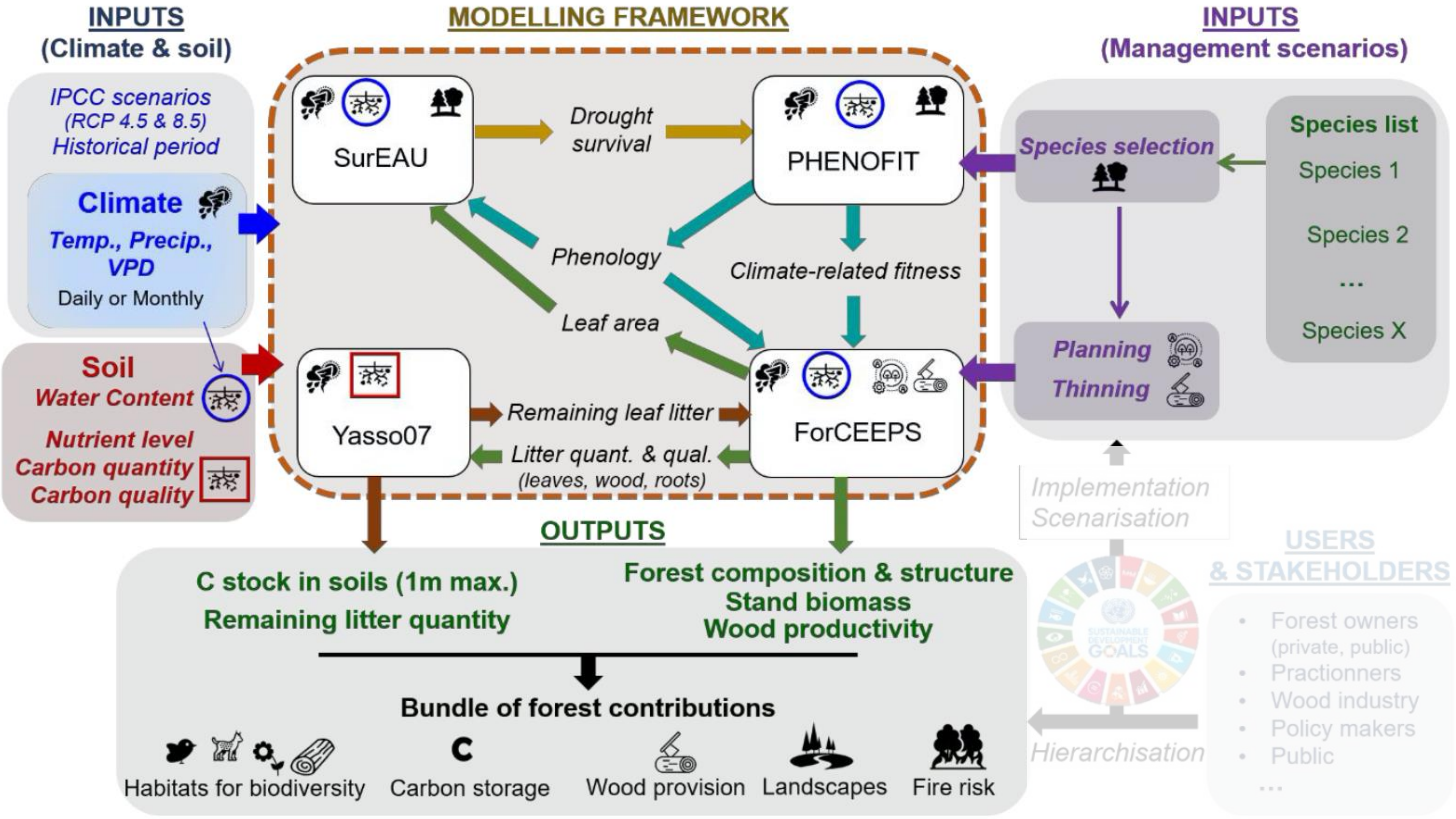
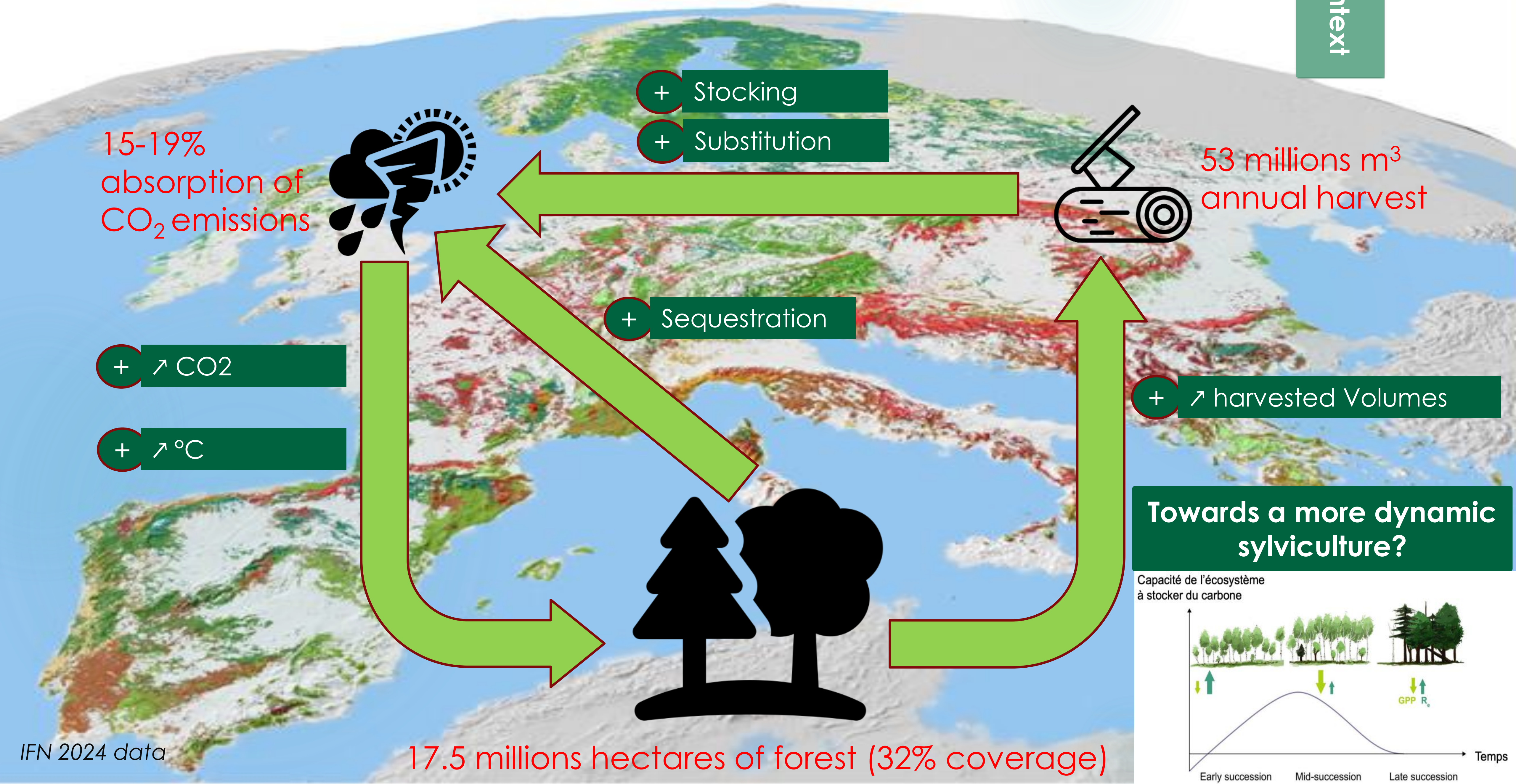
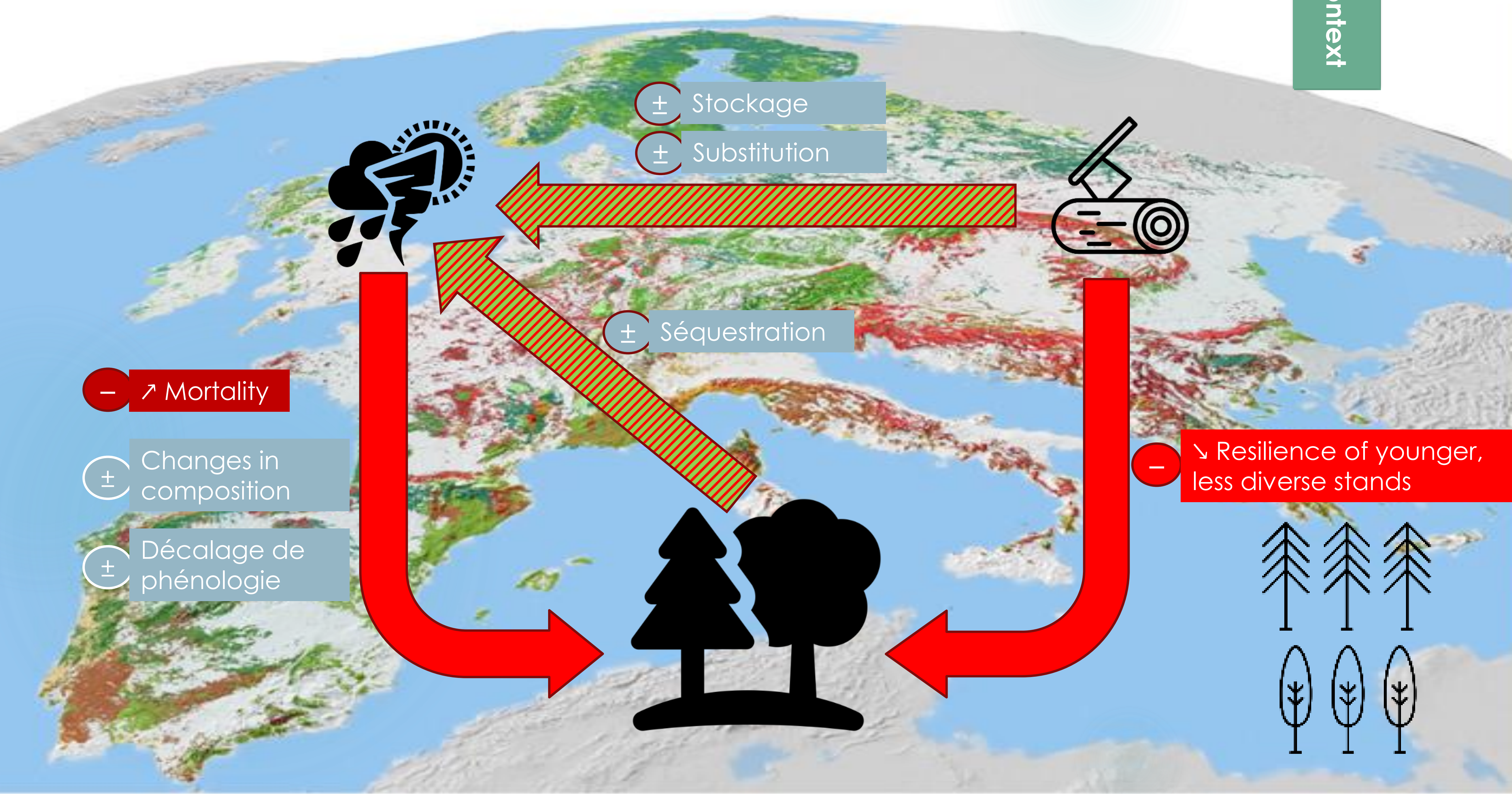

INPUTS
(Climate & soil)
MODELLING FRAMEWORK
INPUTS
(Management scenarios)
IPCC scenarios
(RCP 4.5 & 8.5)
Historical period
Climate
Temp., Precip., VPD
Daily or Monthly
Soil
Water Content
Nutrient level
Carbon quantity
Carbon quality
SurEAU
Drought survival
PHENOFIT
Phenology
Leaf area
Climate-related fitness
Yasso07
Remaining leaf litter
Litter quant. & qual.
(leaves, wood, roots)
ForCEEPS
Species selection
Species list
Species 1
Species 2
...
Species X
Planning
Thinning
Implementation
Scenarisation
OUTPUTS
C stock in soils (1m max.)
Remaining litter quantity
Forest composition & structure
Stand biomass
Wood productivity
Bundle of forest contributions
Habitats for biodiversity
Carbon storage
Wood provision
Landscapes
Fire risk
Hierarchisation
SUSTAINABLE DEVELOPMENT GOALS
USERS
& STAKEHOLDERS
Forest owners
(private, public)
Practionners
Wood industry
Policy makers
Public
...

Forests : a lever to attenuate climate change

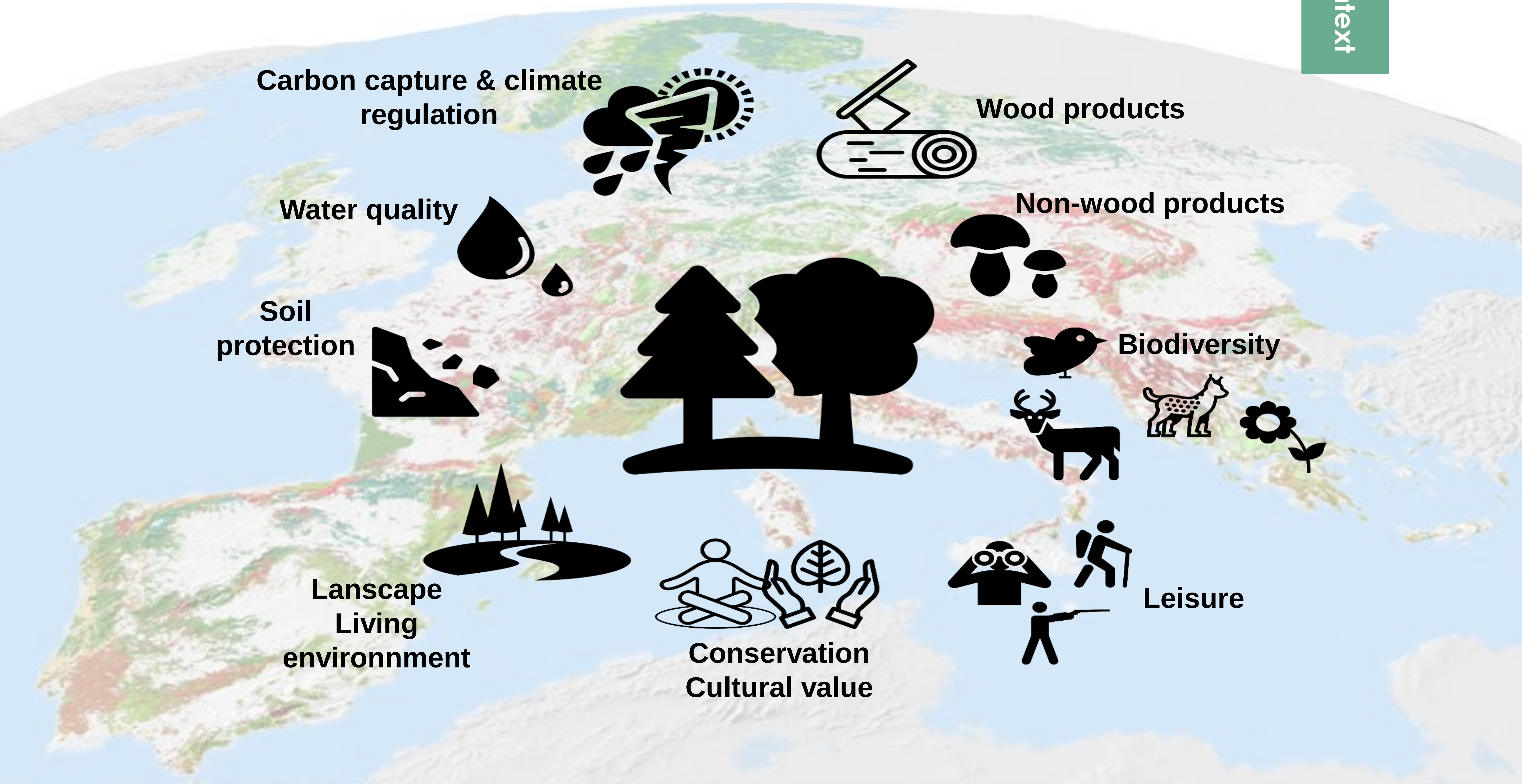
Context



Forests : vulnerability to climate change



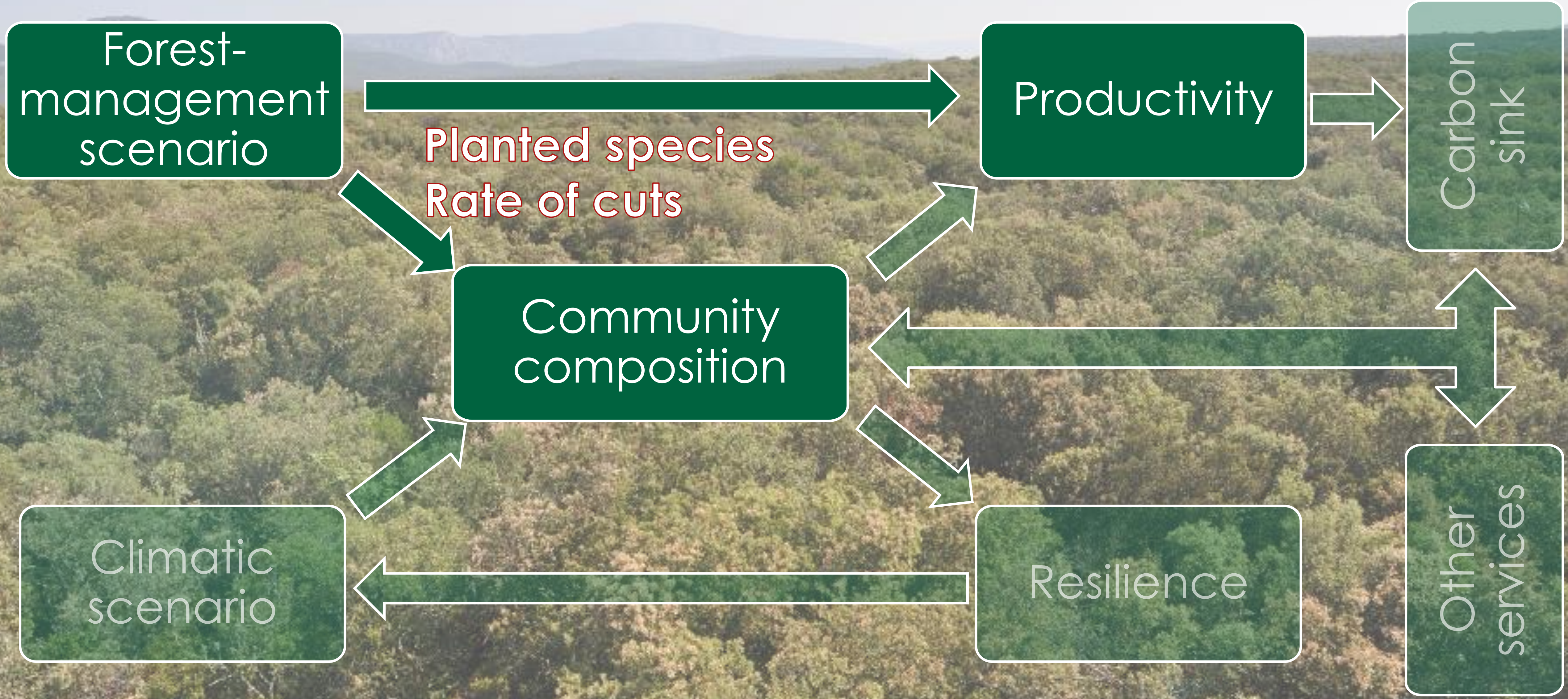
Forests : other services



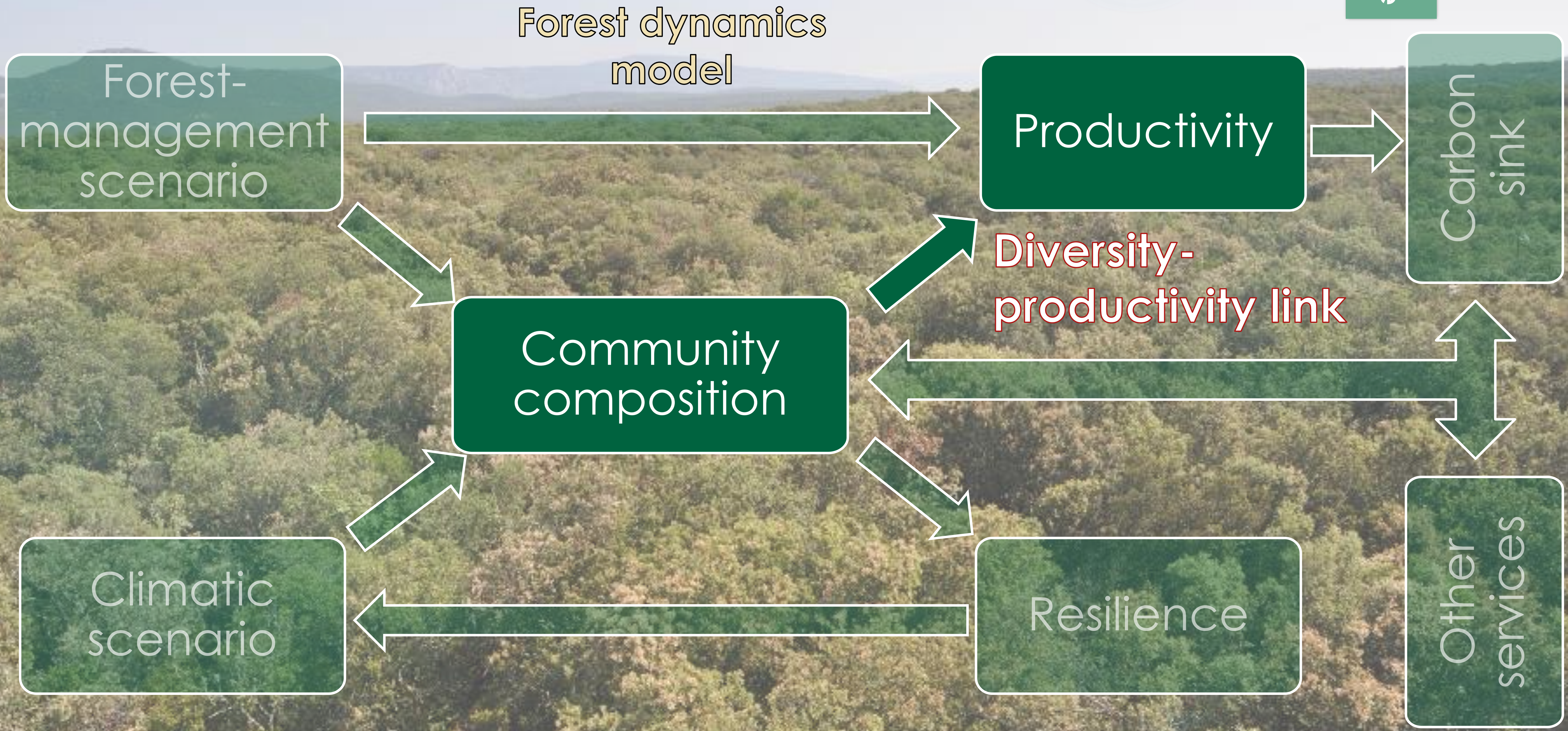
Complex, multifactorial interactions

Complex, multifactorial interactions

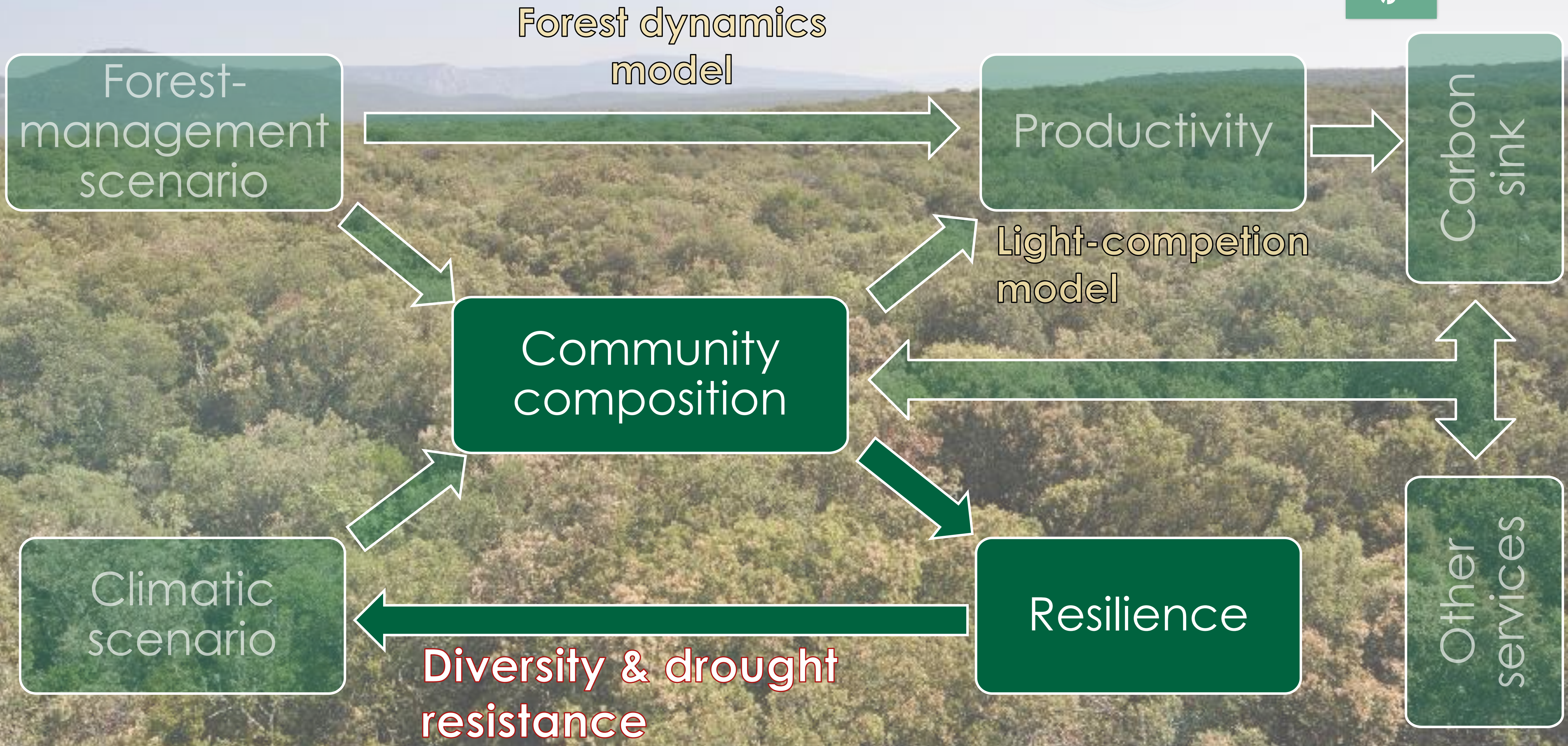
Context



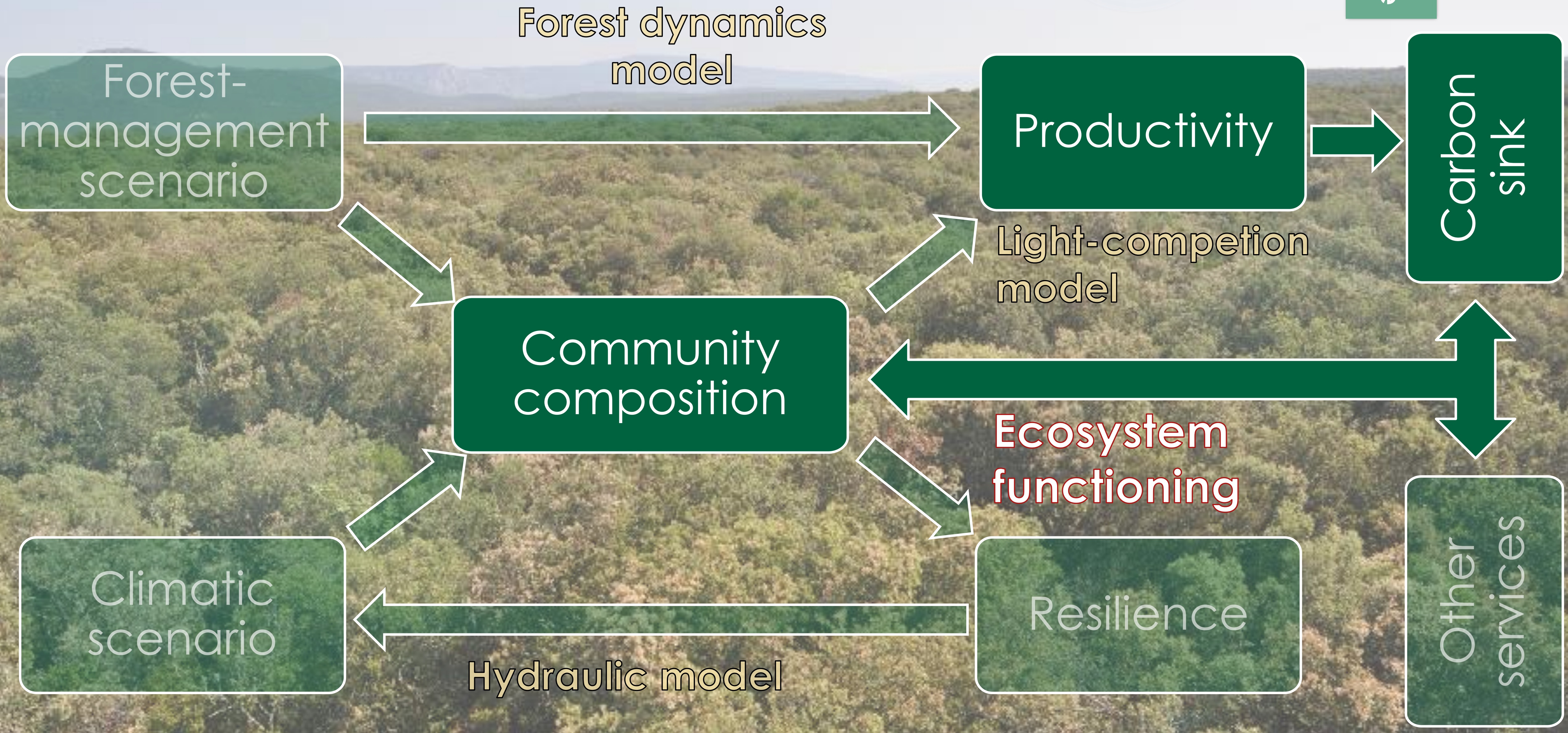
Complex, multifactorial interactions



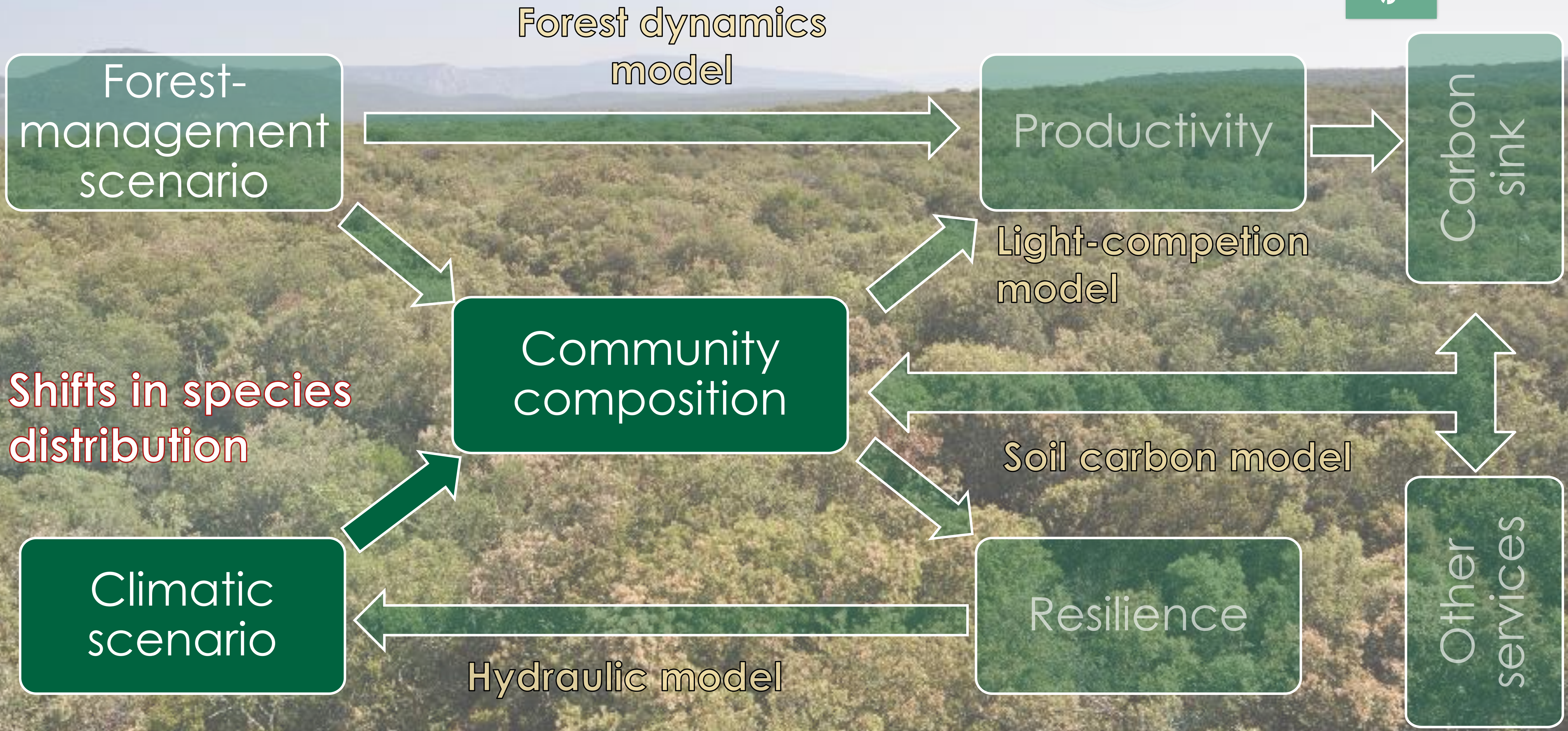
Complex, multifactorial interactions



Complex, multifactorial interactions

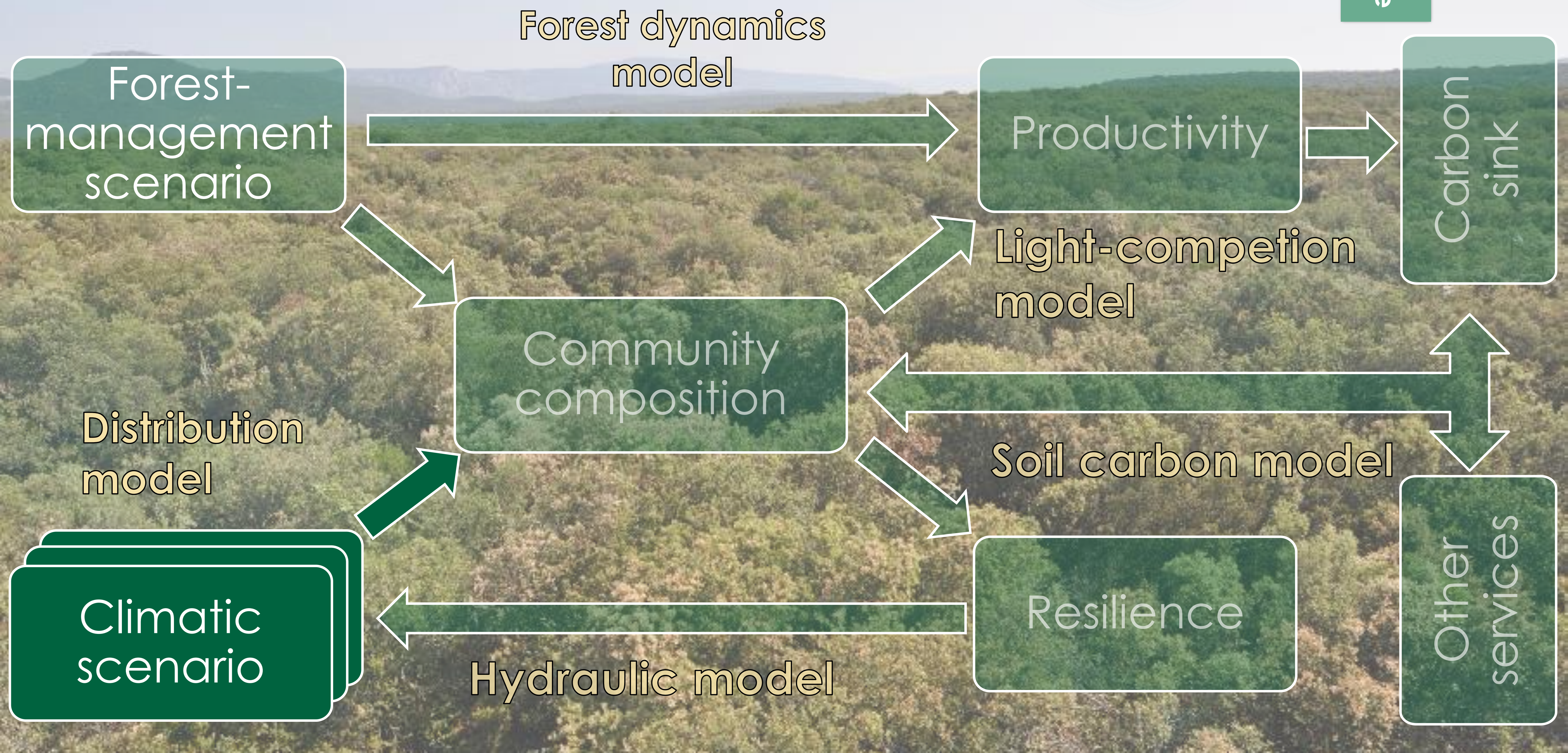


Complex, multifactorial interactions

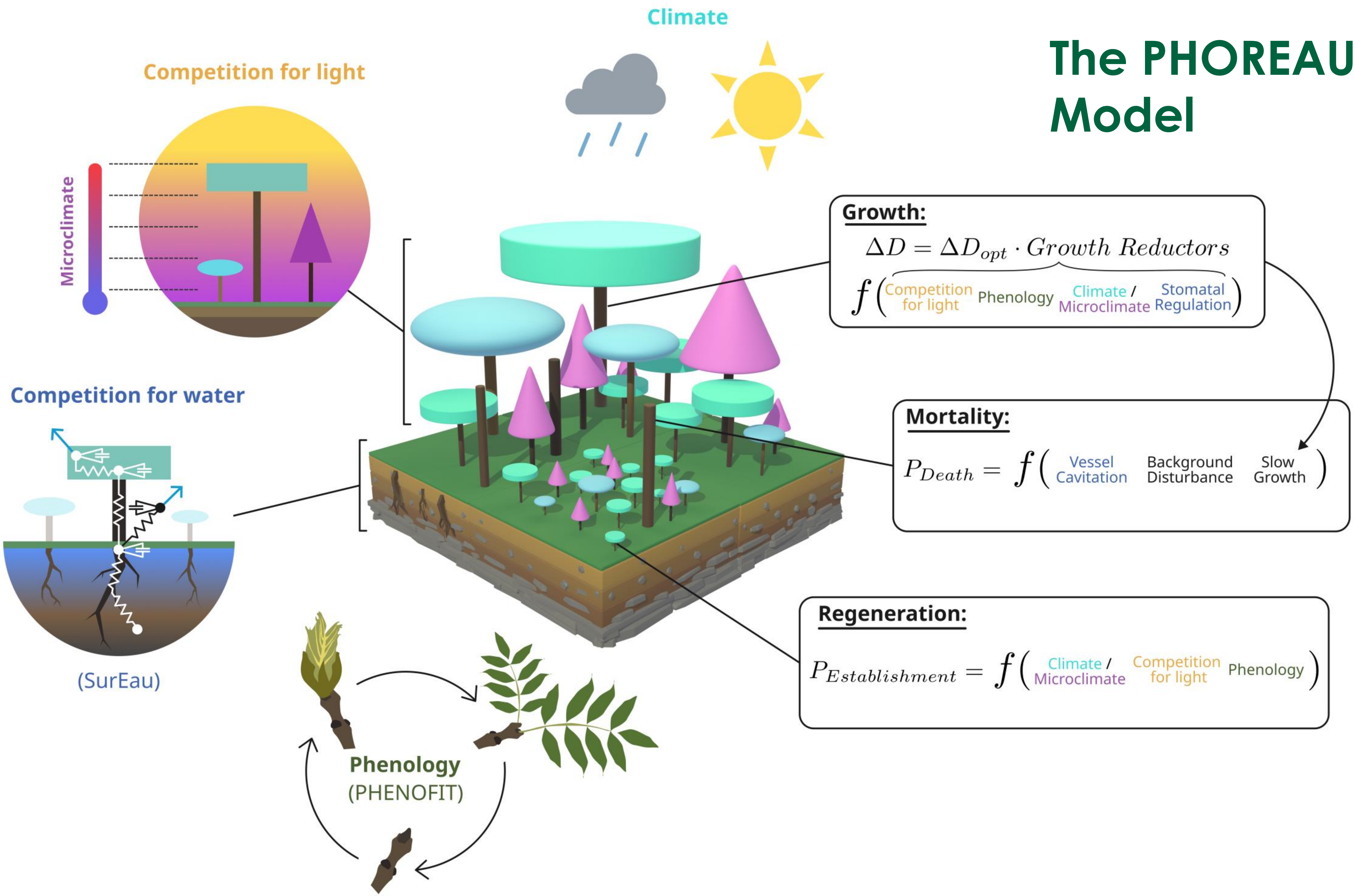


Complex, multifactorial interactions

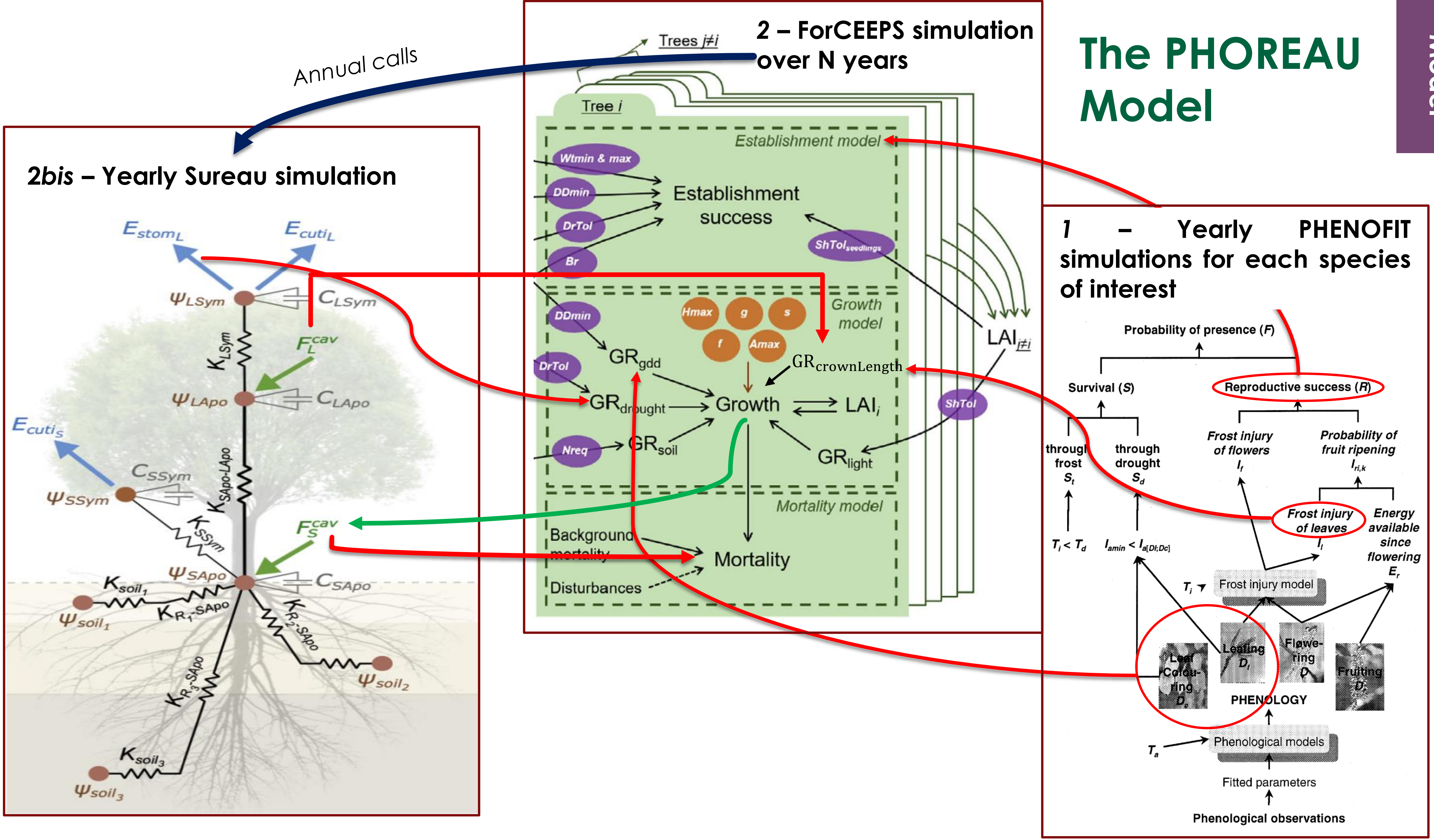
Contexte



The PHOREAU Model



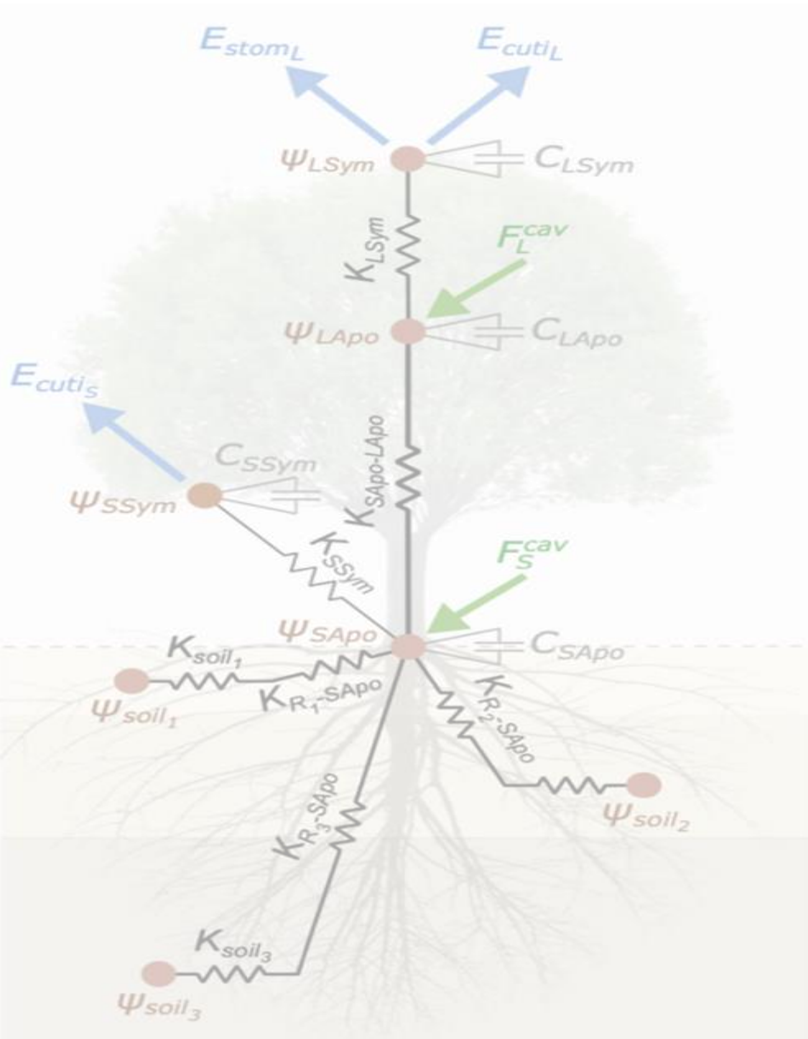
The PHOREAU Model



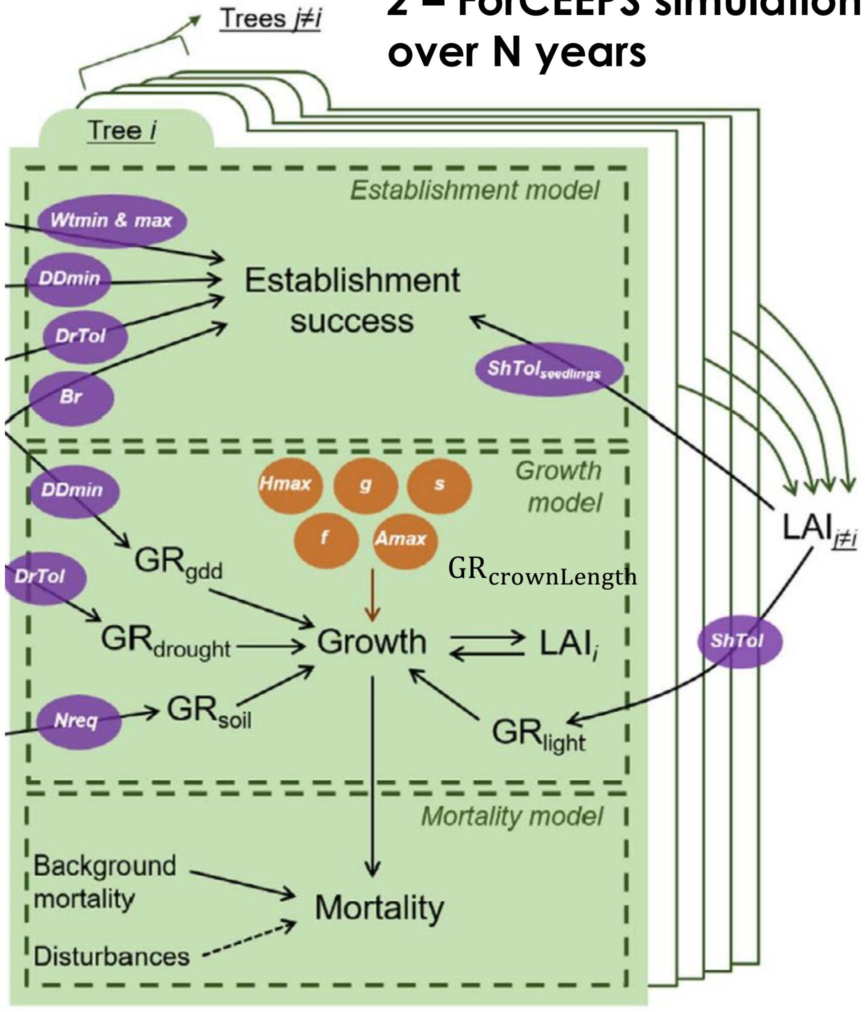
The PHOREAU Model

Model

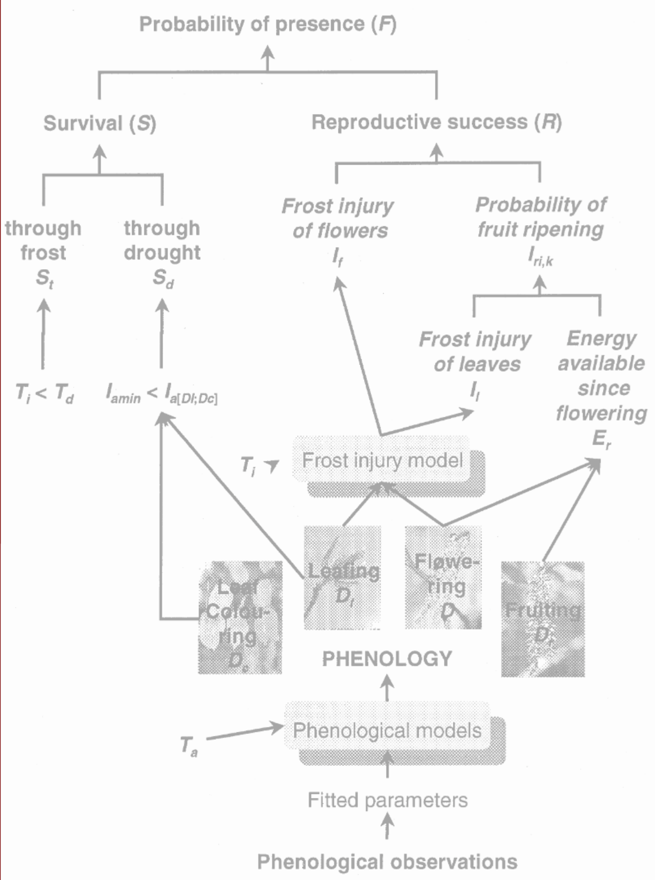
2bis – Yearly Sureau simulation



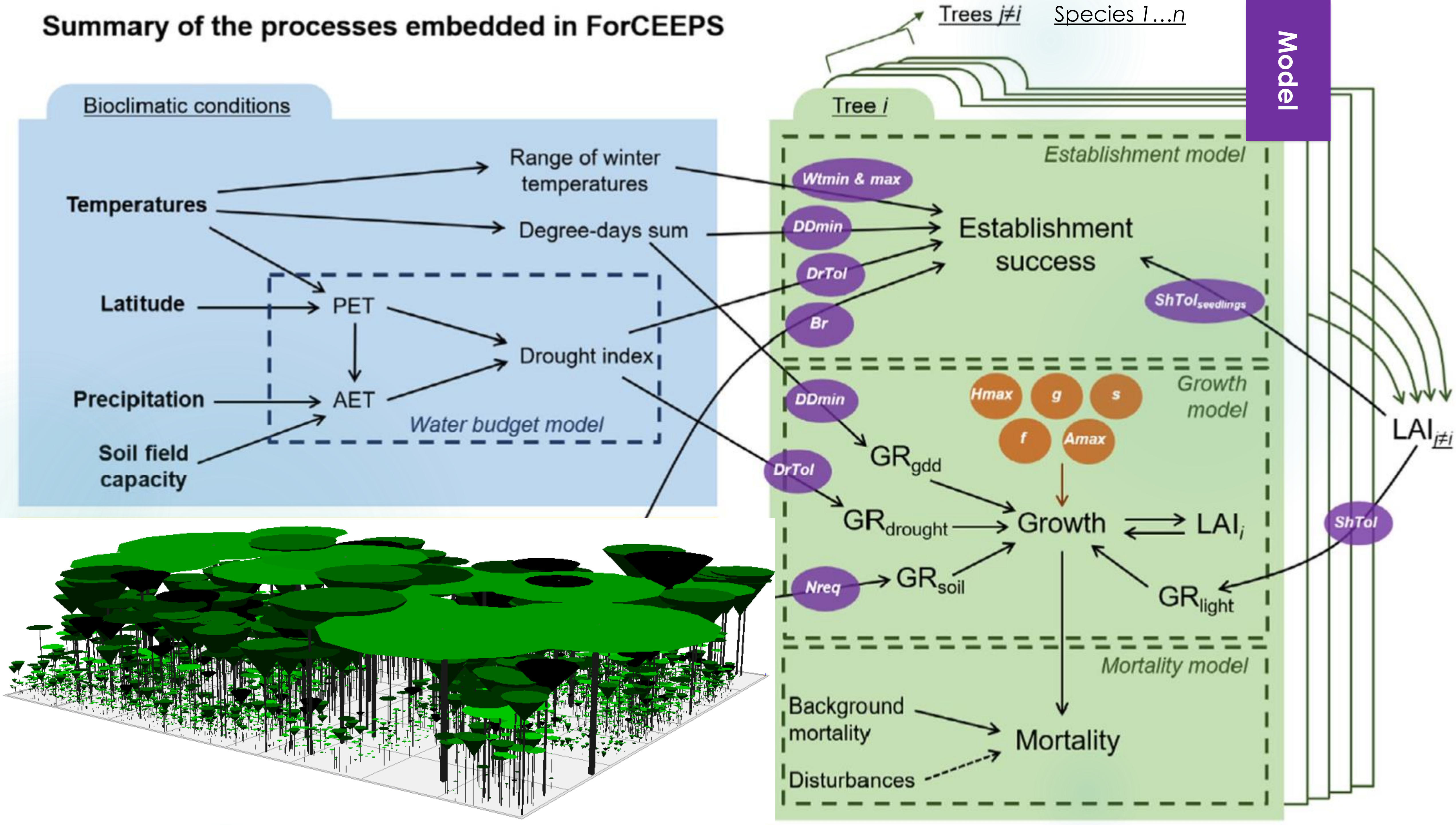
2 – ForCEEPS simulation over N years



1 – Yearly PHENOFIT simulations for each species of interest



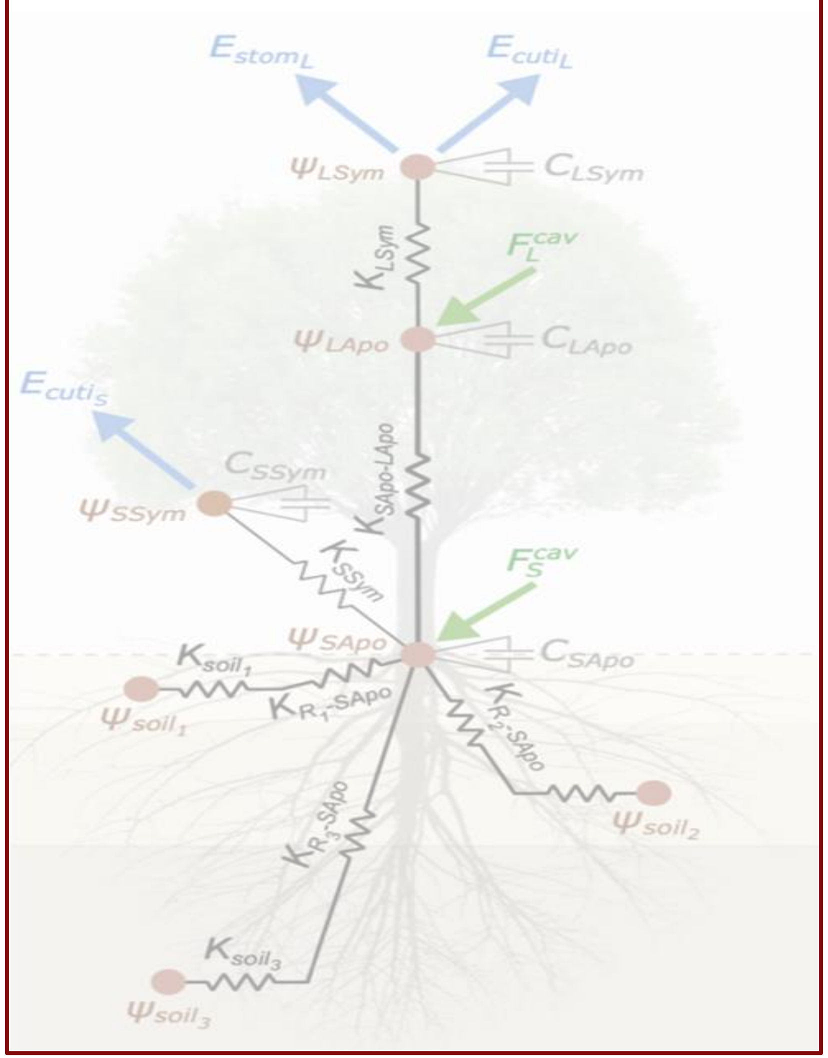
Summary of the processes embedded in ForCEEPS



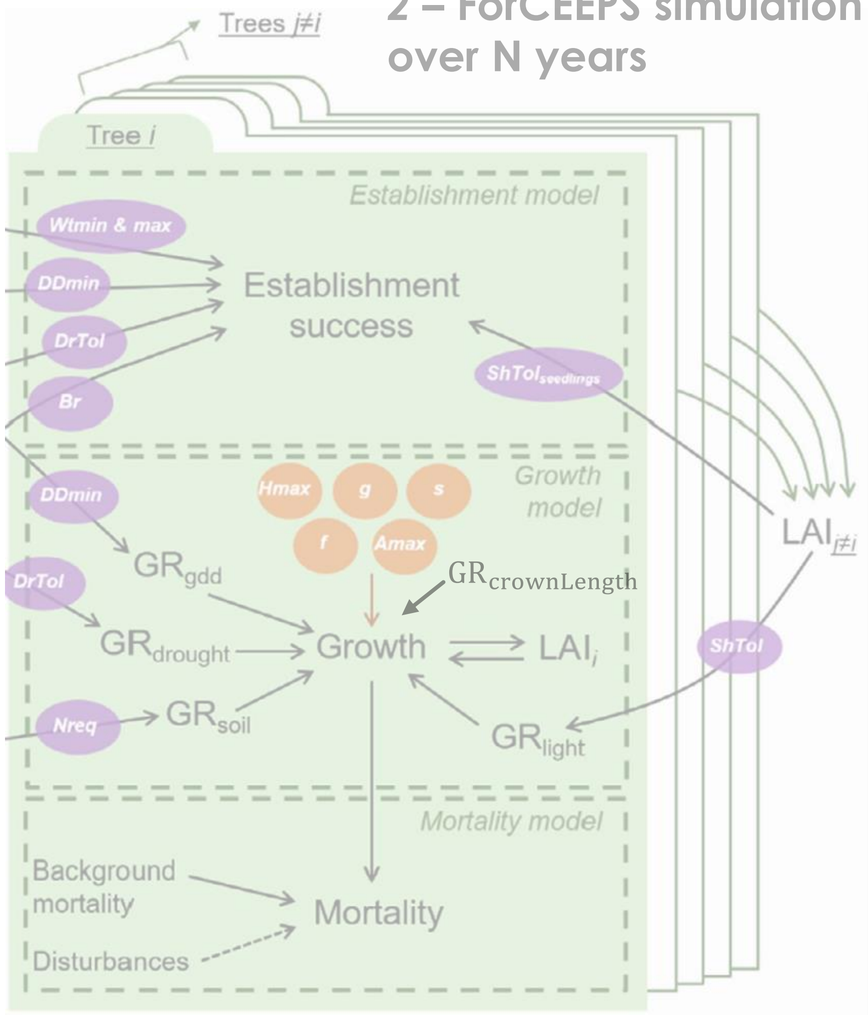
The PHOREAU Model

Model

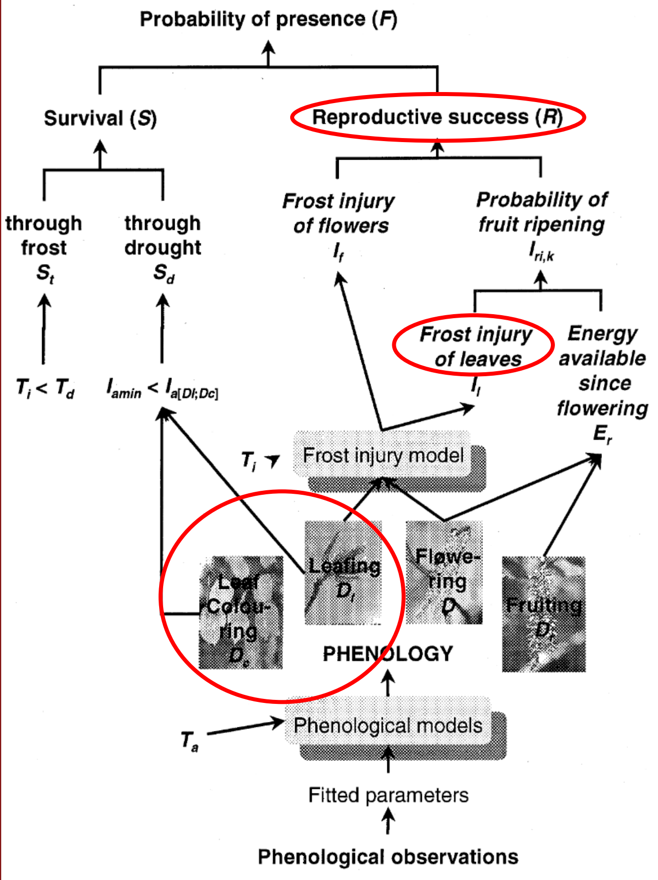
2bis – Yearly Sureau simulation



2 – ForCEEPS simulation over N years

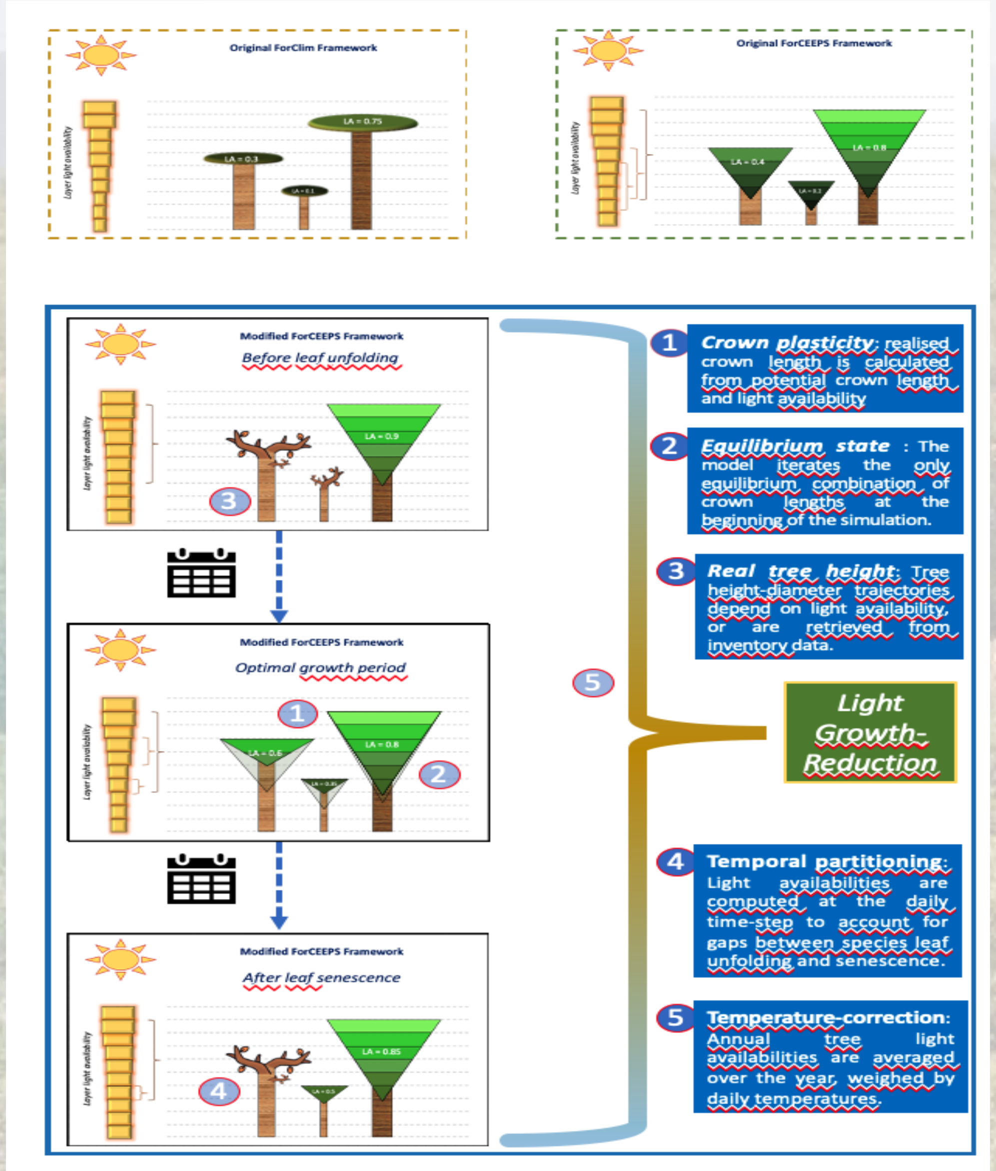


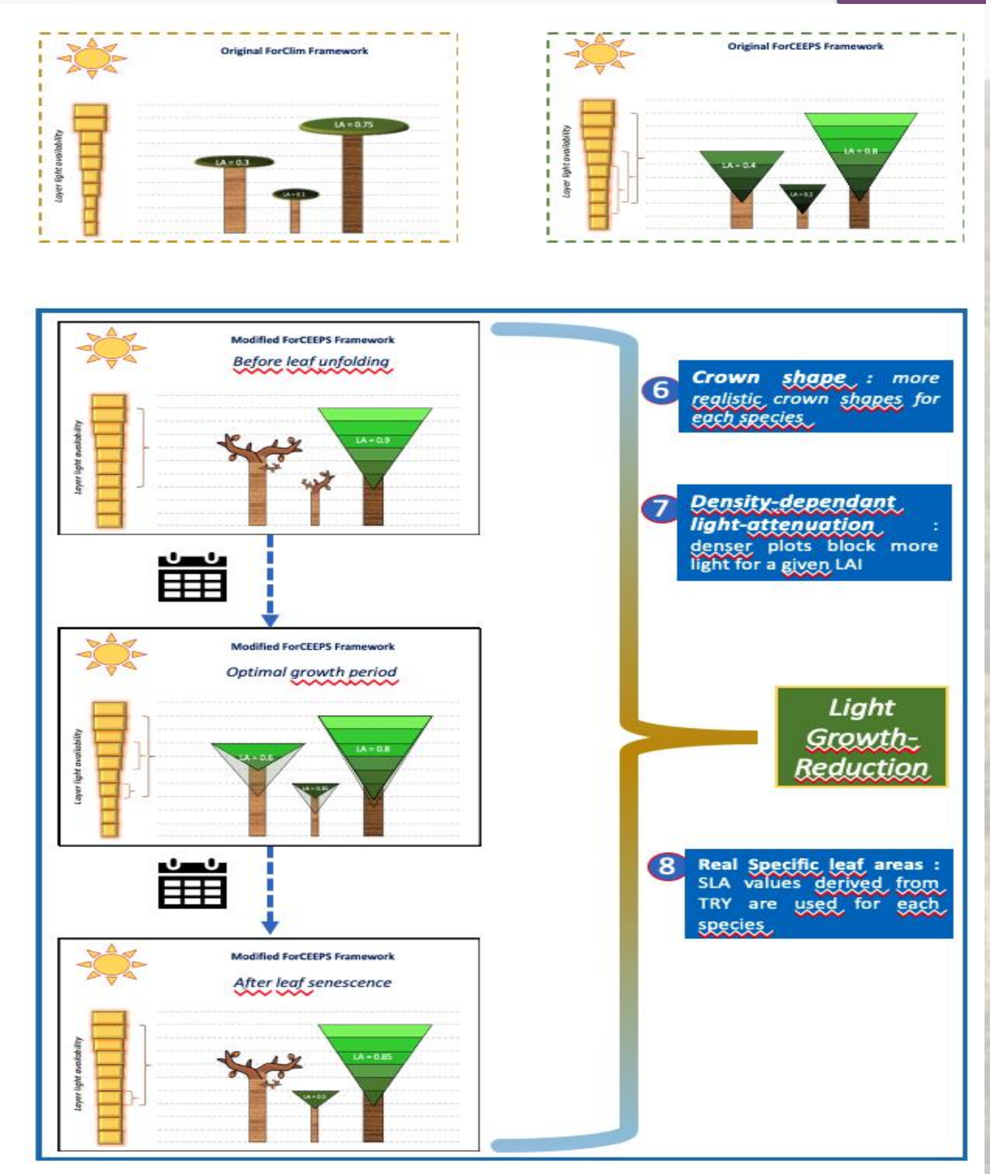
1 – Yearly PHENOFIT simulations for each species of interest



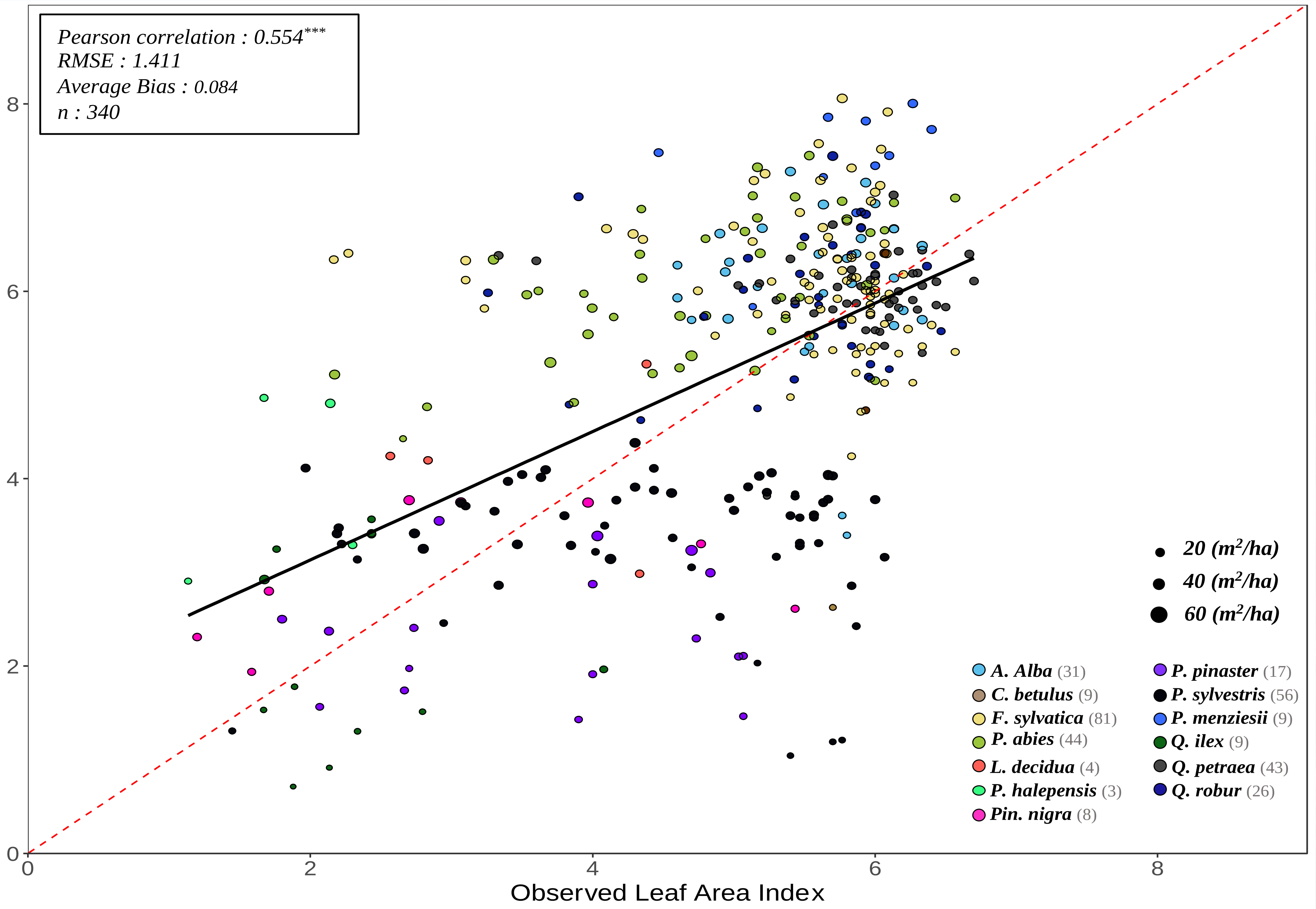
Competition for light module

Model





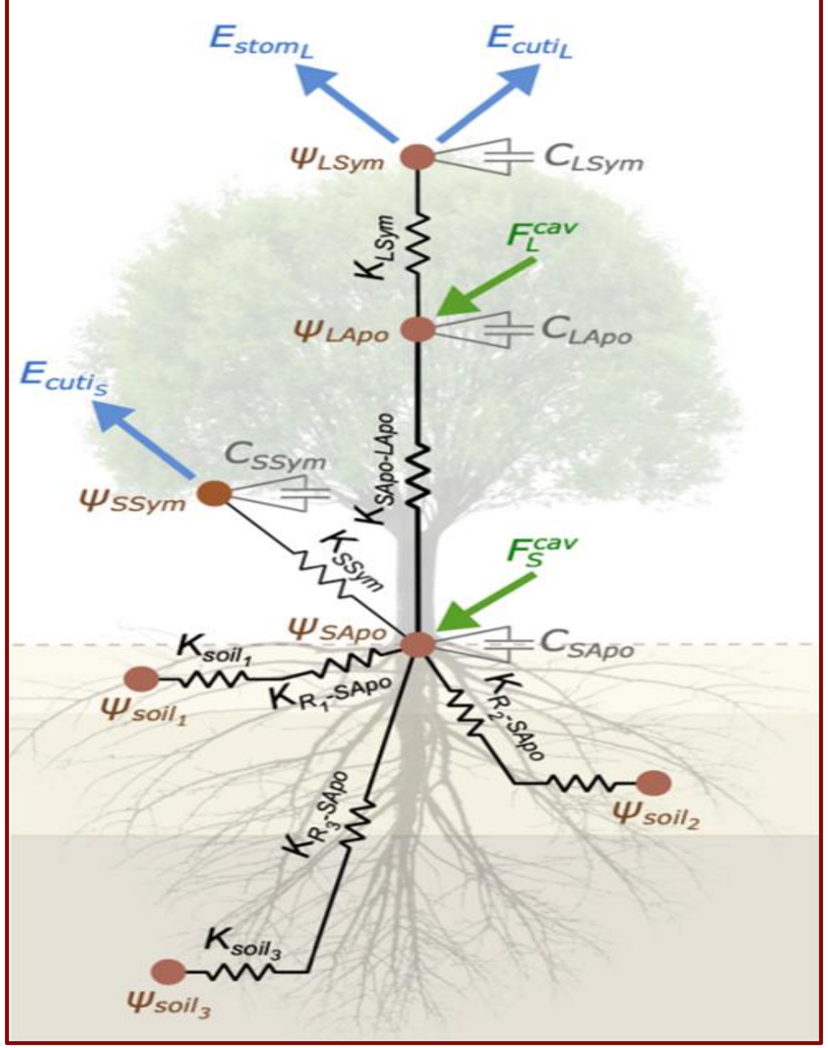
Leaf Area Validation



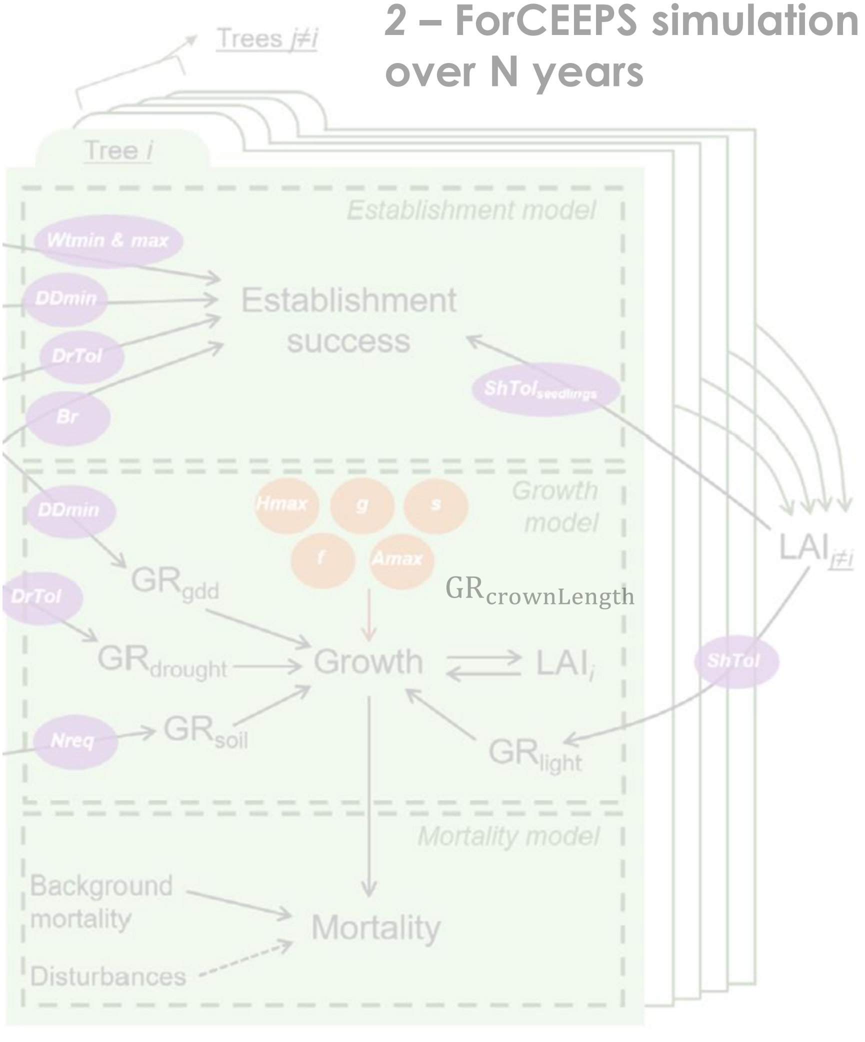
The PHOREAU Model

Model

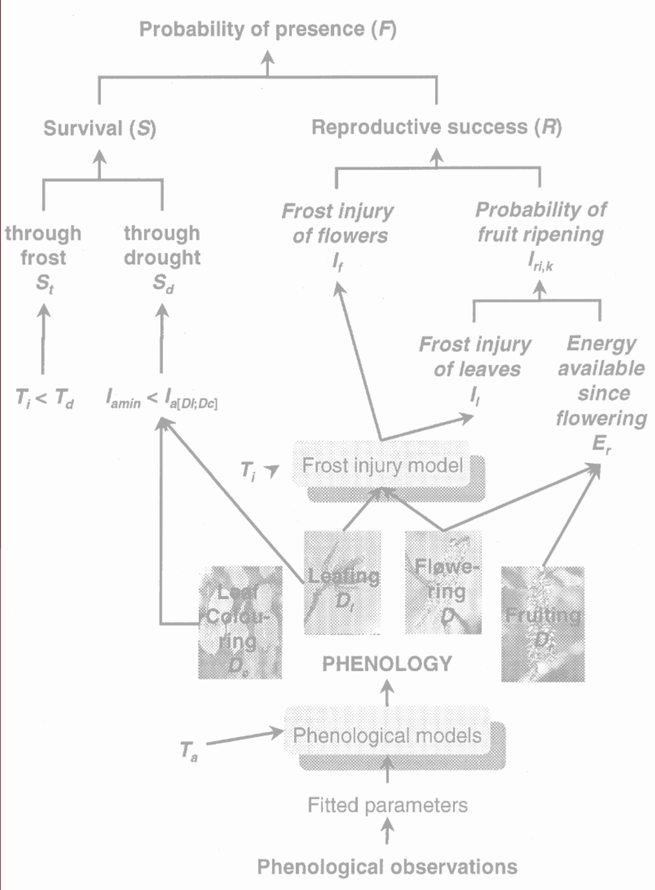
2bis – Yearly Sureau simulation



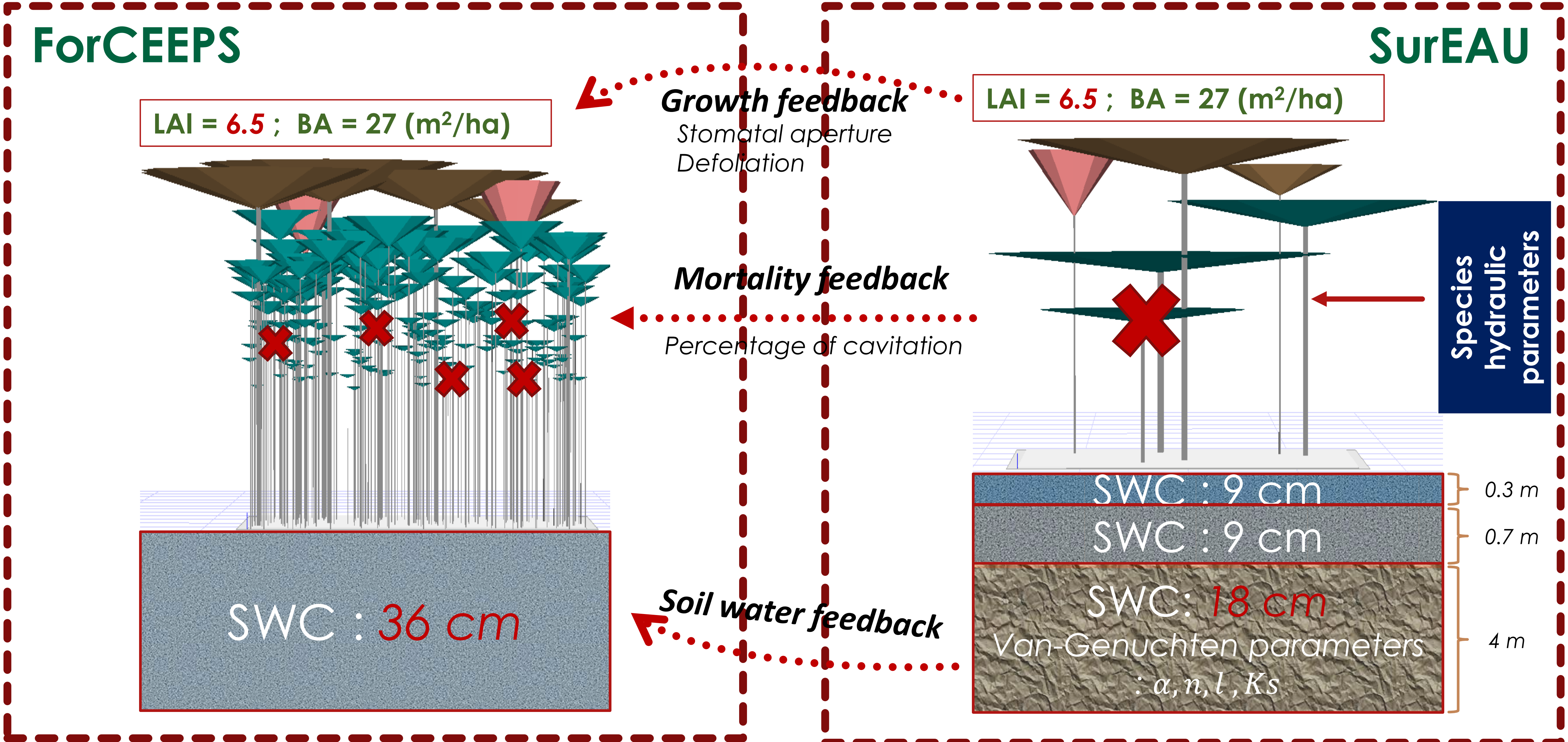
2 – ForCEEPS simulation over N years



1 – Yearly PHENOFIT simulations for each species of interest

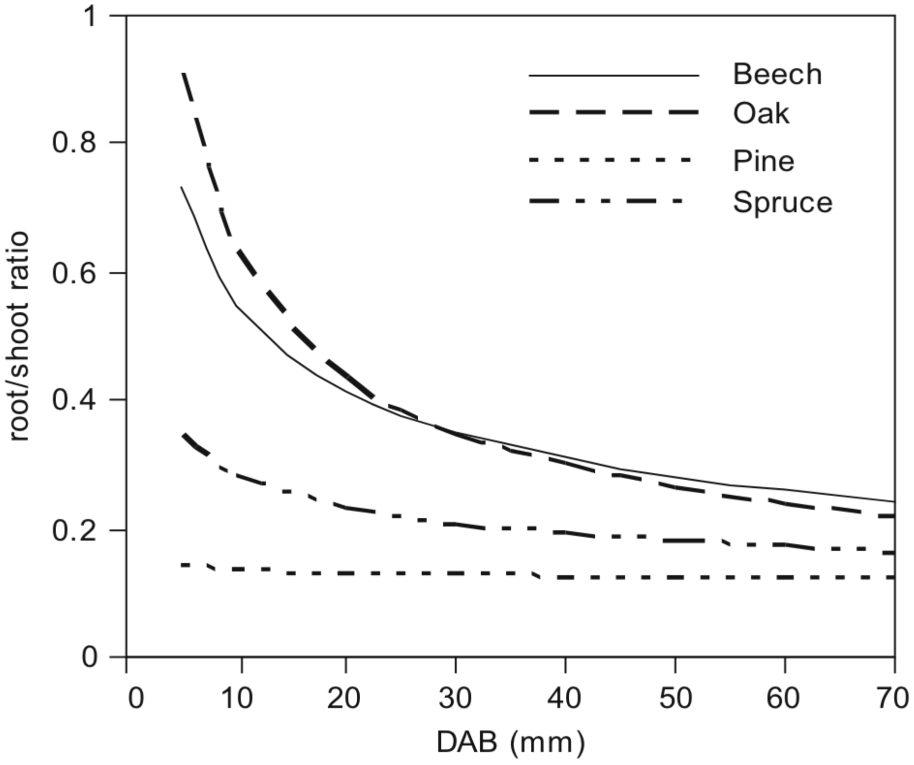


Coupling with SurEau

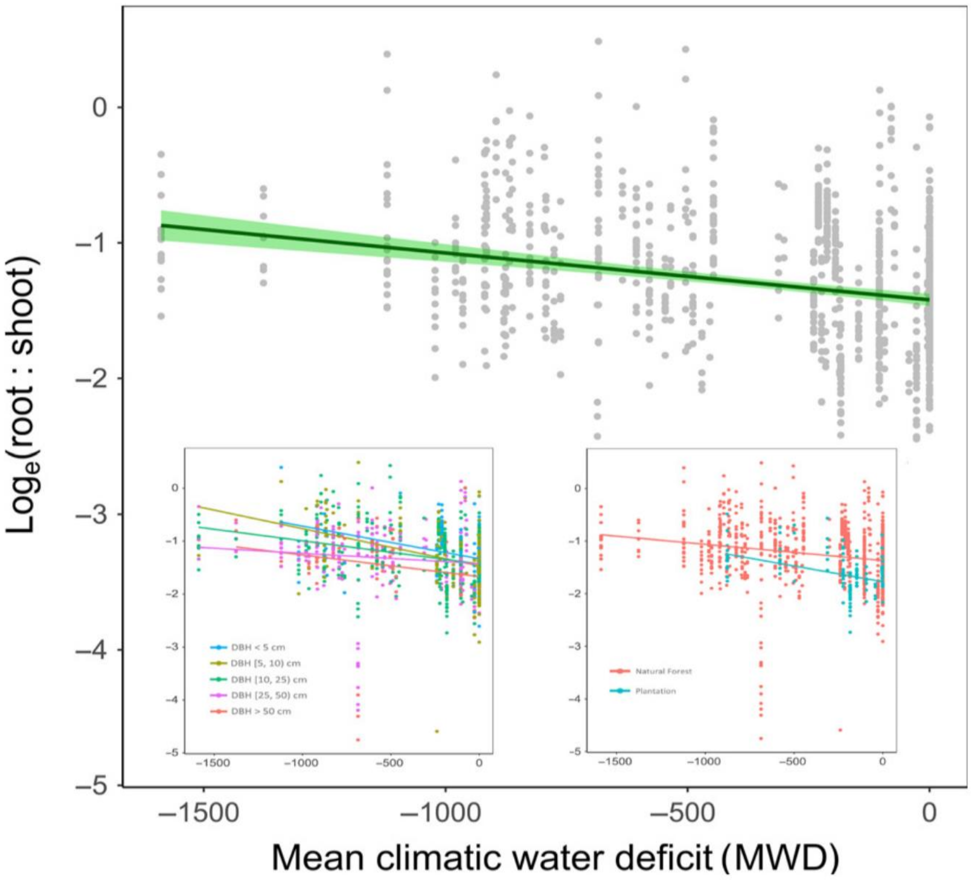


Modelling the root compartment in PHOREAU

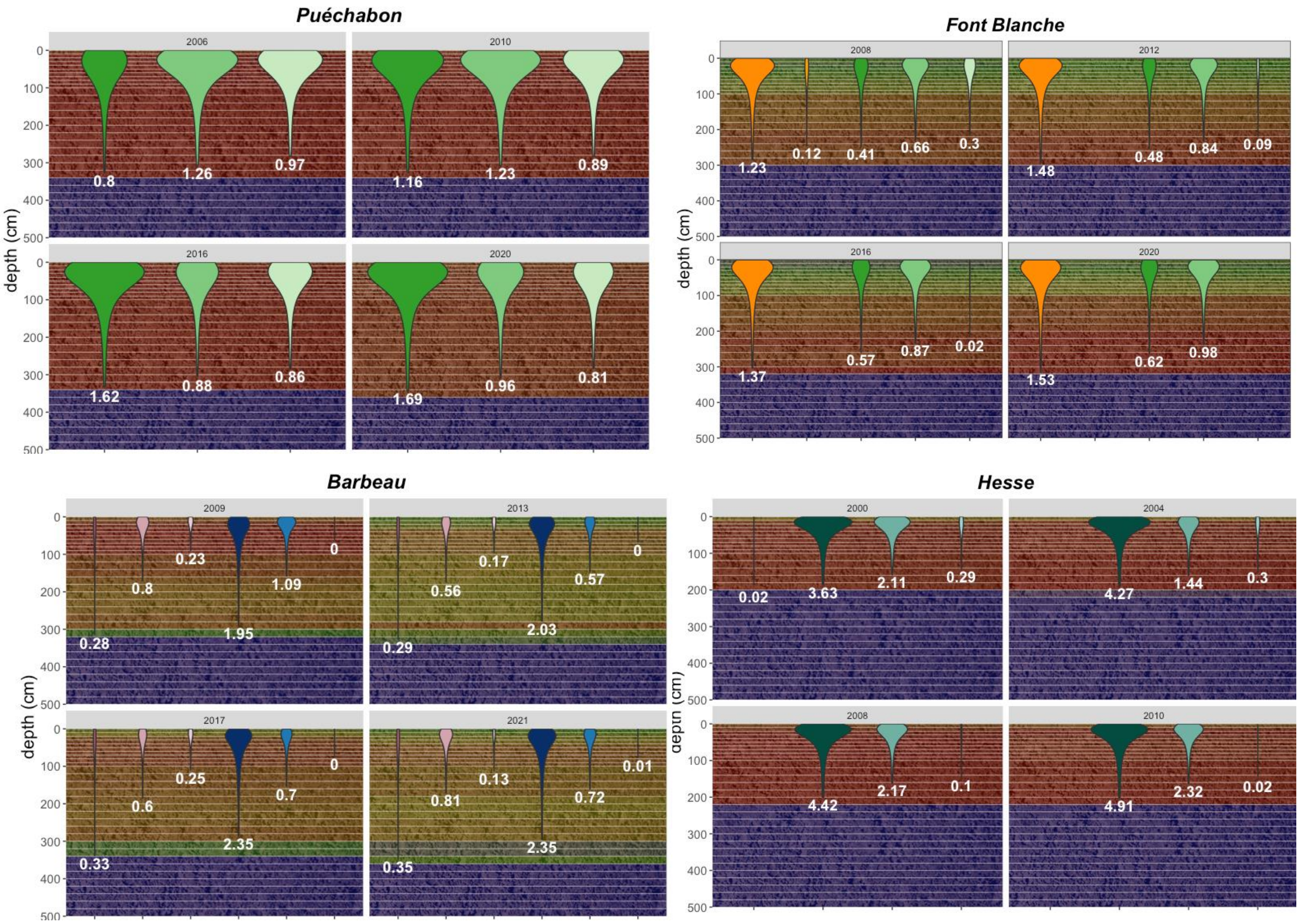
« Variation in individual tree R : S is largely dominated by two effects: **tree size** and **mean water deficit**. » *(Ledo et al. 2017)*



Konôpka et al. 2010



Ledo et al. 2017



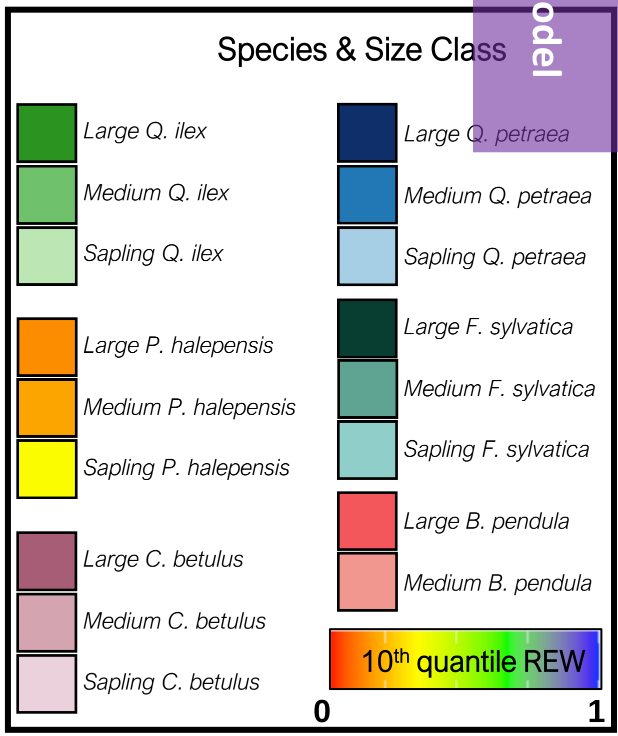
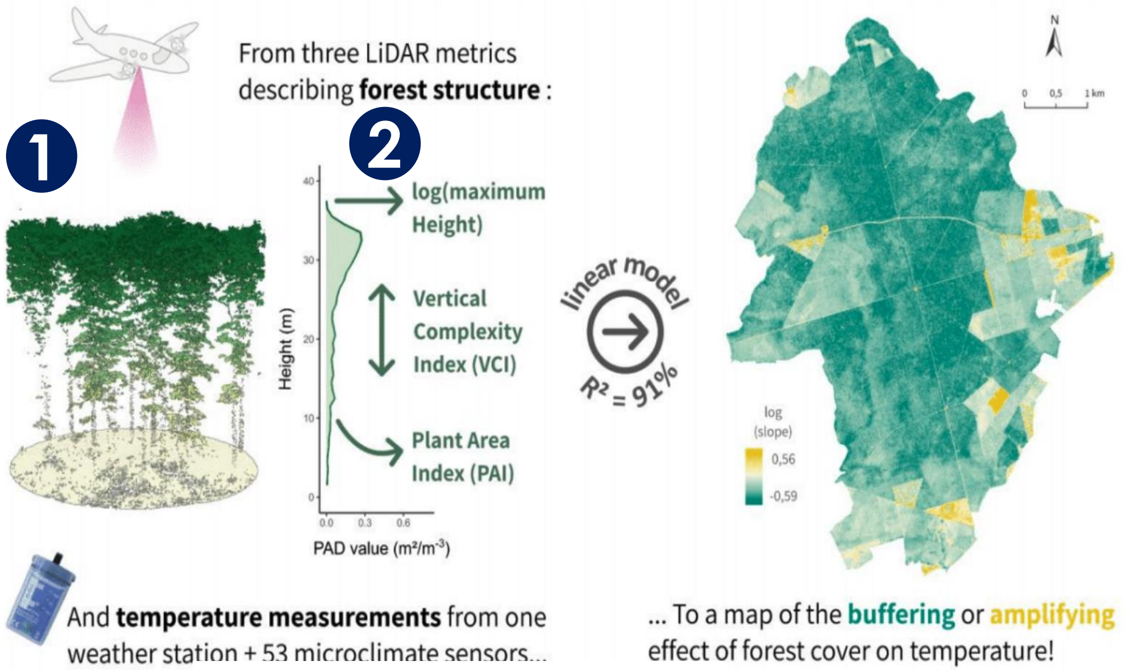


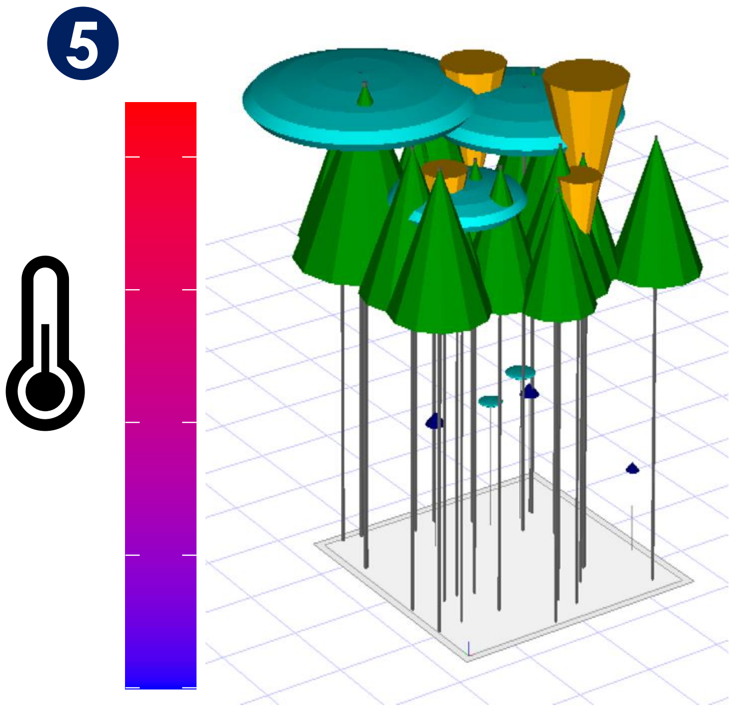
Fig. 5 │ Predicted fine root area distribution over the soil profile. For certain simulation years a partial vertical soil profile is shown, with the overall dryness of each soil layer depicted as a gradient using its 10th quantile relative extractable water (REW) percentage. For each species and size class aggregate tree (refer Annex X for details on the aggregation method), the distribution of the inverse cone along the soil layers represents the predicted location of its fine roots, with its total aggregate fine root area index (FRAI) shown under.

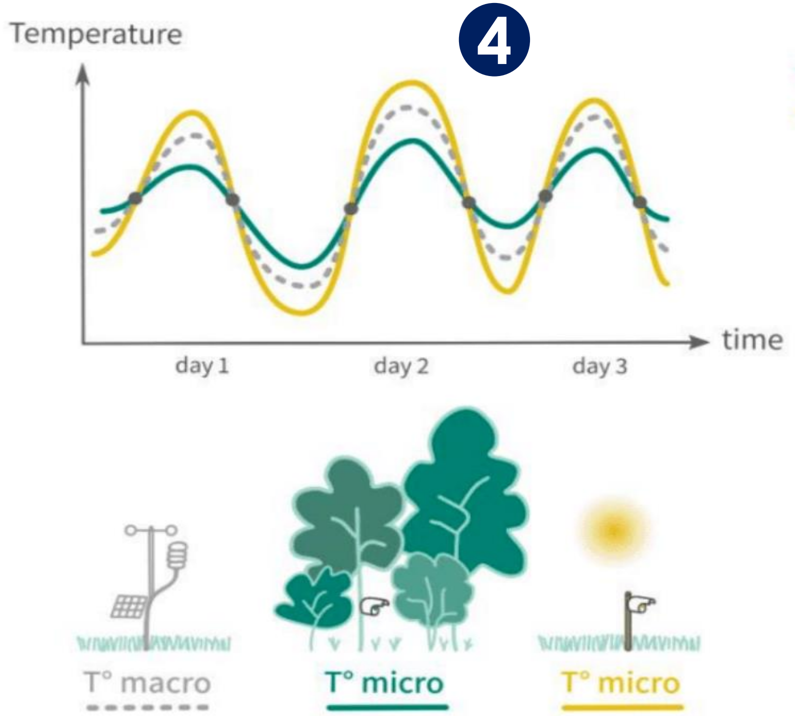
Model

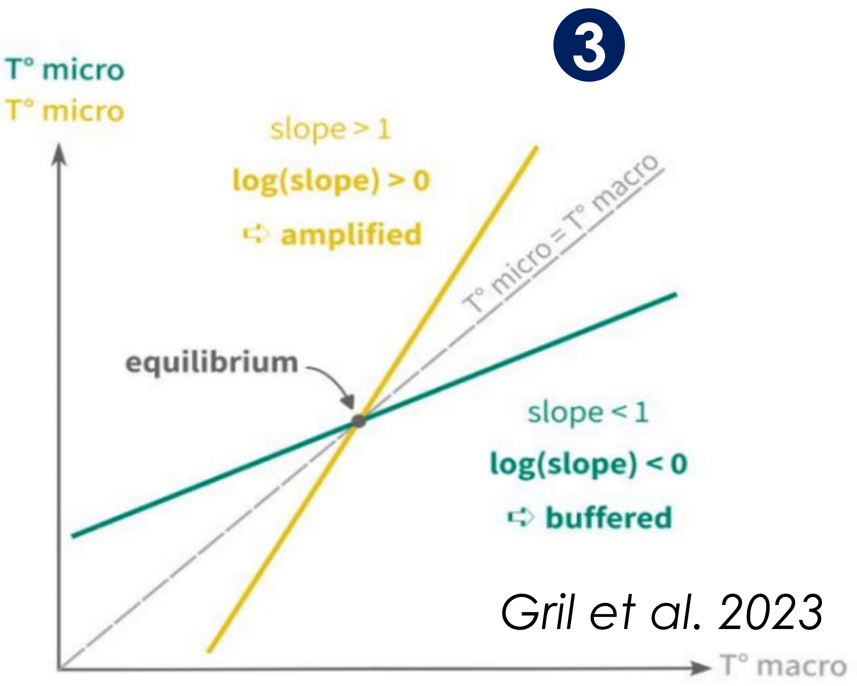
Integration of a simplified microclimate model (derived from the work of EVA GRIL)

1. State of the ForCEEPS stands
2. *Production of structural indices :VCI, LAI, Hmax*
3. Computing the microclimate *slope*
4. Predicting soil microclimate temperatures
5. Interpolation over the vertical profile







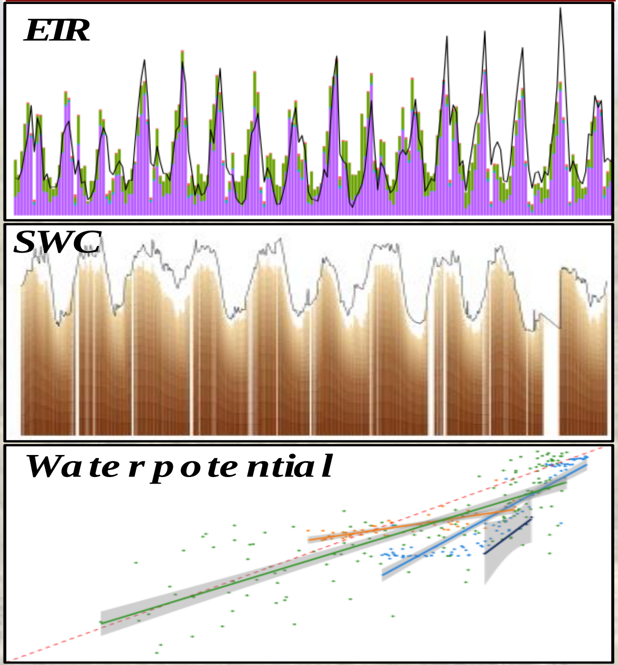


Gril et al. 2023

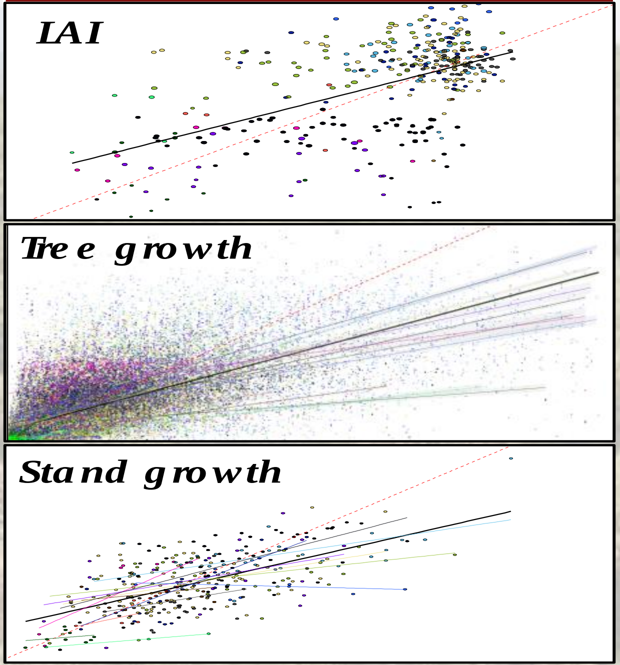
Validation

Proposed framework for PHOREAU validation

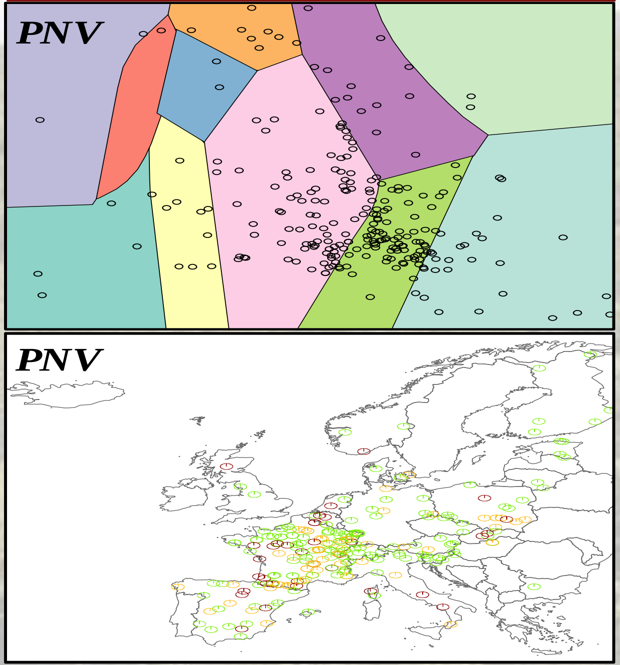
1 Hydrology Validation



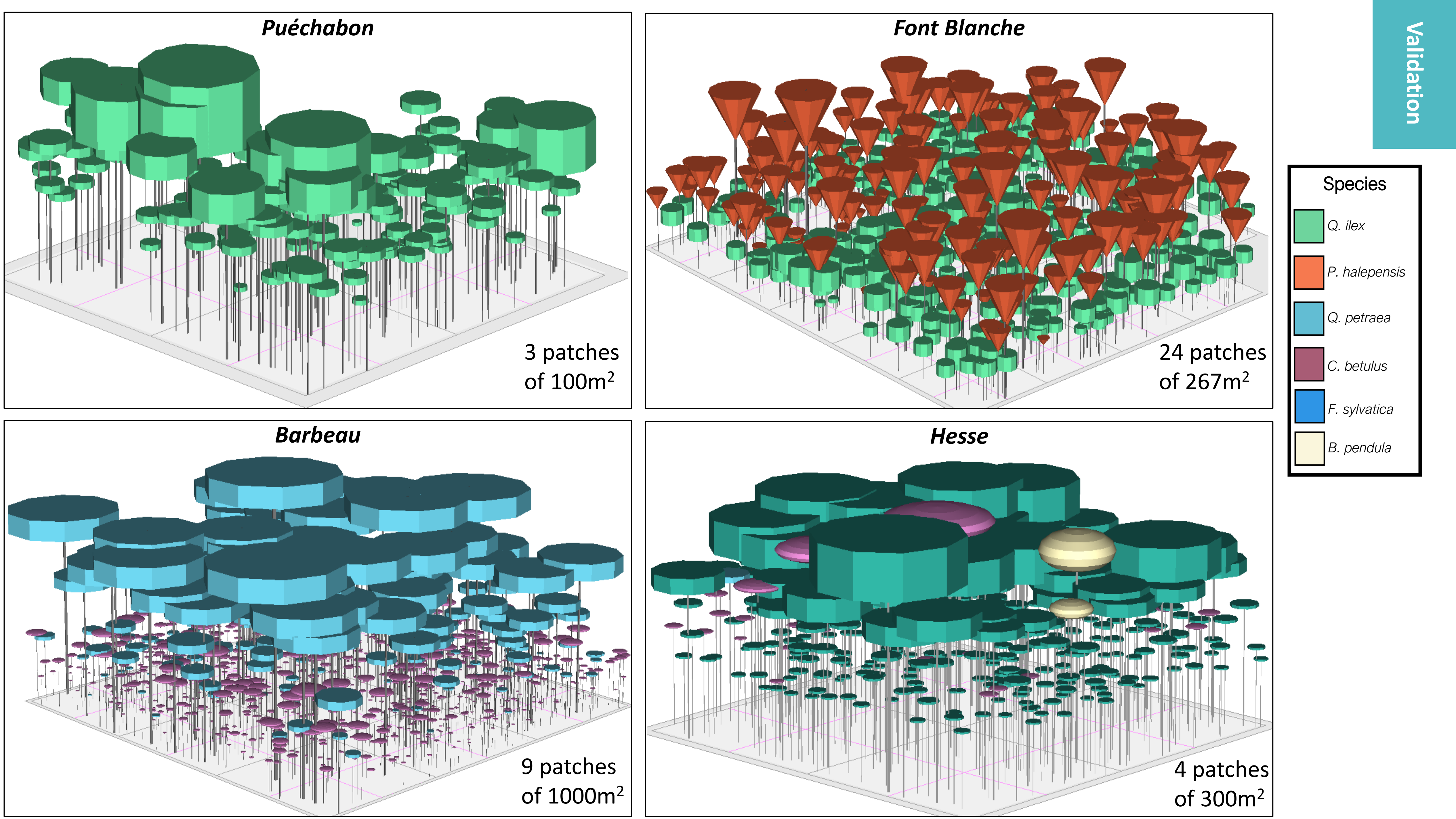
2 Structural Validation



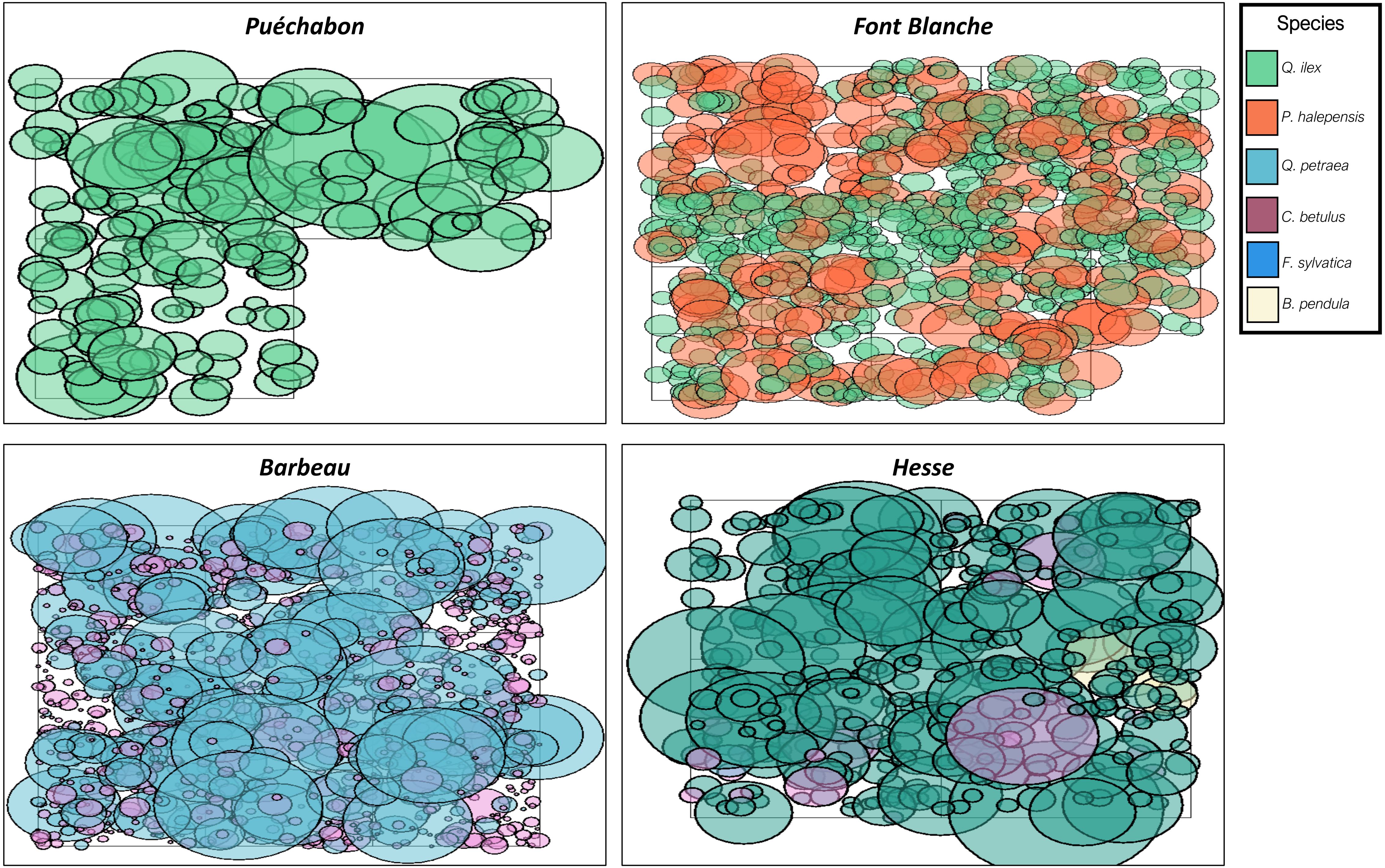
3 Composition Validation



- Simulation Length →
- ← Input data requirements
- Indication of global performance →
- ← Usefulness for calibration



Validation
Puéchabon
3 patches
of 100m²
Font Blanche
24 patches
of 267m²
Barbeau
9 patches
of 1000m²
Hesse
4 patches
of 300m²
Species
Q. ilex
P. halepensis
Q. petraea
C. betulus
F. sylvatica
B. pendula


Puéchabon
Font Blanche
Barbeau
Hesse
Species
Q. ilex
P. halepensis
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Validation

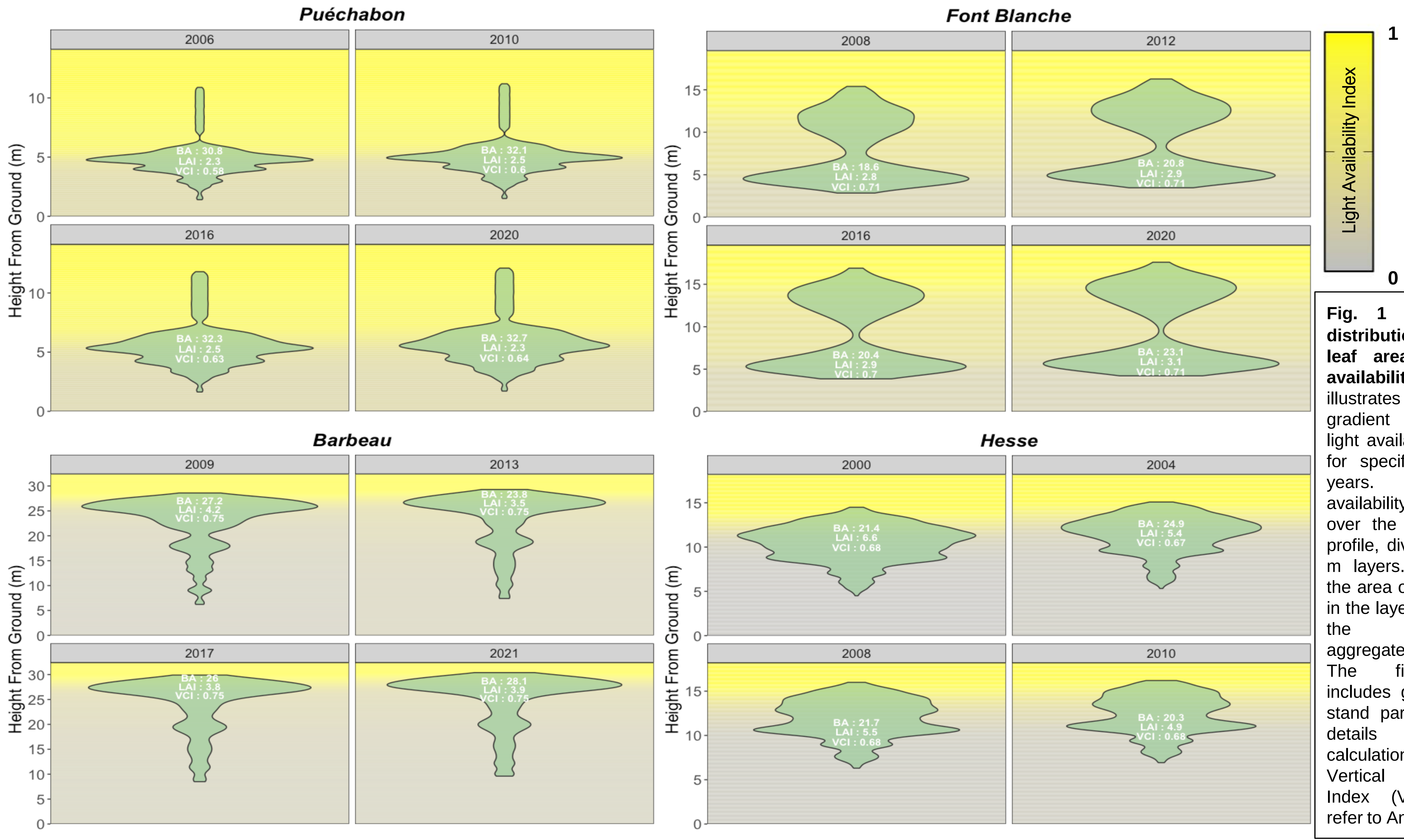
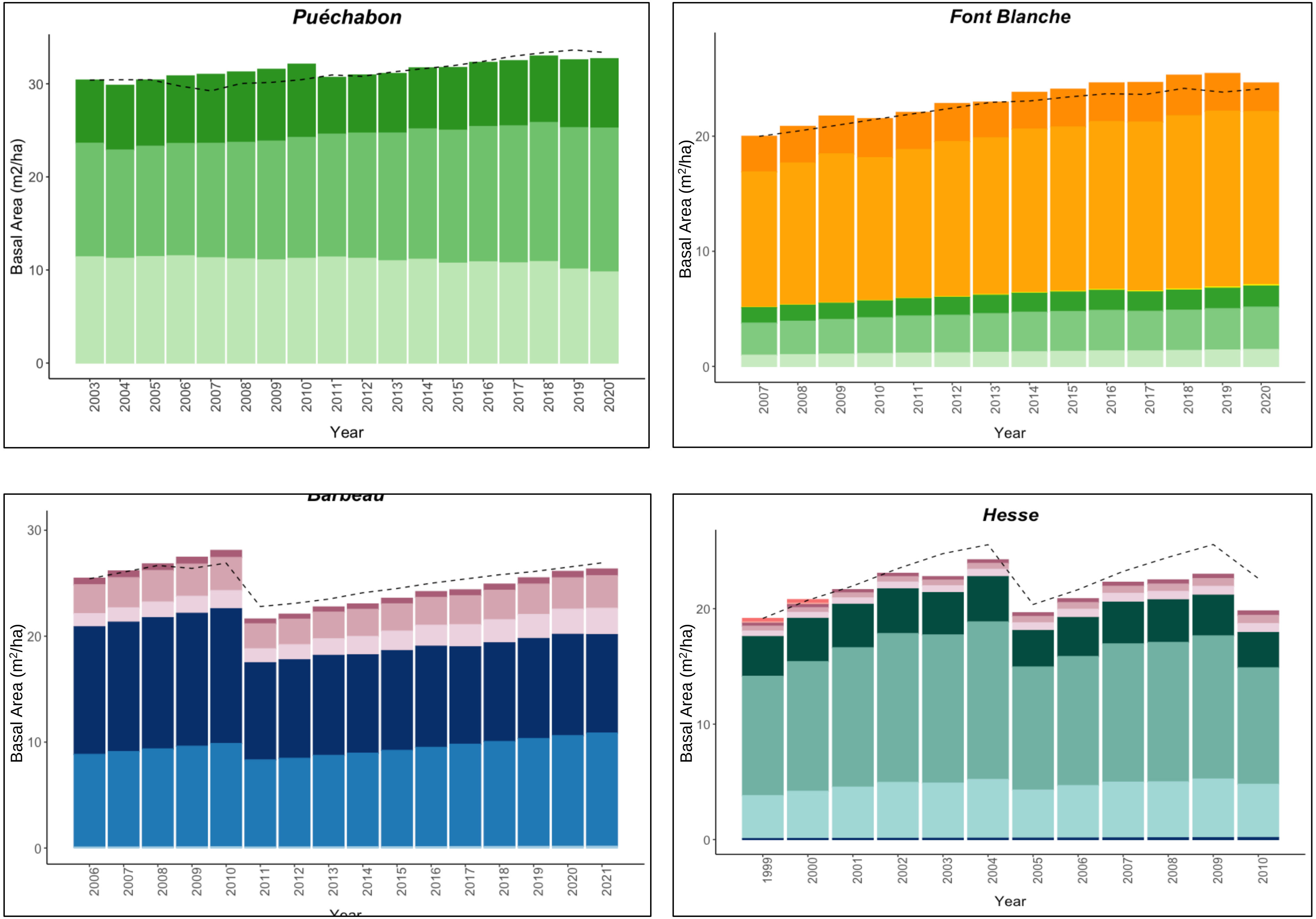


Fig. 1 | Predicted distribution of stand leaf area and light availability. This figure illustrates the vertical gradient of predicted light availability indices for specific simulation years. The light availability is presented over the aboveground profile, divided into 0.1 m layers. In addition, the area of each shape in the layers represents the predicted aggregate leaf area. The figure also includes global annual stand parameters. For details on the calculation of the Vertical Complexity Index (VCI), please refer to Annex X.



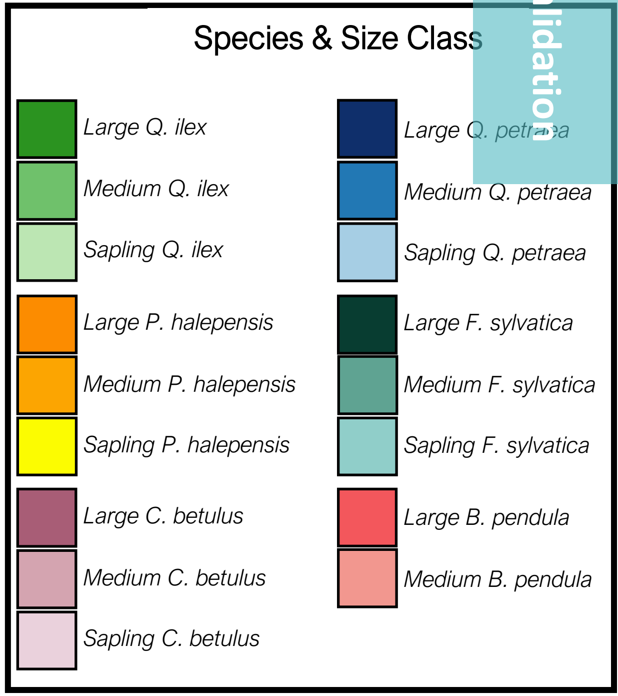
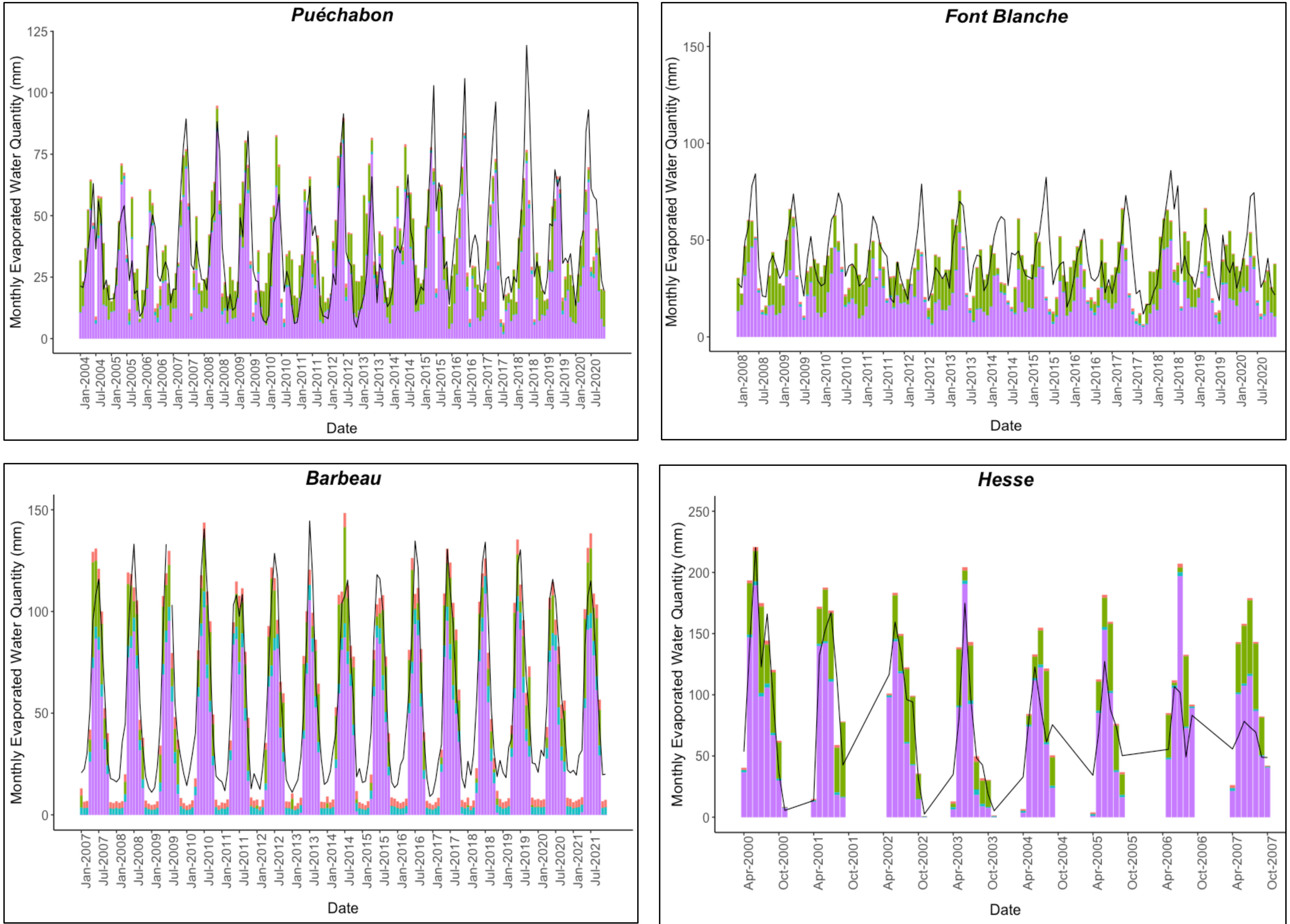


Fig. 2 | Predicted versus observed annual stand basal area. For each simulation site, the bars depict the annual basal area projections generated by the PHOREAU model, broken down by species and size class contributions (refer to Annex X for details). The dashed line represents the observed annual total basal area derived from the inventory. Basal area is defined as the cross-sectional area at breast height of all trees per hectare.



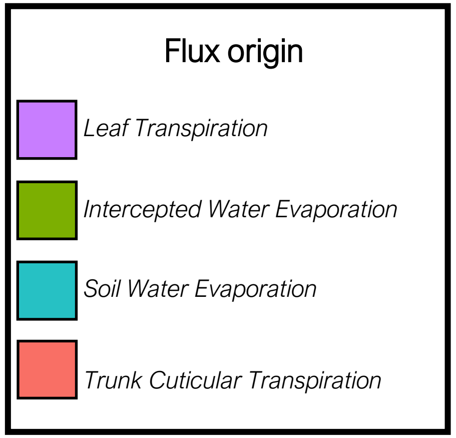
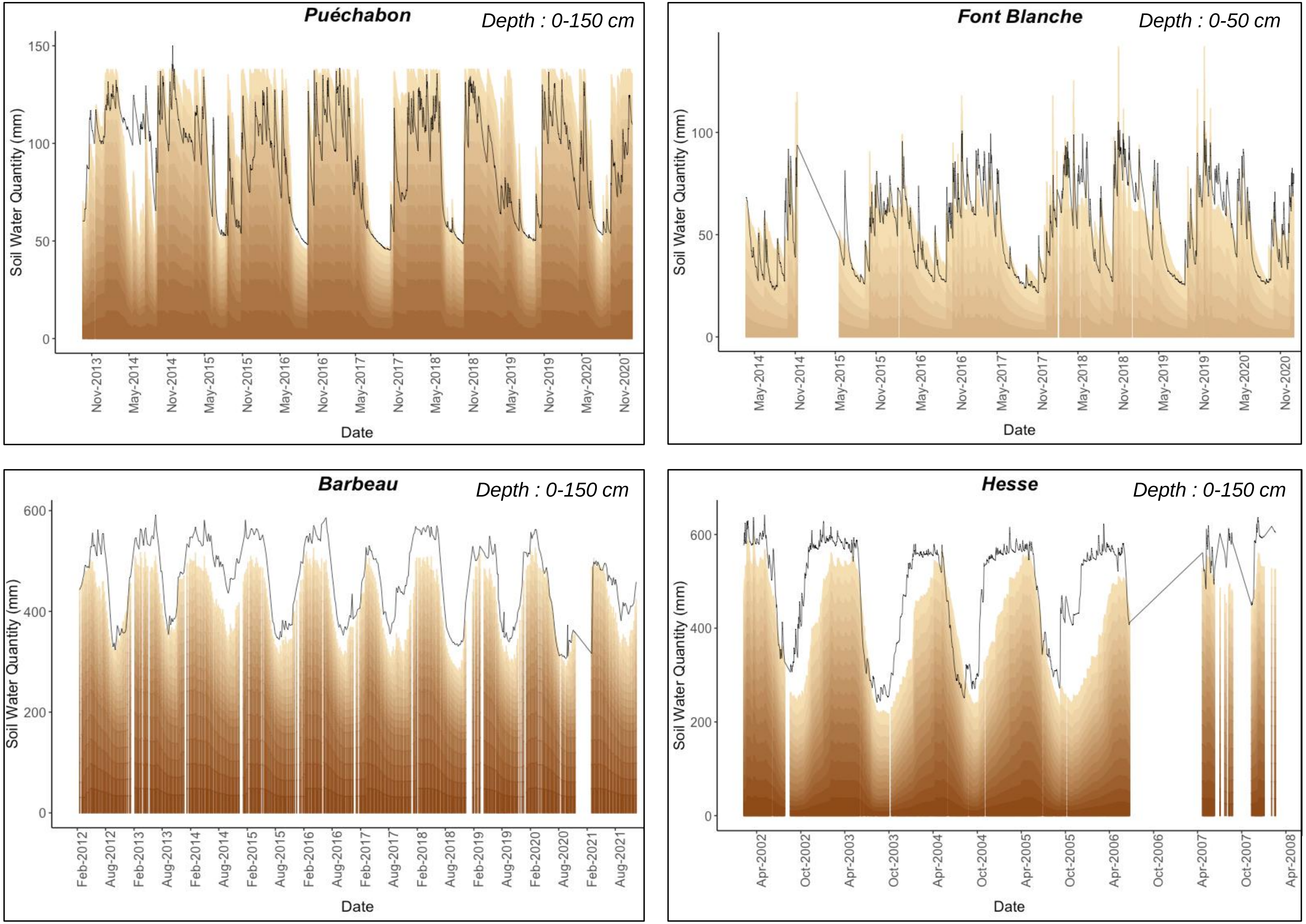


Fig. 3 │ Predicted versus observed evolution of mothly real evapotranspiration (ETR). For each simulation site, the bars depict the monthly ETR (mm) projections generated by the PHOREAU model, broken down by source of flux. Soil and intercepted water evaporation respectively originate from the first layer of soil and the water stored on the surface of leaves, while the two other sources are transpiration from compartments of the PHOREAU tree (refer to Annex X for details). The black line indicates the observed monthly actual evapotranspiration, representing the total water vapor released from the soil and vegetation into the atmosphere, aggregated from hourly or sub-hourly measurements obtained from each site's flux tower.



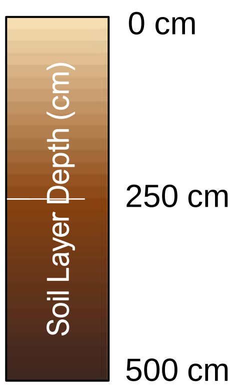


Fig. 4 │ Predicted versus observed evolution of soil water quantity (SWC). For each simulation site, the black line indicates the observed daily actual SWC. The stacked bars depict the daily SWC (mm) projections generated by the PHOREAU model, with individual contributions of each soil layer stacked and color-coded by soil layer (see Fig. 6 for layer details). The projections are confined the maximum measured depth for the each site, as indicated in the upper right corner of the figure. For *Barbeau* and *Font Blanche*, observed SWC were directly obtained from site managers; for *Puéchabon* and *Hesse*, they were interpolated from soil relative humidity ($RH_{\%}$) measured at different depths, using the same rock fractions as used in the simulation.

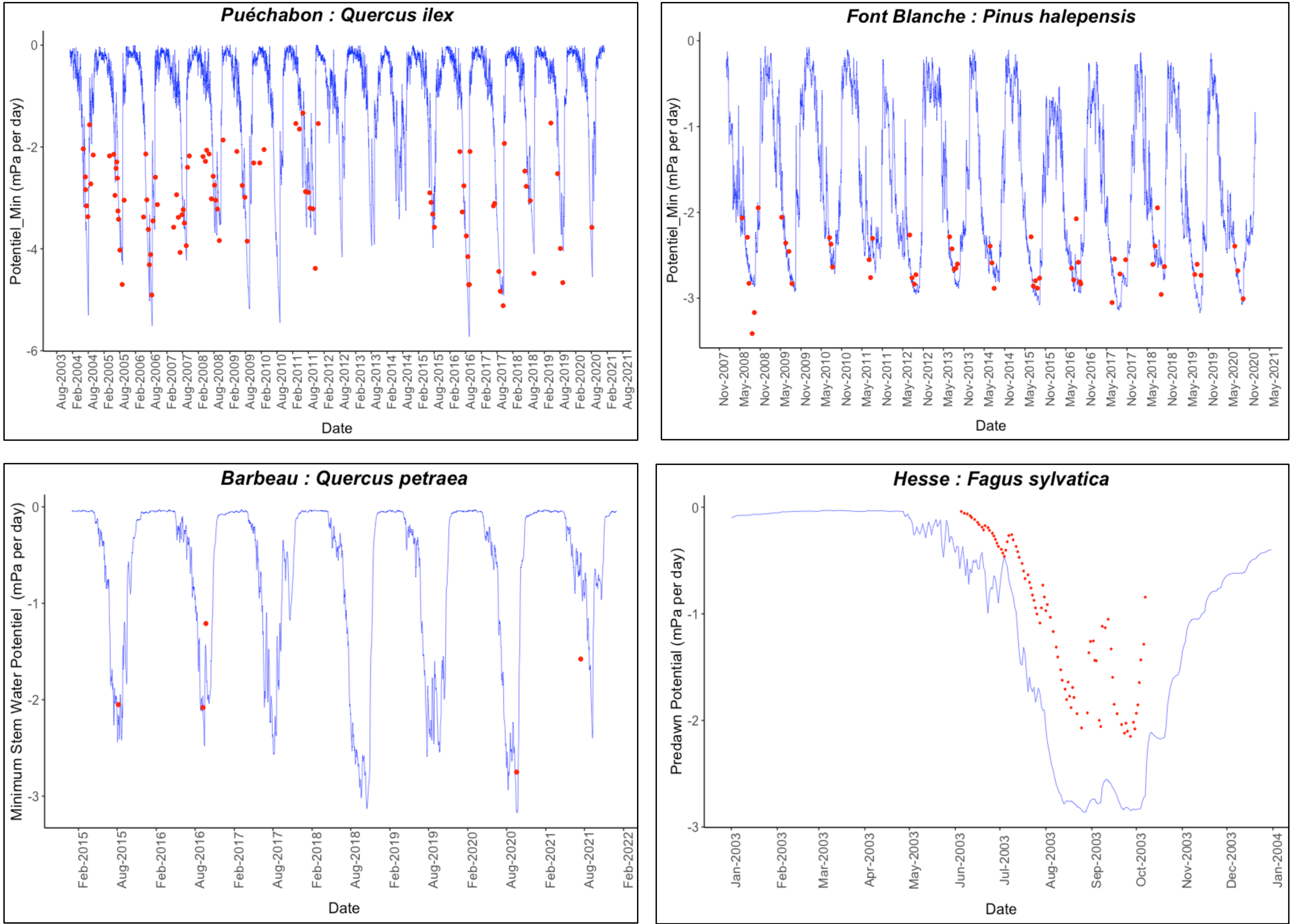
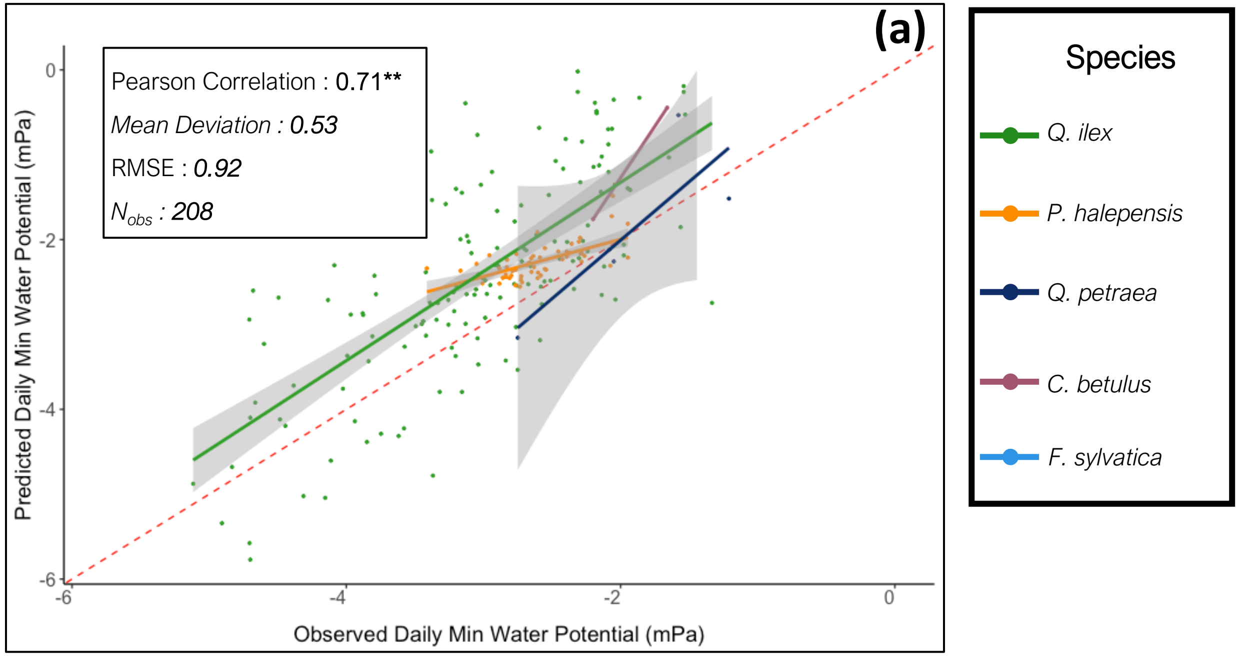


Fig. 5 | Evolution of predicted versus observed stem water potentials. For the dominant species of the four ICOS simulations, the blue line depicts the daily evolution of the stem water potentials (mPa) generated by the PHOREAU model and averaged over the aggregate trees of the species (refer Annex X for details on the aggregation method). The red points represent the observed water potentials, limited to the years for which observational data is available (data sources are detailed in Annex X). For Puéchabon, Font Blanche and Barbeau sites, the minimum daily observed and predicted water potentials are shown. For Hesse, where only predawn observations are available, the maximum predicted water potential is used as a proxy.



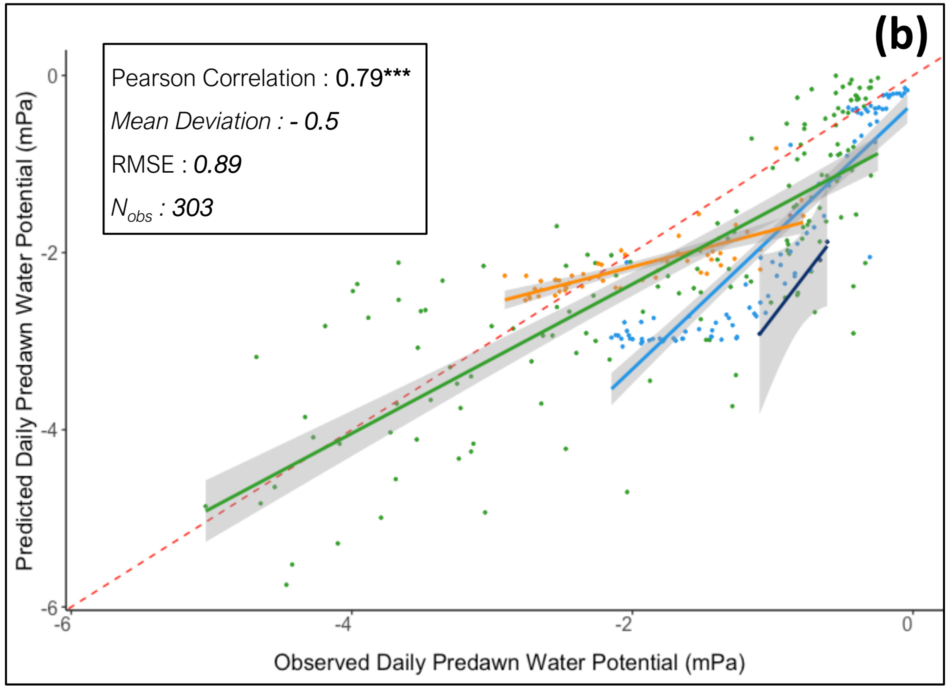


Fig. 6 | Aggregated Predicted versus observed daily stem water potential. All available stem water potentials (mPa) observations are plotted against the PHOREAU projection for the correspoding day and species. For each species, the full colored lines are the regression lines of the linear model of the relationship between observed and predicted minimum water potential, with confidence interval represented with the grey dashed lines. The dashed red line is the 1:1 line. See Annex X for definition of associated statistics. (a) Comparison with minimum water potentials. (b) Comparison with predawn water potentials.

Productivity Validation

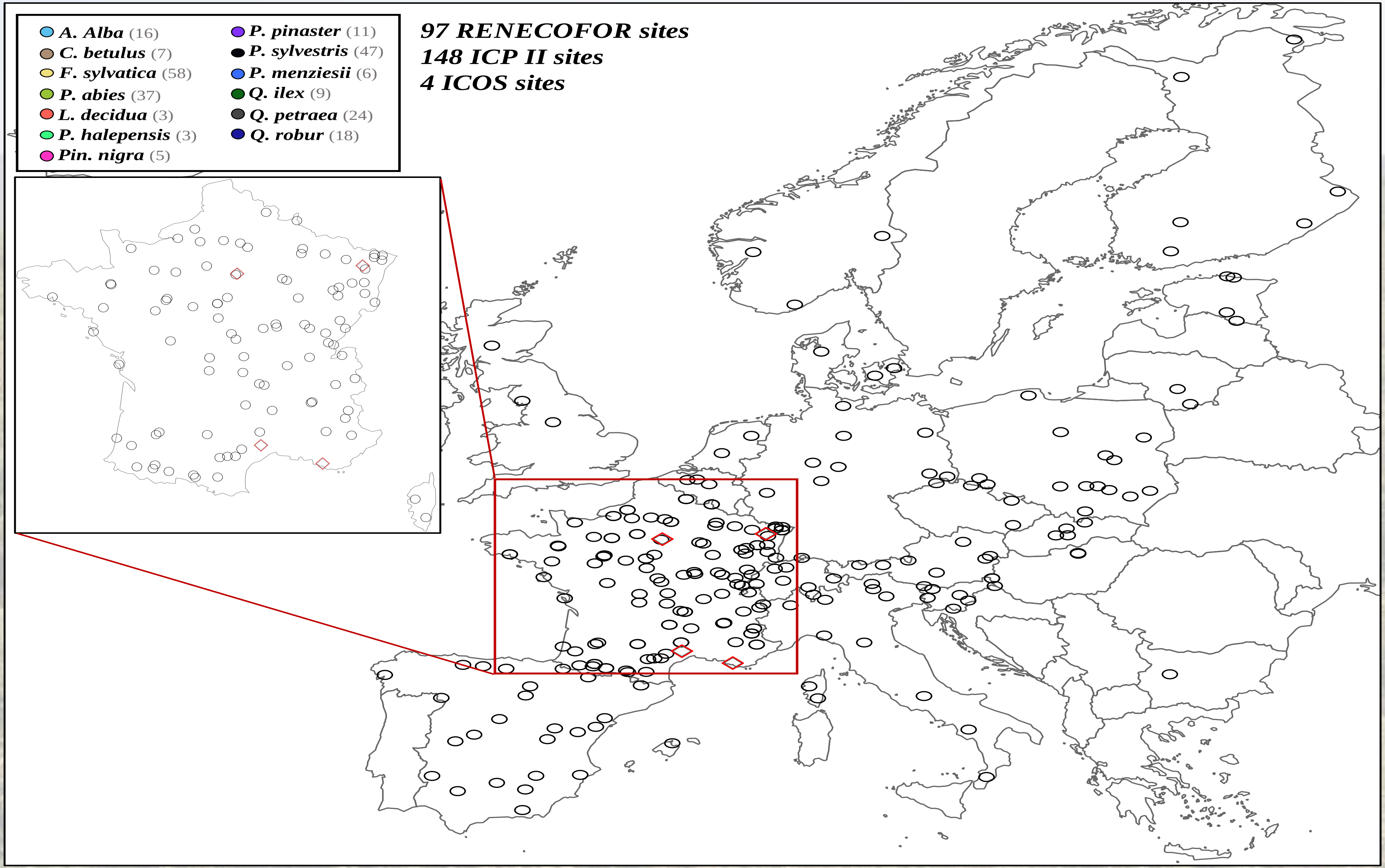
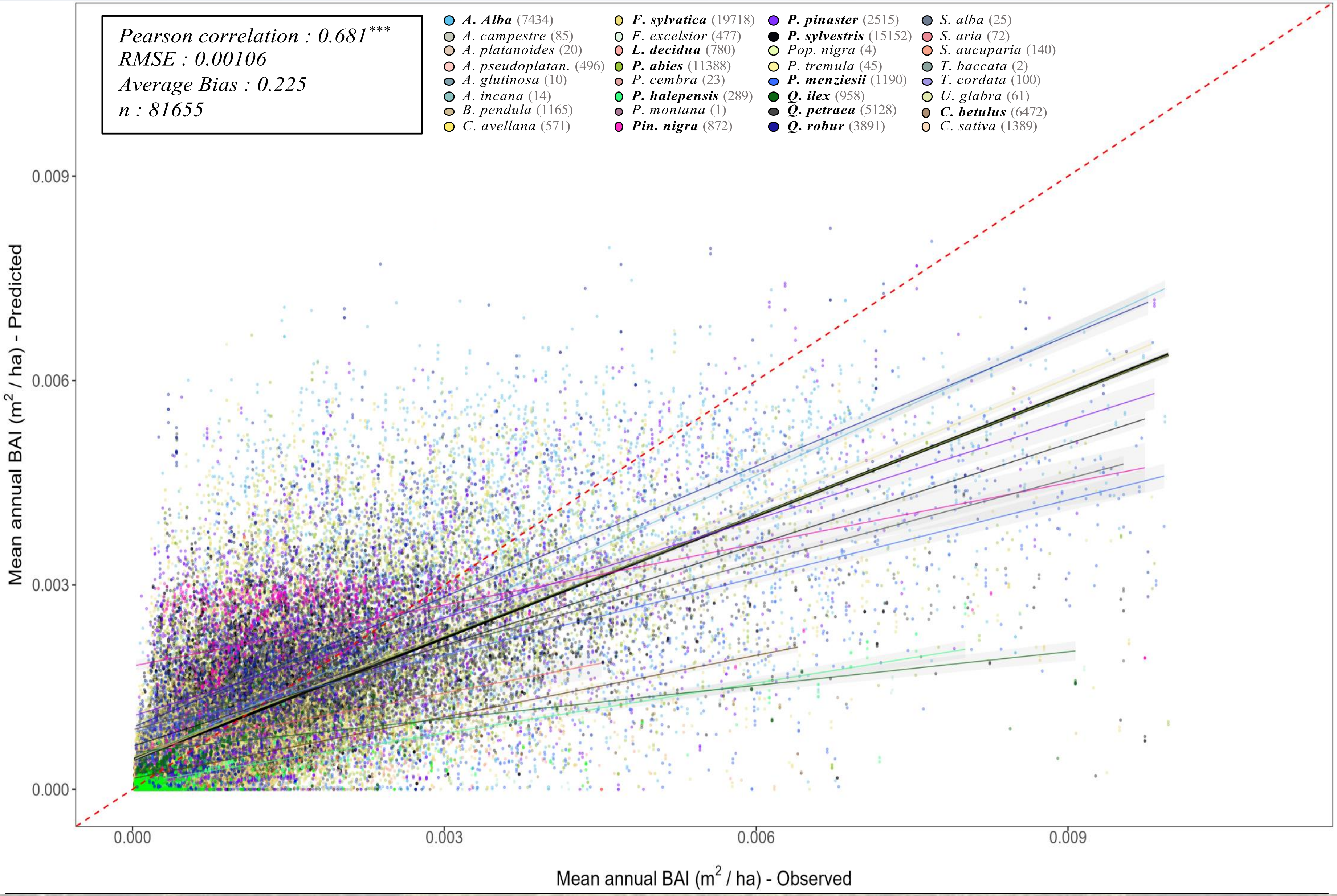
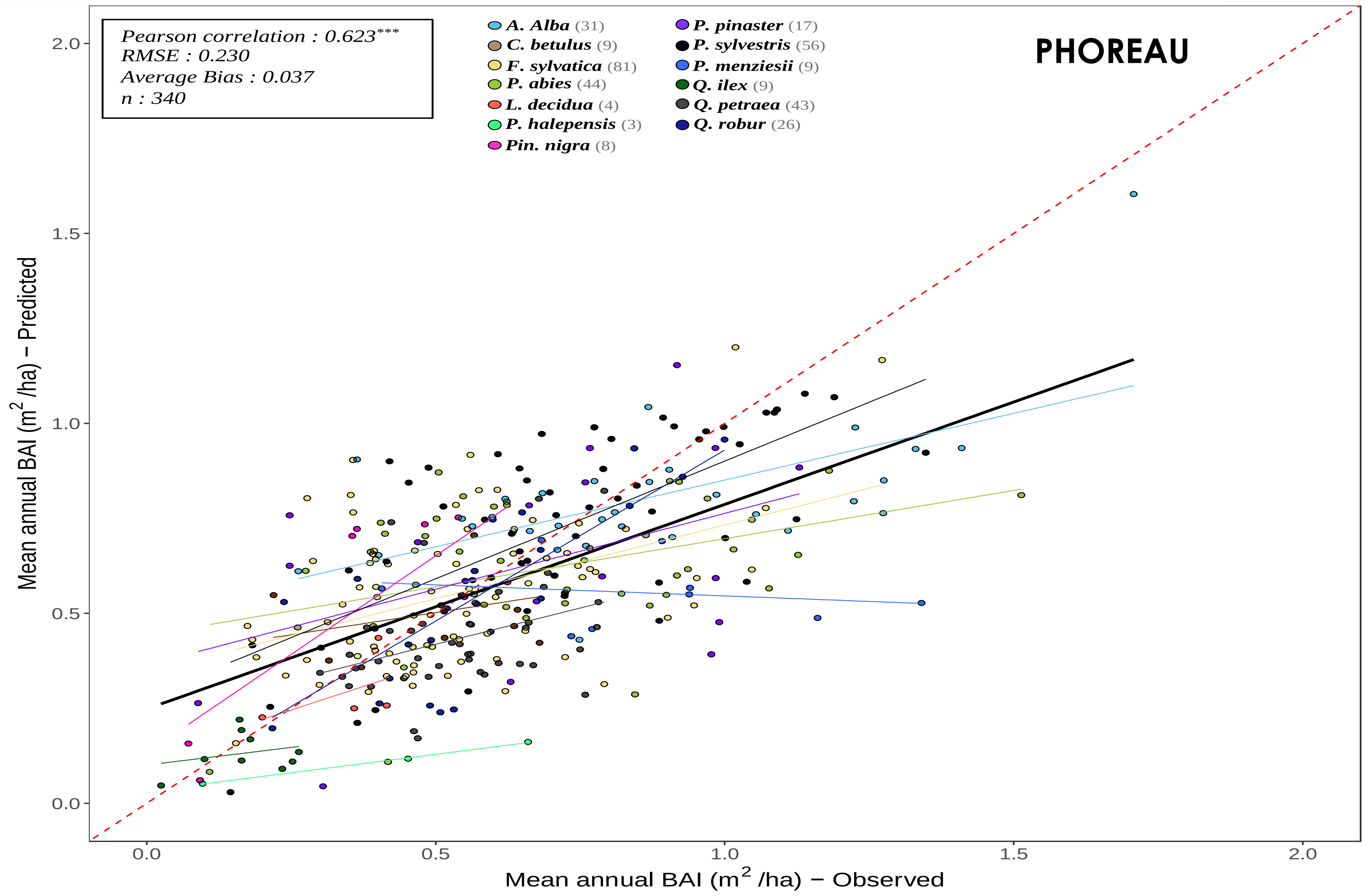


Fig. X | Spatial distribution of sites used for PHOREAU validation. Sites are color-coded based on the dominant species identified in the inventory (see legend in top-left). Red-bordered diamonds represent the four ICOS site (Puéchabon, Font-Blanche, Barbeau, and Hesse) selected for in-depth hydraulic validation.

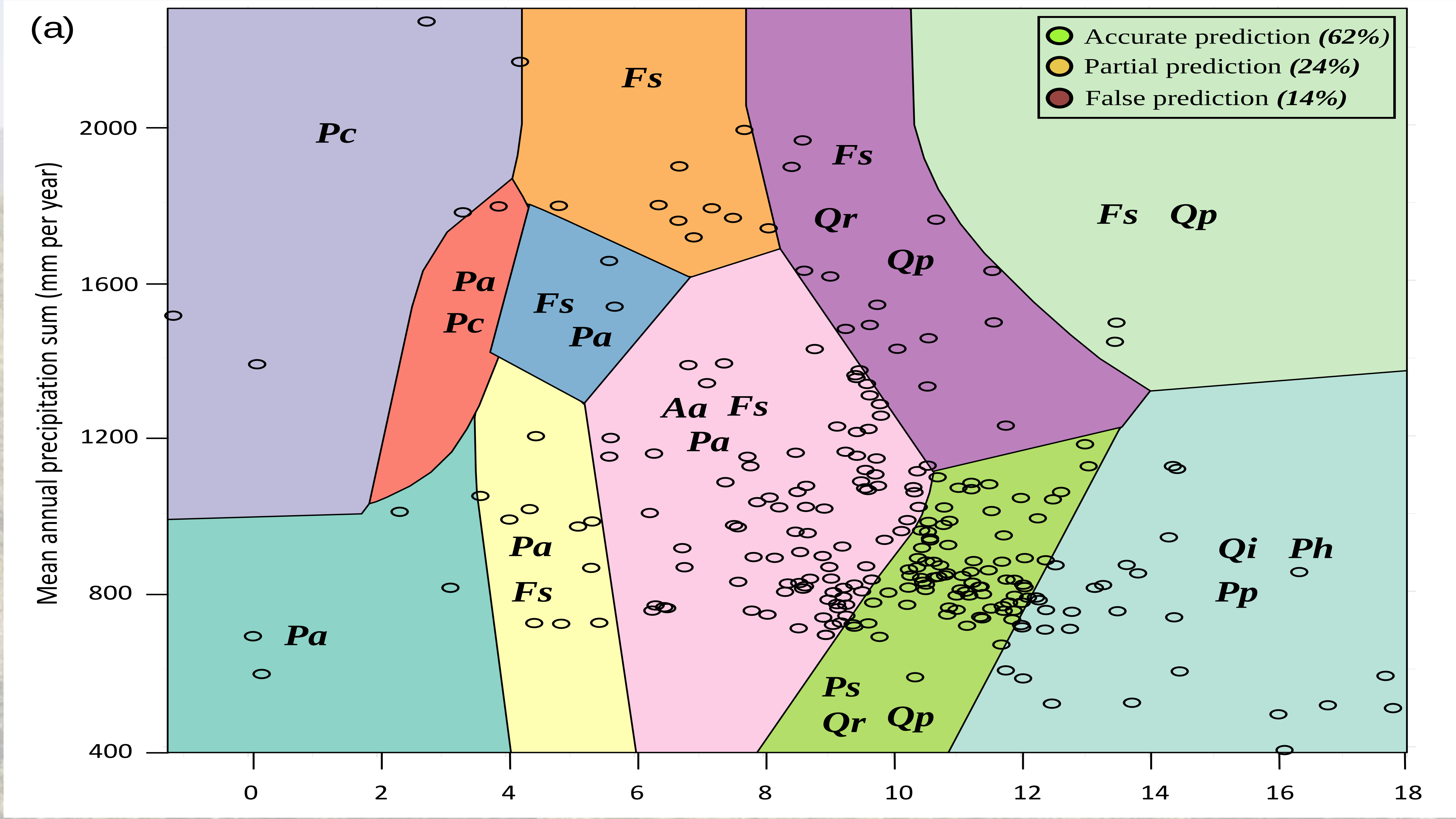
Productivity Validation



Productivity Validation

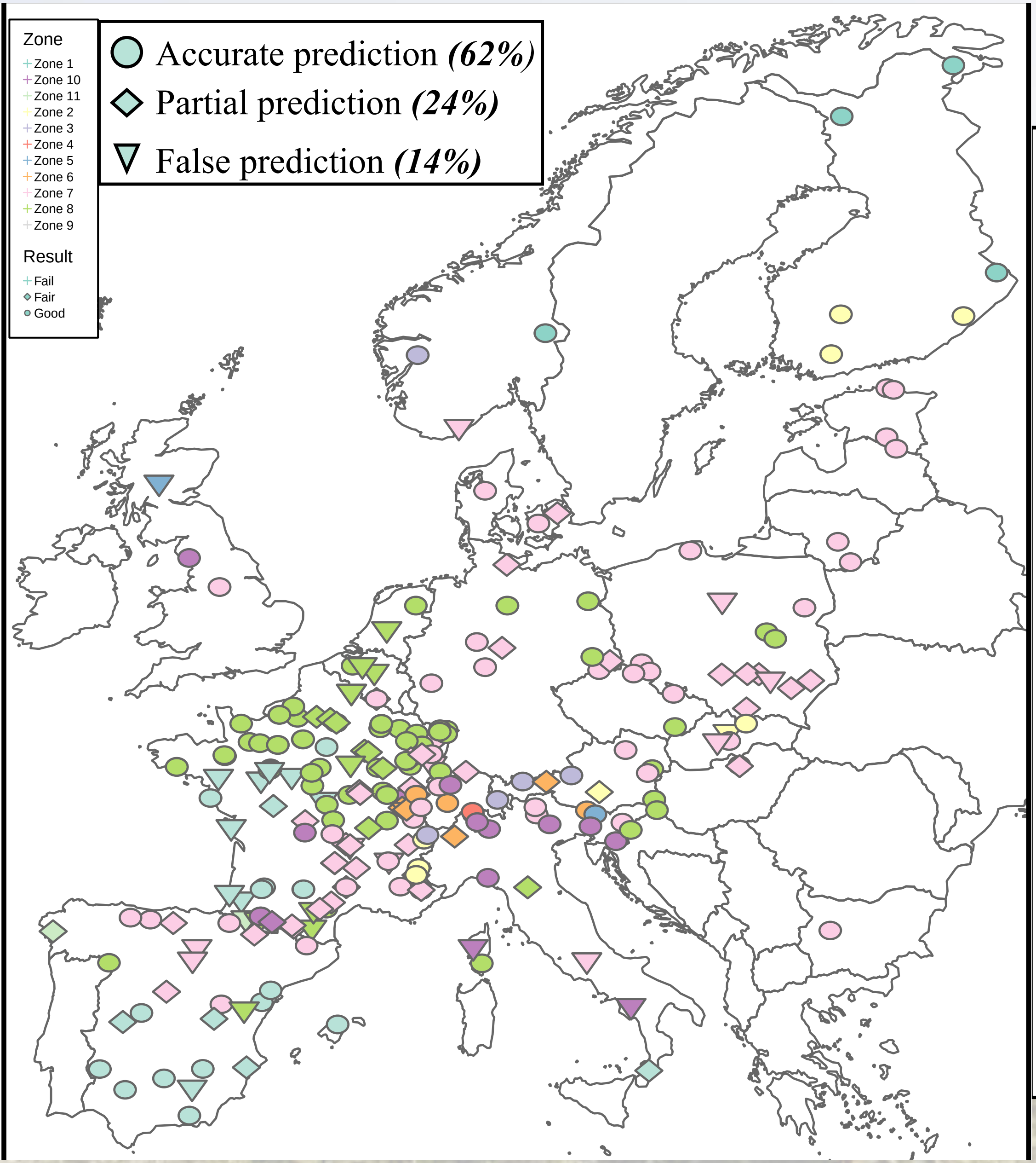


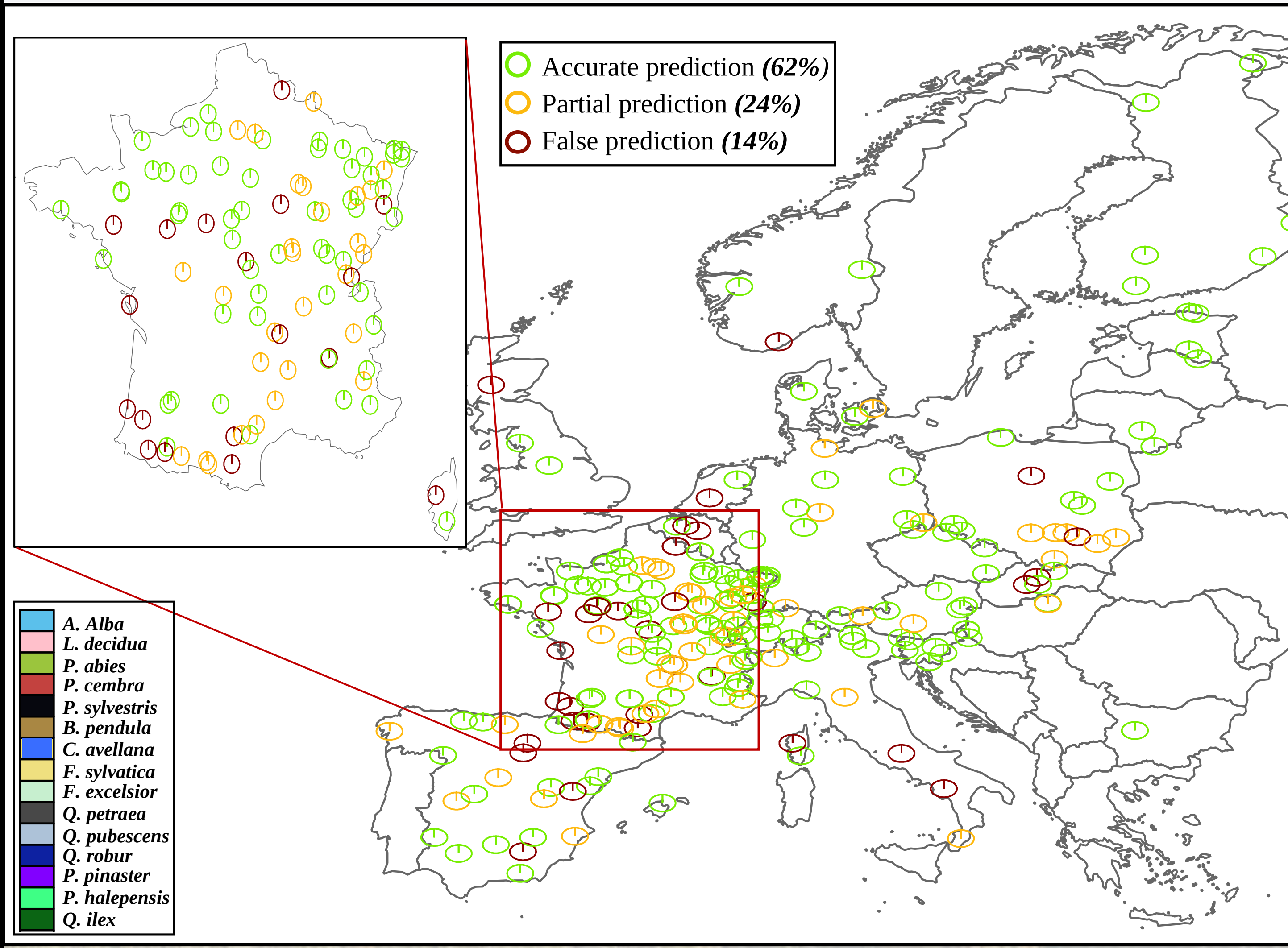
Potential Niche Validation



Bugmann, 1996
Ellenberg, 1986

Potential Niche Validation



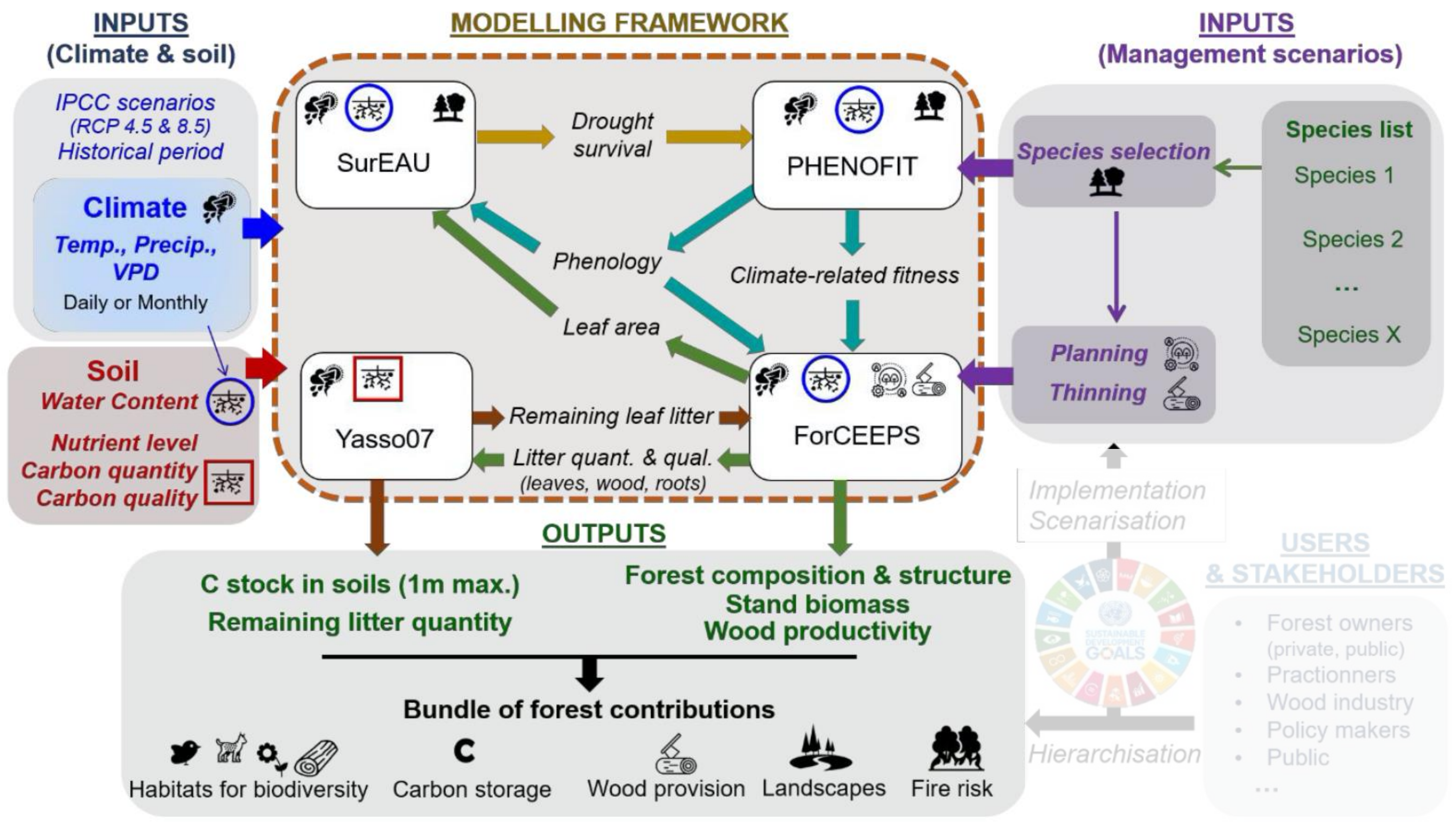


New Results

PhorEau: a new process-based model to predict forest functioning, from tree ecophysiology to forest dynamics and biogeography

Tanguy Postic, François de Coligny, Isabelle Chuine, Nicolas Martin StPaul, Xavier Morin

doi: https://doi.org/10.1101/2025.01.28.635328

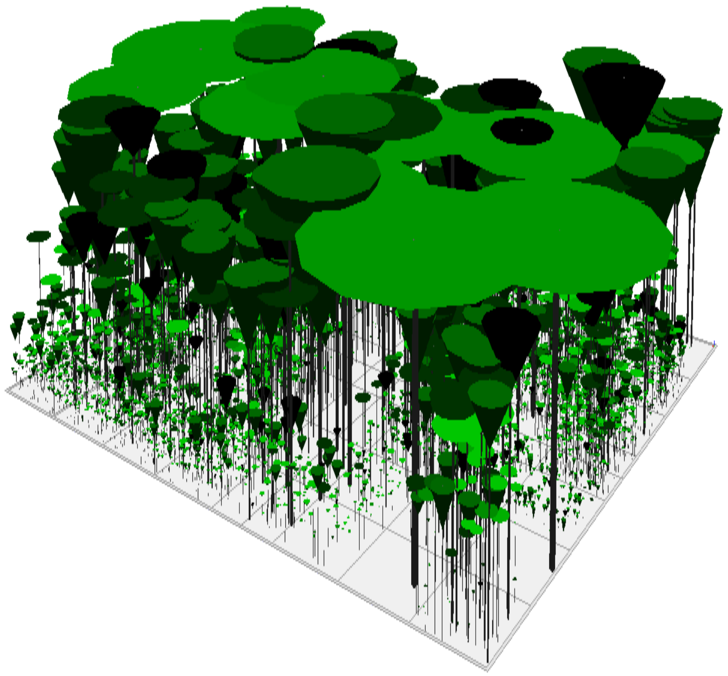

INPUTS
(Climate & soil)
IPCC scenarios
(RCP 4.5 & 8.5)
Historical period
Climate
Temp., Precip.,
VPD
Daily or Monthly
Soil
Water Content
Nutrient level
Carbon quantity
Carbon quality
MODELLING FRAMEWORK
SurEAU
Drought
survival
PHENOFIT
Phenology
Climate-related fitness
Leaf area
Yasso07
Remaining leaf litter
Litter quant. & qual.
(leaves, wood, roots)
ForCEEPS
INPUTS
(Management scenarios)
Species selection
Species list
Species 1
Species 2
...
Species X
Planning
Thinning
Implementation
Scenarisation
OUTPUTS
C stock in soils (1m max.)
Remaining litter quantity
Forest composition & structure
Stand biomass
Wood productivity
Bundle of forest contributions
Habitats for biodiversity
Carbon storage
Wood provision
Landscapes
Fire risk
USERS
& STAKEHOLDERS
Forest owners
(private, public)
Practionners
Wood industry
Policy makers
Public
...
Hierarchisation

Application : Comparing the trajectory of French forests over the next 100 years, for different climatic and management scenarios

Application : Evaluating the trajectory of French forests over the next 100 years, for different climatic and management scenarios

- Modelling the forests carbon stock, including soil carbon

Yasso Coupling : Litter Compartment & Tracking of Soil Carbon



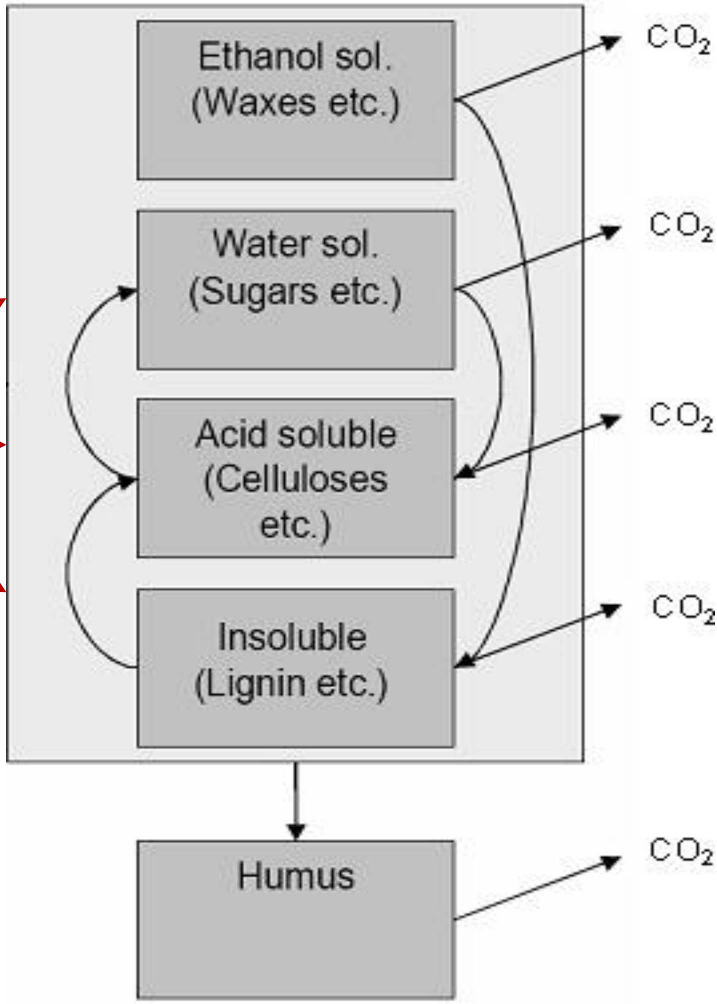
Natural Turnover

Stress-induced crown dieback

Mortality

Logging residue

Species & diameter based repartition



Didion et al., 2014

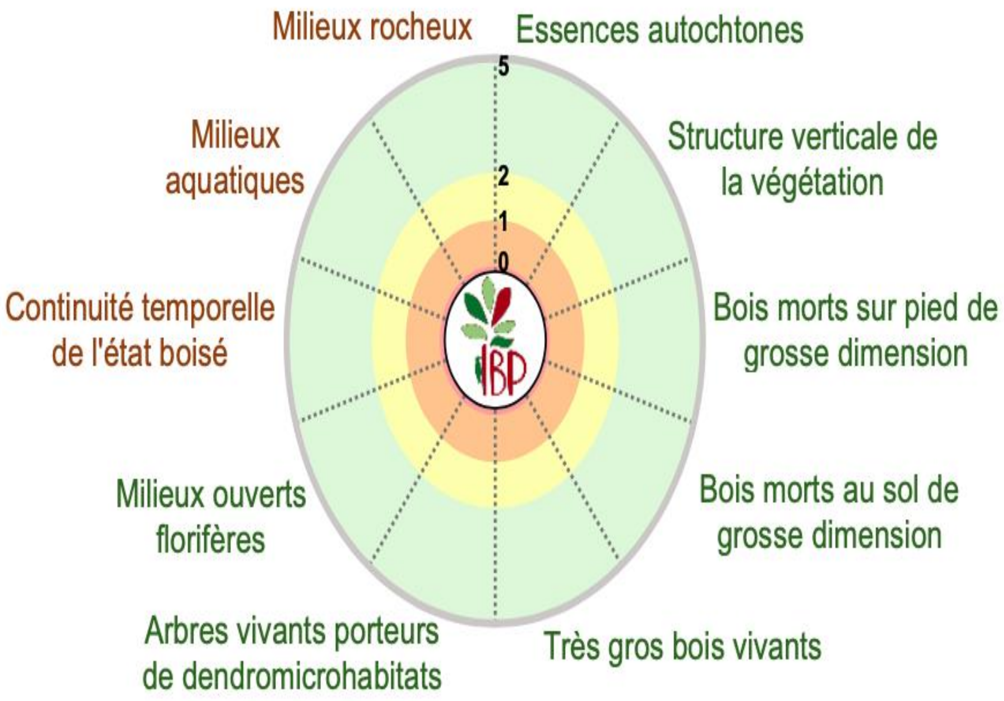
Application : Evaluating the trajectory of French forests over the next 100 years, for different climatic and management scenarios

- ☒ Modelling the forests carbon stock, including soil carbon
- ❑ **Quantifying forest biodiversity potential**

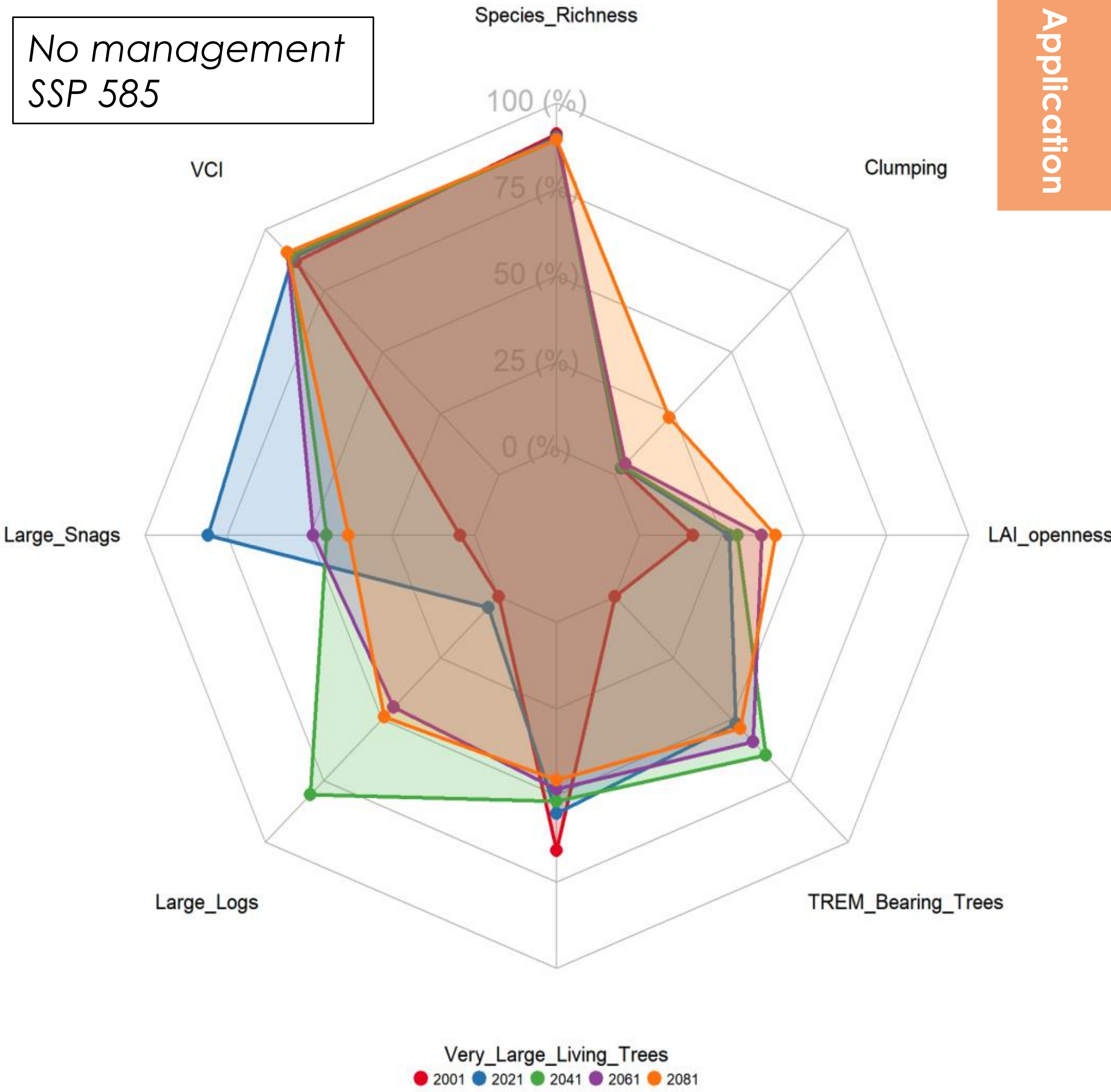
Production of Diversity Indices

Application

Indice de Biodiversité Potentielle (IBP v 3.0)



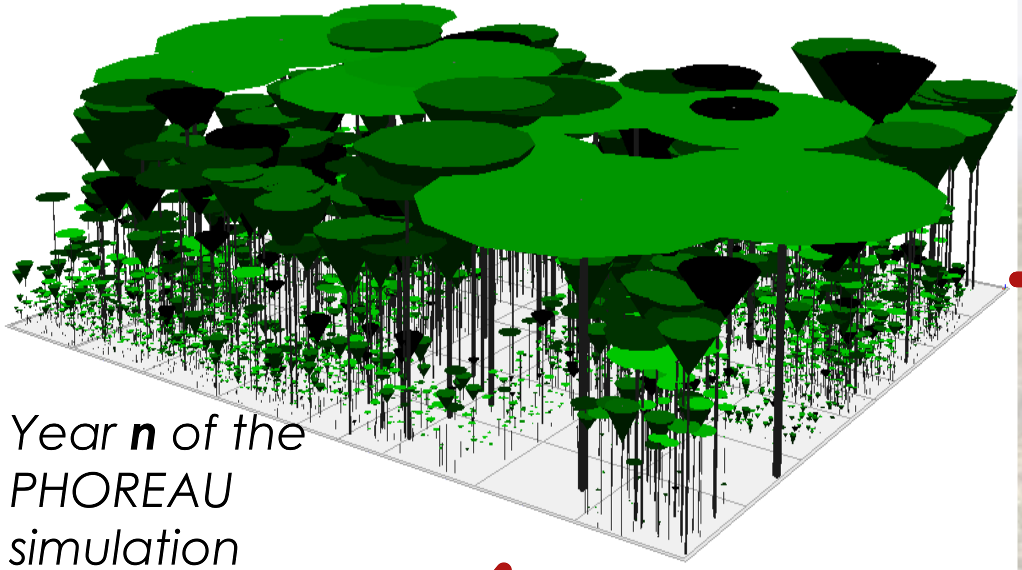
No management
SSP 585



Application : Evaluating the trajectory of French forests over the next 100 years, for different climatic and management scenarios

- ☒ Modelling forests carbon stock, including soil carbon
- ☒ Quantifying forest biodiversity potential
- ❑ Developping flexible forest-management modules

Implementing Dynamic Forest Management Scenarios



*Year **n** of the PHOREAU simulation*

Species 1 : **40%** healthy

...

...

Species j : **90%** healthy

...

...

Species N : **50%** healthy

40% of unhealthy trees **> *Sanitary Cut Threshold***

Sanitary Cut

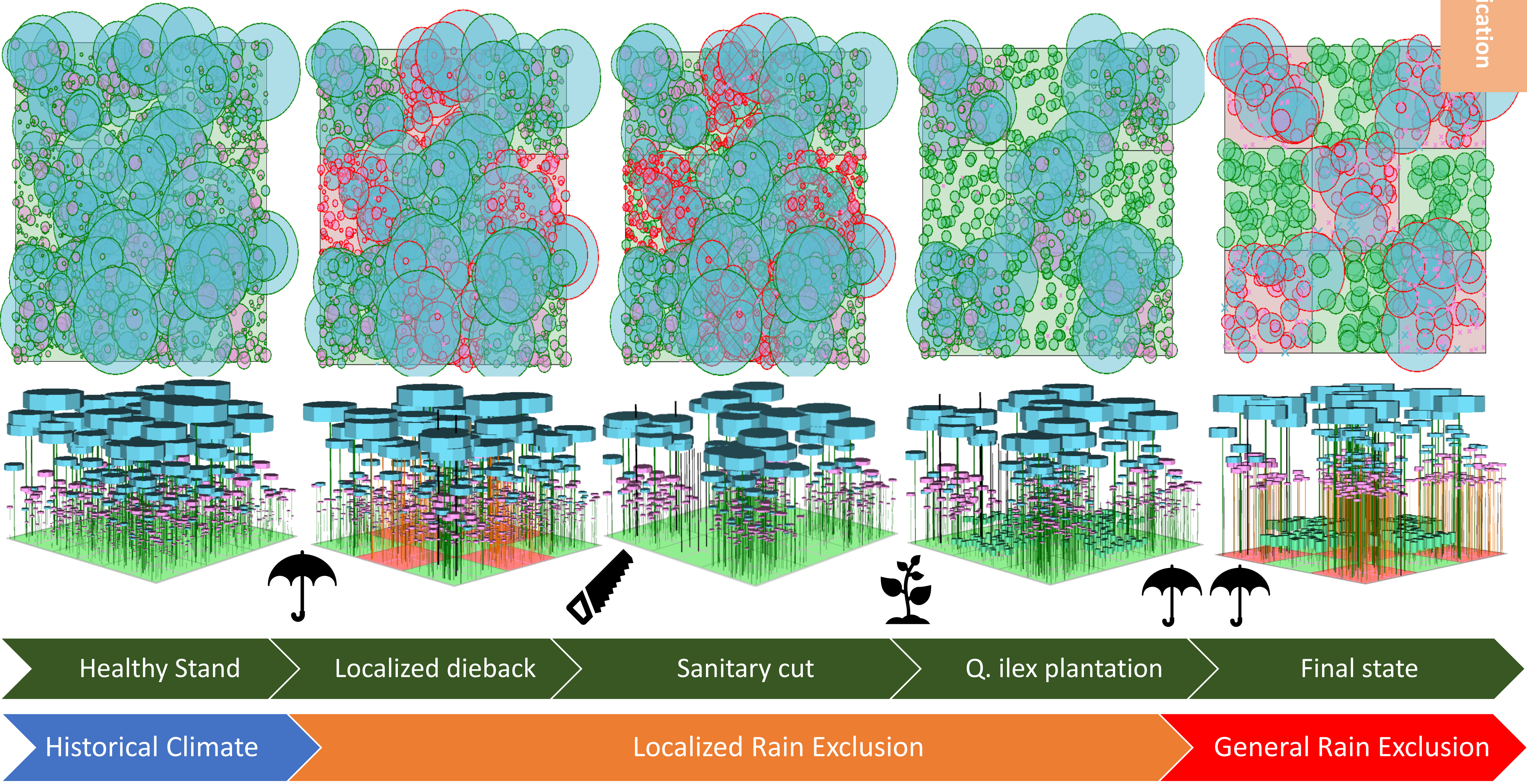
https://foretcitoyenne.org/

Plantation

ONF.fr

PHOREAU Dynamic Management : Proof of Concept

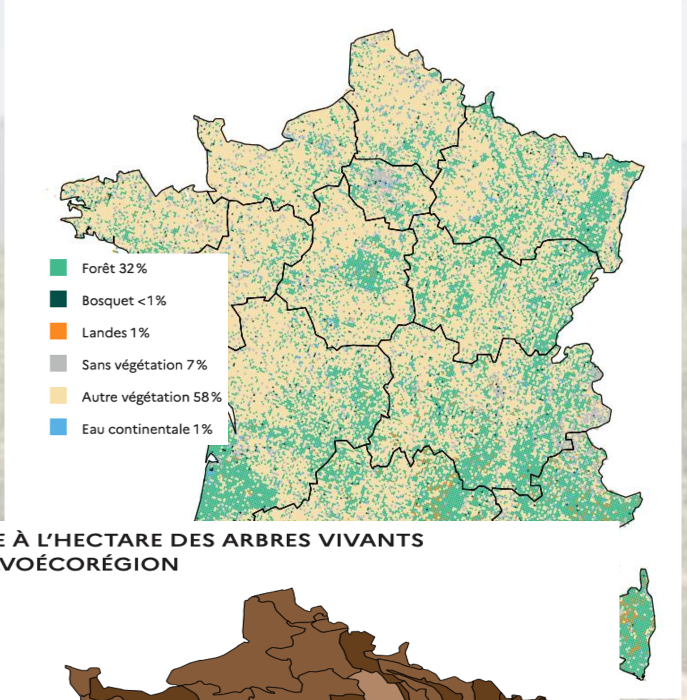
Application

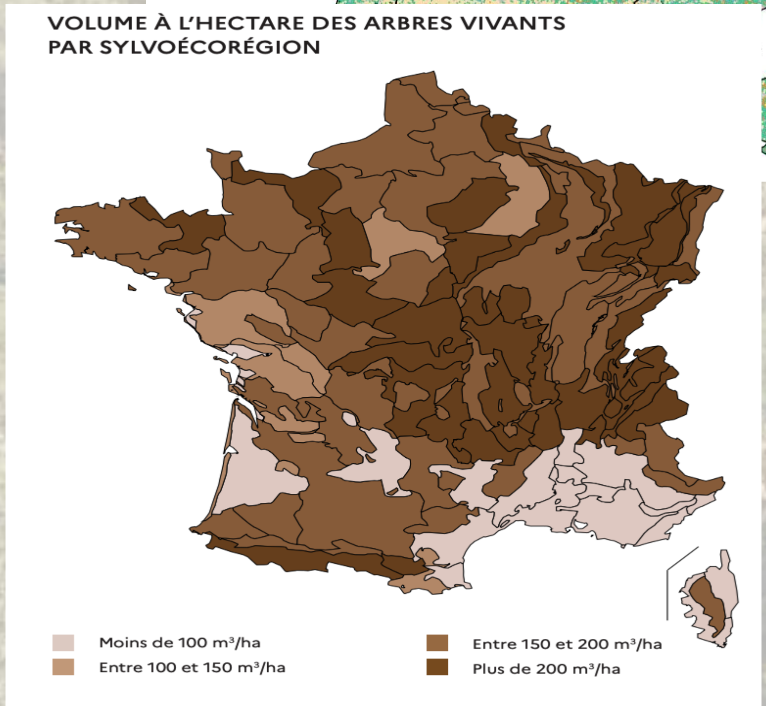


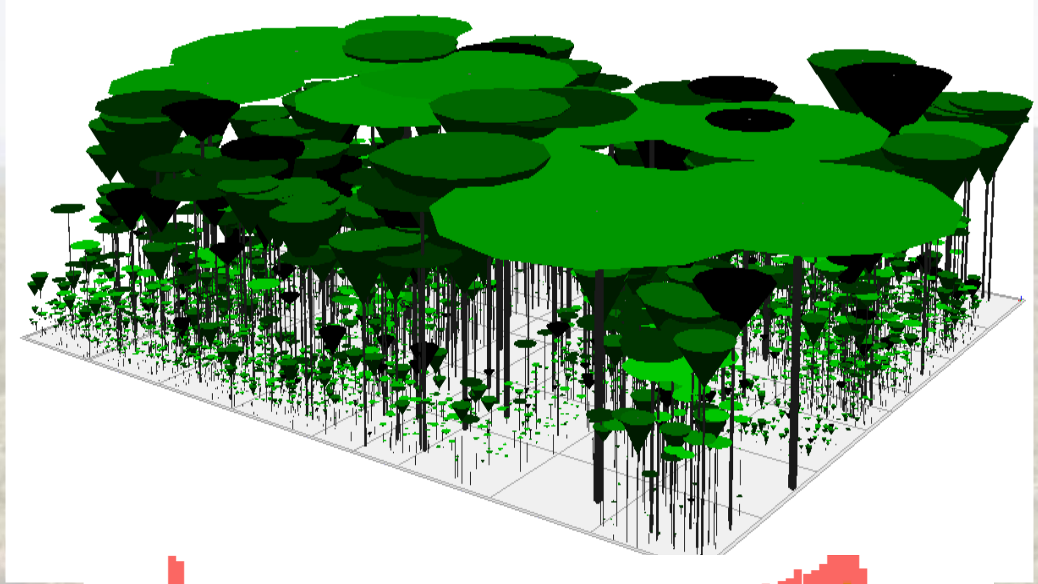
Application : Evaluating the trajectory of the French forest over the next 100 years, for different climatic and management scenarios

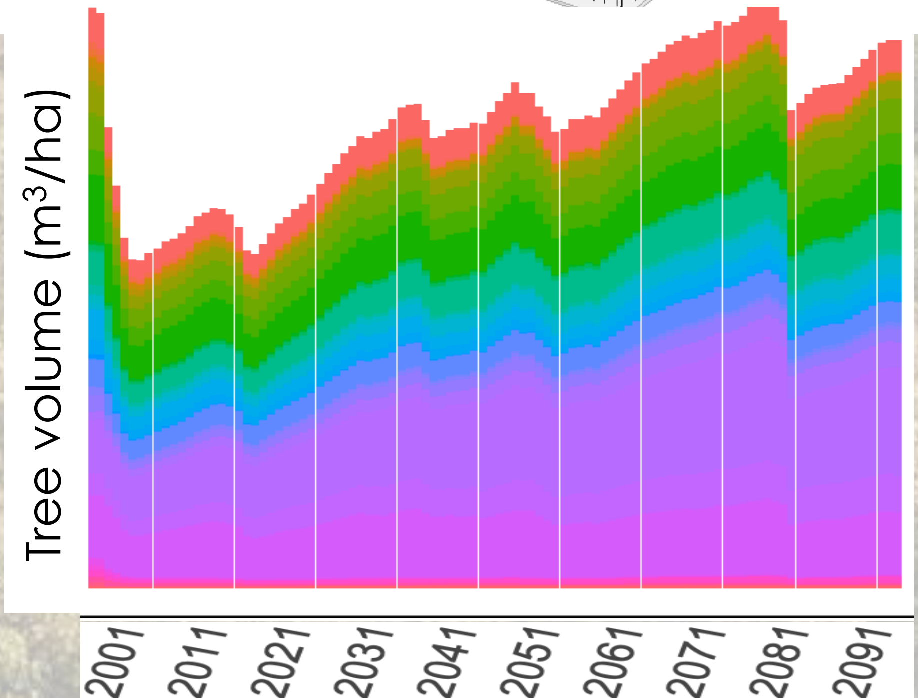
- ☒ Modelling forests carbon stock, including soil carbon
- ☒ Quantifying forest biodiversity potential
- ☒ Developping flexible forest-management modules
- ❑ **Building a representative snapshot of the current state of french forests**

Initializing PHOREAU inventories from IFN study-sites





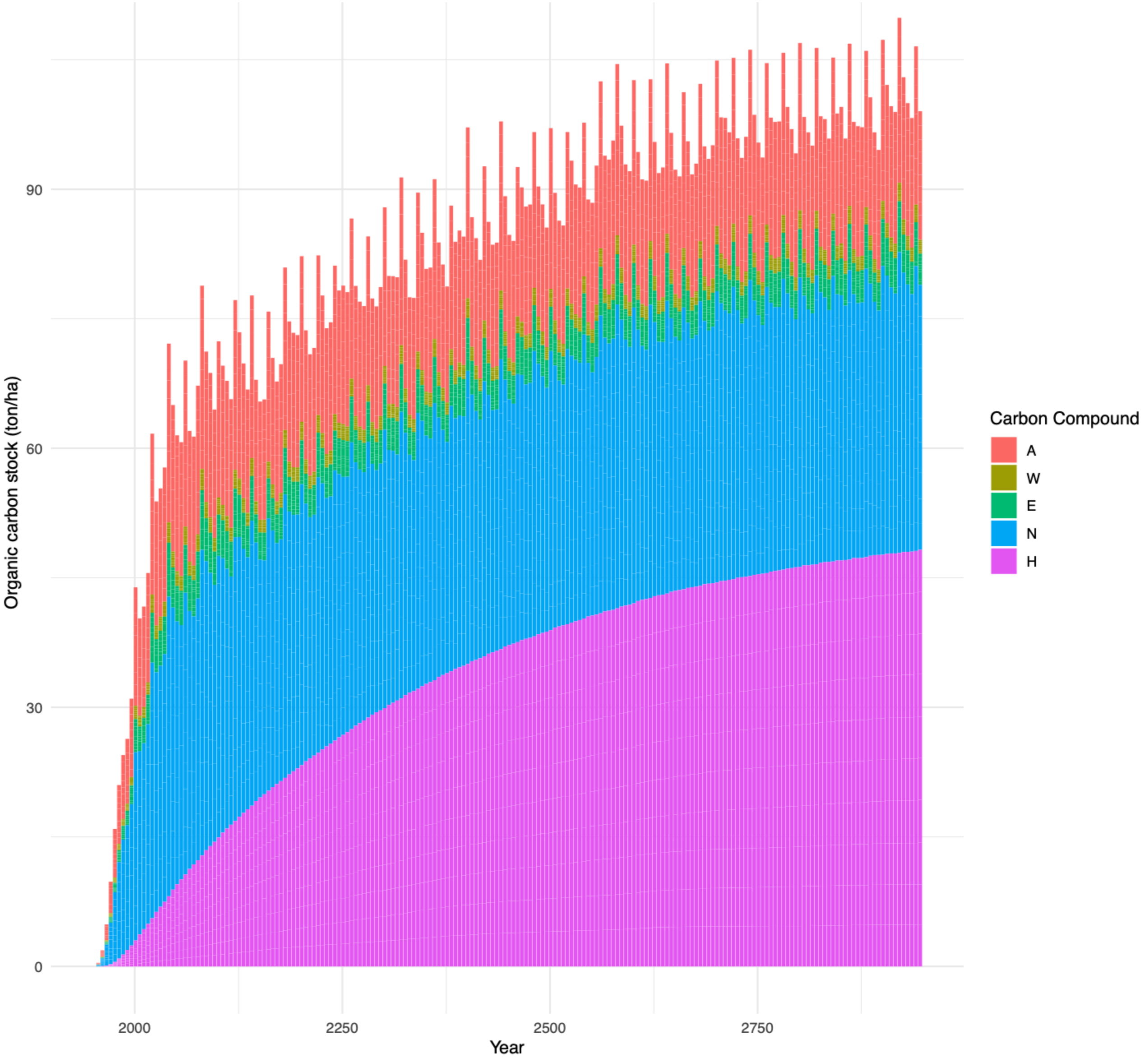




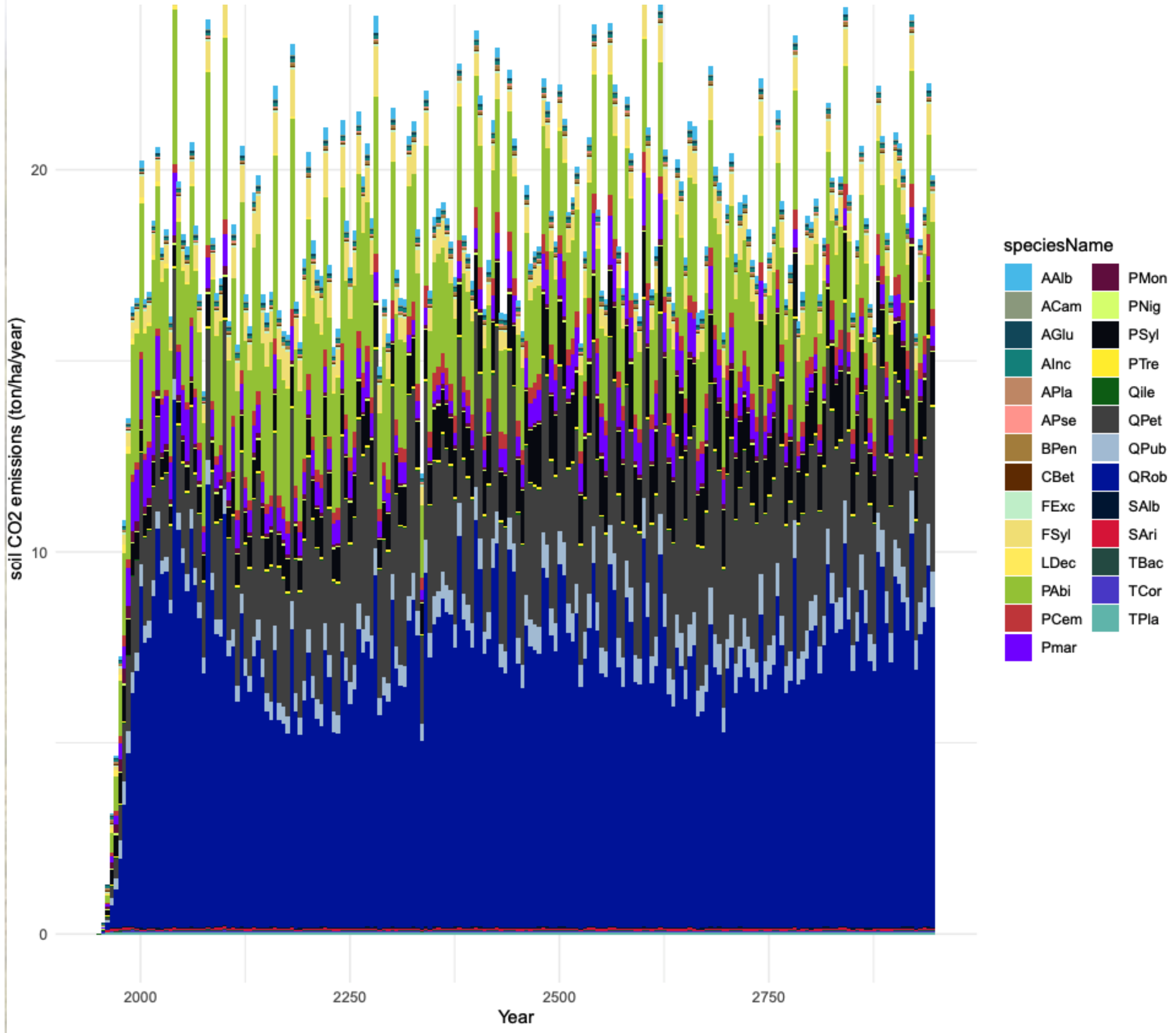
Proof of Concept : Soil Carbon Stocks & Emissions

Forest Services

Evolution of soil carbon stock by compound type



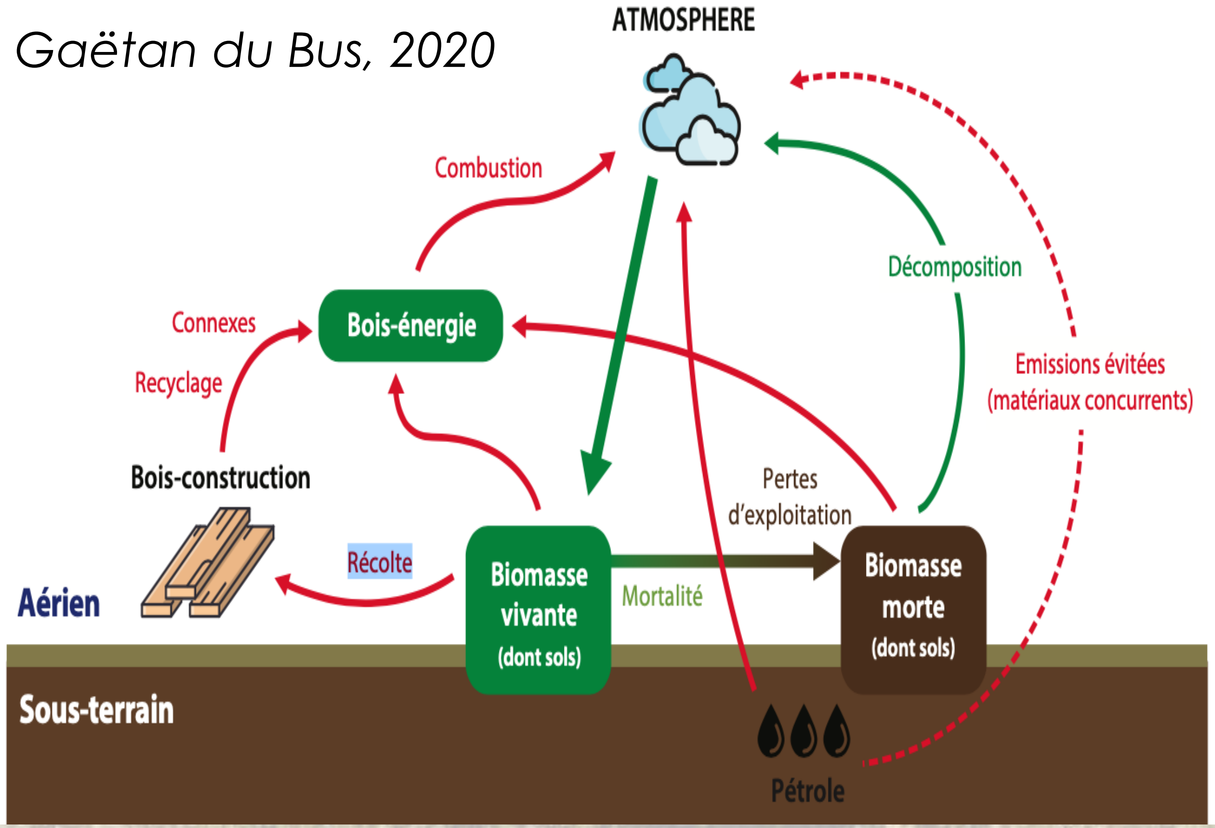
Species contribution to yearly soil CO2 emissions



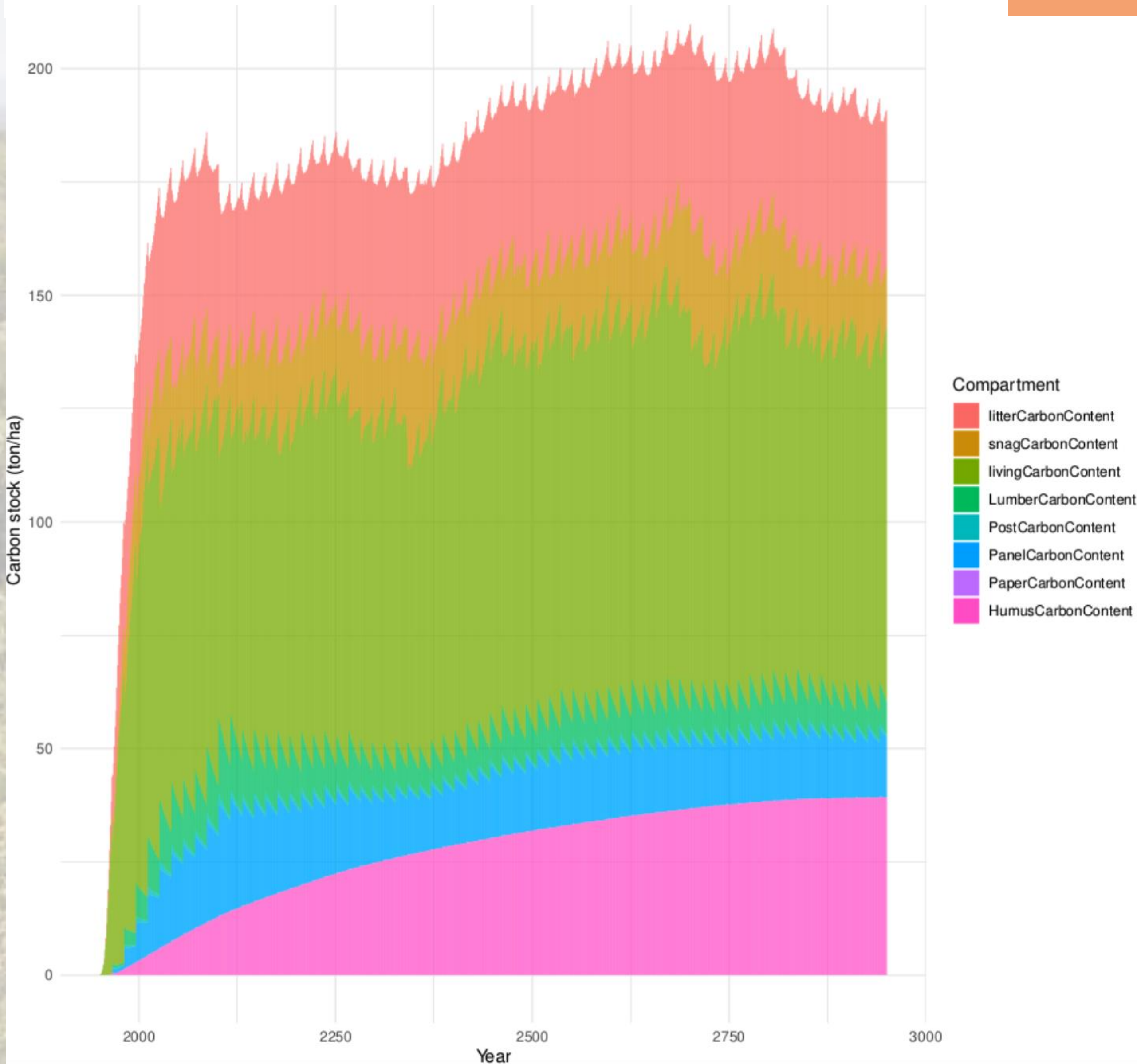
In progress : Carbon sequestration & substitution

1. Allocation of logged wood ?
2. Lifespan of wood-based products ?
3. Coefficient of substitution compared to non-wood products ?
4. Usage of logging residues ?

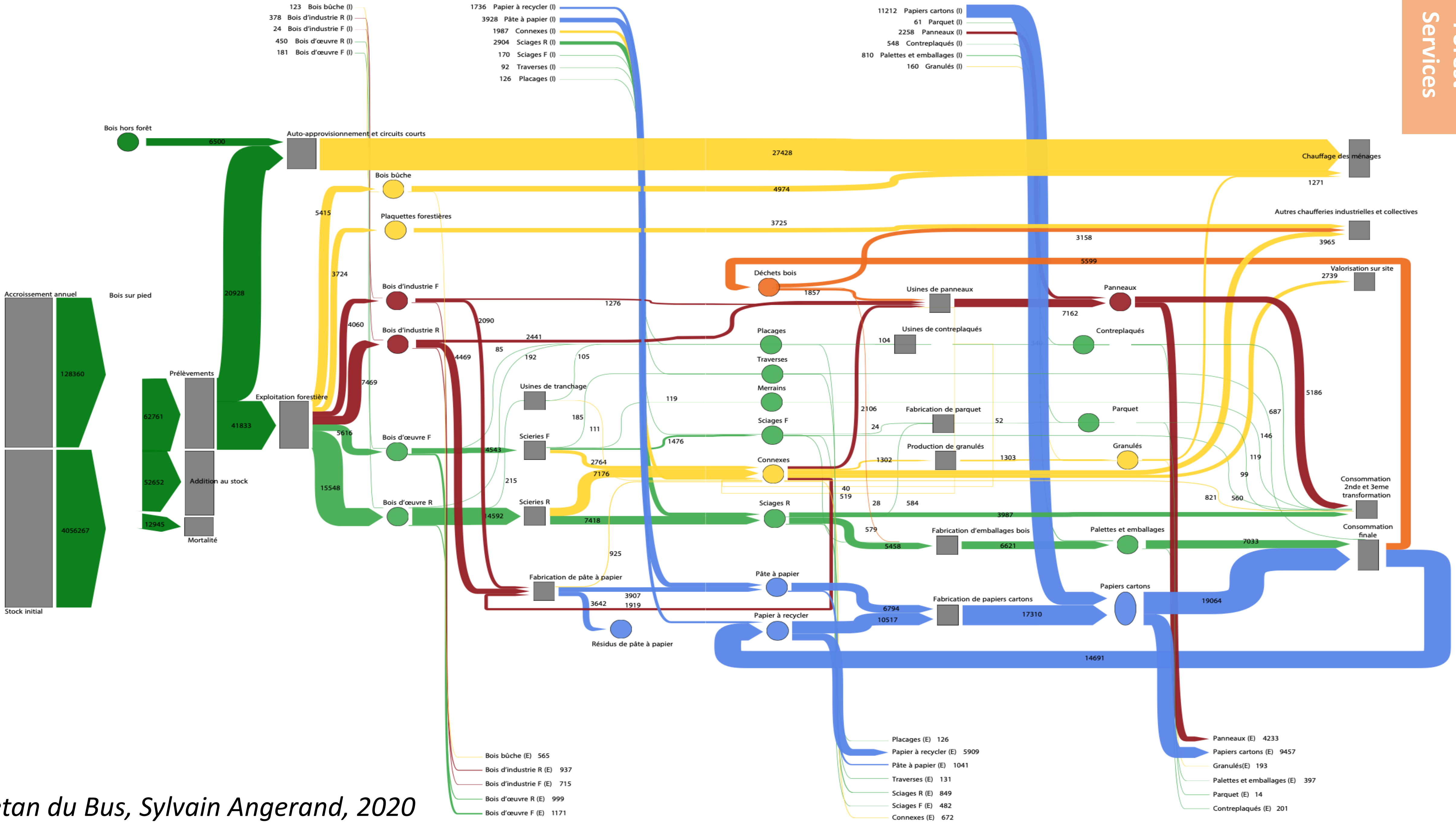
Gaëtan du Bus, 2020



Evolution of predicted sequestred carbon



Forest Services



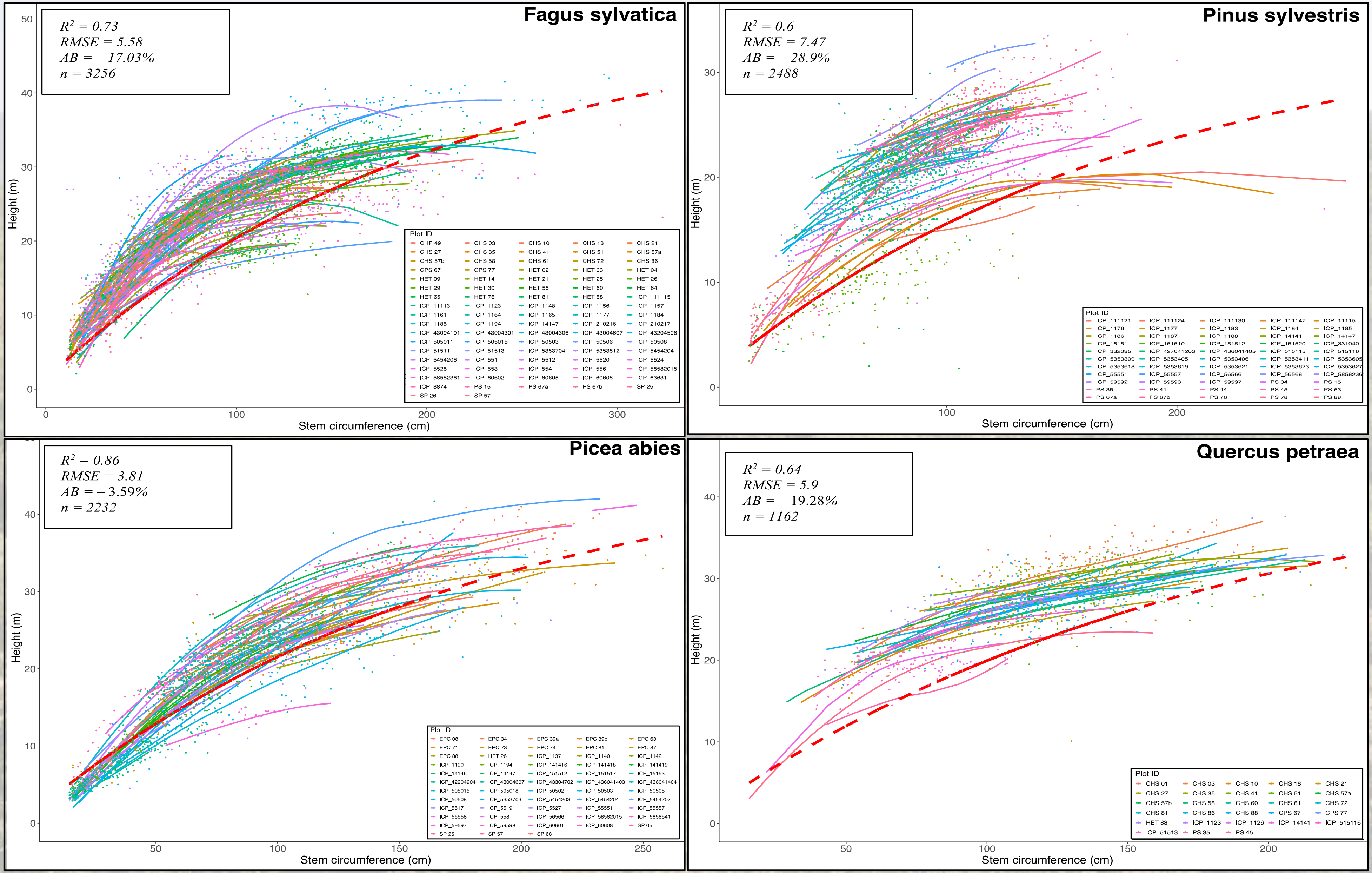
Gäetan du Bus, Sylvain Angerand, 2020

WP3 : Plan de Simulation

- Création des Sols
  - Equilibre hydrologique
  - Equilibre Yasso

WP3 : Plan de Simulation

Forest Services



Octobre 2024

- Échanges avec gestionnaires sites ICOS
- Finalisation validation sur les niches
- Préparation du schéma conceptuel PHOREAU
- Interprétation des résultats

Novembre 2024

- Rédaction Discussion, Conclusion pour la 1ère partie.
- Mise en forme pour publication

Décembre 2024

- Projections de distribution sur l'Europe
- Préparation inventaires IFN pour 3ème partie.

Janvier 2024

- Analyse des résultats de projection de distribution
- Analyse de sensibilité du modèle
- Rédaction de la 2ème partie.

Février 2024

- Préparation scénarios de gestion basés sur les enquêtes sociologiques FISSA
- Revue bibliographique des puits et émissions de carbone liés à la gestion forestière

Mars 2025

Simulation de projection de puits de carbone et de réservoir de biodiversité sur l'ensemble des points IFN, pour plusieurs scénarios de gestion, climatiques, et d'industrie

Rédaction Matériel et Méthode 3ème partie

Avril 2025

Simulation de projection de puits de carbone et de réservoir de biodiversité sur l'ensemble des points IFN, pour plusieurs scénarios de gestion, climatiques, et d'industrie

Rédaction Matériel et Méthode 3ème partie

Mai 2025

Analyse des résultats « carbone »

Juin 2025

Analyse des résultats « diversité »

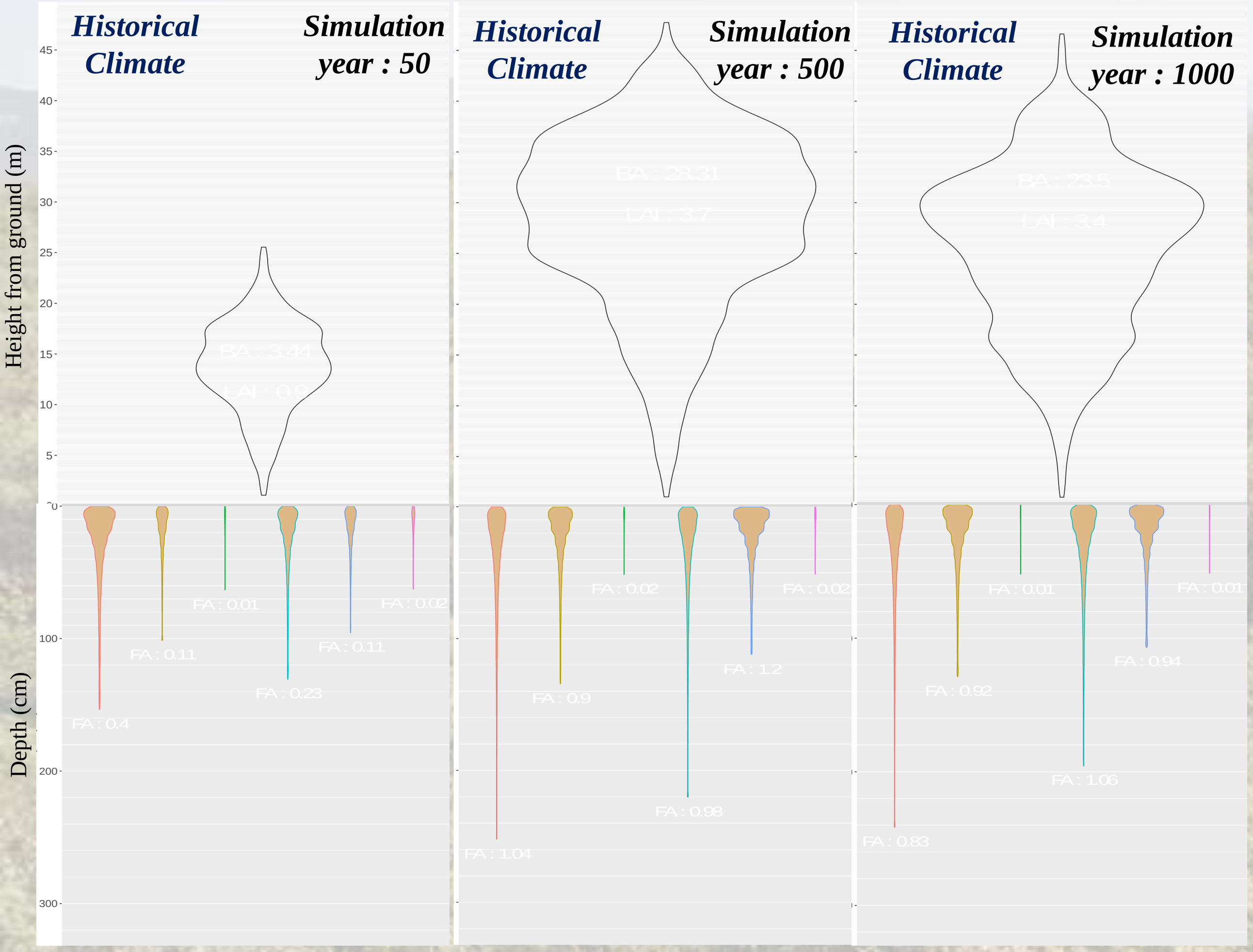
Juillet, Aout, Septembre 2025

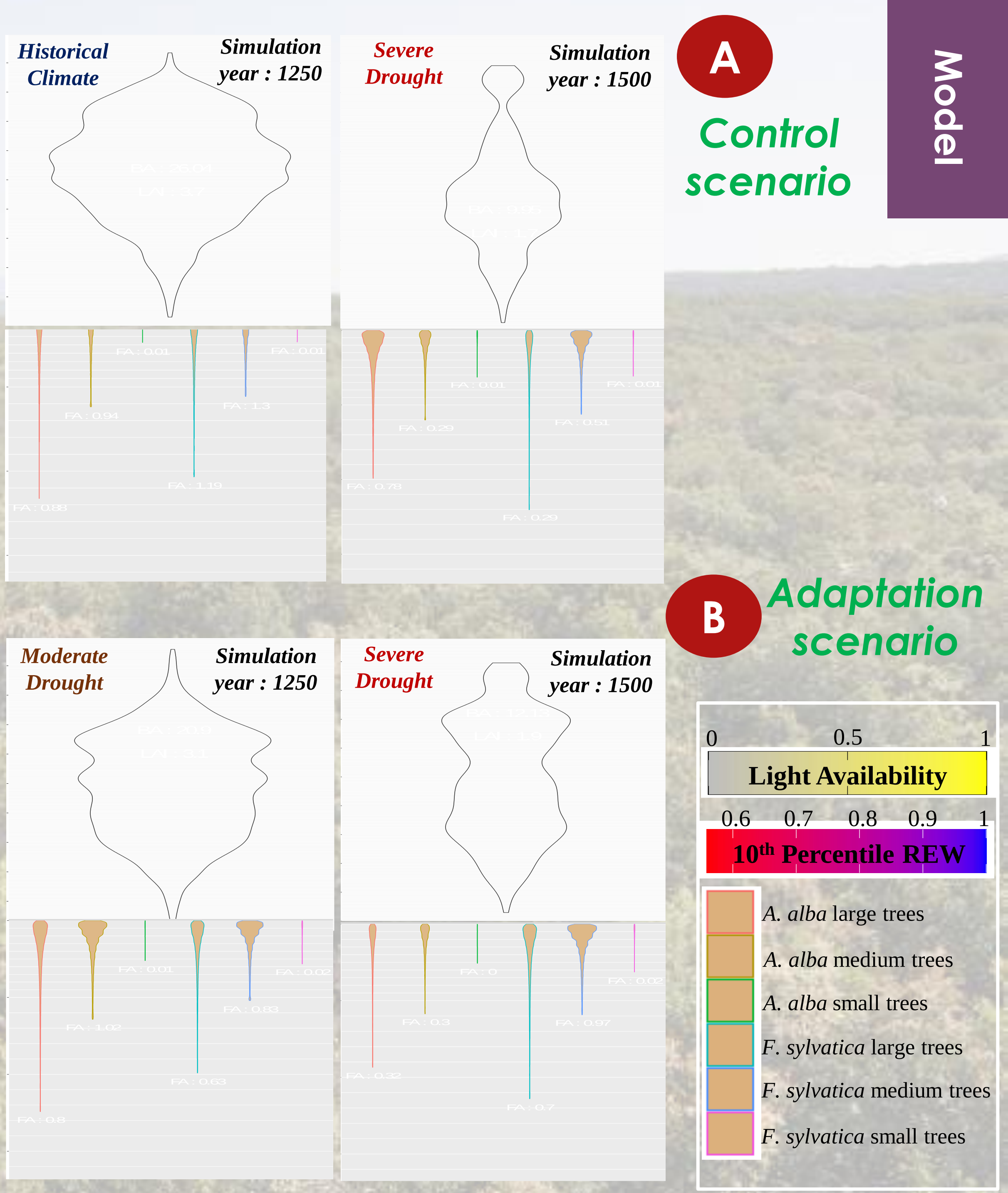
Préparation de l'article « Scénarios de Gestion et Services Forestiers »

Rédaction du manuscrit de thèse

FIN

Proof of Concept : drought-adaptation





Modèle

Application :

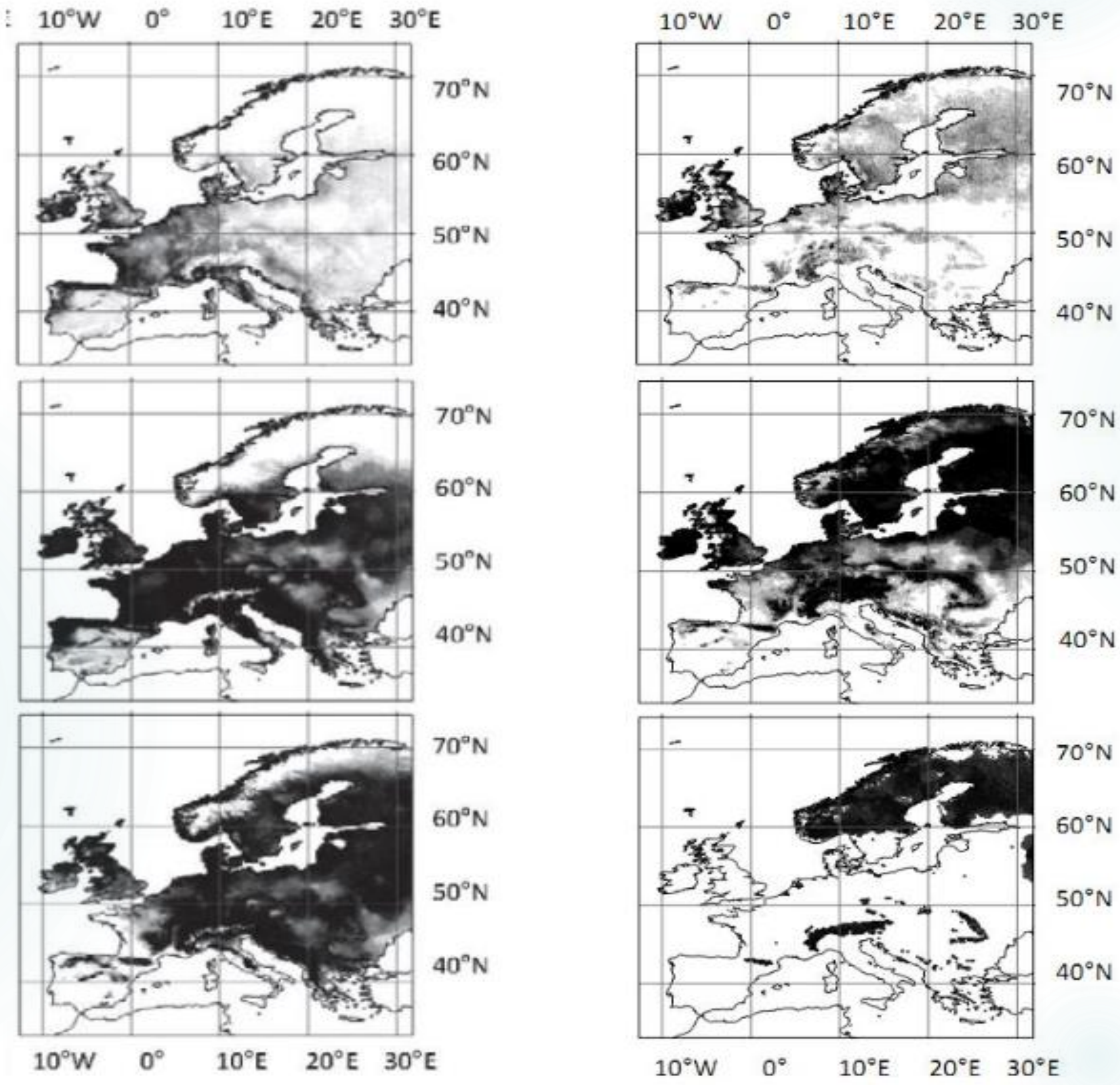
Projection d'aires de répartitions sous différents scénarios climatiques

2000 | **2100 (A1Fi ~+3°C)**

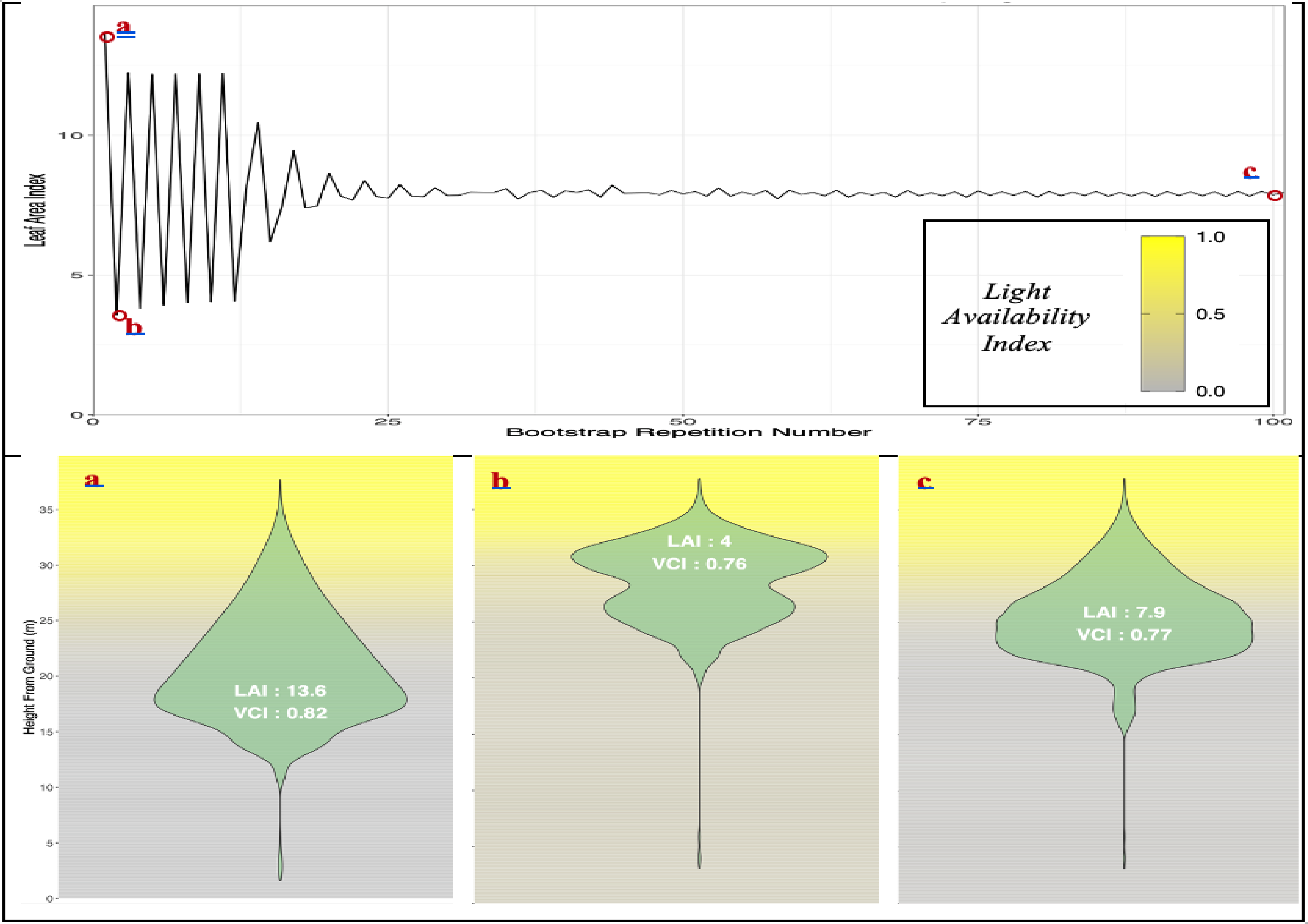
Fagus sylvatica

Quercus robur

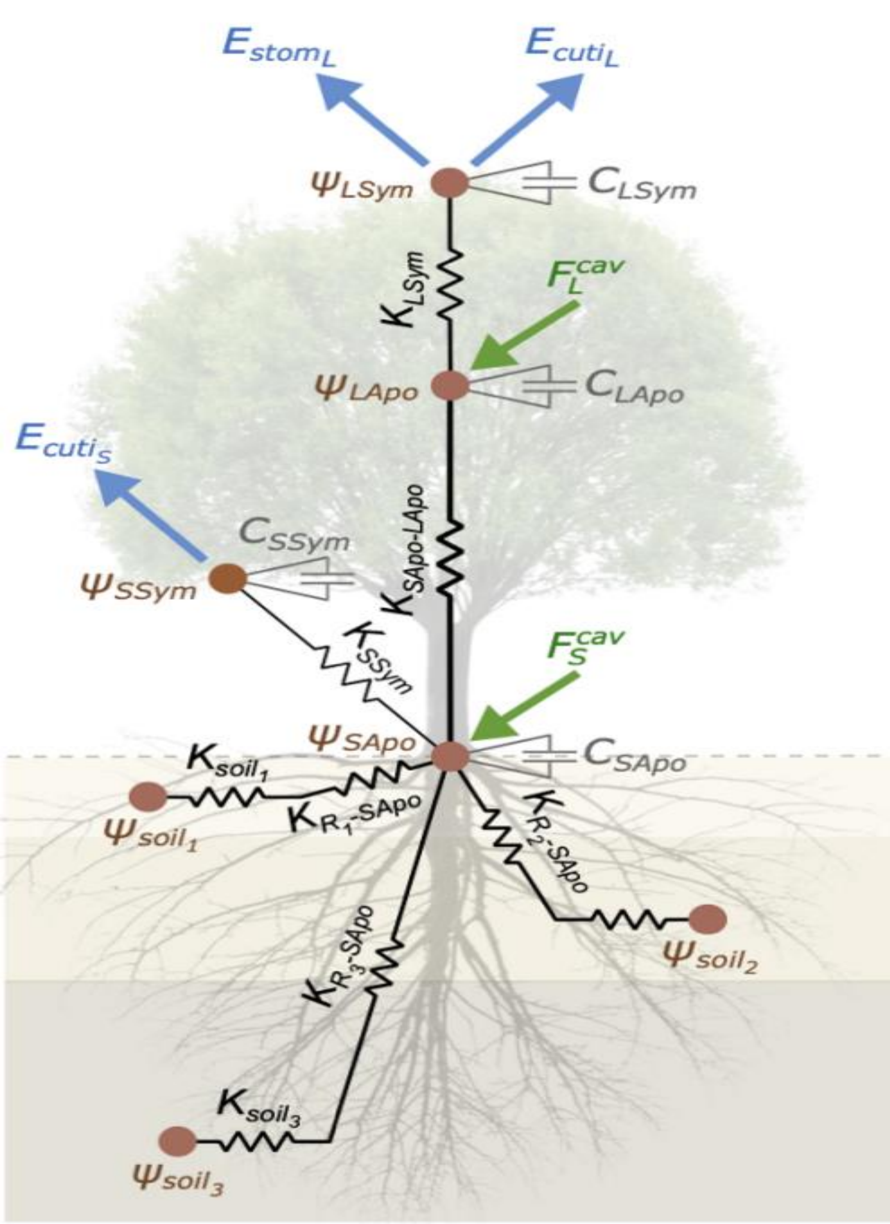
Pinus sylvestris



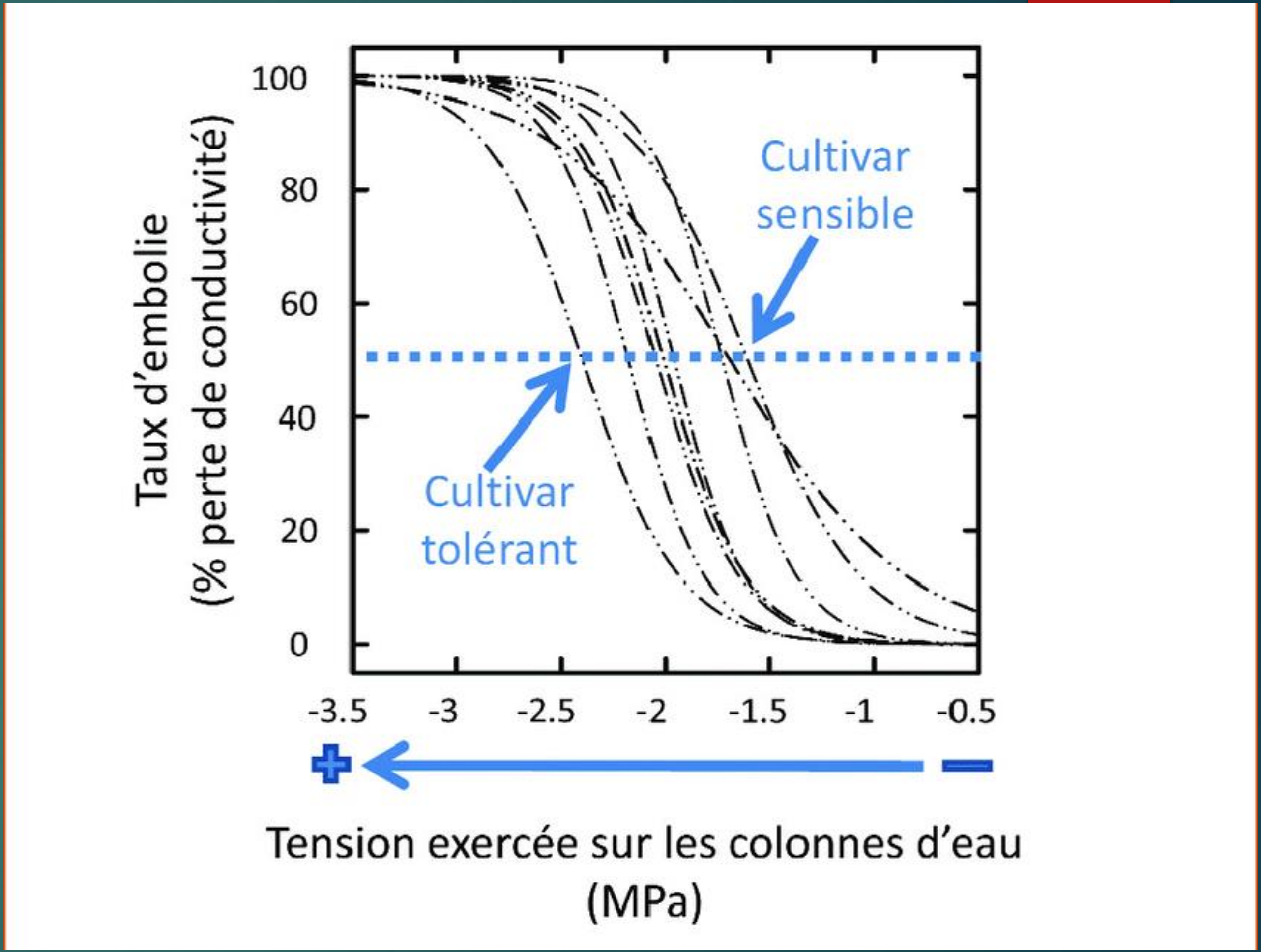
Gritti et al. 2013 MEE



a
b
c
Leaf Area Index
Bootstrap Repetition Number
Light Availability Index
1.0
0.5
0.0
Height From Ground (m)
LAI : 13.6
VCI : 0.82
LAI : 4
VCI : 0.76
LAI : 7.9
VCI : 0.77



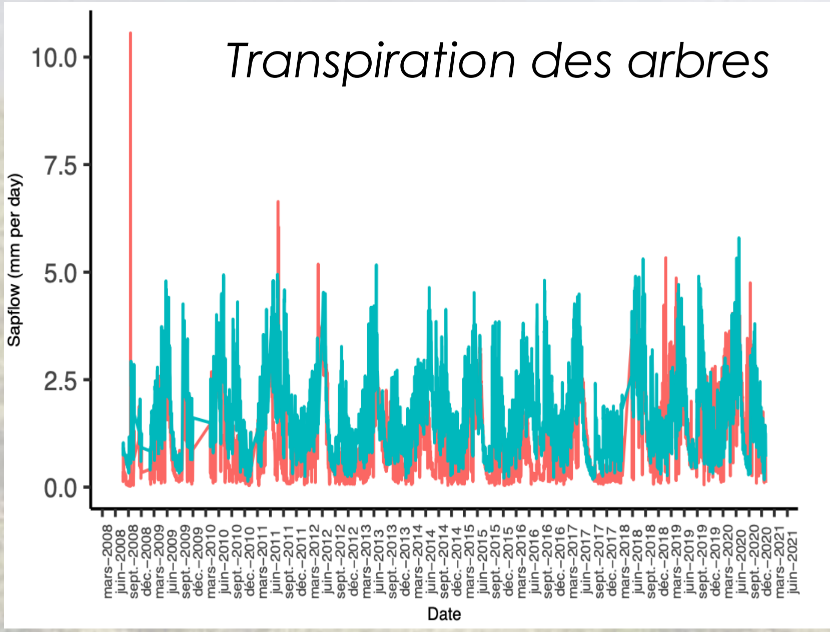
E_{stom_L}
E_{cuti_L}
Ψ_{LSym}
C_{LSym}
K_{LSym}
F_L^{cav}
Ψ_{LApo}
C_{LApo}
E_{cuti_S}
C_{SSym}
$K_{SApo\text{-}LApo}$
Ψ_{SSym}
K_{SSym}
F_S^{cav}
Ψ_{SApo}
C_{SApo}
K_{soil_1}
$K_{R_1\text{-}SApo}$
Ψ_{soil_1}
$K_{R_2\text{-}SApo}$
$K_{R_3\text{-}SApo}$
Ψ_{soil_2}
K_{soil_3}
Ψ_{soil_3}

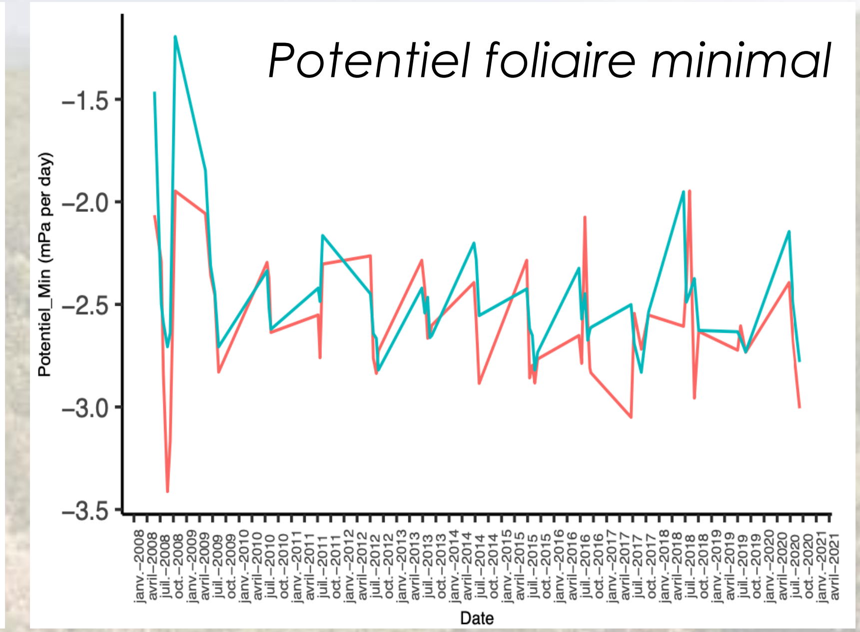


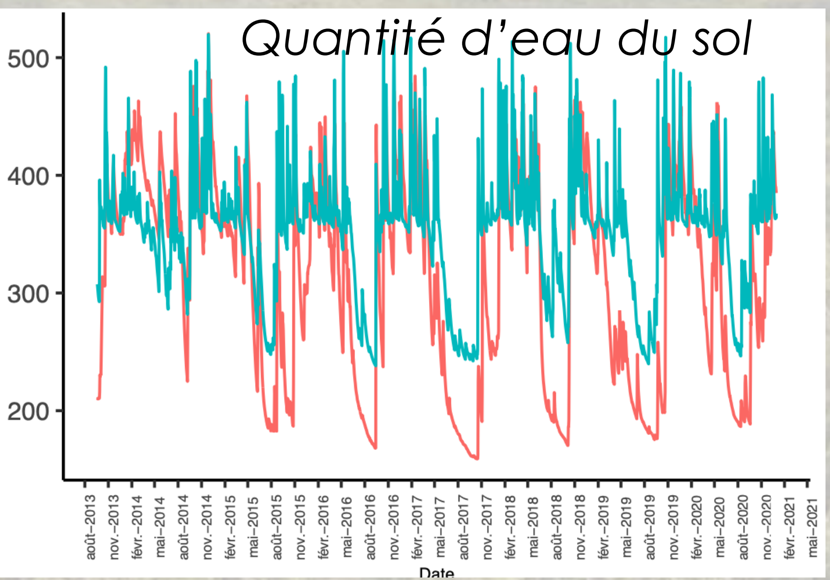
Taux d'embolie
(% perte de conductivité)
100
80
60
40
20
0
Cultivar sensible
Cultivar tolérant
-3.5
-3
-2.5
-2
-1.5
-1
-0.5
+
−
Tension exercée sur les colonnes d'eau
(MPa)

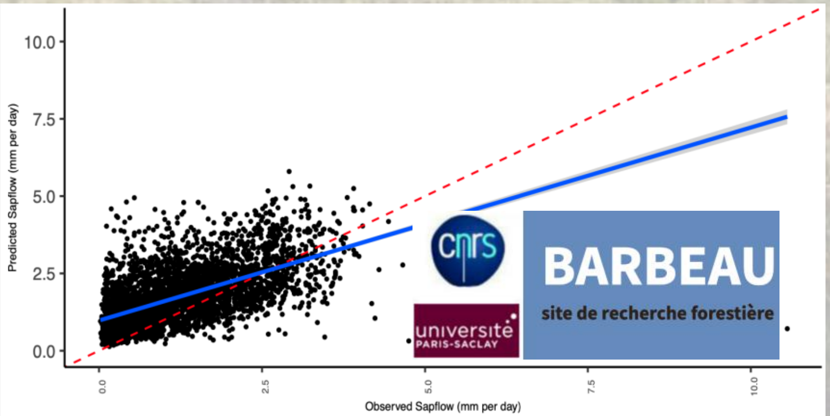
1 Validation sur **l'hydrologie**

Validation

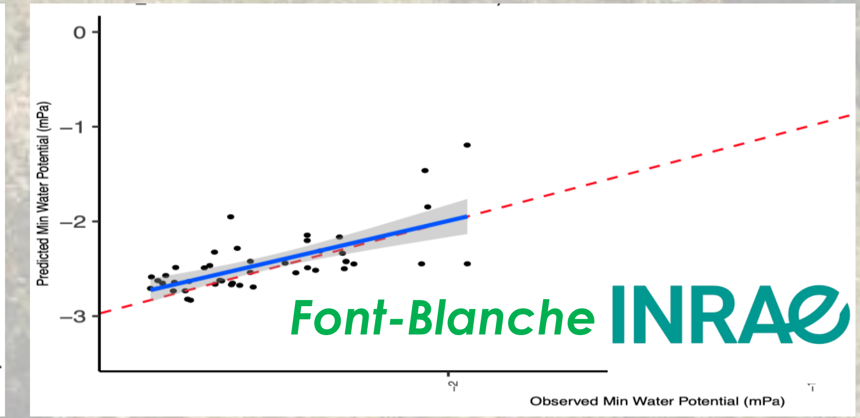




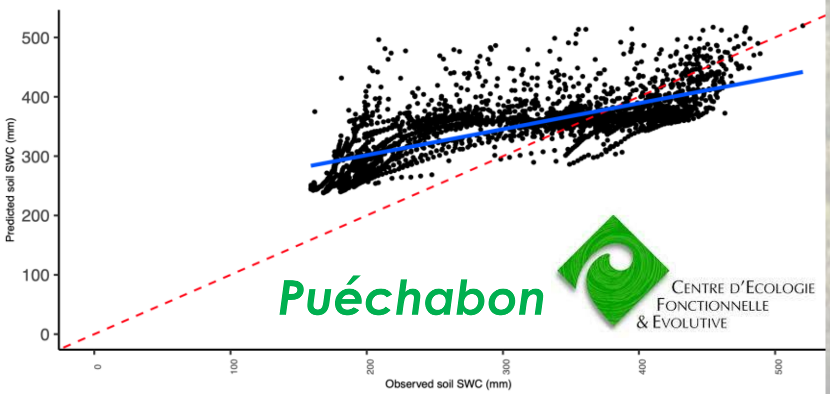




BARBEAU site de recherche forestière



Font-Blanche

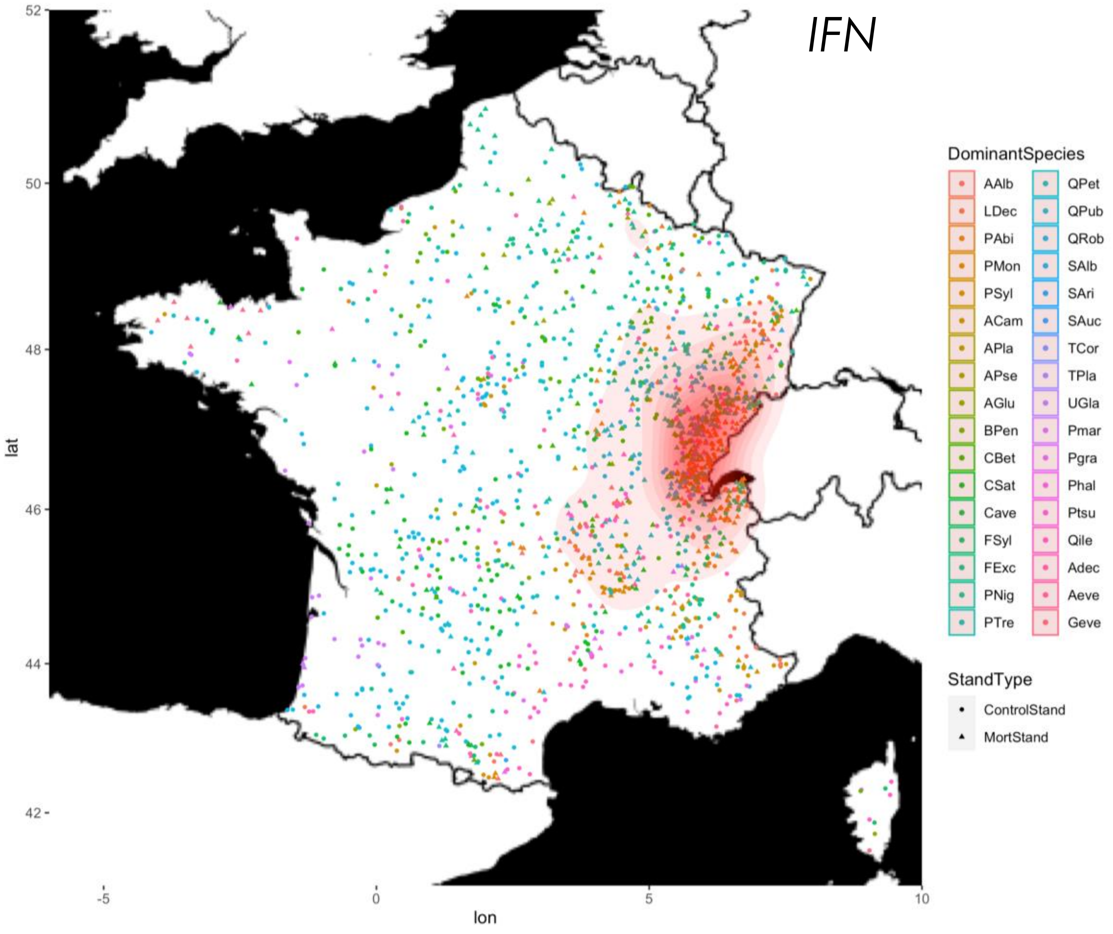


Puéchabon

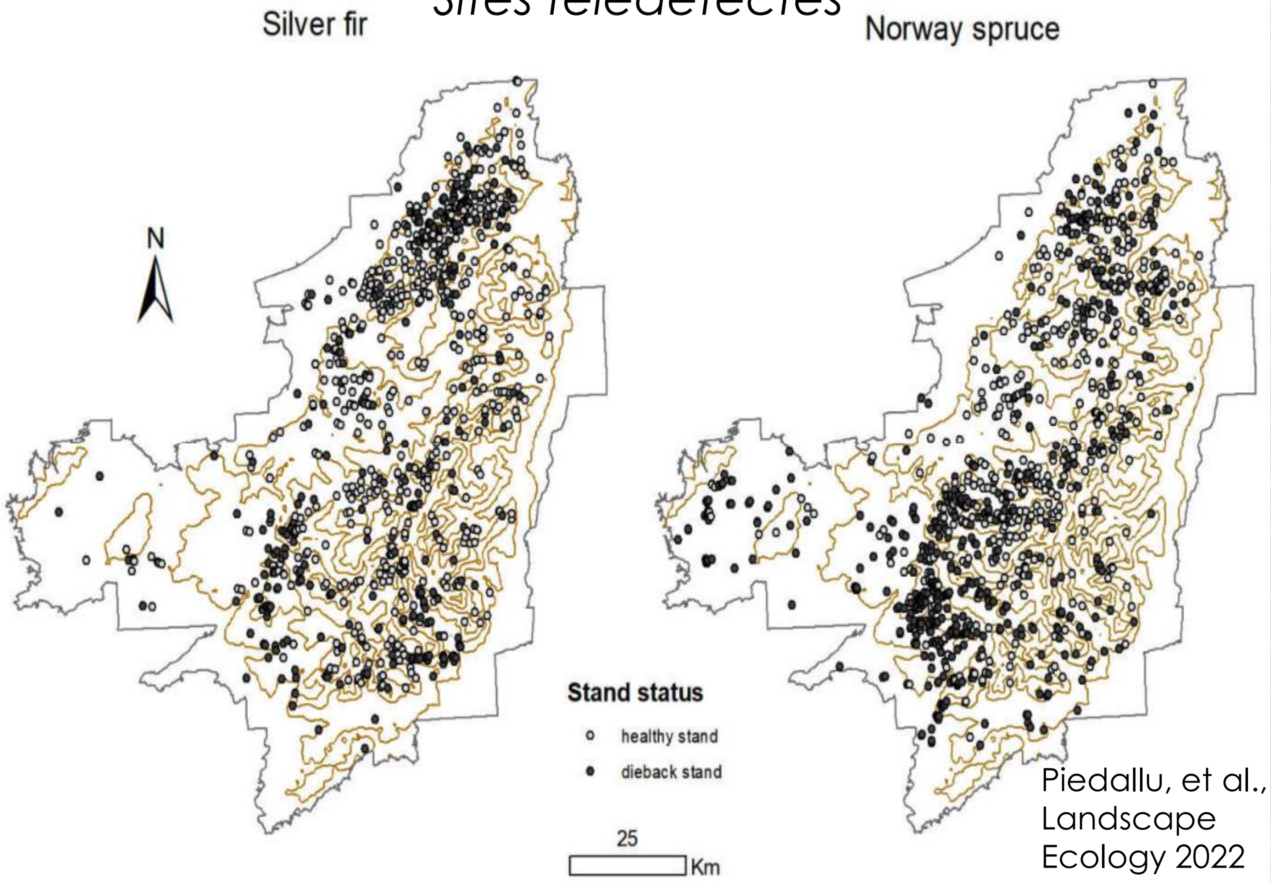
Centre d'Ecologie Fonctionnelle & Evolutive

3 Validation sur la **mortalité**

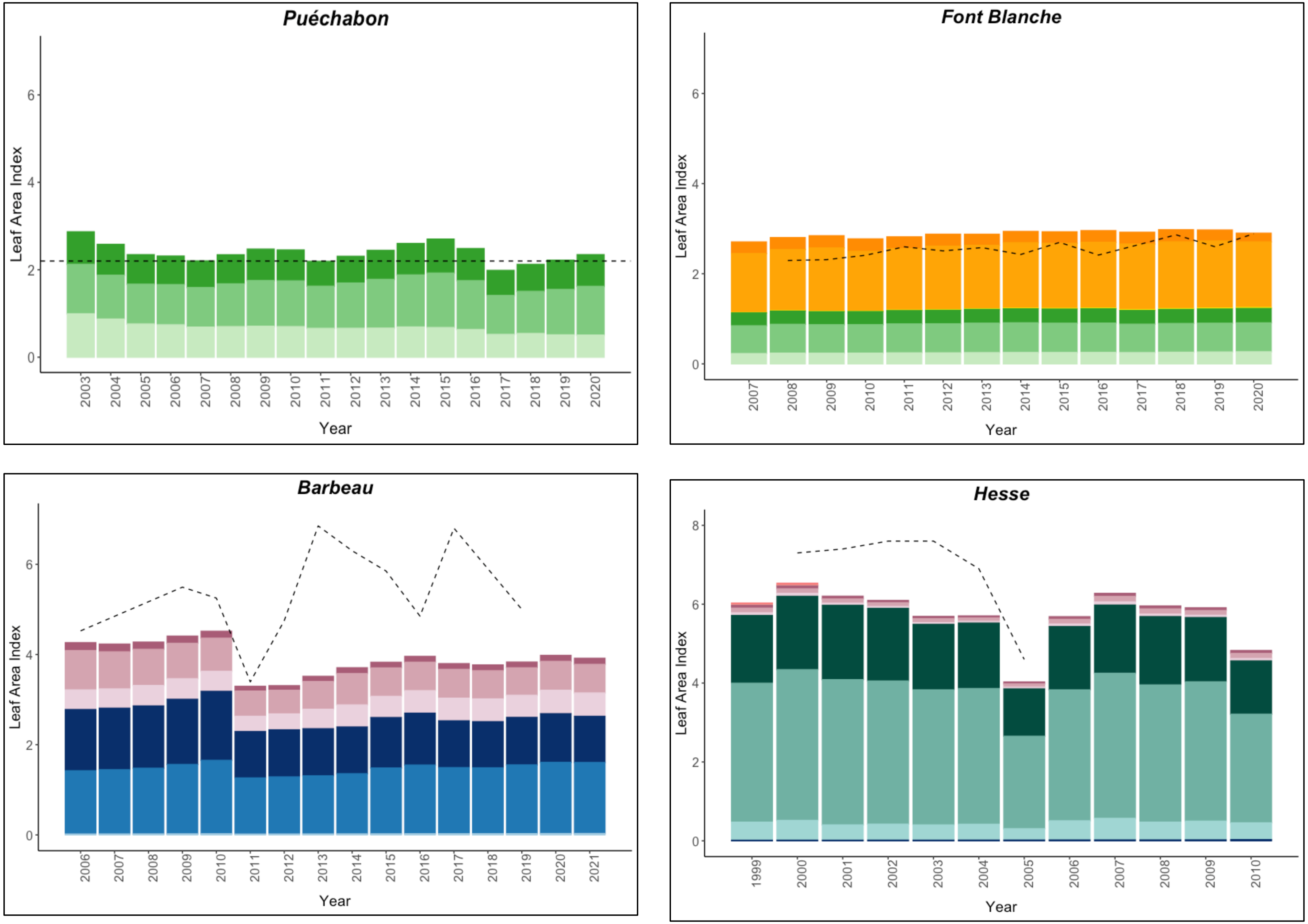
Inventaires IFN



Sites télédétectés



Piedallu, et al., Landscape Ecology 2022



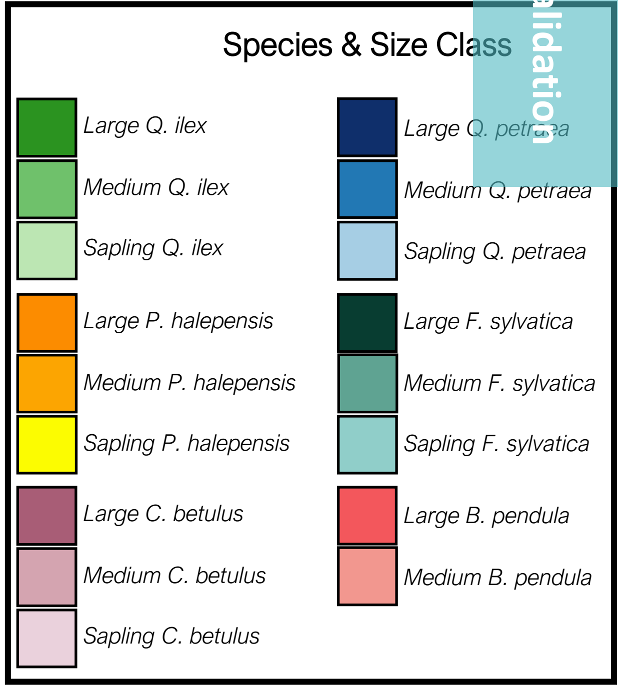
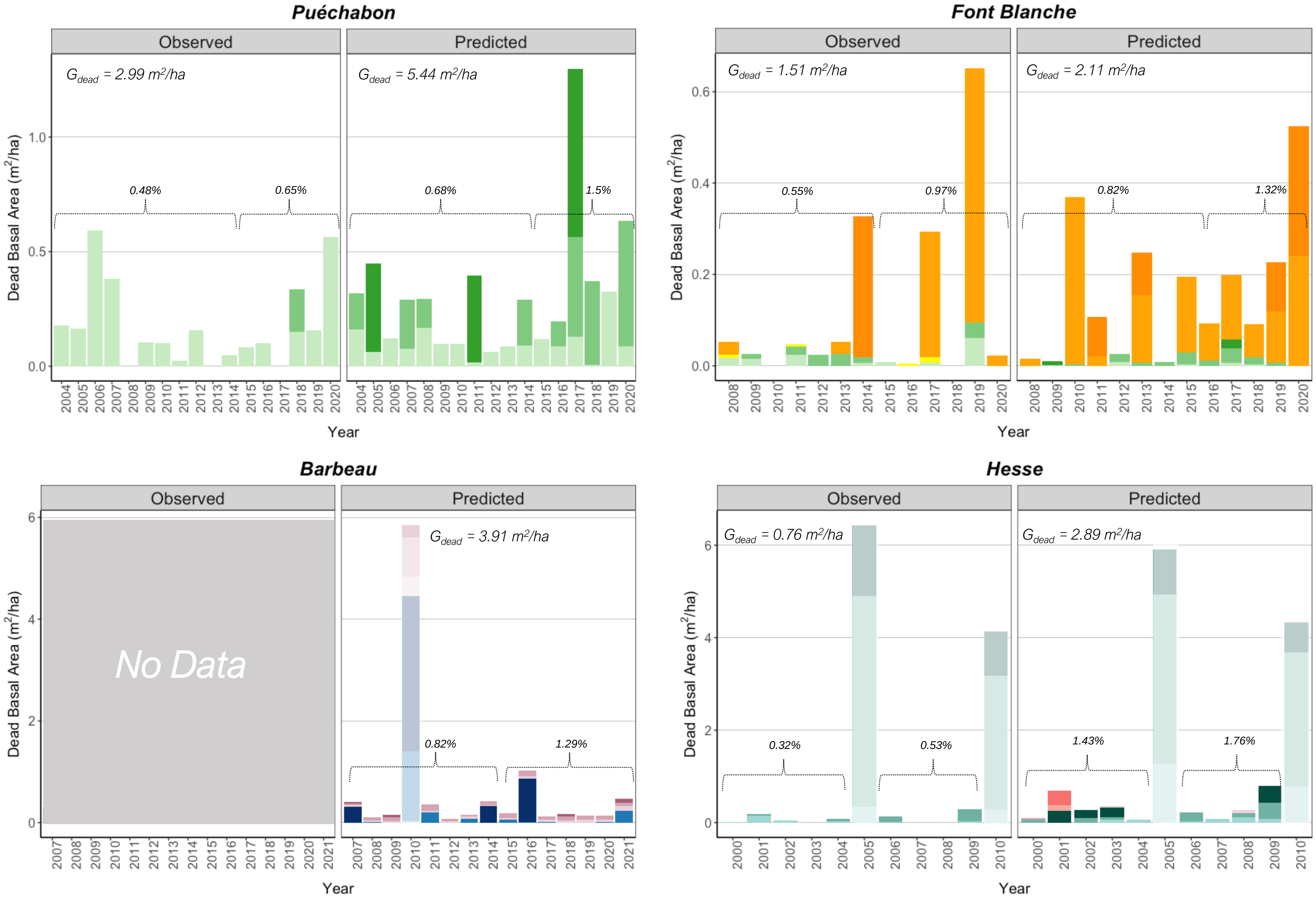


Fig. 2 | Predicted versus observed annual stand leaf area index (LAI). For each simulation site, the bars depict the annual leaf area index projections generated by the PHOREAU model, broken down by species and size class contributions (refer to Annex X for details). The dashed line represents the observed annual stand leaf area index (data sources detailed in Annex X). Leaf area index is defined as the total one-sided leaf area per unit of ground area.

Validation

Fig. 3 | Predicted versus observed annual tree mortality. For each simulation site, the bars depict the total annual number of dead trees, irrespective of cause, broken down by species and size class contributions (refer to Annex X for details). Observed values are derived from stand inventories, while predicted values are generated by the PHOREAU model. Also shown are the annual mortality rates, calculated relative to the initial number of trees for two distinct time periods in each simulation, along with the total number of dead trees by hectare. Transparent bars indicate years with thinnings (see Annex X for details), which are excluded from the mortality statistics.



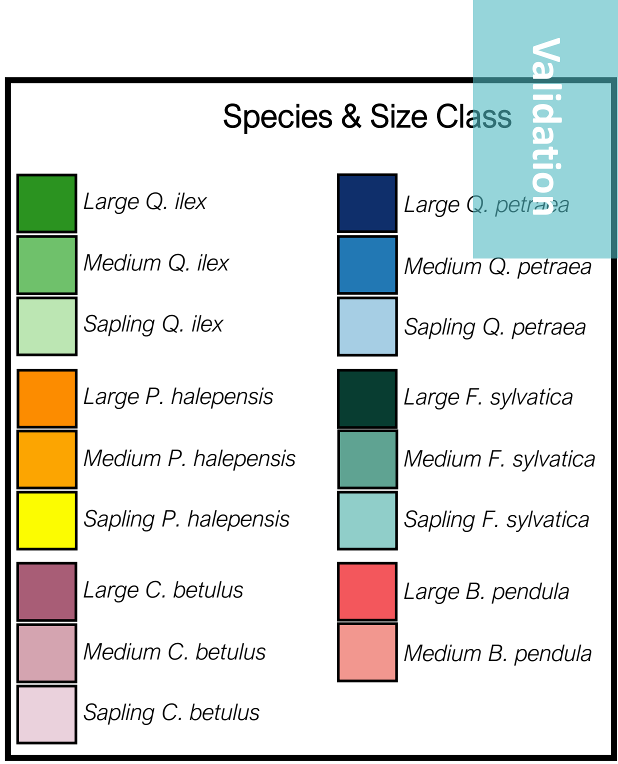
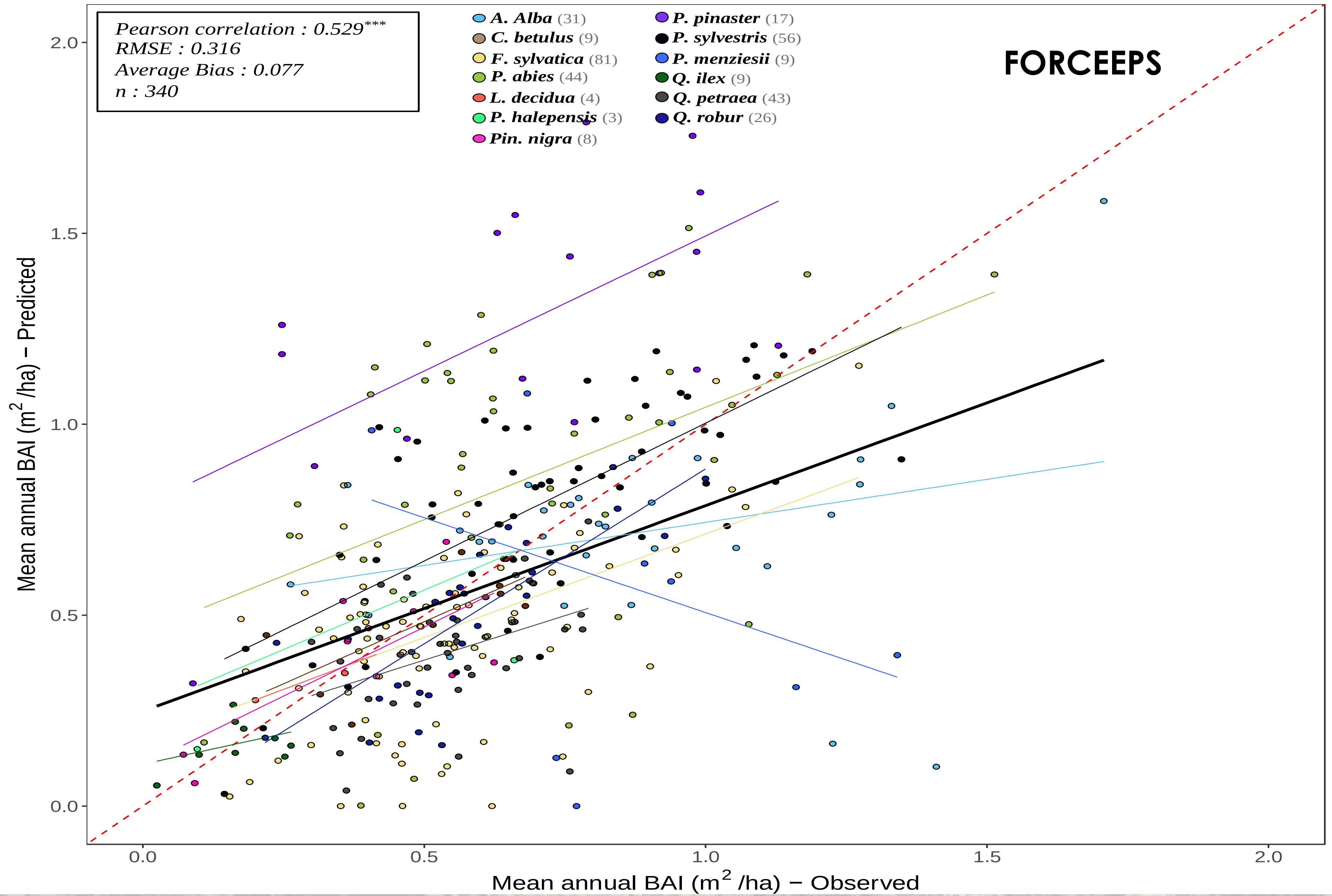


Fig. 4 | Predicted versus observed evolution annual stand basal area loss due to mortality. For each simulation site, the bars depict the summed annual total basal area (m^2/ha) of all dead trees, broken down by species and size class (refer to Annex X for details). Observed values are derived from stand inventories, while predicted values are generated by the PHOREAU model. Also shown are the yearly basal area loss rates, calculated relative to the initial basal area for two distinct time periods in each simulation, along with the total basal area dieback per hectare. Transparent bars indicate years with thinnings (see Annex X for details), which are excluded from the the mortality statistics.

Productivity Validation



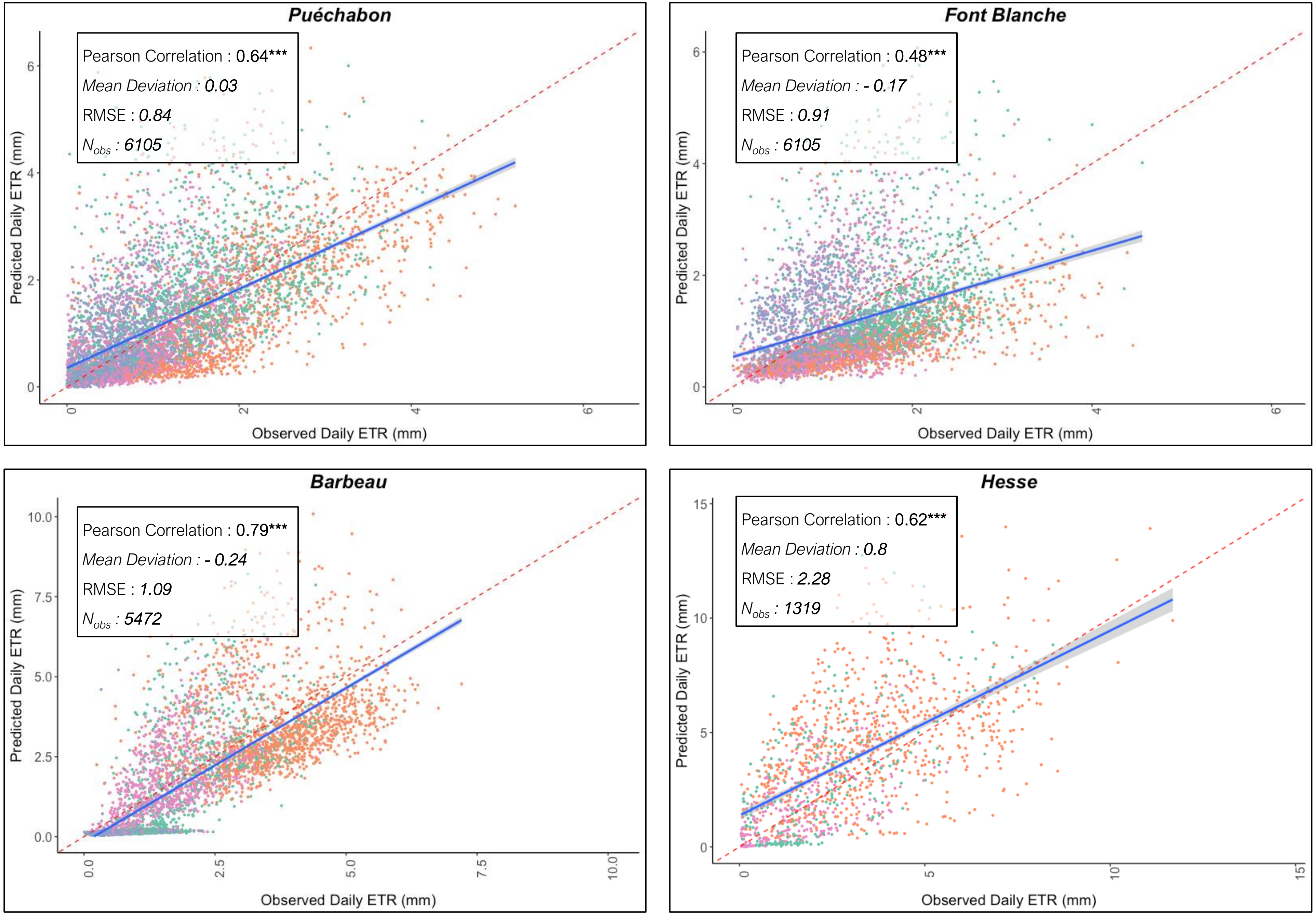


Fig. 9 | Predicted versus observed daily real evapotranspiration (ETR). For each simulation site, the plain blue line is the regression line of the linear model of the relationship between observed and predicted stand daily ETR, with confidence interval represented with the grey dashed lines; the dashed red line is the 1:1 line. See Annex X for definition of associated statistics. Colour code for the seasons as follows :
,Winter; ,Spring; ,Summer; ,Autumn

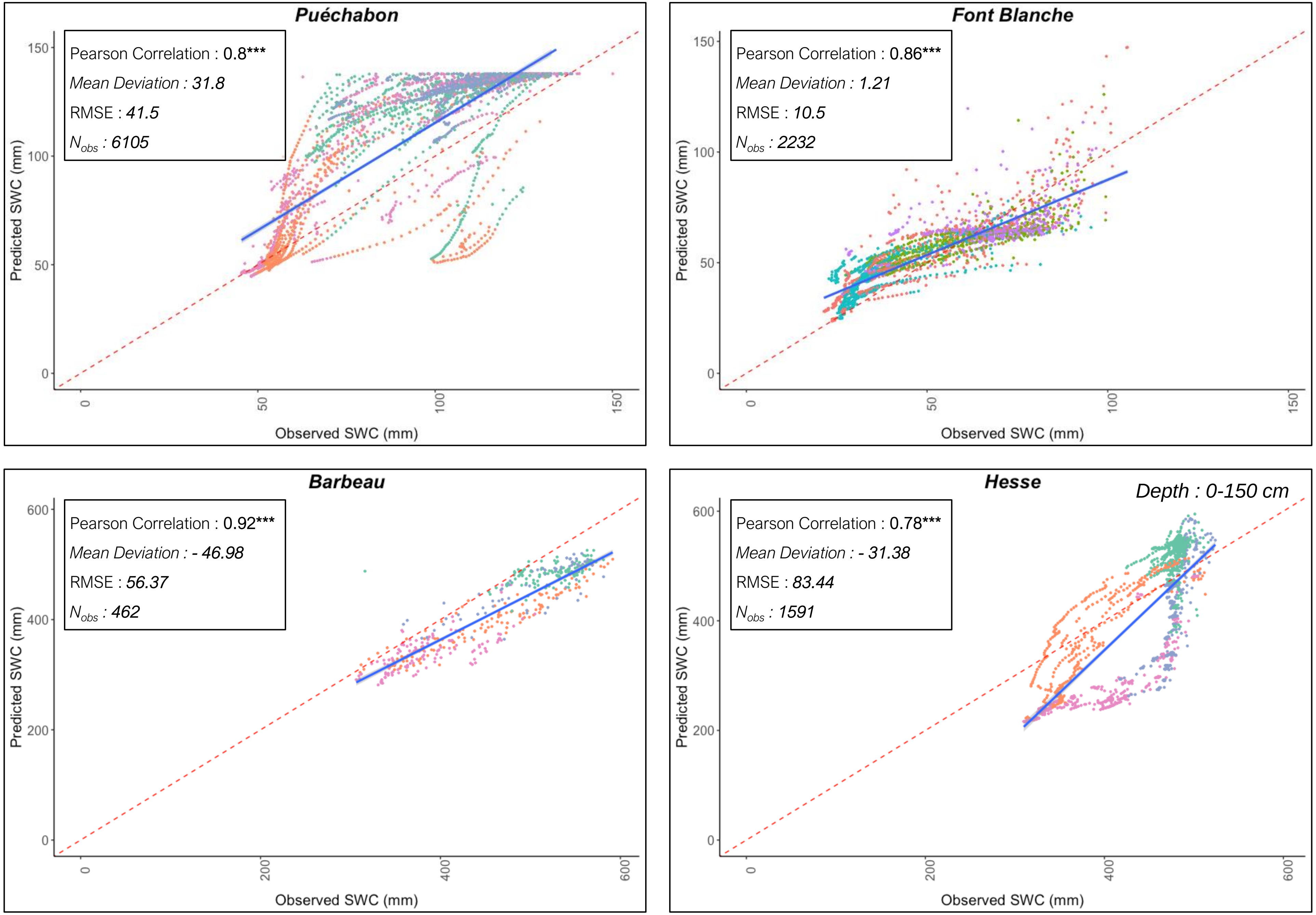


Fig. 11 | Predicted versus observed soil water quantity (SWC). For each simulation site, the plain blue line is the regression line of the linear model of the relationship between observed and predicted SWC, with confidence interval represented with the grey dashed lines; the dashed red line is the 1:1 line. See Annex X for definition of associated statistics. Colour code for the seasons as follows :

●,Winter; ●,Spring; ●,Summer; ●,Autumn

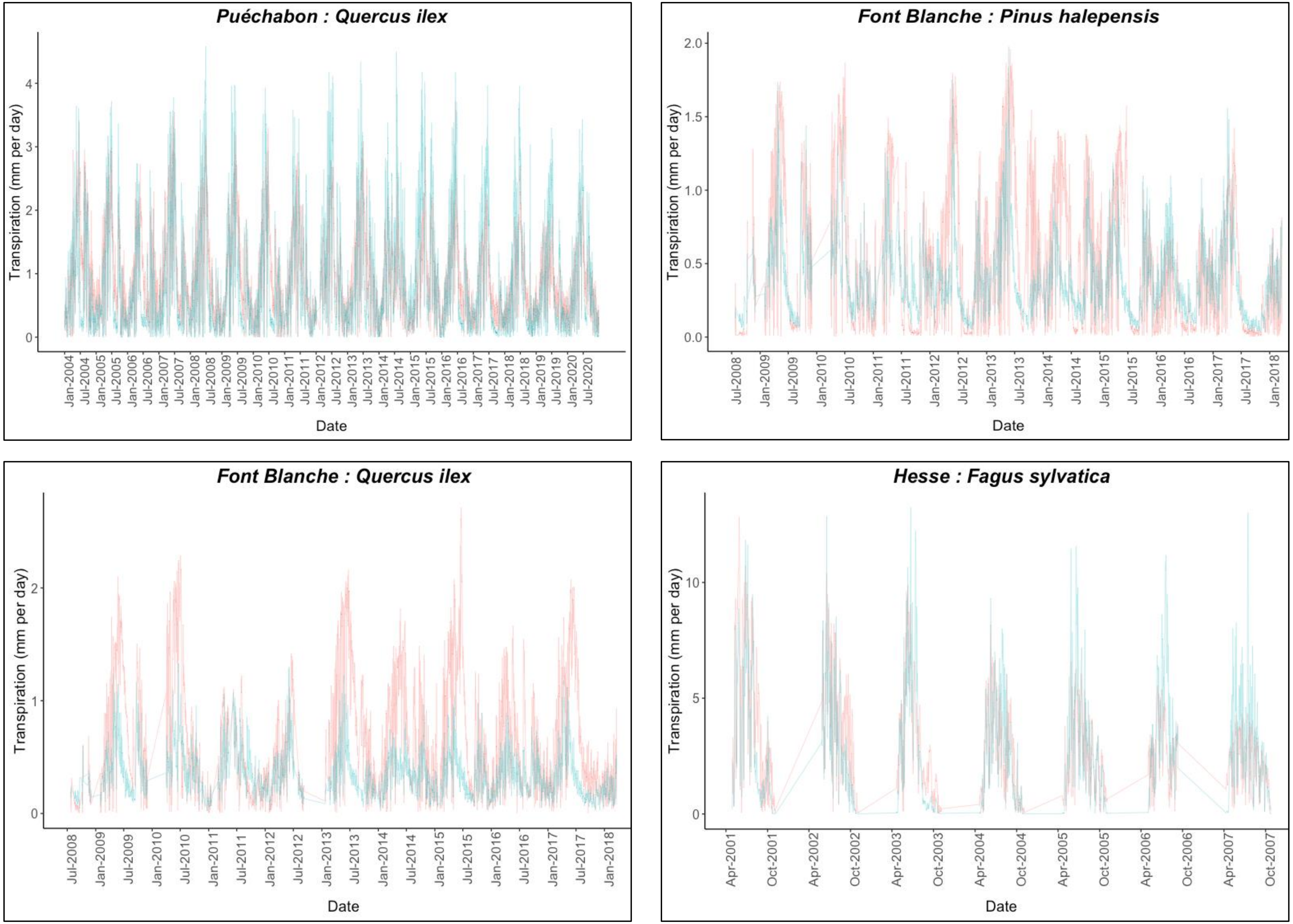


Fig. 12 │ Predicted versus observed evolution of aggregate daily species transpiration. For each simulation site, the blue line depicts the aggregated daily transpiration (mm) generated by PHOREAU from all the trees of the given species. The red line depicts the observed daily transpiration value for this species, upscaled from individual sapflow measurements.

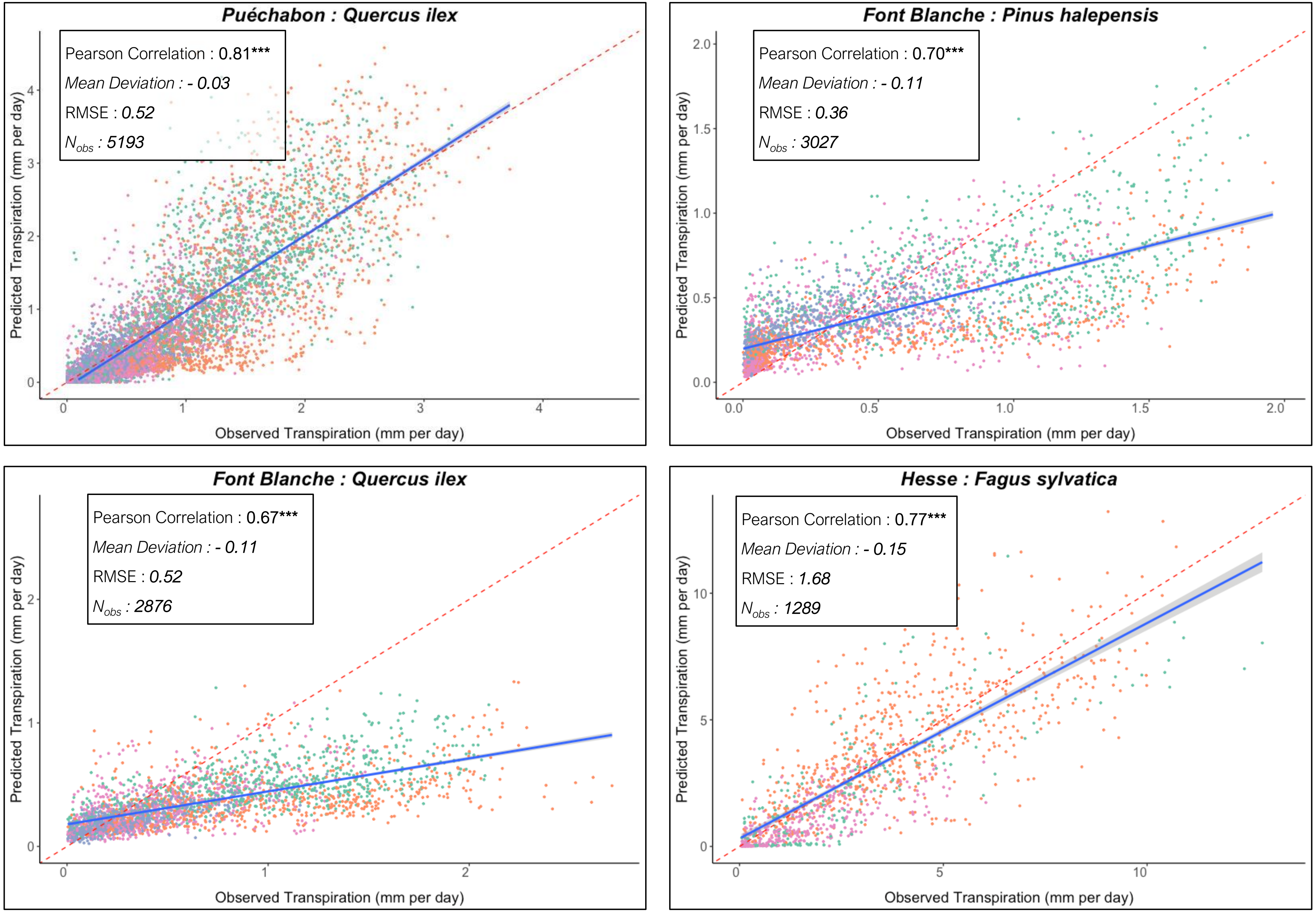
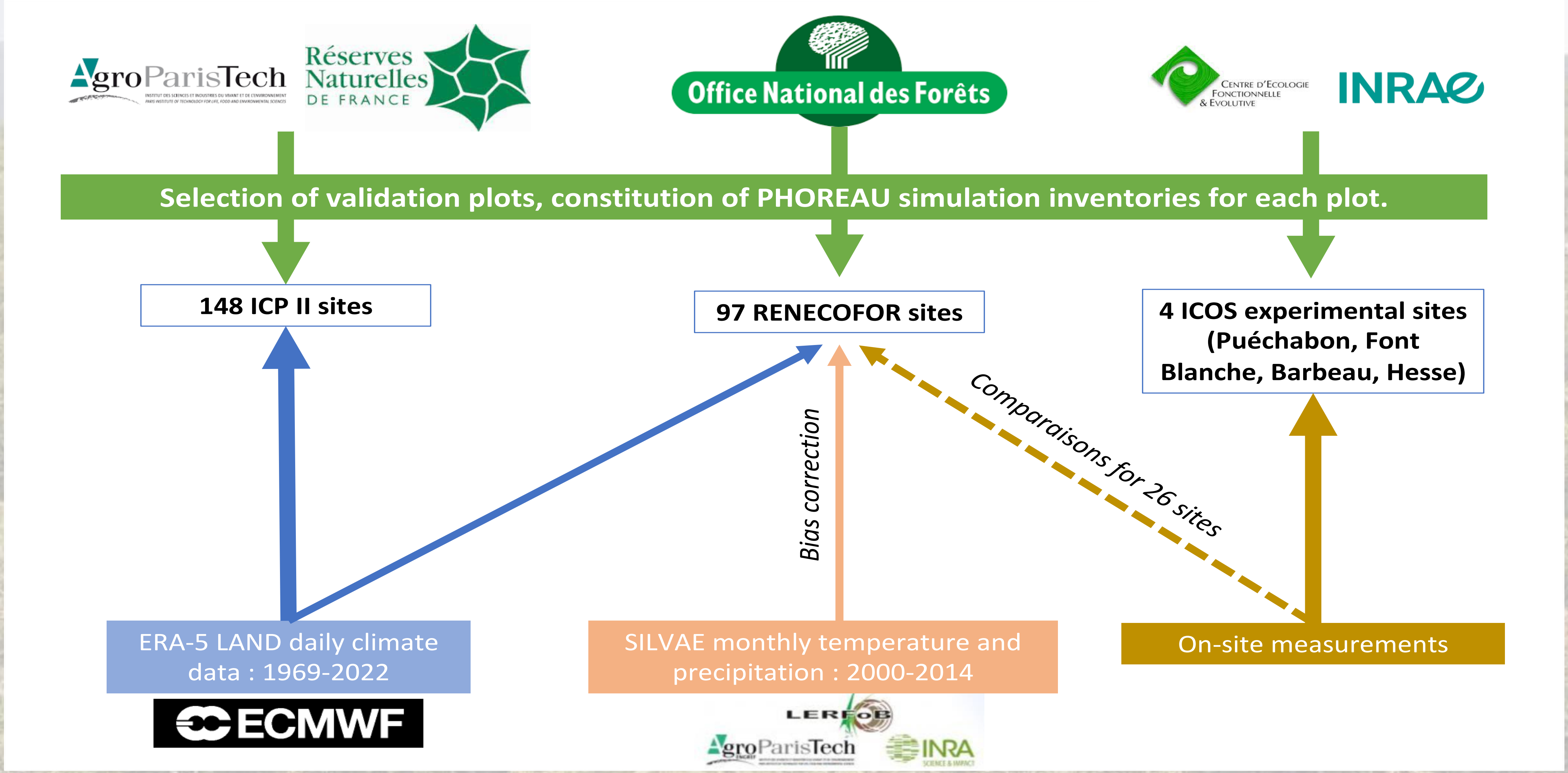


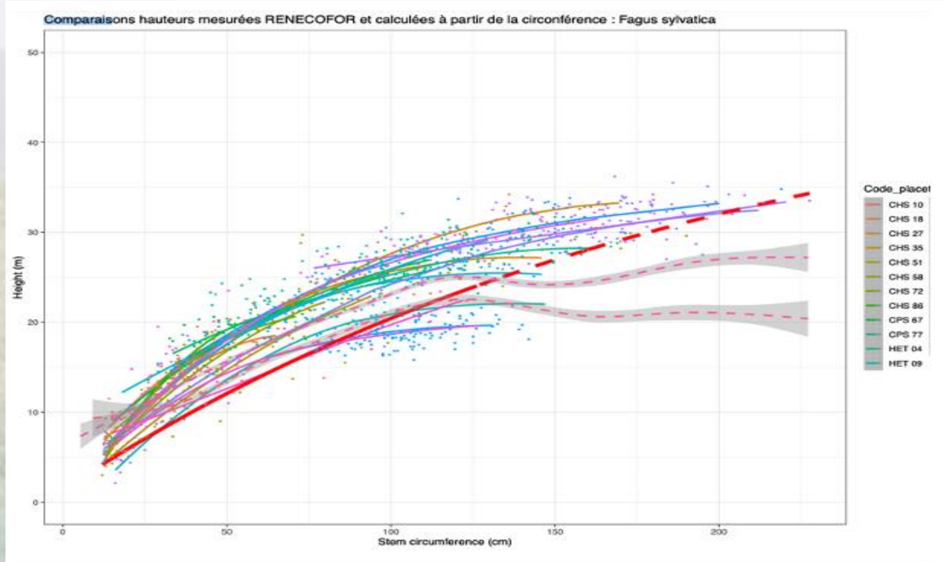
Fig. 13 | Predicted versus observed species aggregate daily transpirations. For each simulation site, the plain blue line is the regression line of the linear model of the relationship between observed and predicted species aggregate daily transpiration (mm), with confidence interval represented with the grey dashed lines; the dashed red line is the 1:1 line. See Annex X for definition of associated statistics. Colour code for the seasons as follows :
● ,Winter; ● ,Spring; ● ,Summer; ● ,Autumn

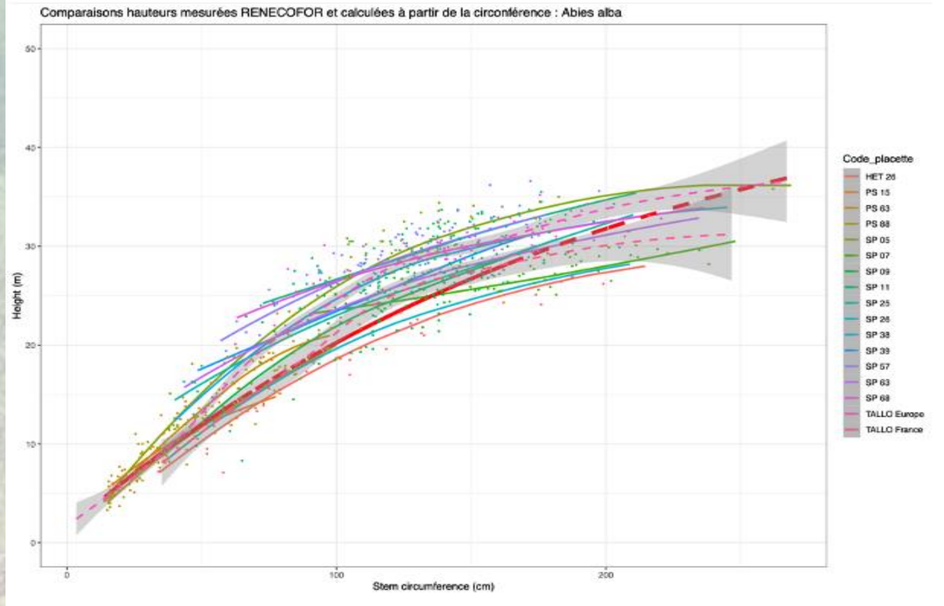
Productivity Validation

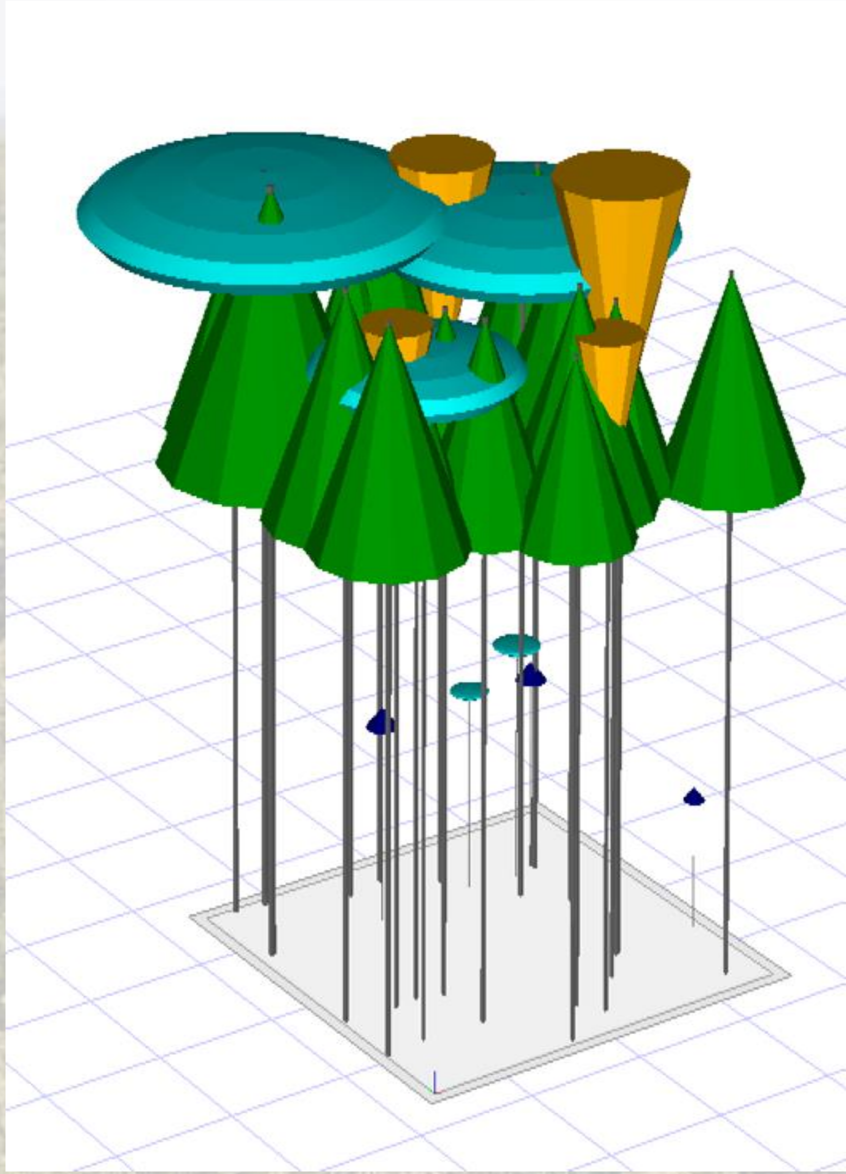


Competition for light module

Model







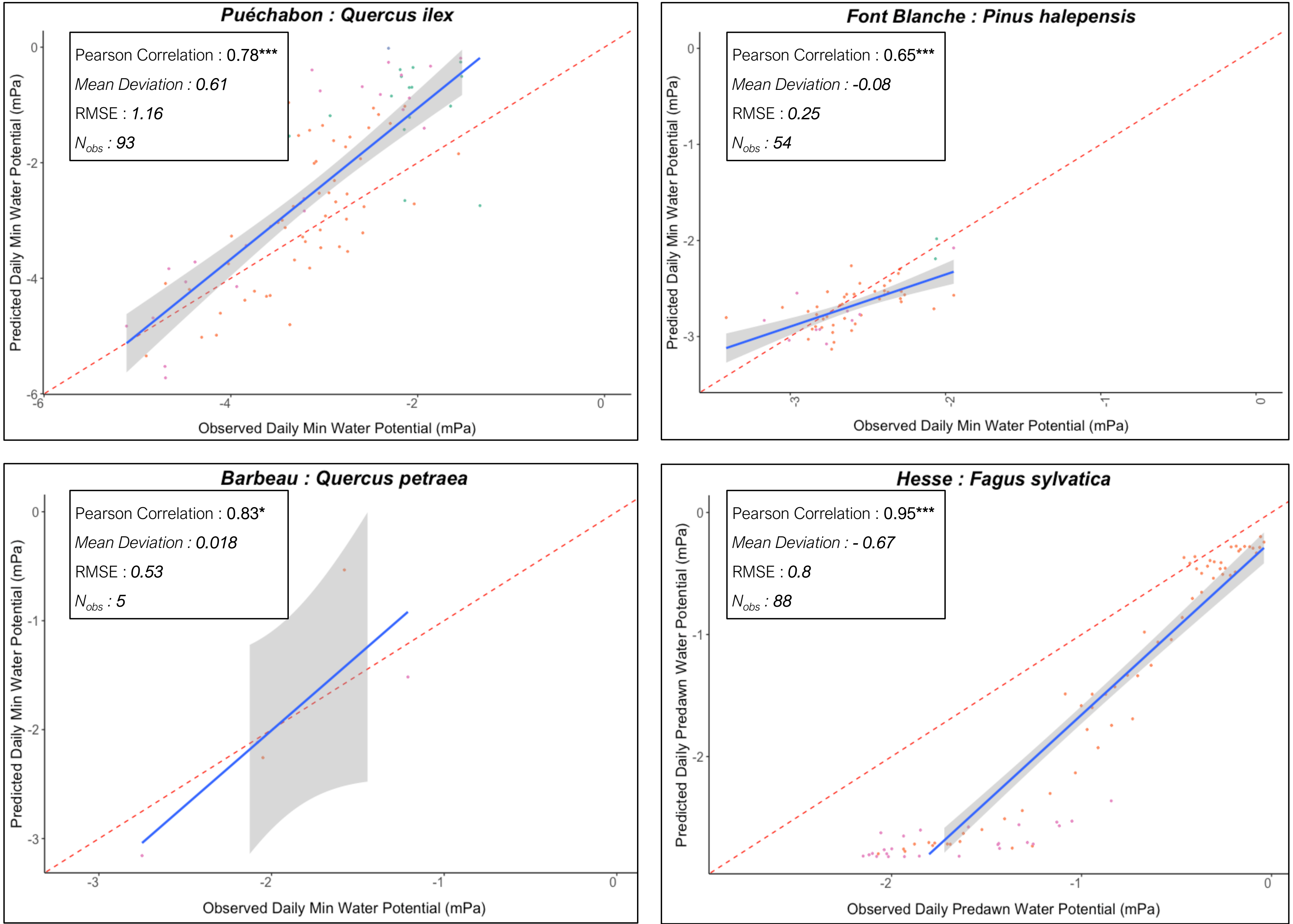


Fig. 15 | Predicted versus observed daily stem water potential. For each dominant species of the four simulation sites, each point represents a day with water potential observations (mPa), plotted against its corresponding predicted value by the PHOREAU model. For Puéchabon, Font Blanche and Barbeau minimum daily water potential is plotted, while the predawn potentials are shown for the Hesse site. The plain blue line is the regression line of the linear model of the relationship between observed and predicted water potential, with confidence interval represented with the grey dashed lines; the dashed red line is the 1:1 line. See Annex X for definition of associated statistics. Colour code for the seasons as follows :

● ,Winter; ● ,Spring; ● ,Summer; ● ,Autumn

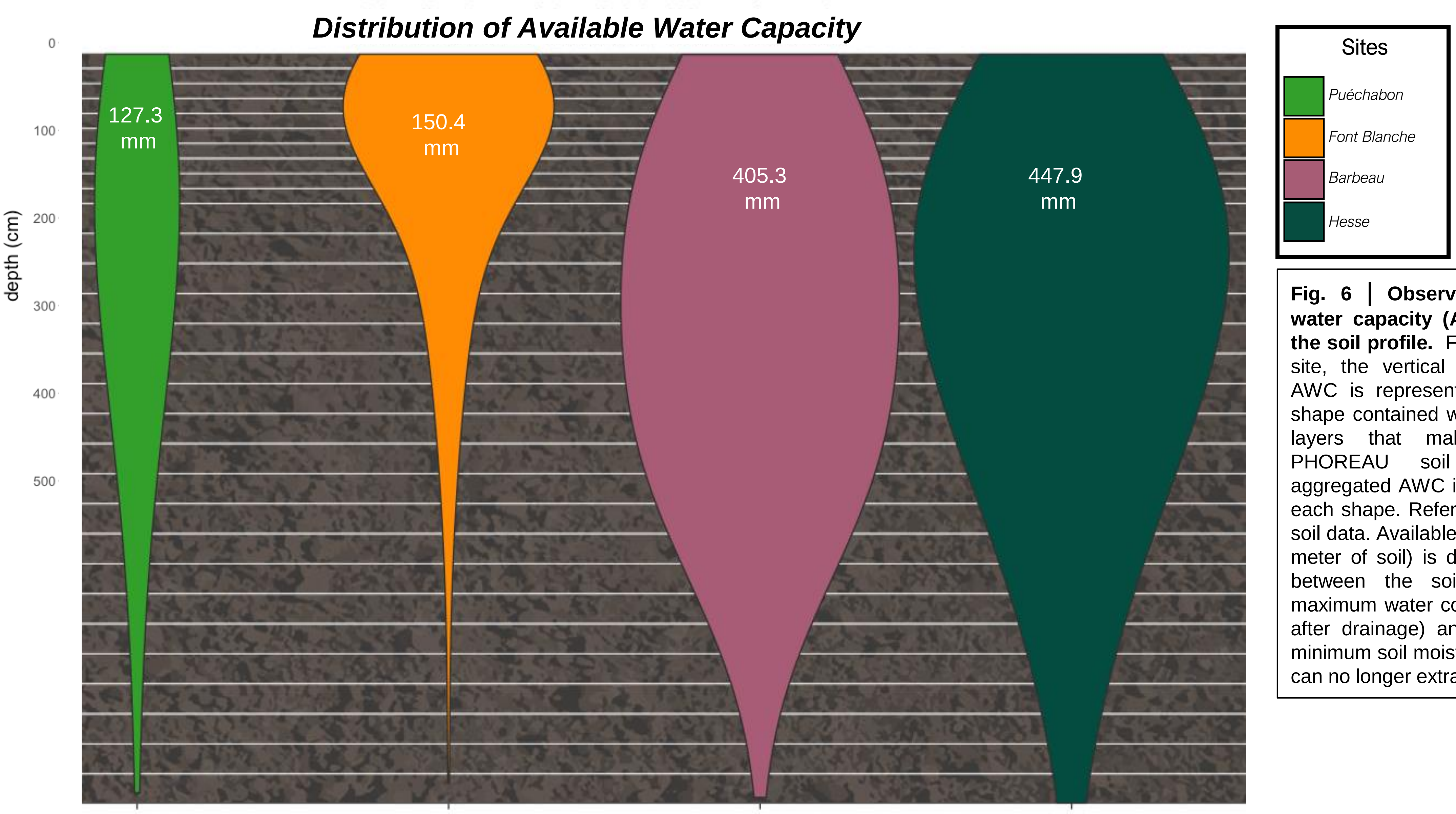


Fig. 6 | Observed potential available water capacity (AWC) distribution over the soil profile. For each simulation ICOS site, the vertical distribution of potential AWC is represented by the area of the shape contained within each of the 30 soil layers that make up the standard PHOREAU soil profile. The total aggregated AWC is shown at the center of each shape. Refer to Annex X for origin of soil data. Available Water Quantity (mm per meter of soil) is defined as the difference between the soil's field capacity (the maximum water content the soil can retain after drainage) and the wilting point (the minimum soil moisture level at which plants can no longer extract water).