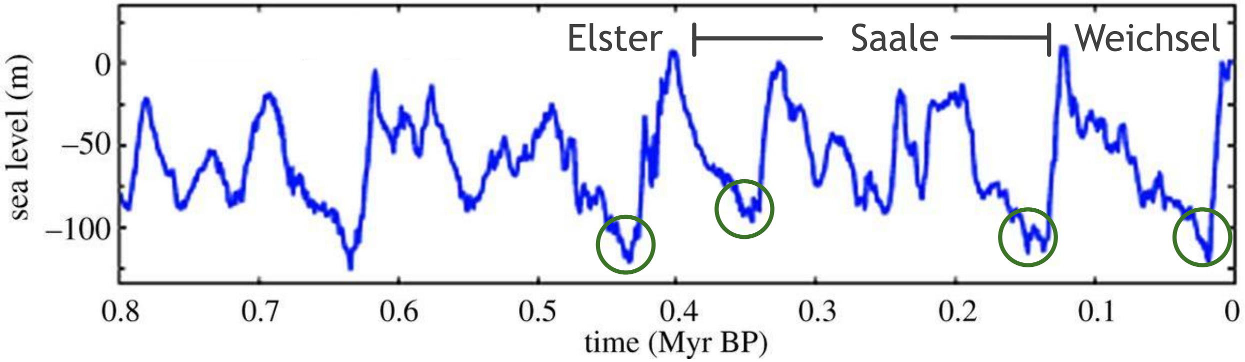


Surface temperature estimate and sea level as compared to current level for the past 800 Kyrs

Introduction

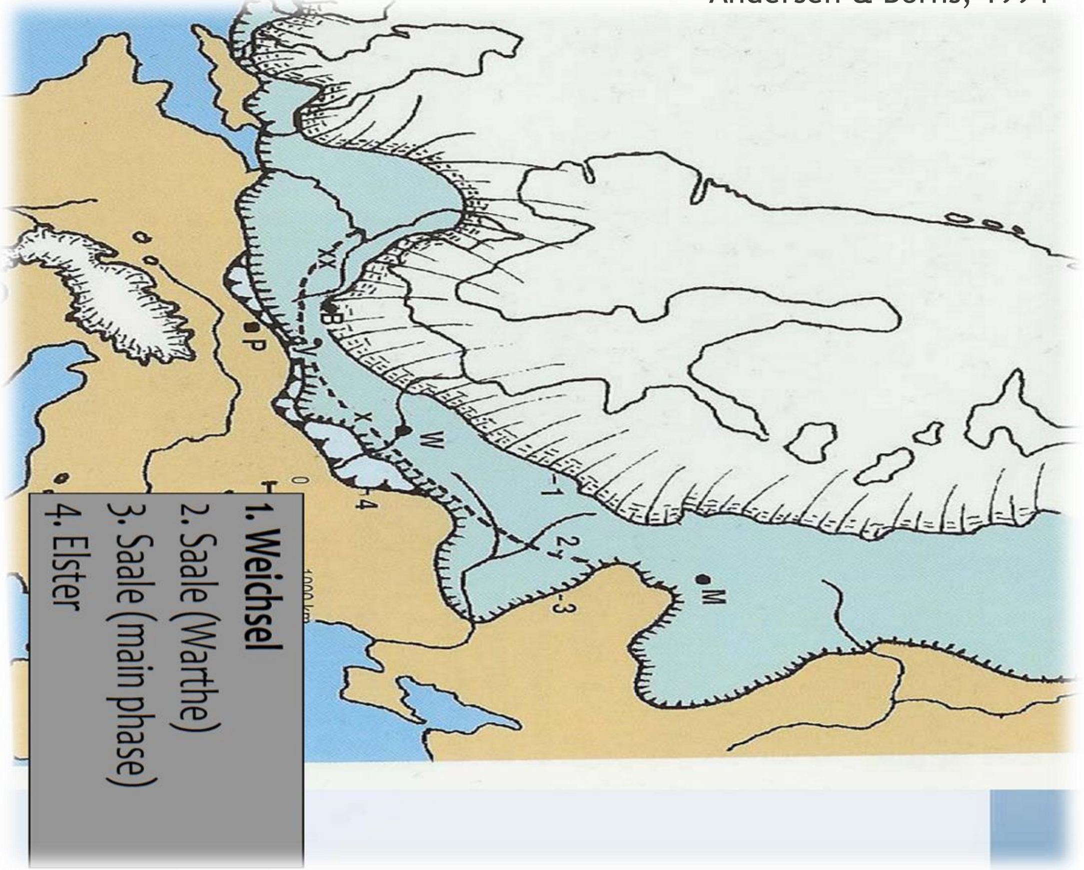
- Climate changes impact the distribution of species
  - Quaternary period = high amplitude climatic oscillations
    - 2.4 Myrs ago – present
    - Glacial/interglacial periods
    - Temperatures and Ice-sheets extent fluctuations

Hansen *et al.*, 2013



Sea level as compared to current level for the past 800 Kyrs

Andersen & Borns, 1994



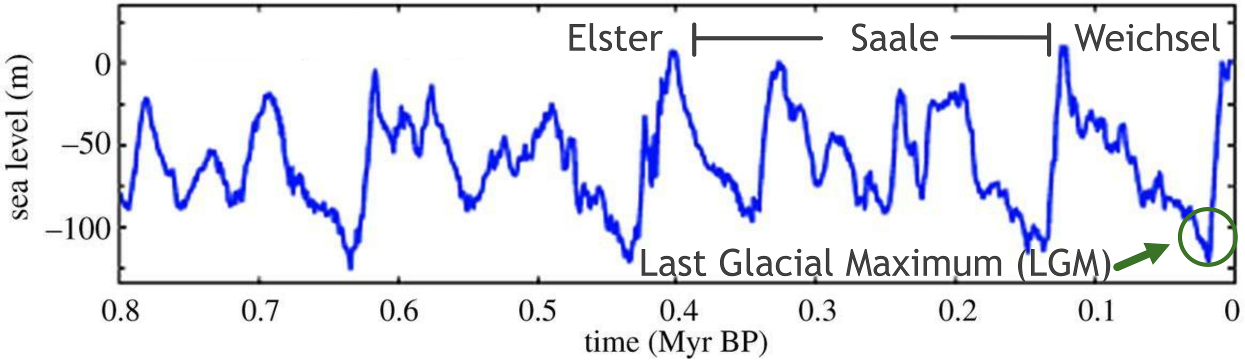
European ice-sheets max. extent of the 4 last glacial periods

Introduction

- Climate changes impact the distribution of species
  - Quaternary period = high amplitude climatic oscillations
    - 2.4 Myrs ago – present
    - Glacial/interglacial periods
    - Temperatures and Ice-sheets extent fluctuations
    - Last Glacial Maximum (LGM, *c.* 22,000 years ago)

→ Current species distributions shaped by LGM!

Hansen *et al.*, 2013



Sea level as compared to current level for the past 800 Kyrs

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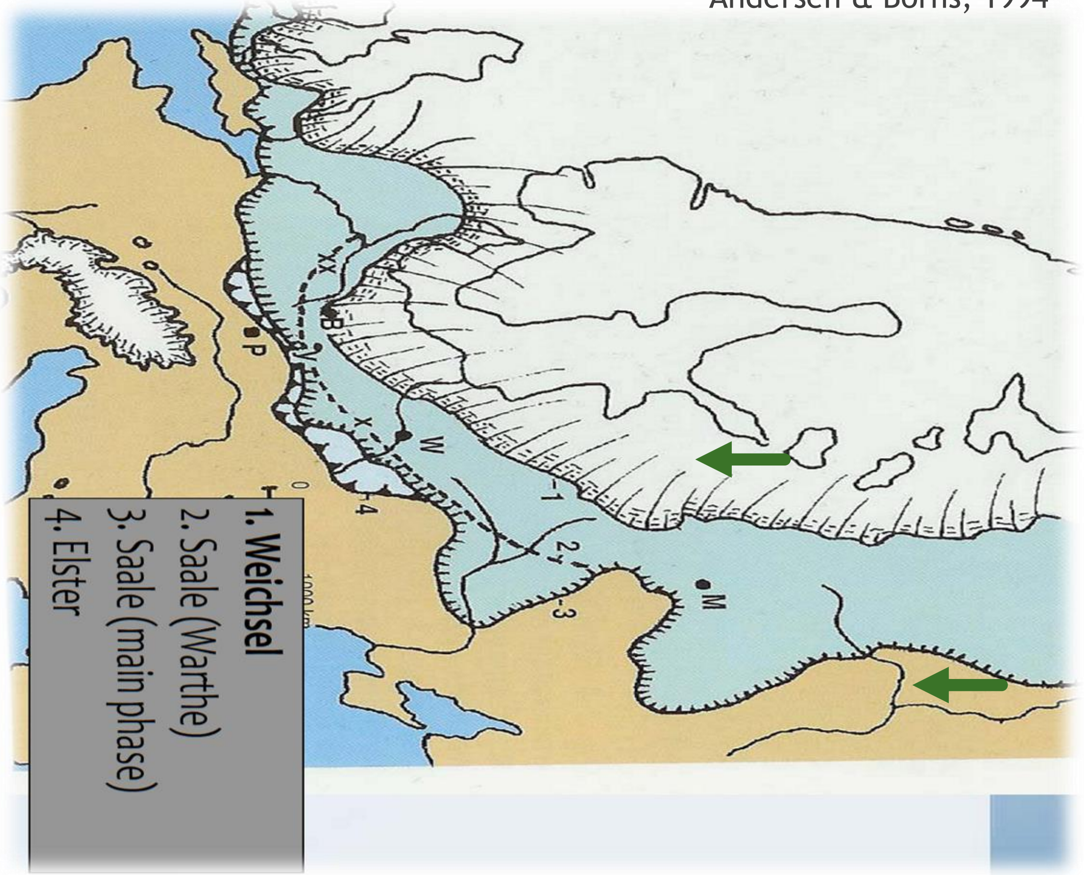


European ice-sheets max. extent of the 4 last glacial periods

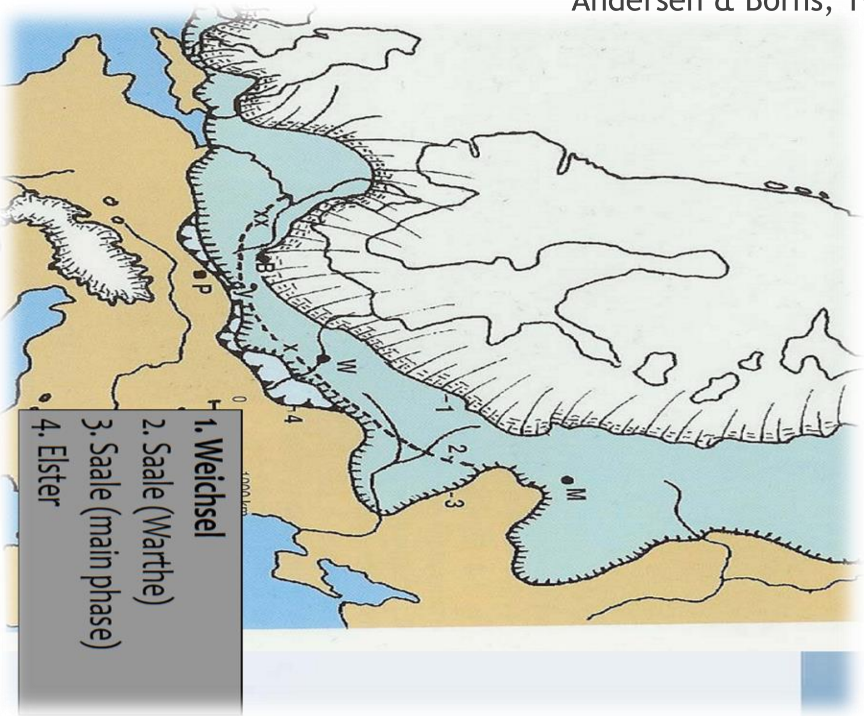
Introduction

- Europe during the Quaternary period = model region

Introduction

- Europe during the Quaternary period = model region
  - Ice-sheets extent fluctuating

Andersen & Borns, 1994

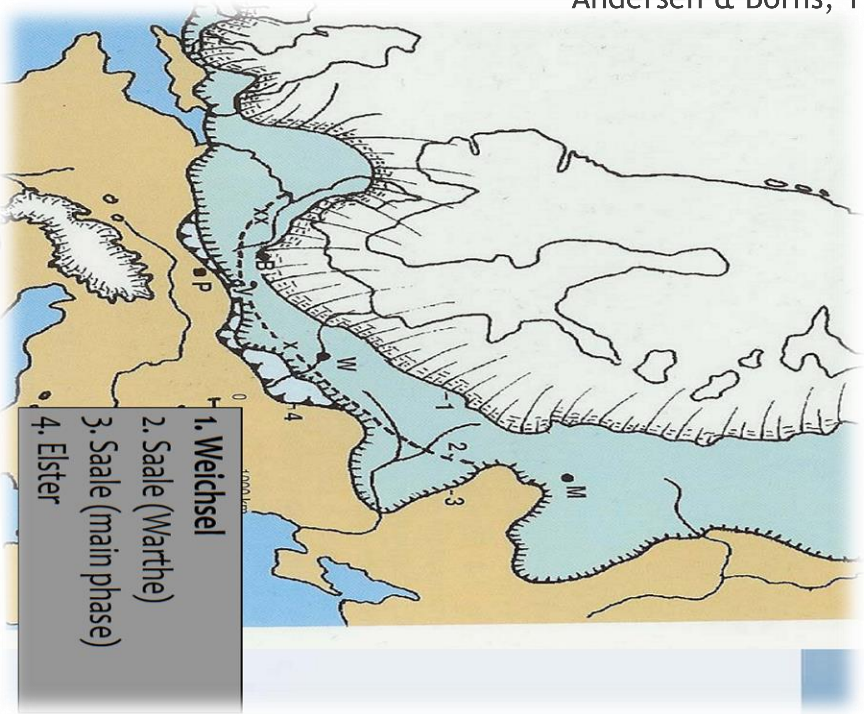


European ice-sheets max. extent of the 4 last glacial periods

Introduction

- Europe during the Quaternary period = model region
  - Ice-sheets extent fluctuating
  - E-W-oriented mountain ranges
    - Barriers to migration

Andersen & Borns, 1994



European ice-sheets max. extent of the 4 last glacial periods

Current European topography

Introduction

- Europe during the Quaternary period = model region

European regions ice-free at LGM

European regions covered in ice at LGM

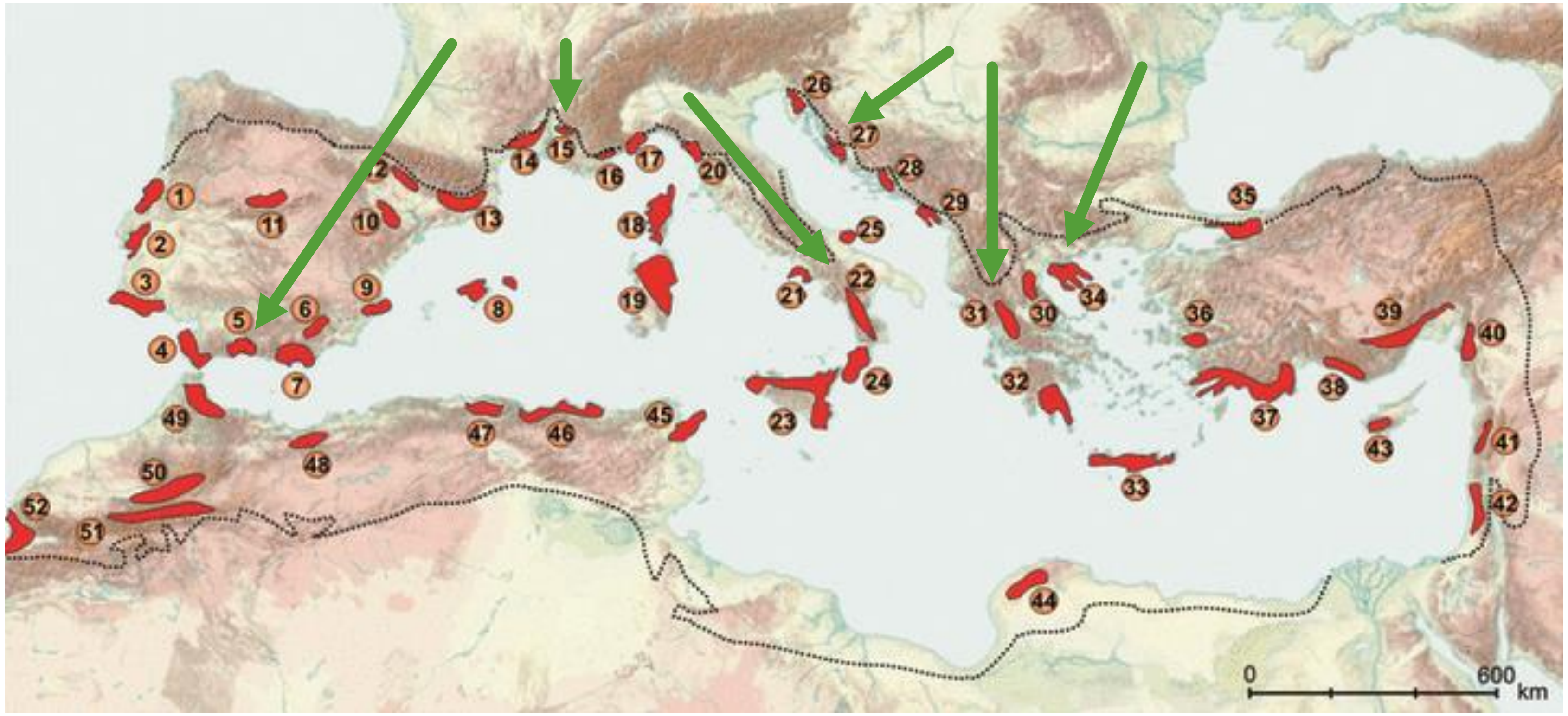
Introduction

- Distribution of ice-free European species during the Quaternary period

Introduction

- Distribution of ice-free European species during the Quaternary period
  - Southern *Refugia* Hypothesis (SRH)
    - Southwards migrations towards southern *refugia* during glacial periods

Médail & Diadema, 2009

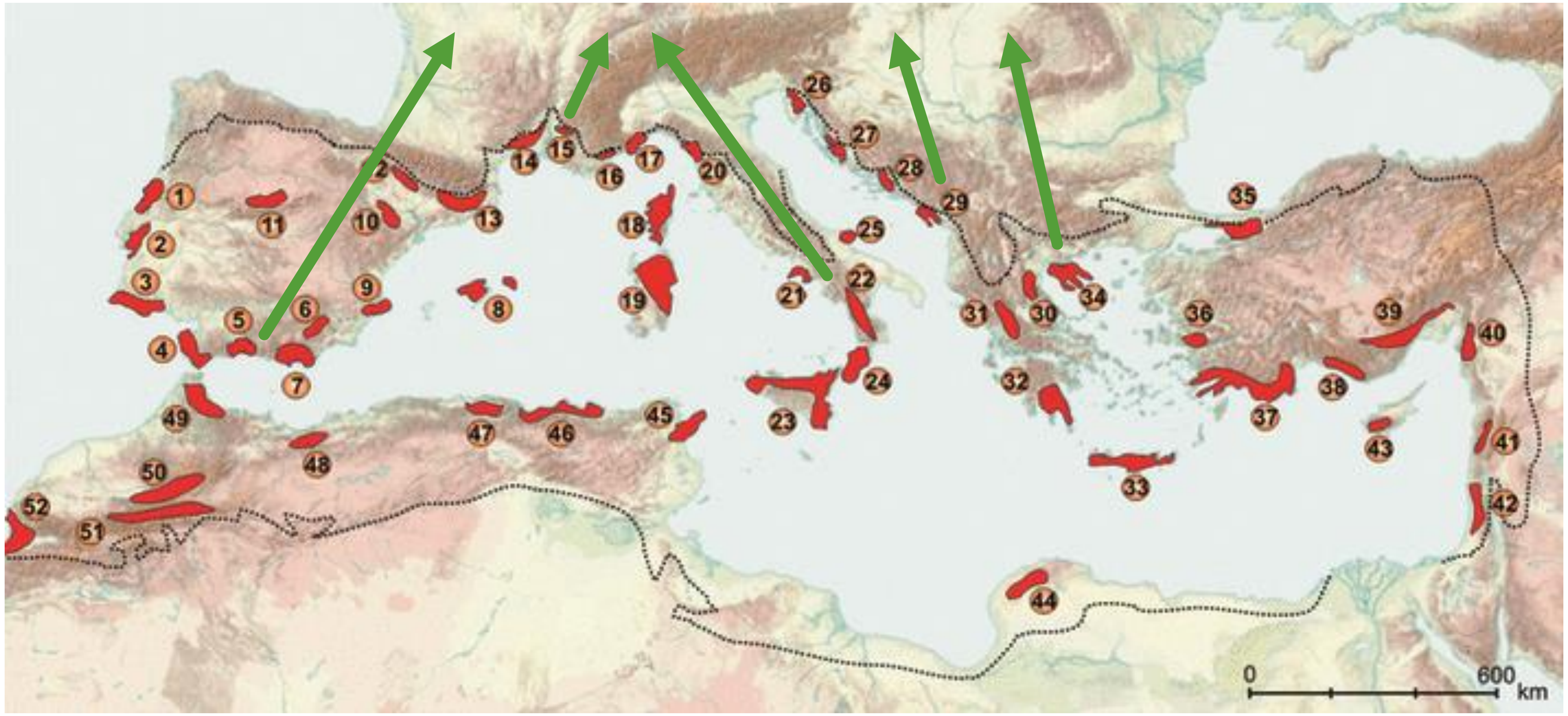


Distribution of 52 putative *refugia* within the Mediterranean region

Introduction

- Distribution of ice-free European species during the Quaternary period
  - Southern *Refugia* Hypothesis (SRH)
    - Southwards migrations towards southern *refugia* during glacial periods
    - Northwards migrations during interglacial periods

Médail & Diadema, 2009



Distribution of 52 putative *refugia* within the Mediterranean region

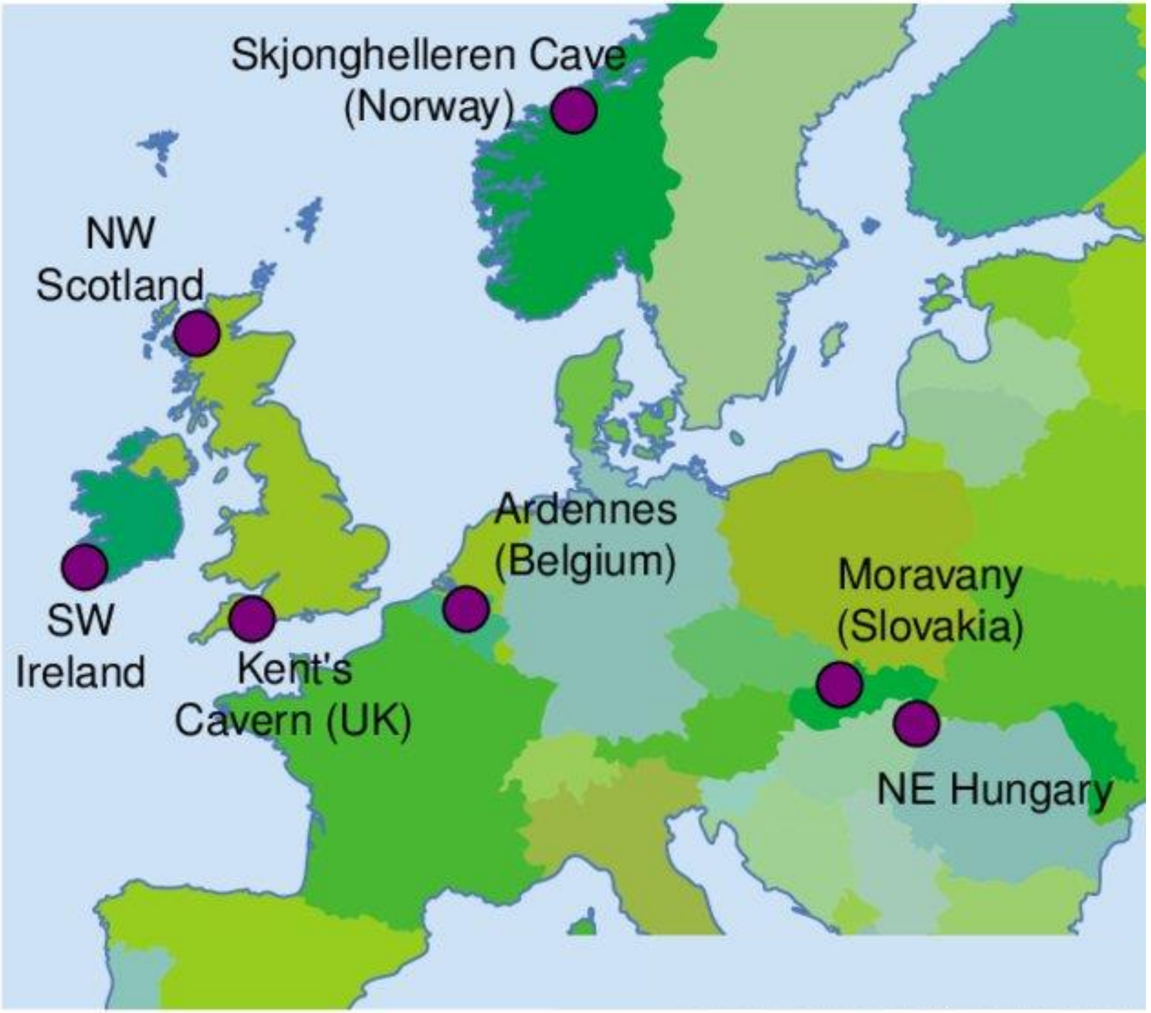
Introduction

- Distribution of ice-free European species during the Quaternary period
  - Northern micro-*Refugia* Hypothesis (NRH)
    - Southern mountains act as barriers to southwards migrations
    - Survival within northern micro-*refugia* during glacial periods


Red squirrel


Red deer

Stewart & Lister, 2001



Distribution of 7 putative northern micro-*refugia*

Introduction

- Distribution of ice-covered European species during the Quaternary period

European regions covered in ice at LGM

Introduction

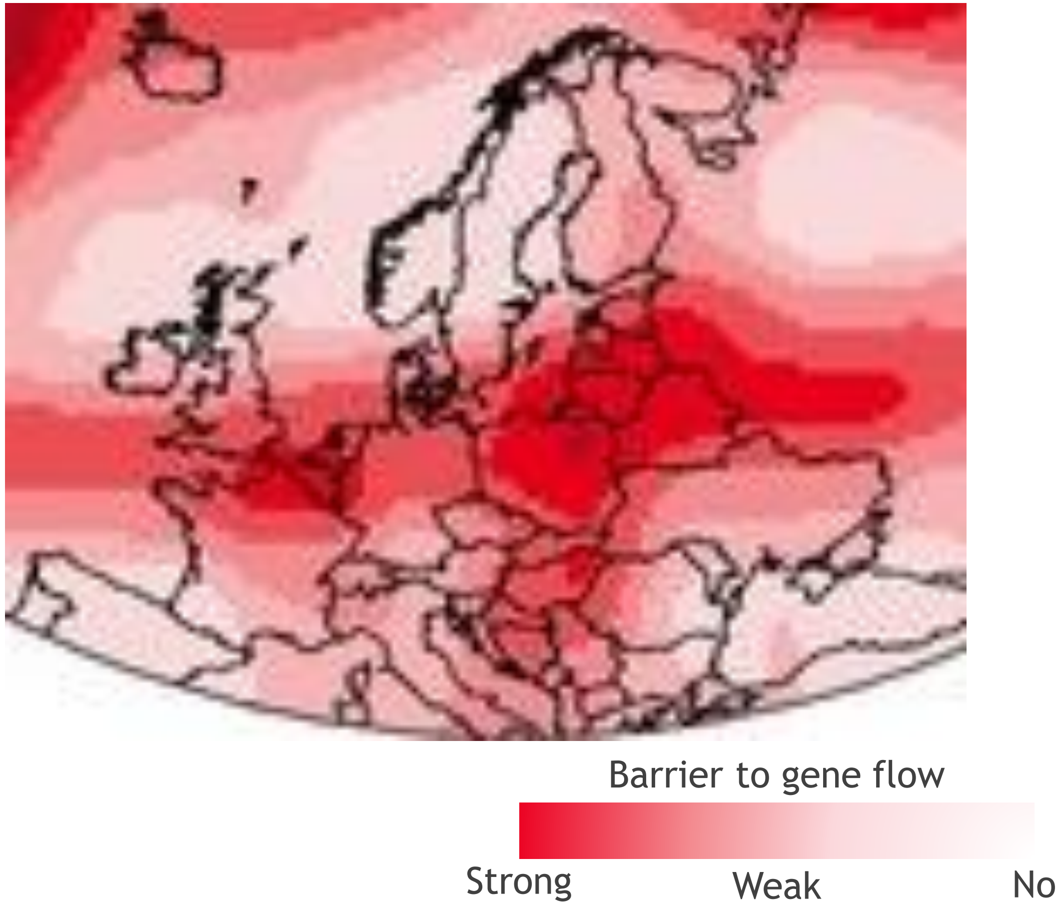
- Distribution of ice-covered European species during the Quaternary period
  - *Tabula rasa* hypothesis
    - No survival under the ice-sheets
    - Migrations towards lowland areas during glacial periods

Minuartia biflora

Introduction

- Distribution of ice-covered European species during the Quaternary period
  - Nunatak/micro-*refugia* hypothesis
    - No survival within lowland areas: too dry
    - Survival in micro-*refugia* within the ice-sheets during glacial periods

Eidesen *et al.*, 2013



Distribution of barriers to gene flow for ice-covered species

Introduction

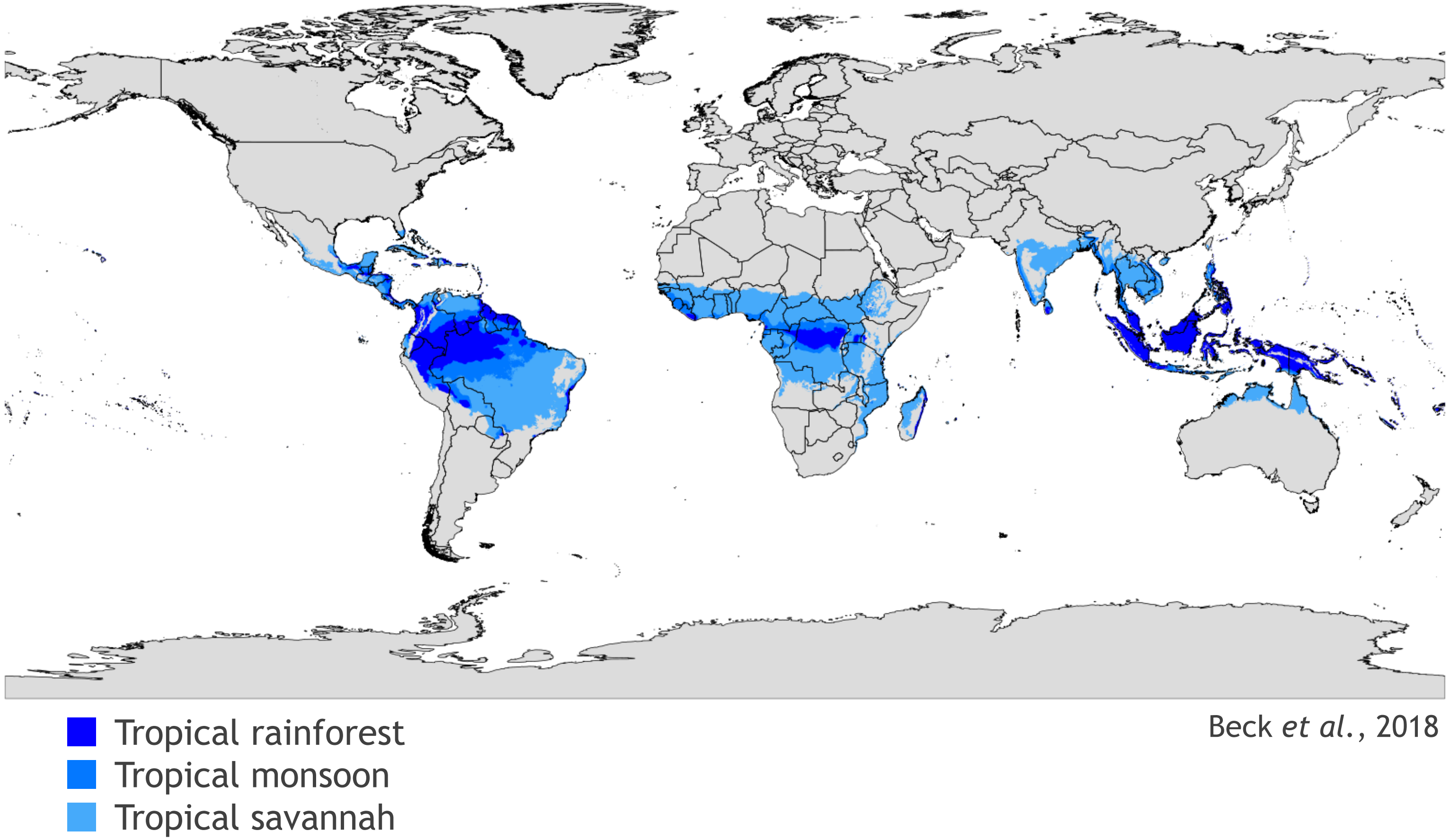
- Distribution of ice-covered European species during the Quaternary period
  - Southern mountains nunatak/micro-*refugia* hypothesis
    - Survival in Micro-*refugia* only in southern mountains during glacial periods
    - Recolonization of northern areas from southern mountains during interglacial periods

Ranunculus glacialis

Introduction

- Tropical regions during the Quaternary period
  - Less studied

Tropical regions

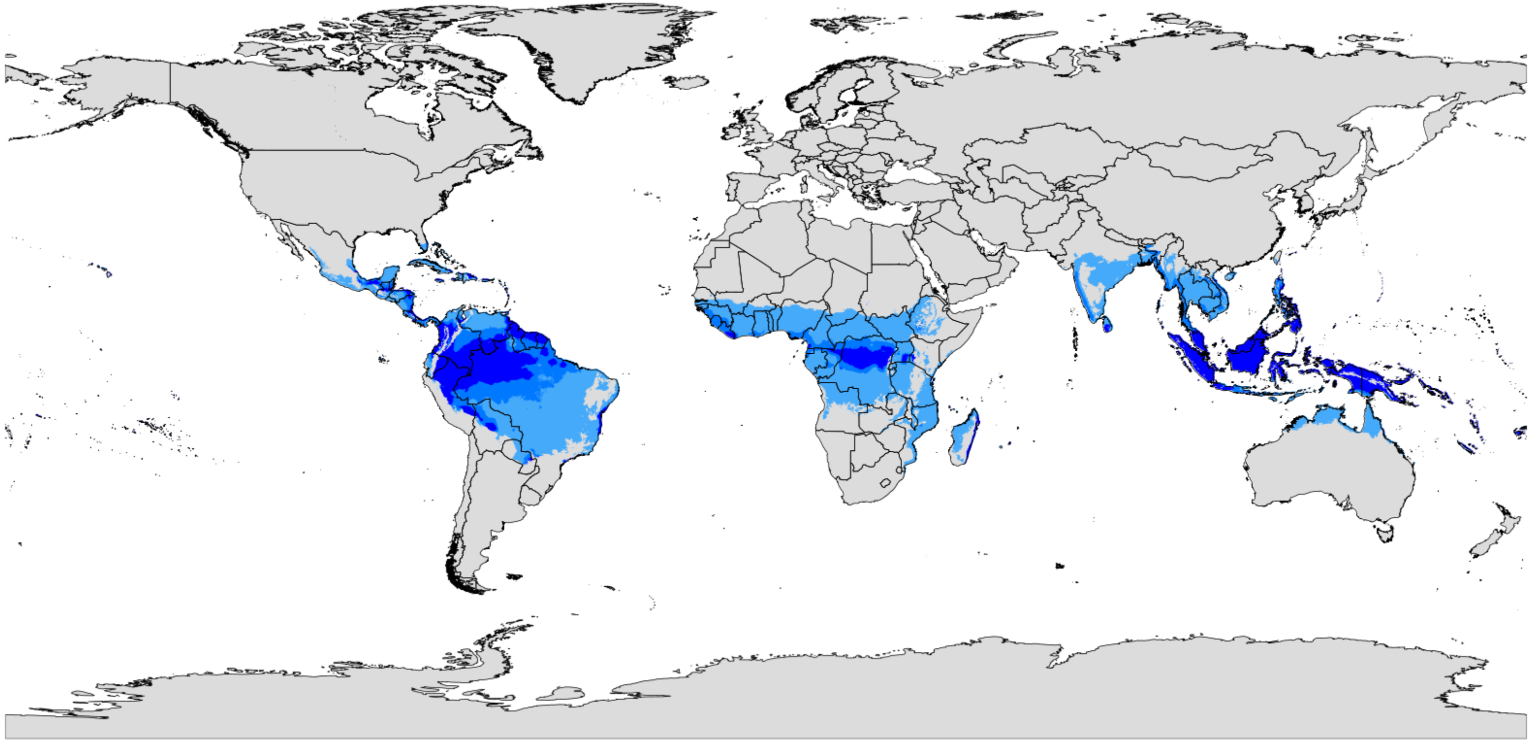


Beck *et al.*, 2018

Introduction

- Tropical regions during the Quaternary period
  - Less studied
    - No ice-sheet
    - Lack of fossils

Tropical regions



- Tropical rainforest
- Tropical monsoon
- Tropical savannah

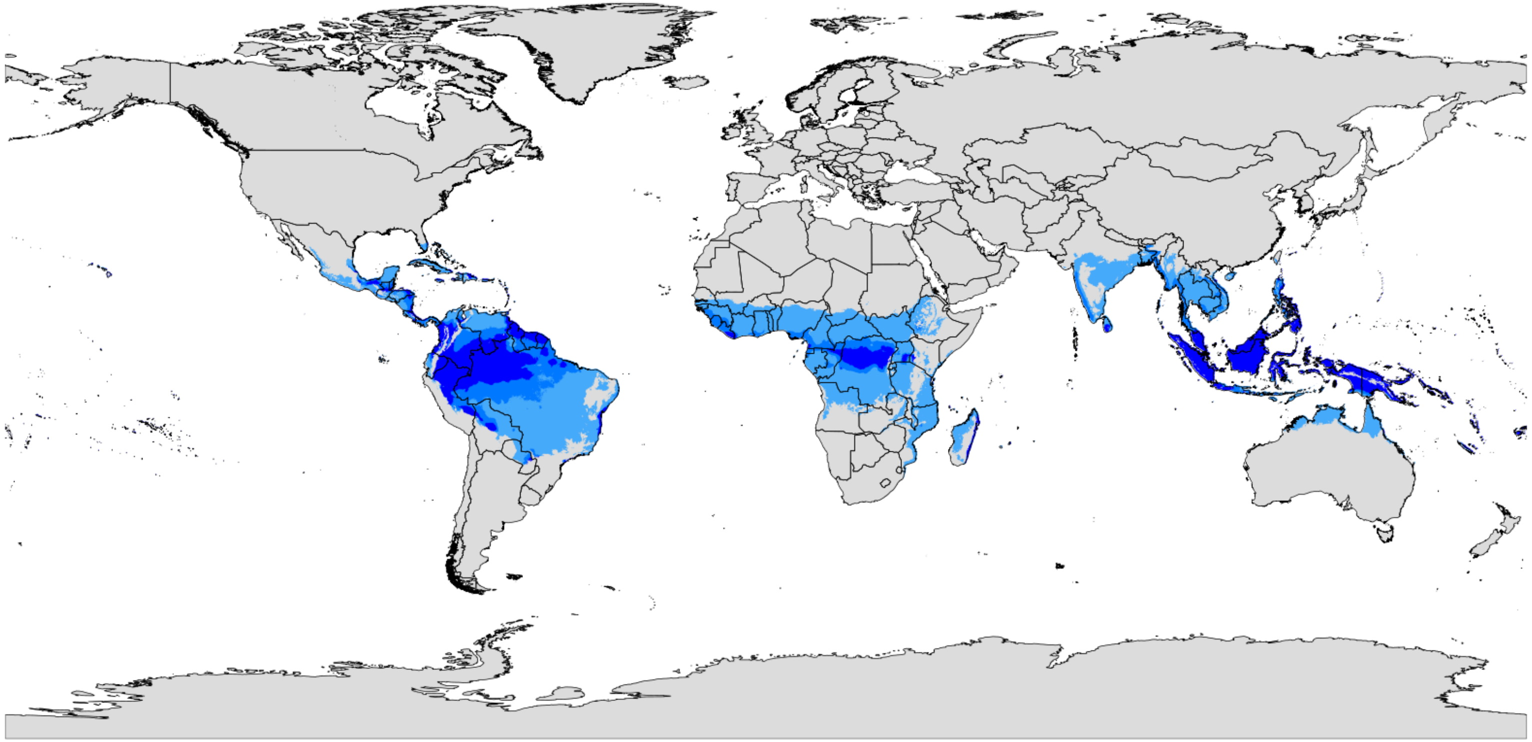
Beck *et al.*, 2018

Introduction

- Tropical regions during the Quaternary period
  - Less studied
    - No ice-sheet
    - Lack of fossils
  - Lowland tropical regions
    - Homogeneous environments
      - No barriers to migration
      - ↘ ß-diversity

Condit *et al.*, 2002

Tropical regions

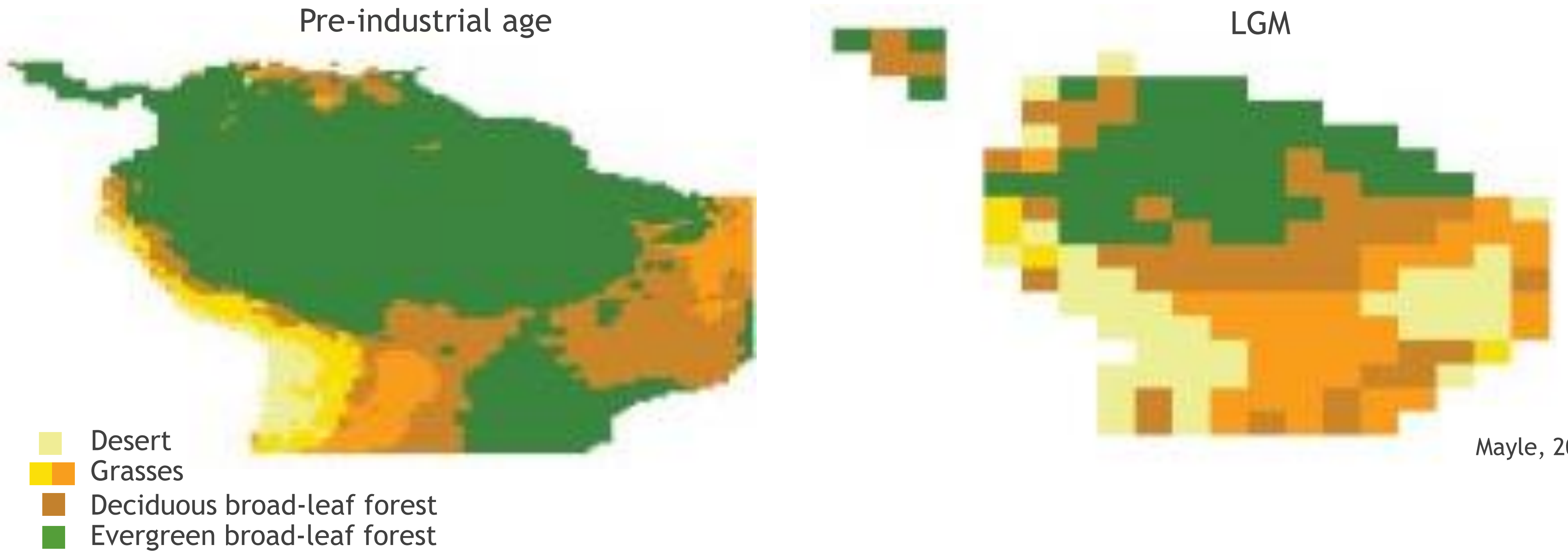


Tropical rainforest
Tropical monsoon
Tropical savannah

Beck *et al.*, 2018

Introduction

- Distribution of lowland Amazonian species during the Quaternary period
  - Contractions of the lowland evergreen forest during glacial periods



Mayle, 2004

Dynamic vegetation models of Amazonia

Model organism: bryophytes

Introduction

- Bryophytes and climate changes
  - Non-vascular = cannot pump up water from soil
  - Poïkilohydric = drought-tolerant, not resistant
  - Lower temperature *optima* than angiosperms

Targionia hypophylla under humid conditions

Targionia hypophylla under dry conditions

1 cm

Introduction

- Bryophytes and climate changes
  - Non-vascular = cannot pump up water from soil
  - Poïkilohydric = drought-tolerant, not resistant
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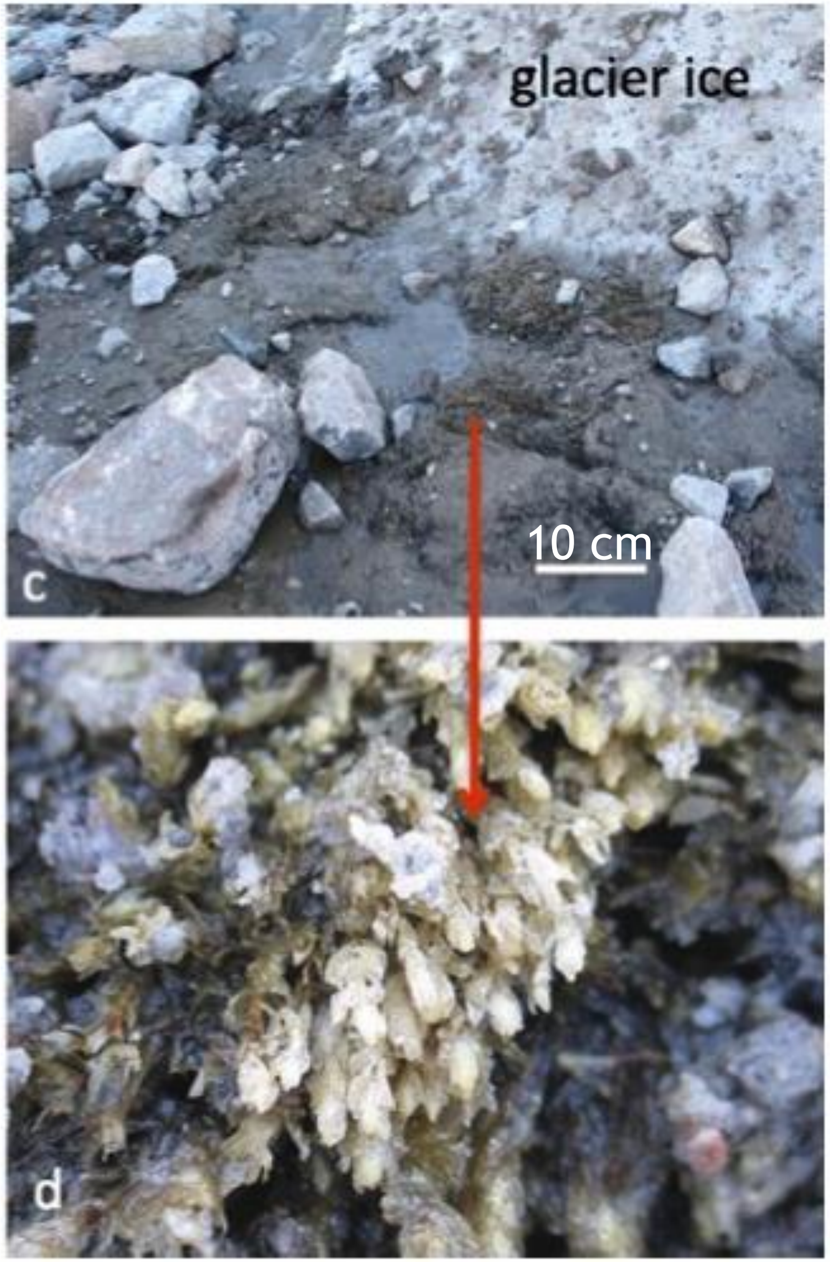
Sensitive to climate changes

Introduction

- Bryophytes and climate changes
  - Non-vascular = cannot pump up water from soil
  - Poïkilohydric = drought-tolerant, not resistant
  - Lower temperature *optima* than angiosperms
  - High cold-tolerance
    - Survive in ice and regenerate after 100's to 1000's of years

→ Good candidates for the northern and nunatak micro-*refugia* hypotheses

La Farge *et al.*, 2013



Emerging subglacial populations of *Aulacomnium turgidum*

Introduction

Whitaker & Edwards, 2010

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  - Non-vascular = cannot pump up water from soil
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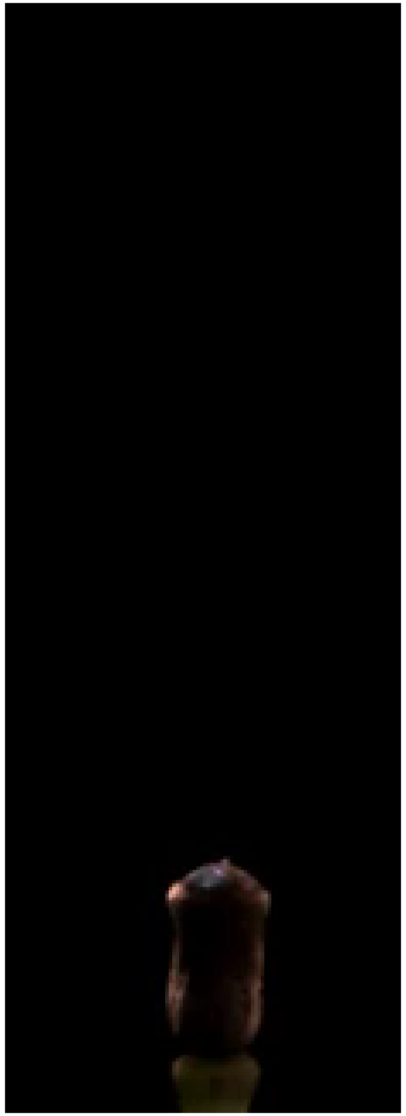
  - Lower temperature *optima* than angiosperms
  - High cold-tolerance
  - High dispersal capacities
    - Small highly dispersive spores (*c.* 20 µm)



Sphagnum affine capsule explosion

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    - Small highly dispersive spores (*c.* 20 µm)
    - Ability to cross oceans

Stenøien *et al.*, 2010

Introduction

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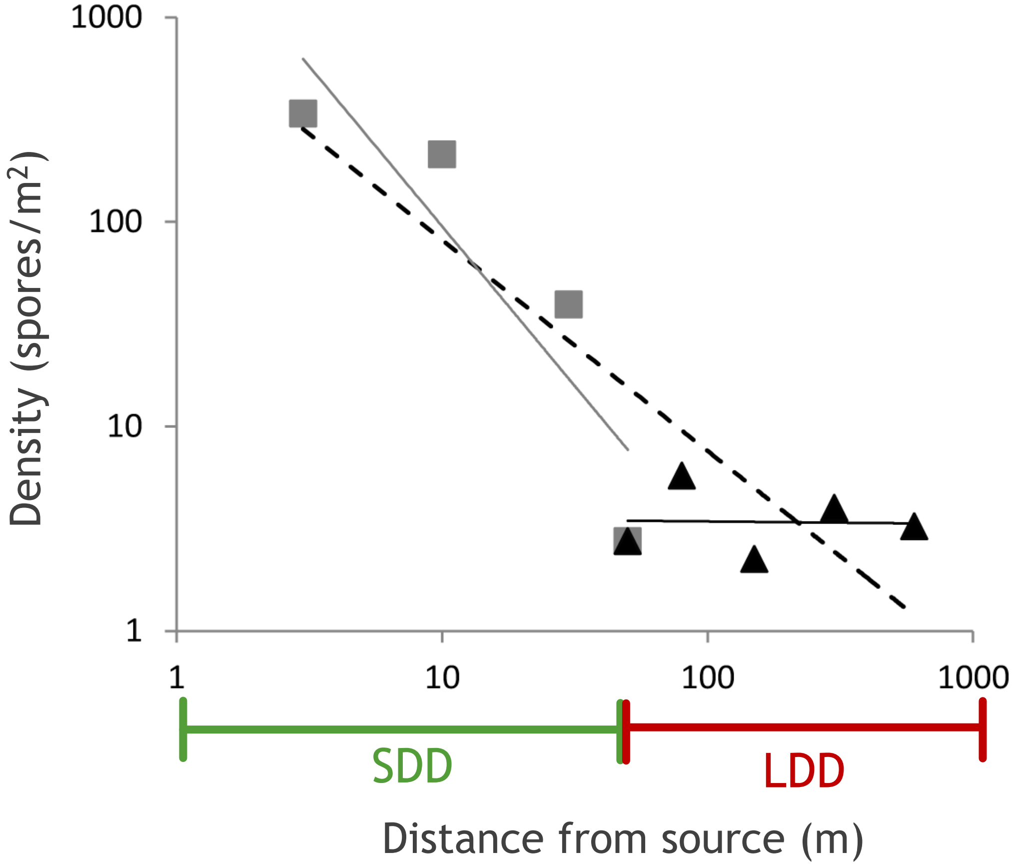
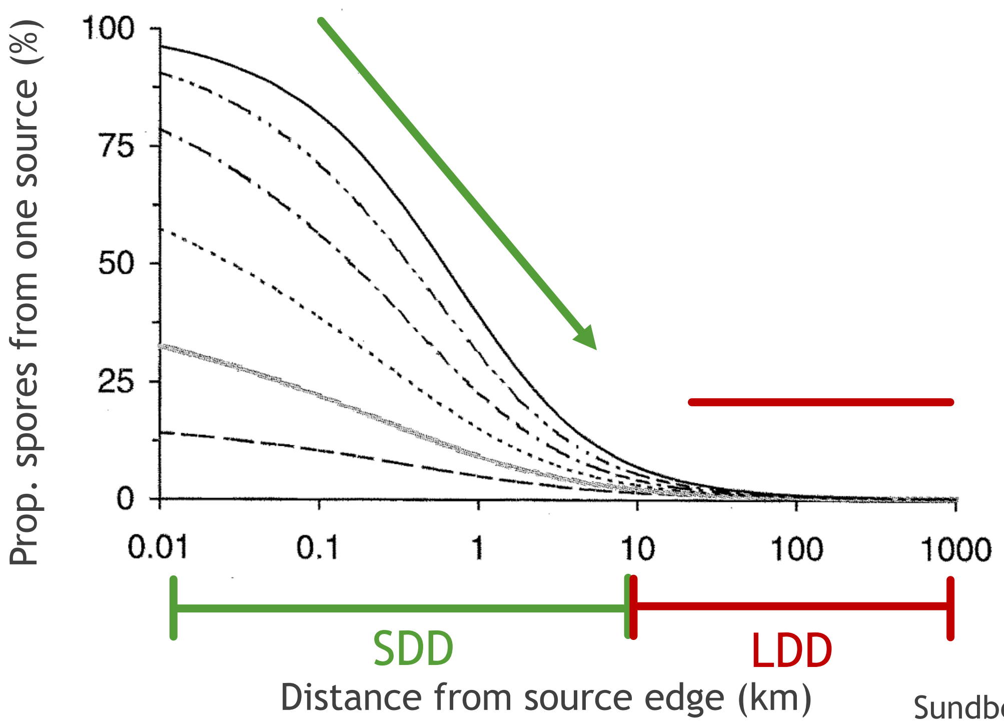
    - Small highly dispersive spores (*c.* 20 µm)
    - Ability to cross oceans
    - Fat-tailed deposition curves
      - SDD: deposition decreases with increasing distances
      - LDD: deposition stable with increasing distances



Lönnell *et al.*, 2012

Introduction

- Bryophytes and climate changes
  - High dispersal capacities
    - Fat-tailed deposition curves → **inverse isolation hypothesis**
      - SDD: individual deposition decreases with increasing distances ↘
      - LDD: individual deposition stable with increasing distances —



Sundberg, 2005

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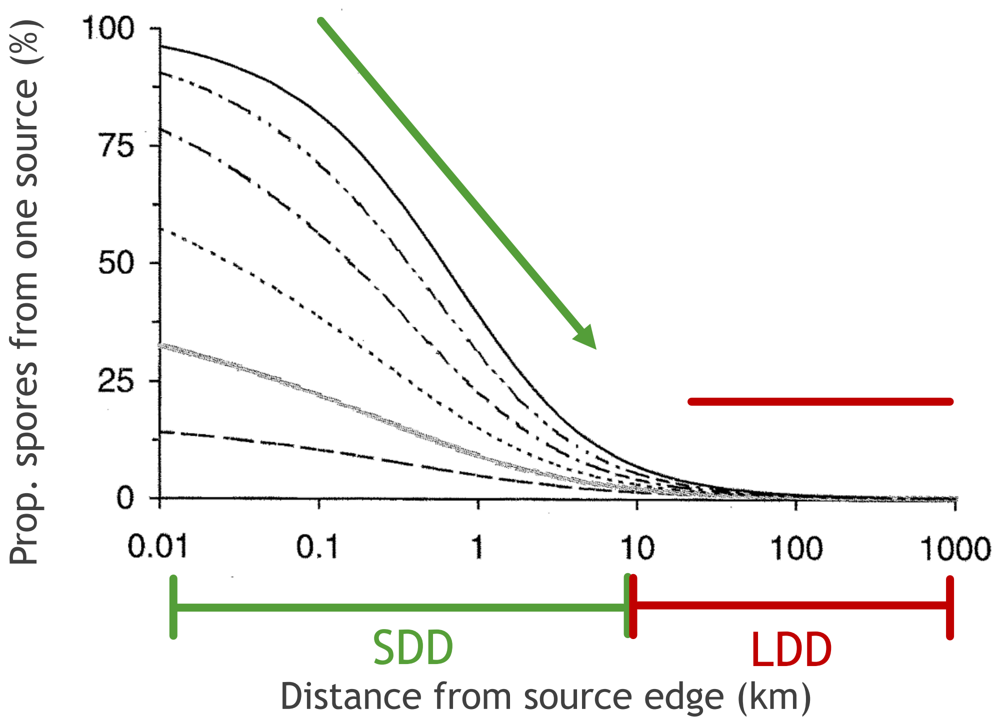

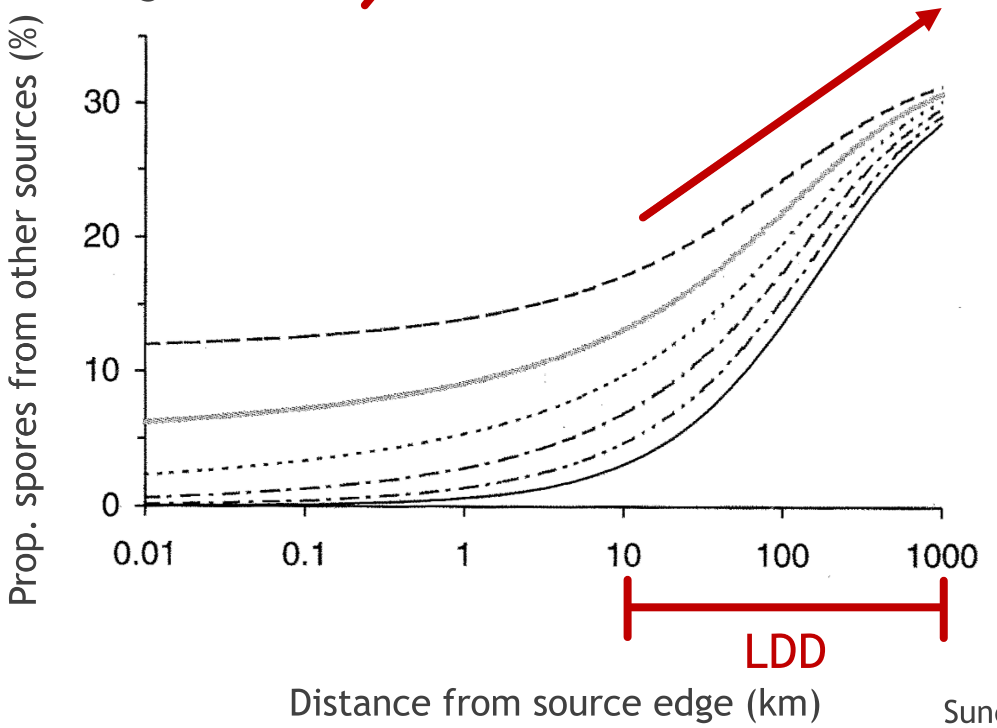

Sundberg, 2005

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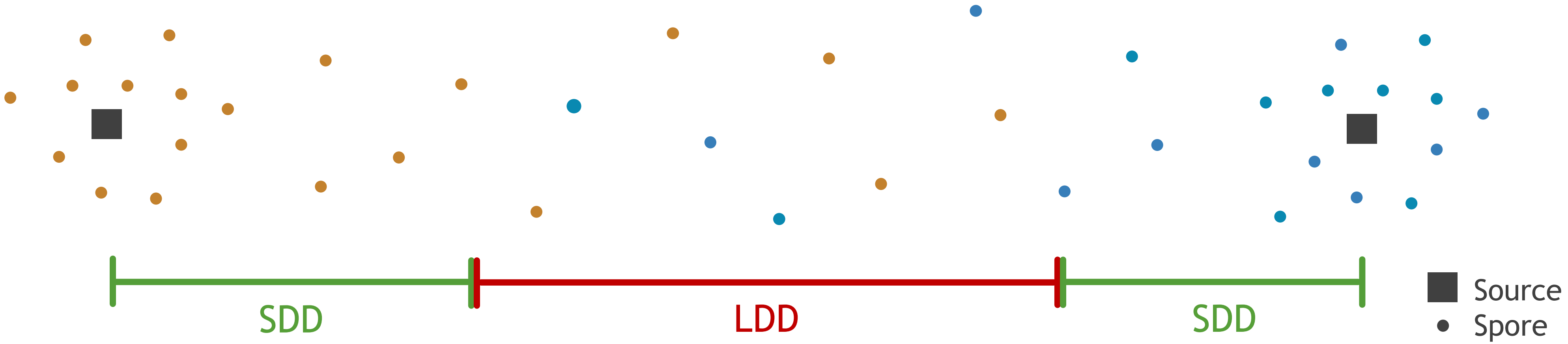

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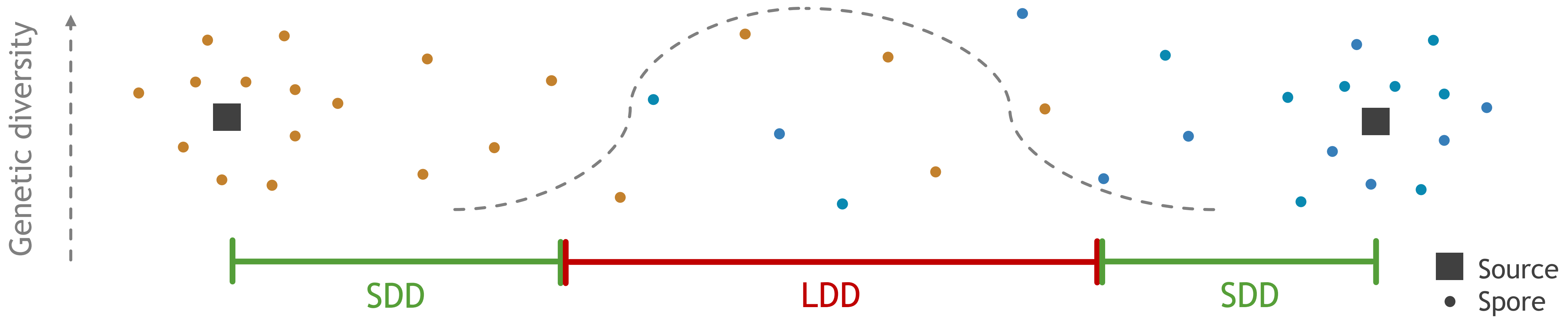
      - LDD: individual deposition stable with increasing distances —
      - LDD: populational deposition increases with increasing distances ↗

      → Higher genetic diversity of colonizing propagules with increasing isolation !

      → Counteracting genetic differentiation

      → No Isolation-By-Distance (IBD) beyond the range of SDD due to efficient LDD



Introduction

- Bryophytes and climate changes
  - High dispersal capacities
    - Ability to cross oceans

      → Extra-European postglacial recolonization?

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    - Inverse isolation hypothesis: no IBD beyond the range of SDD due to efficient LDD
      - Erasure of historical events?
      - No allopatric differentiation/speciation → Other speciation mechanisms? IBE?

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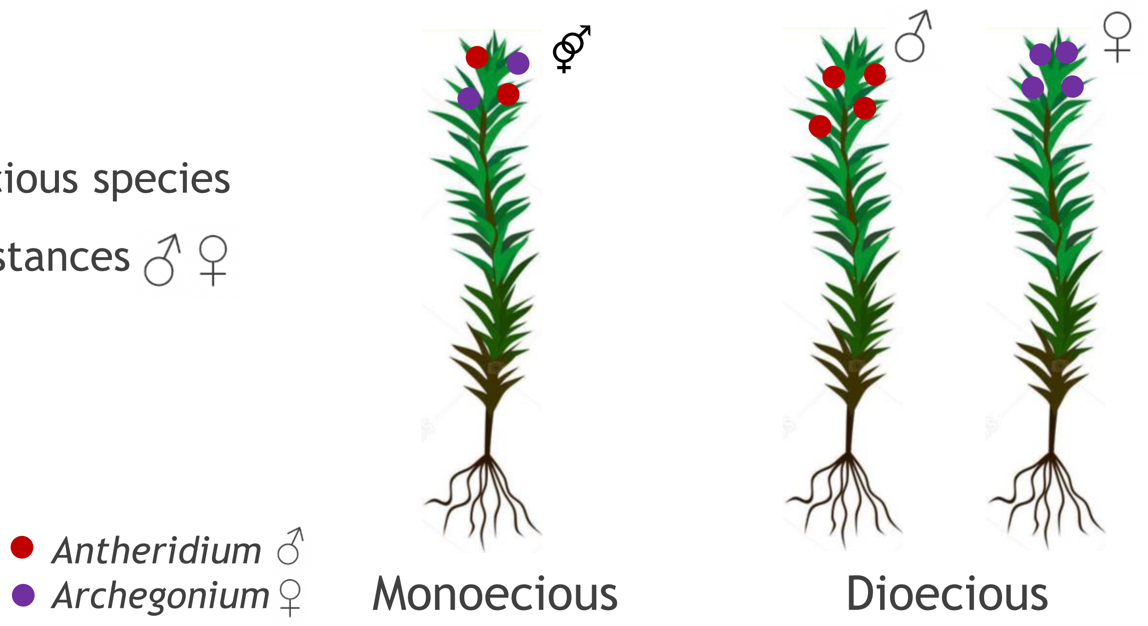
      - No allopatric differentiation/speciation → Other speciation mechanisms? IBE?
    - Inverse isolation hypothesis application
      - High dispersal capacities → higher in monoecious species

        ↗ sporophyte production because of ↘ distances ♂ ♀



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      - Random colonization of propagules → higher in homogeneous environments

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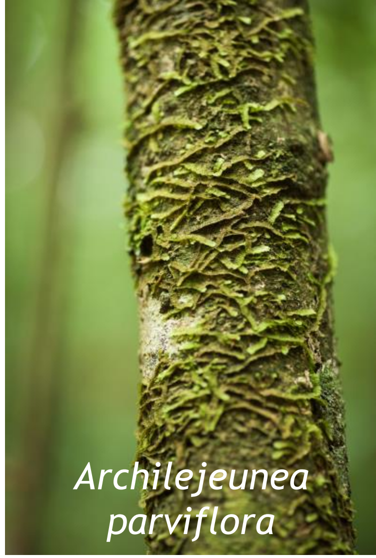
Lowland tropical bryophytes characterized by “higher than normal levels of monoecism”

Longton & Schuster, 1983

Across homogeneous lowland Amazonia “epiphytic bryophytes behave as one single metacommunity”

Mota & ter Steege, 2015

Introduction



Archilejeunea parviflora

- Bryophytes and climate changes
  - High dispersal capacities
    - Ability to cross oceans

      → Extra-European postglacial recolonization?
    - Inverse isolation hypothesis: no IBD beyond the range of SDD due to efficient LDD
      - Erasure of historical events?
      - No allopatric differentiation/speciation → Other speciation mechanisms? IBE?
    - Inverse isolation hypothesis application
      - High dispersal capacities → higher in monoecious species
      - Random colonization of propagules → higher in homogeneous environments

      } Characterize lowland Amazonian bryophytes!

→ Inverse isolation hypothesis is likely to apply to lowland Amazonian bryophytes!

Research aims

Research aims

How bryophytes responded to Quaternary climate changes,

in Europe, E-W-oriented mountain ranges acting as barrier to migration?

in lowland Amazonia, homogeneous without apparent barrier to migration?

Research aims

How bryophytes responded to Quaternary climate changes,

in Europe, E-W-oriented mountain ranges acting as barrier to migration?

in lowland Amazonia, homogeneous without apparent barrier to migration?

Specifically, we tested:

1. Erasure of historical events due to efficient LDD? (H1)
2. IBE as a differentiation/speciation mechanism? (H2)
3. Post-glacial history of bryophytes? (H3)
   A. In Europe
   B. In lowland Amazonia (ongoing study)

Taxonomic & molecular sampling

Taxonomic & molecular sampling

Europe

- 12 ice-free and 3 ice-covered species
- Holarctic

Lowland Amazonia

- 10 species
- 44,000 km^2 area in the Rio Negro Basin

Taxonomic & molecular sampling

Europe

- 12 ice-free and 3 ice-covered species
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  - 1729 samples
    - *Herbaria*

Lowland Amazonia

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Taxonomic & molecular sampling

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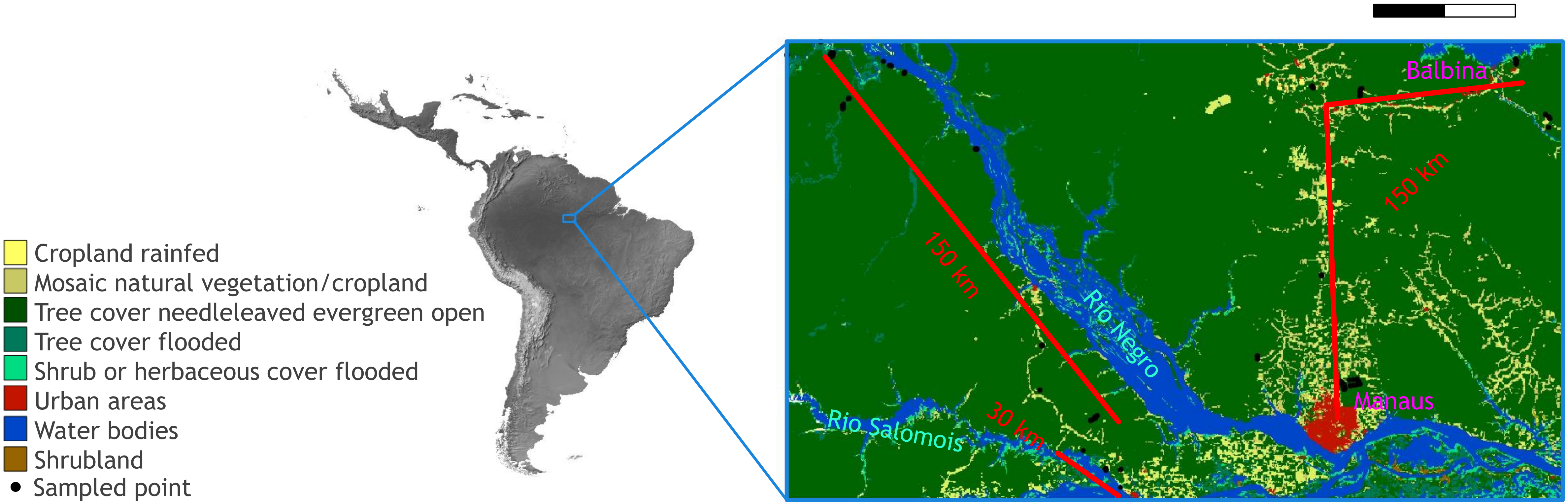
Lowland Amazonia

- 10 species
- 44,000 km^2 area in the Rio Negro Basin
  - 353 samples
    - Team sampling: 3 transects



Taxonomic & molecular sampling

Europe

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Lowland Amazonia

- 10 species
- 44,000 km^2 area in the Rio Negro Basin
  - 353 samples
    - Team sampling: 3 transects
    - 2 forest types

white-sand forest

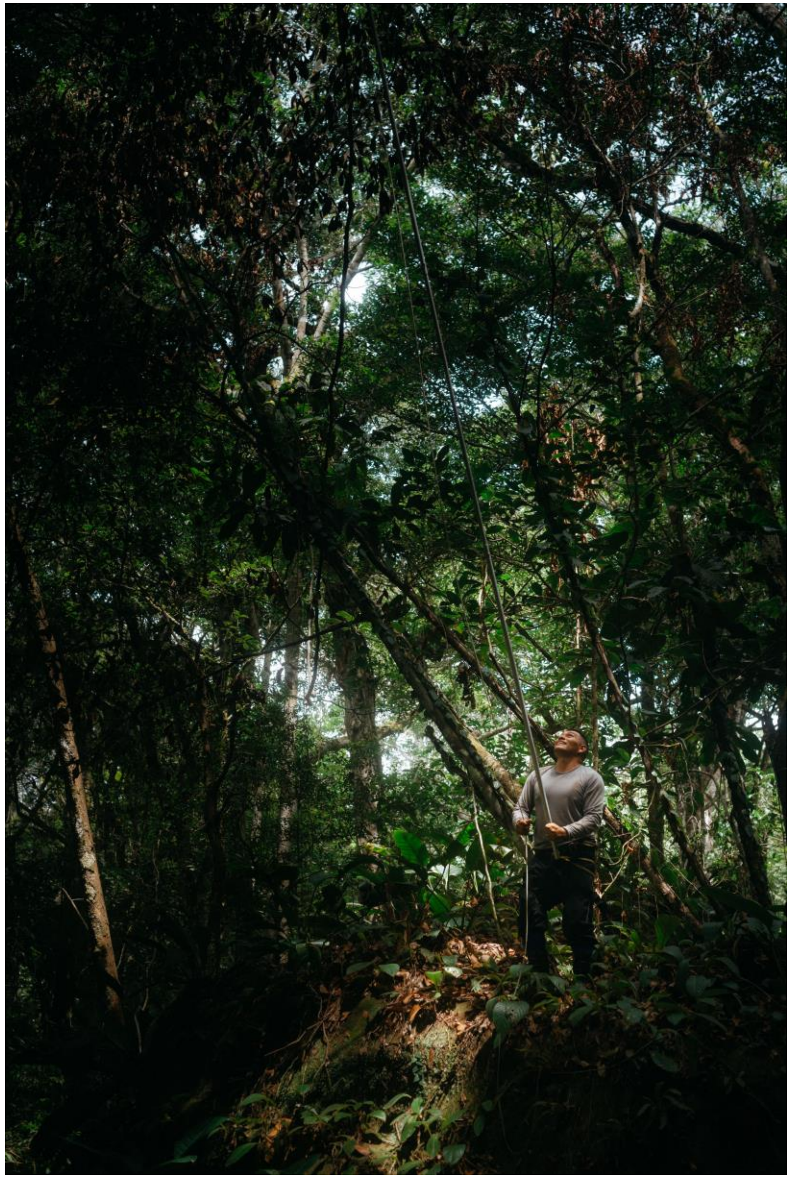
terra firme

Taxonomic & molecular sampling

Taxonomic & molecular sampling

Taxonomic & molecular sampling

Taxonomic & molecular sampling



Taxonomic & molecular sampling

Taxonomic & molecular sampling

Taxonomic & molecular sampling

Europe

- 12 ice-free and 3 ice-covered species
- Holarctic
  - 1729 samples
- Sanger sequencing: 2-3 cpDNA and 0-3 nDNA *loci* (400-700bp)

Lowland Amazonia

- 10 species
- 44,000 km^2 area in the Rio Negro Basin
  - 353 samples
- Sanger sequencing: no genetic variation
- RADseq (NGS): 100-2000 SNPs datasets
  - Protocol modified from Elshire *et al.*, 2011

Taxonomic & molecular sampling

Europe

- 12 ice-free and 3 ice-covered species
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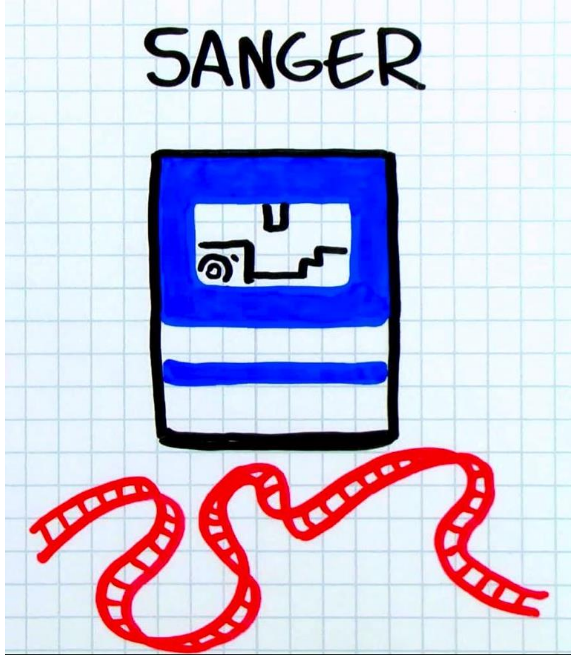

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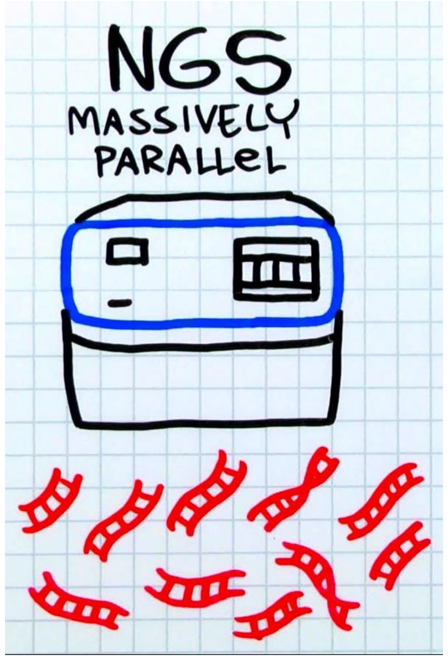
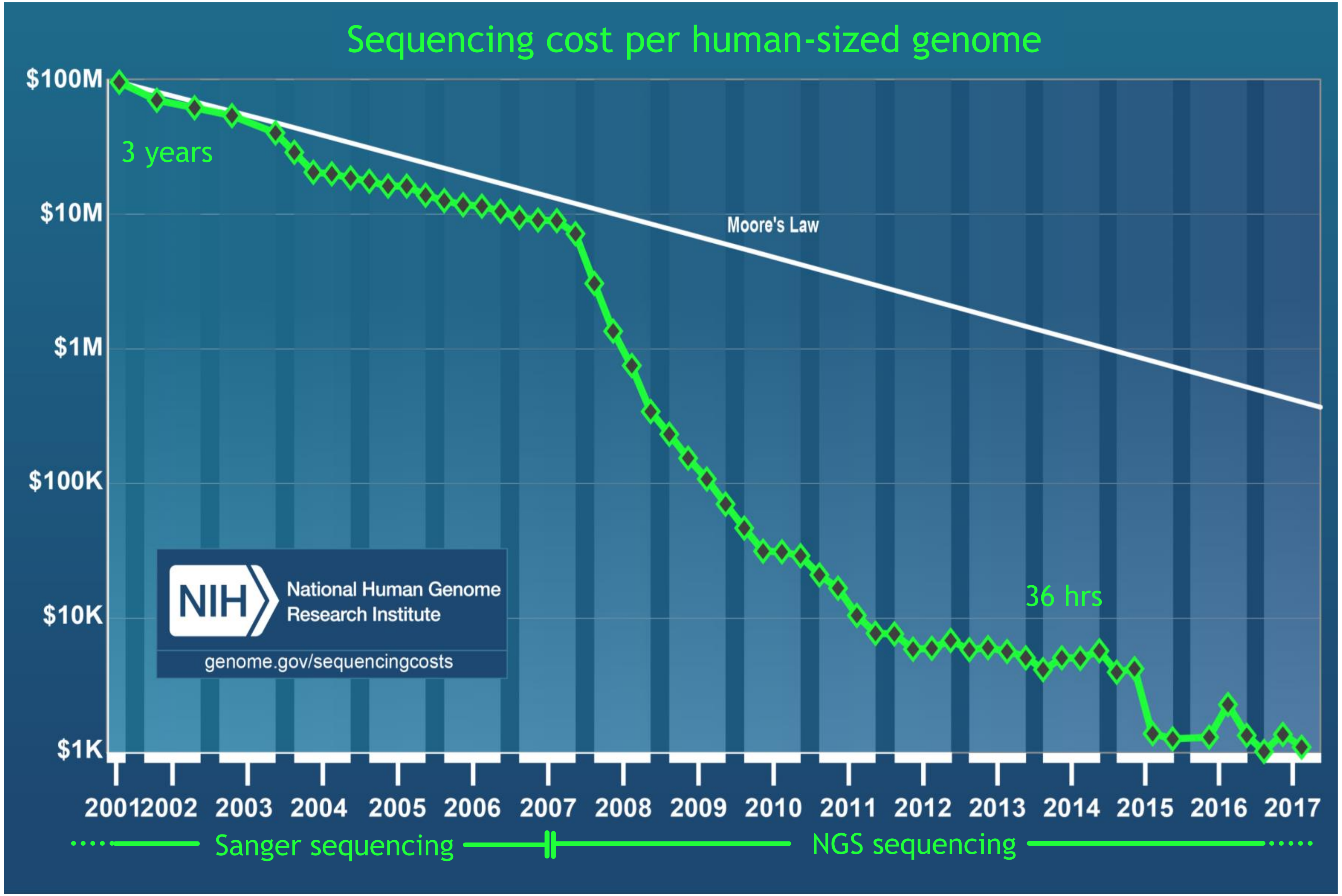


Taxonomic & molecular sampling



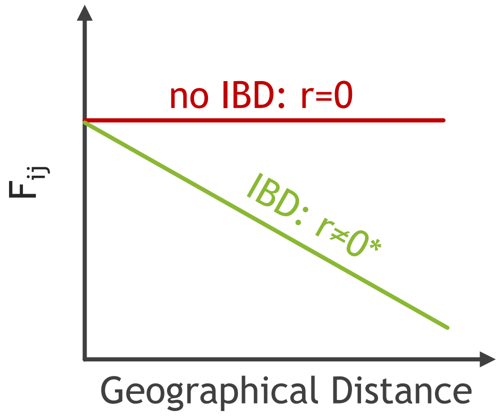
H1: Erasure of historical events due to efficient LDD?

Methods

H1: Erasure of historical events due to efficient LDD?

Paper I: lowland Amazonia

- Does the Inverse isolation hypothesis apply?
  - No IBD beyond the range of SDD due to efficient LDD?
  - Mantel test = regression
    - Kinship coefficient (F_{ij}, degree of genetic identity between individuals)
    - Geographical distance
    - Significant slope ($r \neq 0^*$) = IBD

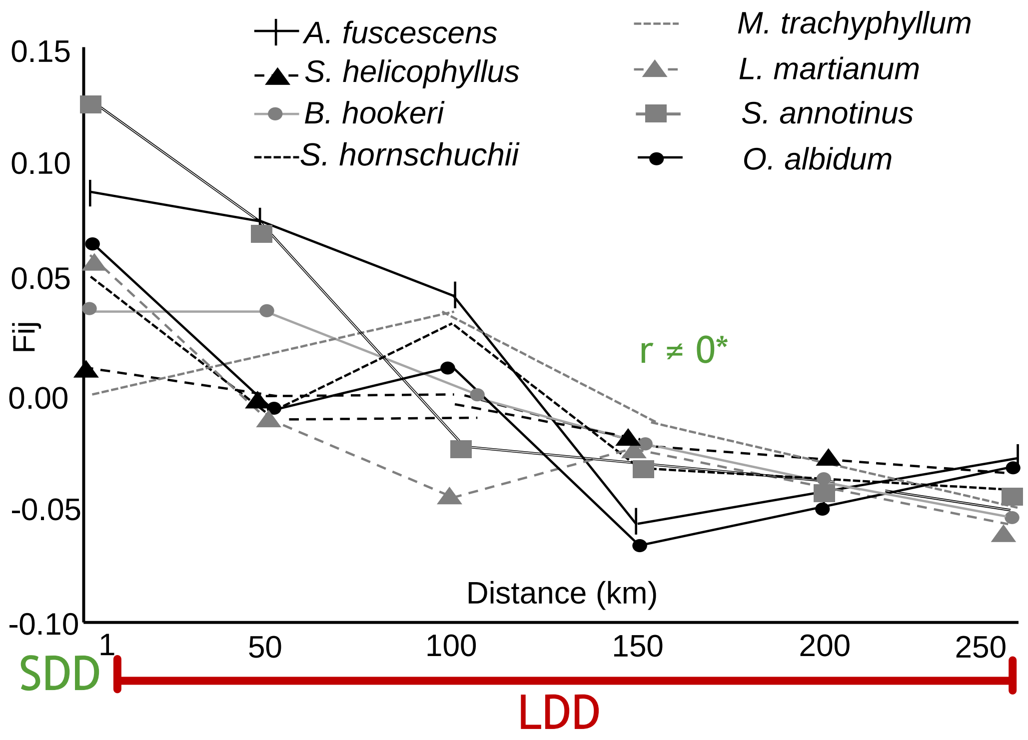


Results and discussion

H1: Erasure of historical events due to efficient LDD?

Paper I: lowland Amazonia

- Does the Inverse isolation hypothesis apply?
  - No IBD beyond the range of SDD due to efficient LDD?
  - Mantel test: IBD in 8 out of 10 species beyond the range of SDD!



Regression between F_{ij} and geographical distance for 8 Amazonian bryophyte species

Results and discussion

H1: Erasure of historical events due to efficient LDD?

Paper I: lowland Amazonia

- Does the Inverse isolation hypothesis apply?
  - No IBD beyond the range of SDD due to efficient LDD?
  - Mantel test: IBD in 8 out of 10 species beyond the range of SDD!

- There is significant spatial genetic variation in sets of DNA sequences!
- Efficient LDD did not erase historical events!
- Data suitable for demographic inference!

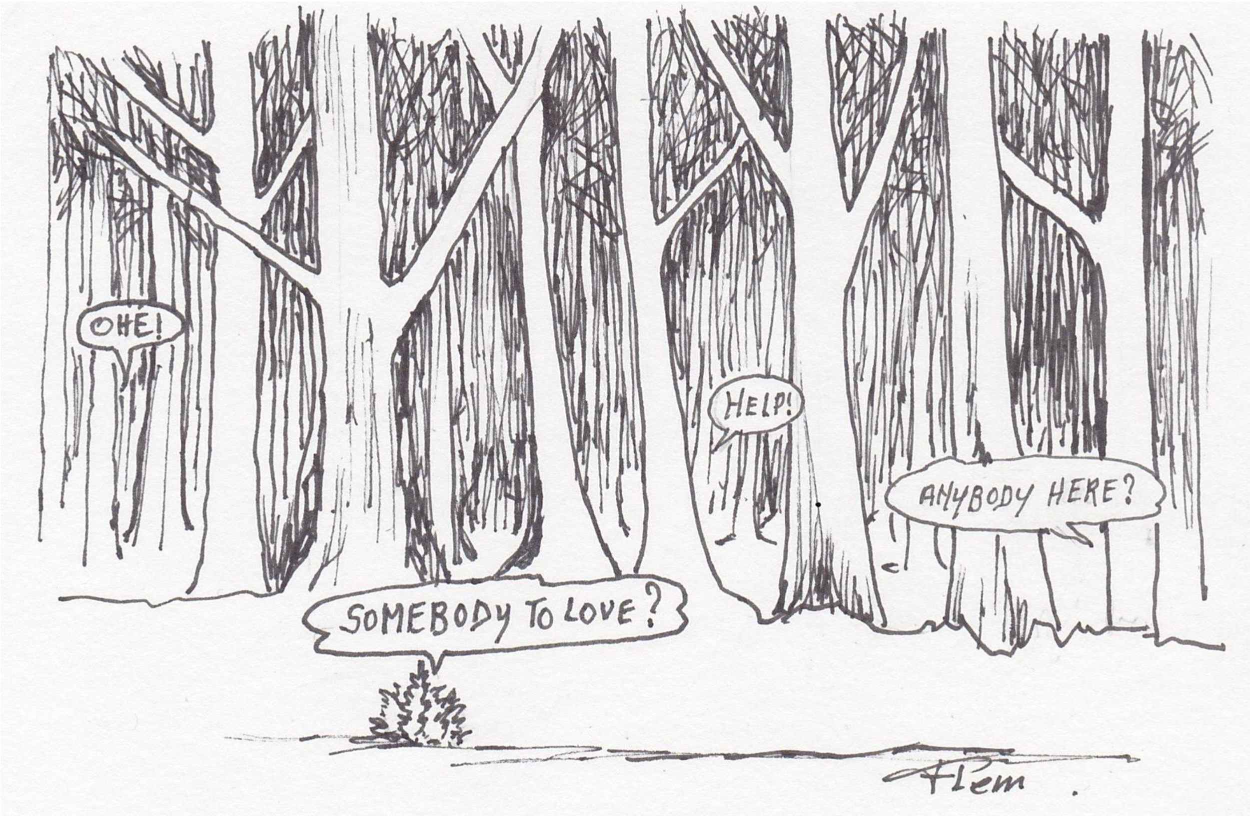
Results and discussion

H1: Erasure of historical events due to efficient LDD?

Paper I: lowland Amazonia

- Does the Inverse isolation hypothesis apply?
  - No IBD beyond the range of SDD due to efficient LDD?
  - Mantel test: IBD in 8 out of 10 species beyond the range of SDD!

- Inverse isolation hypothesis rejected in 80% of the cases
  - Amazonian bryophytes do not behave as one single metacommunity!
  - Dispersal capacities of Amazonian bryophytes much more limiting than hypothesized!



H2: IBE as a differentiation/speciation mechanism?

Methods

H2: IBE as a differentiation/speciation mechanism?

Paper I: global scale

- F_{st} between TF and WSF individuals

Paper II: sibling species case

- *Syrrhopodon annotinus* & *S. simmondsii*

Methods

H2: IBE as a differentiation/speciation mechanism?

Paper I: global scale

- F_{st} between TF and WSF individuals
  - F_{st} = index of genetic divergence
  - WSF individuals ≠ TF individuals?
  - Significant F_{st} = IBE

white-sand forest

terra firme

Paper II: sibling species case

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white-sand forest

terra firme

Paper II: sibling species case

- *Syrrhopodon annotinus* & *S. simmondsii*
  - Sympatric
  - White-sand forest exclusive
    - *S. annotinus* = mineral substrates
    - *S. simmondsii* = organic substrates

Methods

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white-sand forest

terra firme

Paper II: sibling species case

- *Syrrhopodon annotinus* & *S. simmondsii*
  - Sympatric
  - White-sand forest exclusive
    - *S. annotinus* = mineral substrates
    - *S. simmondsii* = organic substrates
  - Morphologically distinct
  - Genetically distinct?

Methods

H2: IBE as a differentiation/speciation mechanism?

Paper I: global scale

- F_{st} between TF and WSF individuals
  - F_{st} = index of genetic divergence
  - WSF individuals ≠ TF individuals?
  - Significant F_{st} = IBE

Paper II: sibling species case

- F_{st} between species
  - F_{st} = index of genetic divergence
  - Mineral individuals ≠ organic individuals?
  - Significant F_{st} = genetically distinct

white-sand forest

terra firme

Results and discussion

H2: IBE as a differentiation/speciation mechanism?

Paper I: global scale

- F_{st} between TF and WSF individuals
  - IBE in 2 species

Species	F_{st} (P-value)
Archilejeunea fuscescens	0.14 (P=0.004)
Octoblepharum pulvinatum	0.29 (P=0.002)

white-sand forest

terra firme

Paper II: sibling species case

- F_{st} between species

Results and discussion

H2: IBE as a differentiation/speciation mechanism?

Paper I: global scale

- F_{st} between TF and WSF individuals
  - IBE in 2 species
  - IBE does not globally contribute to Amazonian genetic structure
  - Bryophytes = "multi-purpose" genotypes
    - 1 genotype in several environments

white-sand forest

terra firme

Paper II: sibling species case

- F_{st} between species

Results and discussion

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white-sand forest

terra firme

Paper II: sibling species case

- F_{st} between species
  - F_{st} = 0.059 (P-value = 0.004)

Results and discussion

H2: IBE as a differentiation/speciation mechanism?

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- F_{st} between TF and WSF individuals
  - IBE in 2 species
  - IBE does not globally contribute to Amazonian genetic structure
  - Bryophytes = “multi-purpose” genotypes
    - 1 genotype in several environments

white-sand forest

terra firme

Paper II: sibling species case

- F_{st} between species
  - F_{st} = 0.059 (P-value = 0.004)
  - Genetically distinct!

Results and discussion

H2: IBE as a differentiation/speciation mechanism?

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  - IBE does not globally contribute to Amazonian genetic structure
  - Bryophytes = "multi-purpose" genotypes
    - 1 genotype in several environments

white-sand forest

terra firme

Paper II: sibling species case

- F_{st} between species
  - Genetically distinct!
- IBE as speciation mechanism?
  - Habitat differentiation triggered or followed speciation?

Results and discussion

H2: IBE as a differentiation/speciation mechanism?

Paper I: global scale

- F_{st} between TF and WSF individuals
  - IBE in 2 species
  - **IBE does not globally contribute to Amazonian genetic structure**
  - Bryophytes = “multi-purpose” genotypes
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white-sand forest

terra firme

Paper II: sibling species case

- F_{st} between species
  - Genetically distinct!
  - **IBE might contribute to Amazonian genetic structure in some groups**

Results and discussion

H2: IBE as a differentiation/speciation mechanism?

Paper I: global scale

- F_{st} between TF and WSF individuals
  - IBE in 2 species
  - **IBE does not globally contribute to Amazonian genetic structure**
  - Bryophytes = "multi-purpose" genotypes
    - 1 genotype in several environments

white-sand forest

terra firme

Paper II: sibling species case

- F_{st} between species
  - Genetically distinct!
  - **IBE might contribute to Amazonian genetic structure in some groups**
  - Bryophytes = "multi-purpose" genotypes?
  - Growing evidence for genetic divergence observed along environmental gradients

H3: Post-glacial history of bryophytes?

Methods

H3: Post-glacial history of bryophytes?

Paper III: Europe

- ABC based on coalescent simulations
    - Compare demographic scenarios

Ongoing study: lowland Amazonia

- ABC based on coalescent simulations
    - Compare demographic scenarios

Methods

H3: Post-glacial history of bryophytes?

Paper III: Europe

- ABC based on coalescent simulations
  - Compare demographic scenarios
  - Classic coalescent population model
    - Pre-defined panmictic populations
    - Sink and source from literature

■ = extra-European range (0)
■ = northern European range (1)
■ = southern European range (2)

Ongoing study: lowland Amazonia

- ABC based on coalescent simulations
  - Compare demographic scenarios

Methods

H3: Post-glacial history of bryophytes?

Paper III: Europe

- ABC based on coalescent simulations
  - Compare demographic scenarios
  - Classic coalescent population model
    - Pre-defined panmictic populations
    - Sink and source from literature

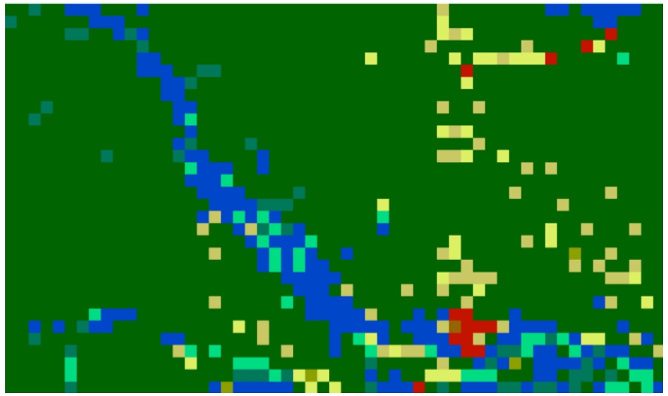
Ongoing study: lowland Amazonia

- ABC based on coalescent simulations
  - Compare demographic scenarios
  - Spatially explicit coalescent model
    - Continuous portions of species range
    - Matrix of pixels = panmictic populations
    - Amazonia = Homogeneous

■ = extra-European range (0)
■ = northern European range (1)
■ = southern European range (2)

Cropland rainfed
Mosaic natural vegetation/cropland
Tree cover needleleaved evergreen open
Tree cover flooded
Shrub or herbaceous cover flooded
Urban areas
Water bodies
Shrubland

1 pixel = 25 km^2



Methods

H3: Post-glacial history of bryophytes?

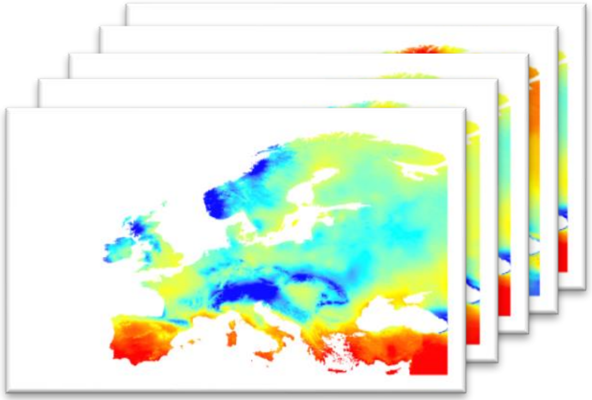
Paper III: Europe

- ABC based on coalescent simulations
  - Compare demographic scenarios

- Species Distribution Models (SDMs)
  - Confirm *refugia* location
  - Ecological models localizing suitable habitats
    - Dependent data: species occurrences
    - Independent data: environmental factors

Species occurrences

+



Environmental factors

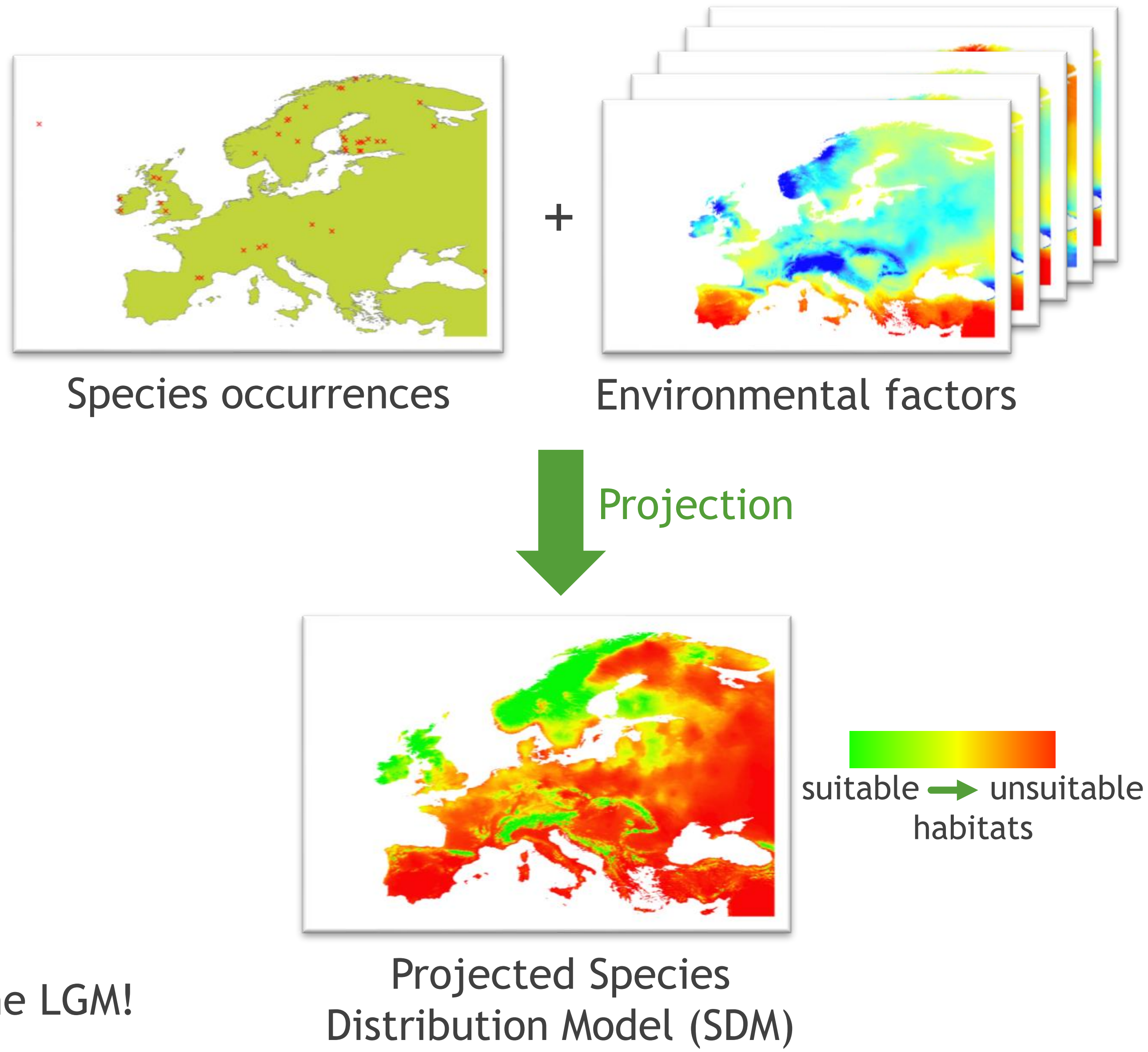
Methods

H3: Post-glacial history of bryophytes?

Paper III: Europe

- ABC based on coalescent simulations
  - Compare demographic scenarios
- Species Distribution Models (SDMs)
  - Confirm *refugia* location
  - Ecological models localizing suitable habitats
    - Dependent data: species occurrences
    - Independent data: environmental factors
  - Projected into region/time of interest
    - LGM climatic conditions
    - Holarctic

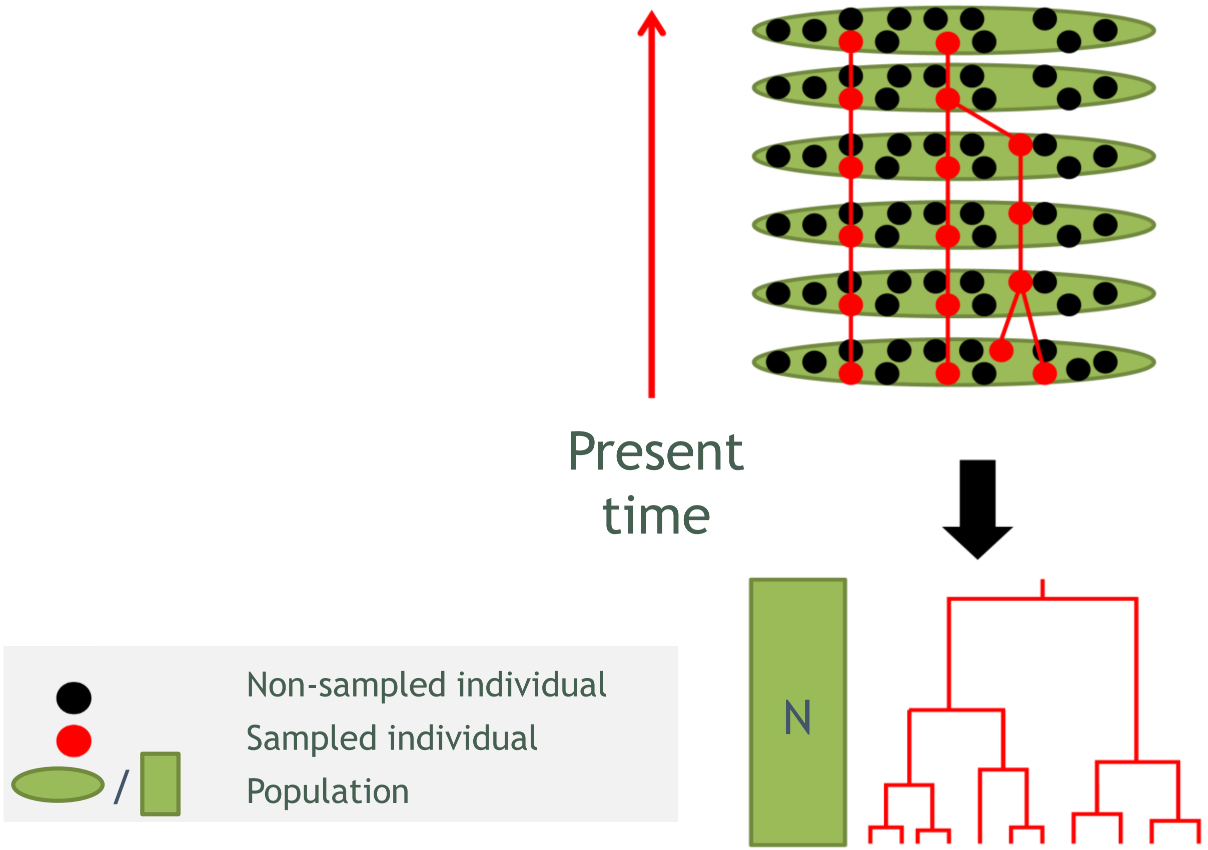
→ Identify location of potential *refugia* during the LGM!



Methods

H3: Post-glacial history of bryophytes?

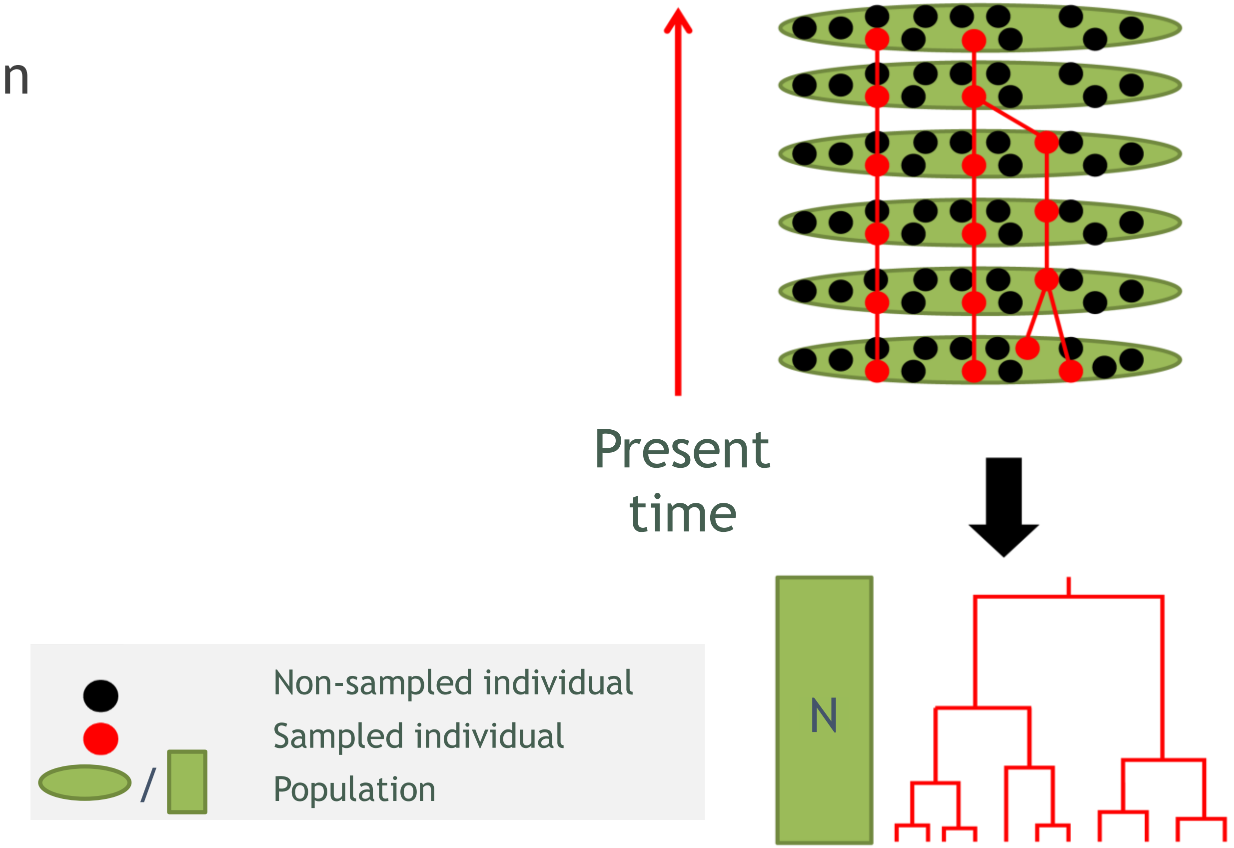
- Coalescent simulations
  - Aim: reconstruct gene genealogies of populations to infer their past demographies
    - Grouping sampled gene copies until last common ancestral copy



Methods

H3: Post-glacial history of bryophytes?

- Coalescent simulations
  - Aim: reconstruct gene genealogies of populations to infer their past demographies
    - Grouping sampled gene copies until last common ancestral copy
  - Probability of coalescence in a population
    - $Pc \approx n(n-1)/2N$
    - Depends on
      - Sample size (n)
      - Effective population size (N)



Methods

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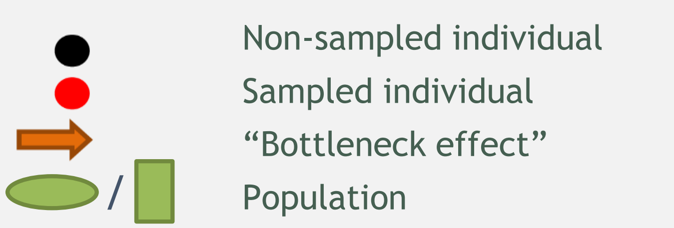
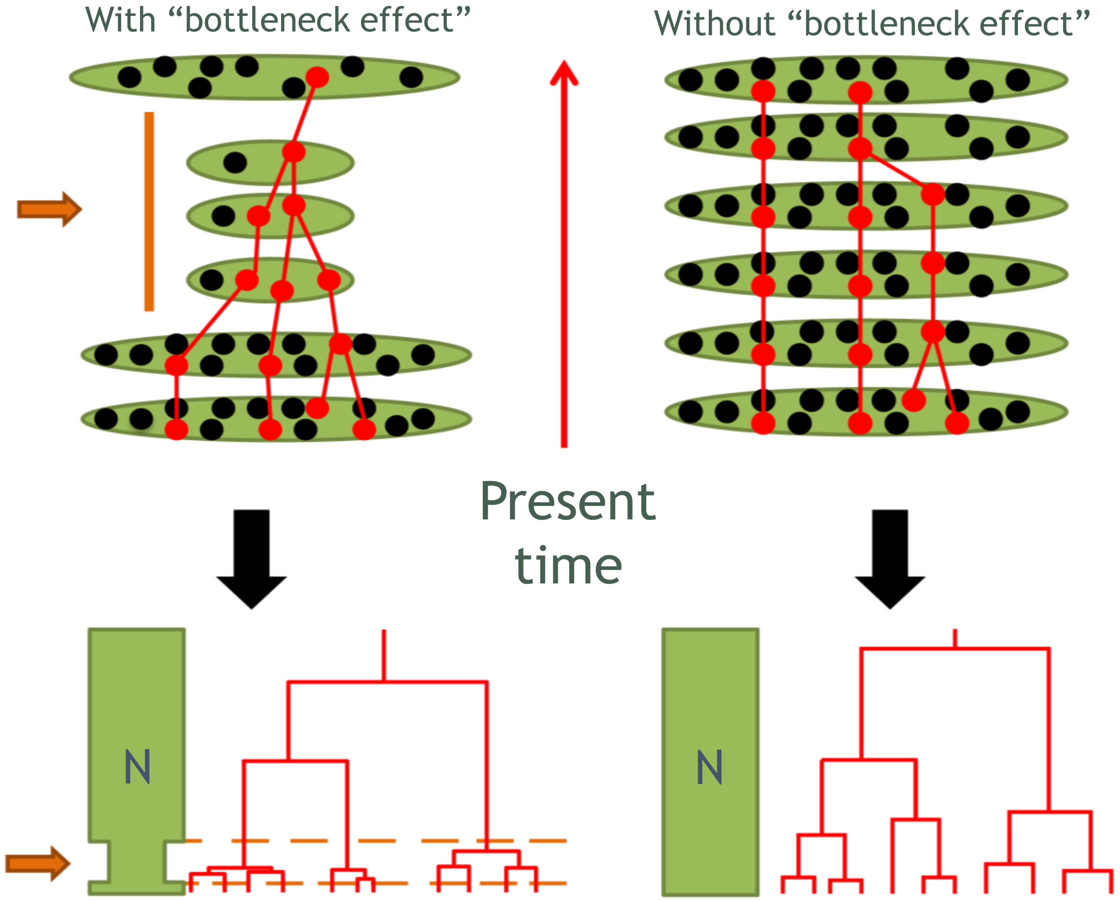
      - Effective population size (N)
      - Probability ↗ when N ↘





Methods

H3: Post-glacial history of bryophytes?

- Coalescent simulations
  - Aim: reconstruct gene genealogies of populations to infer their past demographies
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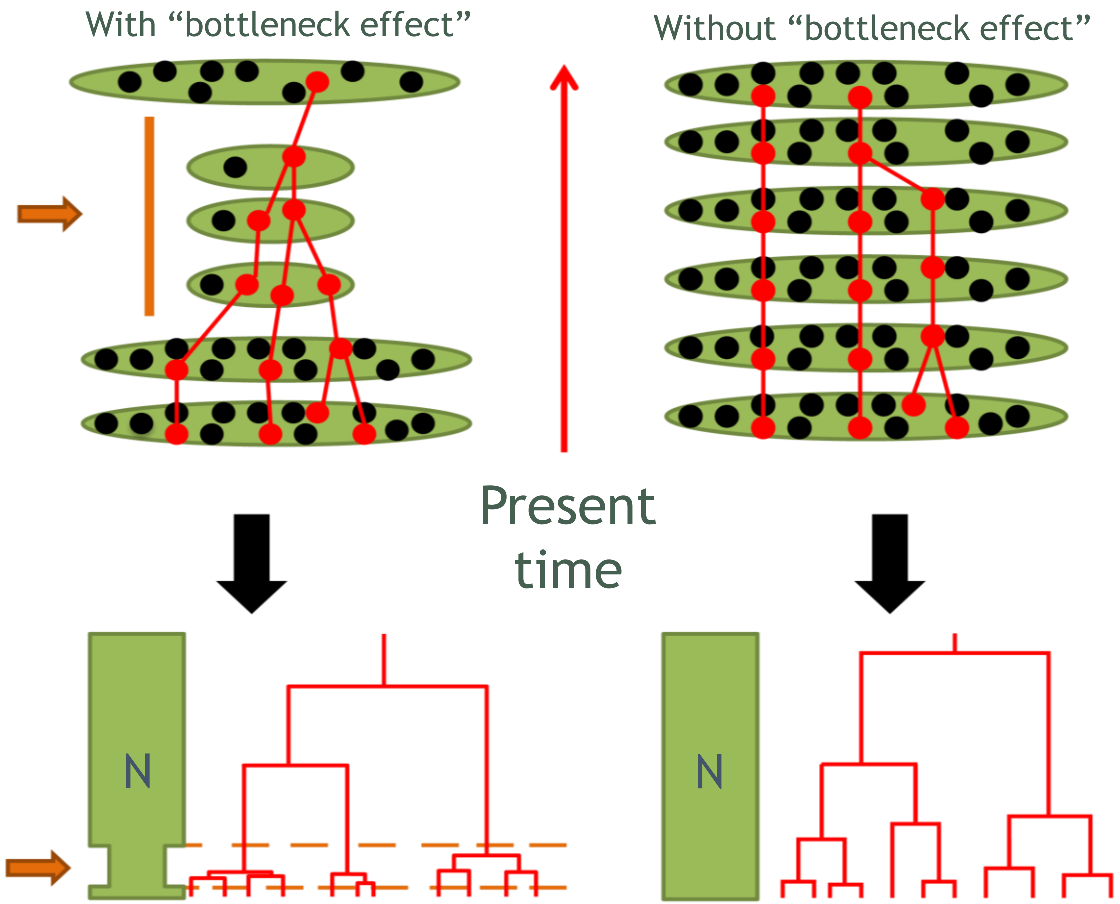
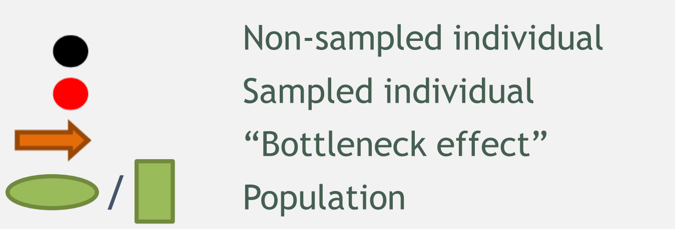
    - $Pc \approx n(n-1)/2N$
    - Depends on
      - Sample size (n)
      - Effective population size (N)
      - Probability ↗ when N ↘
    - → Constraint by demographic events





Methods

H3: Post-glacial history of bryophytes?

- Coalescent simulations in ABC
  - Aim: compare demographic scenarios with observed set of DNA sequences

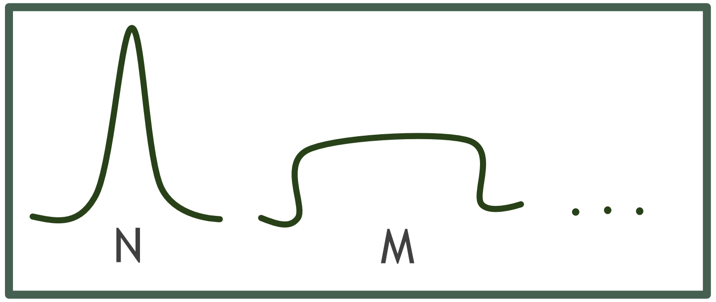
- ABC in 3 steps
  1. Simulation of gene genealogies = demographic process
  2. Simulation of matrices of DNA sequences = mutation process
  3. Selection of the best-fit scenario = computational process

Methods

H3: Post-glacial history of bryophytes?

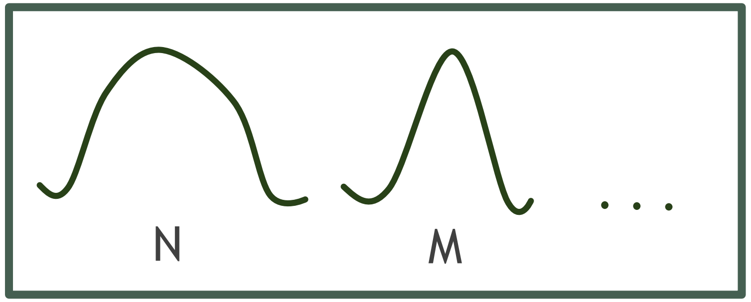
1. Simulation of gene genealogies
   - Coalescent model
   - Under the constraint of different demographic scenarios
   - Through definition of *prior* range of values of demographic parameters
     - Effective population size (N)
     - Migration rate (M)
     - …

Scenario 1



Prior range of values

Scenario 2



Prior range of values

Methods

H3: Post-glacial history of bryophytes?

1. Simulation of gene genealogies
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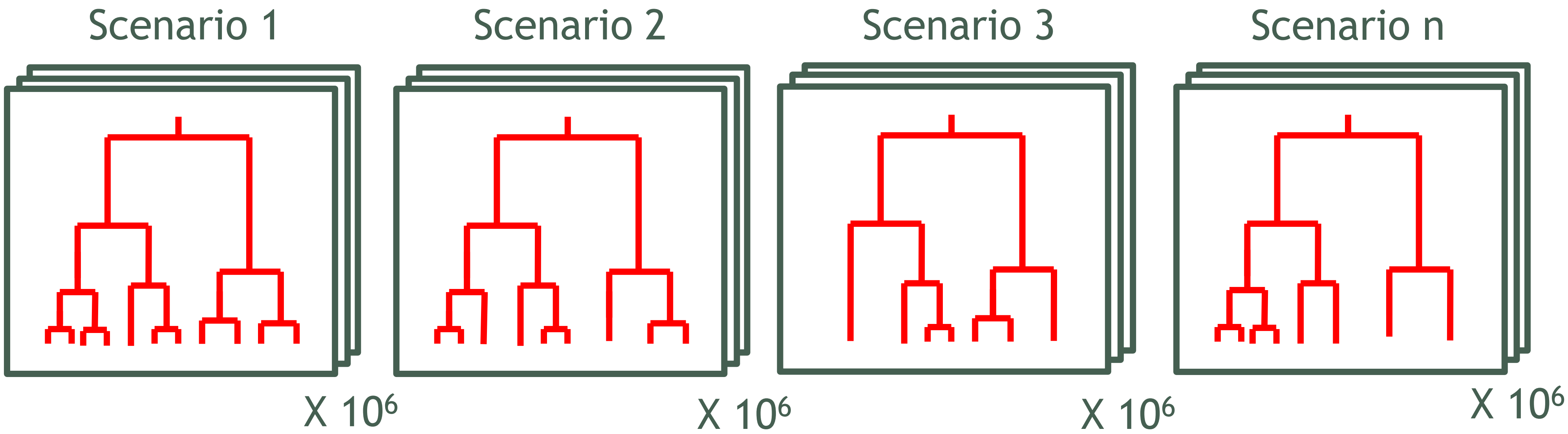
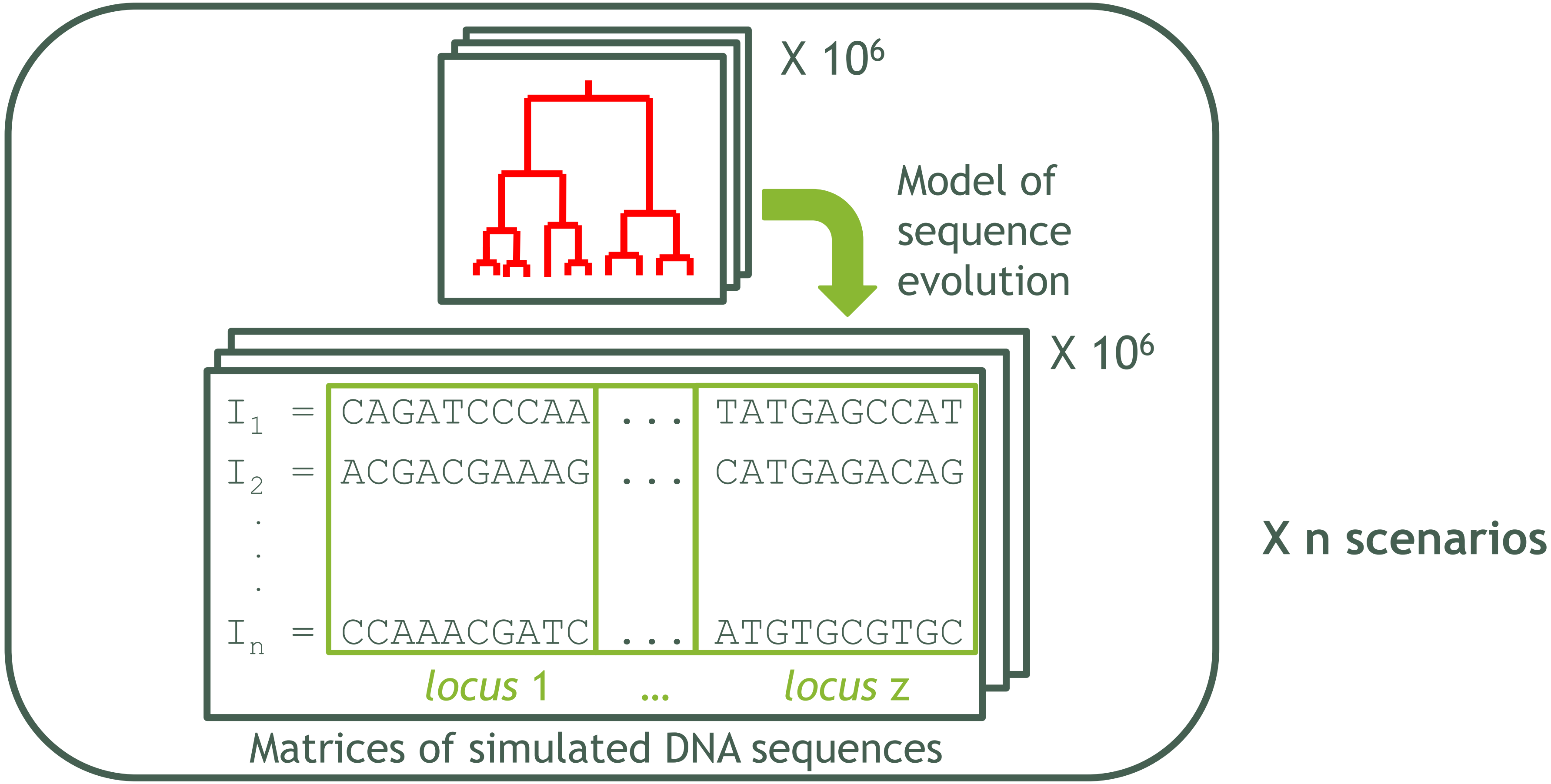


Methods

H3: Post-glacial history of bryophytes?

2. Simulation of matrices of DNA sequences

- Using models of sequence evolution
- Along each gene genealogy



Methods

H3: Post-glacial history of bryophytes?

3. Selection of the best-fit scenario

- Summary statistics to synthesize observed and simulated matrices of DNA sequences

Matrices of DNA sequences

Methods

H3: Post-glacial history of bryophytes?

3. Selection of the best-fit scenario

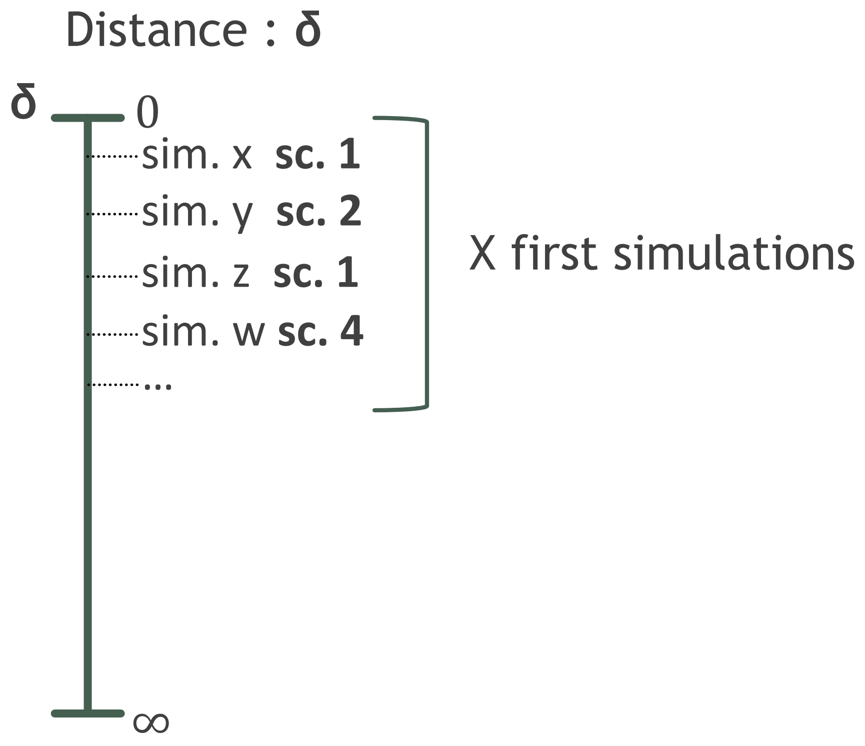
- Summary statistics to synthesize observed and simulated matrices of DNA sequences
- Euclidian distance between
  - The set of observed summary statistics
  - Each set of simulated summary statistics

Methods

H3: Post-glacial history of bryophytes?

3. Selection of the best-fit scenario

- Summary statistics to synthesize observed and simulated matrices of DNA sequences
- Euclidian distance between
  - The set of observed summary statistics
  - Each set of simulated summary statistics
- Select the X first simulations



Methods

H3: Post-glacial history of bryophytes?

3. Selection of the best-fit scenario

- Summary statistics to synthesize observed and simulated matrices of DNA sequences
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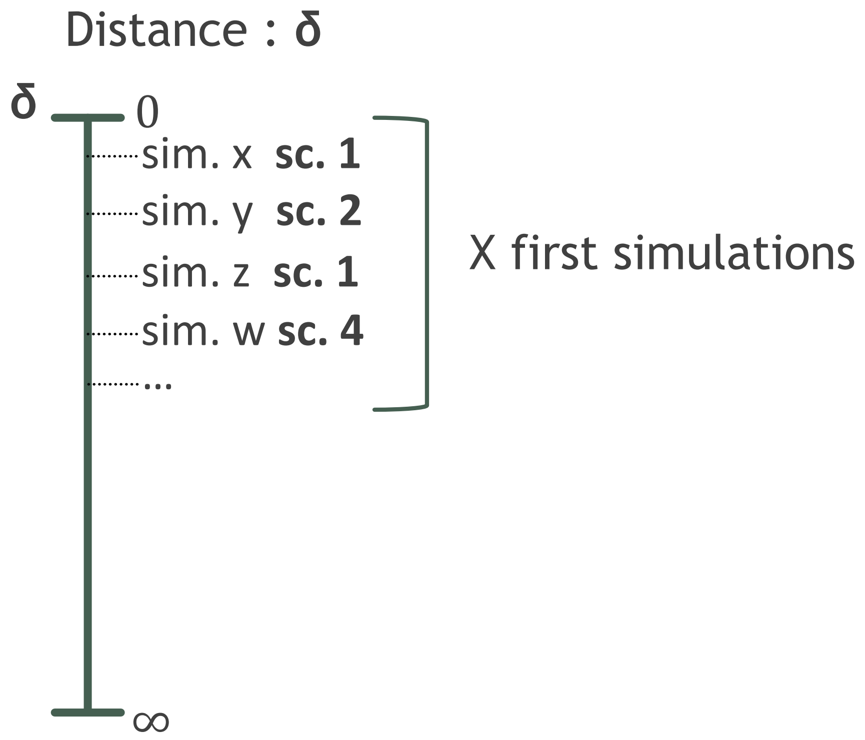
- Select the X first simulations
  - Determine *Posterior* Probability (PP) of each scenario

	Sc.1	Sc.2	…	Sc.4/6
PP	0.001	0.95	…	0.02



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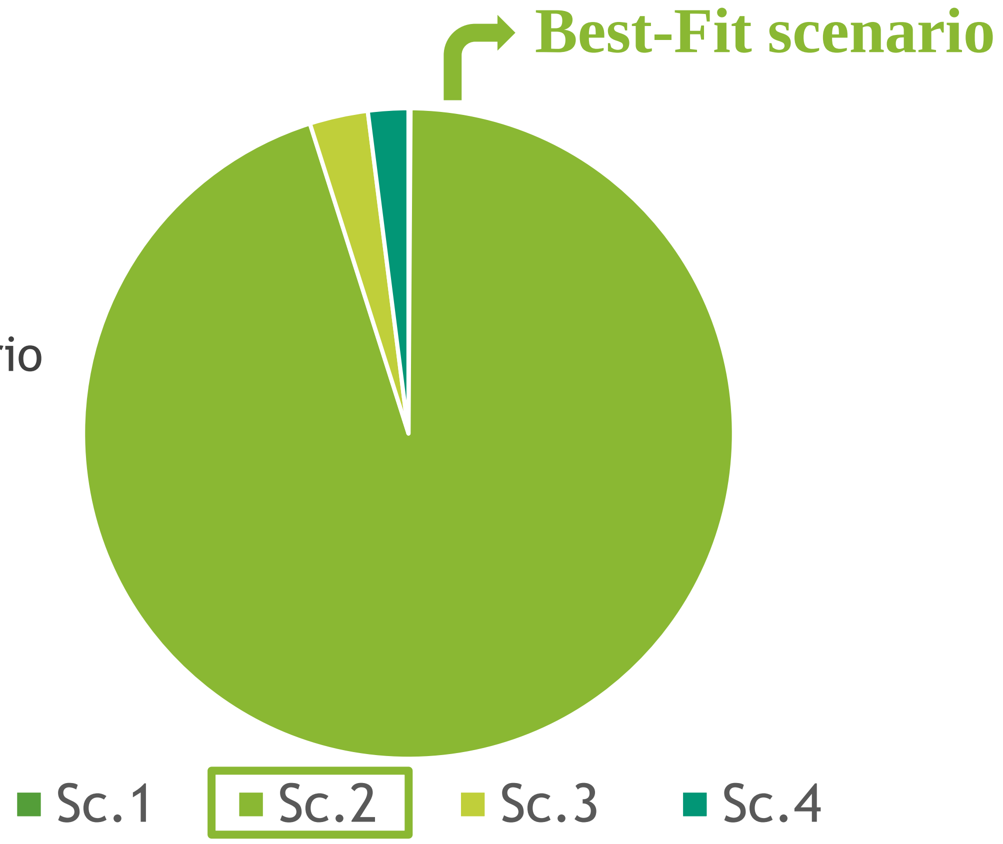
	Sc.1	Sc.2	…	Sc.4/6
PP	0.001	0.95	…	0.02

Best-Fit scenario

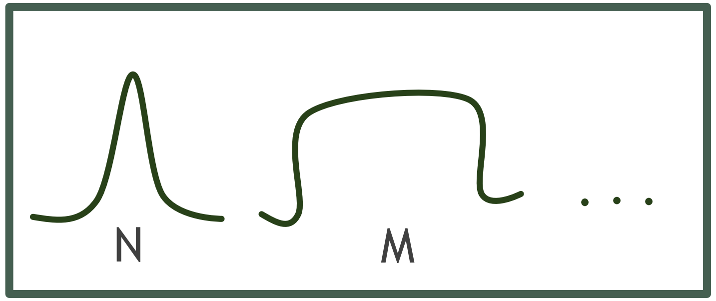


Methods

H3: Post-glacial history of bryophytes?

3. Selection of the best-fit scenario

- Summary statistics to s synthesize observed and simulated matrices of DNA sequences
- Euclidian distance between
  - The set of observed summary statistics
  - Each set of simulated summary statistics
- Select the X first simulations
  - Determine *Posterior* Probability (PP) of each scenario
  - Select the best-fit scenario
  - Compute *Posterior* range of values of demographic parameters



Posterior range of values

Methods

H3: Post-glacial history of bryophytes (Europe, Paper III)?

Methods

H3: Post-glacial history of bryophytes (Europe, Paper III)?

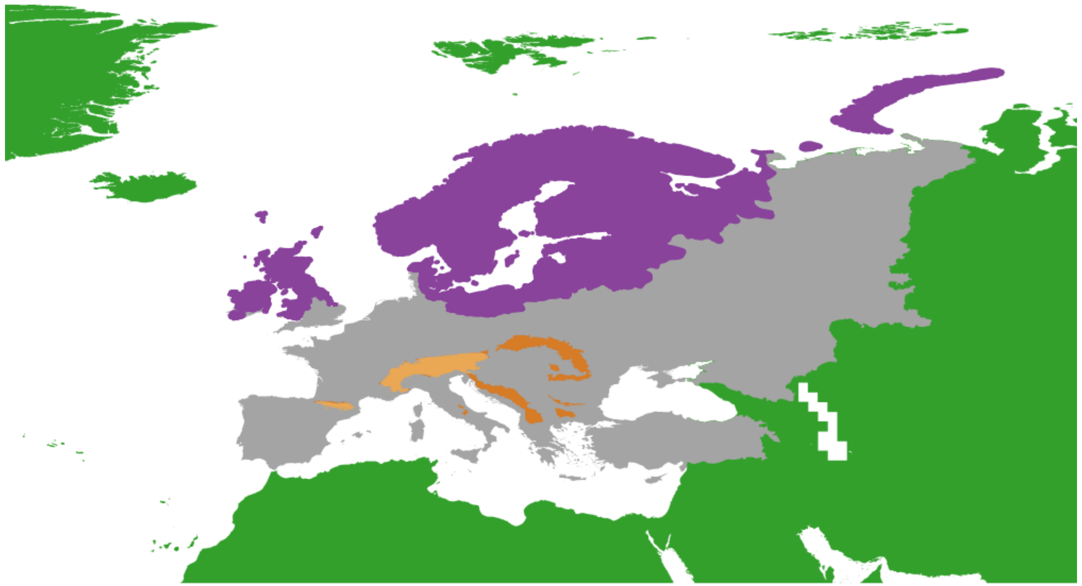
Ice-free species

- 3 regions

■ = extra-European range
■ = northern range
■ = southern range

Ice-covered species

- 5 regions



■ = extra-European range
■ = northern range iced at LGM
■ = southern mountains range iced at LGM
■ = southern mountains range ice-free at LGM
■ = lowland range South of the ice sheet at LGM

Methods

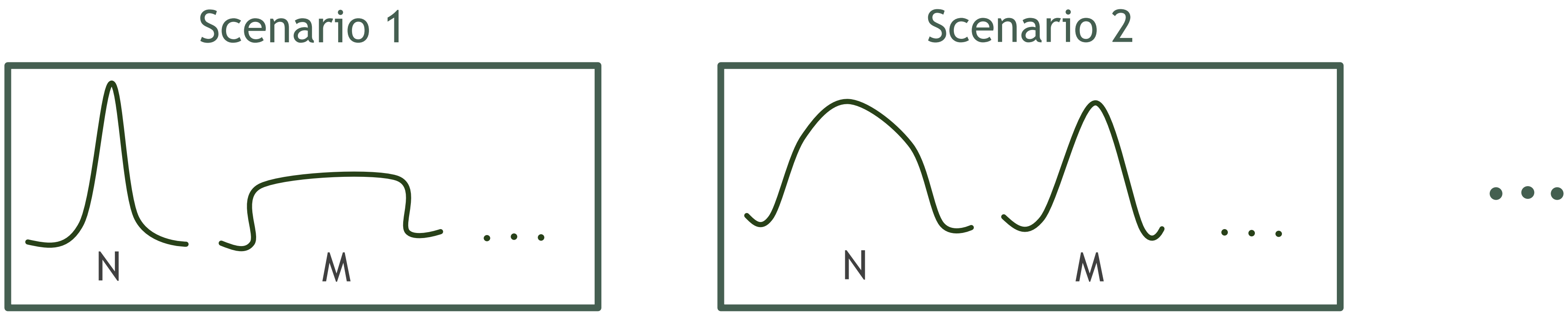
H3: Post-glacial history of bryophytes (Europe, Paper III)?

Ice-free species

- 3 regions
- 3 demographic scenarios

Ice-covered species

- 5 regions
- 4 demographic scenarios



Prior range of values

Prior range of values

Methods

H3: Post-glacial history of bryophytes (Europe, Paper III)?

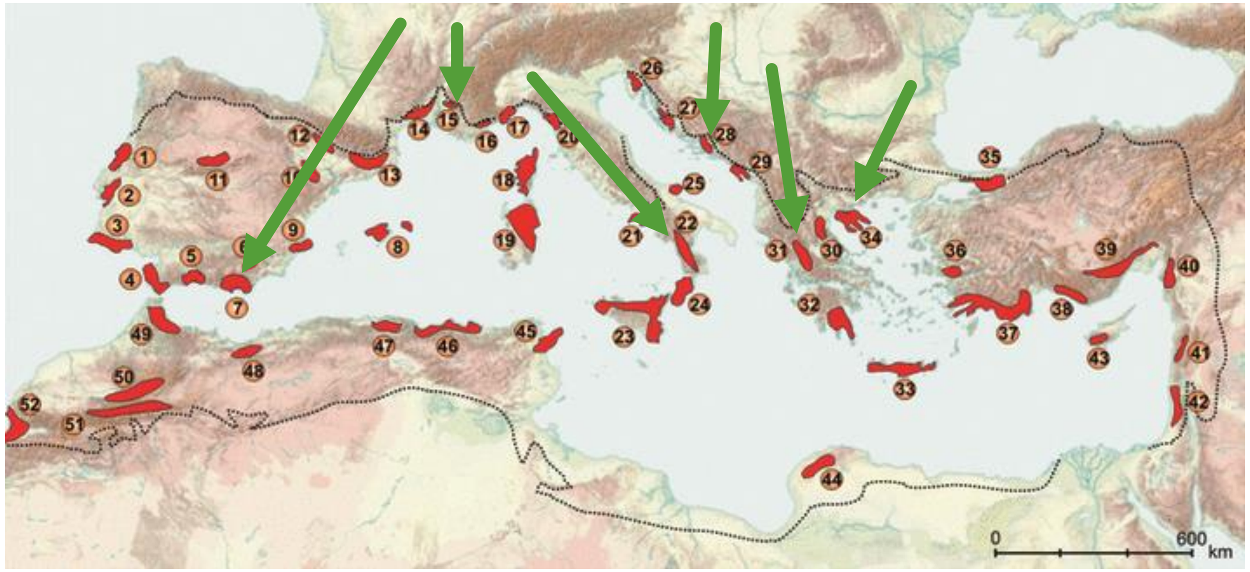
Ice-free species

- 3 regions
- 3 demographic scenarios
  - Classical southern *refugia* scenario

Ice-covered species

- 5 regions
- 4 demographic scenarios

Médail & Diadema, 2009



Distribution of 52 putative *refugia* within the Mediterranean region

Methods

H3: Post-glacial history of bryophytes (Europe, Paper III)?

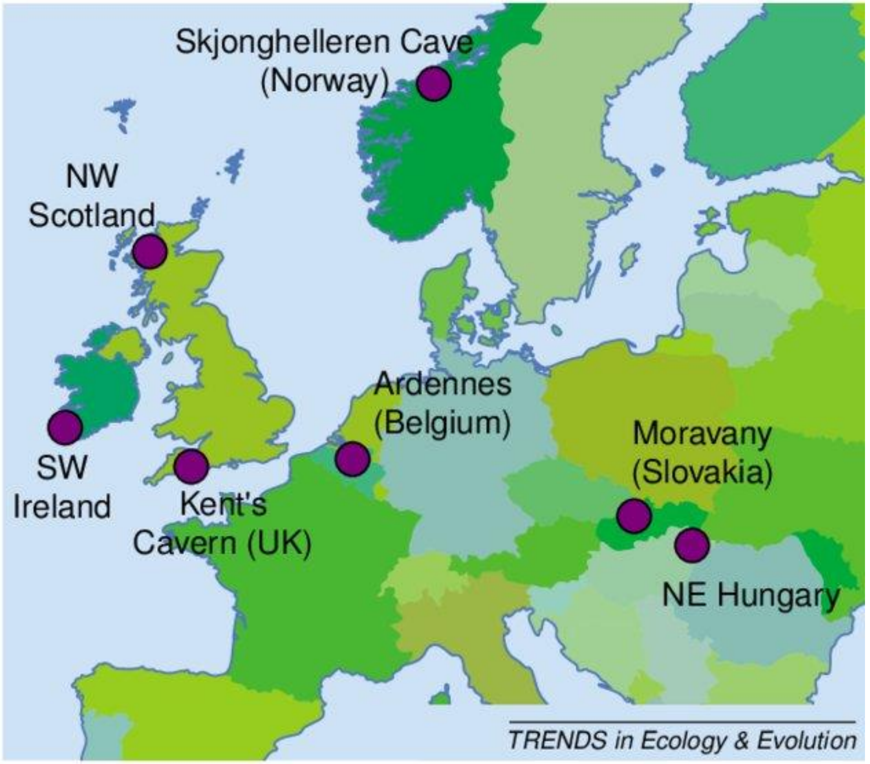
Ice-free species

- 3 regions
- 3 demographic scenarios
  - Classical southern *refugia* scenario
  - Expected northern micro-*refugia* scenario

Ice-covered species

- 5 regions
- 4 demographic scenarios

Stewart & Lister, 2001



Distribution of 7 putative northern micro-*refugia*

Methods

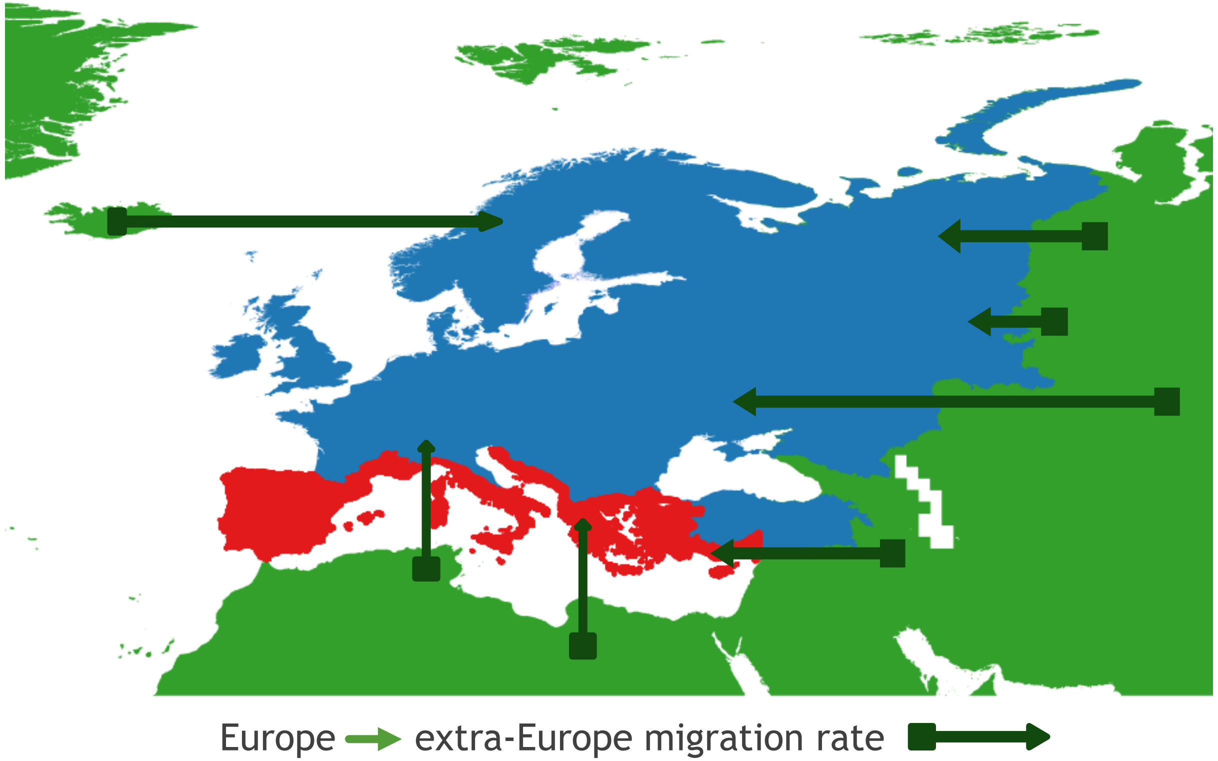
H3: Post-glacial history of bryophytes (Europe, Paper III)?

Ice-free species

- 3 regions
- 3 demographic scenarios
  - Classical southern *refugia* scenario
  - Expected northern micro-*refugia* scenario
  - Extra-European post-glacial recolonization scenario

Ice-covered species

- 5 regions
- 4 demographic scenarios



Methods

H3: Post-glacial history of bryophytes (Europe, Paper III)?

Ice-free species

- 3 regions
- 3 demographic scenarios
  - Classical southern *refugia* scenario
  - Expected northern micro-*refugia* scenario
  - Extra-European post-glacial recolonization scenario

Ice-covered species

- 5 regions
- 4 demographic scenarios
  - Classical *Tabula rasa* scenario

Methods

H3: Post-glacial history of bryophytes (Europe, Paper III)?

Ice-free species

- 3 regions
- 3 demographic scenarios
  - Classical southern *refugia* scenario
  - Expected northern micro-*refugia* scenario
  - Extra-European post-glacial recolonization scenario

Ice-covered species

- 5 regions
- 4 demographic scenarios
  - Classical *Tabula rasa* scenario
  - Expected nunatak/micro-*refugia* scenario

Methods

H3: Post-glacial history of bryophytes (Europe, Paper III)?

Ice-free species

- 3 regions
- 3 demographic scenarios
  - Classical southern *refugia* scenario
  - Expected northern micro-*refugia* scenario
  - Extra-European post-glacial recolonization scenario

Ice-covered species

- 5 regions
- 4 demographic scenarios
  - Classical *Tabula rasa* scenario
  - Expected nunatak/micro-*refugia* scenario
  - Specific southern mountains nunatak/micro-*refugia* scenario

Ranunculus glacialis

Methods

H3: Post-glacial history of bryophytes (Europe, Paper III)?

Ice-free species

- 3 regions
- 3 demographic scenarios
  - Classical southern *refugia* scenario
  - Expected northern micro-*refugia* scenario
  - Extra-European post-glacial recolonization scenario

Ice-covered species

- 5 regions
- 4 demographic scenarios
  - Classical *Tabula rasa* scenario
  - Expected nunatak/micro-*refugia* scenario
  - Specific southern mountains nunatak/micro-*refugia* scenario
  - Extra-European post-glacial recolonization scenario

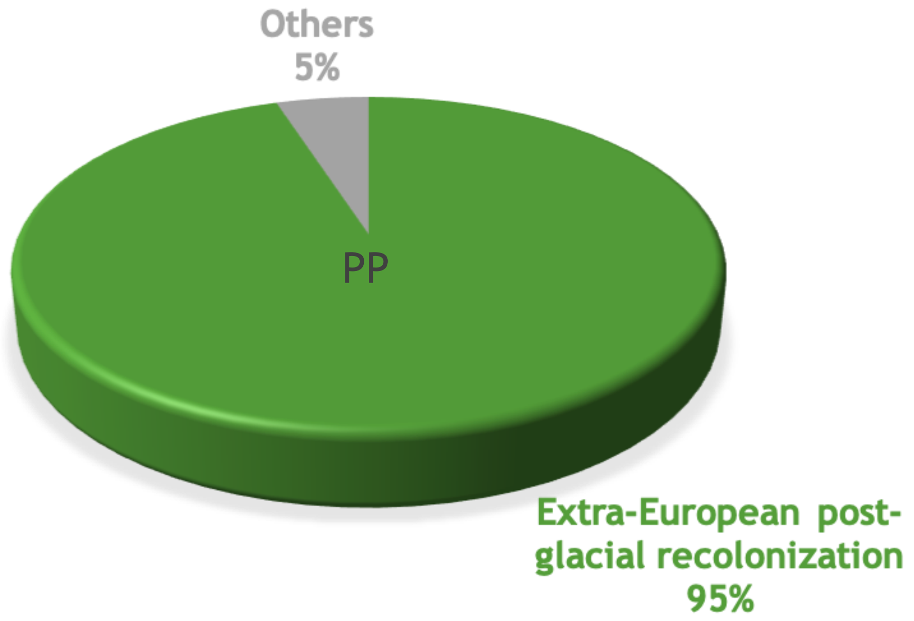
Results and discussion

H3: Post-glacial history of bryophytes (Europe, Paper III)?

Ice-free species

Ice-covered species

- Best-fit scenarios
  - Extra-European post-glacial recolonization: 7/12 species

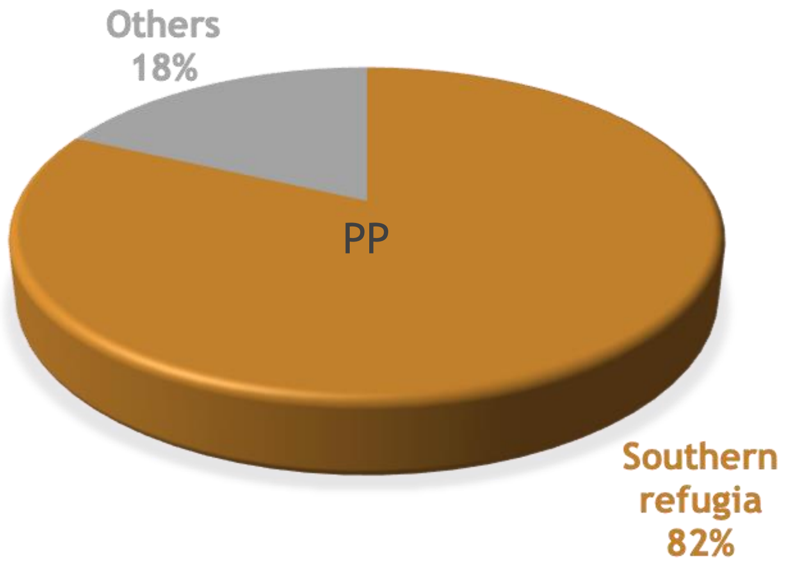


Results and discussion

H3: Post-glacial history of bryophytes (Europe, Paper III)?

Ice-free species

- Best-fit scenarios
  - Extra-European post-glacial recolonization: 7/12 species
  - Southern *refugia*: 3/12 species



Ice-covered species

Results and discussion

H3: Post-glacial history of bryophytes (Europe, Paper III)?

Ice-free species

Ice-covered species

- Best-fit scenarios
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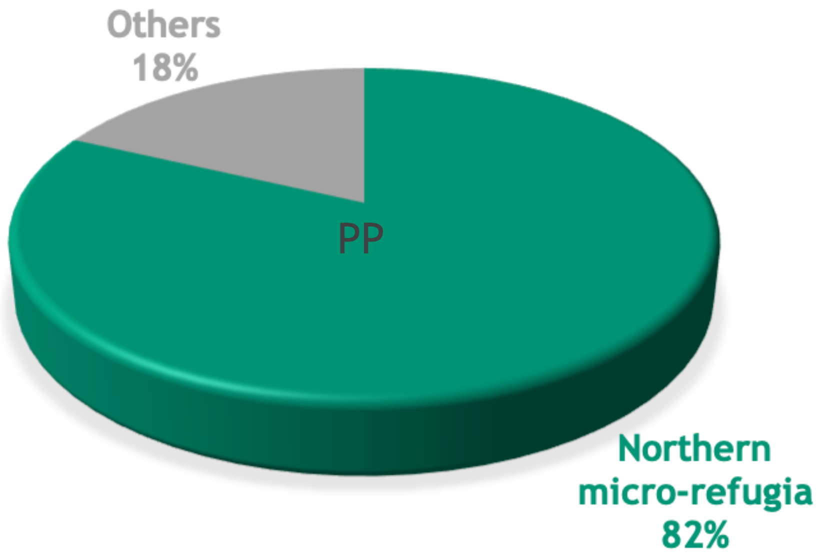
  - Southern *refugia*: 3/12 species
  - Northern micro-*refugia*: 2/12 species



Results and discussion

H3: Post-glacial history of bryophytes (Europe, Paper III)?

Ice-free species

- Best-fit scenarios
  - Extra-European post-glacial recolonization: 7/12 species
  - Southern *refugia*: 3/12 species
  - Northern micro-*refugia*: 2/12 species

Ice-covered species

- Best-fit scenarios
  - Nunatak/micro-*refugia*: 2/3 species

Results and discussion

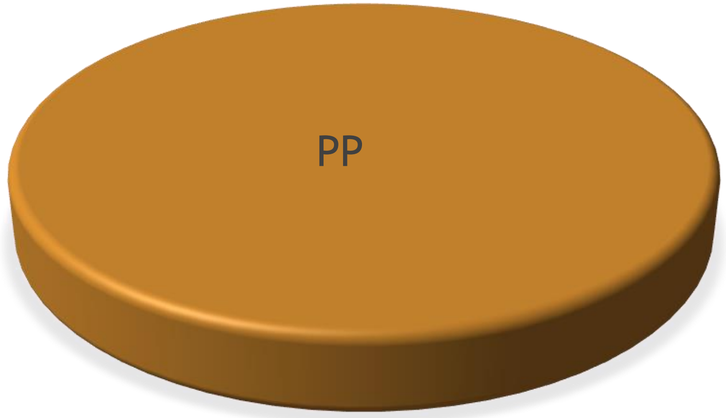
H3: Post-glacial history of bryophytes (Europe, Paper III)?

Ice-free species

- Best-fit scenarios
  - Extra-European post-glacial recolonization: 7/12 species
  - Southern *refugia*: 3/12 species
  - Northern micro-*refugia*: 2/12 species

Ice-covered species

- Best-fit scenarios
  - Nunatak/micro-*refugia*: 2/3 species
  - *Tabula rasa*: 1/3 species



Results and discussion

H3: Post-glacial history of bryophytes (Europe, Paper III)?

Ice-free species

- Best-fit scenarios
  - Extra-European post-glacial recolonization: 7/12 species
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→ Post-glacial assembly of Europe = complex history from multiple sources!

Results and discussion

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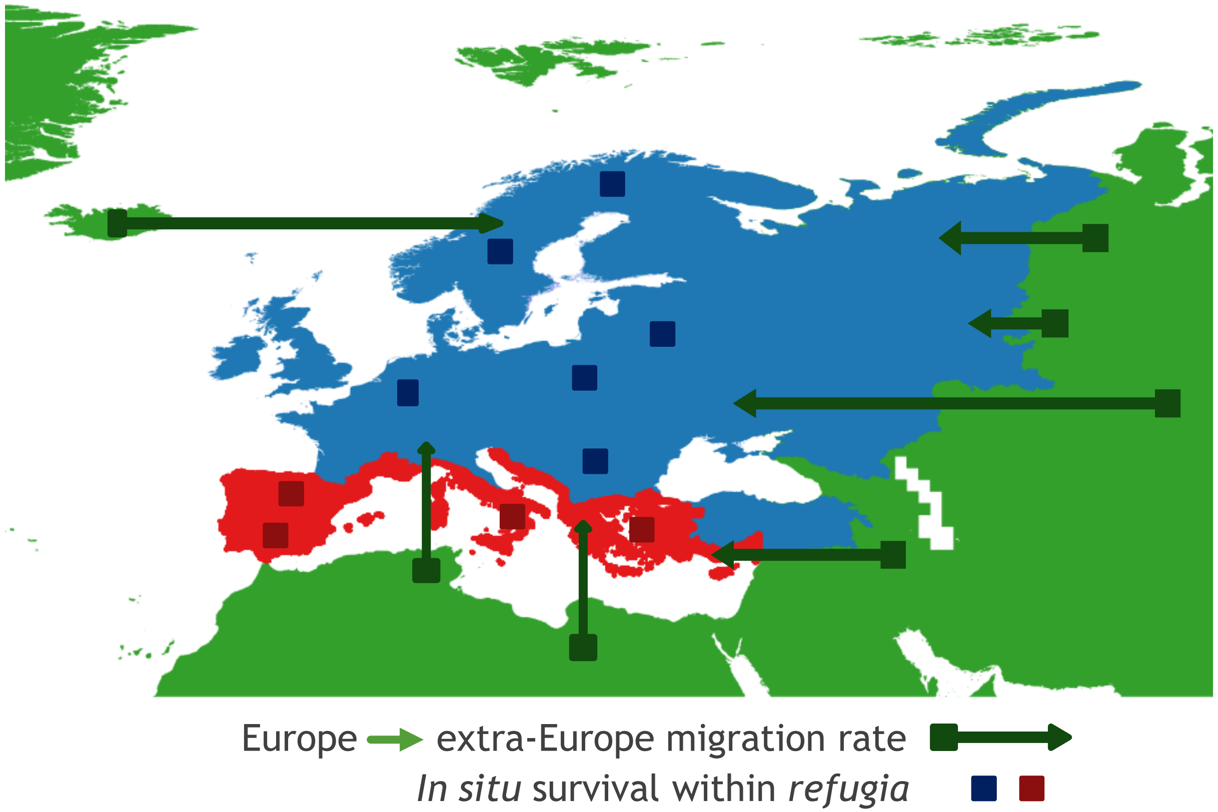

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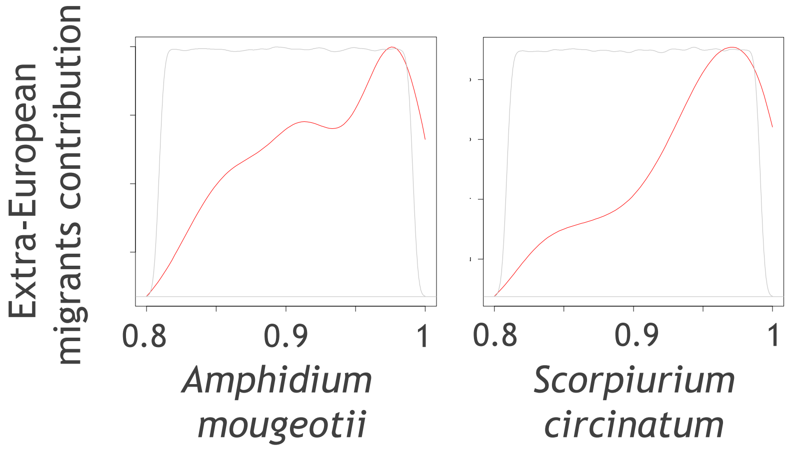

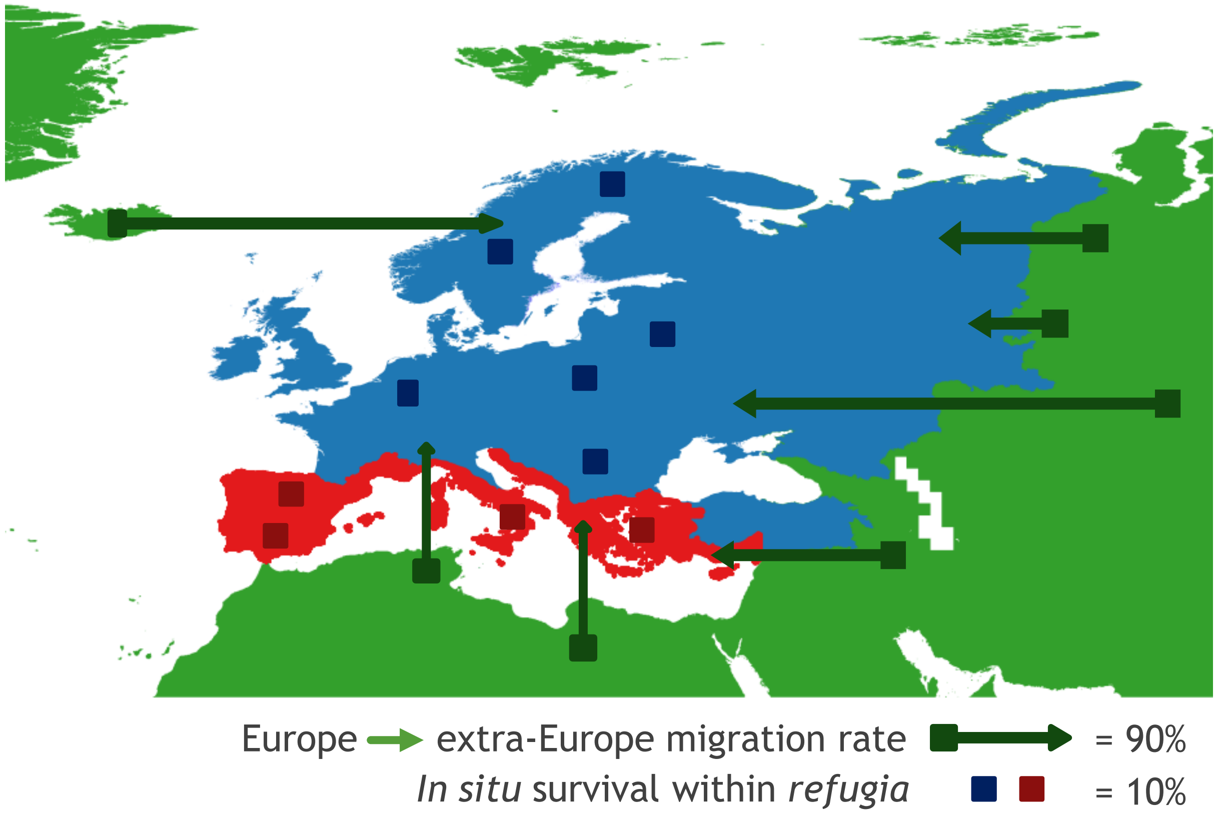

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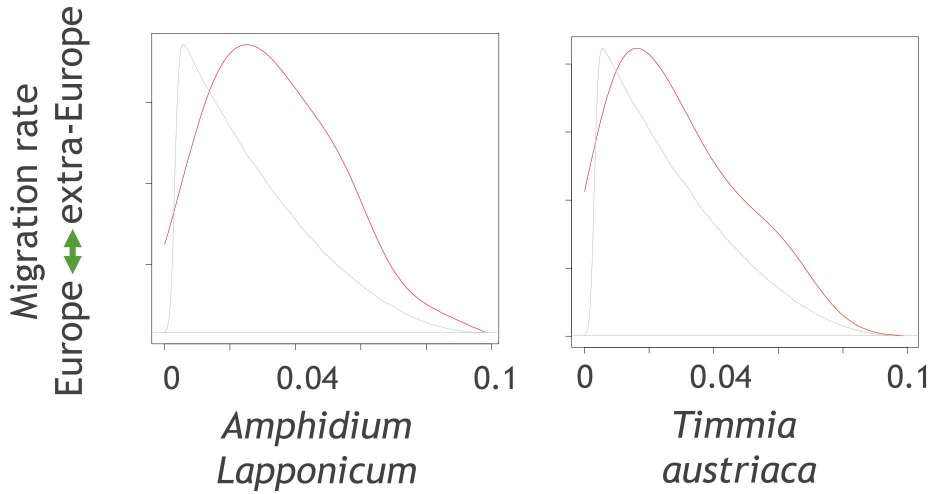

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→ Importance of LDD for the post-glacial recolonization of Europe by bryophytes!

Results and discussion

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Results and discussion

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✓

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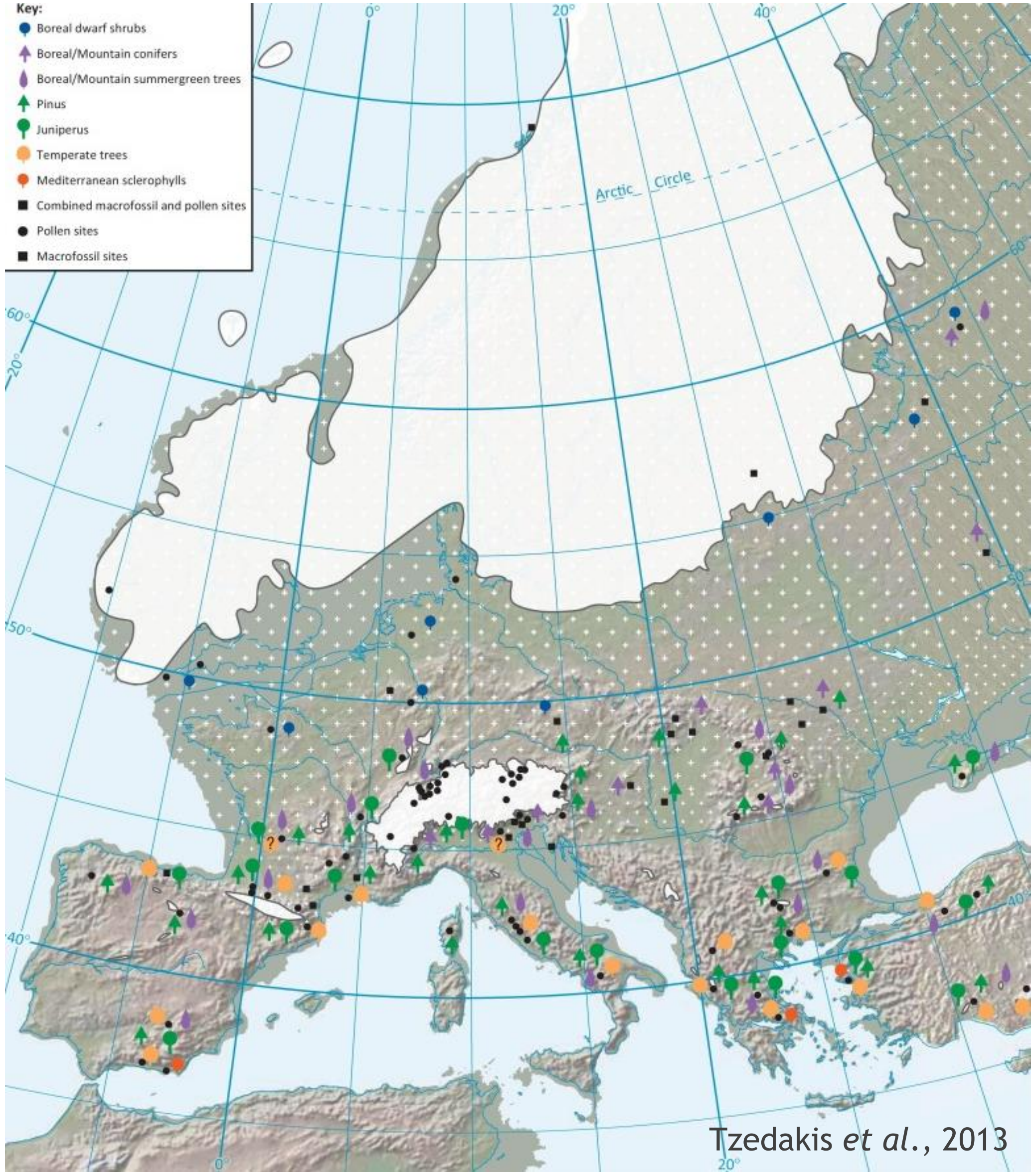

Tzedakis *et al.*, 2013

European paleoenvironments at LGM

Results and discussion

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X

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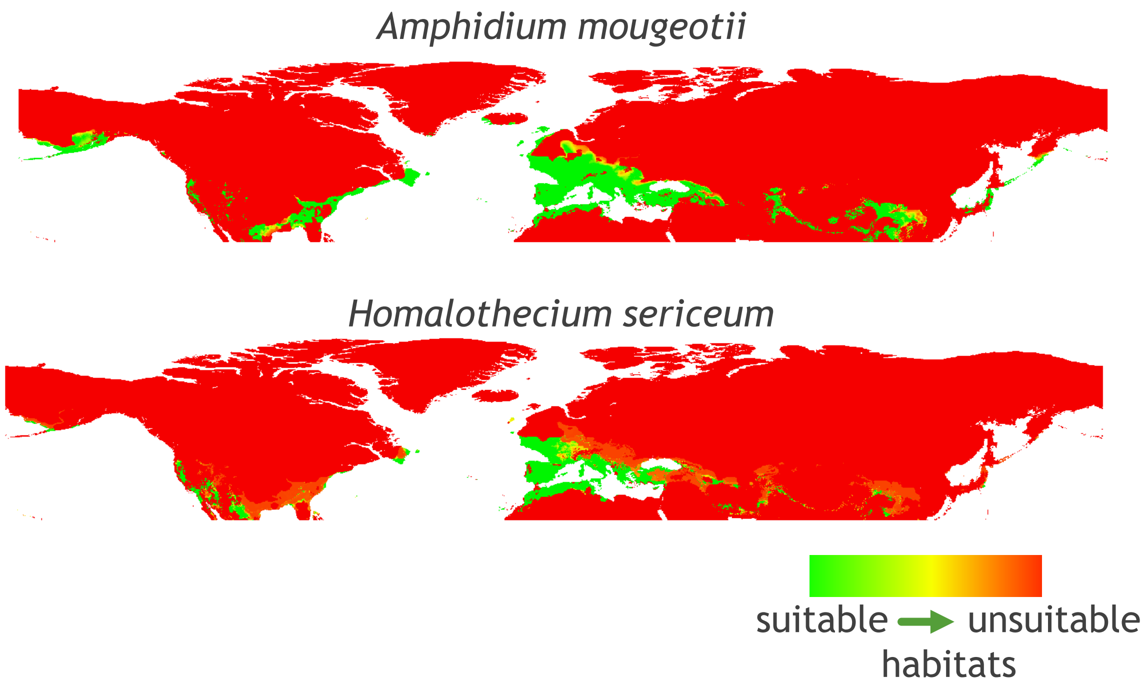
SDMs projected onto LGM climatic conditions



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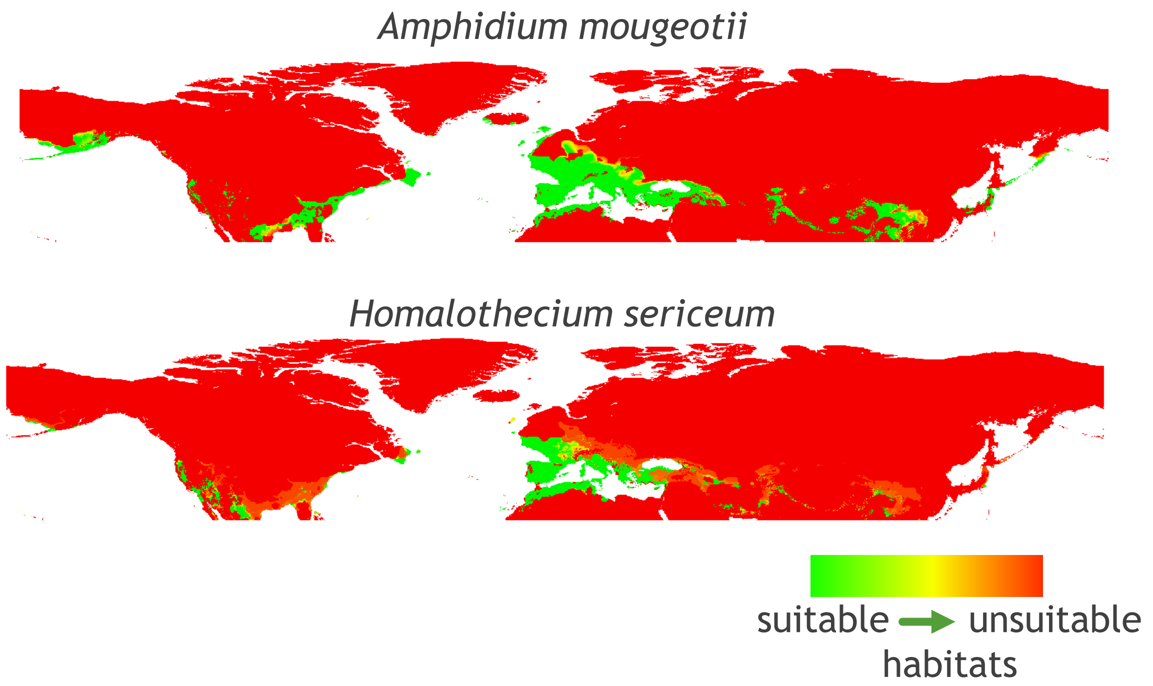

"A long-known feature of LGM climate simulations is that they underestimate the degree of cooling"
Tzedakis *et al.*, 2013

→ Too optimistic LGM paleoclimatic reconstructions?
→ Warm bias?

Overall remark

Europe

- Dispersal does not seem limited!
  - Post-glacial recolonization mainly from extra-European migrants
    - Importance of LDD events

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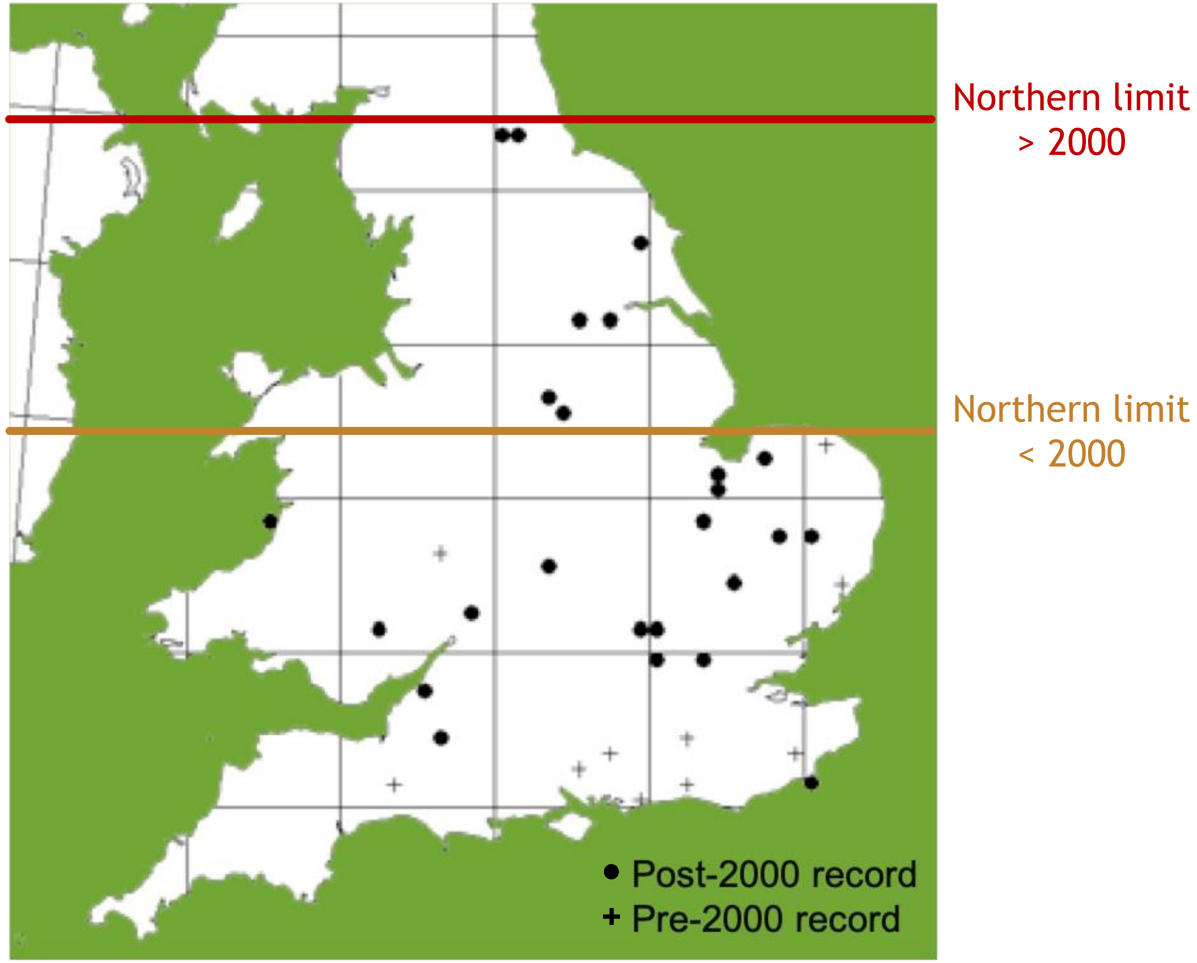
Bosanquet *et al.*, 2012



Distribution of vagrant *Orthotrichaceae* species in England and Wales

Overall remark

Europe

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Lowland Amazonia

- Dispersal limited!
  - IBD in most species
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Lowland Amazonia

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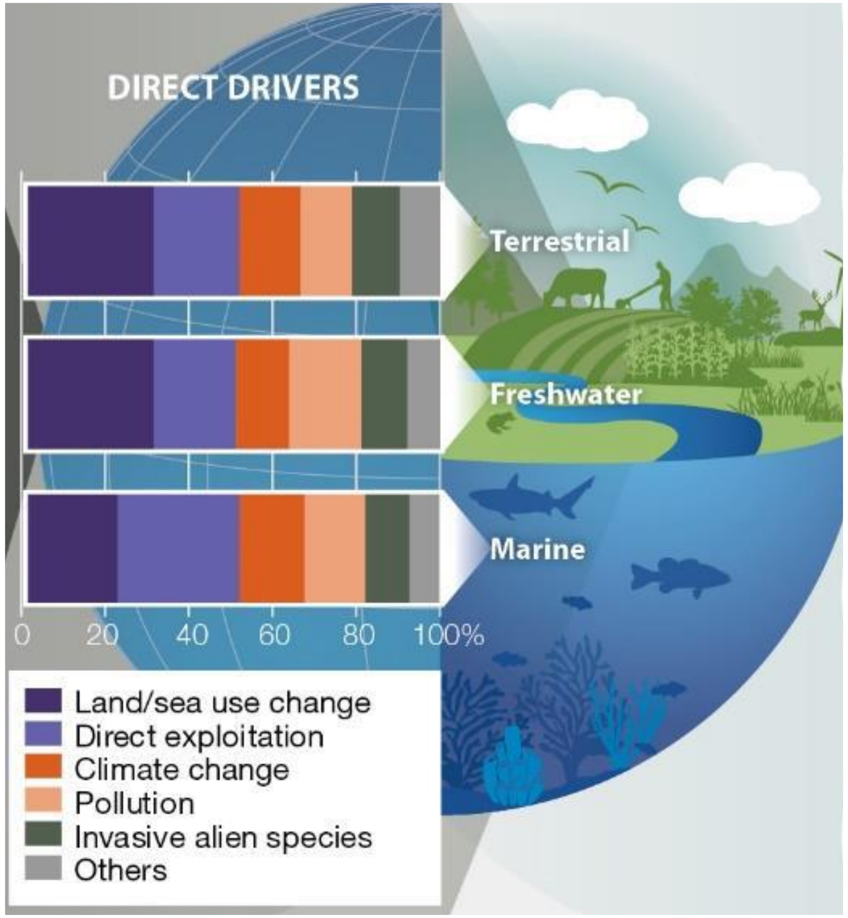
- Vulnerable to current global change!

Perspectives

Perspectives

- Ongoing global change
  - Land/sea-use conversion= 1st direct driver of global declines in nature!

Direct drivers of global declines in nature

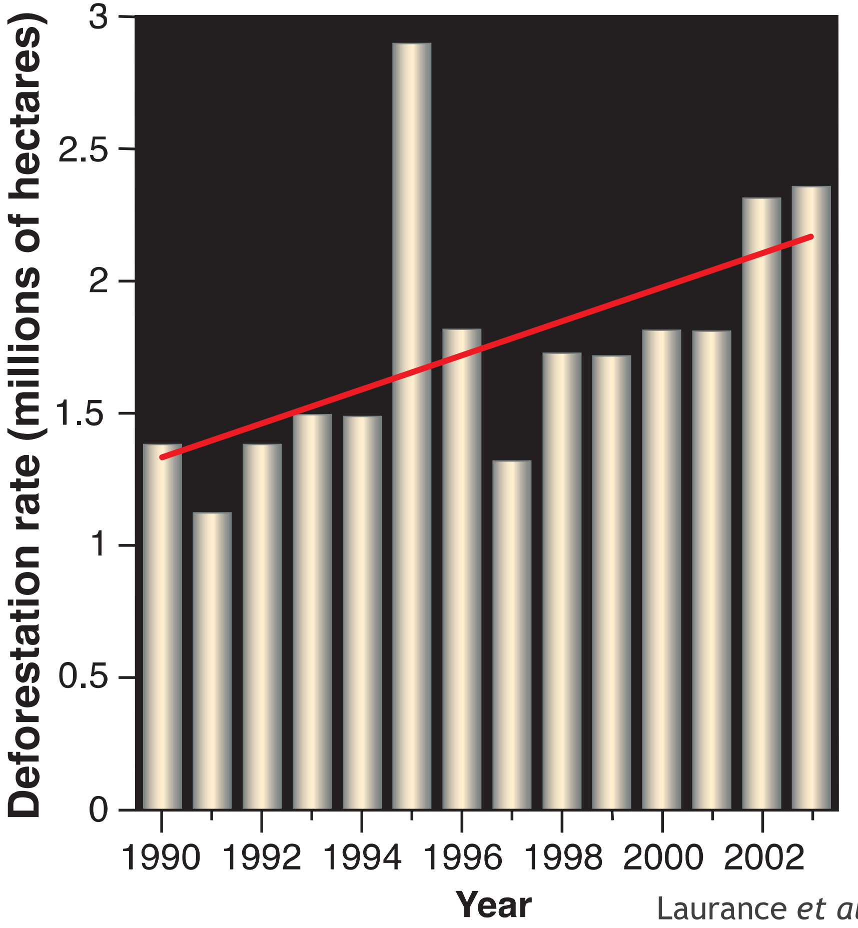


Diaz *et al.*, 2019

Perspectives

- Ongoing global change
  - Land/sea-use conversion= 1st direct driver of global declines in nature!
  - Deforestation = most measured land-use process!
    - Amazonia: highest deforestation rate in the world (*c.* 2.4 million ha/yr)

Deforestation in Brazilian Amazonia



Laurance *et al.*, 2004

Perspectives

- Ongoing study
  - Comparing the relative impact of past climate changes and deforestation in Amazonia
  - Spatially explicit coalescent simulations
    - Scenario 1: LGM bottleneck
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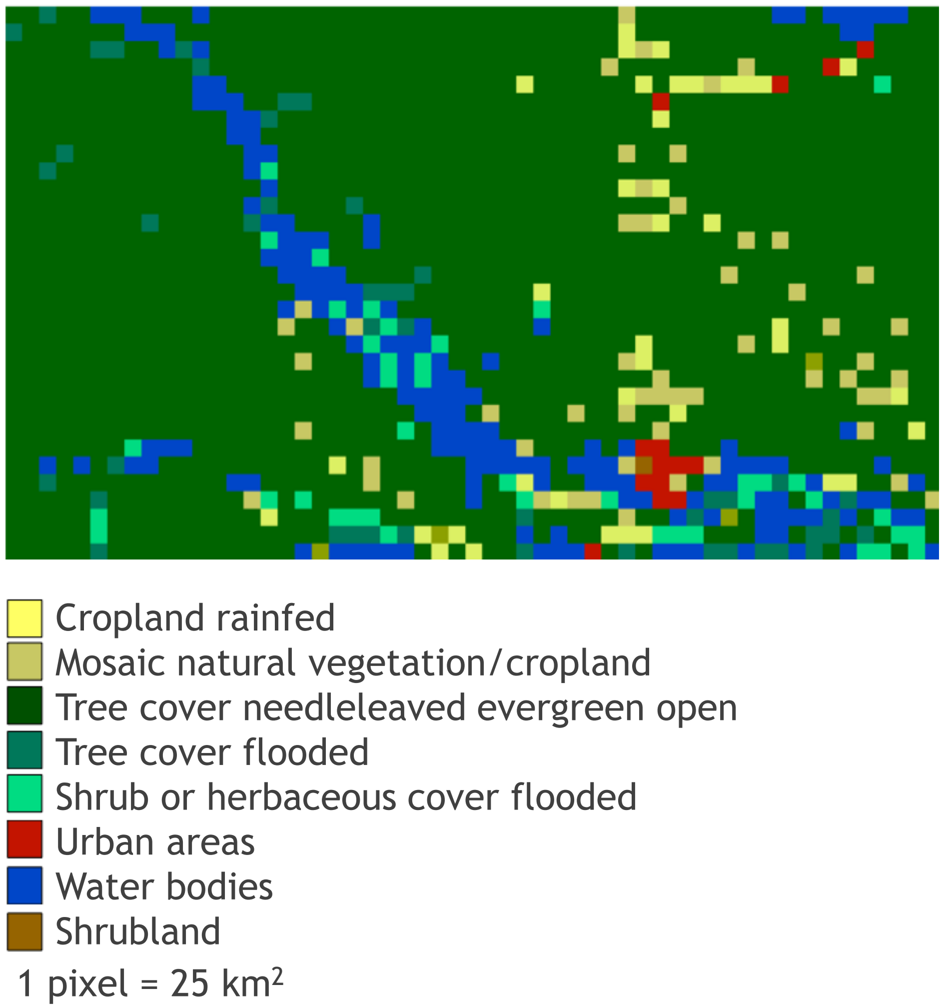

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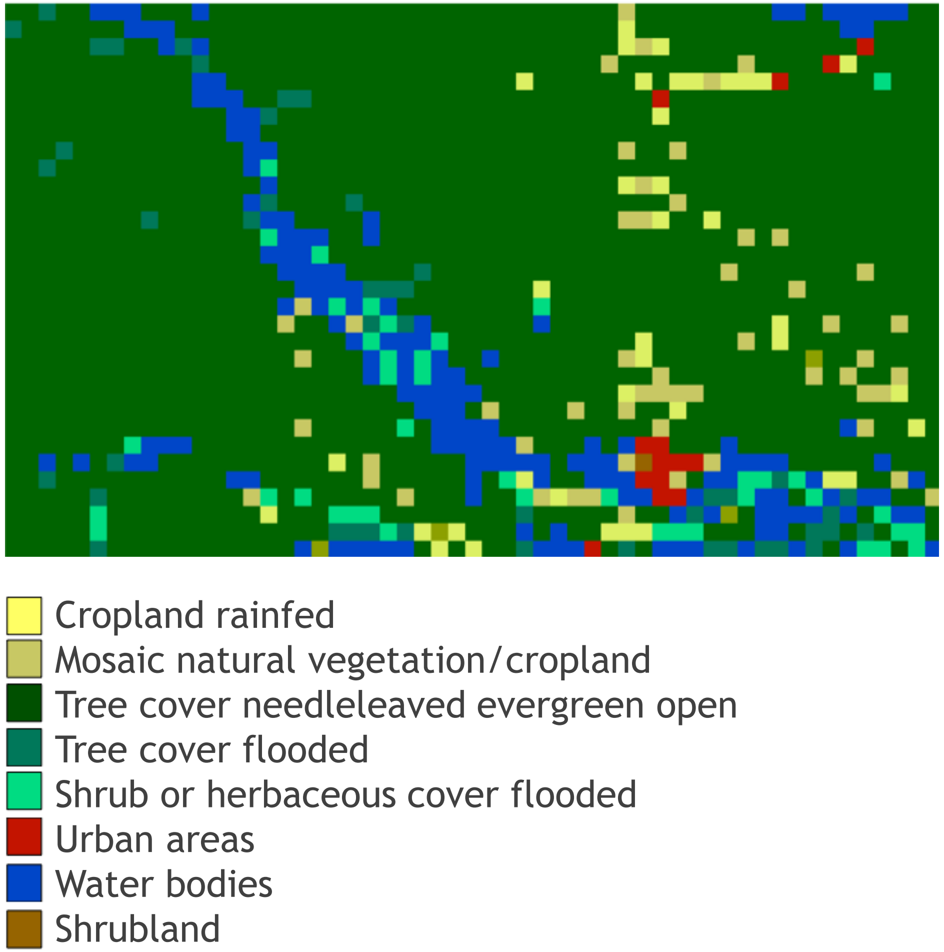

1 pixel = 25 km^2

Perspectives

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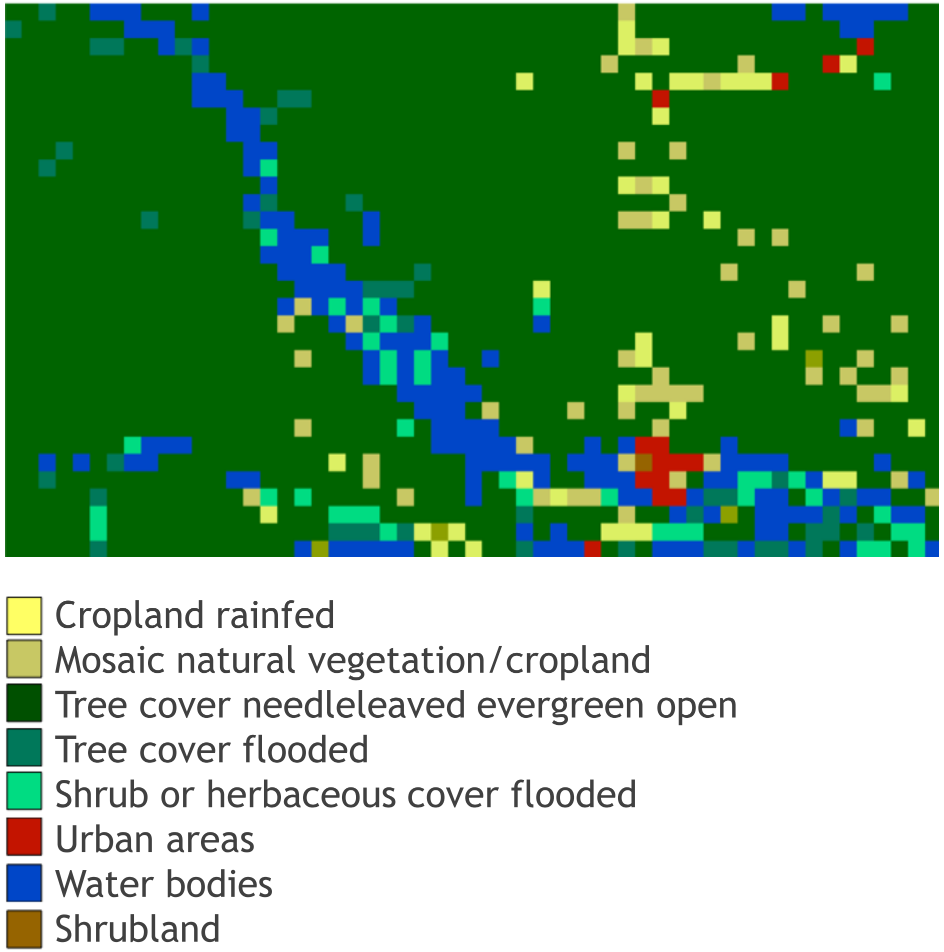
→ Predict to what extent Amazonian bryophytes might suffer from ongoing deforestation!



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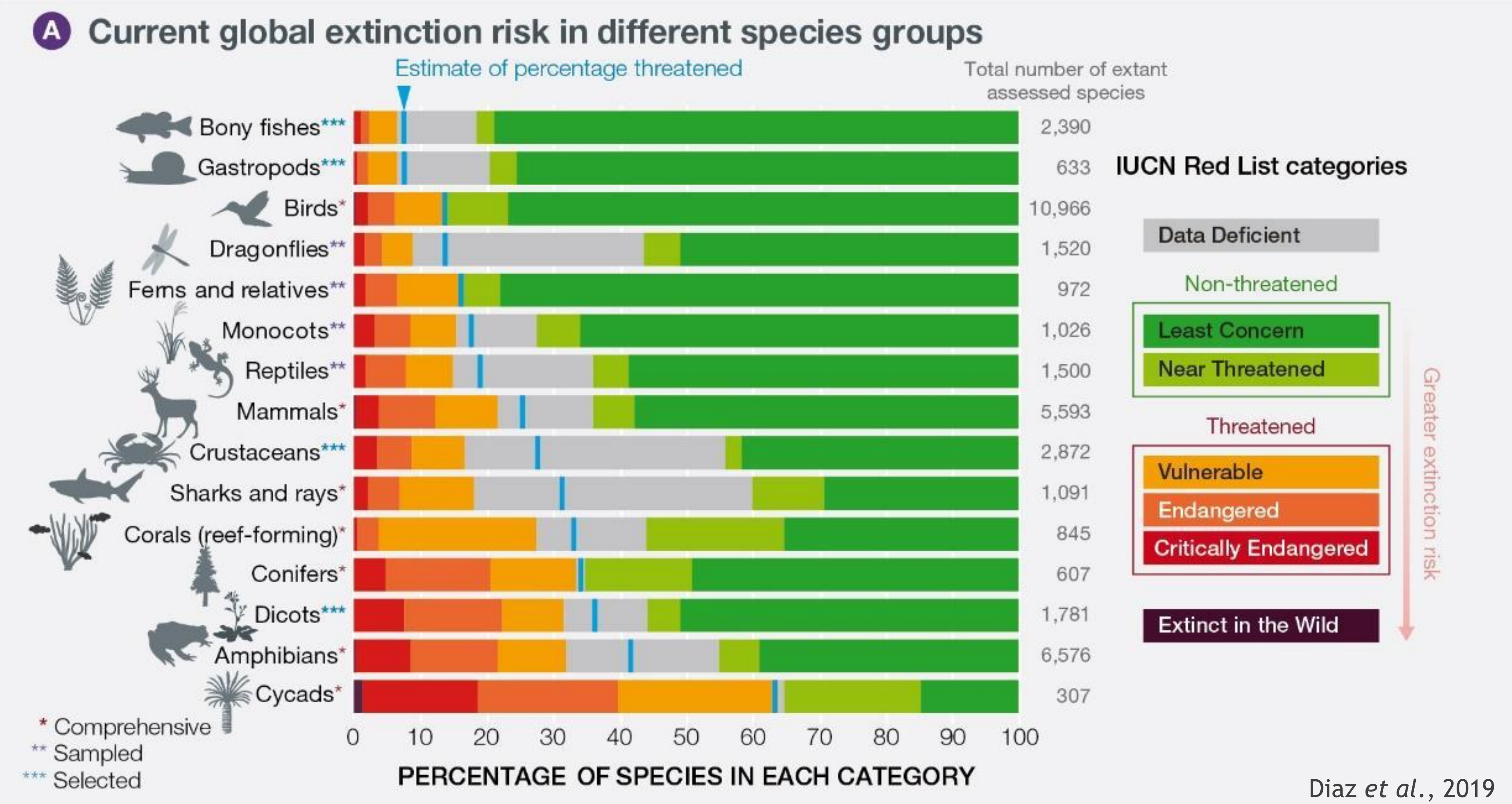
Perspectives

- 1 million species currently face extinction because of human actions!
  - Around 25% of species in all assessed animal and plant groups threatened!



Diaz *et al.*, 2019

Perspectives

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→ Let's evaluate our impact BUT ALSO act to not reach that number!

Perspectives

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Acknowledgments

- Supervisors
  - Alain Vanderpoorten (ULiège)
  - Patrick Mardulyn (ULB)

- Mentors & colleagues during internships
  - Norman Wickett: Chicago Botanic Garden
  - Love Dalén: Swedish Museum of Natural History

CHICAGO BOTANIC GARDEN

Naturhistoriska riksmuseet

- Members and past members of our lab

- Family and friends

Orthotrichum stramineum

Thank you for your attention!

Time for questions!


SAM SUFFIT
Them