Towards improving the explanatory power in landscape genomics

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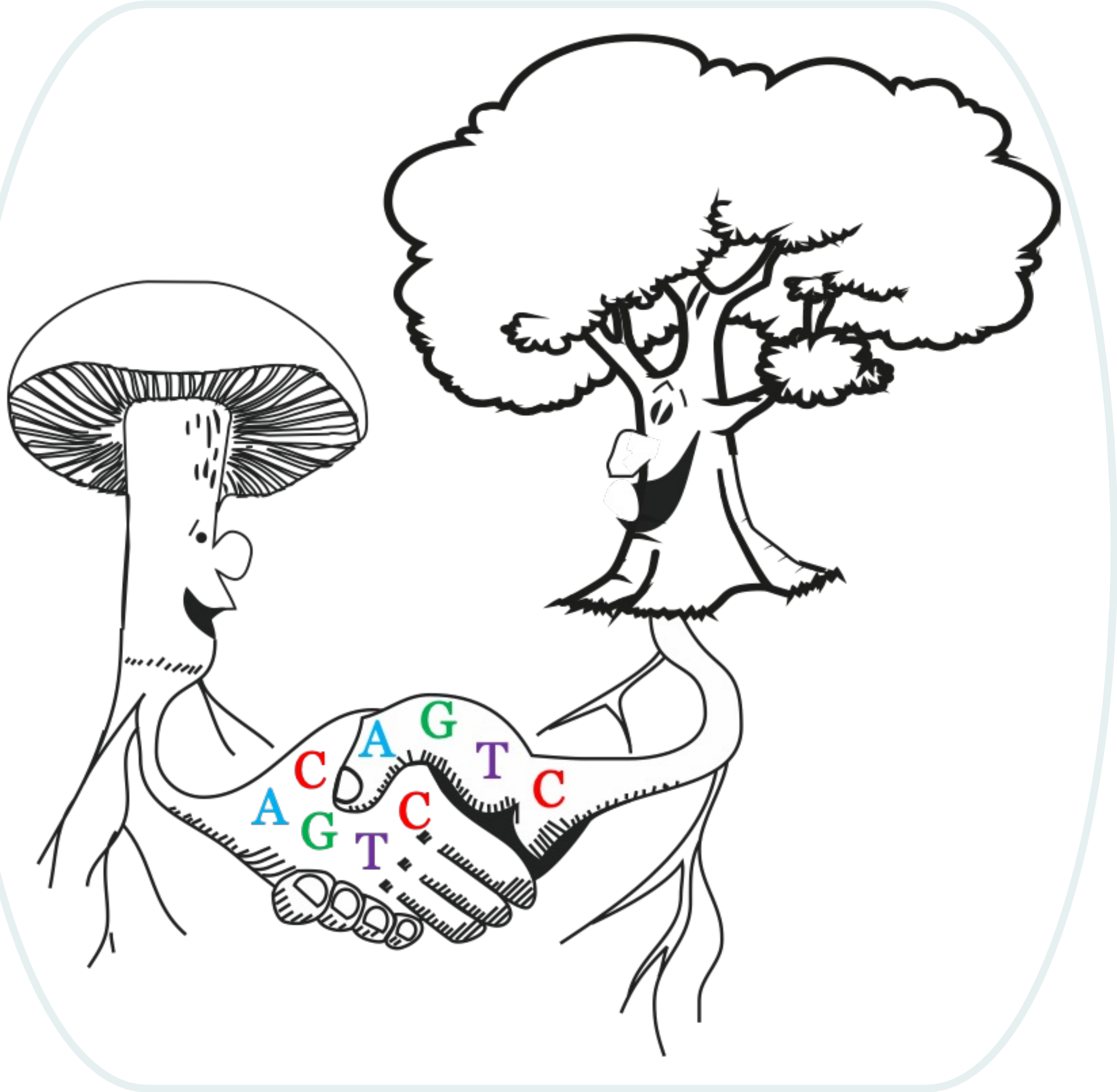
Summer School SSMPG - 21.09.2022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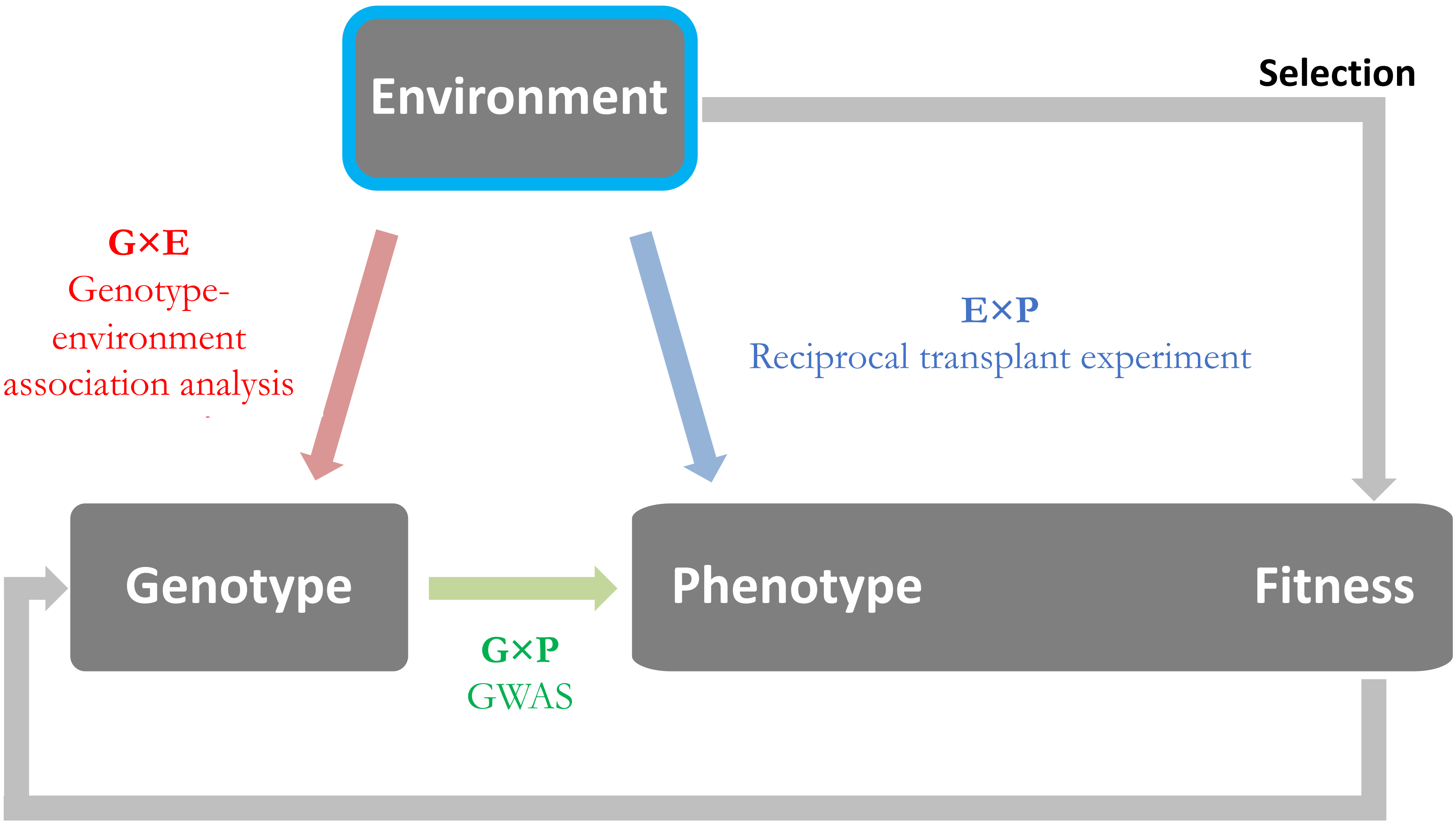
Focus



Rellstab et al. 2015

Outline

I. General introduction

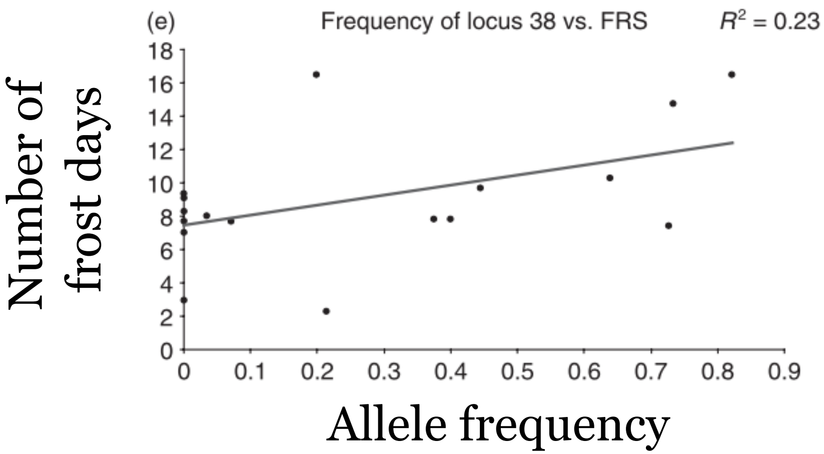
II. A brief portray of environmental data

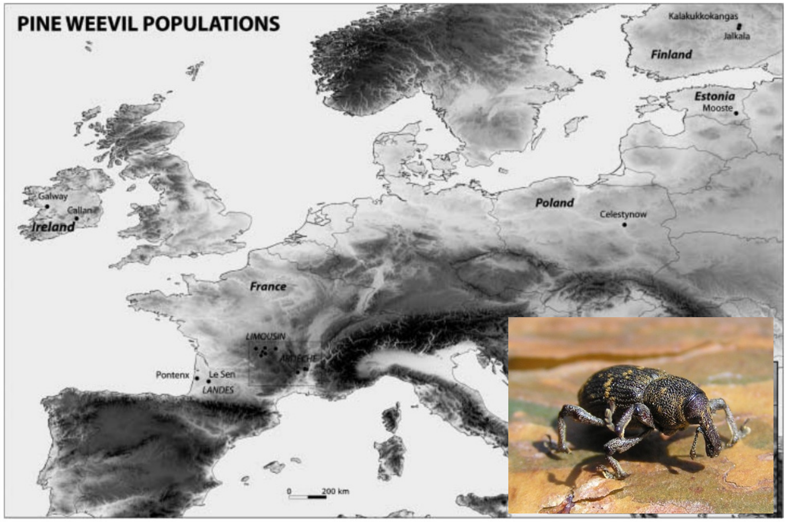
III. A short tutorial on how to handle environmental data in R

IV. Reduction of environmental variables

Landscape genomics

a field that searches for associations between environmental conditions and adaptive genetic variation in natural populations (Joost et al. 2007).



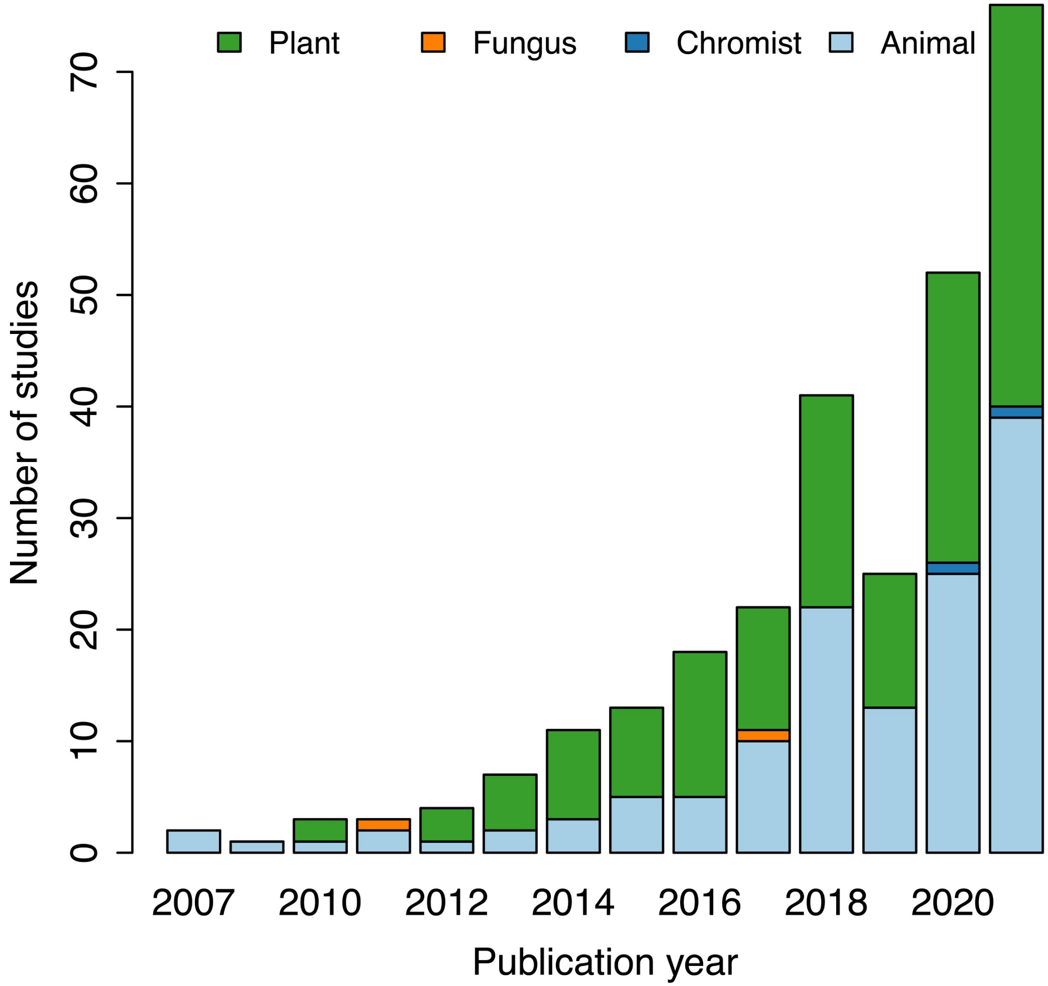


Ecological genomics

a field that aims to understand the genetic mechanisms underlying responses of organisms to their natural environment, **including experimental approaches** (Ungerer et al. 2008)

Where are we with landscape genomics?

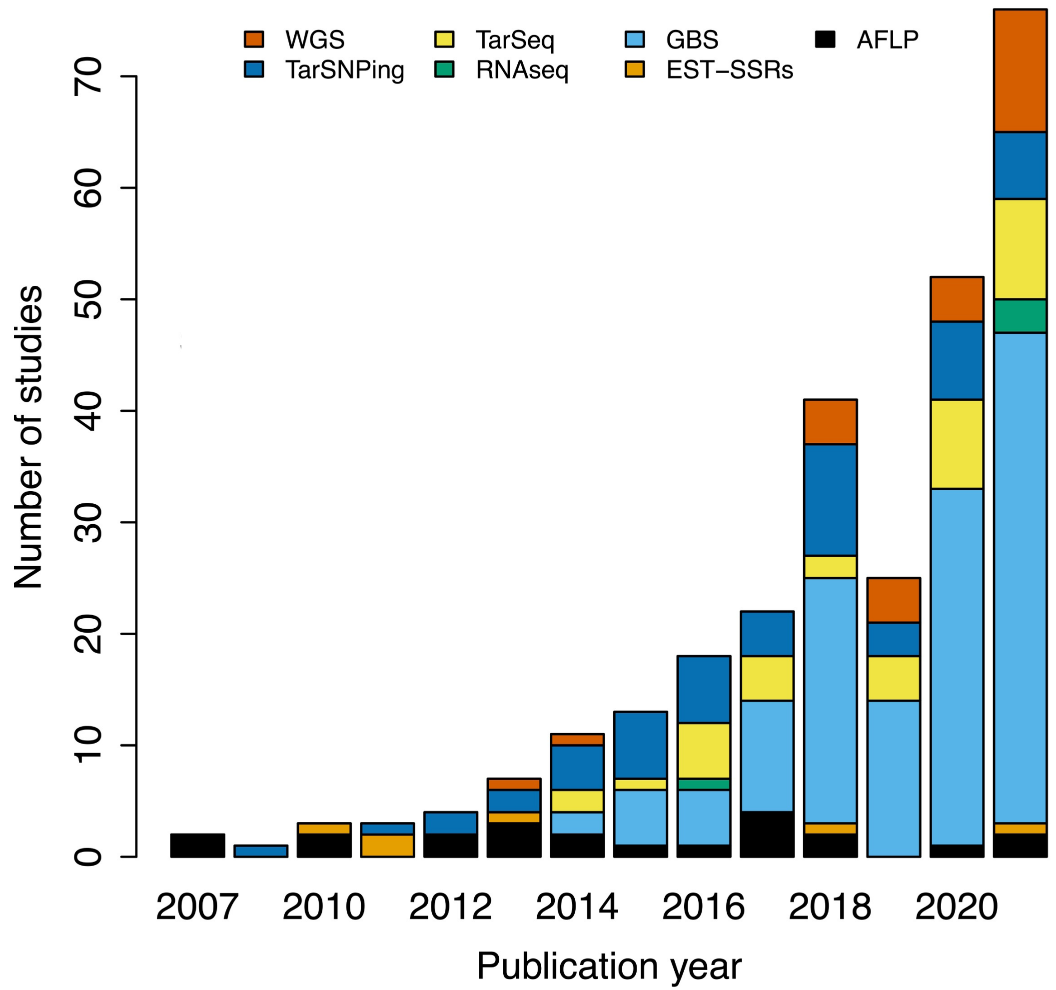
Landscape genomics is still a growing field…



Survey of 278 studies

Dauphin et al. in review

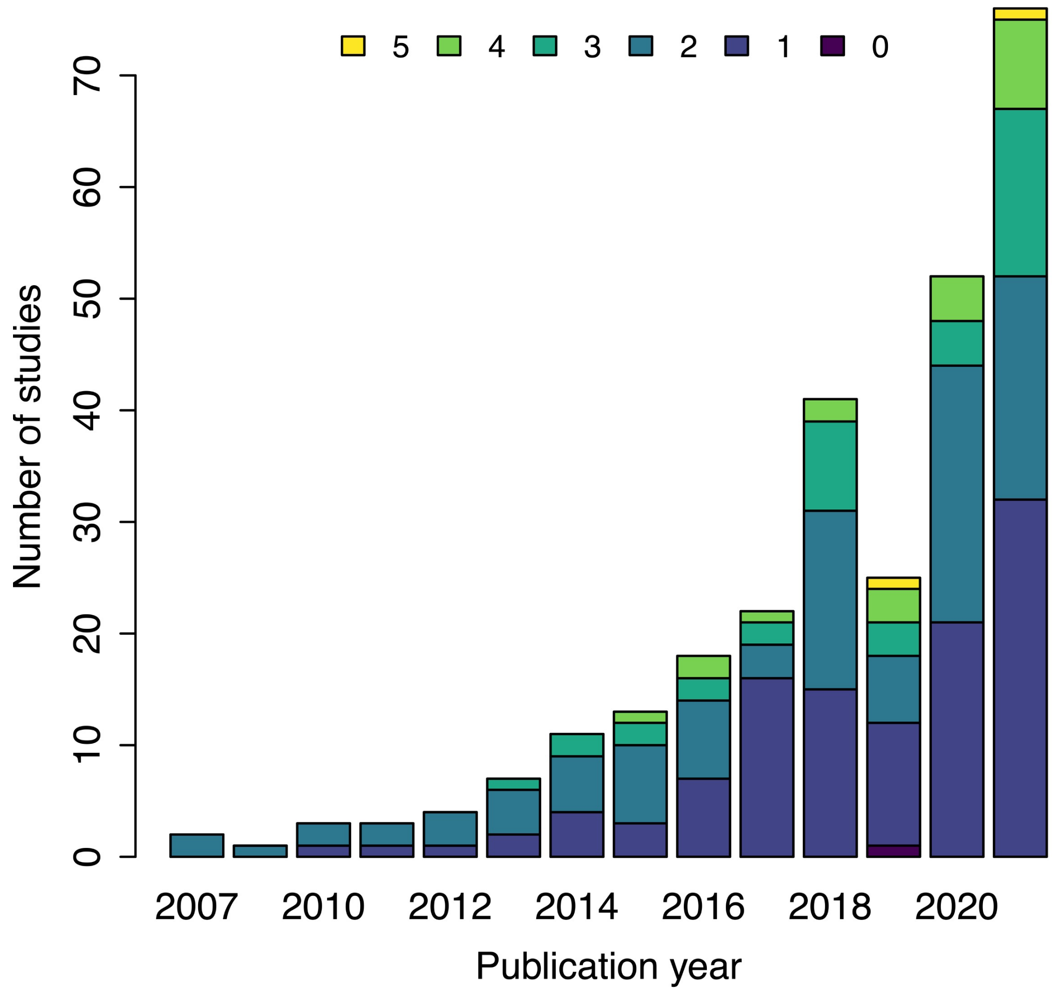
taking benefit of (new) sequencing techniques…



Survey of 278 studies

Dauphin et al. in review

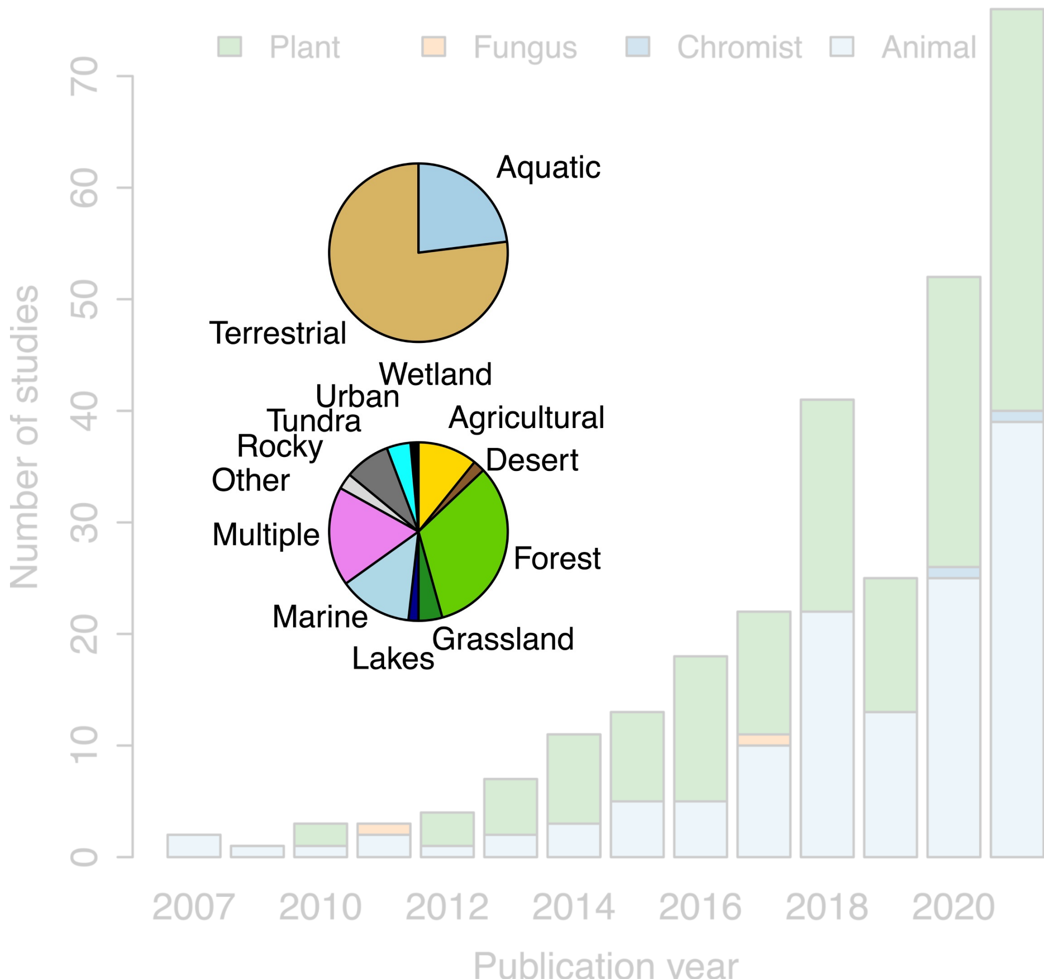
… and increasingly integrative environmental datasets



Survey of 278 studies

Dauphin et al. in review

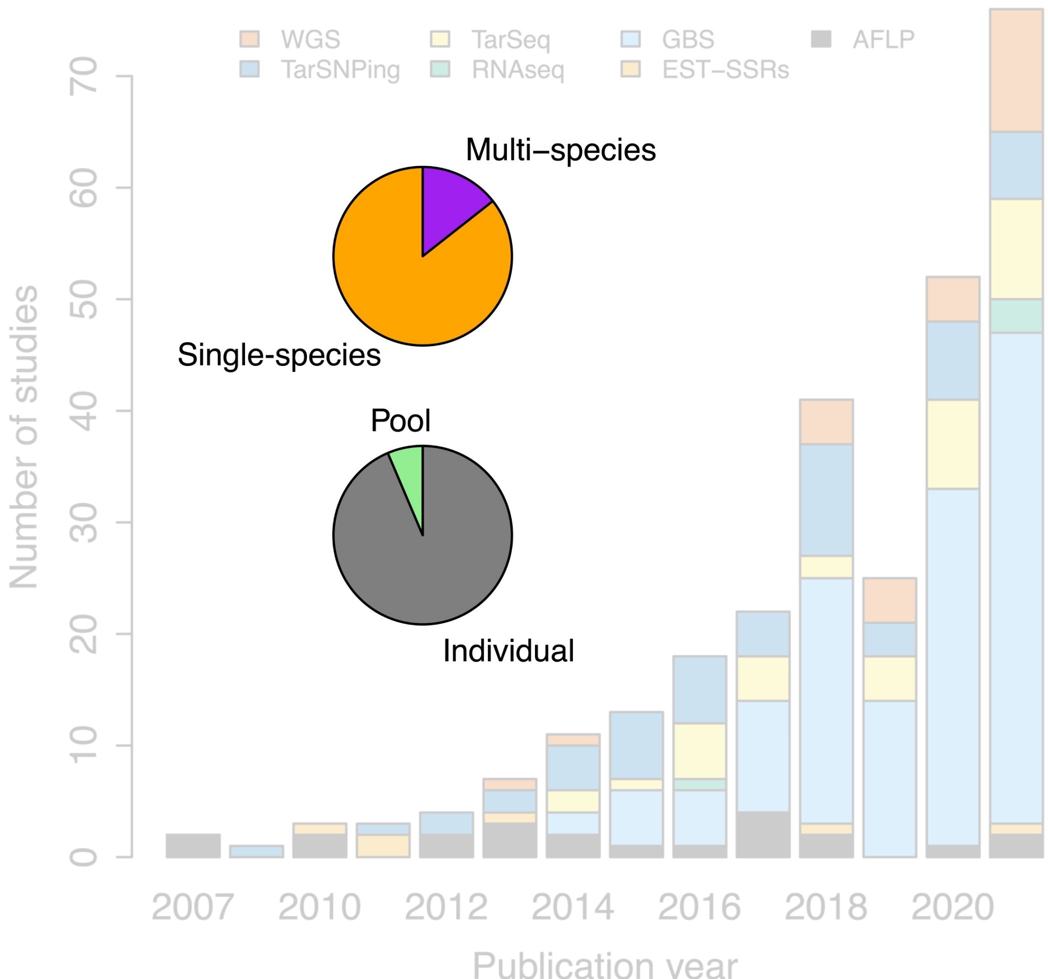
However, some ecosystems are under-represented…



Survey of 278 studies

Dauphin et al. in review

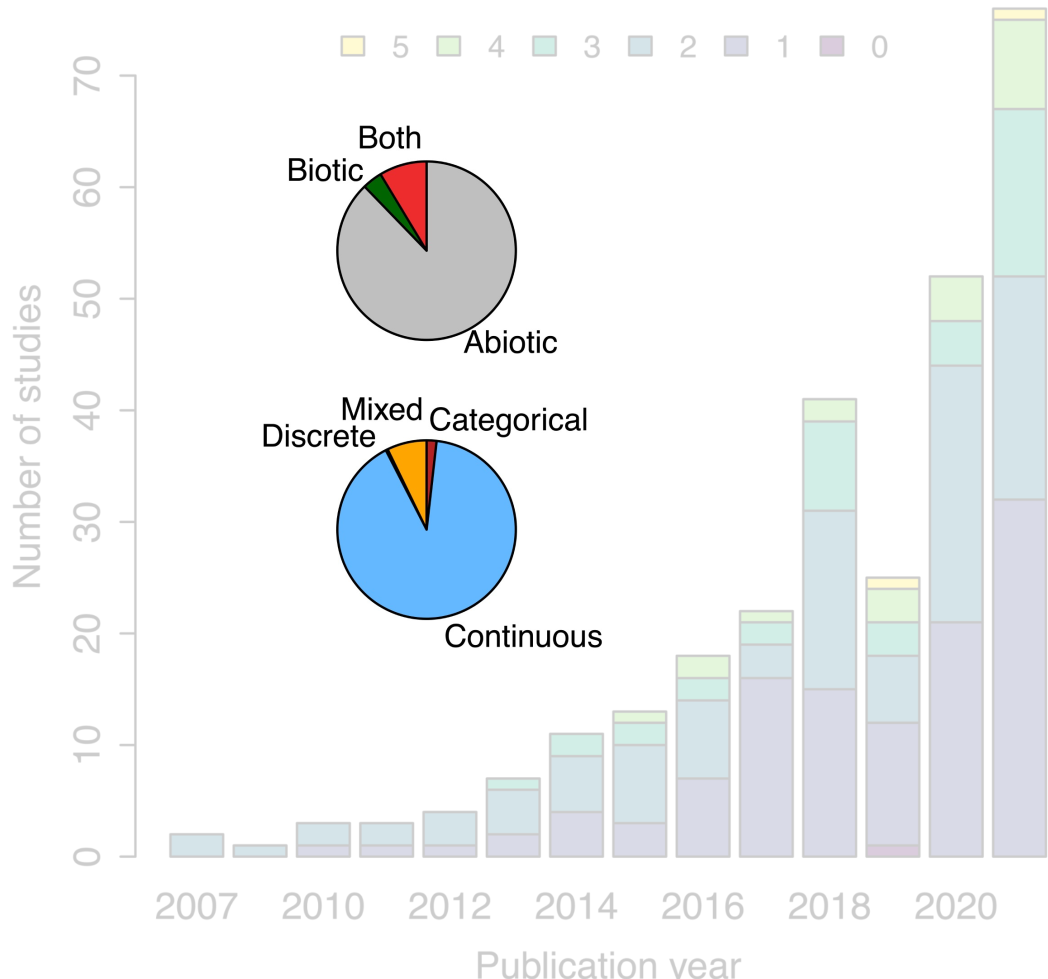
most studies focused on a single species…



Survey of 278 studies

Dauphin et al. in review

… and considered abiotic environmental conditions

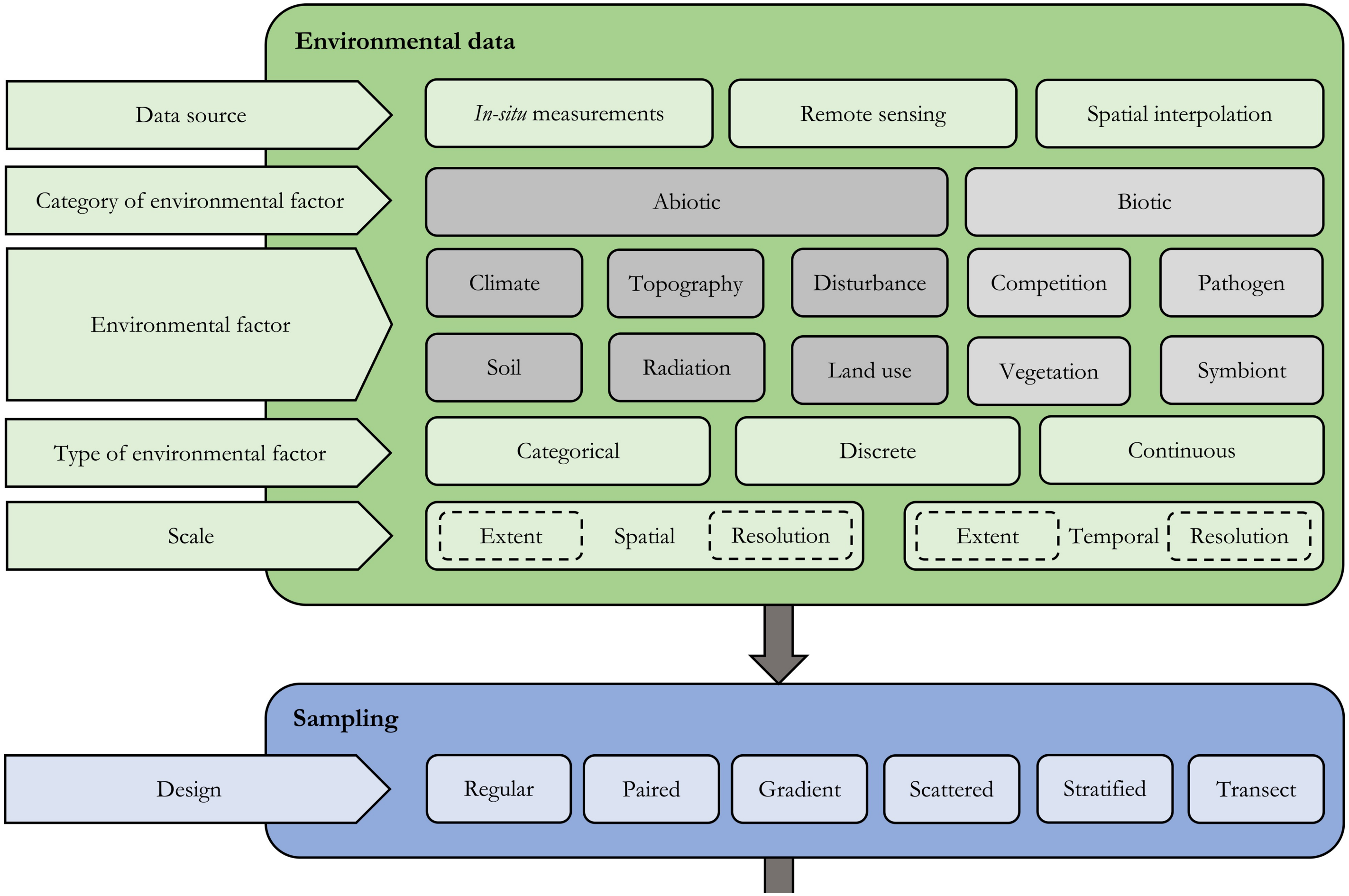


Survey of 278 studies

Dauphin et al. in review

Where shall we start when investigating local adaptation?

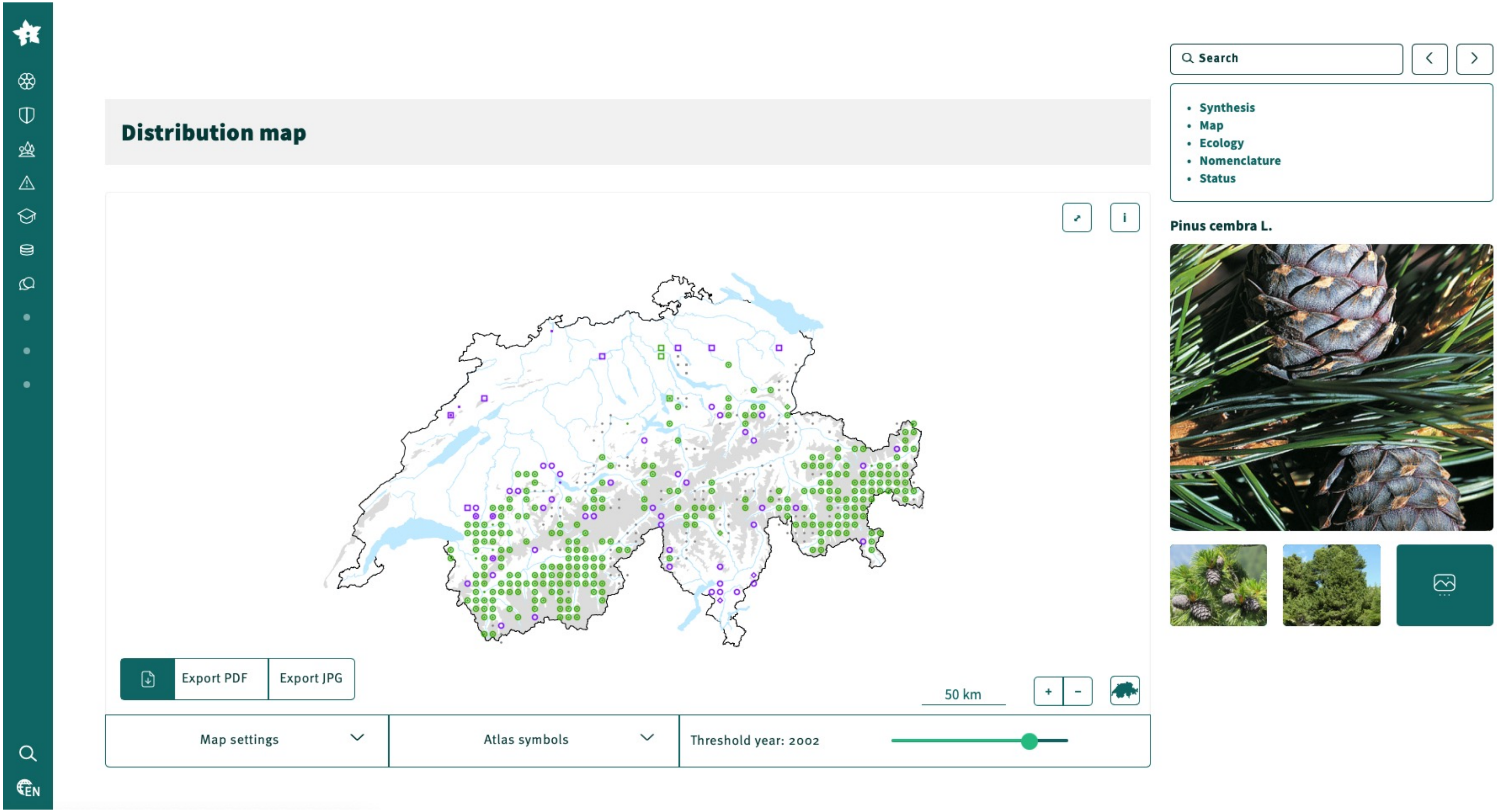
Explore environmental data before sampling



… with some precautions

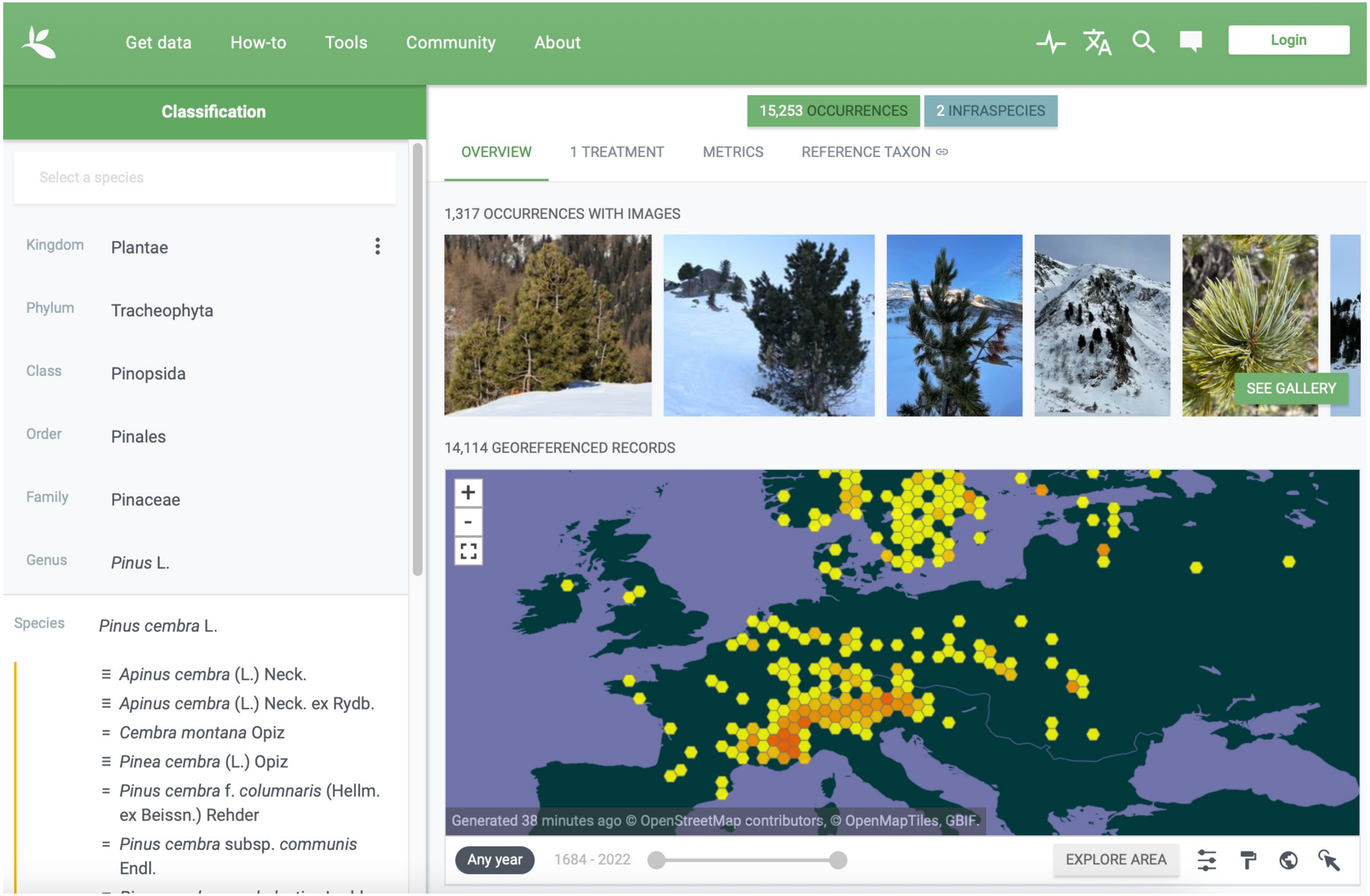
Dauphin et al. in review

Use the known species range to identify gradient(s) / contrast(s)



https://www.infoflora.ch/en/flora/pinus-cembra.html

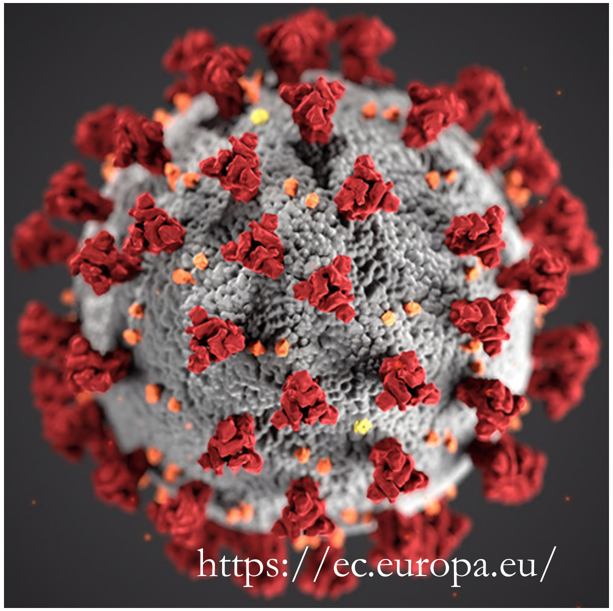
Although curation of occurrence data may be required



https://www.gbif.org/species/5285134

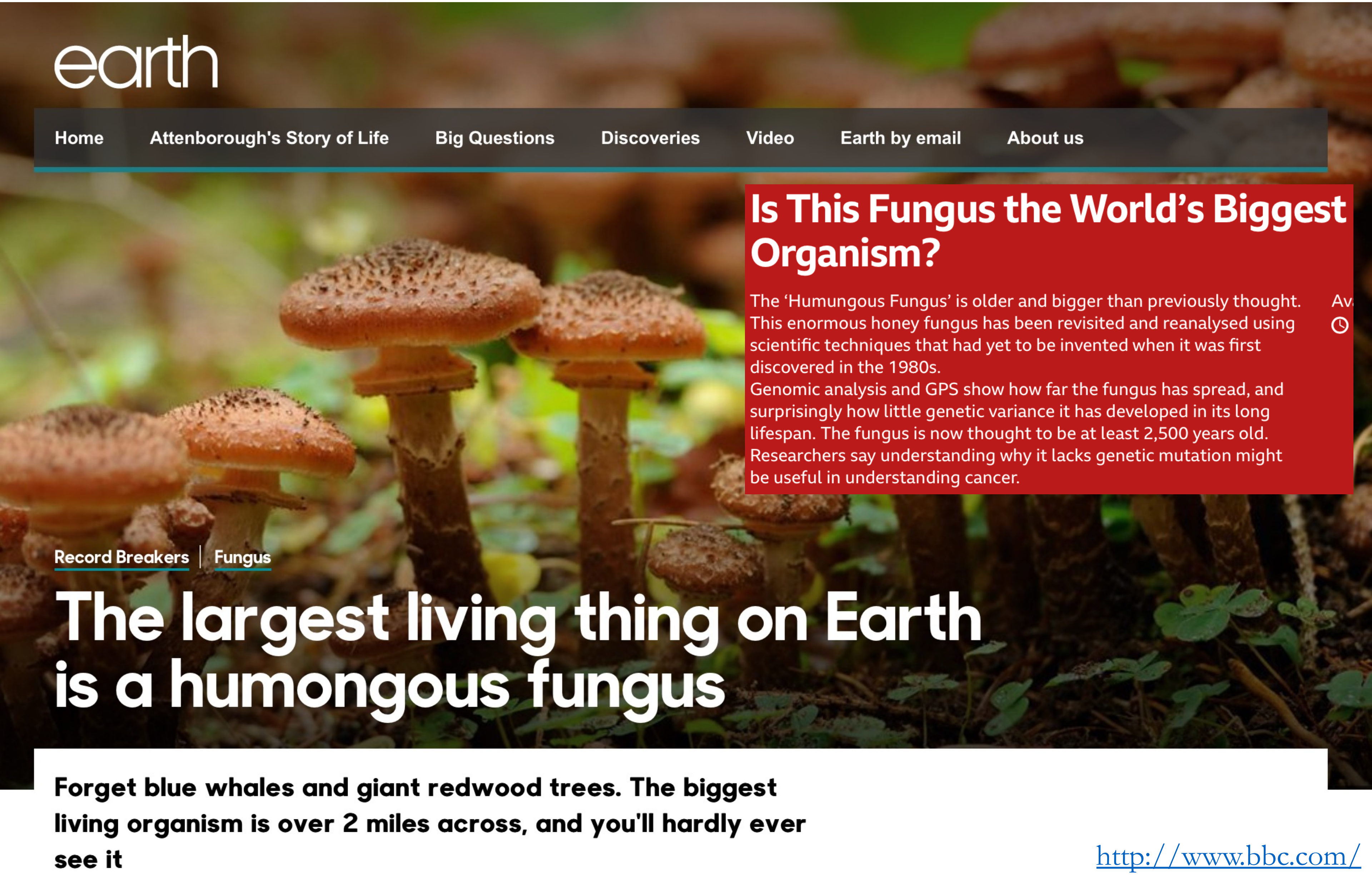
Environment, from the infinitely small to the infinitely large

~ 9–12 nanometres



~ 115 metres

But the largest organism is not the one we think…



http://www.bbc.com/

And the oldest organism is …

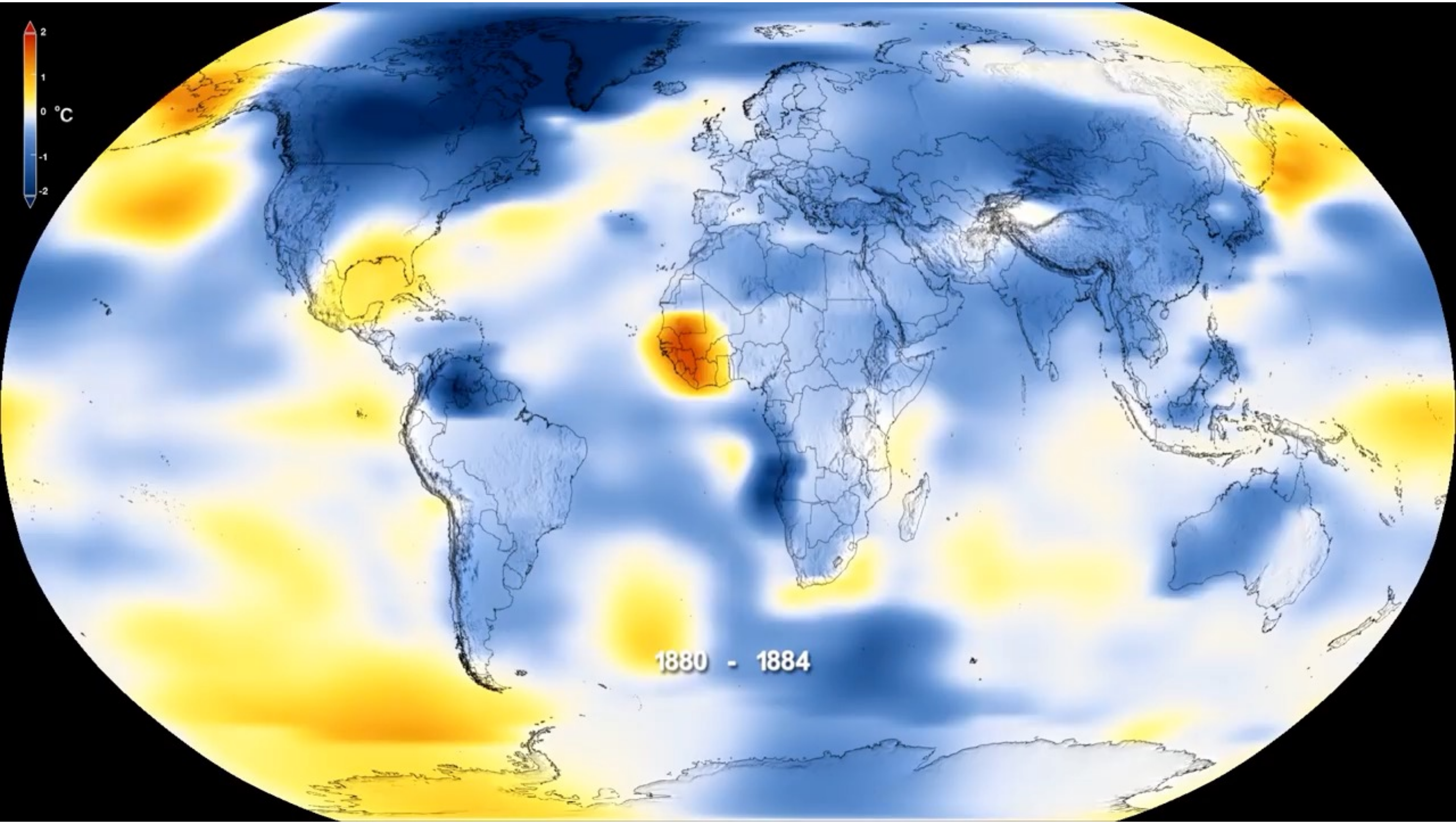
The Great Basin bristlecone pine is found in the western United States

http://www.bbc.com/

Species	Age	Type	ID	Location	Collector(s), Dater(s), Reference
4000+ years					
Pinus longaeva, Great Basin bristlecone pine	4900**	XD	WPN-114, Prometheus	Wheeler Peak, Nevada, USA	Currey 1965; Salzer and Baisan 2018
Pinus longaeva, Great Basin bristlecone pine	4850*	XD	Methuselah	White Mountains, California, USA	Ed Schulman, Tom Harlan
3000+ years					
Fitzroya cupressoides, alerce	3622	XD		Chile	Lara and Villalba 1993
Sequoiadendron giganteum, giant sequoia	3266**	XD	CBR26	Sierra Nevada, California, USA	Malcolm Hughes, Ramzi Touchan, Ed Wright
Sequoiadendron giganteum, giant sequoia	3220**	XD	D-21	Sierra Nevada, California, USA	Douglass 1919
Sequoiadendron giganteum, giant sequoia	3075**	XD	D-23	Sierra Nevada, California, USA	Douglass 1919
Sequoiadendron giganteum, giant sequoia	3033**	XD	CMC 3	Sierra Nevada, California, USA	Tom Swetnam, Chris Baisan
2000+ years					
Juniperus occidentalis, western juniper	2675**	XD	Scofield Juniper	Sierra Nevada, California, USA	Miles and Worthington 1998

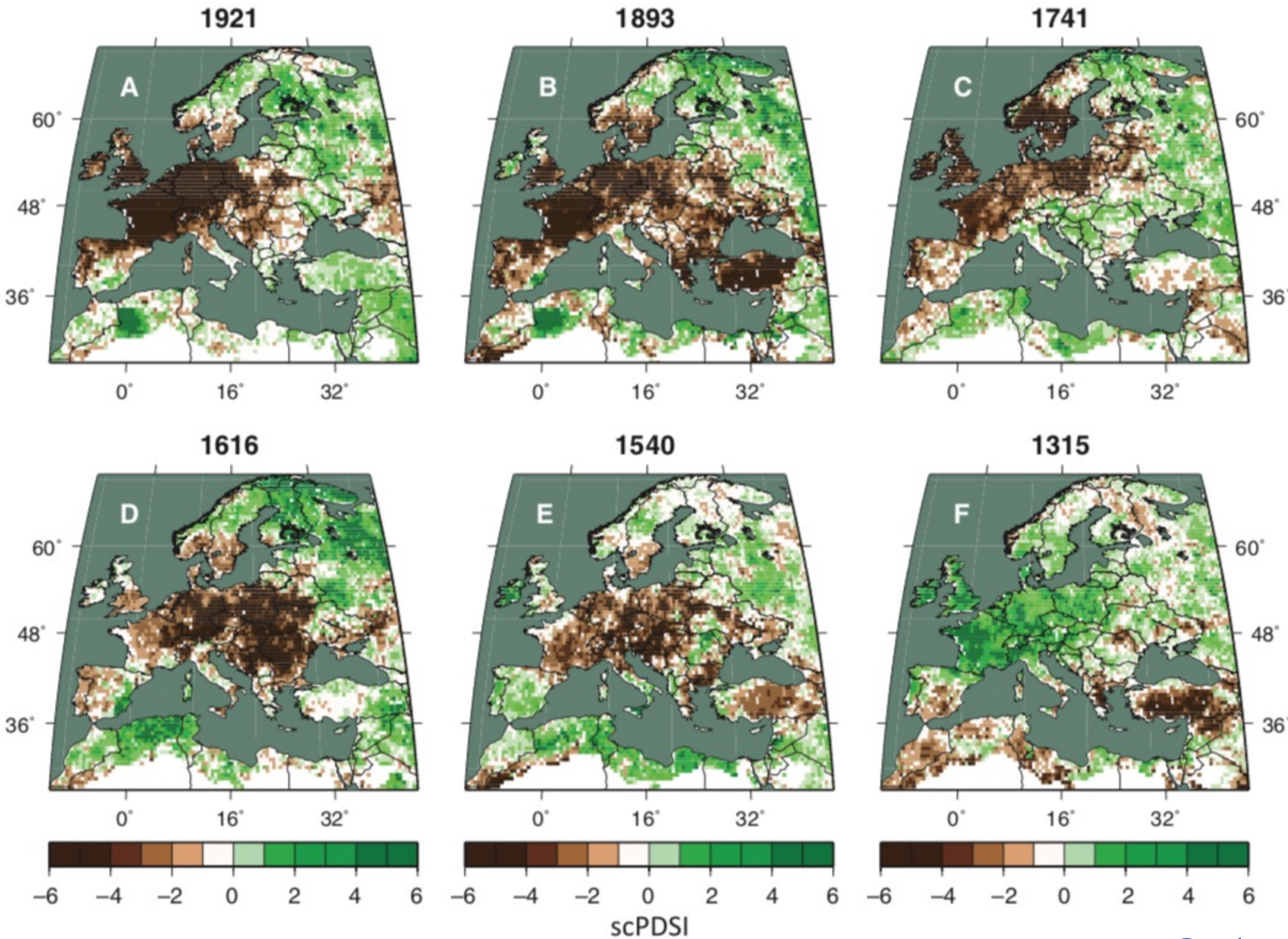
http://www.rmtrr.org/

Temperature anomalies through space from 1880



NASA climate change 2018

Spatial distribution and severity of past drought events



Cook et al. 2015

Outline

I. General introduction

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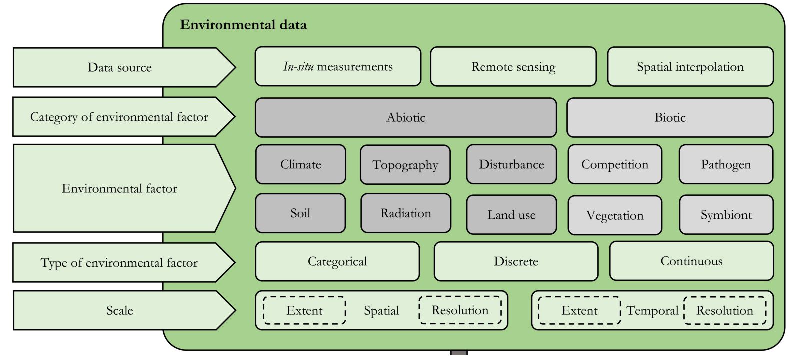
IV. Reduction of environmental variables

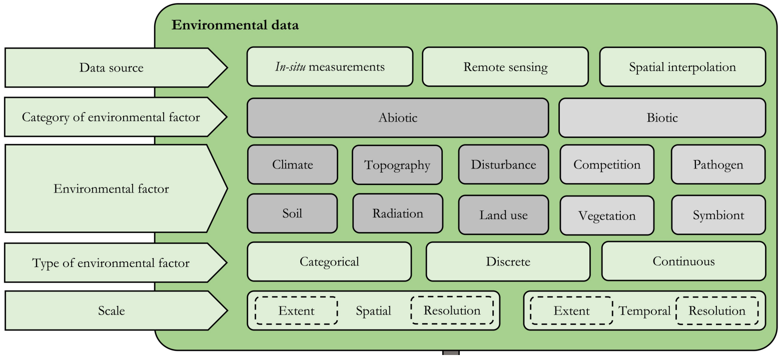
Source of environmental data



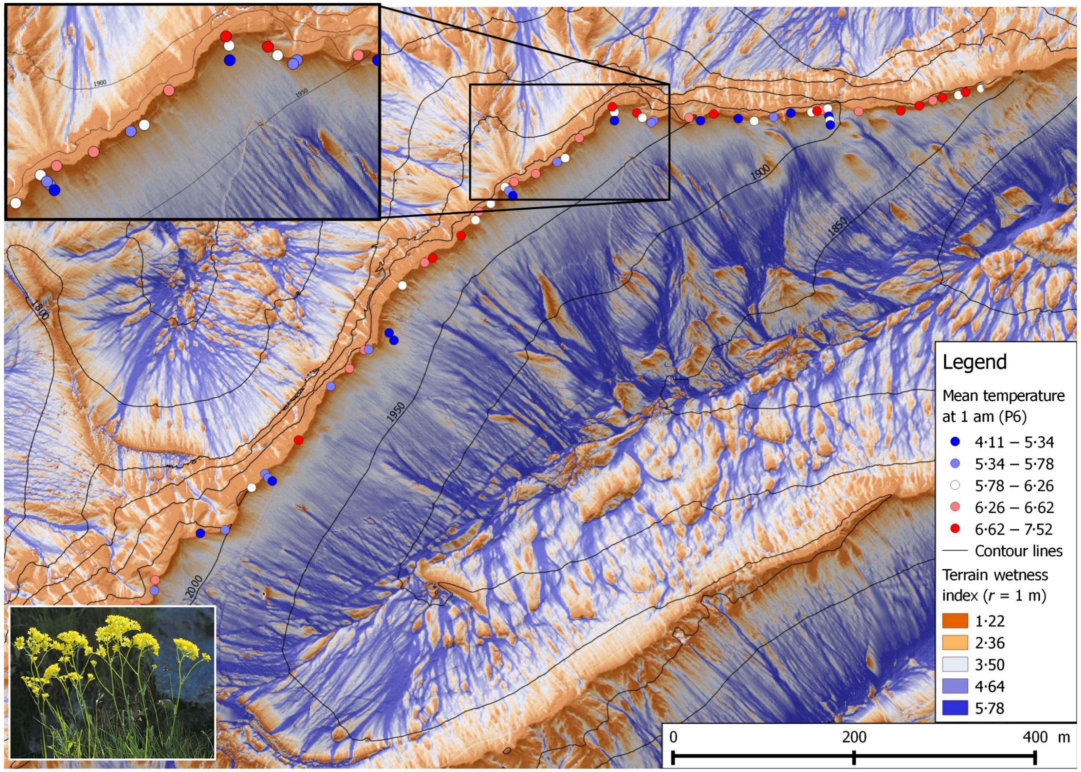
Measures on the field….

or modelling from observations

Categories of environmental data



- Abiotic:
  - Soil
  - Climate
  - Nutriments
  - Topography
  - …
- Biotic:
  - Pathogens
  - Symbionts
  - Herbivory
  - Pollinators
  - Vegetation
  - Competition
  - …



Leempoel et al. 2015

Type of environmental factors

Categorical …

- A variable that contains a **finite number of categories** or distinct groups

Discrete …

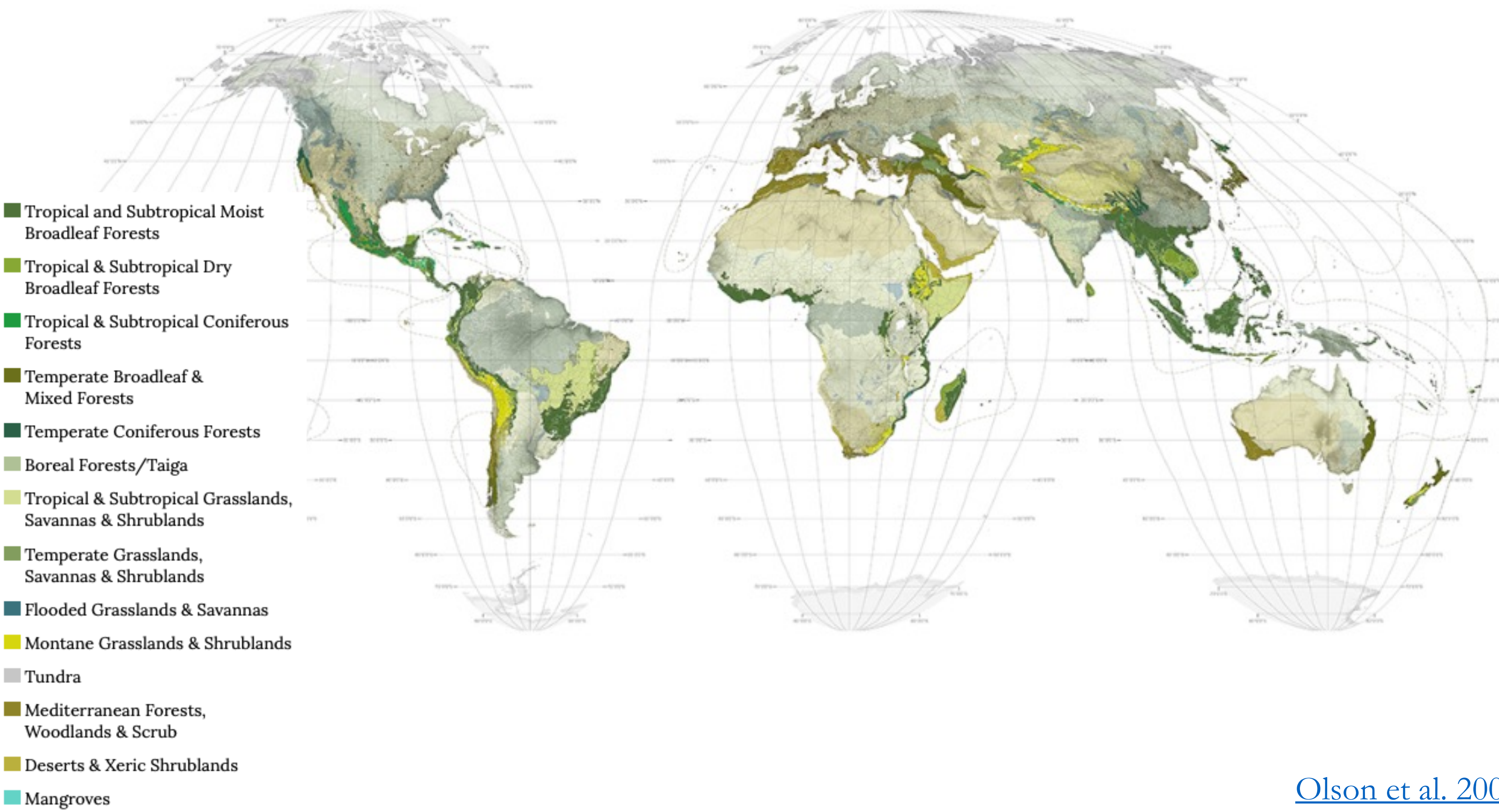
- A variable that can take **only certain values** along an interval

… versus Continuous environmental data

- A variable that can take **any valu**e at any point along an interval

Example of categorical environmental variable

- Geographic (e.g., biogeographical areas, **ecoregions**, among others…)



[Olson et al. 2001]

Example of discrete environmental variable

- Floristic bioindicators (e.g., Landolt indicators among others…)

Pinus cembra L.

Species 304900

Search | Previous | Next

Pinaceae / Pinus / Pinus cembra L.

Synthesis | Map | Ecology | Nomenclature | Status | 1034060

Ecological indicator values by Landolt & al. (2010)

Soil factors		Climatic factors		Salinity tolerance	
Humidity Value H	3	Light Value L	3	Salinity Index	--
Reaction Value R	2	Temperature factor T	2		
Nutriments value N	2	Continentality K	4		

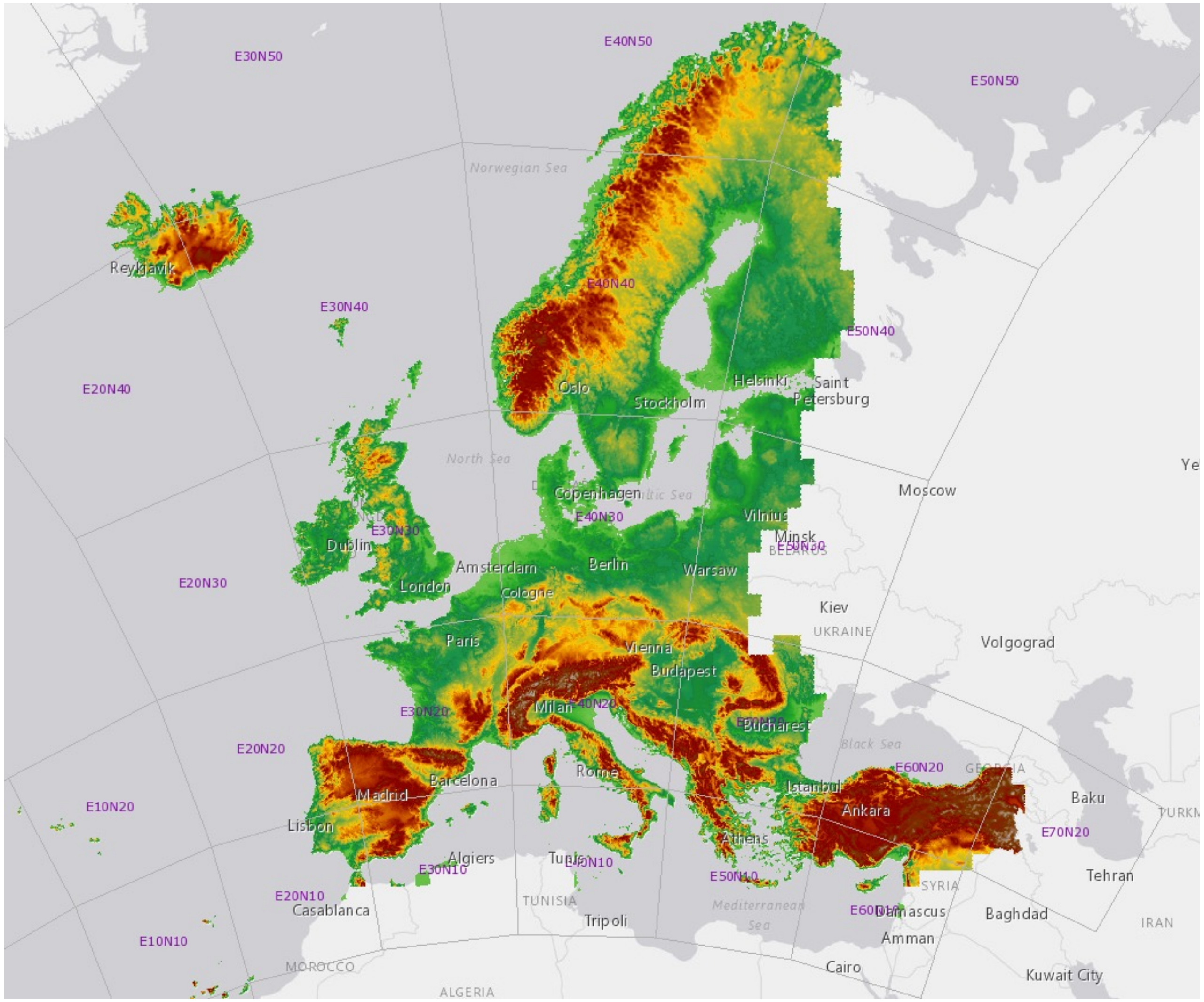
Nutriments value N	
1	very low in nutrients
2	low in nutriments
3	medium-poor to medium-rich in nutrients
4	rich in nutriments
5	very rich in nutriments

Light Value L	
1	very shady
2	shady
3	lighted areas
4	luminous
5	highly luminous

InfoFlora 2022

Example of continuous environmental variable

- Topography on a European scale with Copernicus



www.eea.europa.eu/

Some environmental databases

Soil

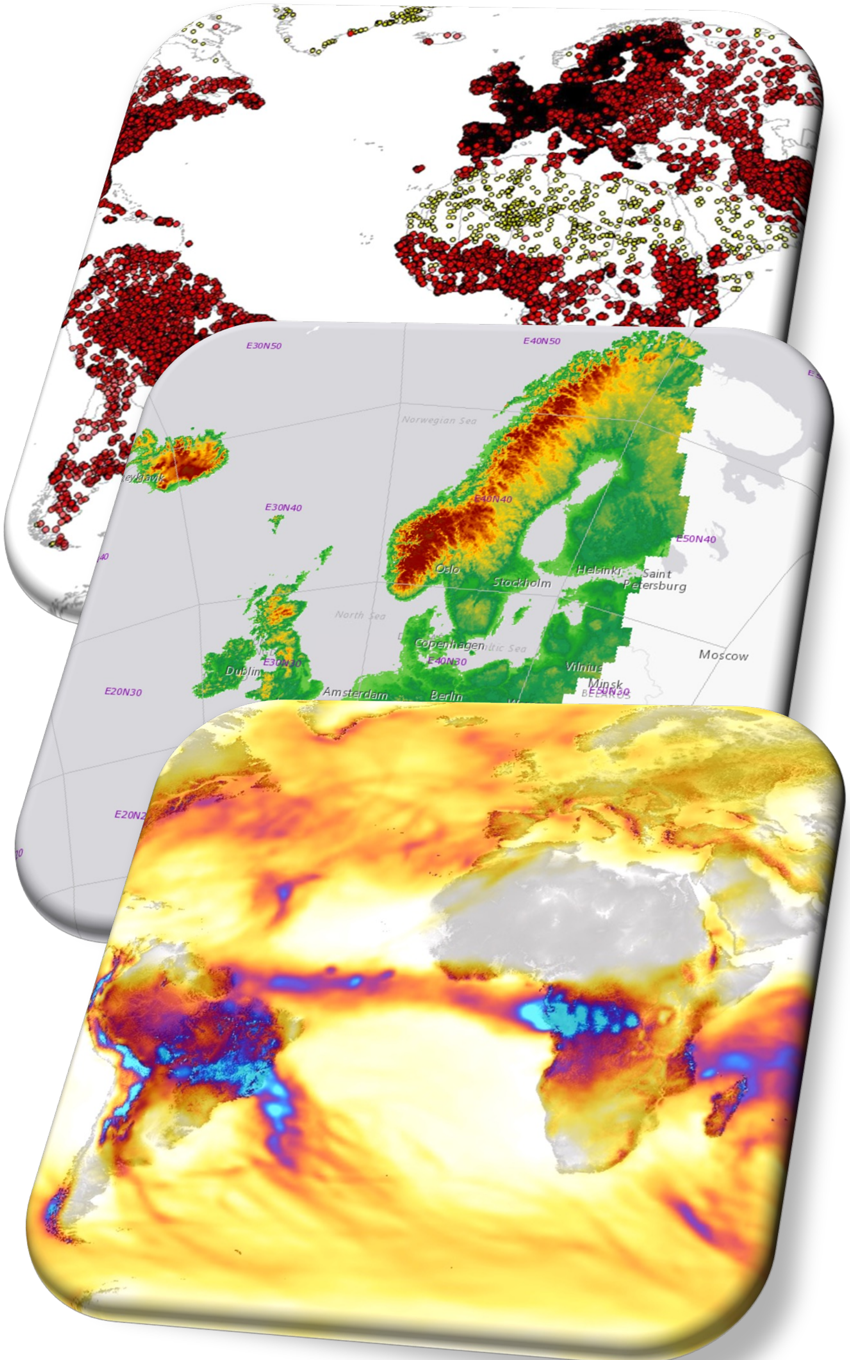
- SoilGrids
- CORINE Land Cover
- US Land Cover Database
- Global soil temperature
- …

Topography

- Copernicus EU-DEM
- GMTED2010
- SRTM
- …

Climate

- CHELSA
- WorldClim
- World Ocean Database
- …



Why using CHELSA?

CHELSA

Climatologies at high resolution for the earth's land surface areas

Comparison to other high resolution climate products

CHELSA, as most other climate products is a 'model' that aims at representing reality as precise as possible. Nevertheless, it is just a model, and has its strength and weaknesses. Here, we want to provide a simple comparison to some other products such as PRISM or WorldClim, to illustrate some of the differences between these models.

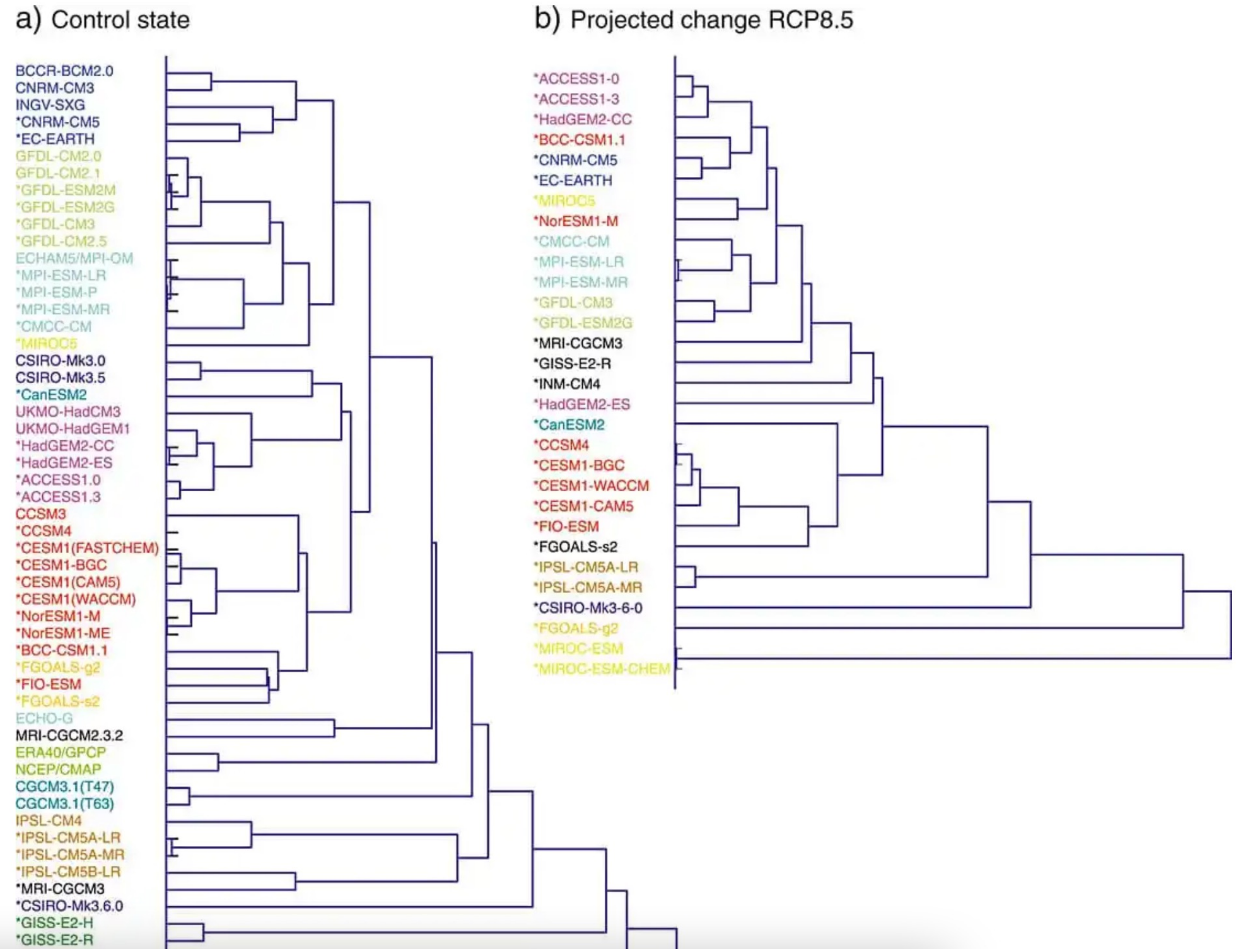
The comparison of the predictions with existing products and station data indicates an improvement in the spatio-temporal performance of the precipitation data based on cloud cover-informed downscaling. For this newly developed semi-mechanistic downscaling approach for daily precipitation, high resolution (30 arc sec) satelite-derived cloud frequency was incorporated.

For more information see:

Karger, D.N., Wilson, A.M., Mahony, C., Zimmermann, N.E., Jetz, W. (2021): Global daily 1km land surface precipitation based on cloud cover-informed downscaling. ***Scientific Data.*** doi.org/10.1038/s41597-021-01084-6

Selection of climate models

Consider those that are less interdependent under current and/or future conditions



Sanderson et al. 2015

File formats of environmental data

Vector data:

- Points: e.g., occurrence data
- Lines: e.g., barrier to migration
- Polygons: e.g., species range

“shapefile” is the most common vector file type

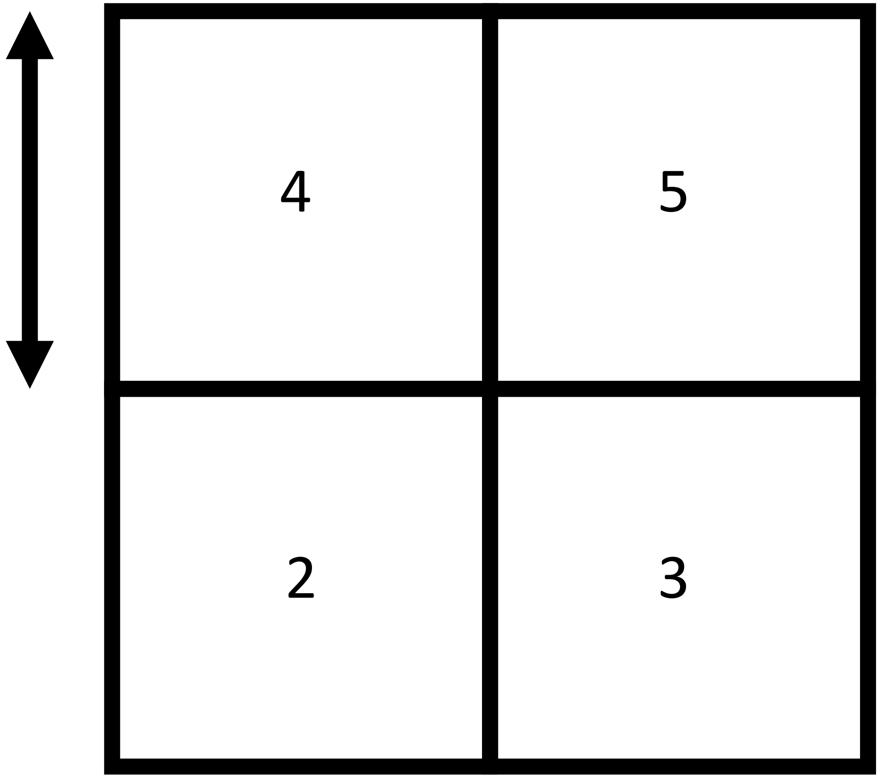
Raster data:

- Made of pixels regularly spaced (usually!)
- Pixels represent values (continuous) or classes (discrete)
- Possible to work at multiple spatial resolutions
  (e.g. Leempoel et al 2015, Methods Ecol. Evol.)

“GeoTIFF”, “Esri Grid” and “ASCII Grid” are the most popular raster file types

https://gisgeography.com/gis-formats/

Spatial resolution of interpolated environmental data



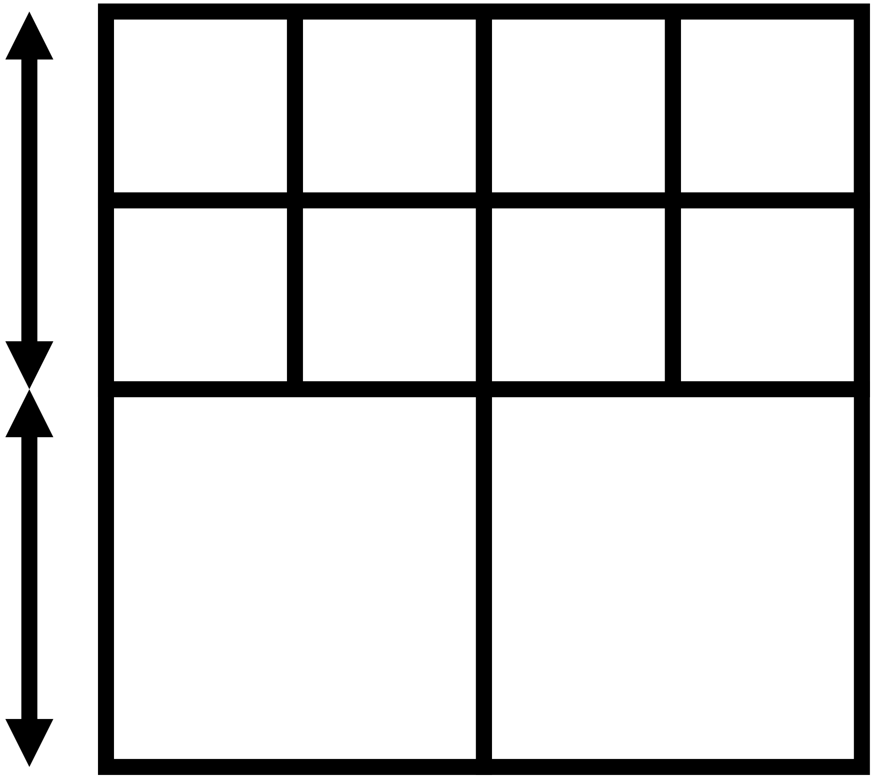
"Spatial resolution refers to the size of the smallest object that can be resolved on the ground. In a digital image, the resolution is limited by the pixel size, i.e. the smallest resolvable object cannot be smaller than the pixel size."

https://crisp.nus.edu.sg/

Spatial resolution of interpolated environmental data

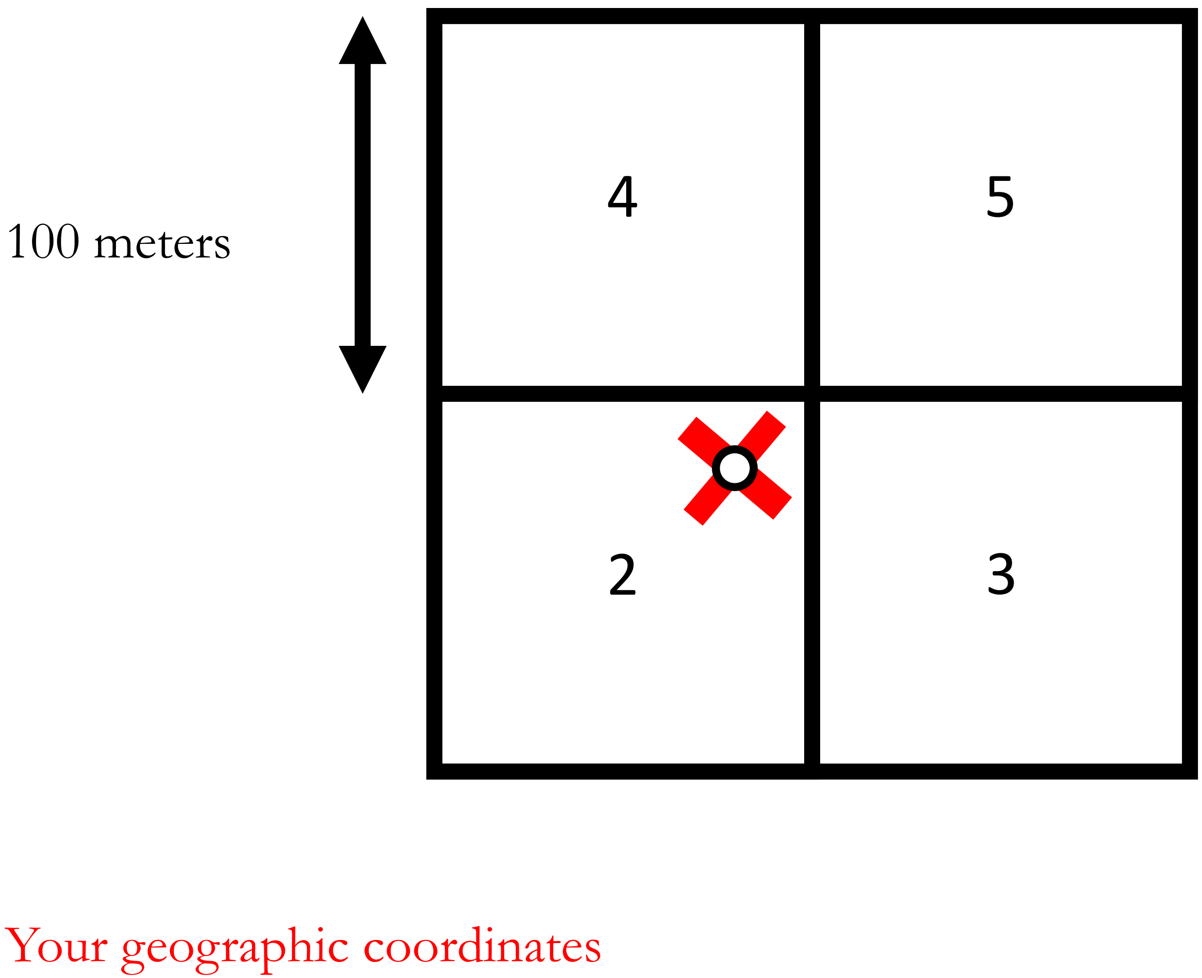
High resolution

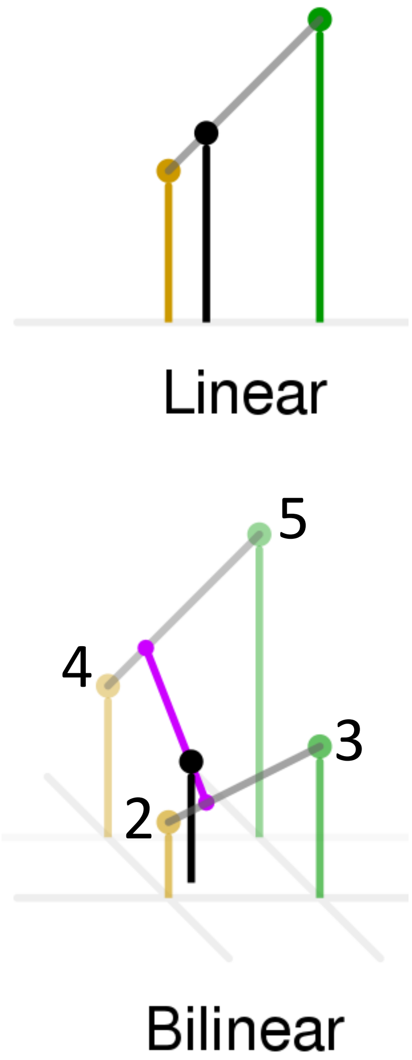
Low resolution



But the resolution does not inform about the accuracy of data !

The trick of data extraction with bilinear interpolation





Wikipedia 2020

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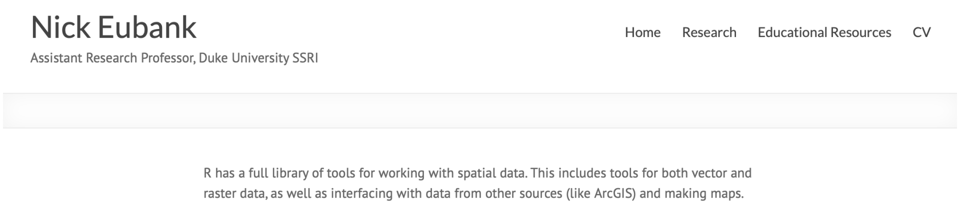
Software used to handle environmental data

- R packages: e.g. raster, sf, rgdal, maps…

- QGIS: https://www.qgis.org/en/site/
- SAGA: https://saga-gis.sourceforge.io/en/index.html
- ArcGIS: https://www.arcgis.com/index.html



https://www.nickeubank.com/gis-in-r/

http://132.72.155.230:3838/r/

GenTree EU project – *Fagus sylvatica* populations

https://www.gentree-h2020.eu

GENTREE

Optimizing the management and sustainable use of forest genetic resources in Europe

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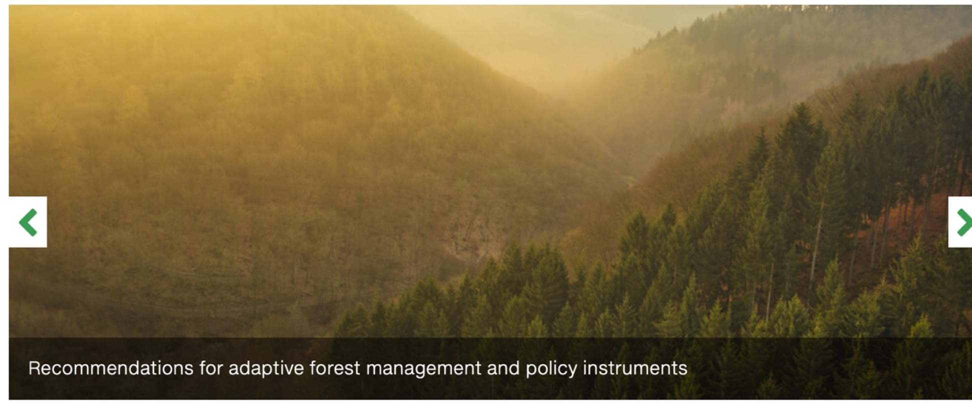
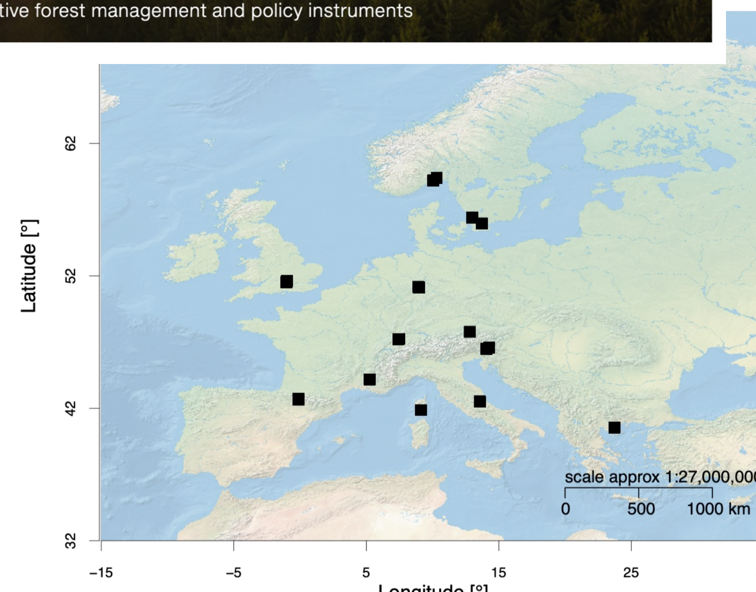
Horizon 2020
European Union Funding
for Research & Innovation





Genetic, environmental, phenotypic, dendrochronological, and leaf trait data of trees species across Europe

Exome capture sequencing:

- *Betula pendula* (silver birch)
- *Fagus sylvatica* (European beech)
- *Picea abies* (Norway spruce)
- *Pinus pinaster* (maritime pine)
- *Pinus sylvestris* (Scots pine)
- *Populus nigra* (European black poplar)
- *Quercus petraea*. (sessile oak)

➢ 18-24 populations; ~25 indiv./pop.

Single Primer Enrichment Technology genotyping:

- *Abies alba* (silver fir)
- *Pinus cembra* (Swiss stone pine)
- *Pinus halepensis* (Aleppo pine)
- *Pinus nigra* (European black pine)
- *Taxus baccata* (English yew)

➢ 10-14 populations; ~25 indiv./pop.

OXFORD (GIGA)^n SCIENCE

GigaScience, 10, 2021, 1–13

doi: 10.1093/gigascience/giab010
DATA NOTE

DATA NOTE

The GenTree Platform: growth traits and tree-level environmental data in 12 European forest tree species

Lars Opgenoorth[1,2,*], Benjamin Dauphin[2], Raquel Benavides[3], Katrin Heer[1], Paraskevi Alizoti[4], Elisabet Martínez-Sancho[2], . . .

. . .

SCIENTIFIC DATA

OPEN

DATA DESCRIPTOR

The GenTree Dendroecological Collection, tree-ring and wood density data from seven tree species across Europe

Elisabet Martínez-Sancho *et al.*[#]

. . .

DATA PAPER

Global Ecology and Biogeography · WILEY

The GenTree Leaf Collection: Inter- and intraspecific leaf variation in seven forest tree species in Europe

Raquel Benavides[1] | Bárbara Carvalho[1] | Cristina C. Bastias[1,2] | David López-Quiroga[1] | Antonio Mas[1] | Stephen Cavers[3] | Alan Gray[3] |

. . .

Tutorial and online resources – GitHub project

1. Get a background map and project it

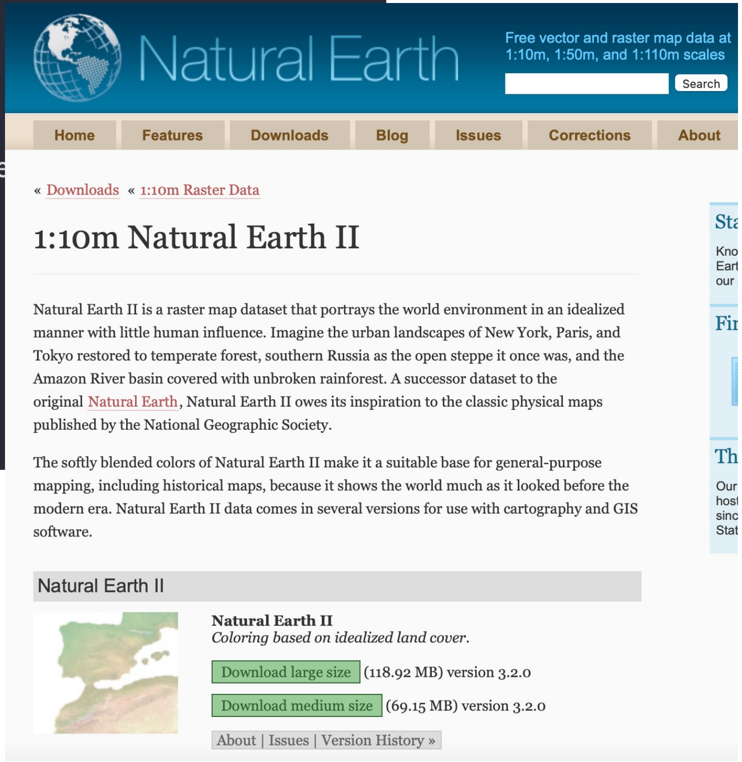
```
# Download manually the raster layer and paste the zip file into the dat/ folder
browseURL("http://www.naturalearthdata.com/downloads/10m-raster-data/10m-natural-earth-2/",
          browser=getOption("browser"), encodeIfNeeded=F)
unzip(zipfile=paste(path2,"NE2_LR_LC.zip",sep=""), exdir=paste(path2,"NE2_LR_LC",sep=""))

# Load it
back.map <- stack(paste(path2,"NE2_LR_LC/NE2_LR_LC.tif",sep=""))

# Define geographic coordinate system
browseURL("https://epsg.io", browser=getOption("browser"), encodeIfNe
crs(back.map) <- CRS("+init=EPSG:4326")

# Global map
plotRGB(back.map, axes=F)

# Europe map
plotRGB(back.map, ext=eu.extent, axes=F)
```



Tutorial and online resources – GitHub project

2. Get occurrence data and species range

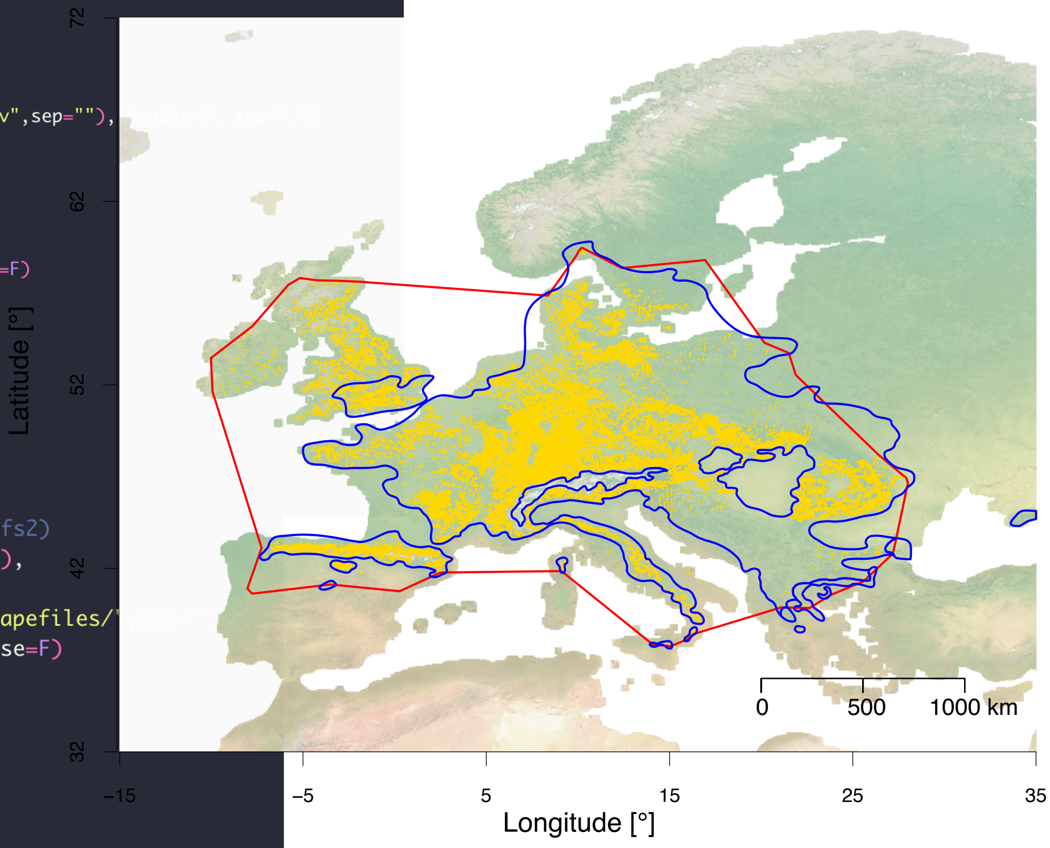
```r
# Download manually tree occurrences and extent (shapefile) and paste it into the dat/ folder
browseURL("https://figshare.com/collections/A_high-resolution_pan-European_tree_occurrence_dataset/3288407/1",
          browser=getOption("browser"), encodeIfNeeded=F)

# Download manually tree species range (shapefile) and paste it into the dat/ folder
browseURL("https://www.euforgen.org/species/fagus-sylvatica/",
          browser=getOption("browser"), encodeIfNeeded=F)

# Load tree occurrence data
occ <- read.table(paste(path2,"EUForestTreeOccurrences/EUForestspecies.csv",sep=""), header=T, sep=",")
occ.fs <- data.frame(occ[occ$SPECIES.NAME=="Fagus sylvatica",])
head(occ.fs); dim(occ.fs)
plot(occ.fs$X, occ.fs$Y, cex=0.2)

# Transform coordinates from ETRS89 to WGS84
browseURL("https://epsg.io", browser=getOption("browser"), encodeIfNeeded=F)
d <- data.frame(lon=occ.fs$X, lat=occ.fs$Y)
coordinates(d) <- c("lon", "lat")
proj4string(d) <- CRS("+init=epsg:3035") # ETRS89 / ETRS-LAEA
CRS.new <- CRS("+init=epsg:4326") # WGS84
d.wgs84 <- spTransform(d, CRS.new)
str(d.wgs84)
cd <- data.frame(d.wgs84@coords)
occ.fs$lonwgs84 <- cd$lon
occ.fs$latwgs84 <- cd$lat
# Load the species' occurrence (rg.fs1) and natural range (rg.fs2)
rg.fs1 <- readOGR(dsn=paste(path2,"EUForestTreeRanges/",sep=""),
                  layer="Fagus_sylvatica", verbose=F)
rg.fs2 <- readOGR(dsn=paste(path2,"FsylSpeciesRangeEuforgen/shapefiles/",sep=""
                  layer="Fagus_sylvatica_sylvatica_plg", verbose=F)
crs(rg.fs1) <- CRS('+init=EPSG:4326')
crs(rg.fs2) <- CRS('+init=EPSG:4326')
rg.fs1 <- raster::crop(rg.fs1, eu.extent)
rg.fs2 <- raster::crop(rg.fs2, eu.extent)

# Visualise occurrence data and species' natural range
pdf(paste(path1,"FS_OccurrencesAndRange.pdf",sep=""), width=7.5, height=6.15)
par(mfrow=c(1,1), oma=c(4,4,0.5,0.5), mai=c(0,0,0,0), mar=c(0,0,0,0), mgp=c(0,1,0))
```



Tutorial and online resources – GitHub project

3. Download environmental data

```
# Climate -- download rasters from CHELSA
browseURL("https://chelsa-climate.org/downloads/",
          browser=getOption("browser"), encodeIfNeeded=F)
getOption("timeout") # check the time out setting
options(timeout=1000) # set a longer time if needed
for(i in 1:length(bio.nb1)){⟺} # download climatic layers

download.file("https://chelsa-climate.org/wp-admin/download-page/CHELSA_tech_specification_V2.pdf",
              paste(path3,"CHELSA/CHELSA_tech_specification_V2.pdf",sep="")) # download the documentation too

# Topography -- download raster from GMTED2010
browseURL("https://topotools.cr.usgs.gov/gmted_viewer/gmted2010_global_grids.php",
          browser=getOption("browser"), encodeIfNeeded=F)
download.file("https://edcintl.cr.usgs.gov/downloads/sciweb1/shared/topo/downloads/GMTED/Grid_ZipFiles/mn30_grd.zip",
              paste(path2,"mn30_grd.zip",sep=""))
unzip(zipfile=paste(path2,"mn30_grd.zip",sep=""), exdir=paste(path2,"mn30_grd",sep=""))

# Soil -- download rasters from ISRIC
browseURL("https://data.isric.org/geonetwork/srv/eng/catalog.search#/metadata/2fdf1a33-487f-4aa7-a6b6-b2b49483ad48",
          browser=getOption("browser"), encodeIfNeeded=F)
download.file("https://files.isric.org/soilgrids/latest/data_aggregated/1000m/phh2o/phh2o_5-15cm_mean_1000.tif",
              paste(path2,"SoilGrid/phh2o_5-15cm_mean_1000.tif",sep=""))
download.file("https://files.isric.org/soilgrids/latest/data_aggregated/1000m/phh2o/phh2o_60-100cm_mean_1000.tif",
              paste(path2,"SoilGrid/phh2o_60-100cm_mean_1000.tif",sep=""))
```

Tutorial and online resources – GitHub project

4. Extract environmental data from occurrences

```
#### Extract environmental data from occurrences ####
head(occ.fs); dim(occ.fs)
env.fs <- occ.fs
for(i in 1:length(bio.nb2)){⟺}

gmted <- raster::raster(paste(path2, "mn30_grd/mn30_grd/w001000.adf", sep=""))
env.fs$gmted <- raster::extract(gmted, env.fs[, c("lonwgs84","latwgs84")], "bilinear")

pH.top <- raster::raster(paste(path2, "SoilGrid/phh2o_5-15cm_mean_1000.tif", sep="")) # ISRIC layers
pH.top <- projectRaster(pH.top, crs=CRS("+init=EPSG:4326"))
raster::plot(pH.top)
env.fs$pH.top <- raster::extract(pH.top, env.fs[, c("lonwgs84","latwgs84")], "bilinear") / 10
pH.dee <- raster::raster(paste(path2, "SoilGrid/phh2o_60-100cm_mean_1000.tif", sep="")) # ISRIC laye
pH.dee <- projectRaster(pH.dee, crs=CRS("+init=EPSG:4326"))
raster::plot(pH.dee)
env.fs$pH.dee <- raster::extract(pH.dee, env.fs[, c("lonwgs84","latwgs84")], "bilinear") / 10

head(env.fs)
env.fs <- env.fs[,-c(3:10)]
write.table(env.fs, paste(path1, "FS_OccurrencesEnvDatExtracted.csv", sep=""),
            row.names=F, col.names=T, quote=F, sep=";") # save table with extracted environmental da
```

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5. Crop layers for EU extent

6. Visualise environmental data / explore ecological gradients

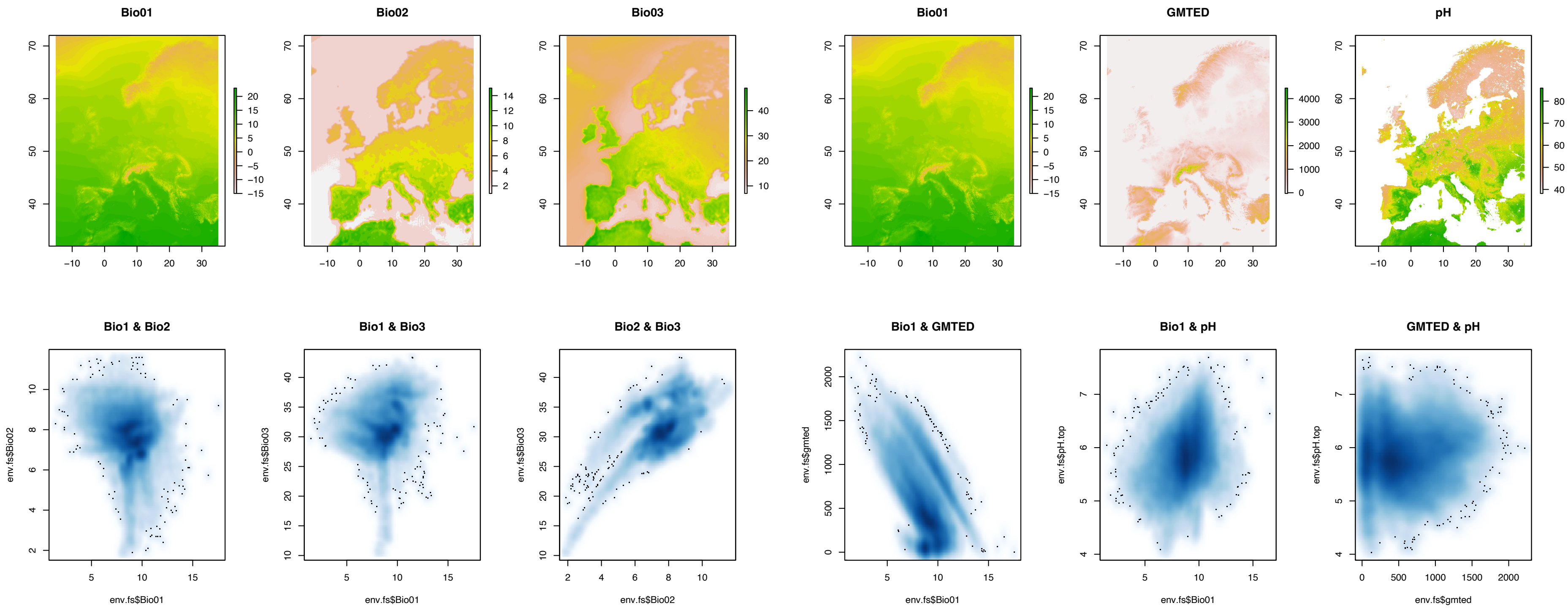
```
#### Crop layers for EU extent ####
bio01.c <- crop(bio01, eu.extent)
bio02.c <- crop(bio02, eu.extent)
bio03.c <- crop(bio03, eu.extent)
gmted.c <- crop(gmted, eu.extent)
pH.top.c <- crop(pH.top, eu.extent)
pH.dee.c <- crop(pH.dee, eu.extent)

#### Visualise environmental data and explore ecological gradients ####
pdf(paste(path1,"FS_OccurrencesEnvDatExtracted1.pdf",sep=""), width=7.5*1.2, height=6.15*1.2)
par(mfrow=c(2,3))
plot(bio01.c, main=paste("Bio",bio.nb2[1],sep=""), alpha=150)
plot(bio02.c, main=paste("Bio",bio.nb2[2],sep=""), alpha=150)
plot(bio03.c, main=paste("Bio",bio.nb2[3],sep=""), alpha=150)
smoothScatter(env.fs$Bio01, env.fs$Bio02, main="Bio1 & Bio2")
smoothScatter(env.fs$Bio01, env.fs$Bio03, main="Bio1 & Bio3")
smoothScatter(env.fs$Bio02, env.fs$Bio03, main="Bio2 & Bio3")
dev.off()

pdf(paste(path1,"FS_OccurrencesEnvDatExtracted2.pdf",sep=""), width=7.5*1.2, height=6.15*1.2)
par(mfrow=c(2,3))
plot(bio01.c, main=paste("Bio",bio.nb2[1],sep=""), alpha=150)
plot(gmted.c, main=paste("GMTED",sep=""), alpha=150)
plot(pH.top.c, main=paste("pH",sep=""), alpha=150)
smoothScatter(env.fs$Bio01, env.fs$gmted, main="Bio1 & GMTED")
smoothScatter(env.fs$Bio01, env.fs$pH.top, main="Bio1 & pH")
smoothScatter(env.fs$gmted, env.fs$pH.top, main="GMTED & pH")
dev.off()
```

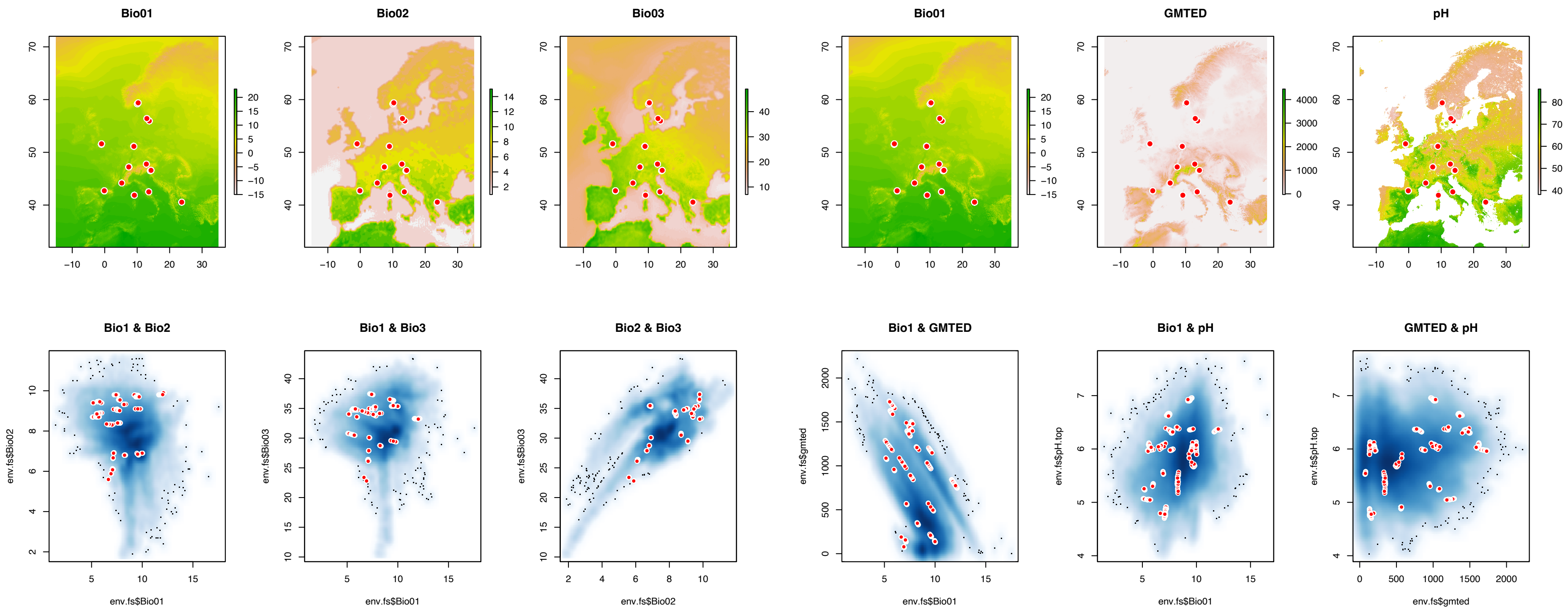
Tutorial and online resources – GitHub project

6. Visualise environmental data / explore ecological gradients



Tutorial and online resources – GitHub project

7. Sampling locations, data extraction and visualisation



Outline

I. General introduction

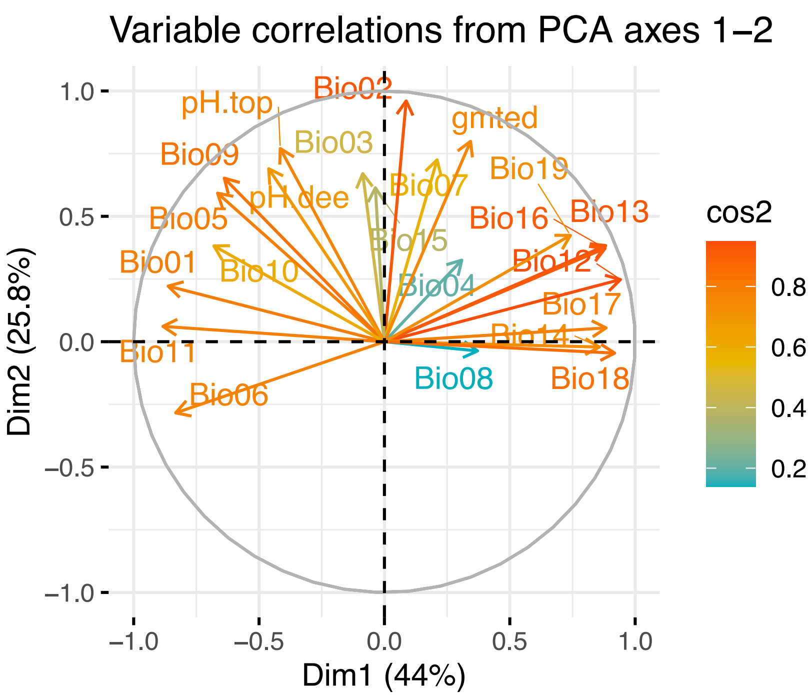
II. A brief portray of environmental data

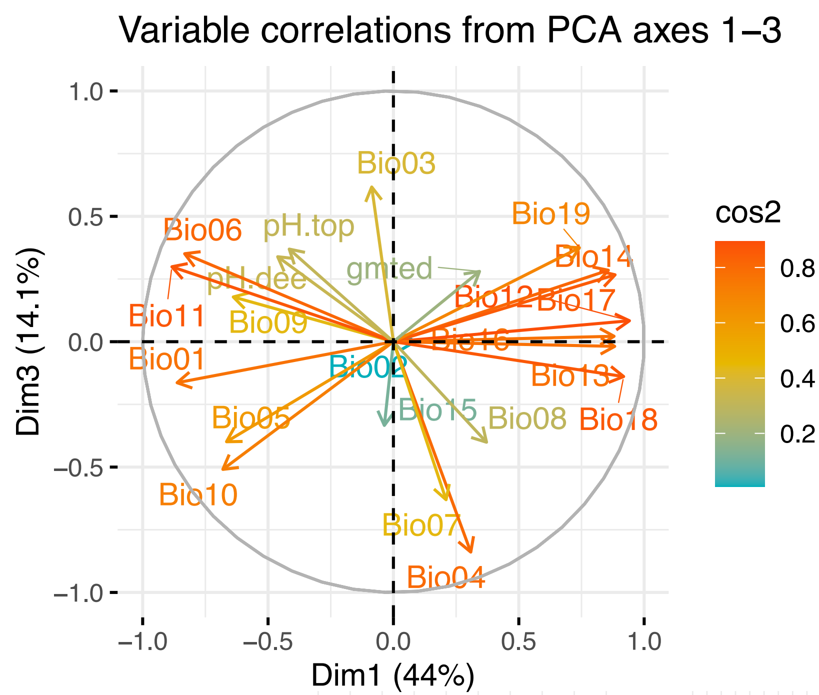
III. A short tutorial on how to handle environmental data in R

IV. Reduction of environmental variables

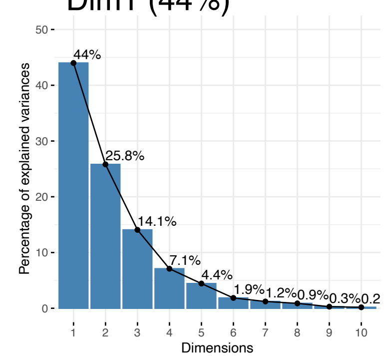
Tutorial and online resources – GitHub project

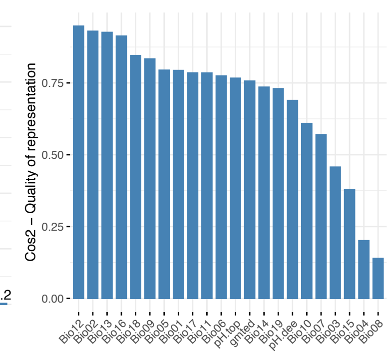
8. PCA of environmental data at the sampling locations





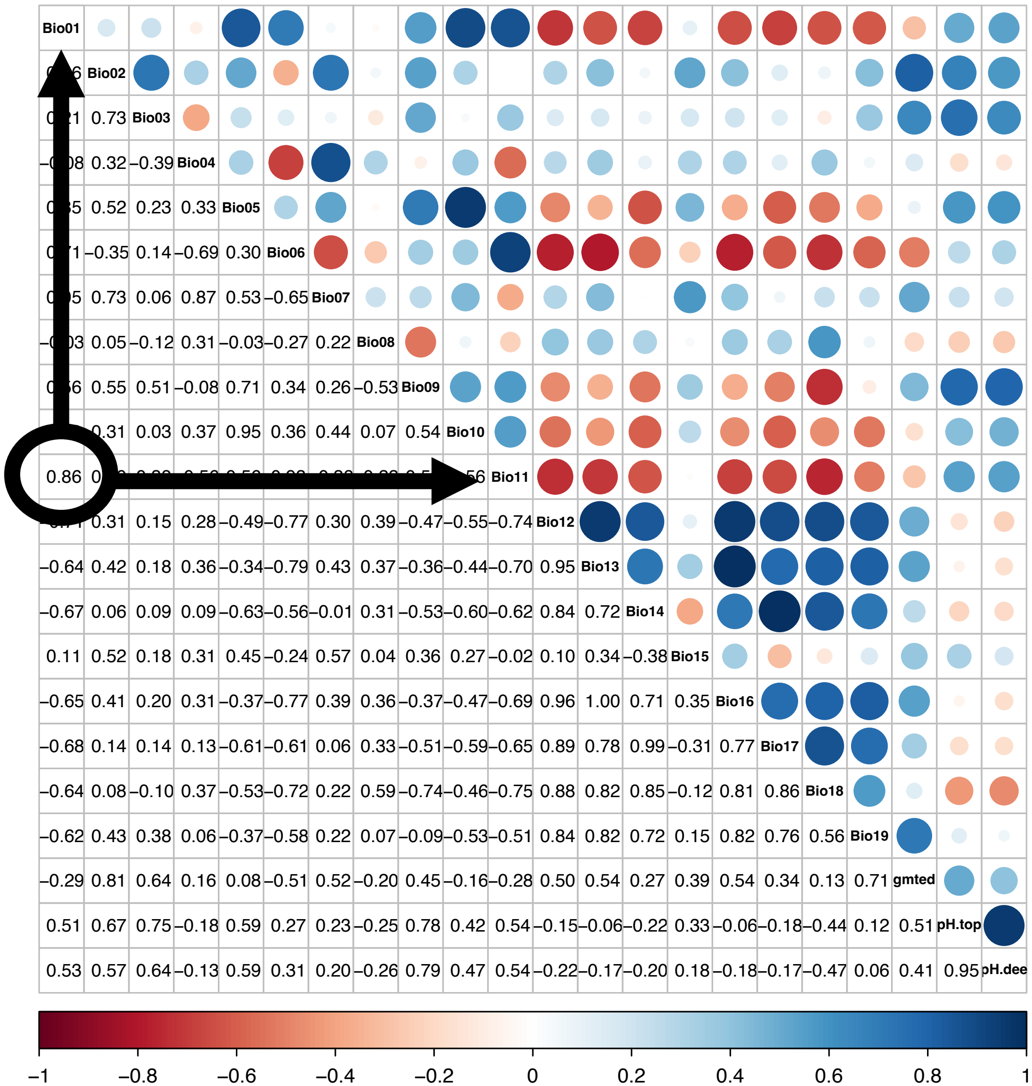
Use principal components as predictors





Tutorial and online resources – GitHub project

9. Correlation plot of environmental data
10. Pearson correlation matrix of environmental data
9. Retain uncorrelated variables based on Pearson's coefficient



	Bio01	Bio04	Bio08	Bio12	Bio15	gmted	pH.top
Bio01		-0.077	-0.025	-0.711	0.106	-0.291	0.507
Bio04	-0.077		0.308	0.276	0.309	0.160	-0.178
Bio08	-0.025	0.308		0.394	0.037	-0.199	-0.246
Bio12	-0.711	0.276	0.394		0.104	0.496	-0.149
Bio15	0.106	0.309	0.037	0.104		0.389	0.330
gmted	-0.291	0.160	-0.199	0.496	0.389		0.507
pH.top	0.507	-0.178	-0.246	-0.149	0.330	0.507	

Bio1 = Annual Mean Temperature
Bio11 = Mean Temperature of Coldest Quarter

Take home message

- Question which environmental data are relevant for your study; measured, interpolated, biotic, abiotic…
- Explore environmental gradients from occurrence data before starting sampling
- Be careful with spatial resolution ≠ accuracy
- An environment variable depends on spatial and temporal scale
- Define the reference period fitting the selective pressures
- Always inspect variable interdependence
- Variable selection is also a way to improve predictive power of env. variables

Acknowledgements

Review manuscript:

Christian Rellstab
Rafael Wüest
Dirk Karger
Rolf Holderegger
Felix Gugerli1
Stéphanie Manel

UNIVERSITÉ DE MONTPELLIER

Many thanks to Thibaut and Olivier for organising SSMPG2022 !!

One and a half year post-doctoral research position on the landscape genomics of forest trees and their ectomycorrhizal fungi

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https://youtu.be/orh1pW_ynNU

WSL locations

Research focus on forest, landscape, biodiversity, natural hazards, and snow and ice.

‹ Menu

Biodiversity and Conservation Biology

- Biodiversity
- **Ecological Genetics**
- Conservation Biology
- Ecosystems Dynamics
- Spatial evolutionary ecology
- Evolutionary genetics
- Environmental Fluid Dynamics

Ecological Genetics

Head: **Dr. Martina Peter**

Identifying seed sources for highly adaptable oak forests in a changing climate

The international BiodivERsA project ACORN aims to identify oak populations capable to cope with future drought-stress due to climate change.

OAKID2

Transferability and phylogenetic extension of species-diagnostic SNP markers in European white oak species

GenWood

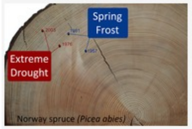
We link genomic and dendro-phenotypic data in Norway Spruce (Picea abies) to study the genomic basis of wood anatomy and assess the adaptive potential of forest trees under climate change.

BLACKDYNAMITE

This Swiss-Spanish project investigates the dynamics and competition of the black Périgord and Burgundy truffles under the influence of climate change.

Root endophytic fungi and their contribution to arctic and alpine climate change feedback

Arctic and Alpine vegetation dynamics under climate change can exert a lasting impact on belowground processes and ultimately on world's largest carbon stocks. This long-term field manipulation investigates the functional significance of plant interactions with species-specific endophytic fungi.



Adaptation of trees to extreme climate events

Extreme climate events are expected to become more frequent with climate warming. We test genetic differentiation in resistance to late frost and drought in silver fir populations planted in the 1980s in Switzerland and abroad.

Tool kit conservation genetics

Partners from the private and academic sector joined to set up a ready-to-use tool kit, which allows authorities and consultancies to apply conservation genetic methods in a standardized way in their everyday work.

Metalink

Soil contamination with heavy metals is a widespread problem affecting natural, cultivated, urban and industrial sites throughout Europe. The main objective in this Swiss/Polish collaboration project is to characterize the links between environmental, genotypic, and phenotypic features in the metal-tolerant plant model Arabidopsis halleri.

GenTree

GenTree aims at providing the European forestry sector with better knowledge, methods and tools for optimizing the management and sustainable use of forest genetic resources in Europe in the context of climate change and continuously evolving demands for forest products and services.

PiCadapt - Adaptive genetic variation of Swiss stone pine in response to environmental gradients across the Alpine timberline ecotone

PiCadapt aims to study gene-encoded nucleotide variation in the bird-dispersed P. cembra, a keystone tree species of the Alpine timberline ecotone, in response to environmental gradients.

GeneScale

GeneScale describes genomic variation in the Alpine rock-cress (Arabis alpina) and seeks indications of local adaptation to small-scale environmental conditions.