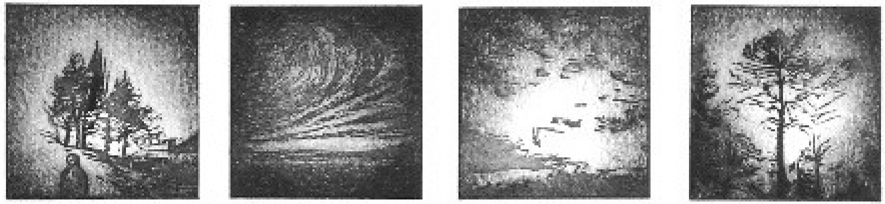
Reliability of species distribution model projections

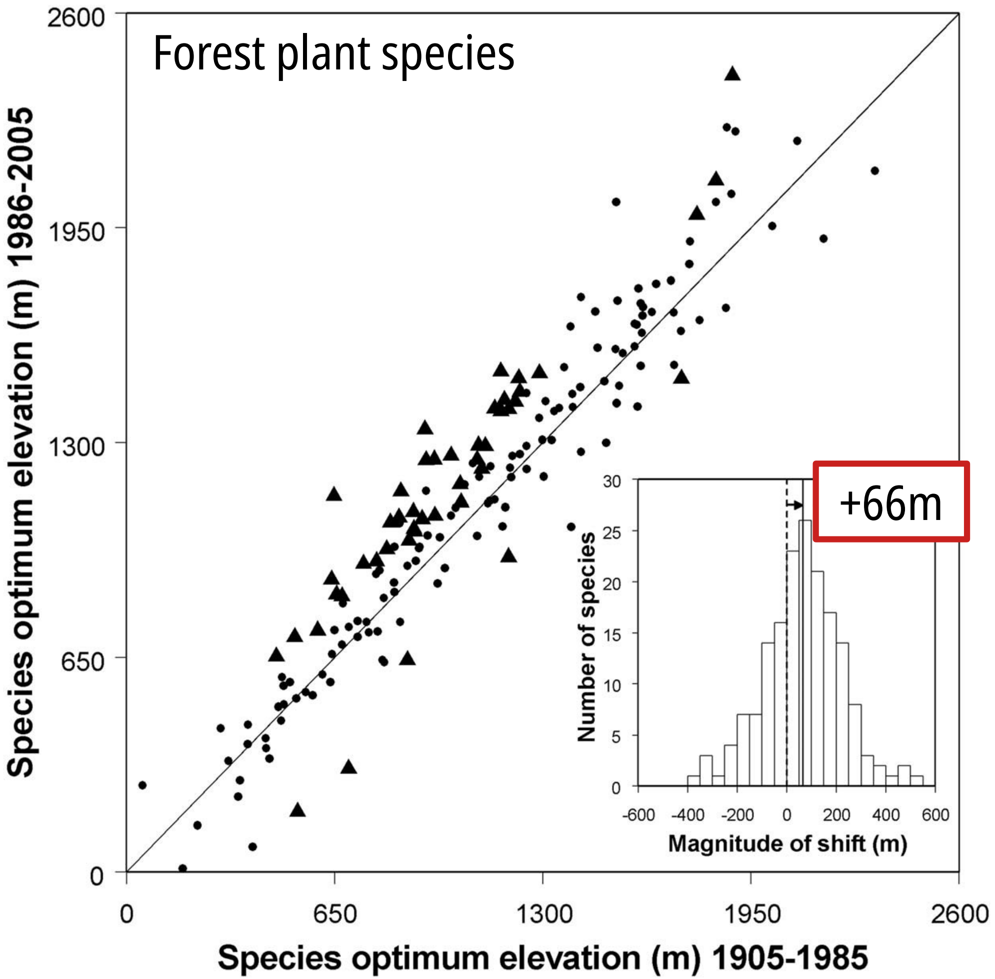


Drawing insights from palaeoecological data

V. Van der Meersch, supervised by I. Chuine

Linocut print by C. Rescan

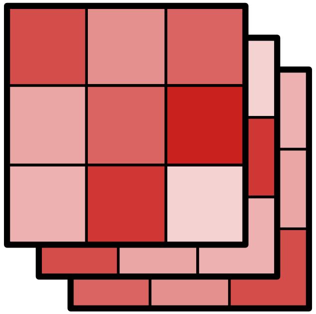
What we observe: species range shifts



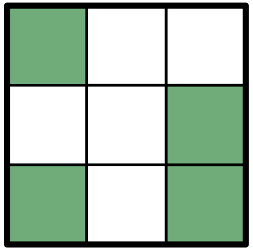
Lenoir et al. (2008)

How we could predict the future: popular statistical approaches

Correlative niche models



Bioclimatic predictors



Current distribution

HOW WE COULD PREDICT THE FUTURE: POPULAR STATISTICAL APPROACHES

Correlative niche models

HOW WE COULD PREDICT THE FUTURE: POPULAR STATISTICAL APPROACHES

Correlative niche models

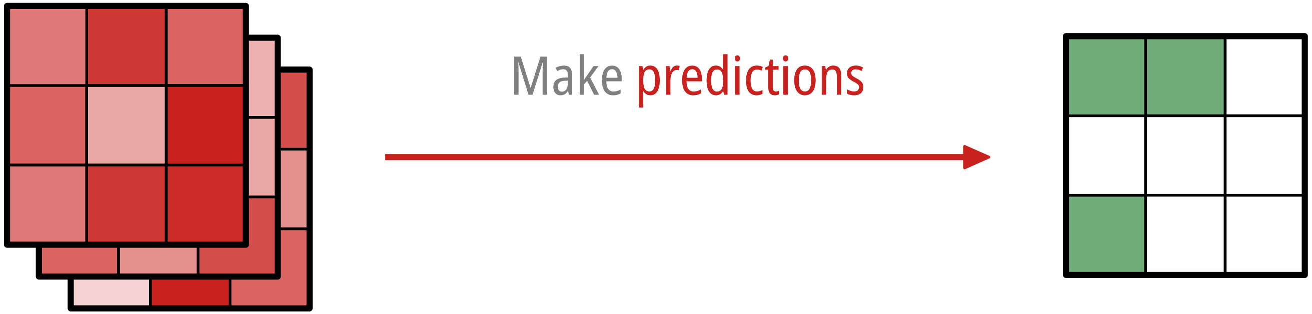
FIND PATTERNS

HOW WE COULD PREDICT THE FUTURE: POPULAR STATISTICAL APPROACHES

Correlative niche models

How we could predict the future: popular statistical approaches

Correlative niche models



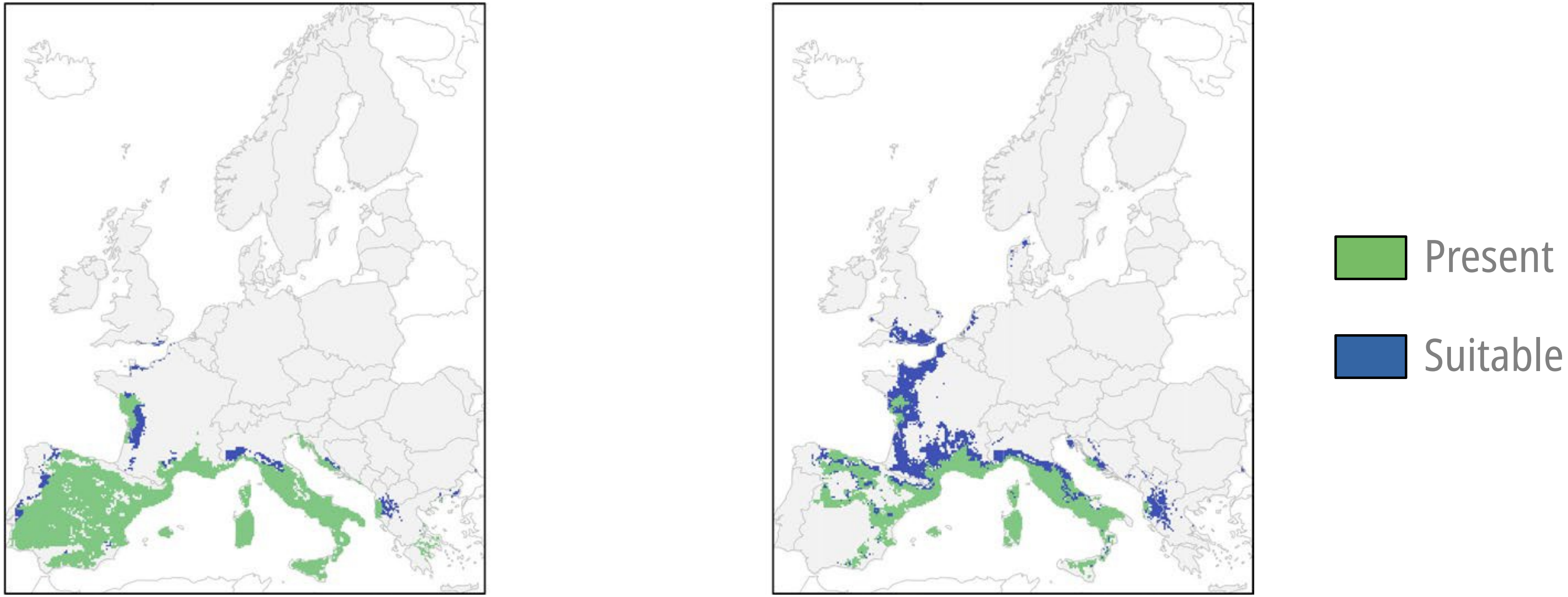
Future predictors

Future distribution

MAIN HYPOTHESIS: CORRELATIONS HOLD TRUE

HOW WE COULD PREDICT THE FUTURE: POPULAR STATISTICAL APPROACHES

Example: *Quercus ilex* projected range shift



CURRENT

2095

Mauri et al. (2022)

HOW WE COULD PREDICT THE FUTURE: POPULAR STATISTICAL APPROACHES

Key advantages

- easy handling of the models
- calibration can be envisaged for many species
- standard methods, reproducibility

HOW WE COULD PREDICT THE FUTURE: POPULAR STATISTICAL APPROACHES

Approach criticized: lack of biological realism?

Ecology, 101(1), 2020, e02912

Correlative climatic niche models predict real and virtual species distributions equally well

Valentin Journé,[1,2,4] Jean-Yves Barnagaud,[3] Cyril Bernard,[1] Pierre-André Crochet,[1] and Xavier Morin[1]

"high predictive power […] not necessarily reflect causal relationships between climate and species distributions"

HOW WE COULD PREDICT THE FUTURE: POPULAR STATISTICAL APPROACHES

Approach criticized: lack of biological realism?

RESEARCH ARTICLE

Methods in Ecology and Evolution BRITISH ECOLOGICAL SOCIETY

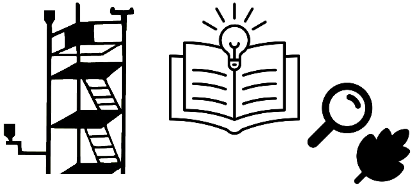
The effects of climate change on Australia's only endemic Pokémon: Measuring bias in species distribution models

Dan L. Warren[1,2] | Alex Dornburg[3] | Katerina Zapfe[3,4] | Teresa L. Iglesias[5,6]

Consistent predictions from meaningless data

HOW WE COULD PREDICT THE FUTURE: PROCESS-BASED APPROACHES

Process-based models, in a nutshell



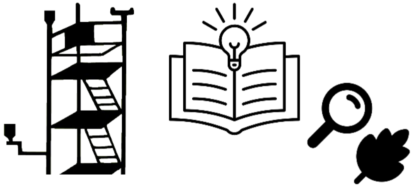
Experimentations

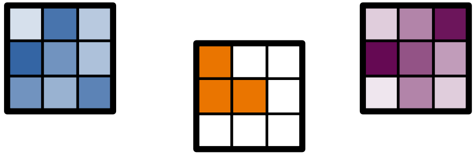
A priori knowledge

Observations

HOW WE COULD PREDICT THE FUTURE: PROCESS-BASED APPROACHES

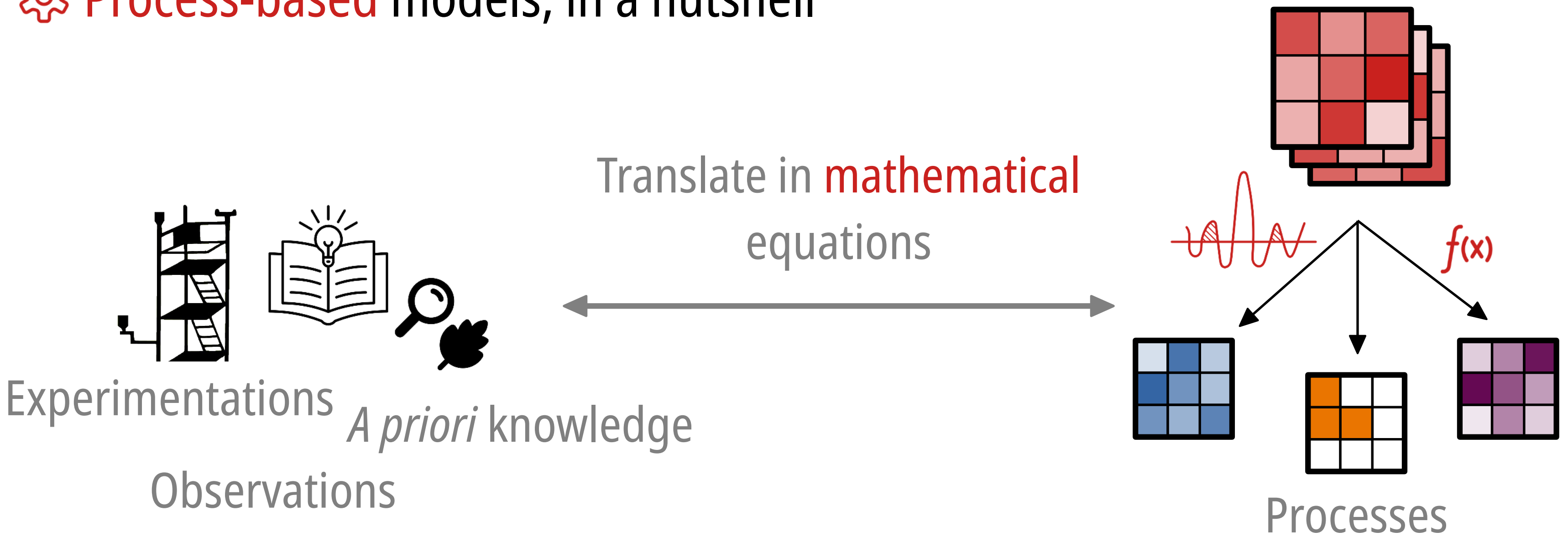
Process-based models, in a nutshell





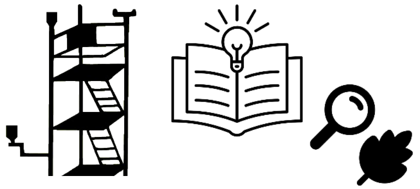
How we could predict the future: process-based approaches

Process-based models, in a nutshell



How we could predict the future: process-based approaches

Process-based models, in a nutshell

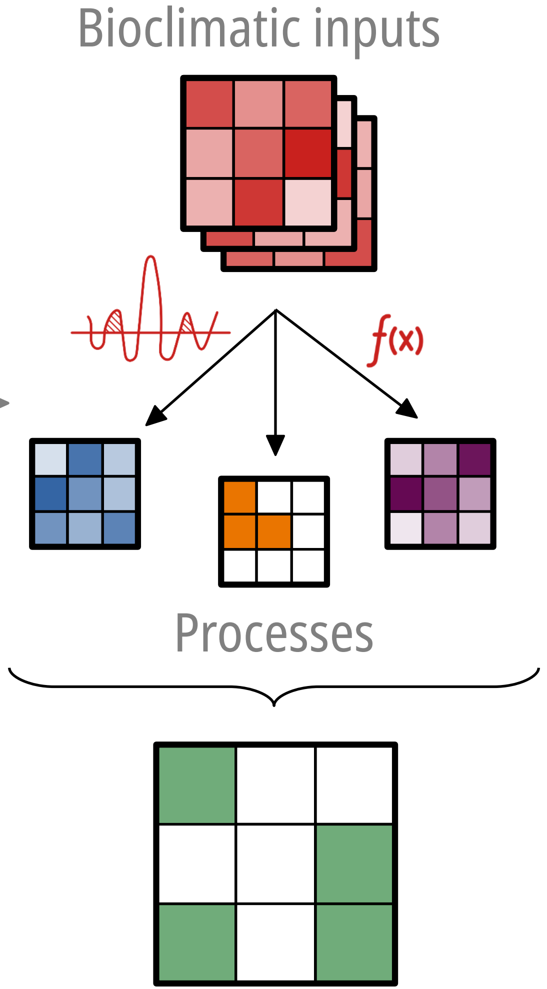


Experimentations

A priori knowledge

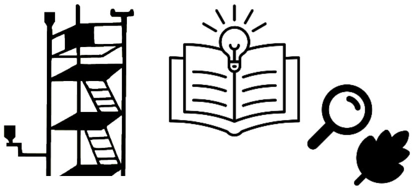
Observations

Translate in mathematical equations



HOW WE COULD PREDICT THE FUTURE: PROCESS-BASED APPROACHES

Process-based models, in a nutshell

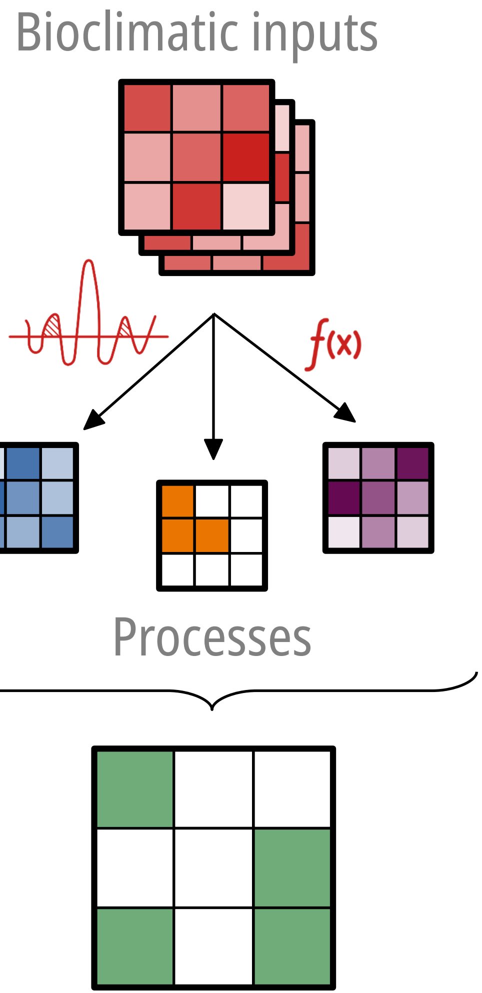


Experimentations

A priori knowledge

Observations

Translate in mathematical equations

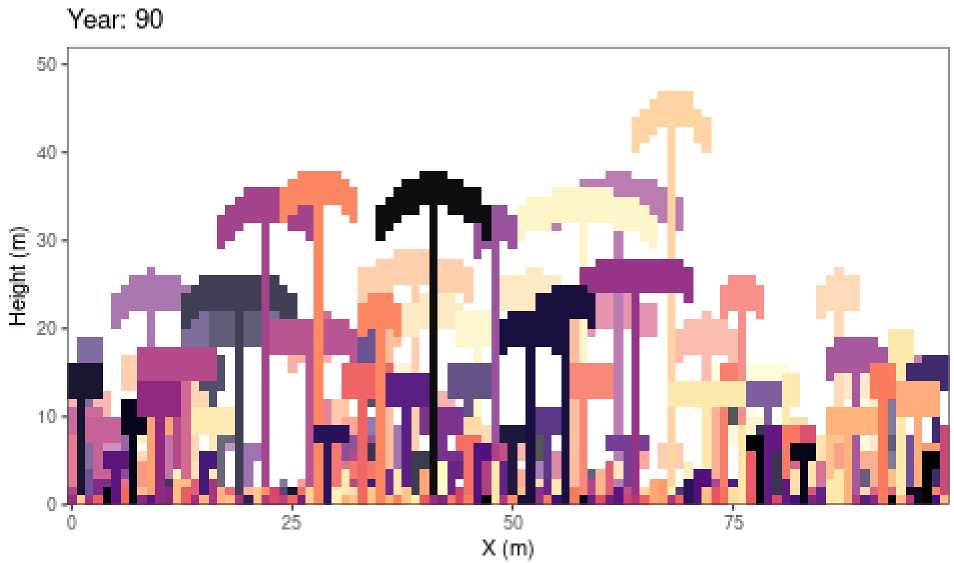


DESCRIBE PROCESSES

HOW WE COULD PREDICT THE FUTURE: PROCESS-BASED APPROACHES

e.g. individual-based models

TROLL model (Maréchaux & Chave, 2017),
ForCEEPS model (Morin et al., 2021)...

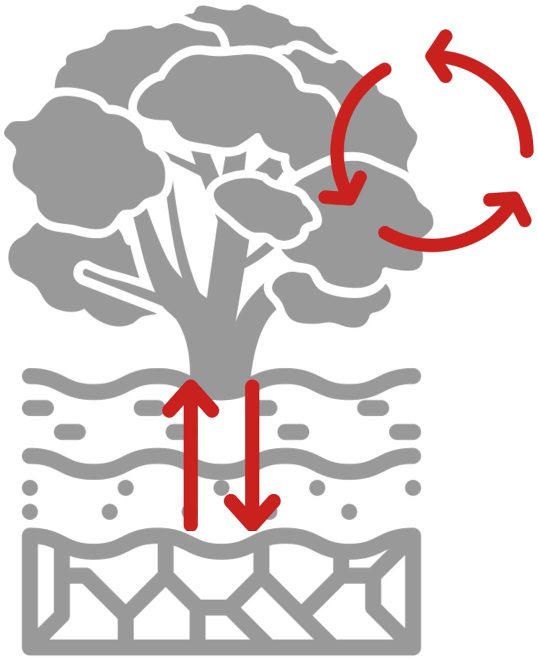


Schmitt et al. (2023)

HOW WE COULD PREDICT THE FUTURE: PROCESS-BASED APPROACHES

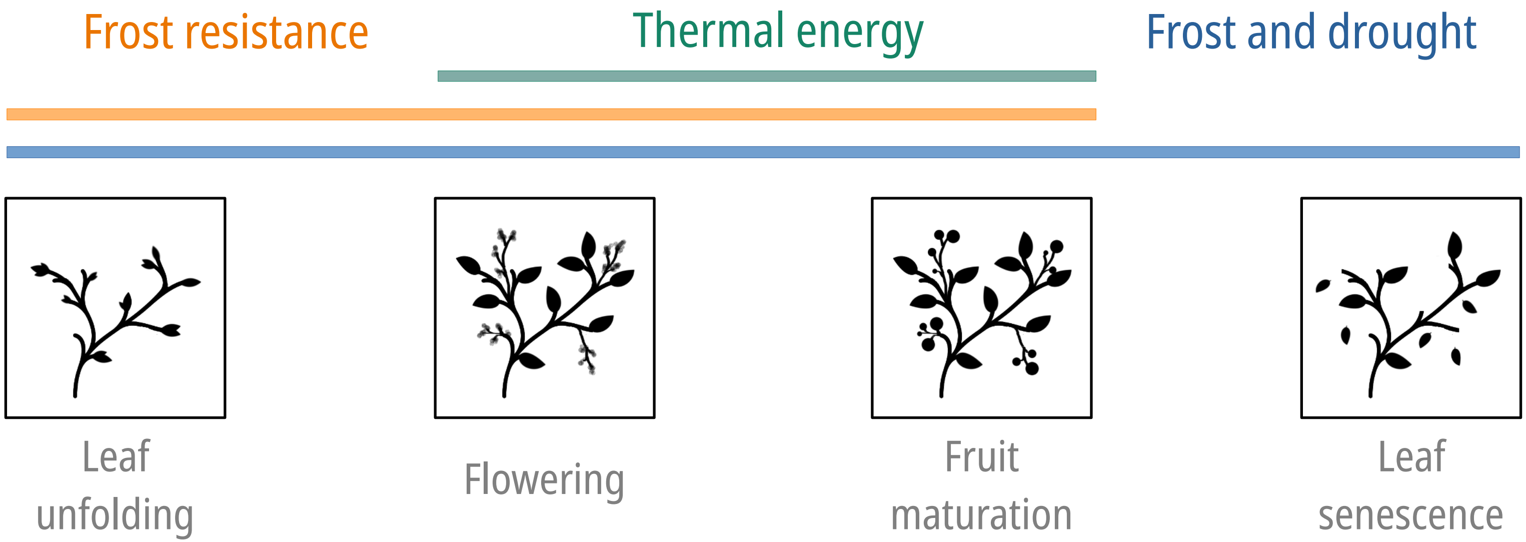
e.g. “average tree” models

CASTANEA model (Dufrêne et al., 2005),
PHENOFIT model (Chuine & Beaubien, 2001)...



How we could predict the future: process-based approaches

PHENOFIT: focus on phenology

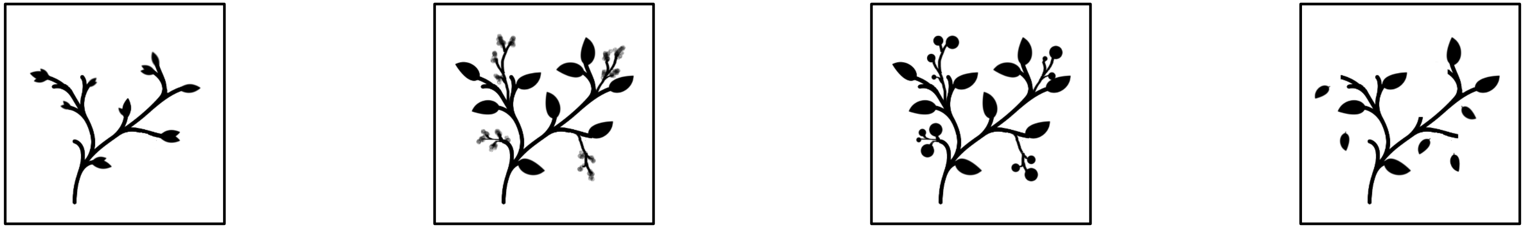


HOW WE COULD PREDICT THE FUTURE: PROCESS-BASED APPROACHES

PHENOFIT: focus on phenology

FITNESS = Reproductive success × Survival

Frost resistance Thermal energy Frost and drought



Leaf unfolding | Flowering | Fruit maturation | Leaf senescence

HOW WE COULD PREDICT THE FUTURE: PROCESS-BASED APPROACHES

Key advantages: greater comprehension of the complexity of ecosystems?

- mathematical formalisation of current knowledge, with a direct biological interpretation
- further validation of our understanding of processes against observations
- testing new hypotheses

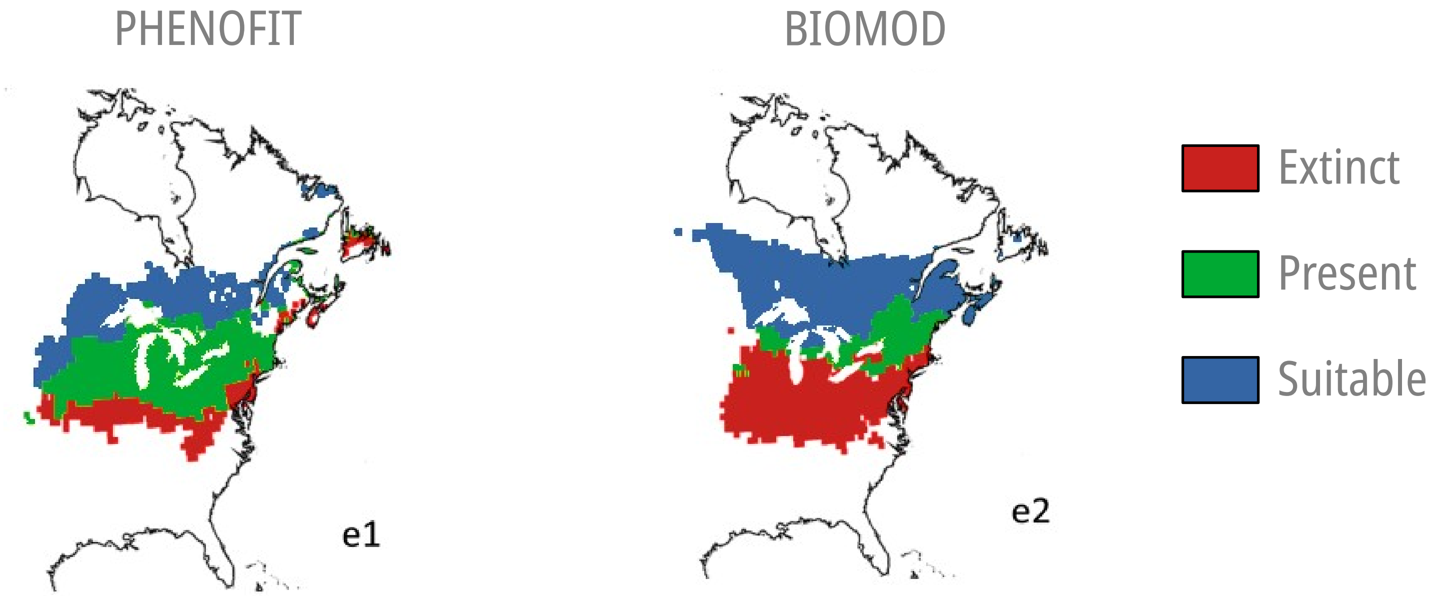
HOW WE COULD PREDICT THE FUTURE: PROCESS-BASED APPROACHES

Main drawbacks: finding the appropriate amount of complexity?

- take more time to develop, more challenging to use
- data available to calibrate them only for a few species
- important role of modeller subjectivity
- lack of transparency

How we could predict the future: divergence between approaches

Different predictions, e.g. *Quercus bicolor* in 2100



Correlative models more pessimistic?

Adapted from Morrin & Thuiller (2009)

HOW WE COULD PREDICT THE FUTURE: CONTINUITY AMONG MODELS

Adapted from Dormann et al. (2012)

HOW WE COULD PREDICT THE FUTURE: CONTINUITY AMONG MODELS

Correlative models | Process-based models

- **implicit** representation of processes
- **explicit** representation of processes

Adapted from Dormann et al. (2012)

HOW WE COULD PREDICT THE FUTURE: CONTINUITY AMONG MODELS

Correlative models | Process-based models

- implicit representation of processes
- calibrated with current distribution data

- explicit representation of processes
- calibrated with process-related data

Adapted from Dormann et al. (2012)

HOW WE COULD PREDICT THE FUTURE: CONTINUITY AMONG MODELS

COMMON ASSUMPTION: PROCESS-BASED MODELS MIGHT PROVIDE
MORE ROBUST PROJECTIONS IN NOVEL CONDITIONS

e.g. Evans (2012), Singer et al. (2016), Urban et al. (2016), Zurell et al. (2016)

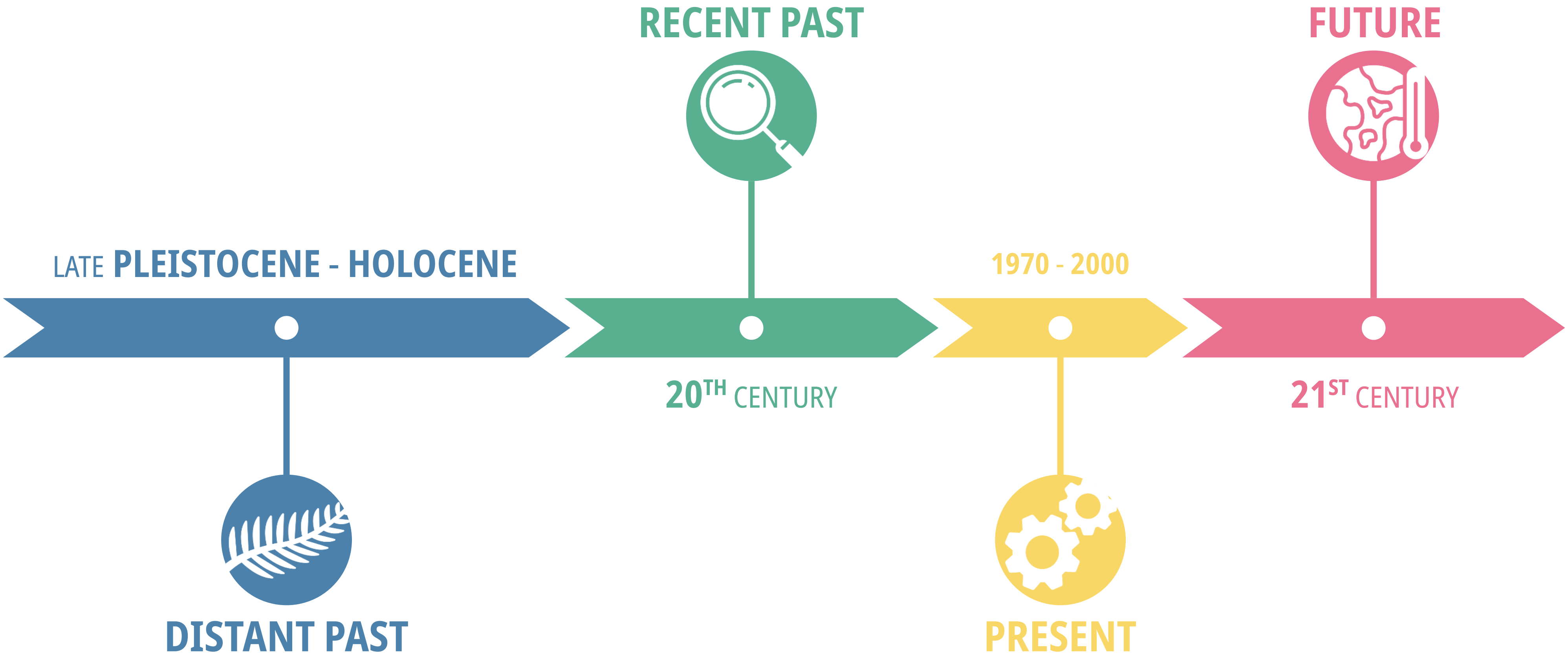
HOW WE COULD PREDICT THE FUTURE: CONTINUITY AMONG MODELS

COMMON ASSUMPTION: PROCESS-BASED MODELS MIGHT PROVIDE
MORE ROBUST PROJECTIONS IN NOVEL CONDITIONS

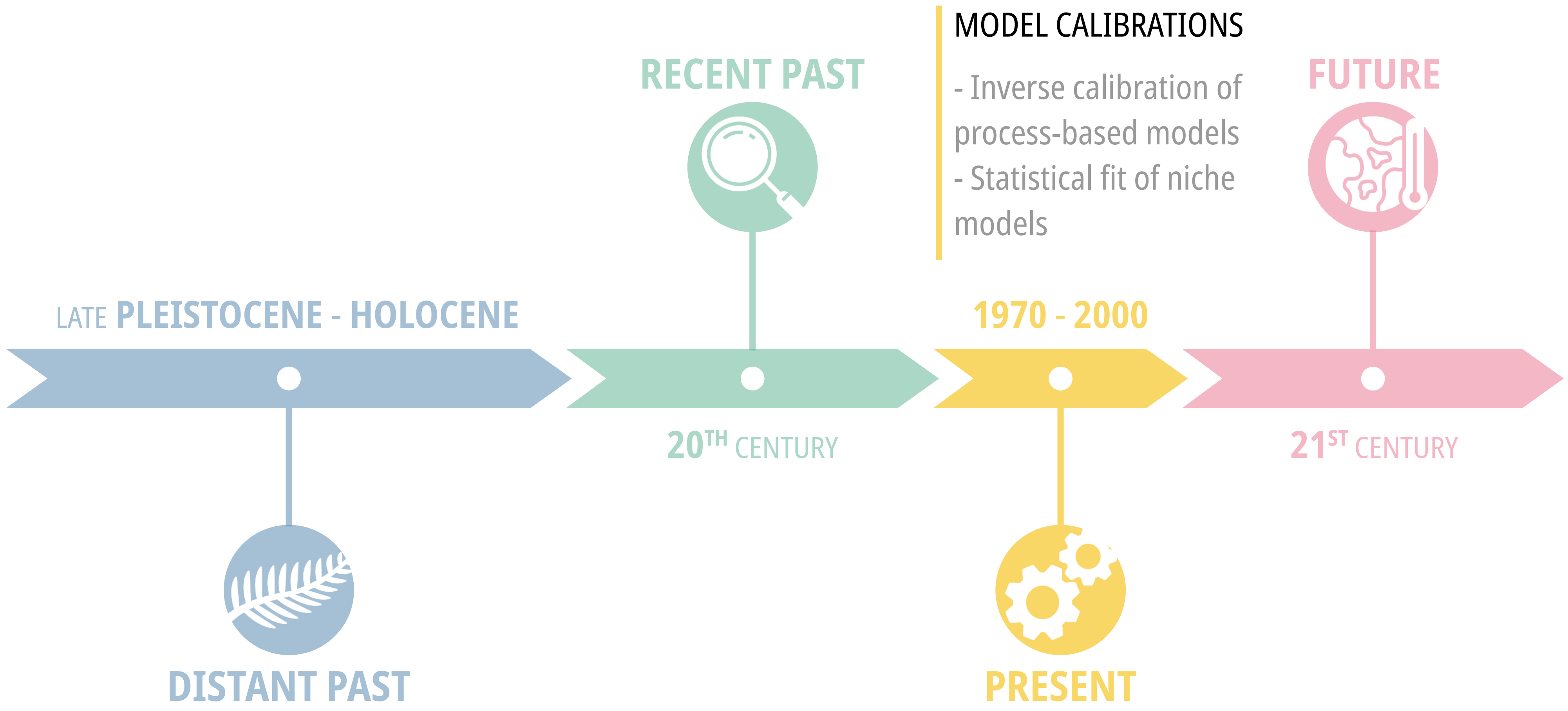
YET TO BE VERIFIED

e.g. Evans (2012), Singer et al. (2016), Urban et al. (2016), Zurell et al. (2016)

THESIS FRAMEWORK



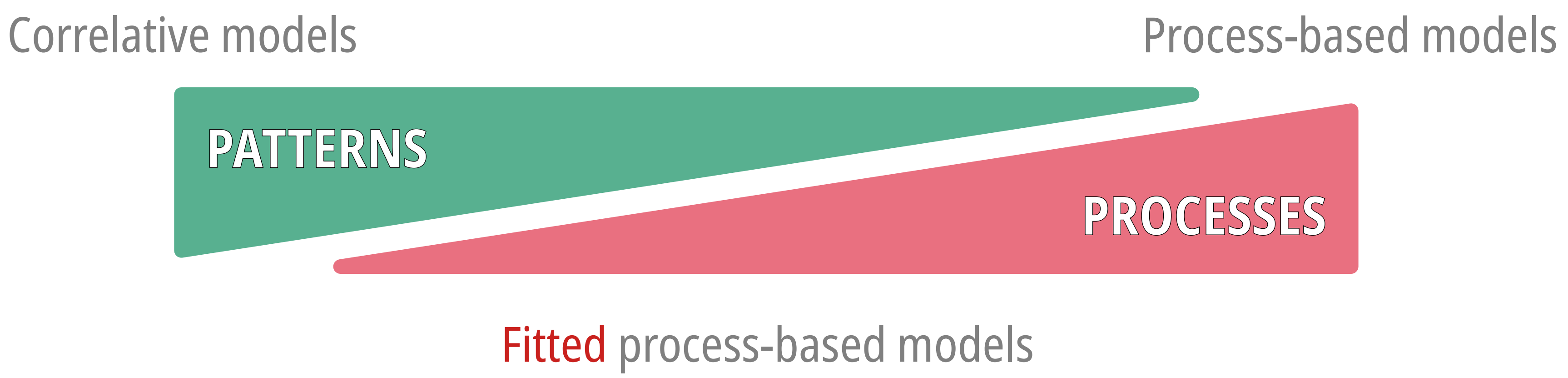
THESIS FRAMEWORK



Inverse calibration of process-based models

Adapted from Dormann et al. (2012)

INVERSE CALIBRATION OF PROCESS-BASED MODELS



Adapted from Dormann et al. (2012)

INVERSE CALIBRATION OF PROCESS-BASED MODELS

Correlative models

Process-based models

Fitted process-based models

- calibrated with current distribution data
- explicit representation of processes

Adapted from Dormann et al. (2012)

INVERSE CALIBRATION OF PROCESS-BASED MODELS

Correlative models

Process-based models

Fitted process-based models

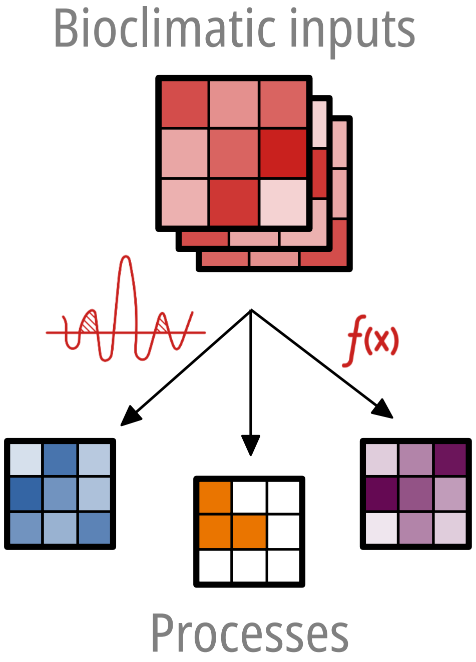
- calibrated with current distribution data
- explicit representation of processes

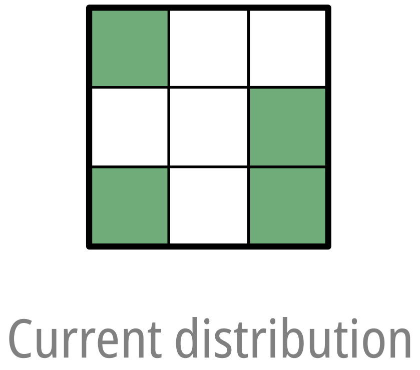
Combine both approaches

Adapted from Dormann et al. (2012)

INVERSE CALIBRATION OF PROCESS-BASED MODELS

Optimisation algorithm: covariance matrix adaptation – evolution strategy

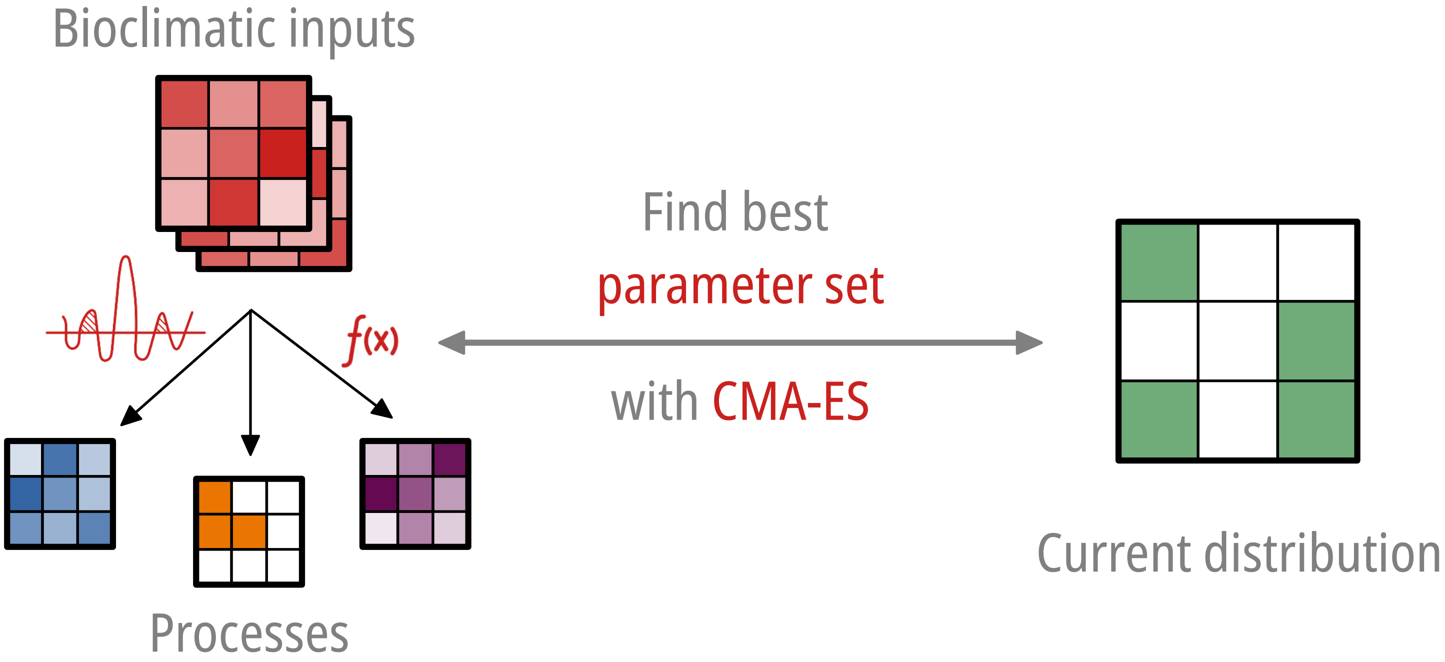




Van der Meersch & Chuine (2023)

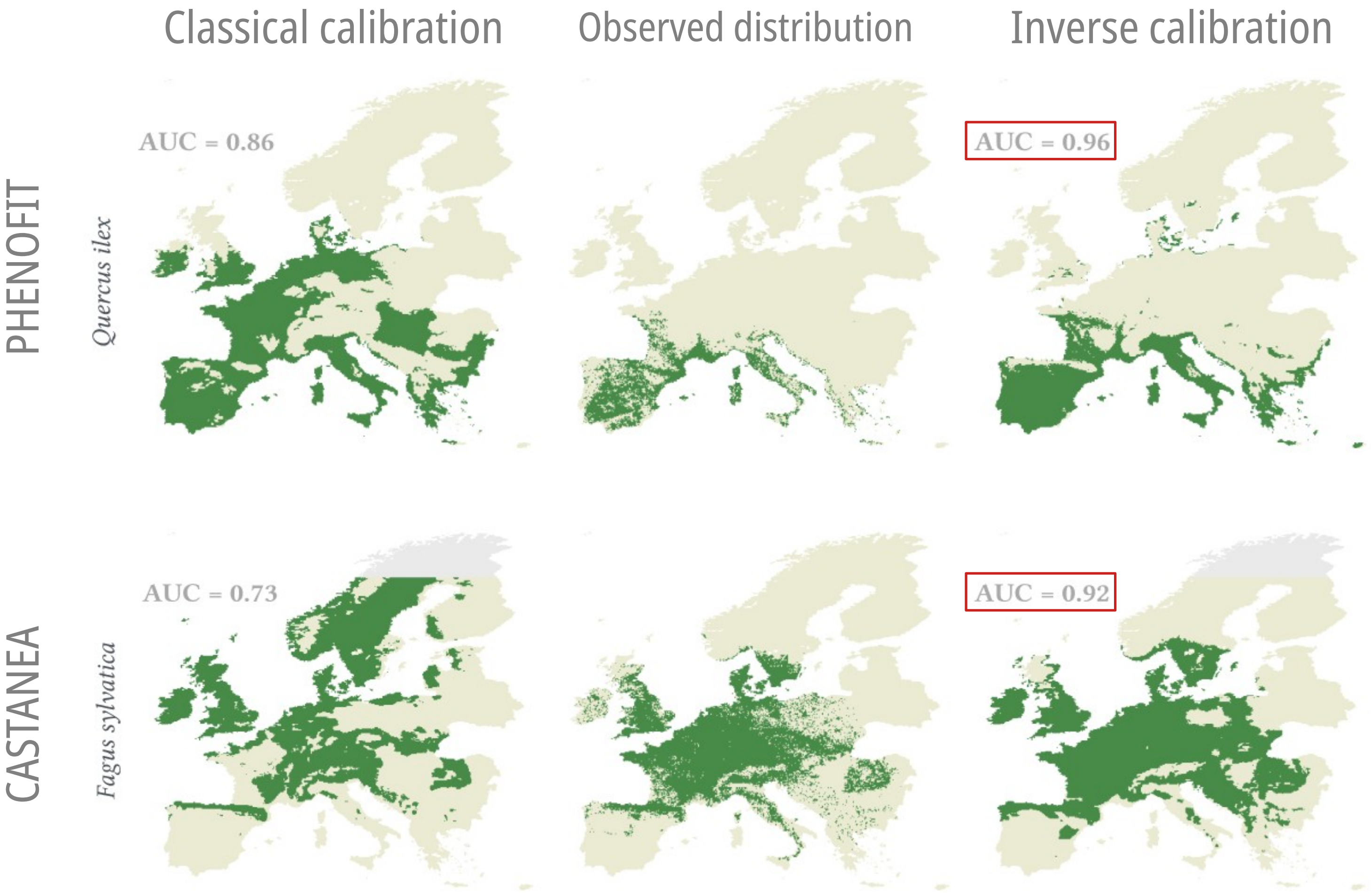
Inverse calibration of process-based models

Optimisation algorithm: covariance matrix adaptation – evolution strategy



Van der Meersch & Chuine (2023)

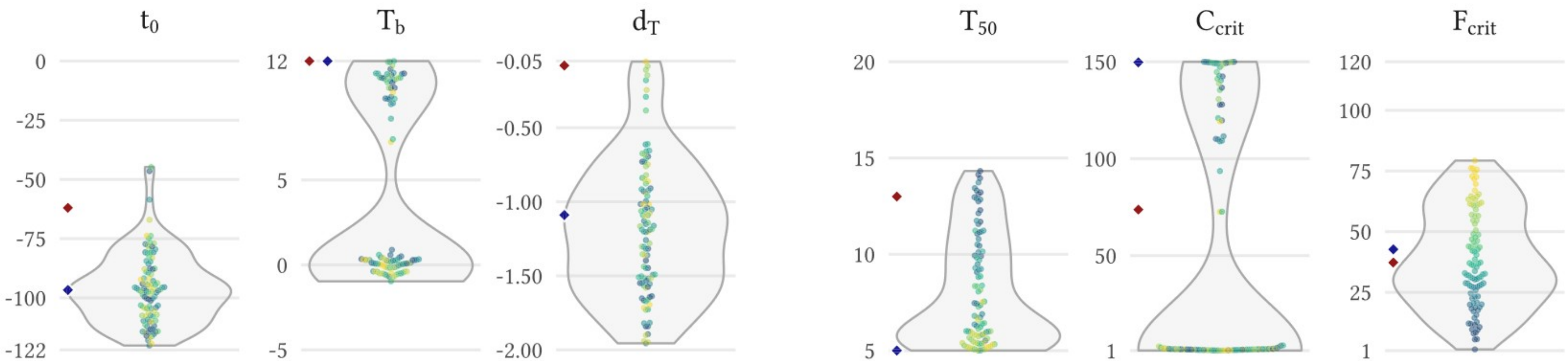
INVERSE CALIBRATION OF PROCESS-BASED MODELS: RESULTS



Van der Meersch & Chuine (2023)

INVERSE CALIBRATION OF PROCESS-BASED MODELS: RESULTS

Expected issue: non-identifiability of parameter values

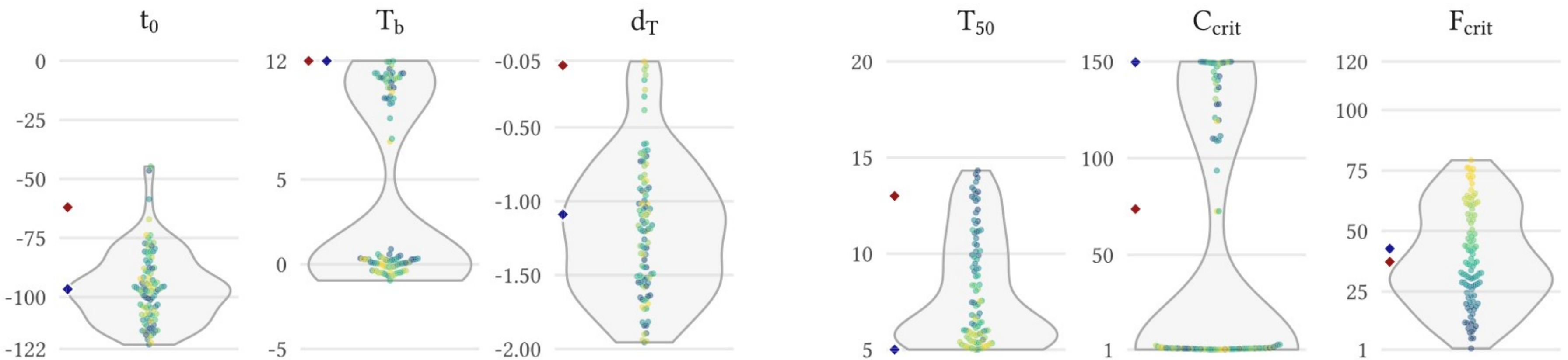


Effects of stochasticity of CMA-ES calibration on PHENOFIT leaf unfolding model parameters

Van der Meersch & Chuine (2023)

INVERSE CALIBRATION OF PROCESS-BASED MODELS: RESULTS

Expected issue: non-identifiability of parameter values

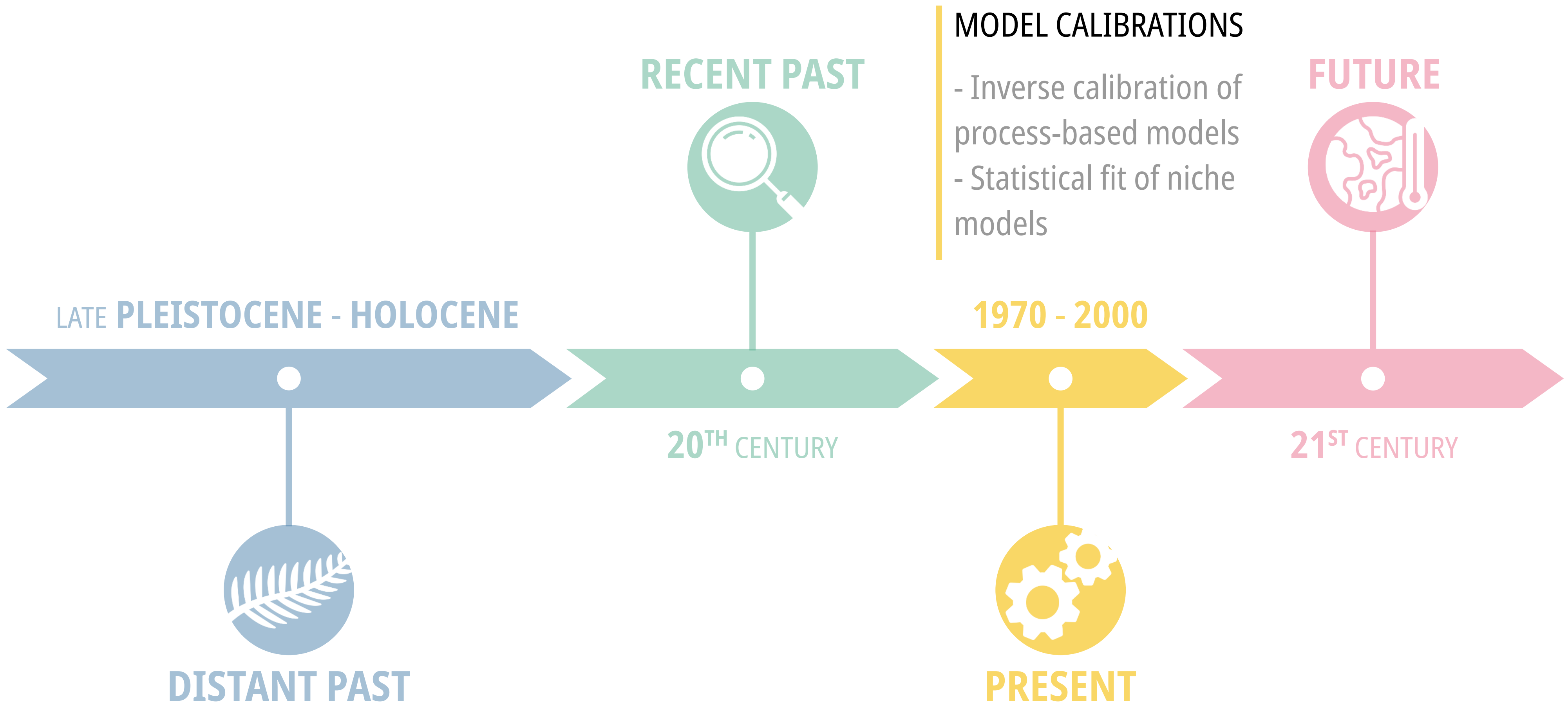


Effects of stochasticity of CMA-ES calibration on PHENOFIT leaf unfolding model parameters

multiple parameter sets produce equally good fits to the observed data

Van der Meersch & Chuine (2023)

THESIS FRAMEWORK



THESIS FRAMEWORK

LESSONS FROM THE PAST

- Comparison of models' predictions to pollen records
- Identify the strengths and weaknesses of each model

MODEL CALIBRATIONS

- Inverse calibration of process-based models
- Statistical fit of niche models

LATE **PLEISTOCENE - HOLOCENE**

DISTANT PAST

RECENT PAST

20TH CENTURY

1970 - 2000

PRESENT

FUTURE

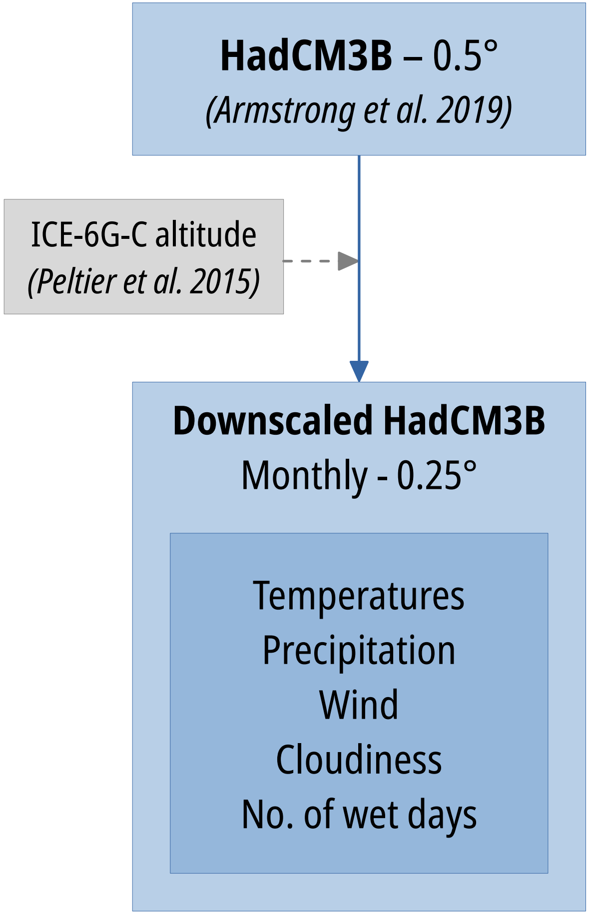
21ST CENTURY

INSIGHTS FROM THE PAST: PROCESSING PALEOCLIMATE SIMULATION

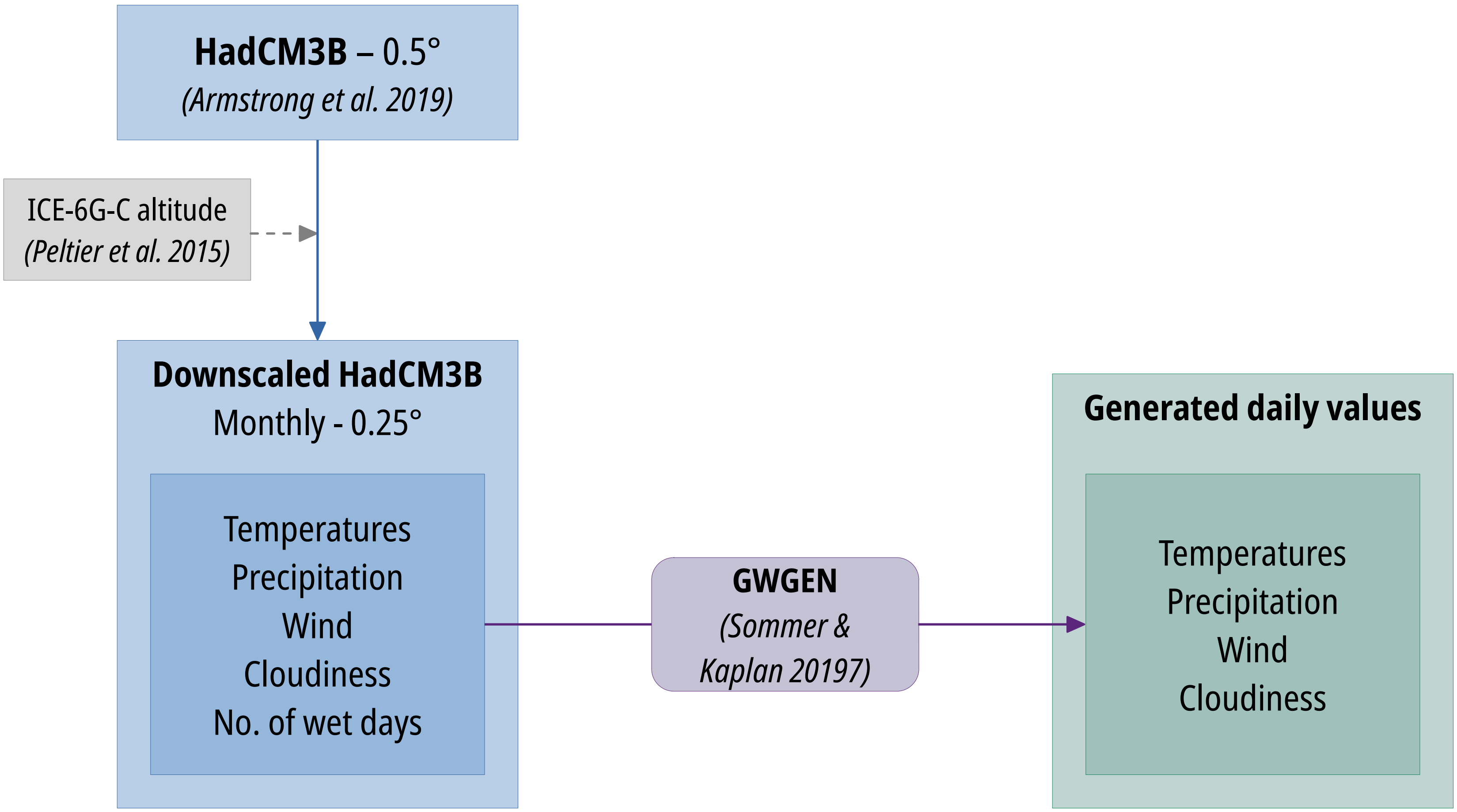
HadCM3B – 0.5°

(Armstrong et al. 2019)

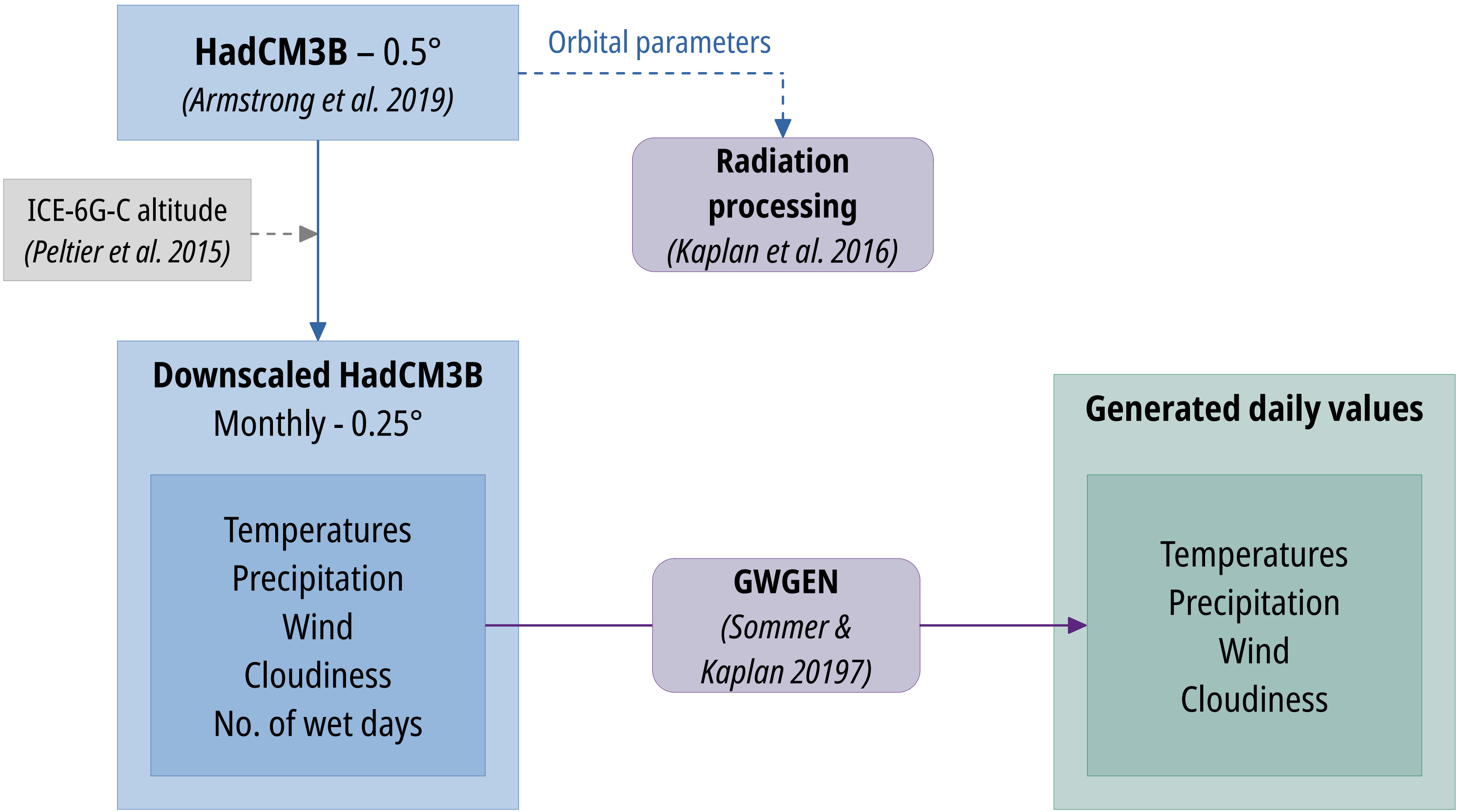
INSIGHTS FROM THE PAST: PROCESSING PALEOCLIMATE SIMULATION



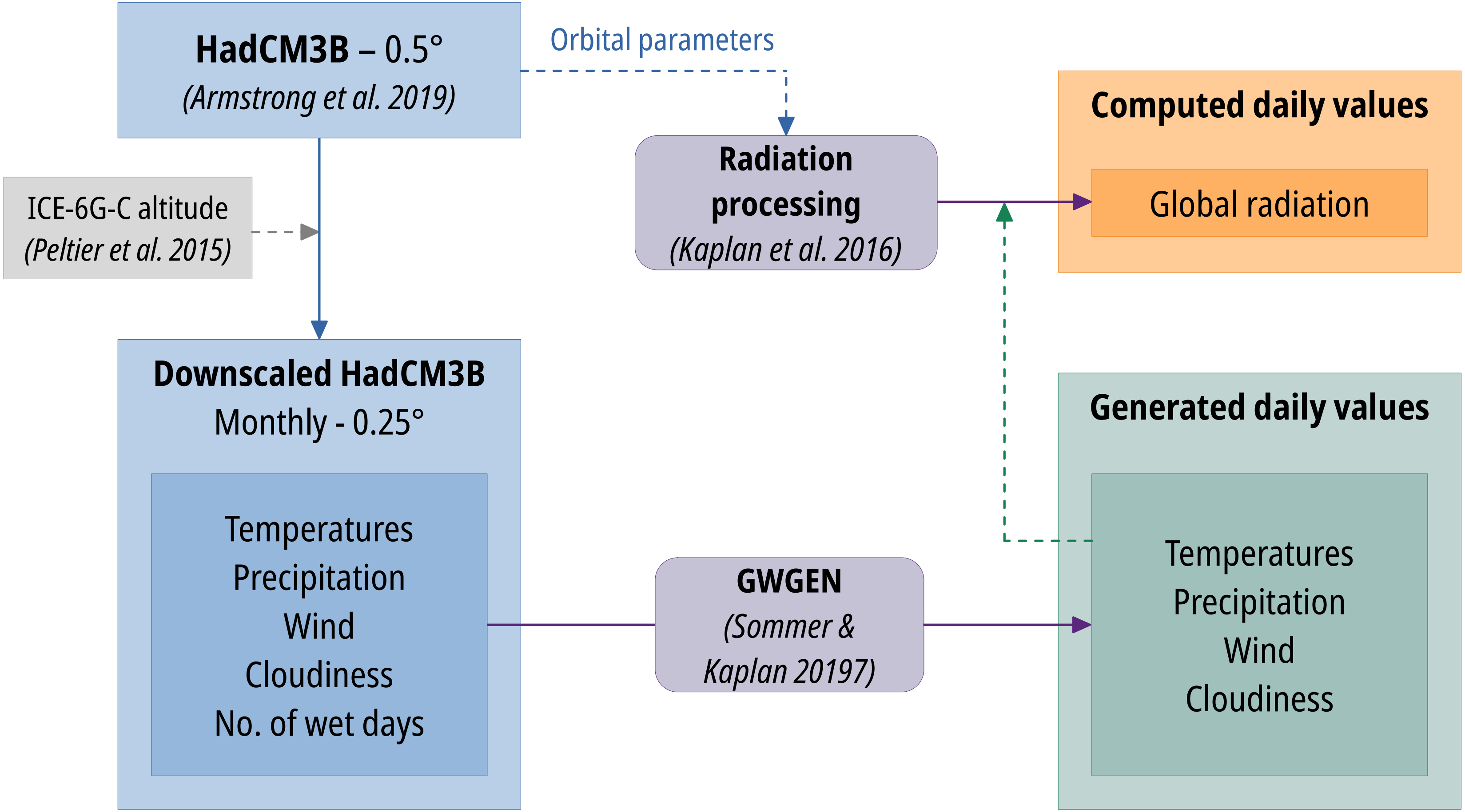
INSIGHTS FROM THE PAST: PROCESSING PALEOCLIMATE SIMULATION



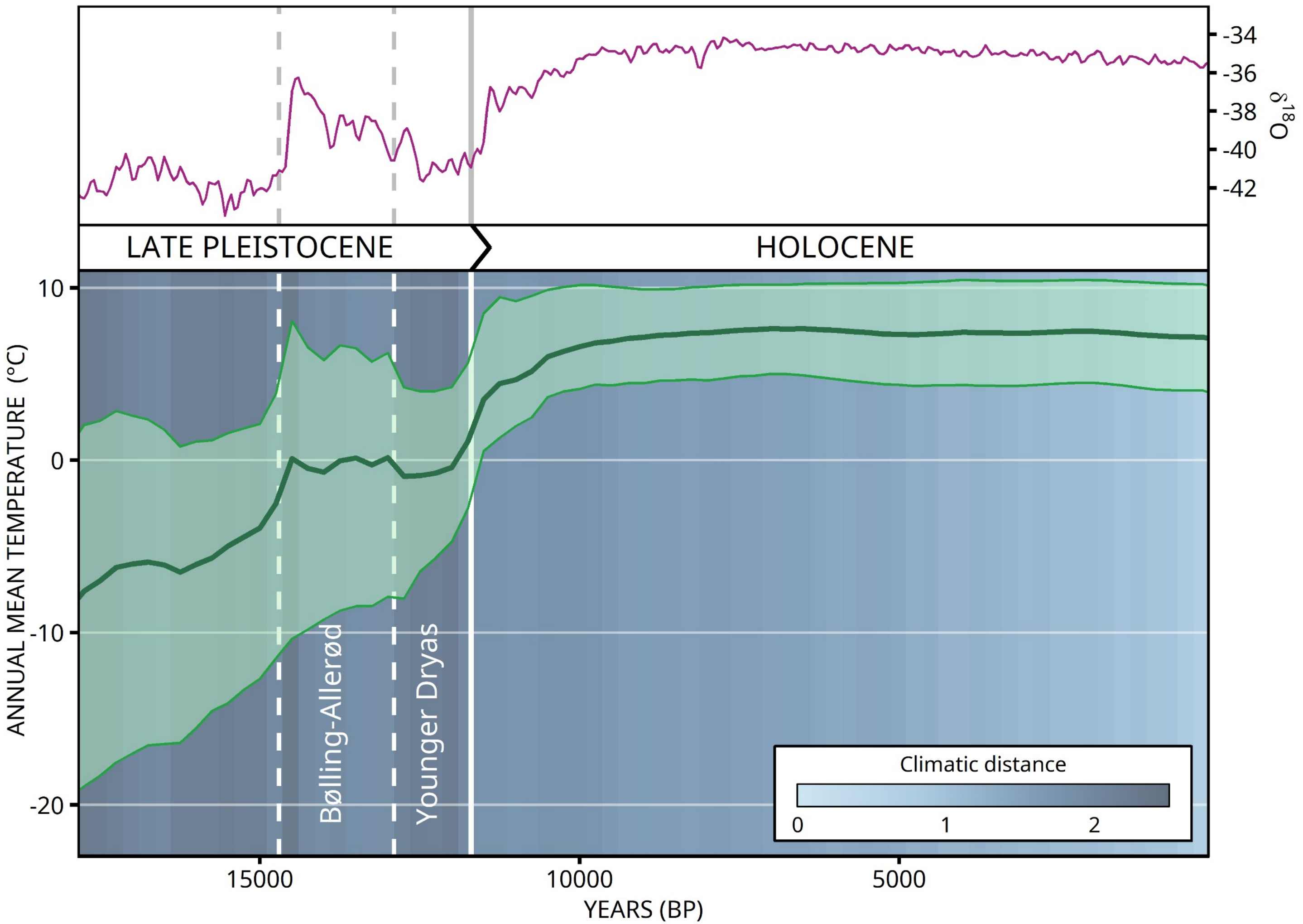
INSIGHTS FROM THE PAST: PROCESSING PALEOCLIMATE SIMULATION



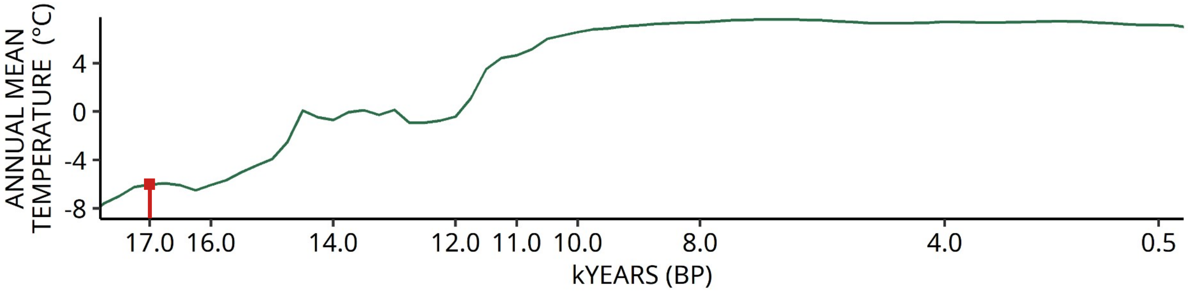
INSIGHTS FROM THE PAST: PROCESSING PALEOCLIMATE SIMULATION

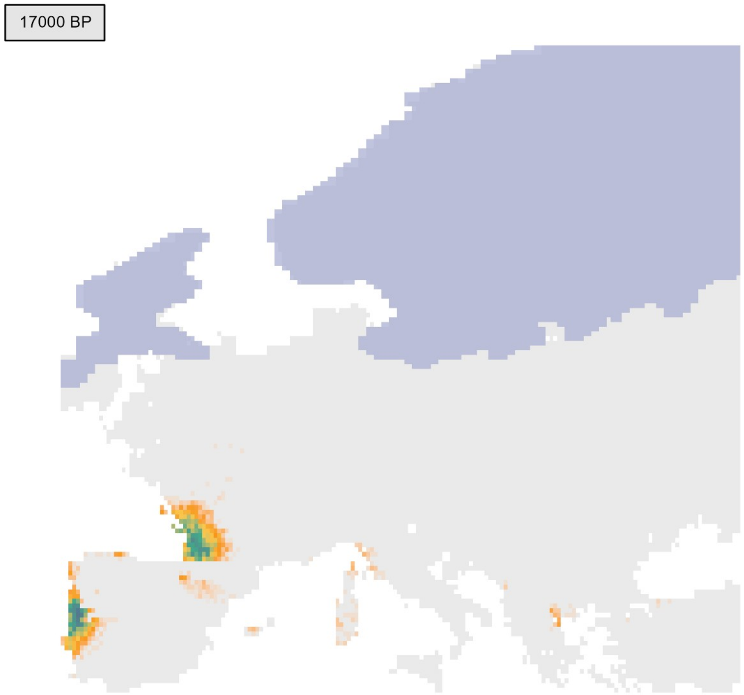


INSIGHTS FROM THE PAST: PROCESSING PALEOCLIMATE SIMULATION



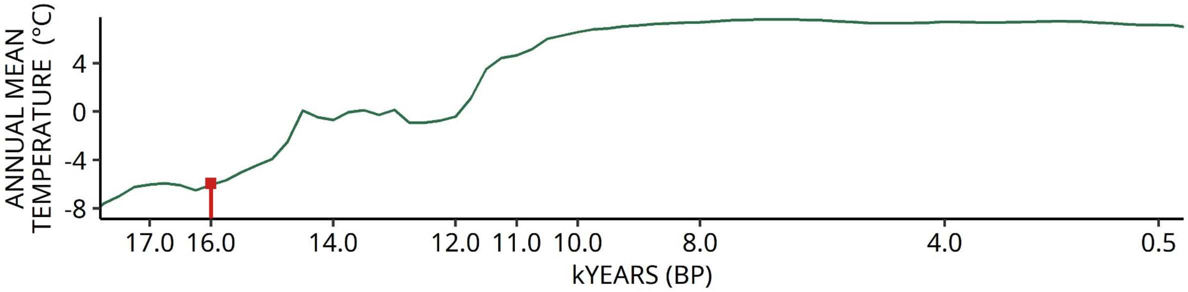
INSIGHTS FROM THE PAST: PHENOFIT PROJECTIONS

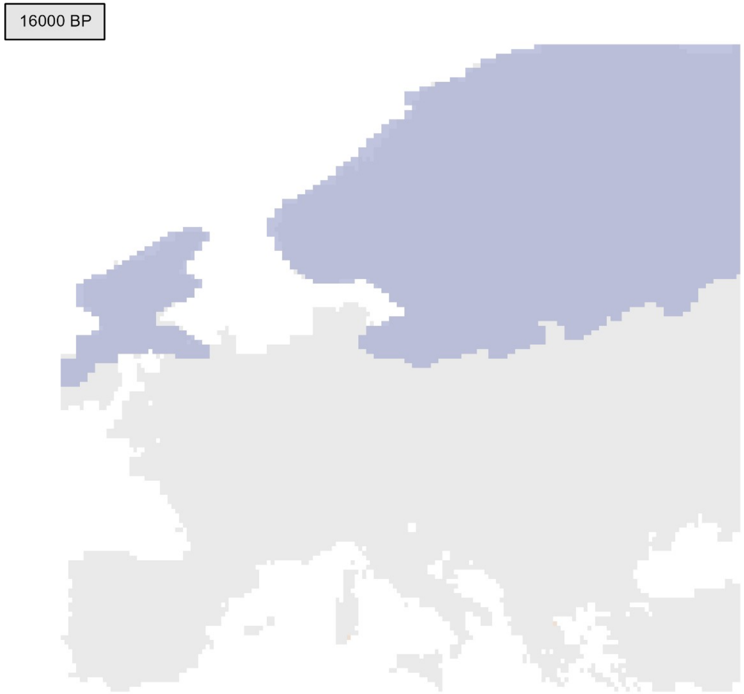




e.g. *Fagus sylvatica*

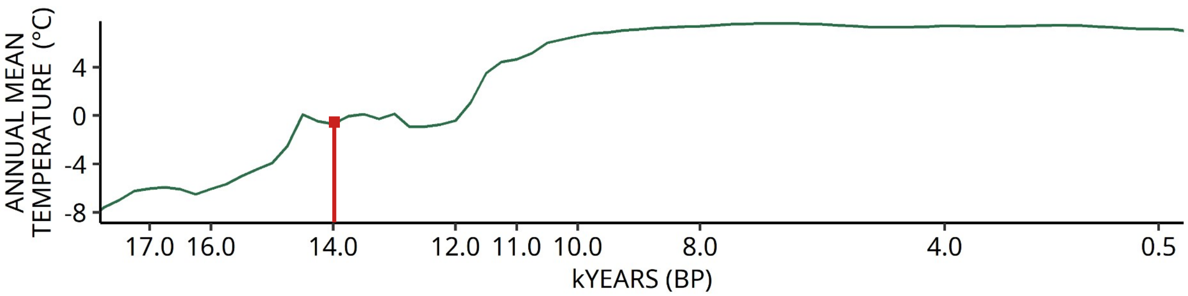
INSIGHTS FROM THE PAST: PHENOFIT PROJECTIONS





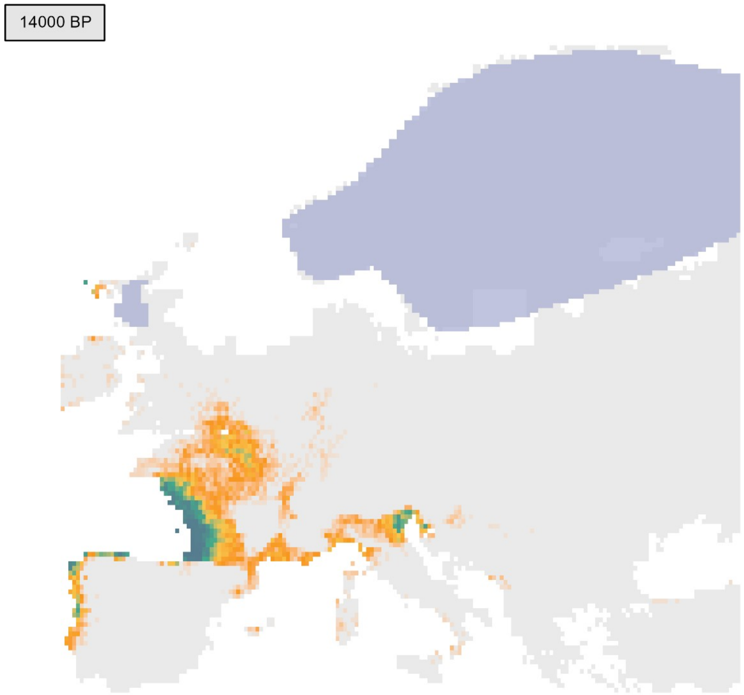
e.g. *Fagus sylvatica*

INSIGHTS FROM THE PAST: PHENOFIT PROJECTIONS



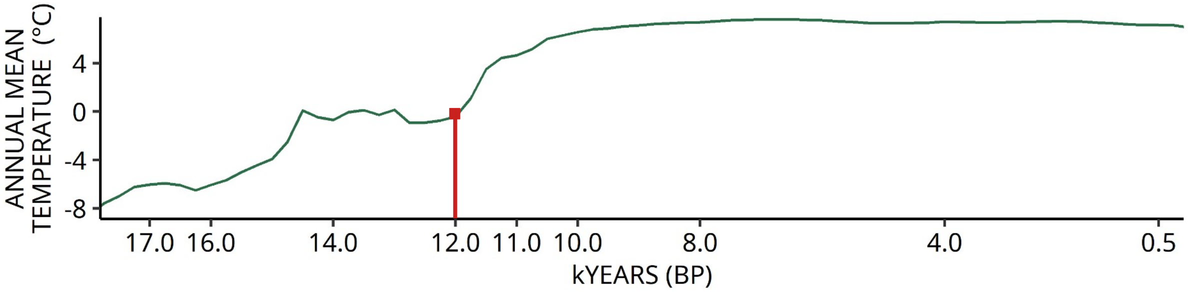
Bølling-Allerød oscillation

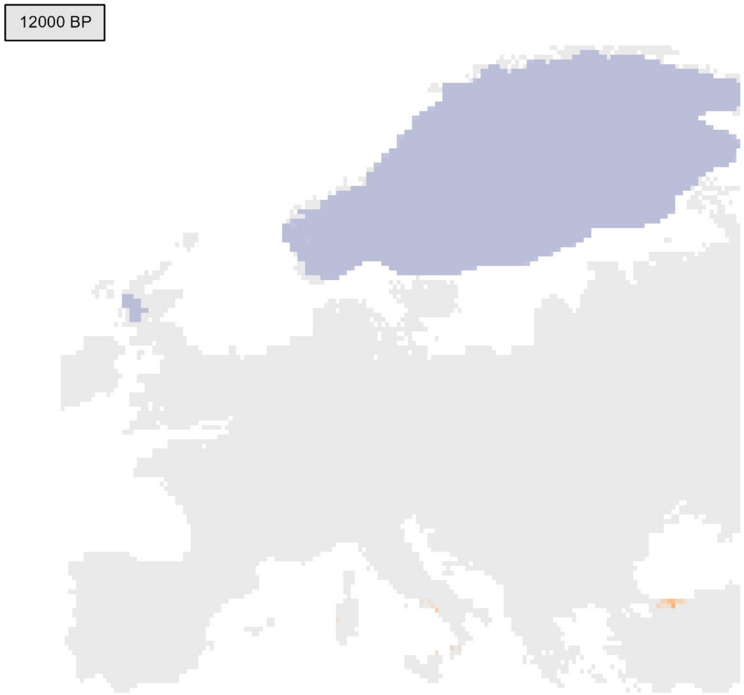
temperate climate



e.g. *Fagus sylvatica*

INSIGHTS FROM THE PAST: PHENOFIT PROJECTIONS



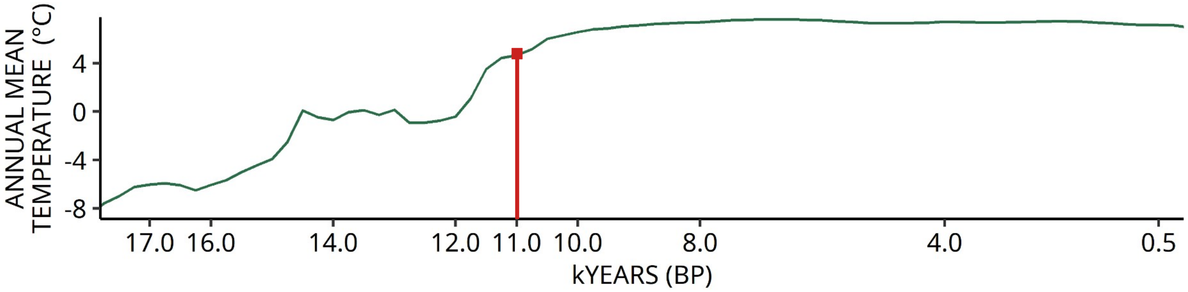


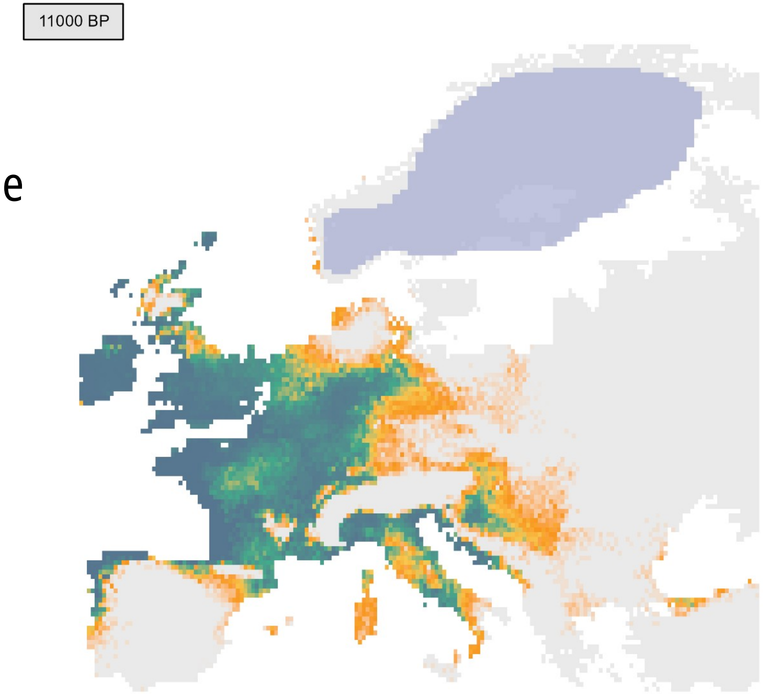
Younger Dryas

glacial conditions

e.g. *Fagus sylvatica*

Insights from the past: PHENOFIT projections

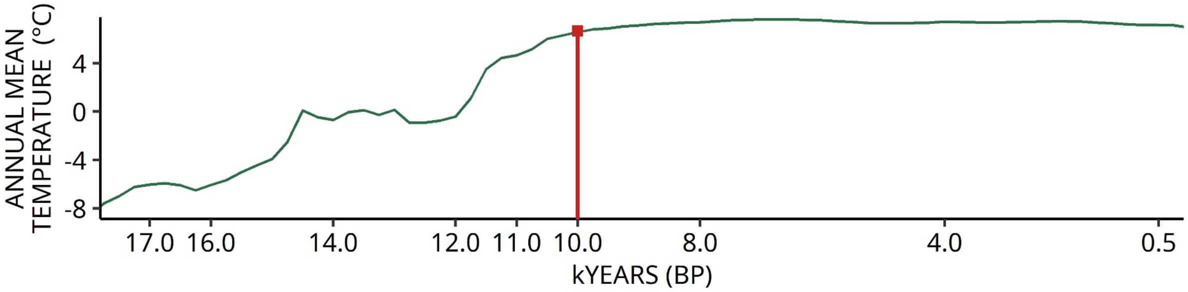


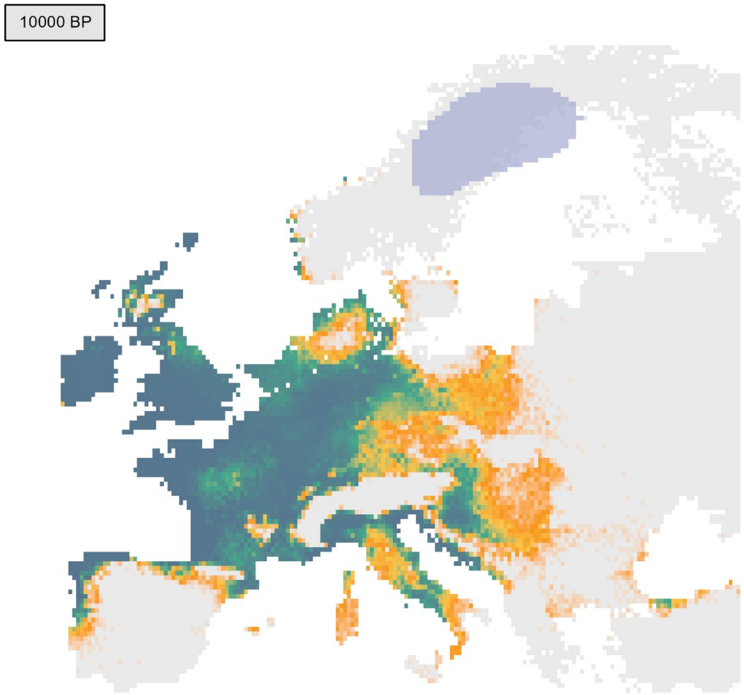


Beginning of the Holocene

e.g. *Fagus sylvatica*

INSIGHTS FROM THE PAST: PHENOFIT PROJECTIONS

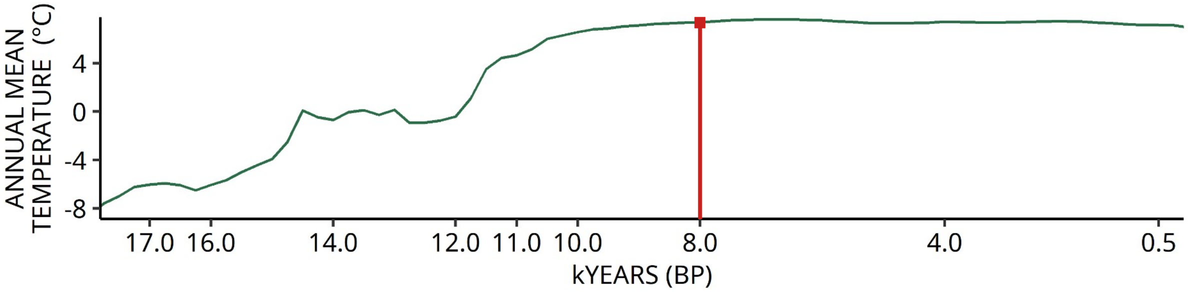




Glacial retreat

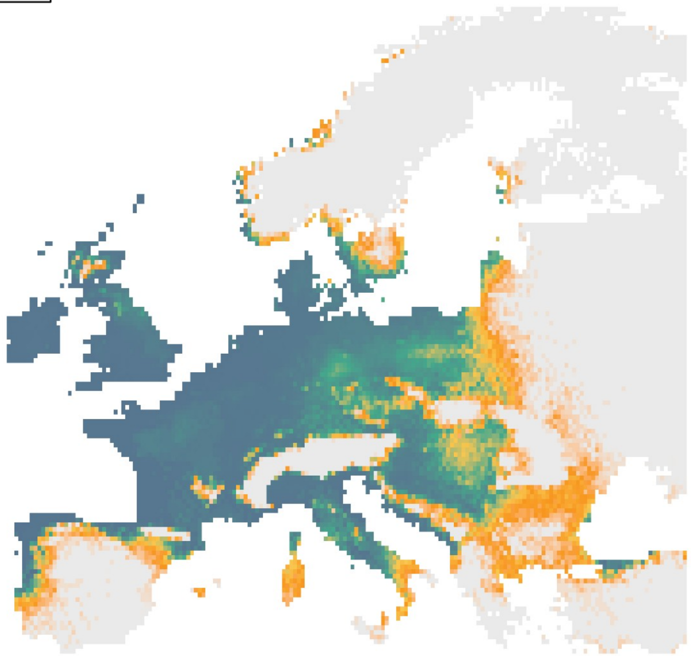
e.g. *Fagus sylvatica*

INSIGHTS FROM THE PAST: PHENOFIT PROJECTIONS



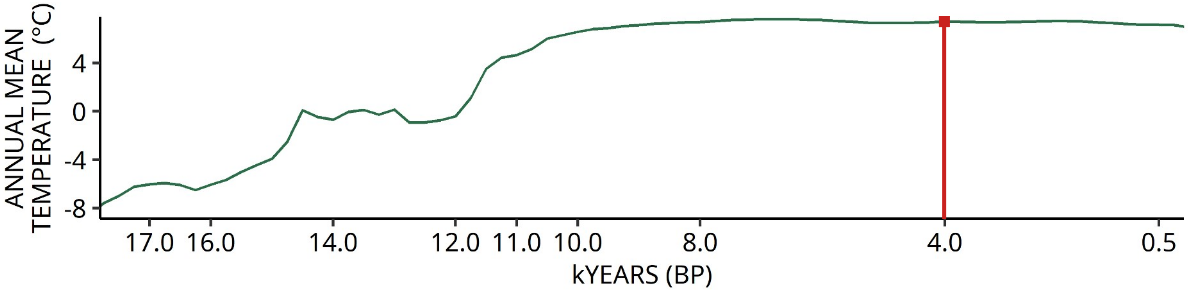
8000 BP

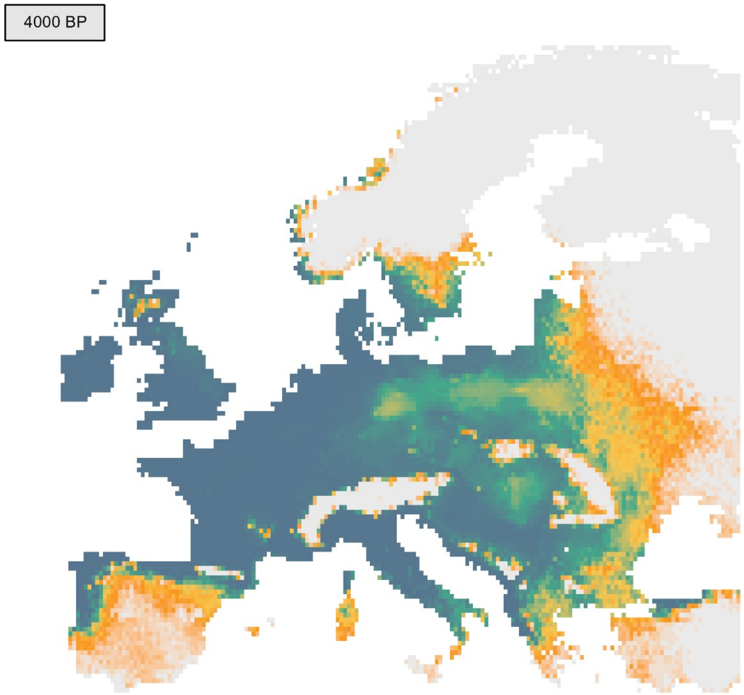
Relatively stable climate



e.g. *Fagus sylvatica*

INSIGHTS FROM THE PAST: PHENOFIT PROJECTIONS

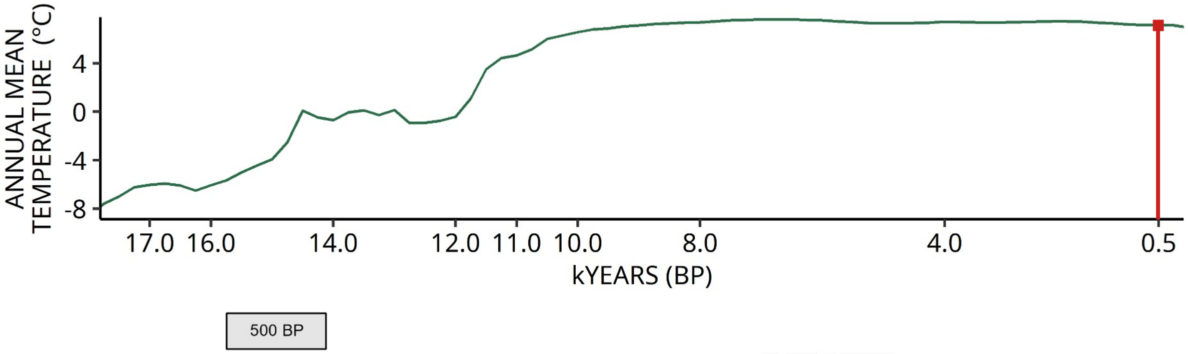




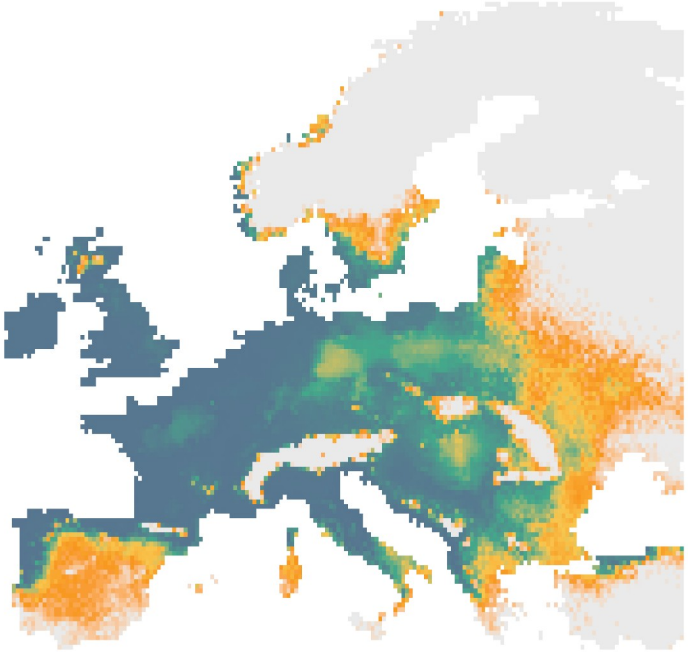
Relatively stable climate

e.g. *Fagus sylvatica*

INSIGHTS FROM THE PAST: PHENOFIT PROJECTIONS



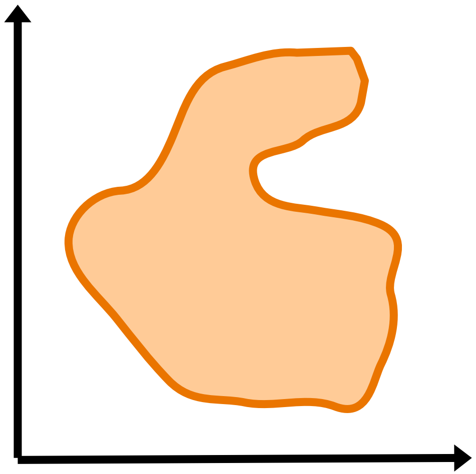
Relatively stable climate



e.g. *Fagus sylvatica*

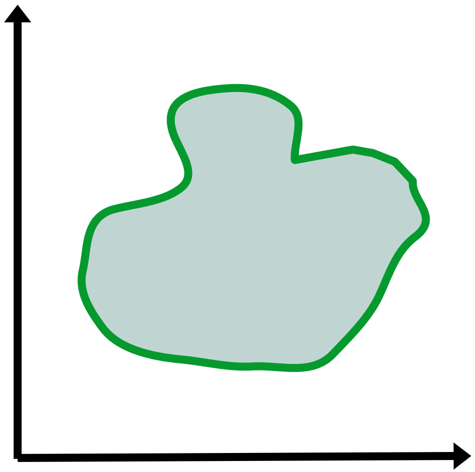
INSIGHTS FROM THE PAST: COMPARE MODEL PROJECTIONS

Predicted niche model A



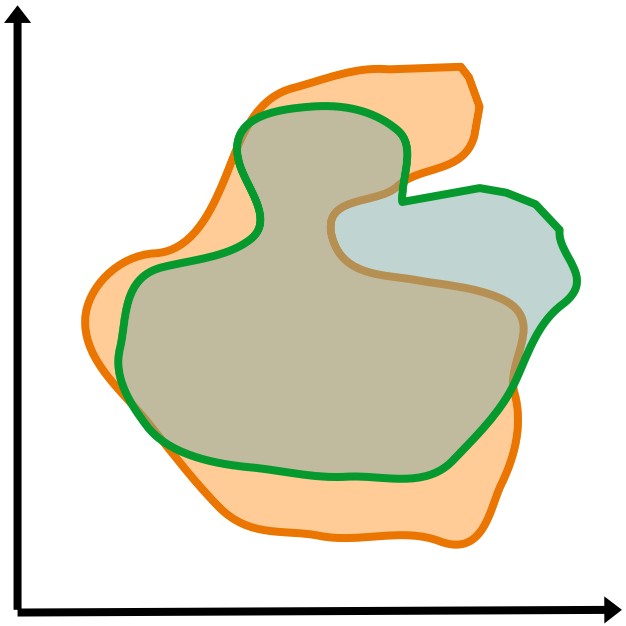
N-dimensional hypervolume

Predicted niche model B



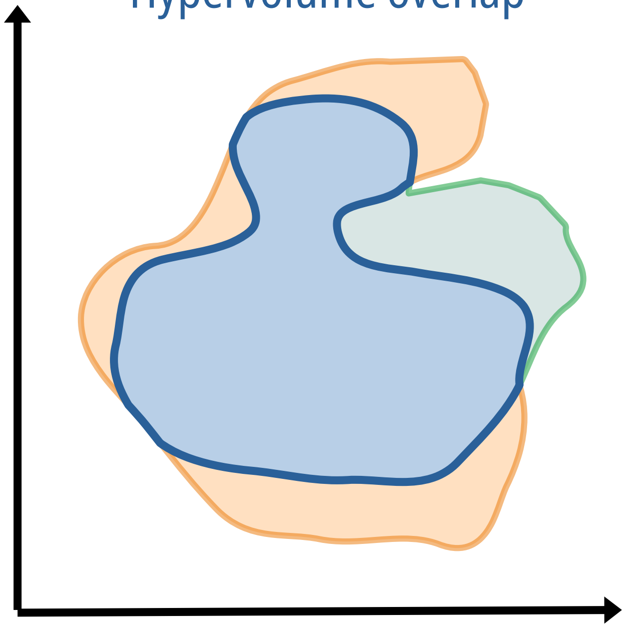
N-dimensional hypervolume

INSIGHTS FROM THE PAST: COMPARE MODEL PROJECTIONS



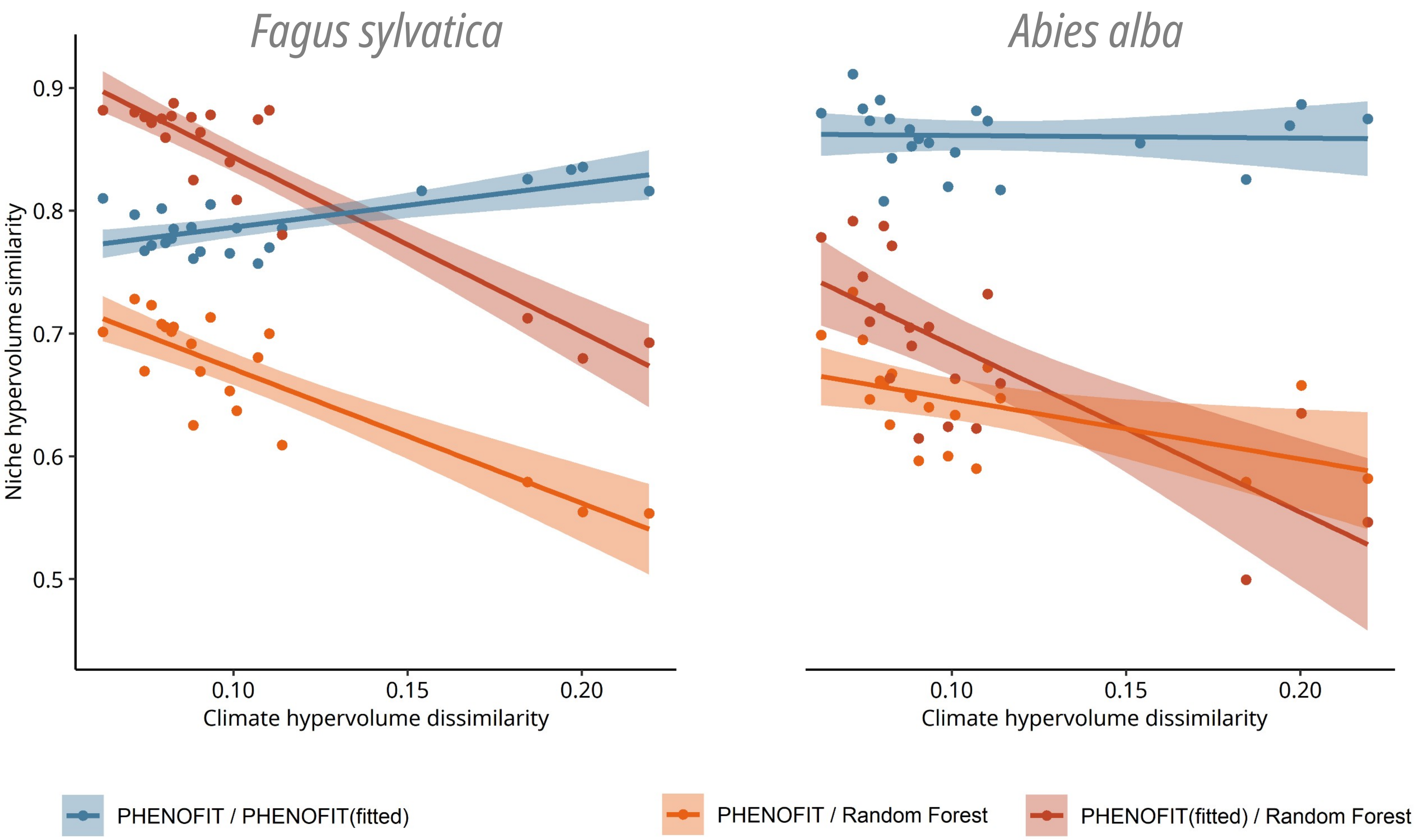
INSIGHTS FROM THE PAST: COMPARE MODEL PROJECTIONS

Hypervolume overlap

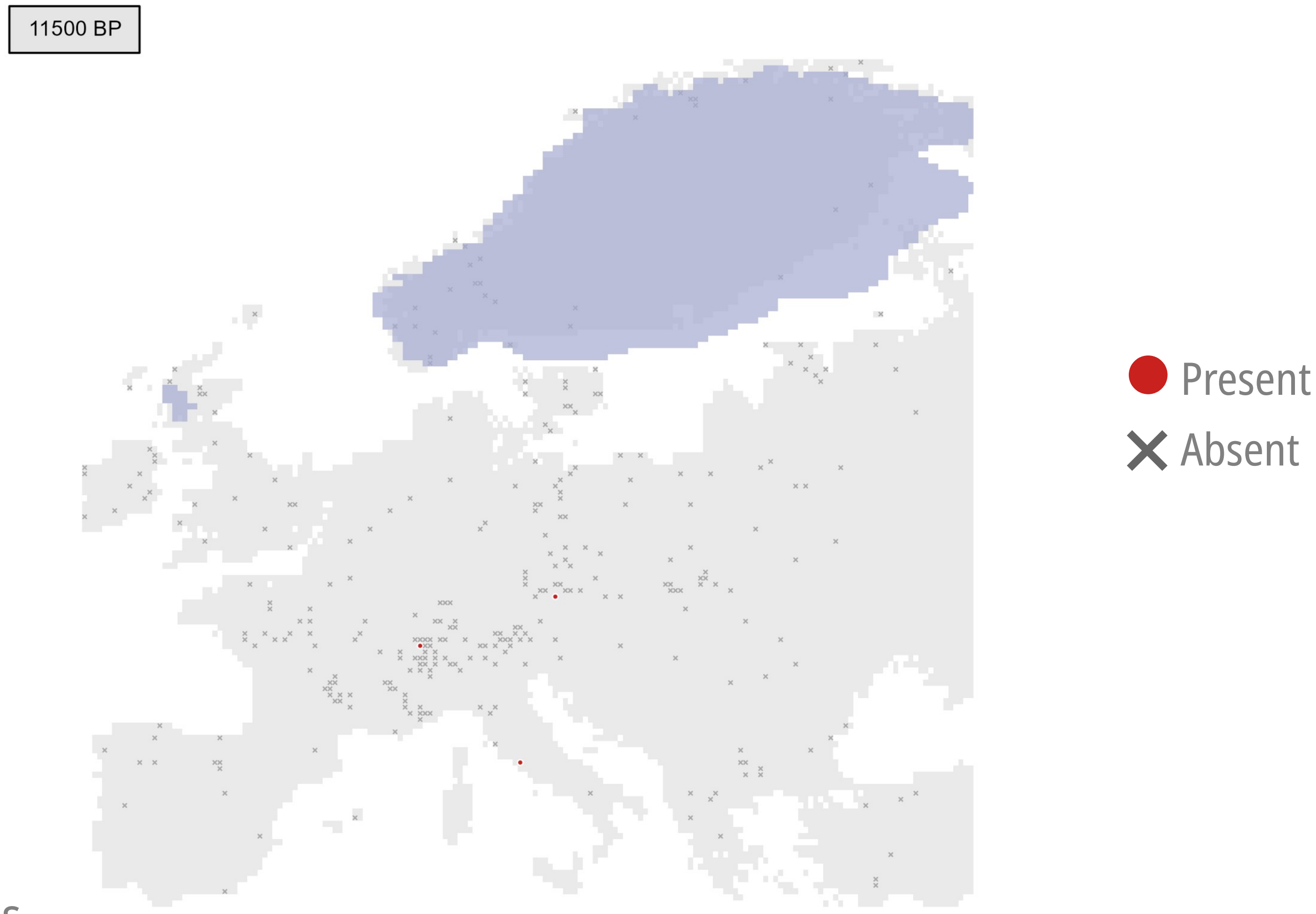


Sørensen similarity $= \dfrac{2\,|A \cap B|}{|A| + |B|}$

INSIGHTS FROM THE PAST: COMPARE MODEL PROJECTIONS

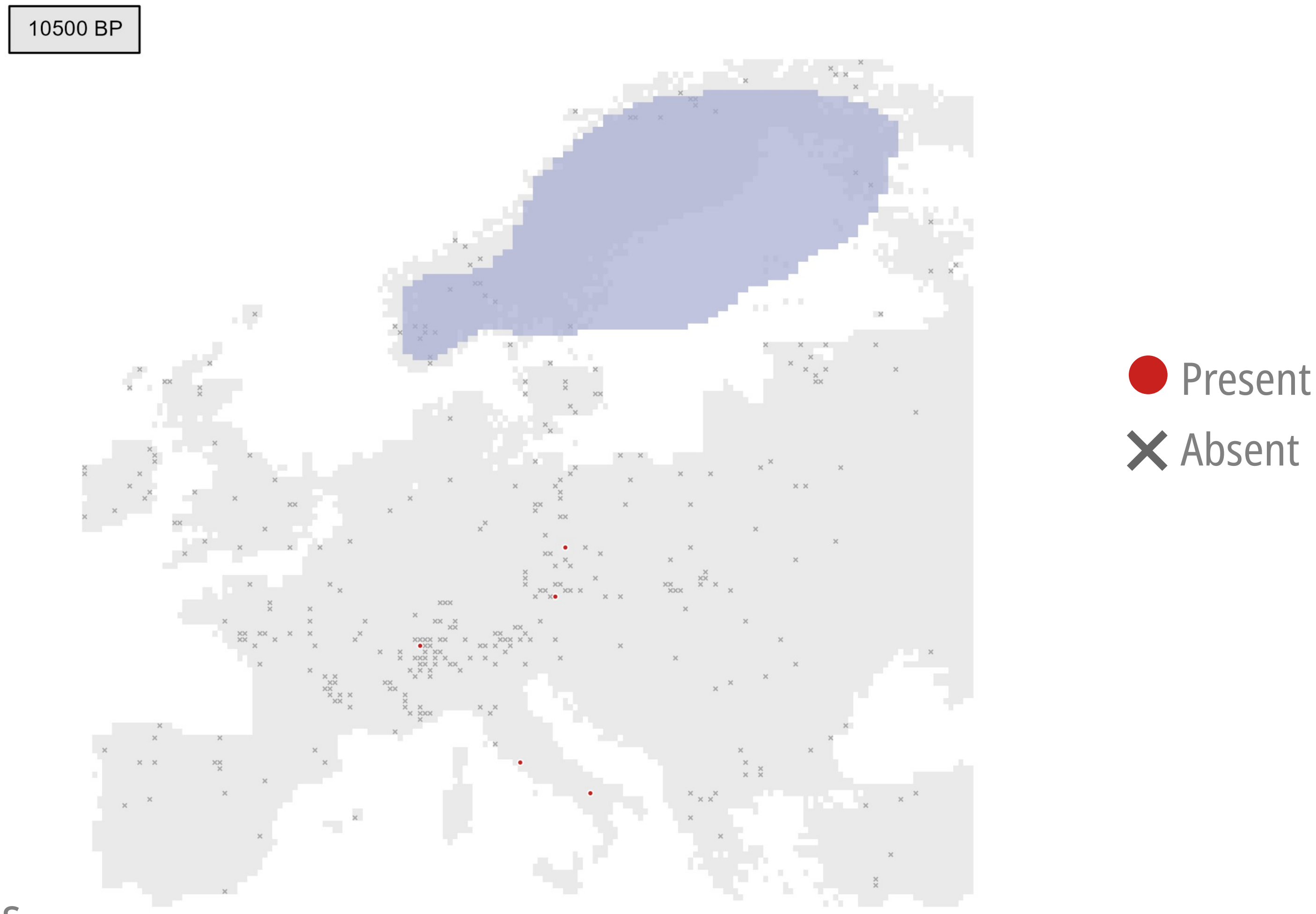


INSIGHTS FROM THE PAST: POLLEN RECORDS



e.g. *Fagus* pollen records

INSIGHTS FROM THE PAST: POLLEN RECORDS



e.g. *Fagus* pollen records

INSIGHTS FROM THE PAST: POLLEN RECORDS

e.g. *Fagus* pollen records

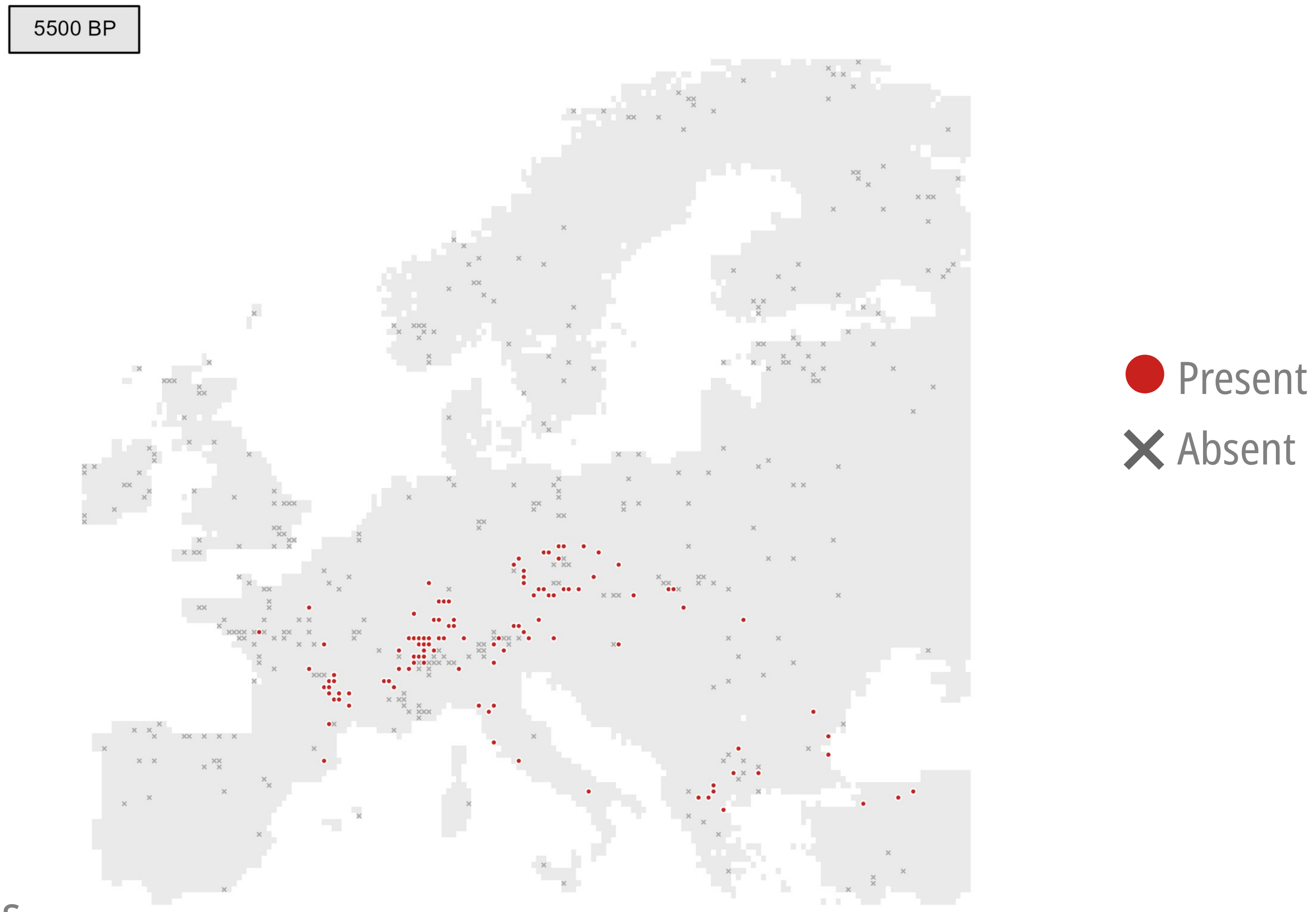
INSIGHTS FROM THE PAST: POLLEN RECORDS

e.g. *Fagus* pollen records

INSIGHTS FROM THE PAST: POLLEN RECORDS

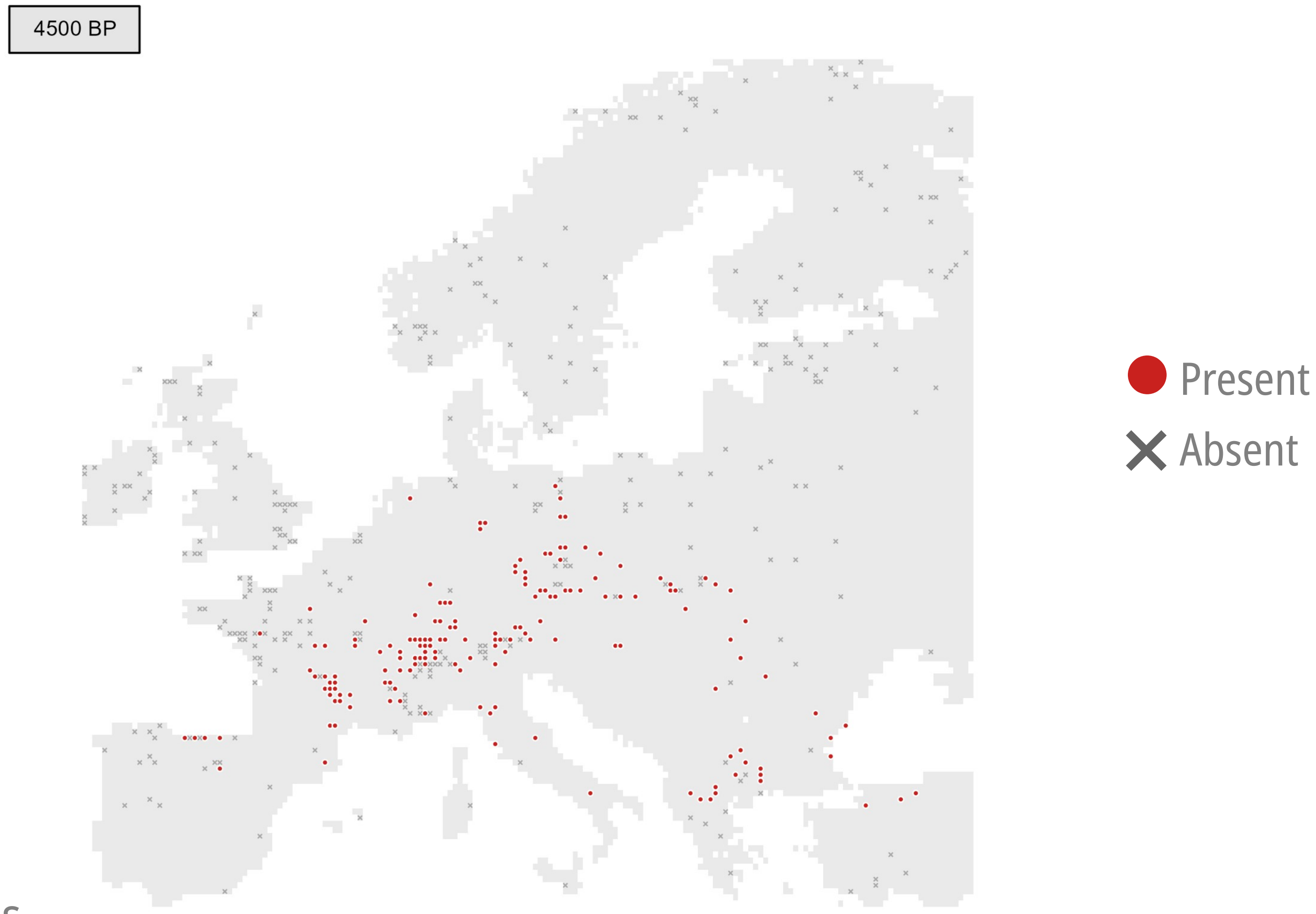
e.g. *Fagus* pollen records

INSIGHTS FROM THE PAST: POLLEN RECORDS



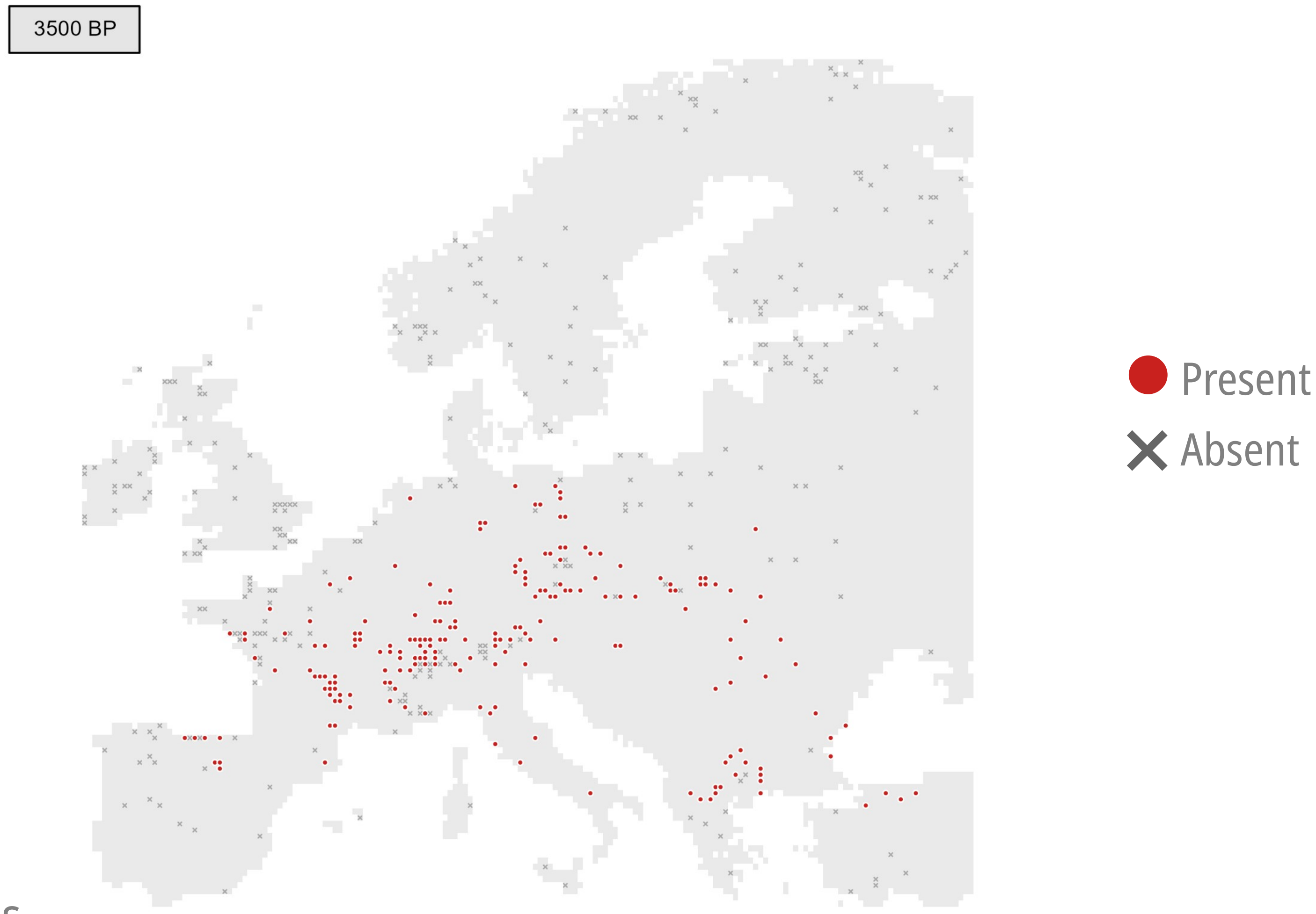
e.g. *Fagus* pollen records

INSIGHTS FROM THE PAST: POLLEN RECORDS



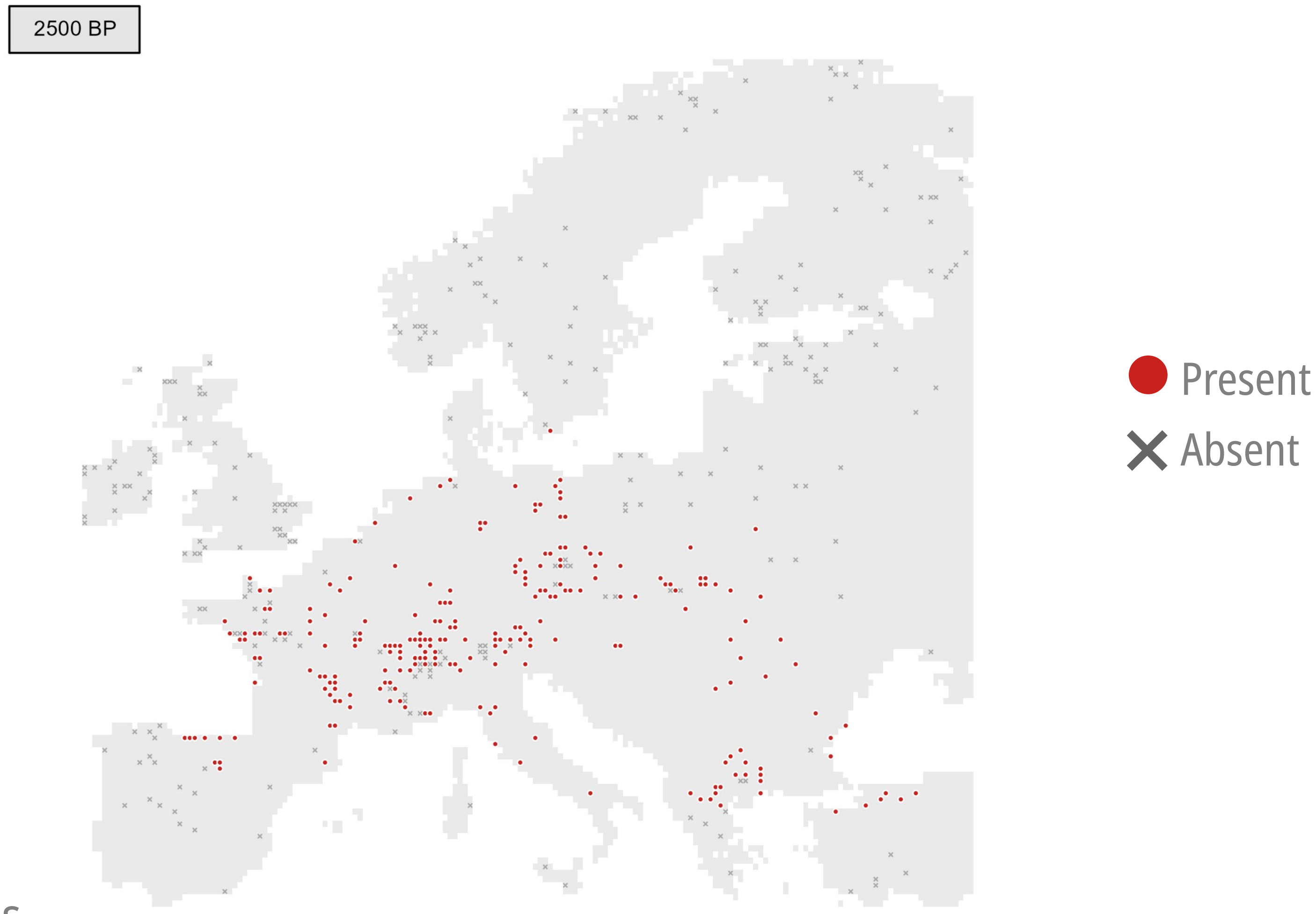
e.g. *Fagus* pollen records

INSIGHTS FROM THE PAST: POLLEN RECORDS



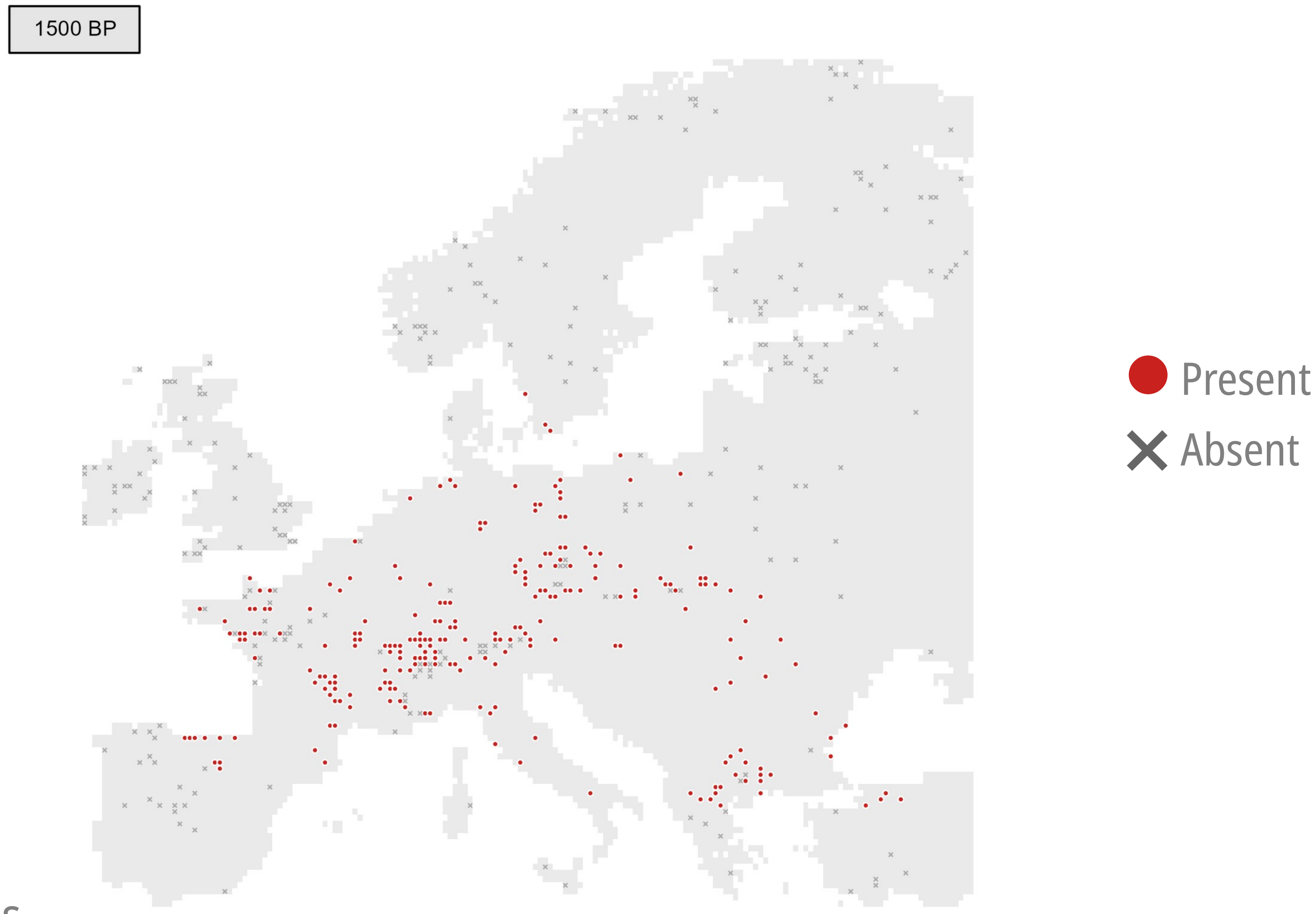
e.g. *Fagus* pollen records

INSIGHTS FROM THE PAST: POLLEN RECORDS



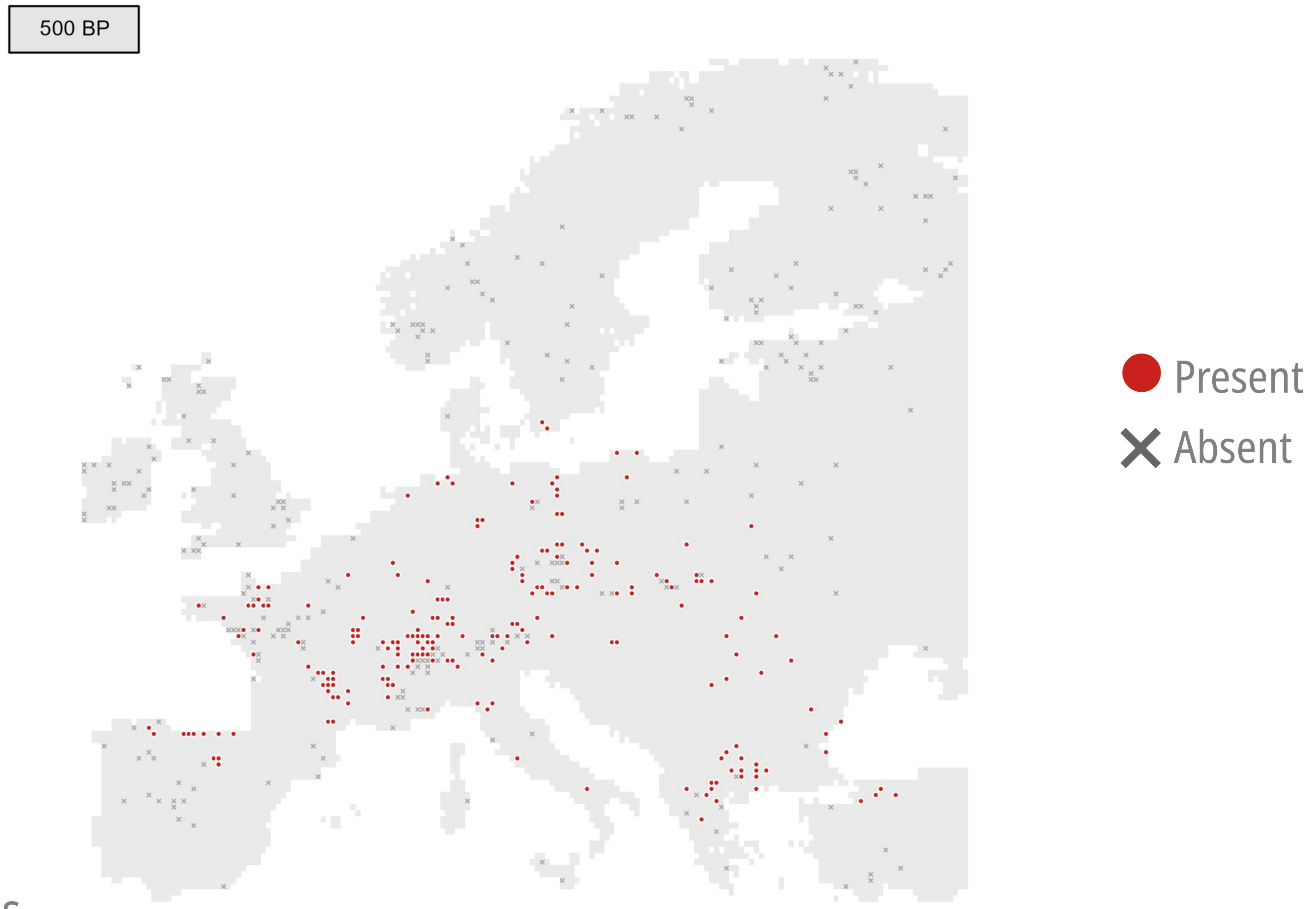
e.g. *Fagus* pollen records

INSIGHTS FROM THE PAST: POLLEN RECORDS



e.g. *Fagus* pollen records

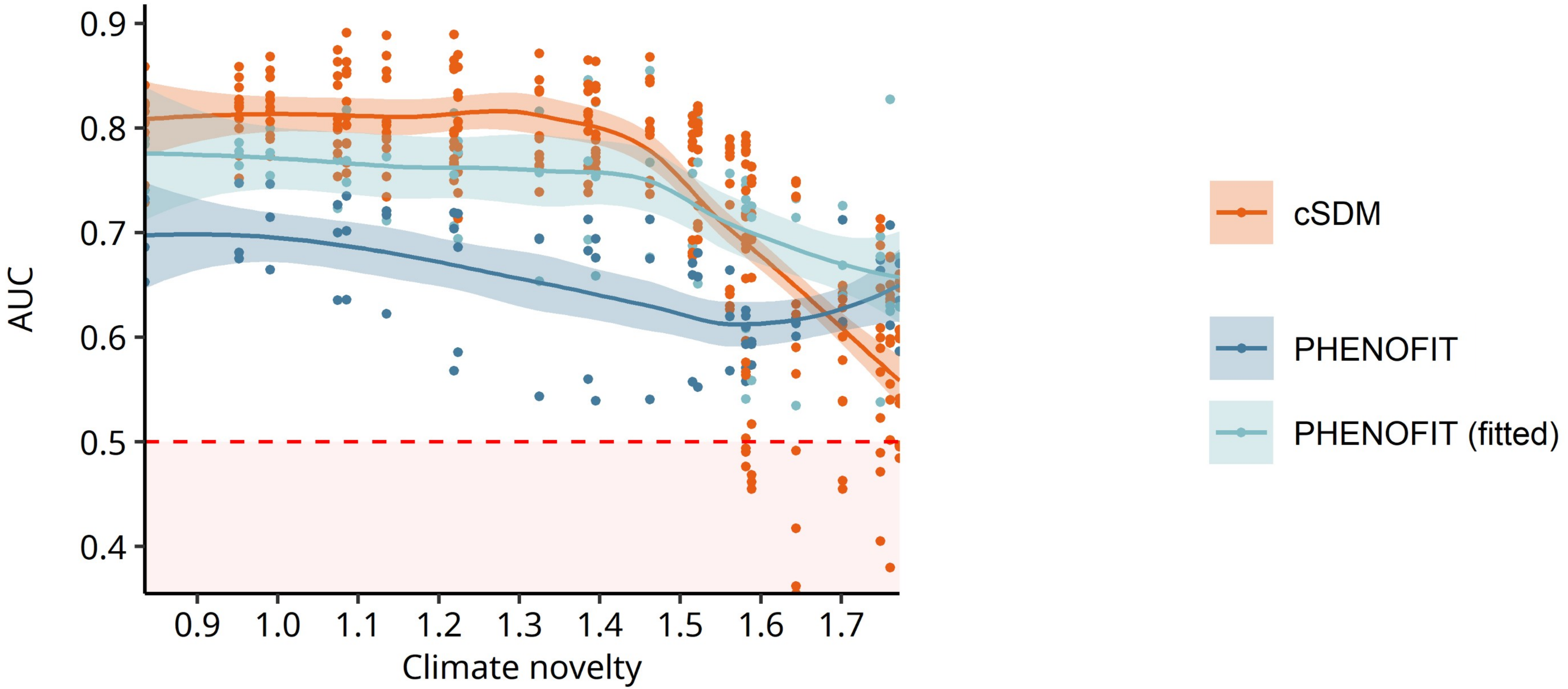
INSIGHTS FROM THE PAST: POLLEN RECORDS



e.g. *Fagus* pollen records

INSIGHTS FROM THE PAST: MODEL PROJECTIONS V.S. POLLEN RECORDS

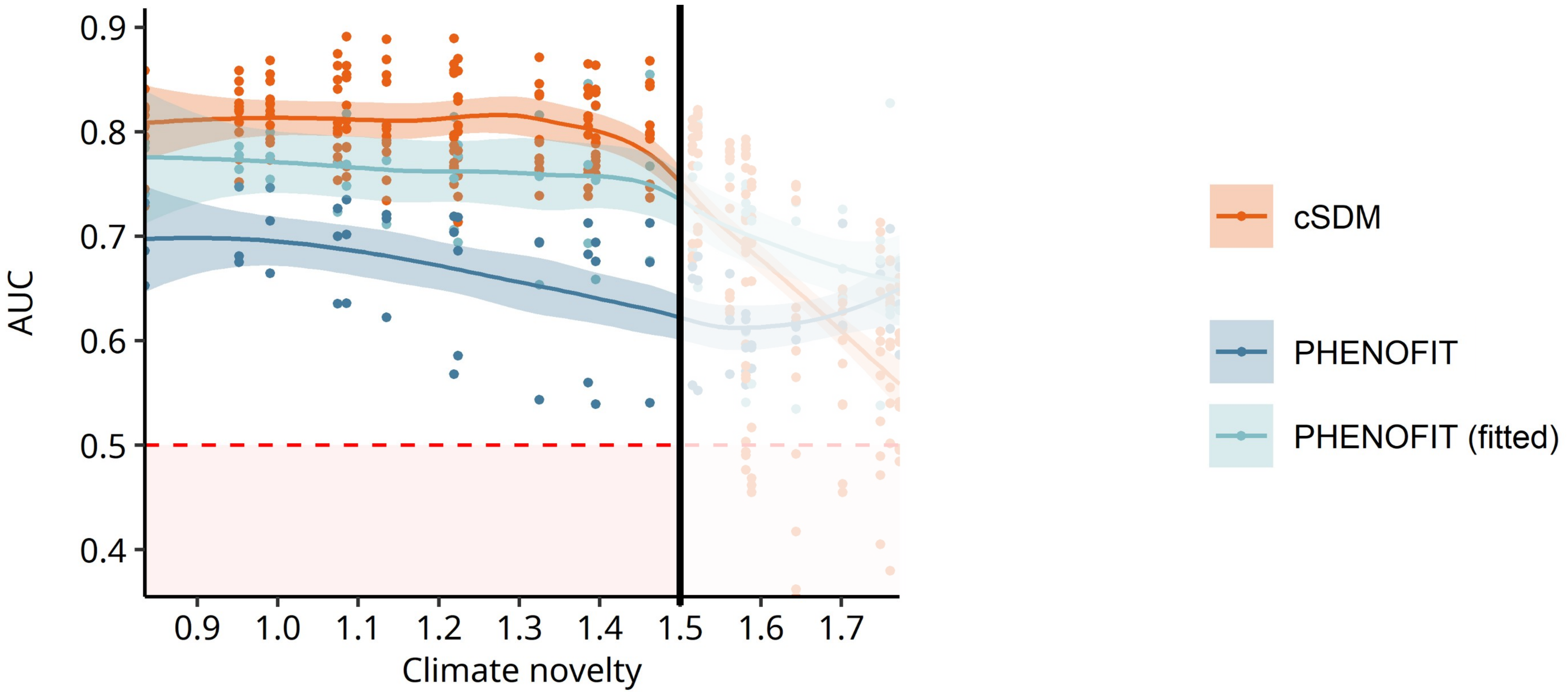
Comparison with three genus-level records



Fagus, *Quercus* and *Abies* (Holocene only)

Insights from the past: model projections v.s. pollen records

Comparison with three genus-level records

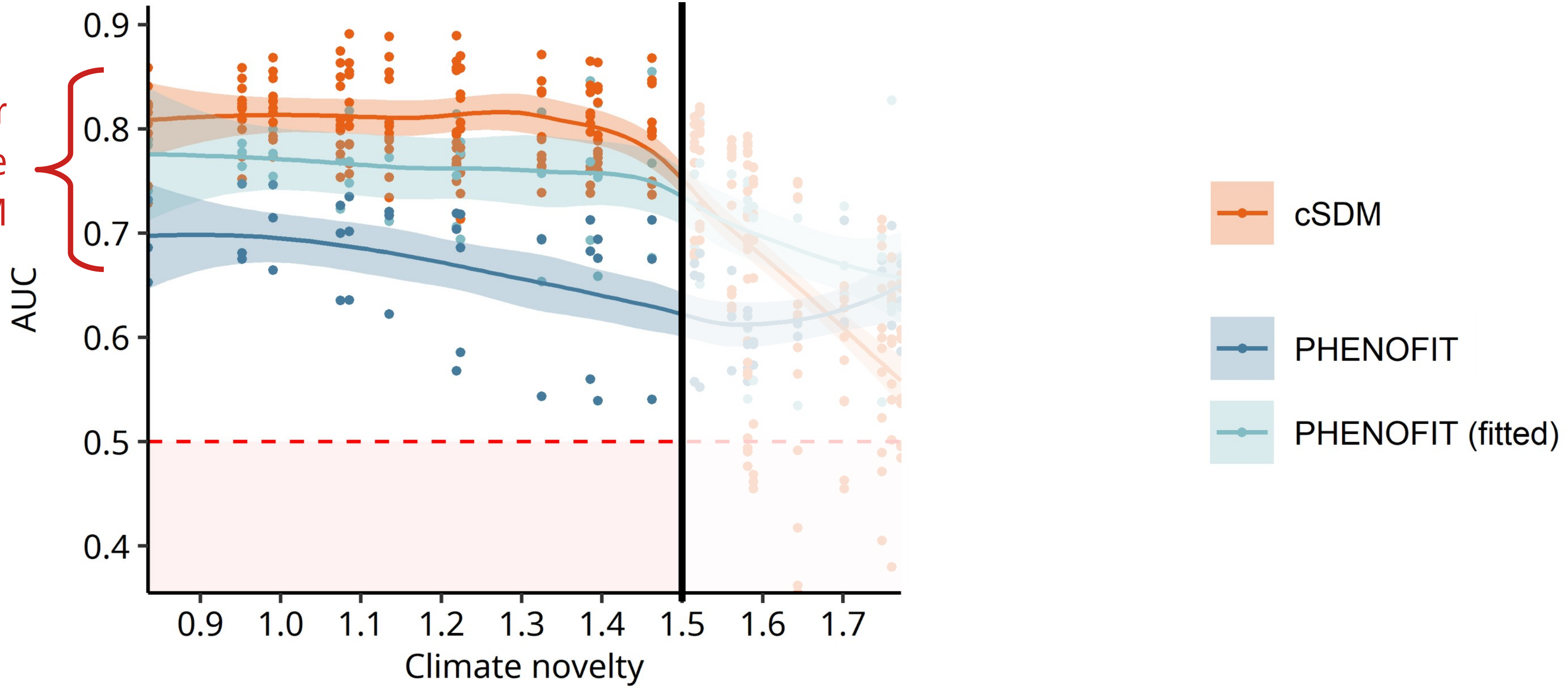


Fagus, *Quercus* and *Abies* (Holocene only)

INSIGHTS FROM THE PAST: MODEL PROJECTIONS V.S. POLLEN RECORDS

Comparison with three genus-level records

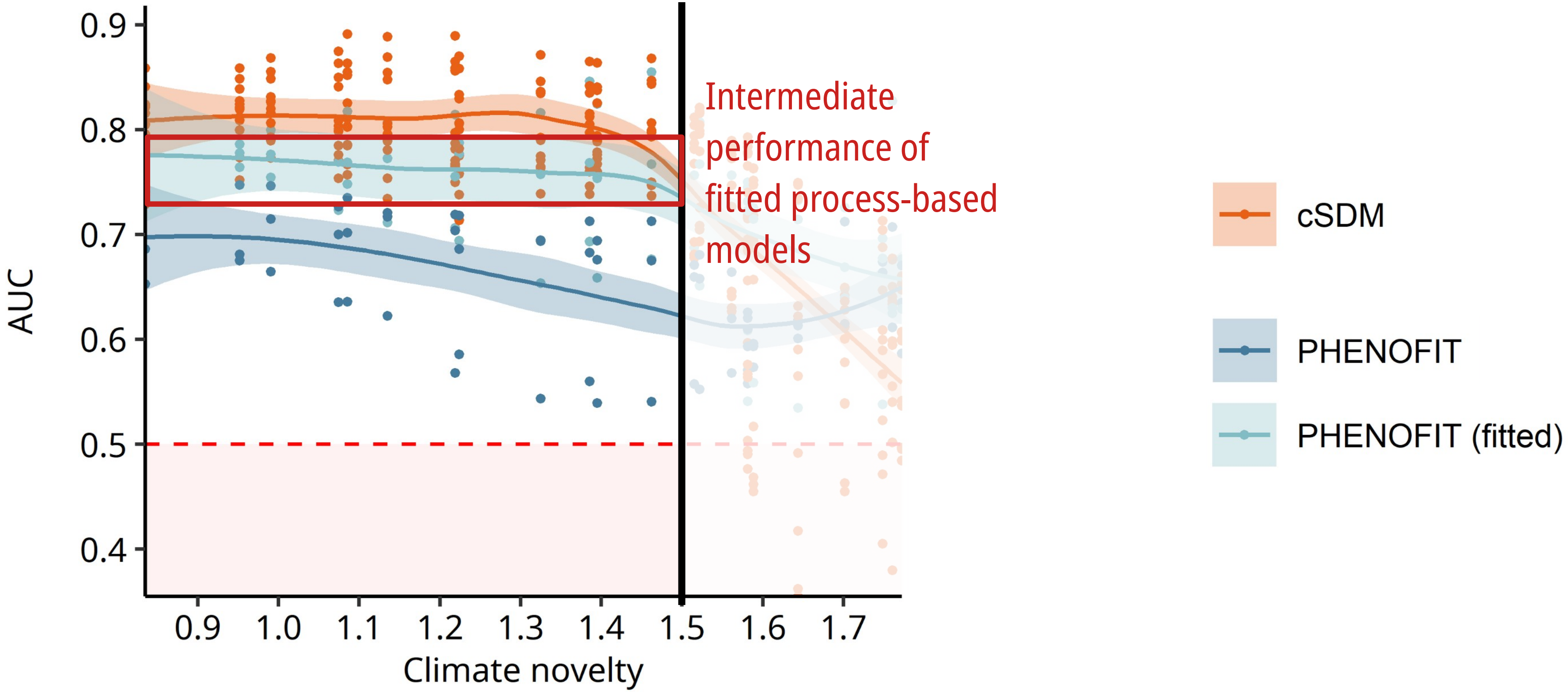
Better performance of cSDM



Fagus, *Quercus* and *Abies* (Holocene only)

INSIGHTS FROM THE PAST: MODEL PROJECTIONS V.S. POLLEN RECORDS

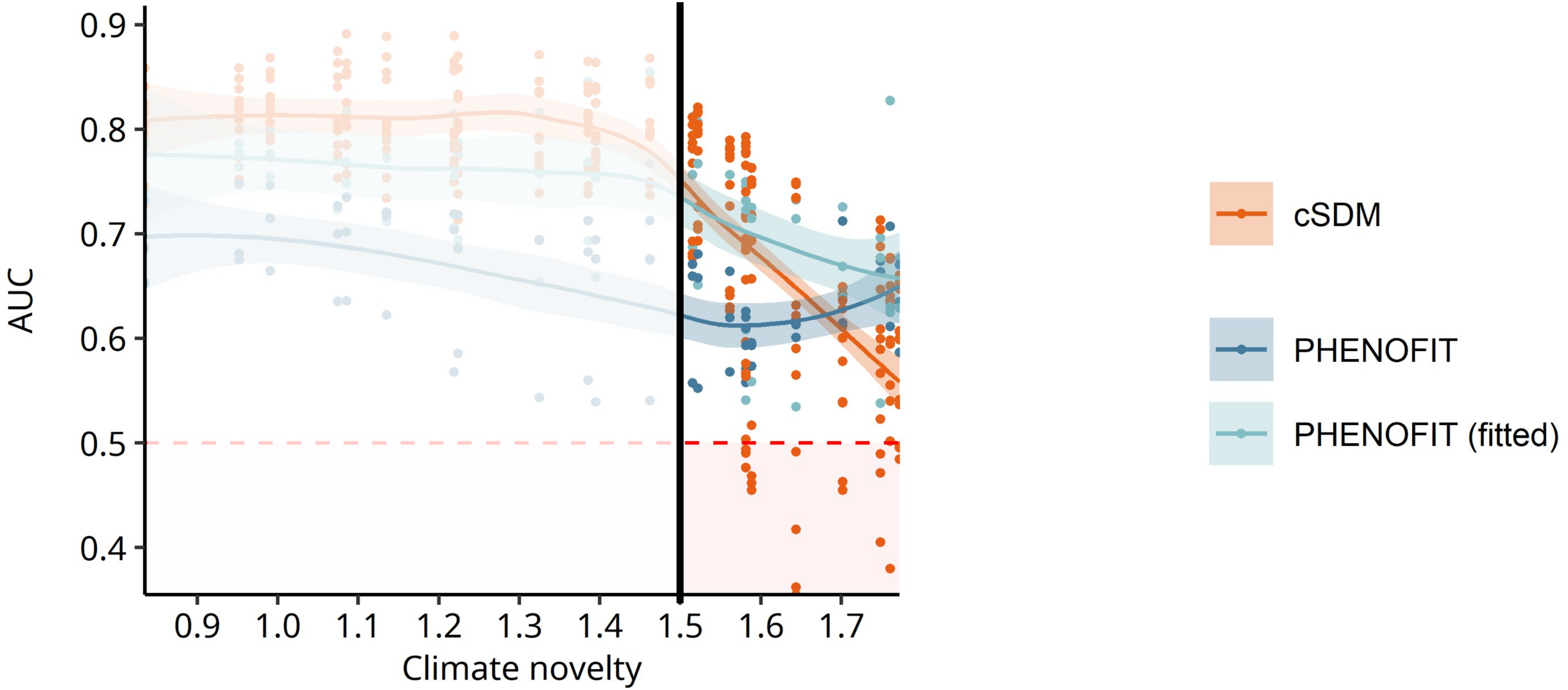
Comparison with three genus-level records



Fagus, *Quercus* and *Abies* (Holocene only)

Insights from the past: model projections v.s. pollen records

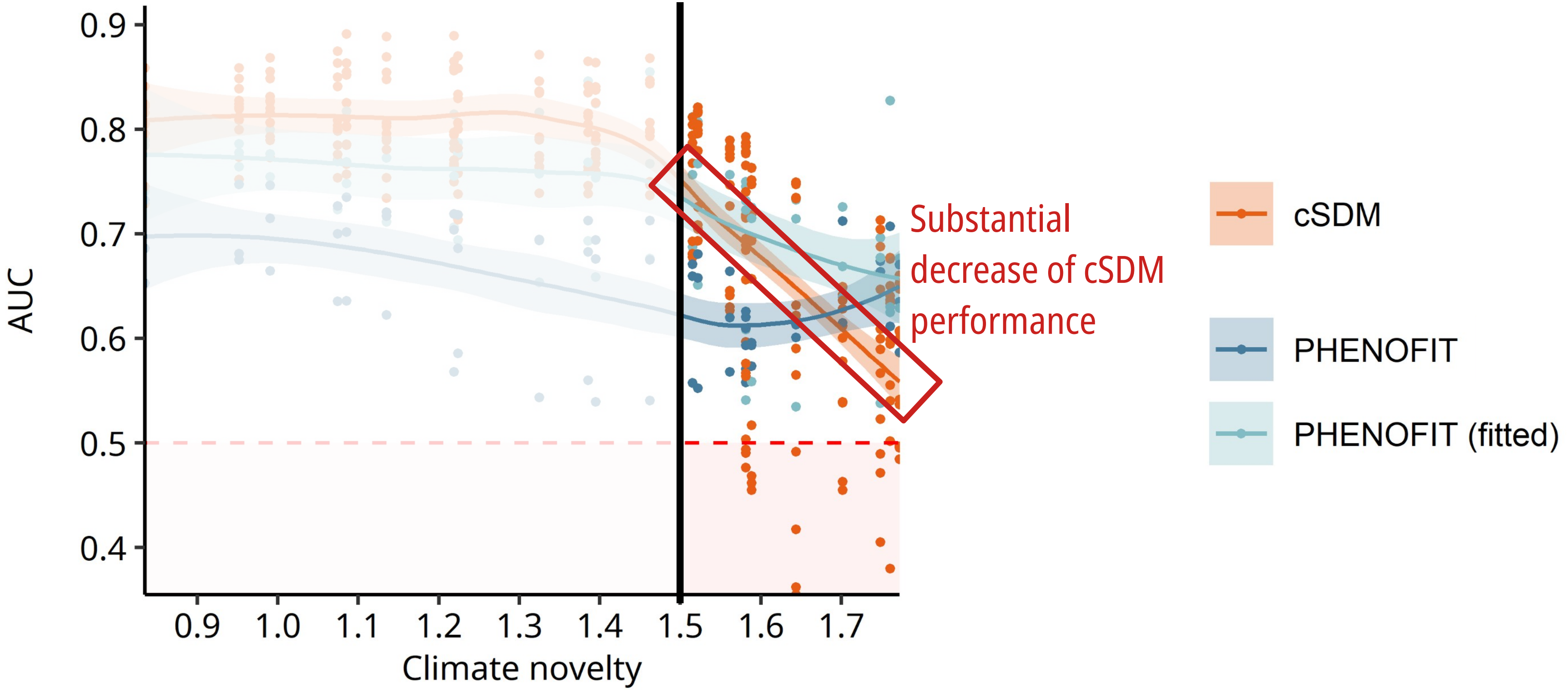
Comparison with three genus-level records



Fagus, *Quercus* and *Abies* (Holocene only)

INSIGHTS FROM THE PAST: MODEL PROJECTIONS V.S. POLLEN RECORDS

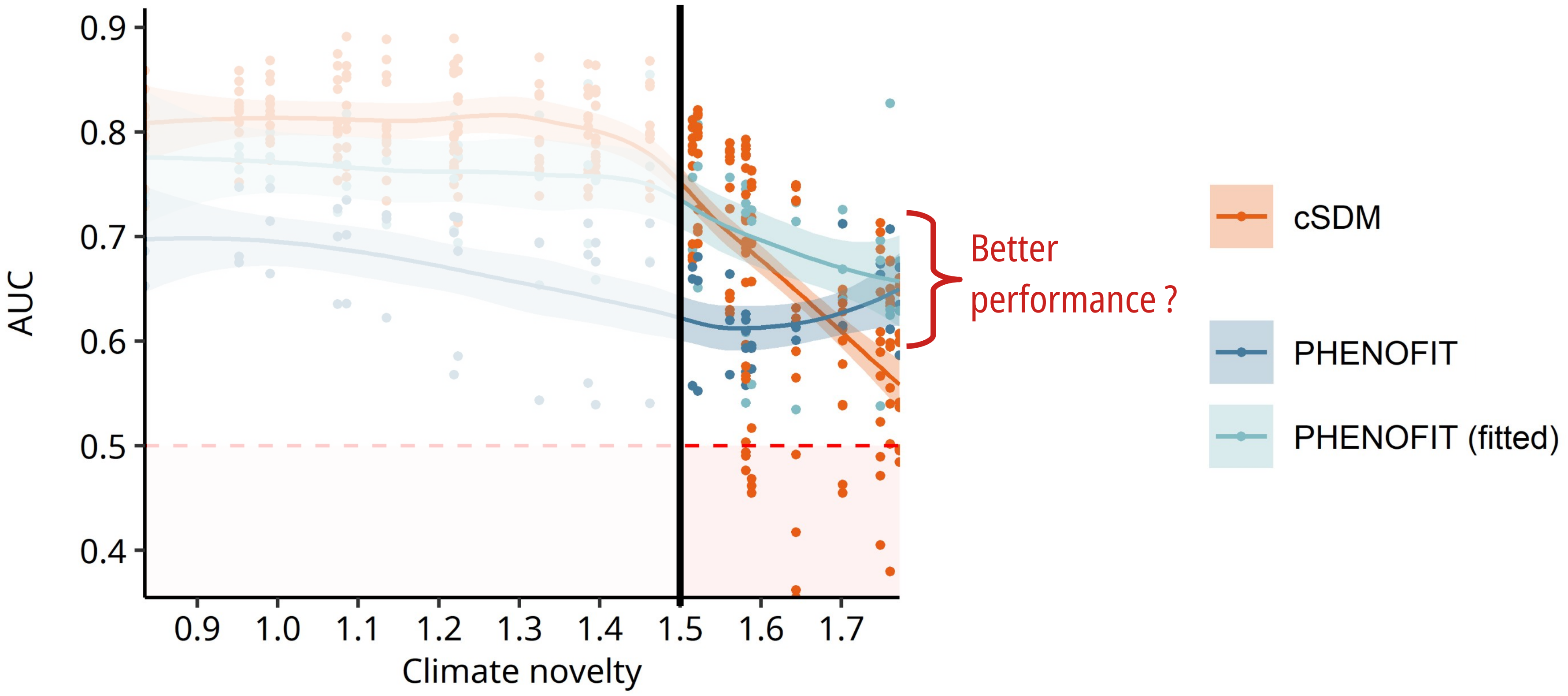
Comparison with three genus-level records



Fagus, *Quercus* and *Abies* (Holocene only)

INSIGHTS FROM THE PAST: MODEL PROJECTIONS V.S. POLLEN RECORDS

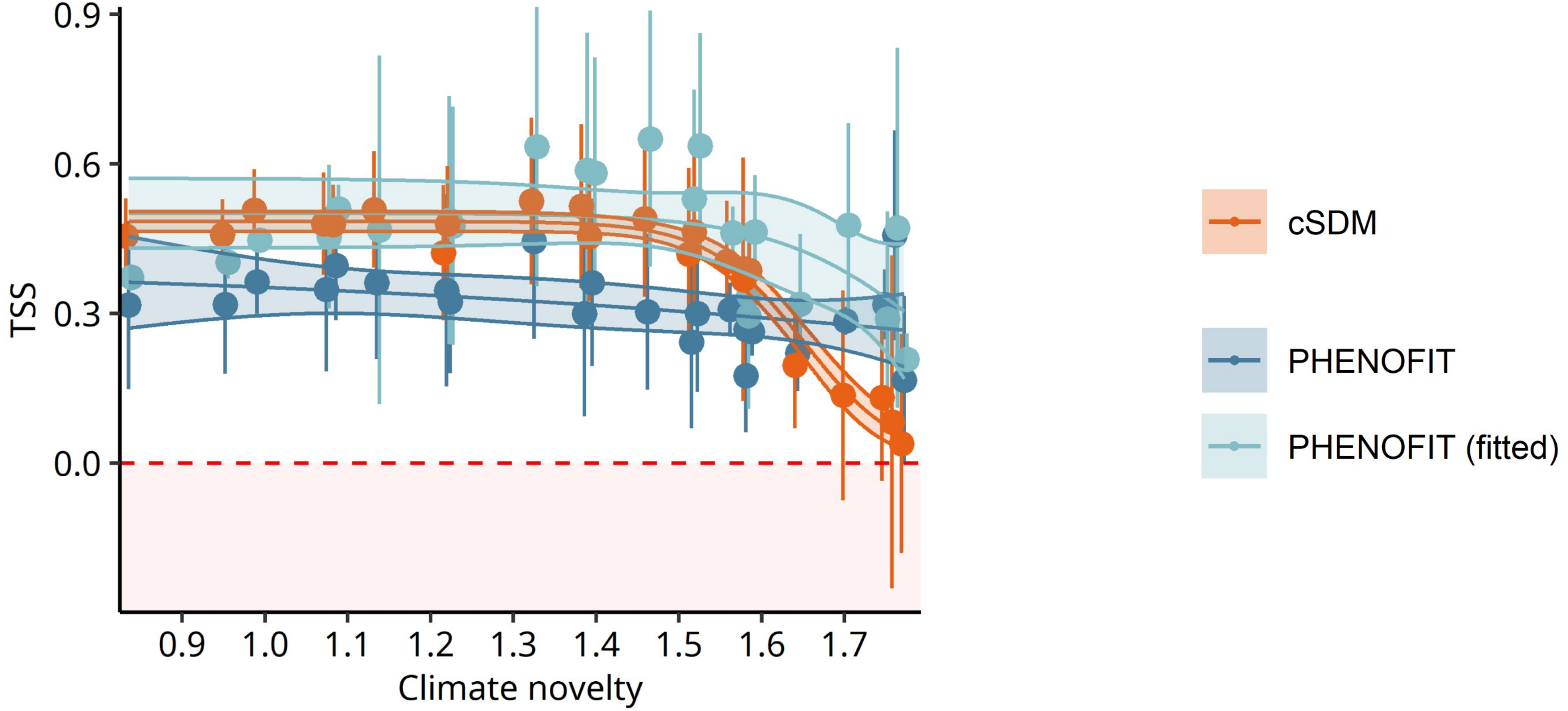
Comparison with three genus-level records



Fagus, *Quercus* and *Abies* (Holocene only)

INSIGHTS FROM THE PAST: MODEL PROJECTIONS V.S. POLLEN RECORDS

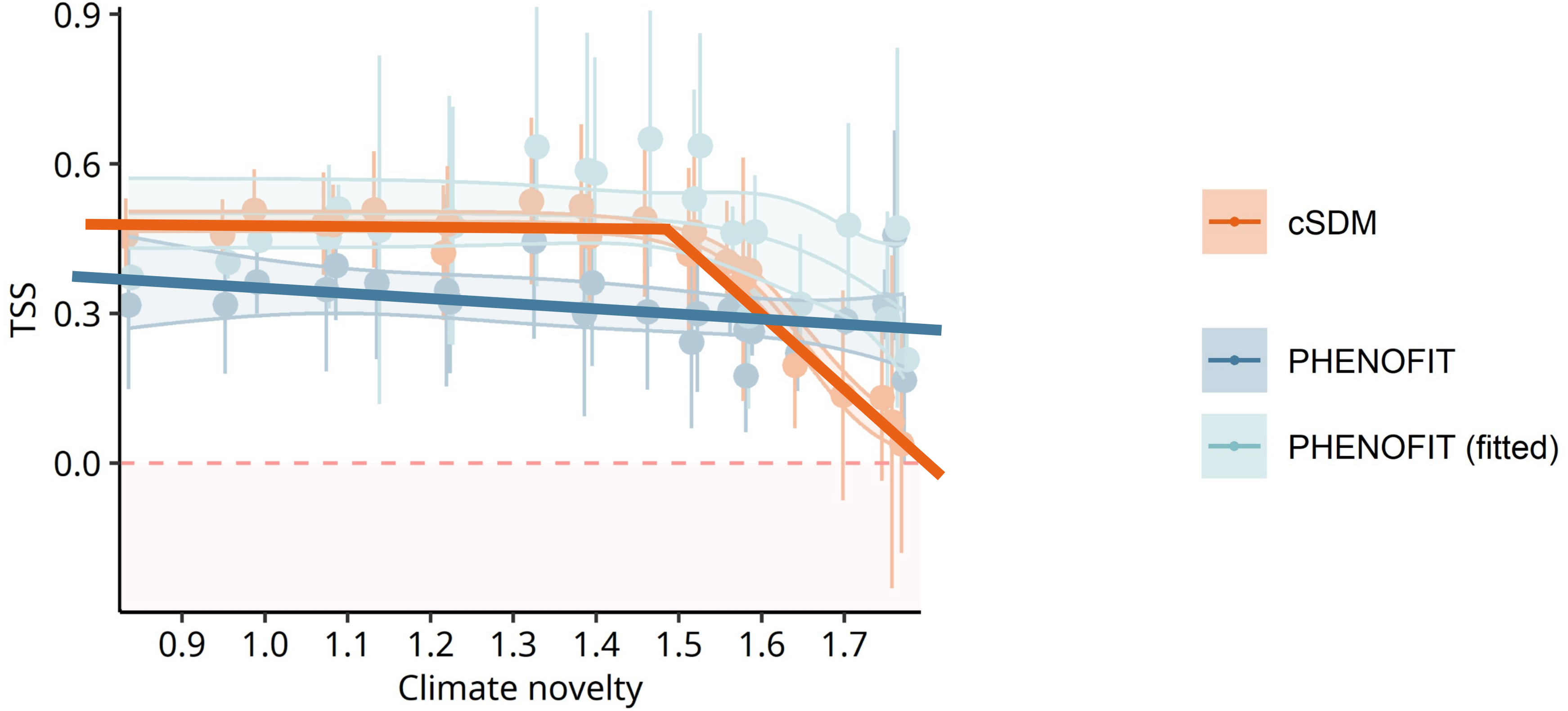
Comparison with three genus-level records



Fagus, *Quercus* and *Abies* (Holocene only)

INSIGHTS FROM THE PAST: MODEL PROJECTIONS V.S. POLLEN RECORDS

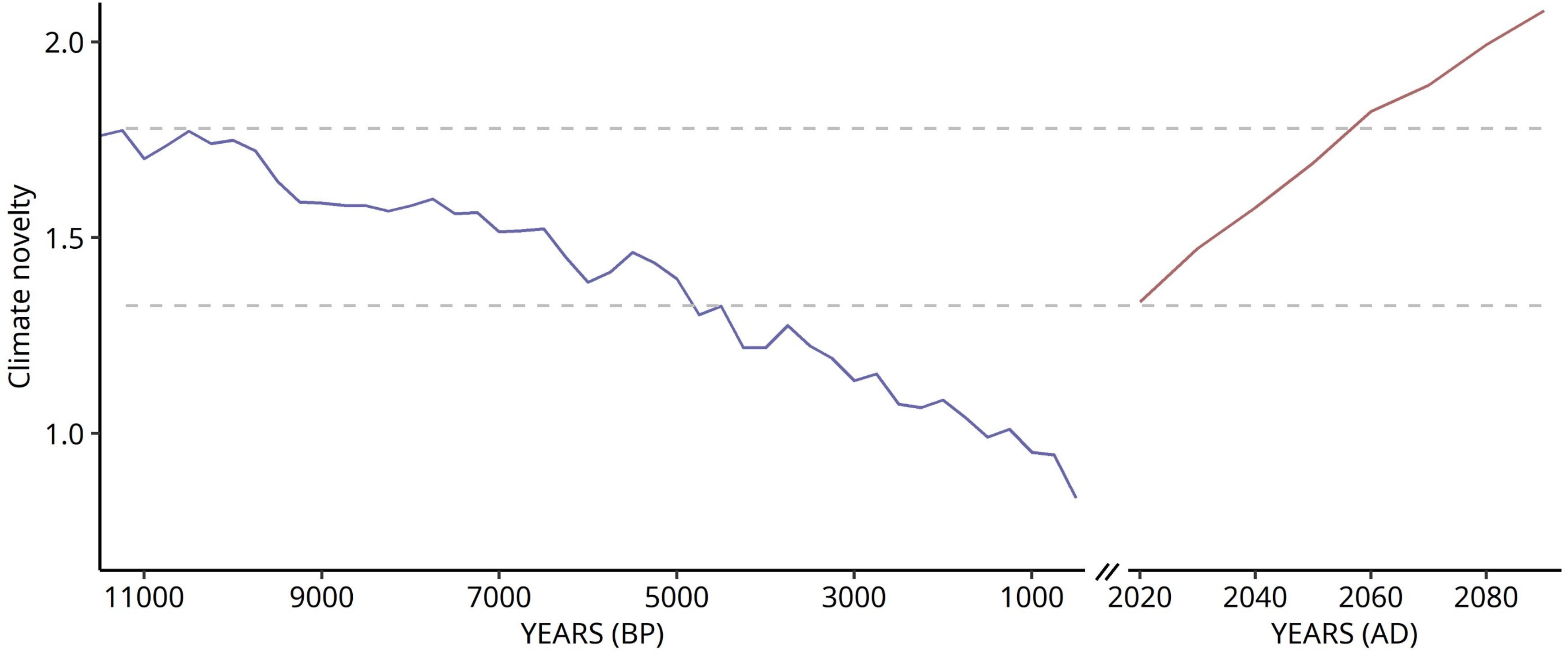
Comparison with three genus-level records



Fagus, *Quercus* and *Abies* (Holocene only)

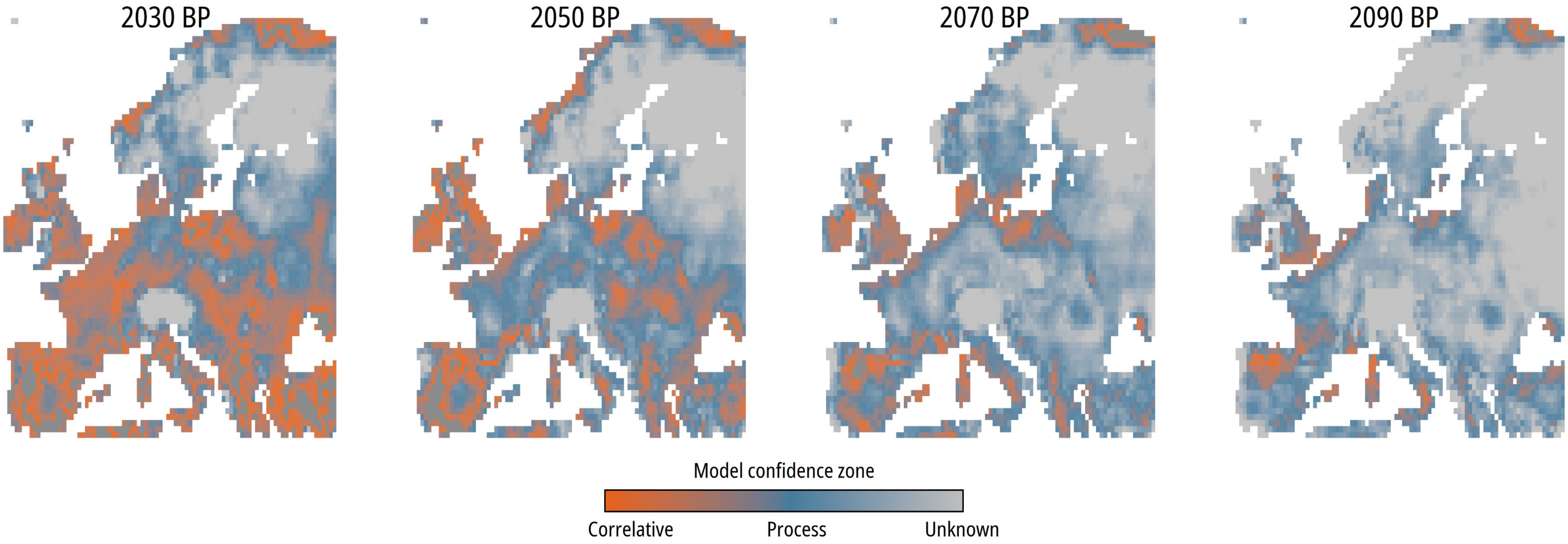
IMPLICATIONS FOR FUTURE CONFIDENCE IN MODEL PROJECTIONS

Future climate states with no analog



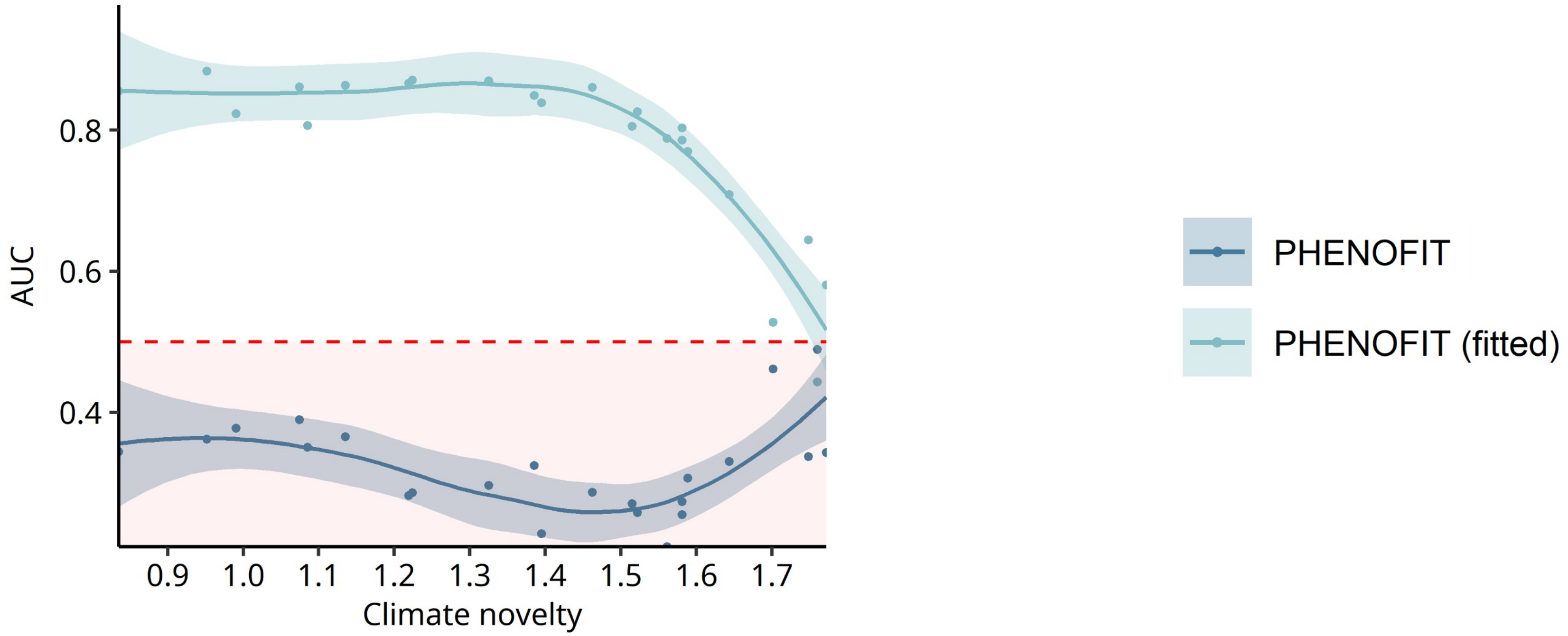
IMPLICATIONS FOR FUTURE CONFIDENCE IN MODEL PROJECTIONS

Strong uncertainties by the end of the 21th century



Challenges to process-based approaches

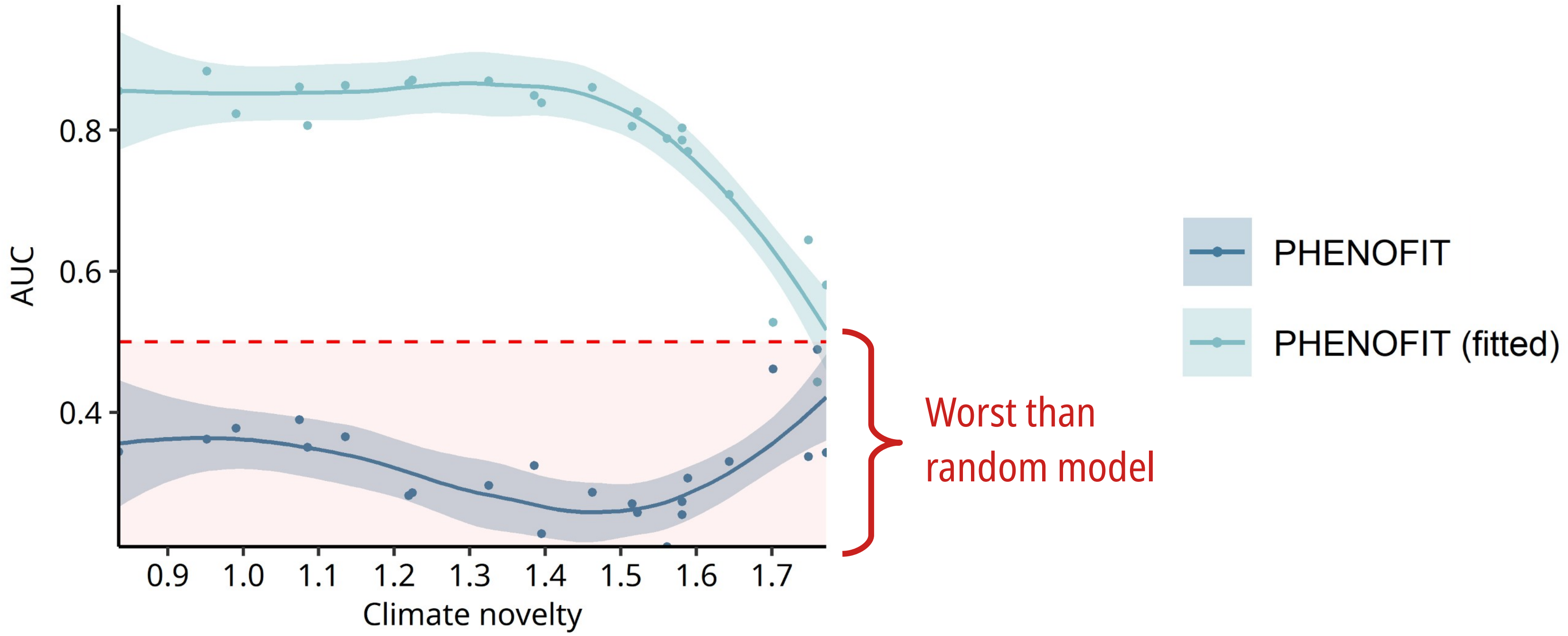
Palaeoecology: a tool for model diagnostics?



Larix

CHALLENGES TO PROCESS-BASED APPROACHES

Palaeoecology: a tool for model diagnostics?

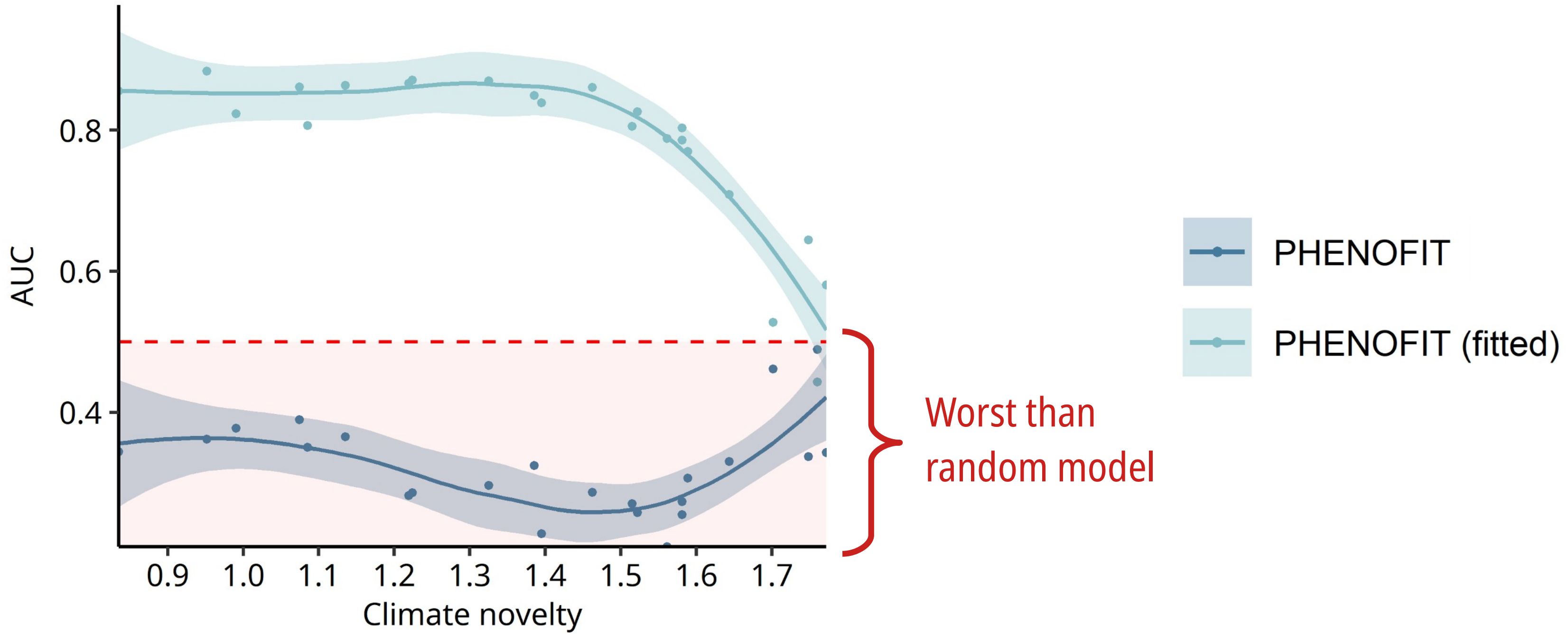


Worst than random model

Larix

CHALLENGES TO PROCESS-BASED APPROACHES

Palaeoecology: a tool for model diagnostics?



Worst than random model

Bad calibration due to scarce data rather than a model misspecification?

Larix

Limitations and Perspectives

- strong limitations of pollen data
- biotic interactions and land-use changes are not taken into account
- for the moment, we do not model migration processes

FINAL THOUGHTS

? Better communication on model uncertainties is crucial

FINAL THOUGHTS

? Better communication on model uncertainties is crucial

- a more comprehensive understanding of the potential errors by decision-makers

FINAL THOUGHTS

? Better communication on model uncertainties is crucial

- a more comprehensive understanding of the potential errors by decision-makers
- prevents the misinterpretation of model outputs as deterministic representations of the reality

Final Thoughts

? Better communication on model uncertainties is crucial

- a more comprehensive understanding of the potential errors by decision-makers

- prevents the misinterpretation of model outputs as deterministic representations of the reality

- directly linked to risk assessment

Final Thoughts

? Better communication on model uncertainties is crucial

- a more comprehensive understanding of the potential errors by decision-makers

- prevents the misinterpretation of model outputs as deterministic representations of the reality

- directly linked to risk assessment

LET'S PROVE OUR MODELS ARE WRONG!

THANK YOU !

Linocut print by C. Rescan