Forest water balance modeling and applications

Miquel De Cáceres

Ecosystem Modeling Facility (EMF)

CREAF

1. **Forest water balance**
   a. Hydrological processes
   b. Physiological processes

2. **Water balance modeling**
   a. Models and scales
   b. Implementation of processes
   c. Sensitivity analysis

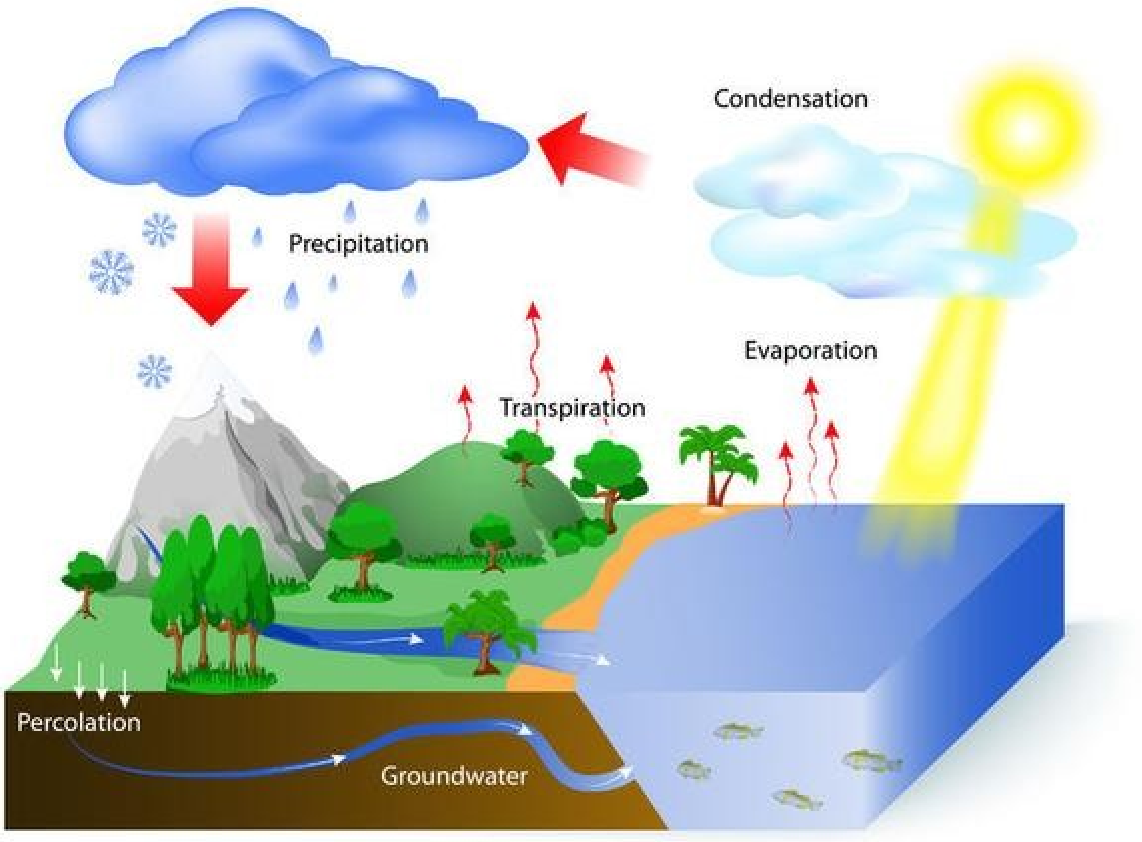
3. **Application of the water balance model**
   a. Forest and water resource management
   b. Forest drought monitoring
   c. Effect of understory management on drought stress
   d. Detailed stand-scale water balance

01

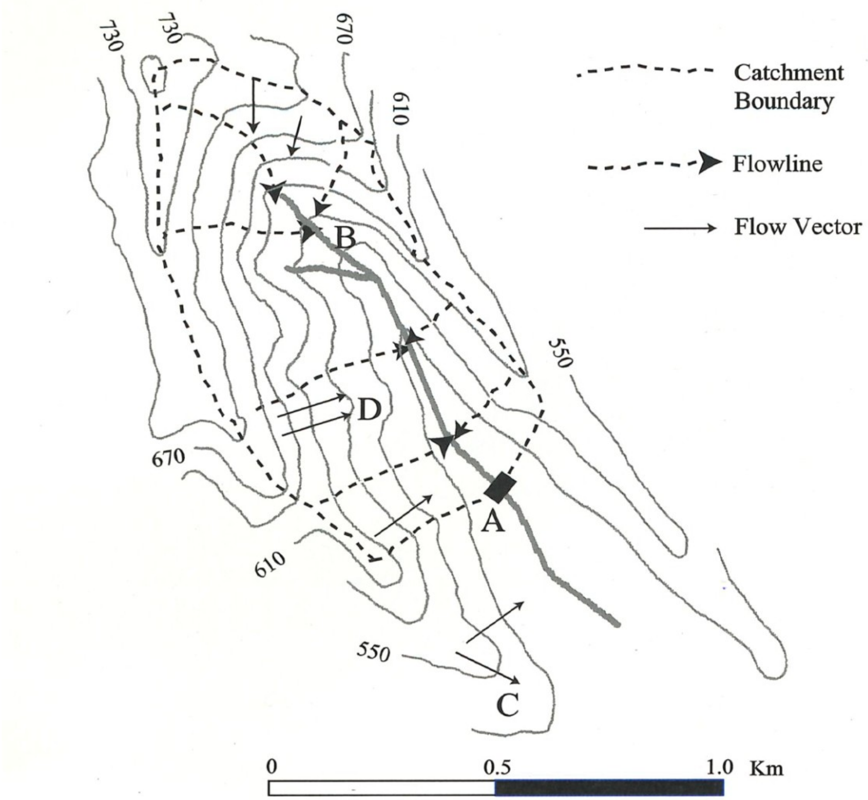
Forest water balance

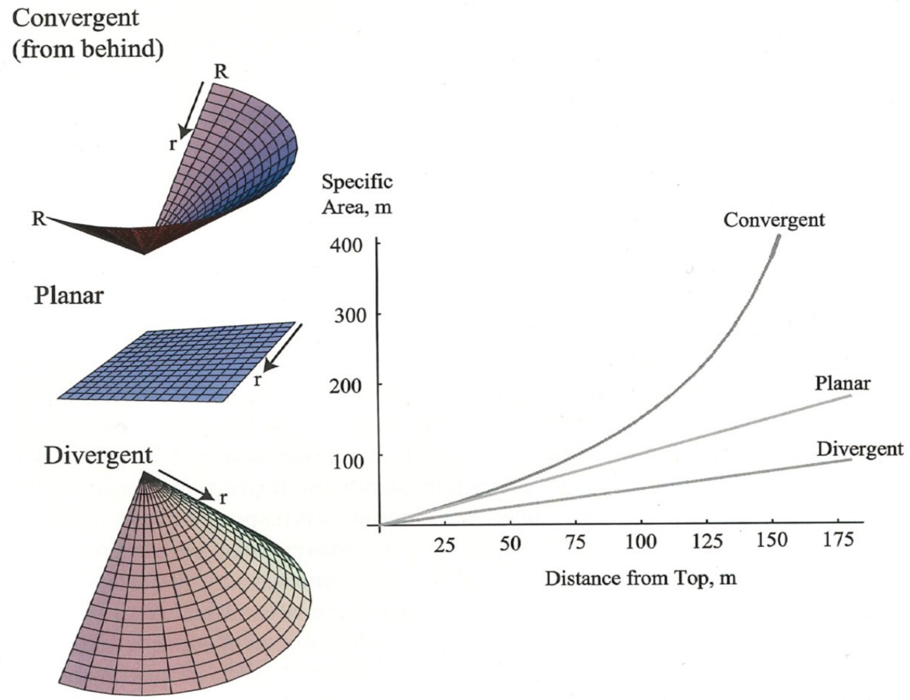
Hydrological processes

Water cycle


Condensation
Precipitation
Transpiration
Evaporation
Percolation
Groundwater

Watershed topography

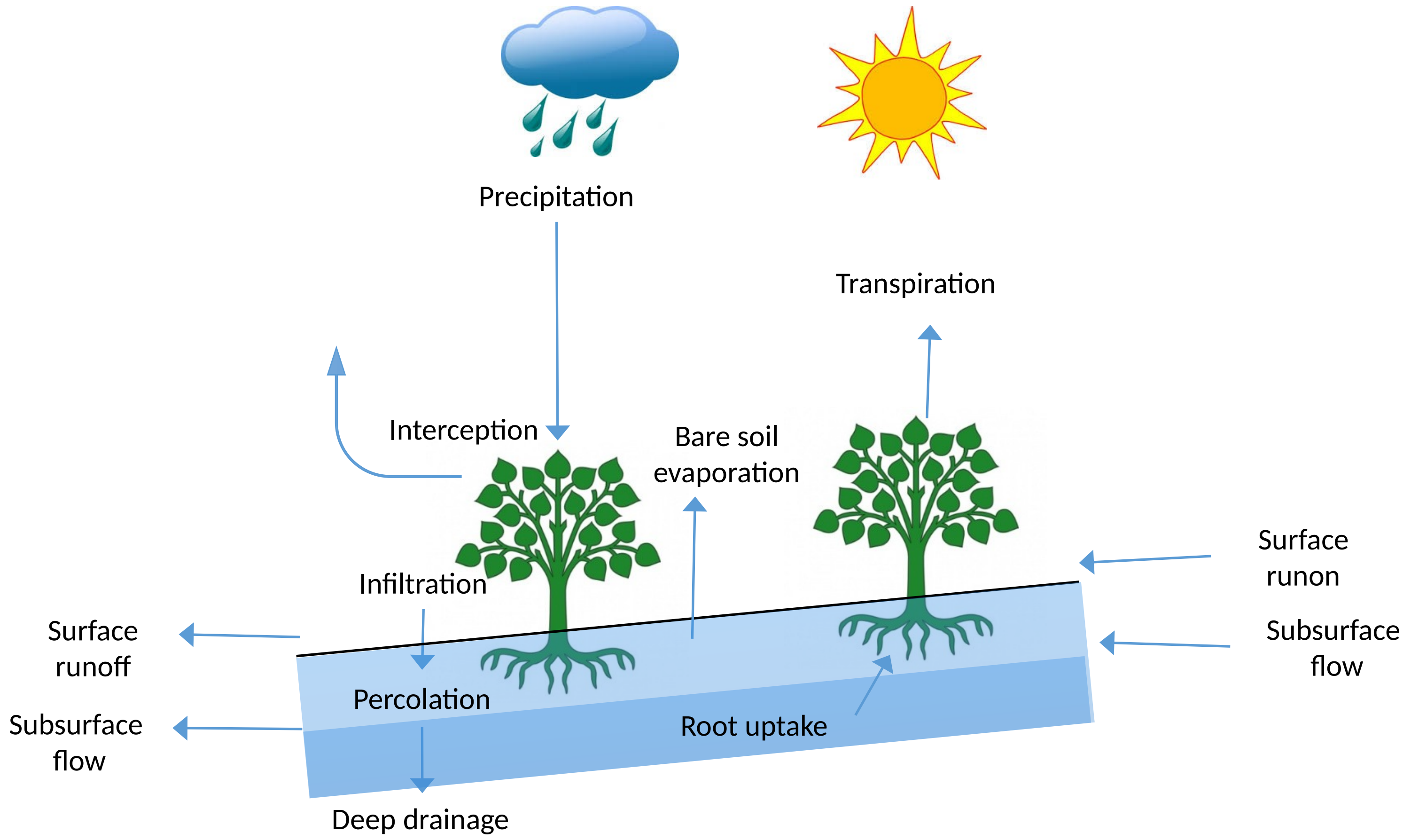




Beven K. (2012). *Rainfall-runoff modelling. The Primer. Wiley-Blackwell*

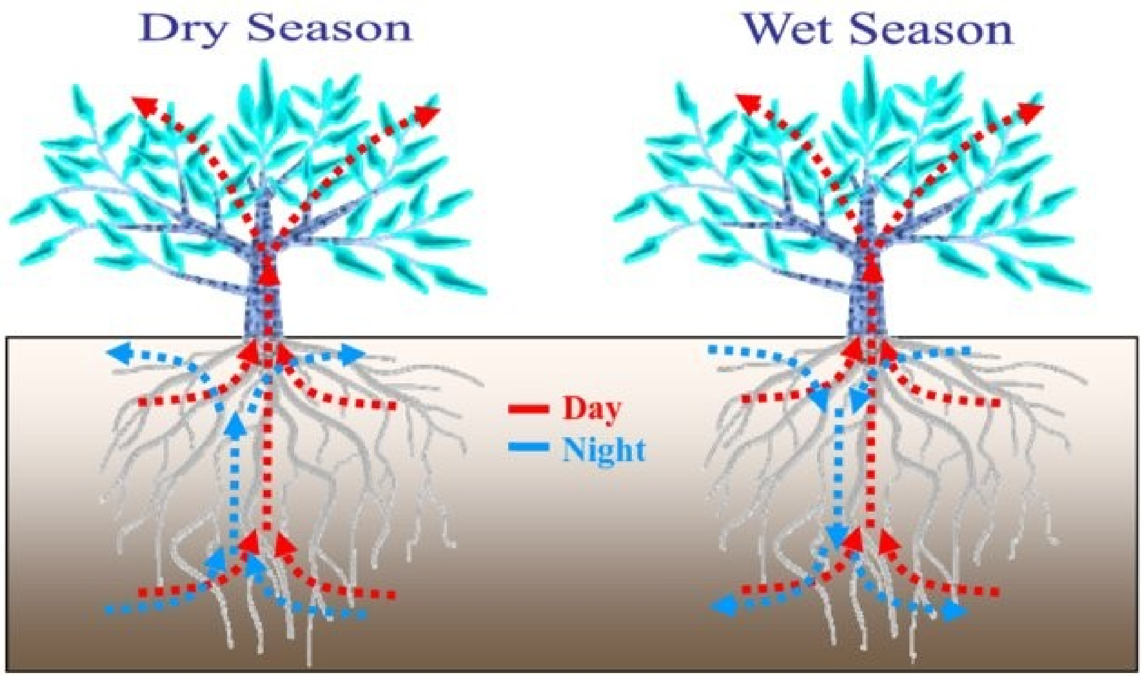
Bren L. (2015). *Forest hydrology and catchment management. Springer*

Local water balance



Hydraulic redistribution

Hydraulic redistribution is the movement of water from moist to dry soil (upward or downward) through plant roots.

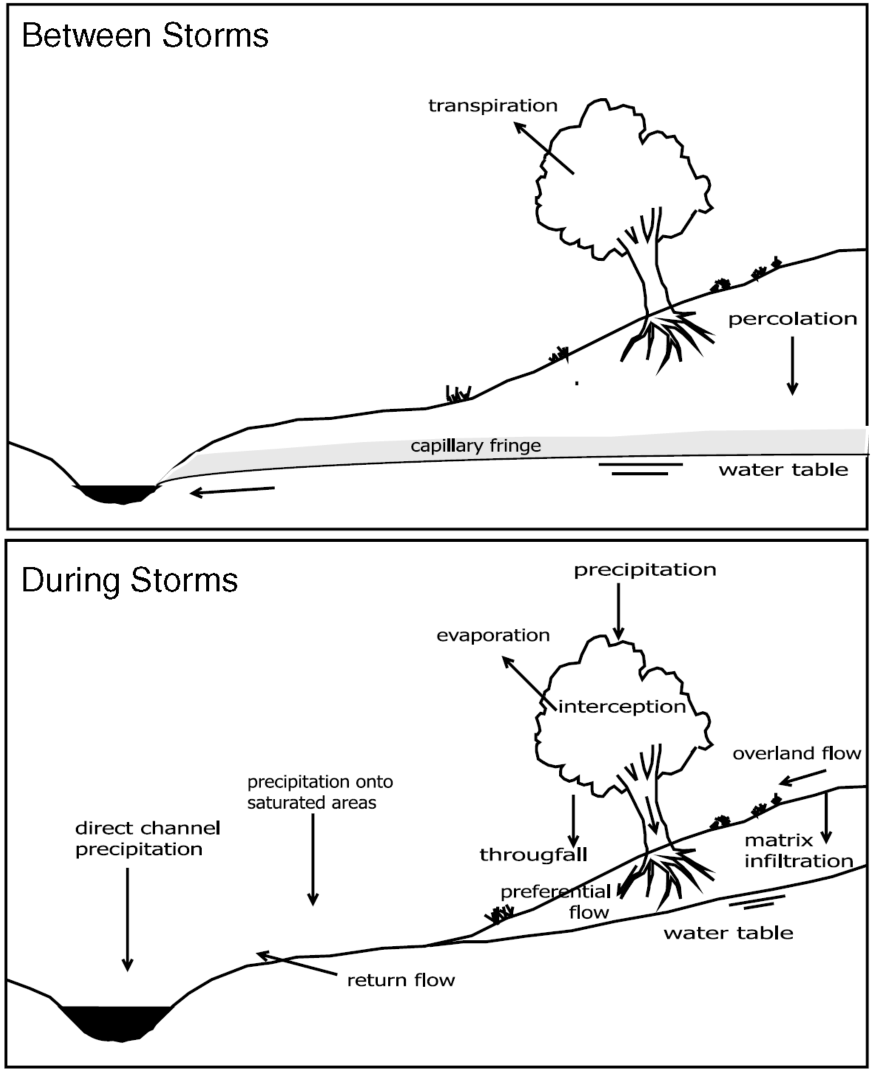


Up to 1.3 mm $H_2O \cdot d^{-1}$

(10-15% of daily transpiration)

Neumann & Cardon (2012). New Phytol., 194, 337-352.

Seasonality of hydrological processes



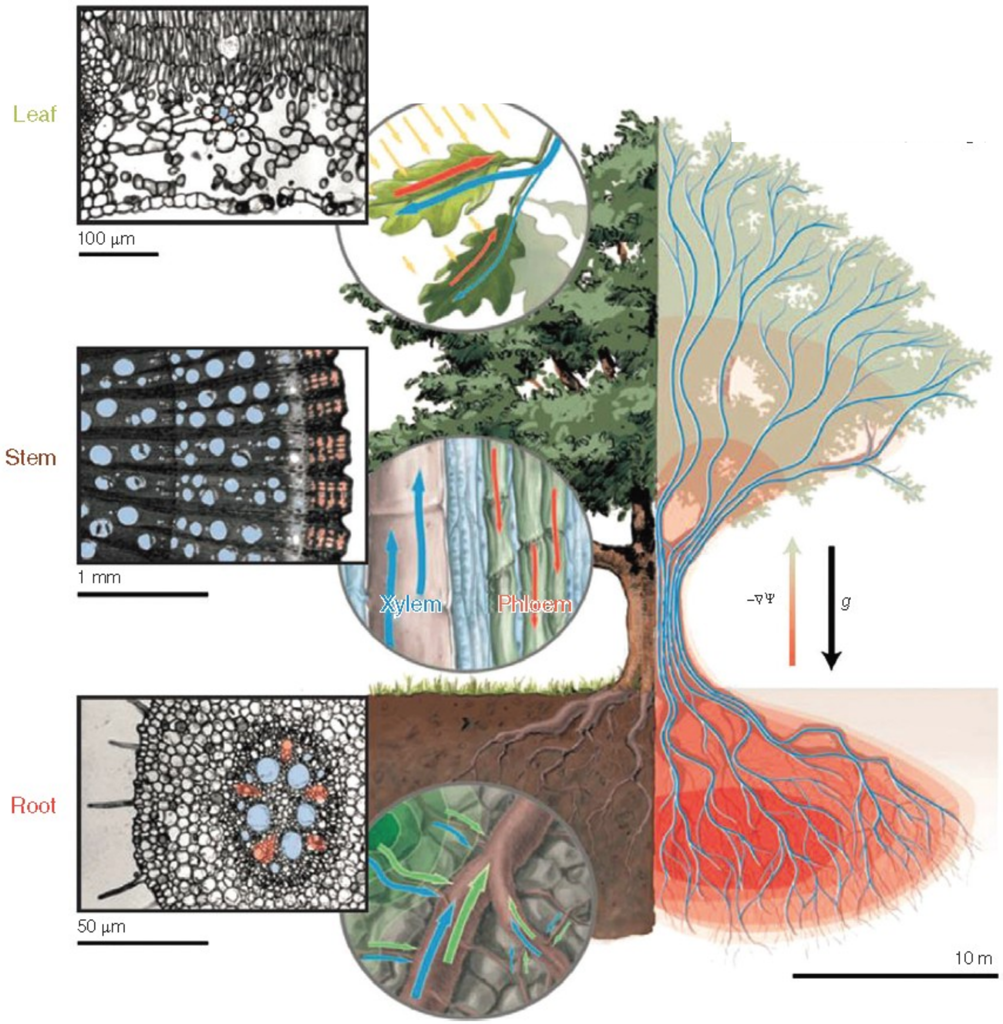
Beven K. (2012). *Rainfall-runoff modelling. The Primer. Wiley-Blackwell*

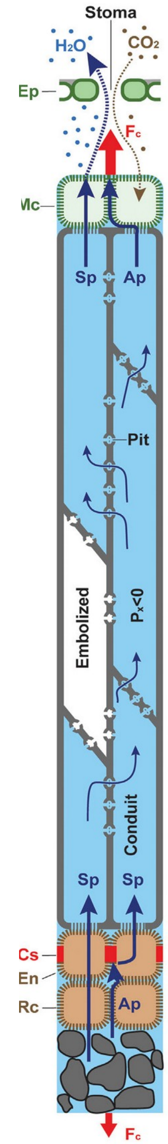
01

Forest water balance

Physiological processes

Water transport inside the plant





Leaf mesophyll

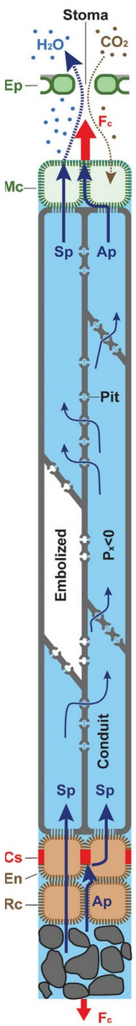
Xylem (sapwood)

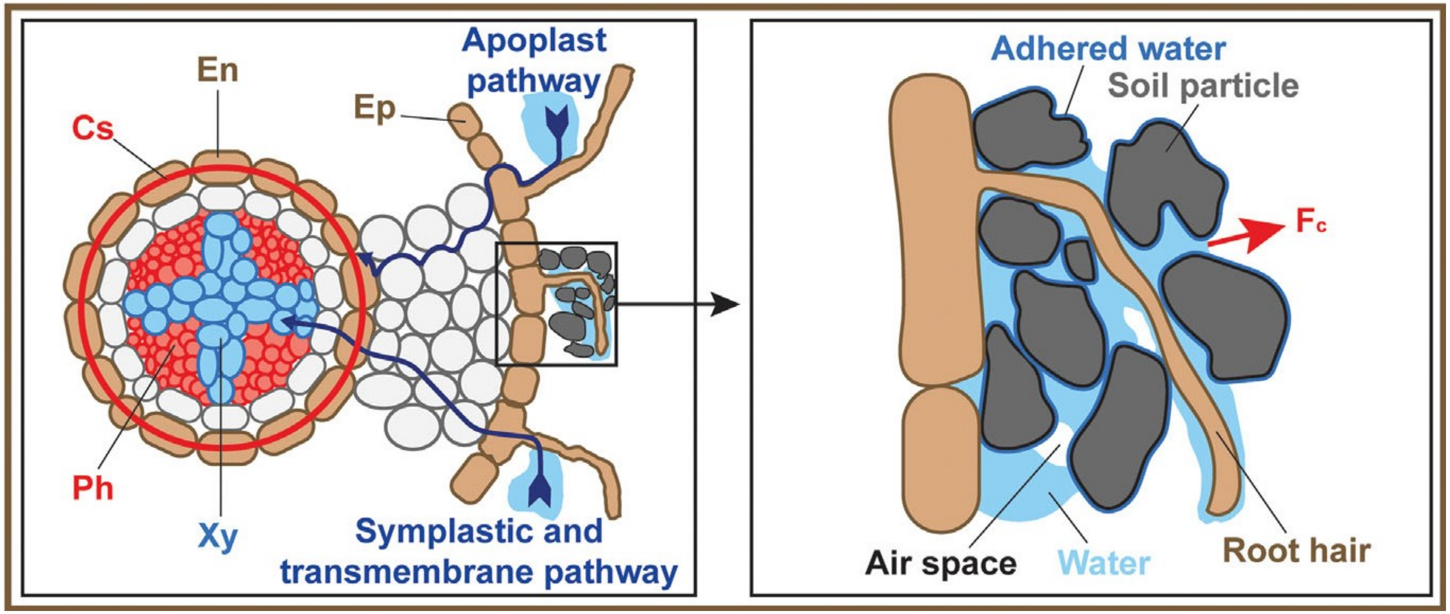
Soil-root interface

Fatichi et al. (2016). WIRE: Water, 3, 327-368.

Venturas et al. (2017). J. Int. Pl. Biol., 59, 356-389.

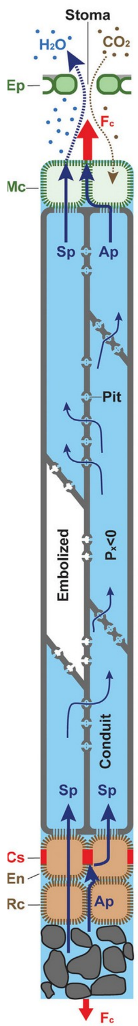
Water uptake by roots

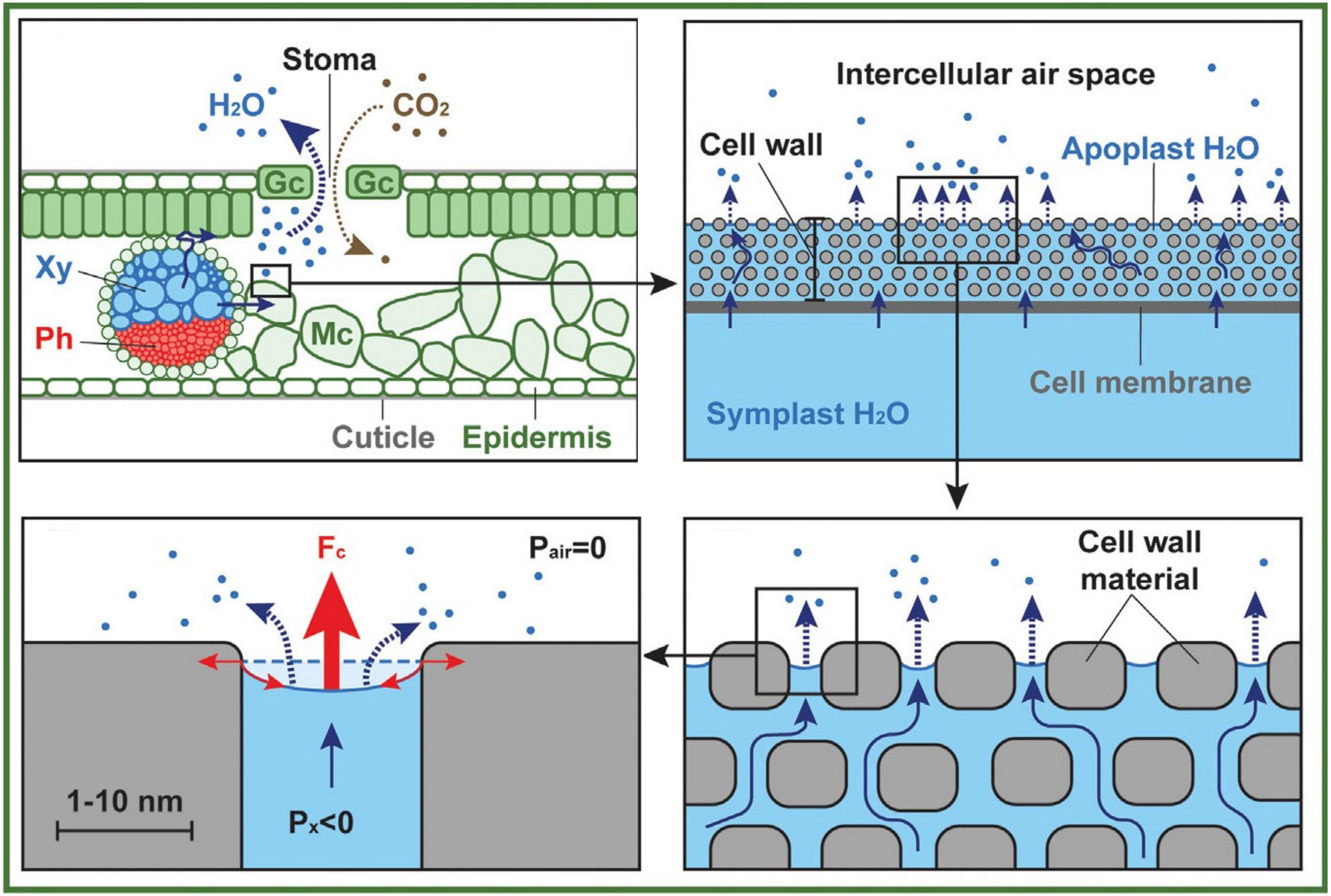




[Venturas et al. (2017). J. Int. Pl. Biol., 59, 356-389.]()

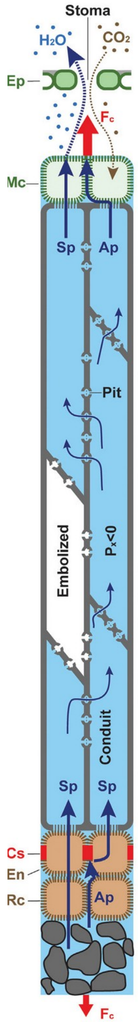
Evaporation and tension-cohesion





Venturas et al. (2017). J. Int. Pl. Biol., 59, 356-389.

Water potential



Water potential is the **potential energy** of water, i.e. the tendency of water to move from one area to another

$$\Psi = \Psi_{\Pi} + \Psi_{p} + \Psi_{g} + \Psi_{m}$$

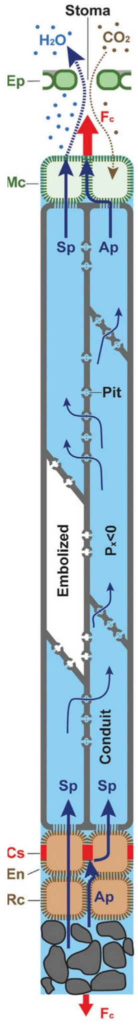
Osmotic potential (negative, living cells)

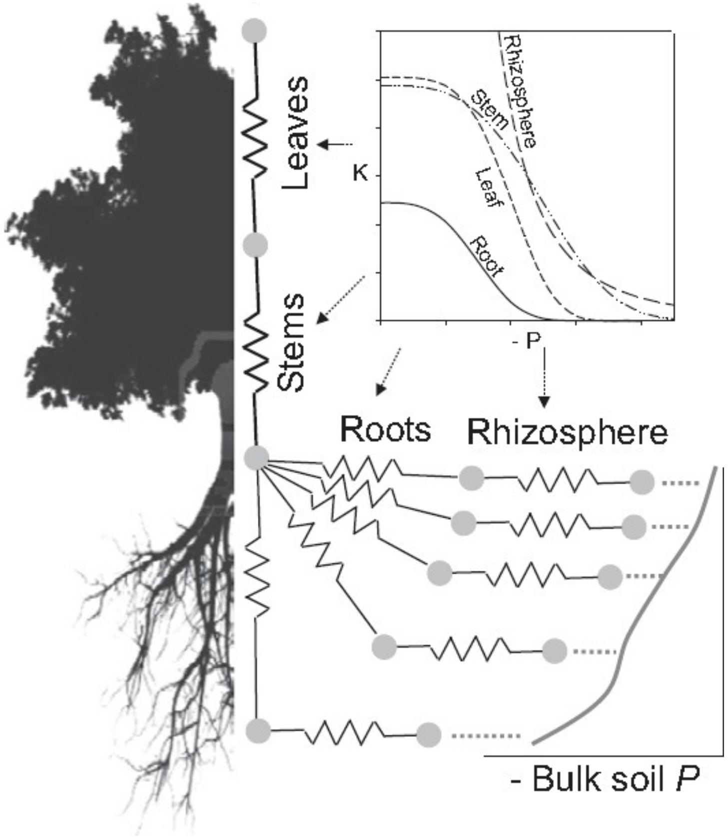
Pressure (positive or negative)

Gravity (negative)

Matric (negative, soils)

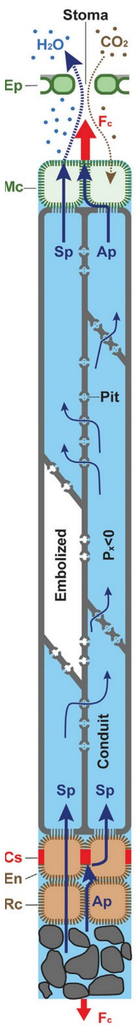
Plant hydraulic resistances

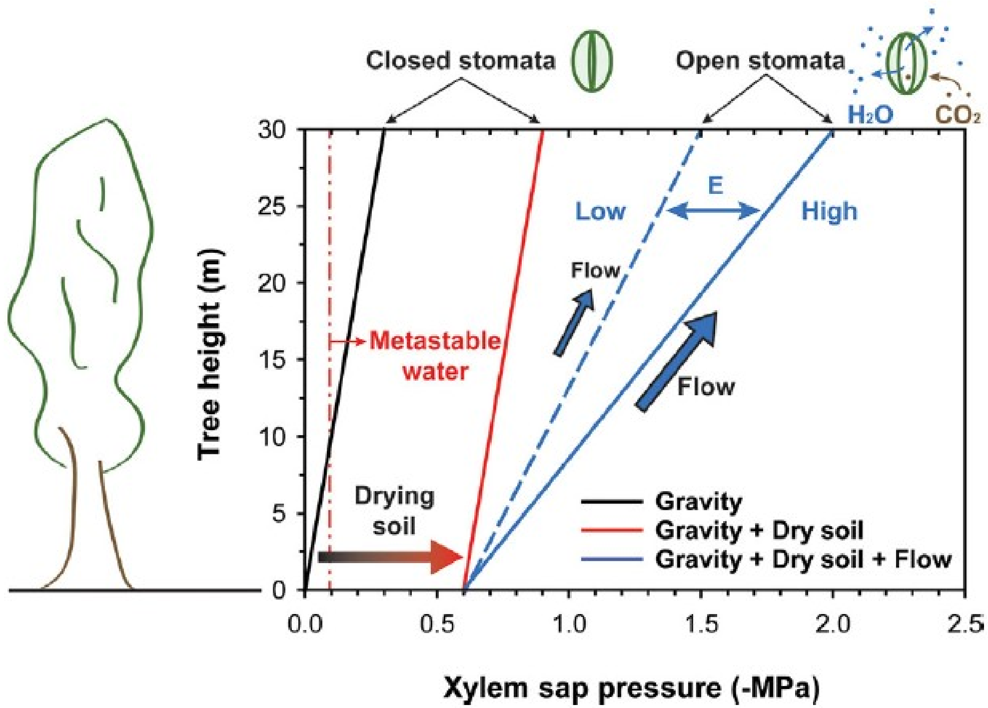




Sperry et al. (2016). New Phytol., 212, 577-589.

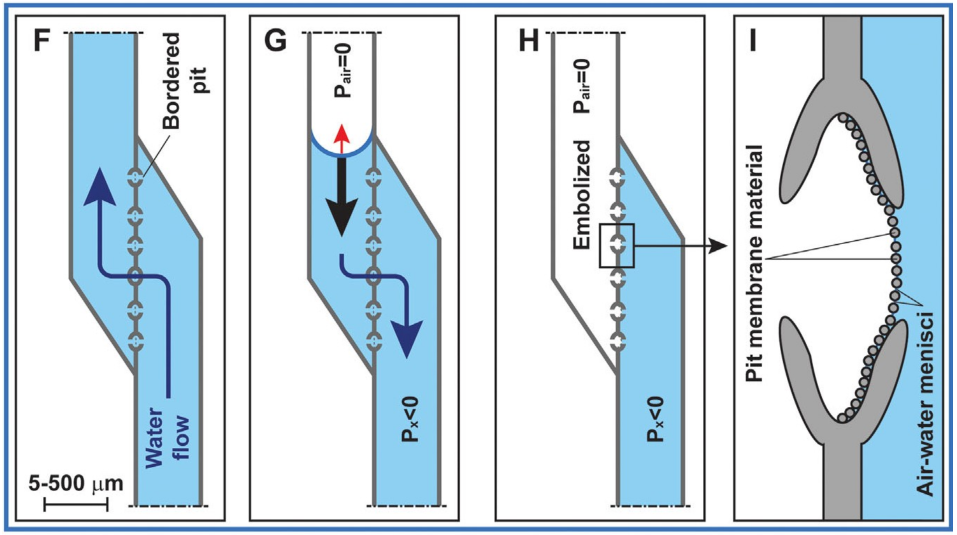
Sap flow and water potential drop





[Venturas et al. (2017). J. Int. Pl. Biol., 59, 356-389.](#)

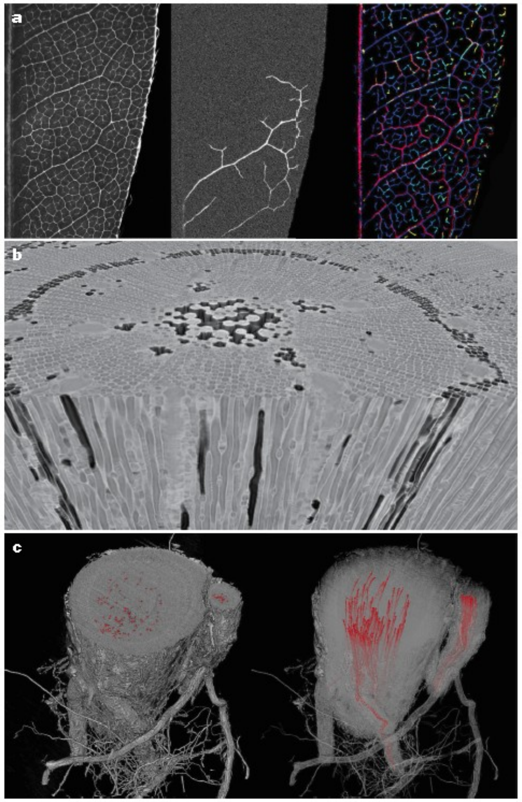
Embolism formation



Leaf

Stem

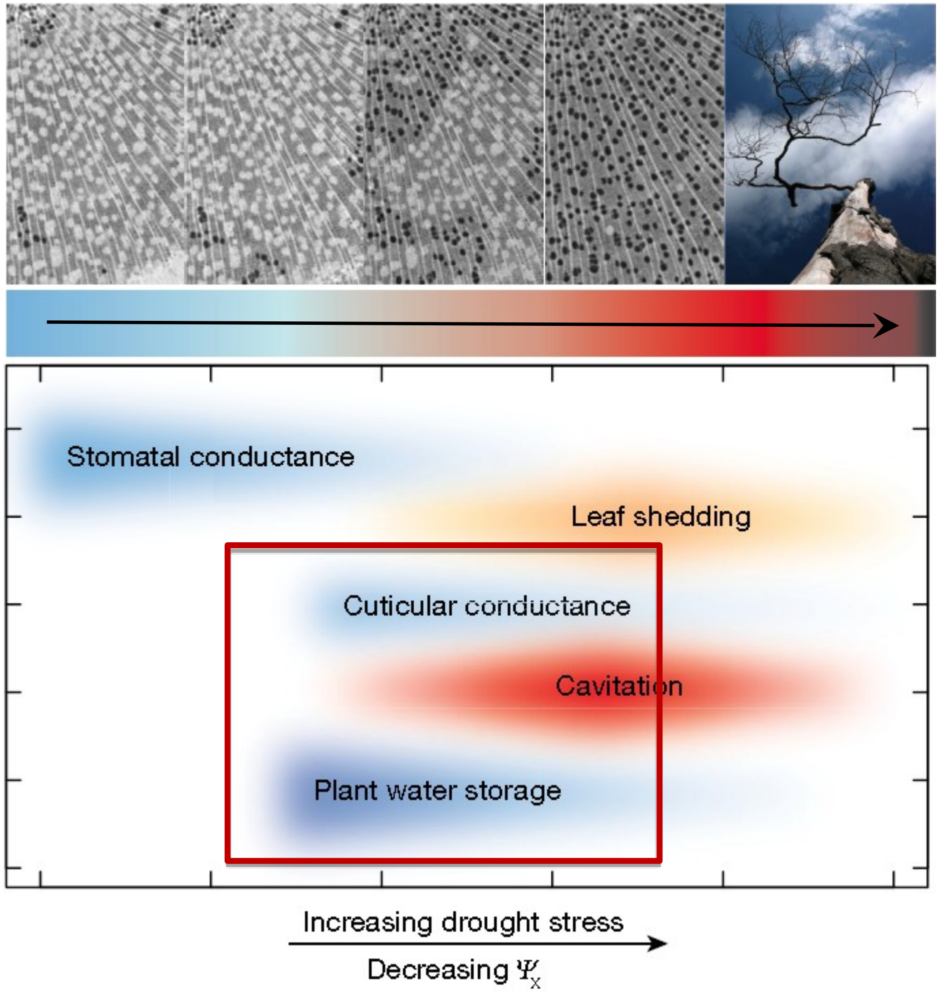
Roots



Venturas et al. (2017). J. Int. Pl. Biol., 59, 356-389.

Choat et al. (2018). Nature, 558, 531-539.

Drought effects

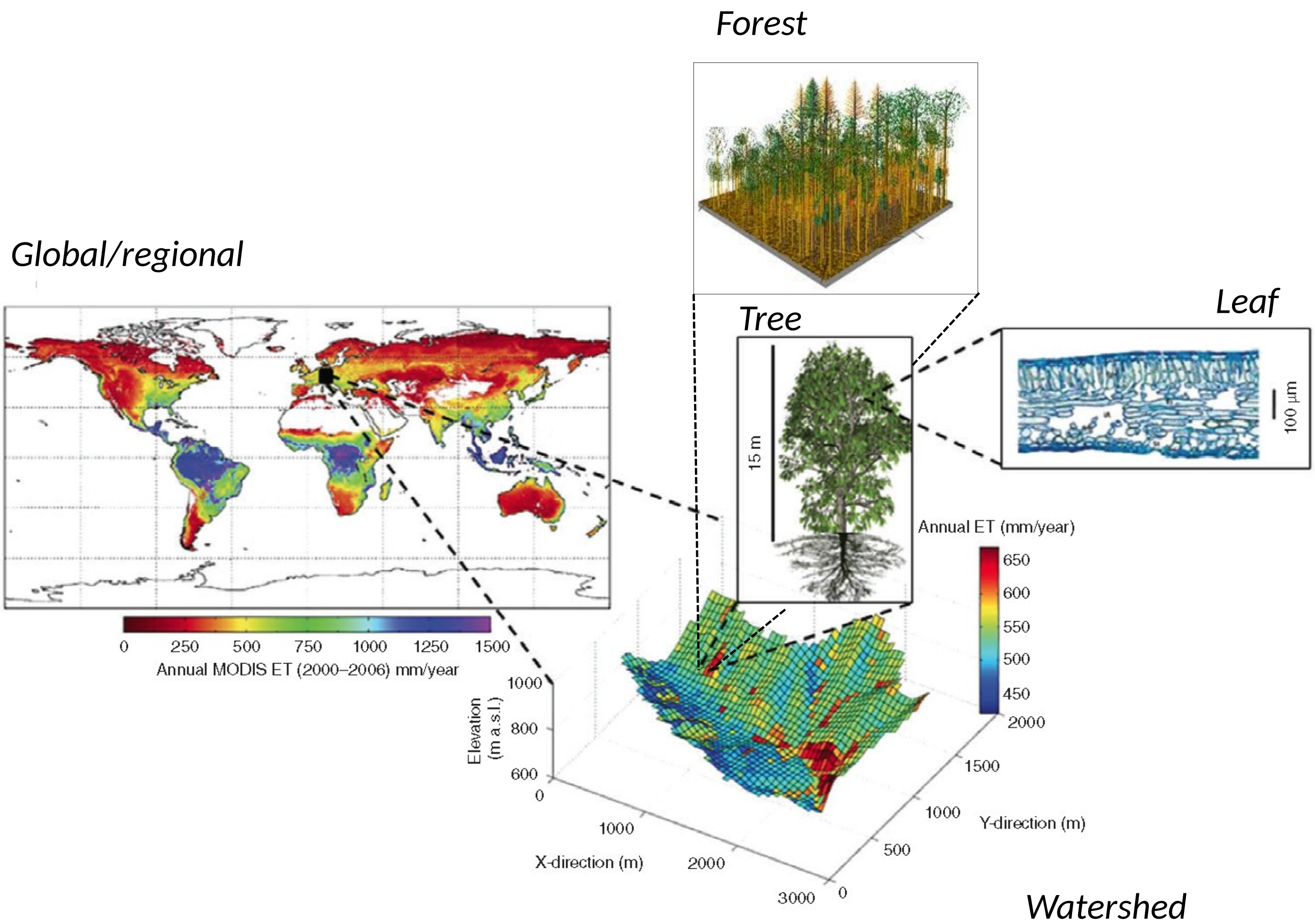


[Choat et al. (2018). Nature, 558, 531-539.]

02

Water balance modeling

Models and scales

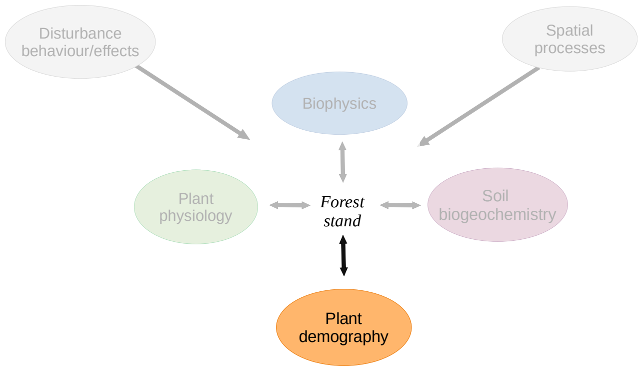


[Fatichi et al. (2016). WIRE: Water, 3, 327-368.]

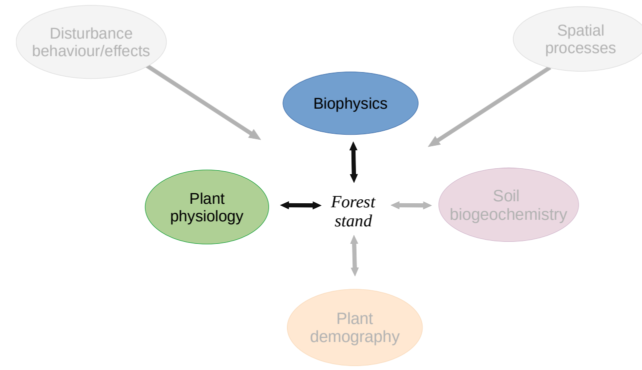
02 Water balance modeling – Models and scales

02 Water balance modeling – Models and scales

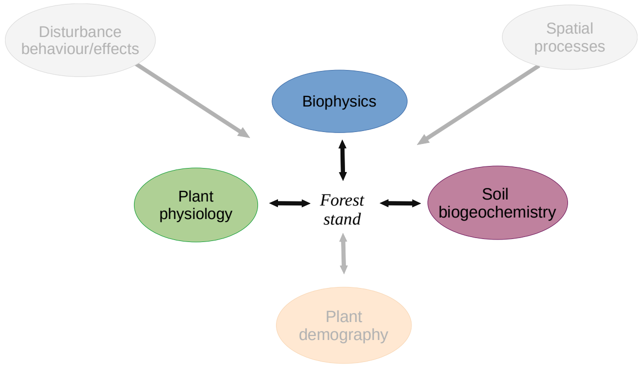
Forest gap model



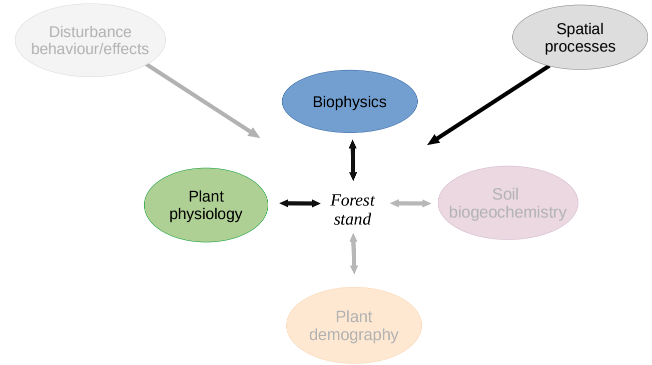
Soil-vegetation-atmosphere transfer model



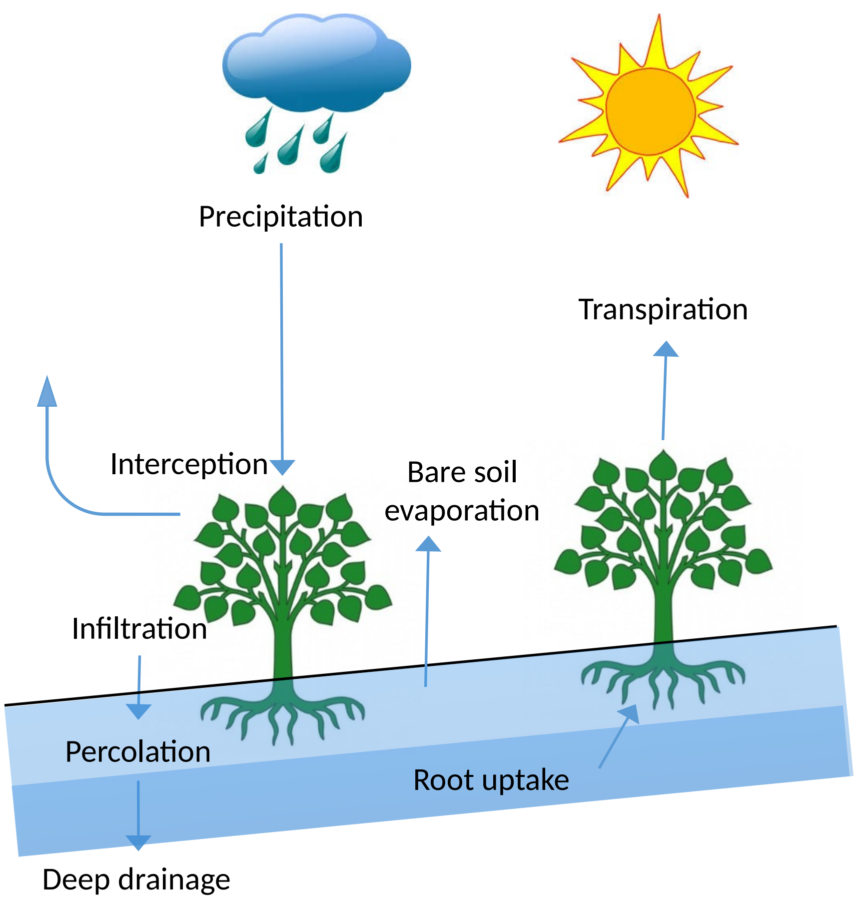
Forest biogeochemical model

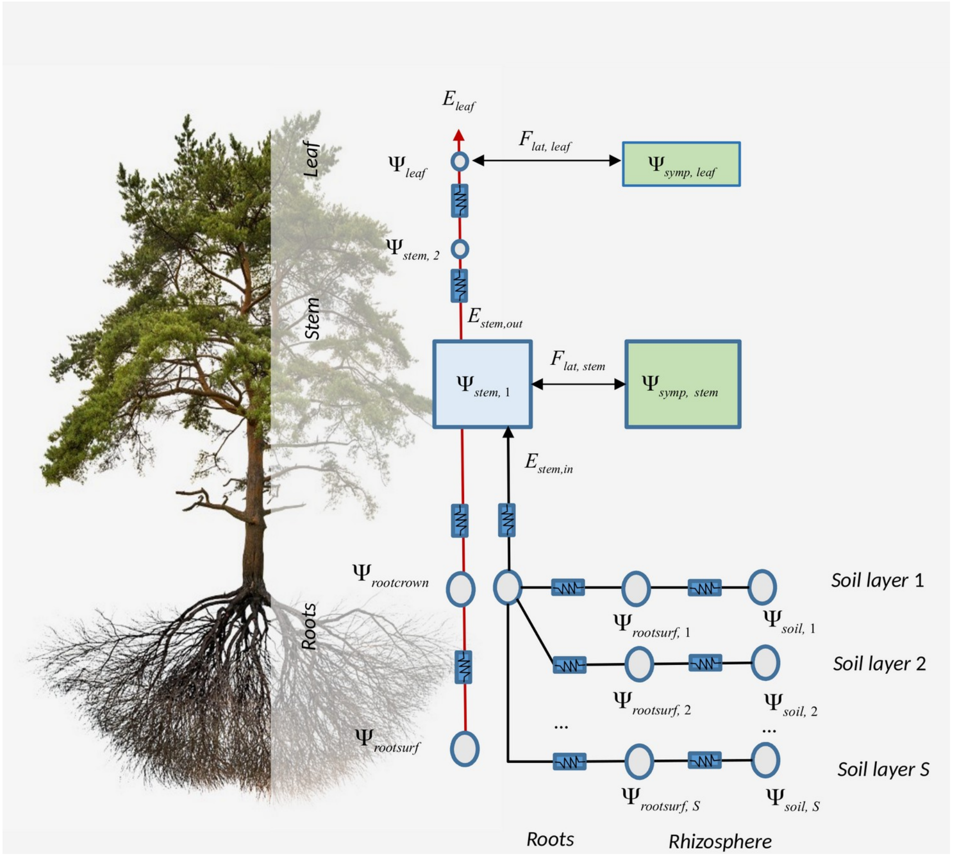


Watershed eco-hydrological model



medfate





De Cáceres et al. (2015). Agr. For. Met., 213, 77-90.

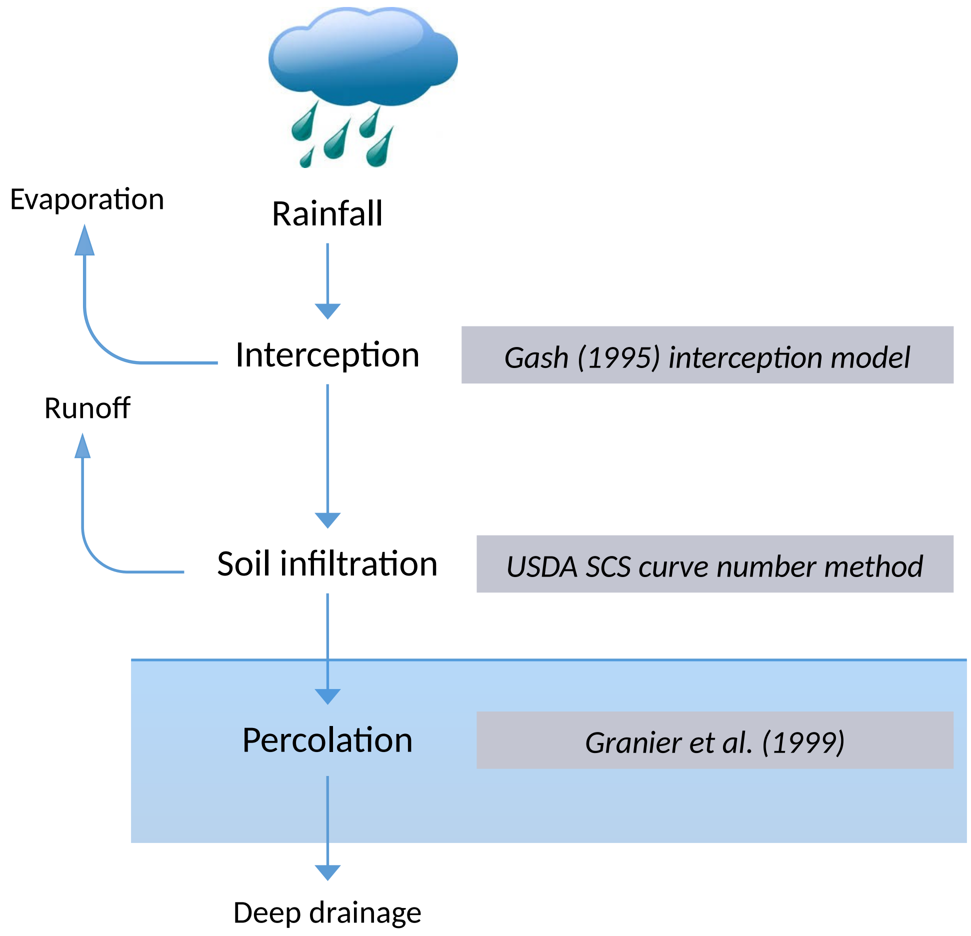
De Cáceres et al. (2021). Agr. For. Met., 296.

02

Water balance modeling

Implementation of processes

Hydrological processes



CREAF

Plant transpiration

1. Calculate maximum transpiration (T_{max}) as function of potential evapotranspiration (PET) and LAI of the stand.

$$\frac{T_{max}}{PET} = -0.006 \cdot LAI_c^2 + 0.134 \cdot LAI_c + 0.036$$

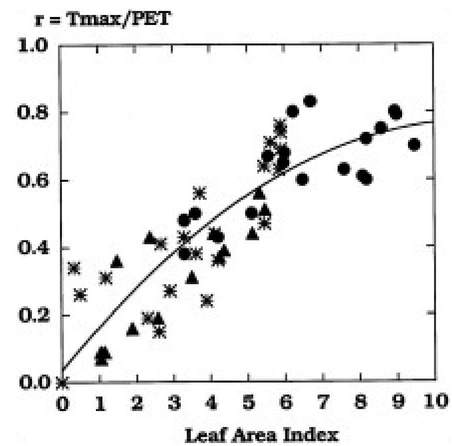


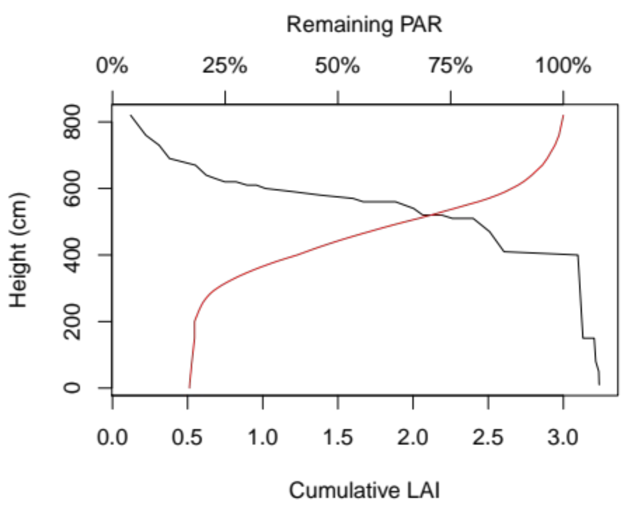
Fig. 1. Ratio (r) of stand transpiration (T_{max}) to potential evapotranspiration (PET) under non-limiting soil water, as a function of stand leaf area index (LAI). Included data are: (1) intra-annual variations of LAI during spring leaf expansion (triangles) and autumn leaf fall (stars) are reported for an oak stand (data from Bréda, 1994), (2) inter-annual variations in maximum LAI (black circles) for an oak stand (data from Bréda and Granier, 1996) and reviewed from literature in different species and site conditions (*Fagus sylvatica* from Savoie et al., 1988 and Biron, 1994; mixed *Fagus* + *Quercus* from Aussenac and Granier, 1979; *Picea abies* from Cienciala et al., 1994 and Biron, 1994; *Pseudotsuga menziesii* from Black, 1979; Aussenac and Boulangeat, 1980; Granier, 1987; tropical rain forest from Granier et al., 1992, 1996; *Elaeis guineens* from Dufrêne et al., 1992). Best fit is: T_{max}/PET = $-0.006 * \mathrm{LAI}^2 + 0.134 * \mathrm{LAI} + 0.036$, $r^2 = 0.85$.

Granier et al. (1999)
Mouillot et al. (2001)
Ruffault et al. (2013)

Plant transpiration

1. Calculate maximum transpiration (T_{max}) as function of potential evapotranspiration (PET) and LAI of the stand.
2. Decrease T_{max} for each plant cohort according to:

    - The proportion of T_{max} that corresponds to the plant cohort, given its **LAI** and available **light**.



$$T_{i,s} = T_{max} \cdot \frac{L_i \cdot LAI_i^{\phi}}{\sum_j L_j \cdot LAI_j^{\phi}} \cdot K_{i,s} \cdot v_{i,s}$$

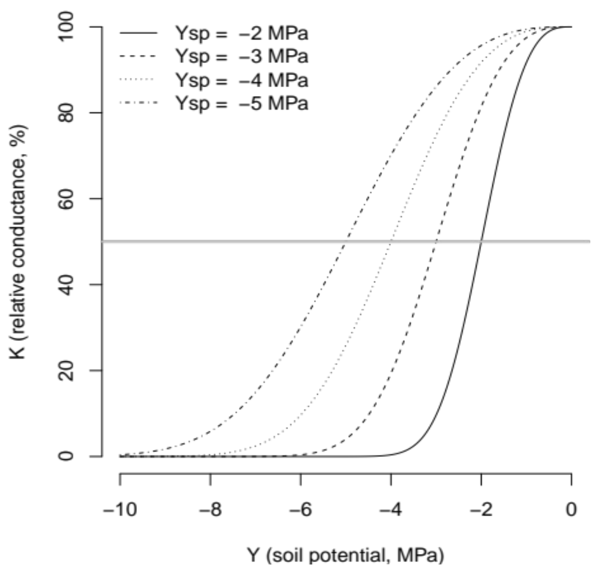
Granier et al. (1999)
Mouillot et al. (2001)
Ruffault et al. (2013)

CREAF

Plant transpiration

1. Calculate maximum transpiration (T_{max}) as function of potential evapotranspiration (PET) and LAI of the stand.
2. Decrease T_{max} for each plant cohort according to:

   - The proportion of T_{max} that corresponds to the plant cohort, given its **LAI** and available **light**.
   - The **relative whole-plant conductance** corresponding to the soil water potential in each layer.



$$T_{i,s} = T_{\max} \cdot \frac{L_i \cdot LAI_i^{\phi}}{\sum_j L_j \cdot LAI_j^{\phi}} \cdot K_{i,s} \cdot v_{i,s}$$

Granier et al. (1999)
Mouillot et al. (2001)
Ruffault et al. (2013)

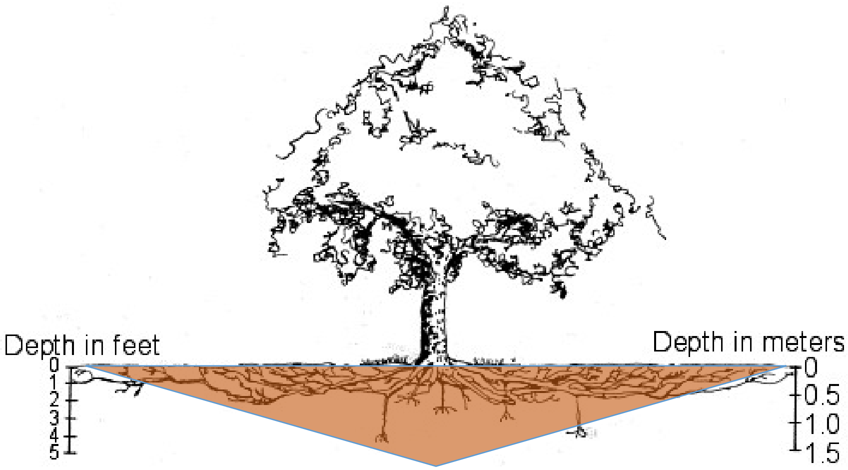
CREAF

Plant transpiration

1. Calculate maximum transpiration (T_{max}) as function of potential evapotranspiration (PET) and LAI of the stand.
2. Decrease T_{max} for each plant cohort according to:

   - The proportion of T_{max} that corresponds to the plant cohort, given its **LAI** and available **light**.
   - The **relative whole-plant conductance** corresponding to the soil water potential in each layer.
   - The **proportion of fine roots** in each soil layer

$$T_{i,s} = T_{max} \cdot \frac{L_i \cdot LAI_i^{\phi}}{\sum_j L_j \cdot LAI_j^{\phi}} \cdot K_{i,s} \cdot v_{i,s}$$



Granier et al. (1999)
Mouillot et al. (2001)
Ruffault et al. (2013)

Drought stress

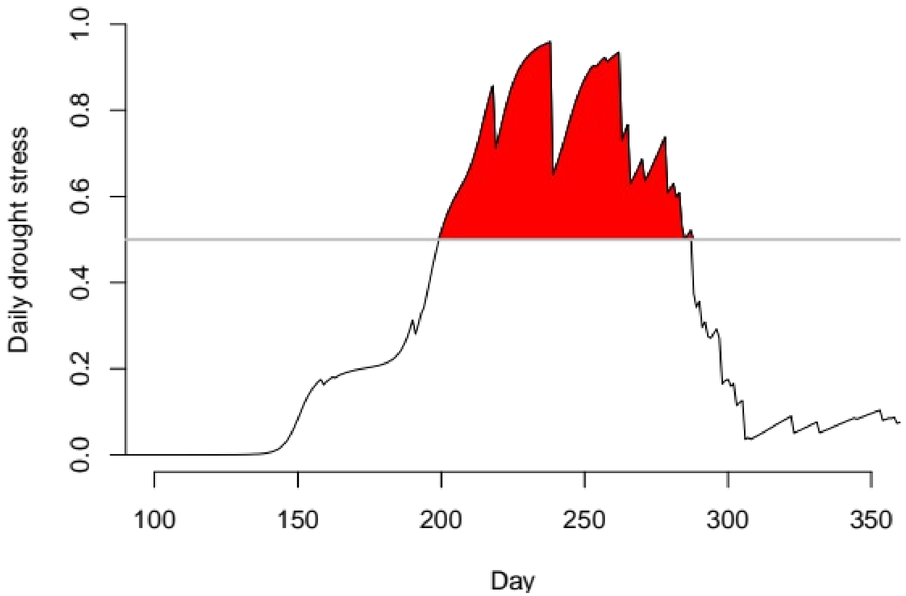
- **Daily drought stress** (*DDS*) of a plant cohort *i* is the one-complement of the whole-plant relative conductance integrated across soil layers:

Leaf phenology

Proportion of roots in layer *s*

$$DDS_i = \phi_i \cdot \sum_s (1 - K_{i,s}) \cdot v_{i,s}$$

Relative conductance in layer *s*

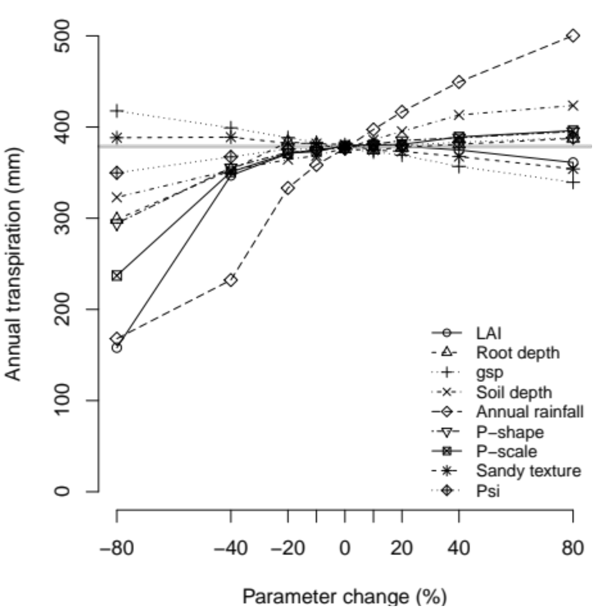


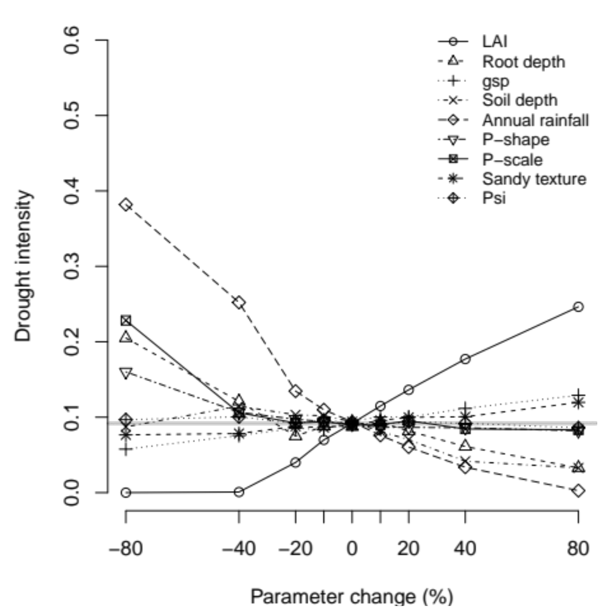
02

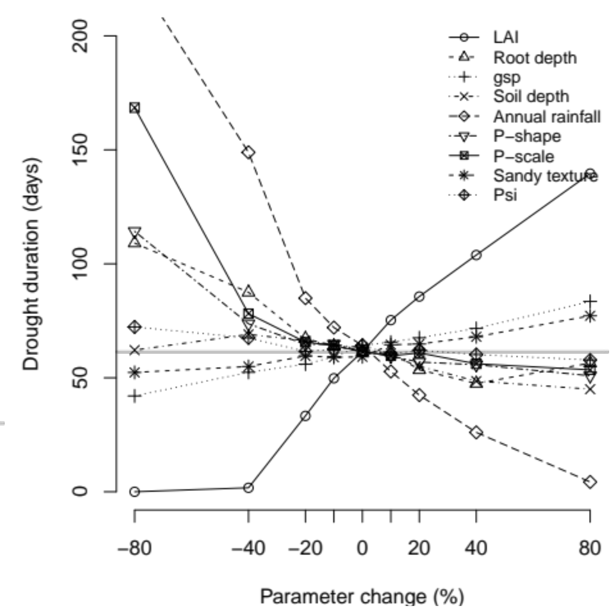
Water balance modeling

Sensitivity analysis

Parameter	Symbol	Units	Initial	Min (-80%)	Max (+80%)
LAI (x2 cohorts)	*LAI*	$m^2 \cdot m^{-2}$	1.6	0.32	2.88
Root depth	*z*	cm	100	20	180
Soil depth (+ rocky layer)	*d*	cm	100	20	180
Soil texture (clay/silt/sand)		%	35/30/35	63/30/7	7/30/63
Canopy water storage	g_{sp}	$mm \cdot LAI^{-1}$	0.5	0.1	0.9
Annual rainfall (dry)	P_{ann}	mm	361	72	649
Annual rainfall (wet)	P_{ann}	mm	622	124	1119
Gamma shape			2	0.4	3.6
Gamma scale			4	0.8	7.4
Potential corresponding to 50% conductance loss	Ψ_{sp}	MPa	-2.0	-0.4	-3.6

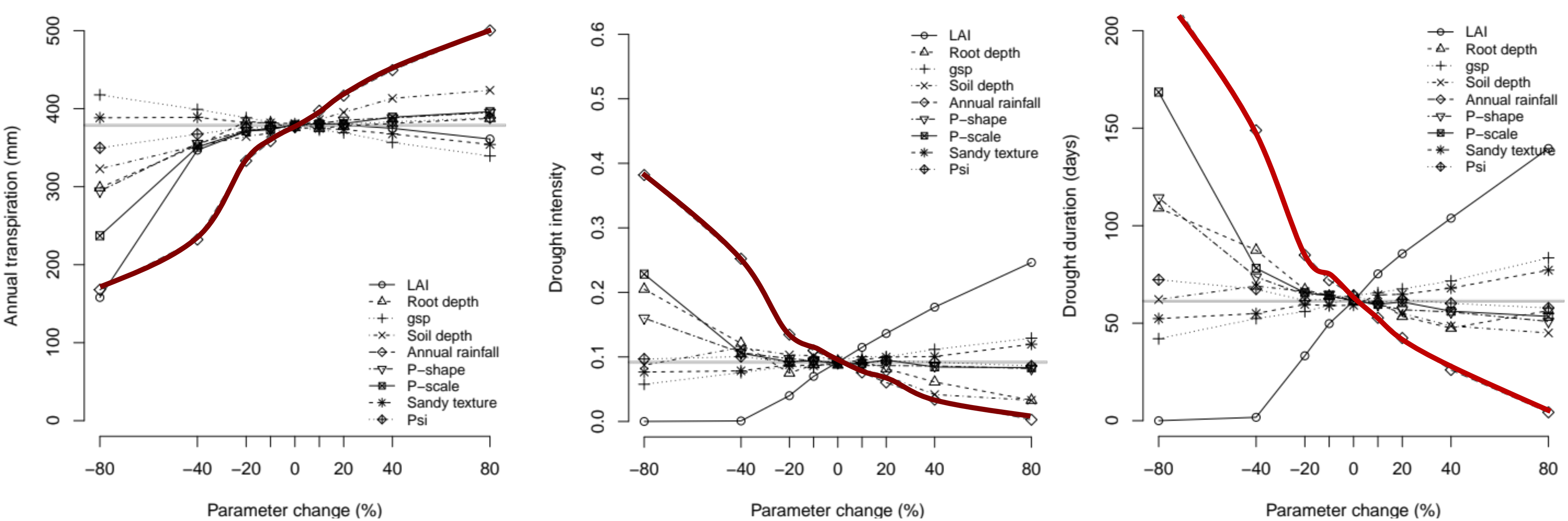






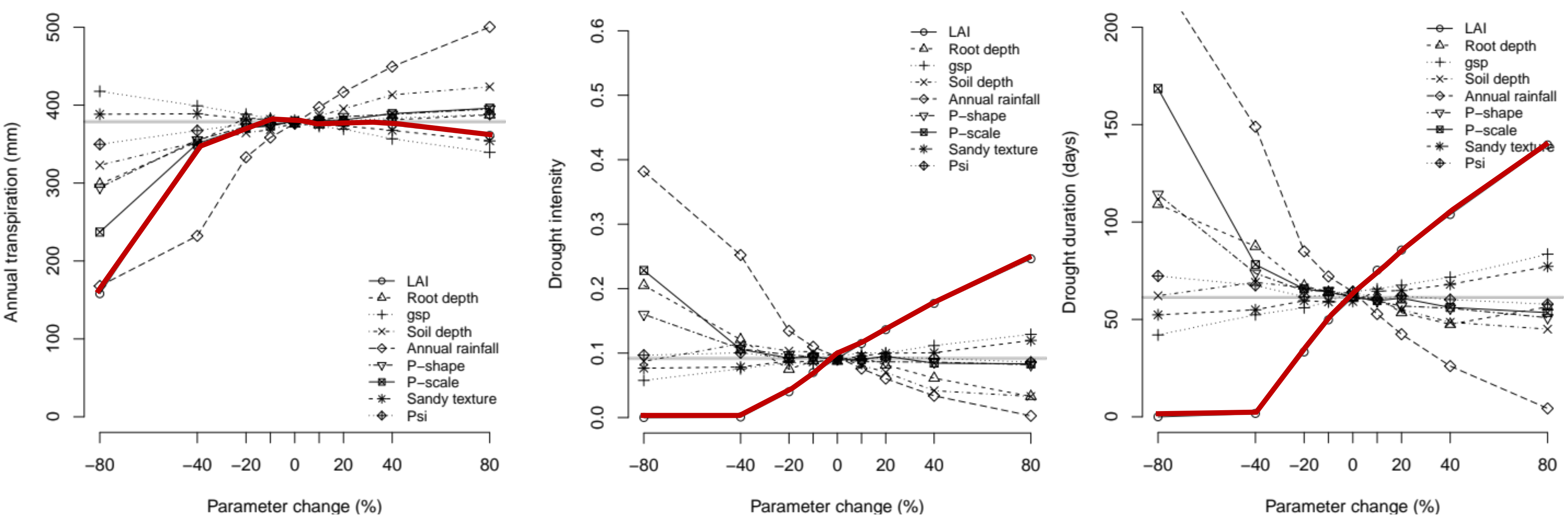
02 Water balance modeling – Sensitivity analysis

1. The most influential variable is **annual rainfall**.

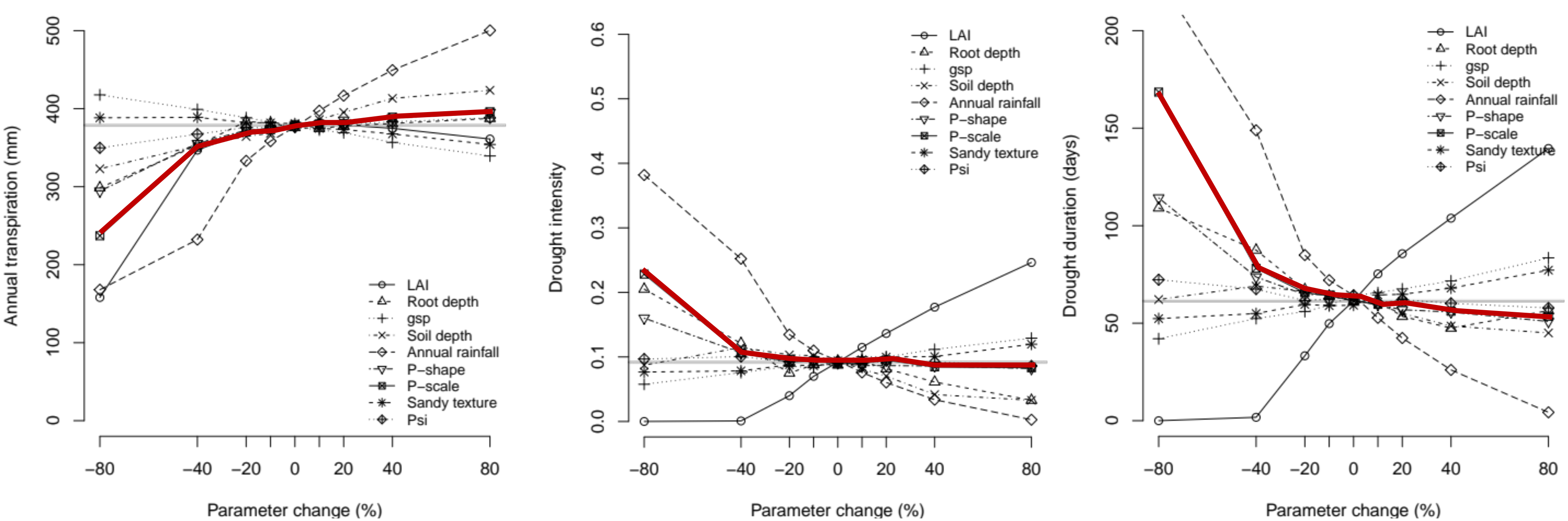


02 Water balance modeling – Sensitivity analysis

1. The most influential variable is **annual rainfall**.
2. **Leaf area index** is another highly influential factor.

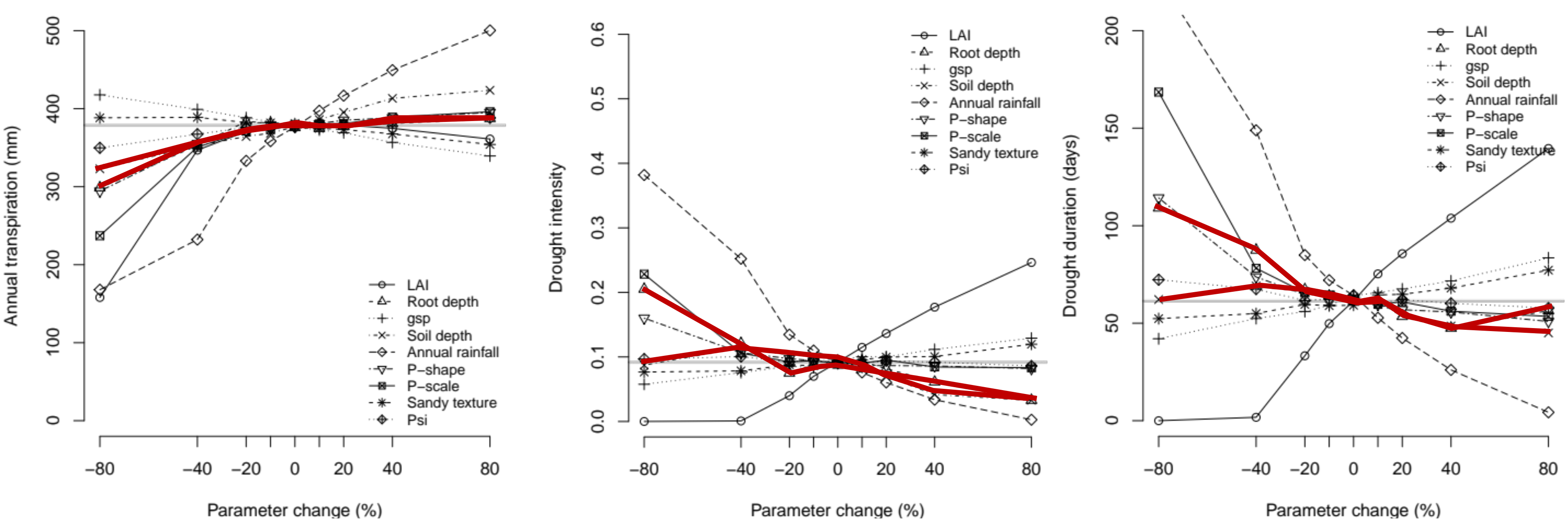


1. The most influential variable is **annual rainfall**.
2. **Leaf area index** is another highly influential factor.
3. Uniform distribution of rainfall leads to higher interception and higher stress.



CREAF

1. The most influential variable is **annual rainfall**.
2. **Leaf area index** is another highly influential factor.
3. Uniform distribution of rainfall leads to higher interception and higher stress.
4. Transpiration decreases and drought stress increases for **shallow roots** and **shallow soils** (water losses in runoff and deep drainage).

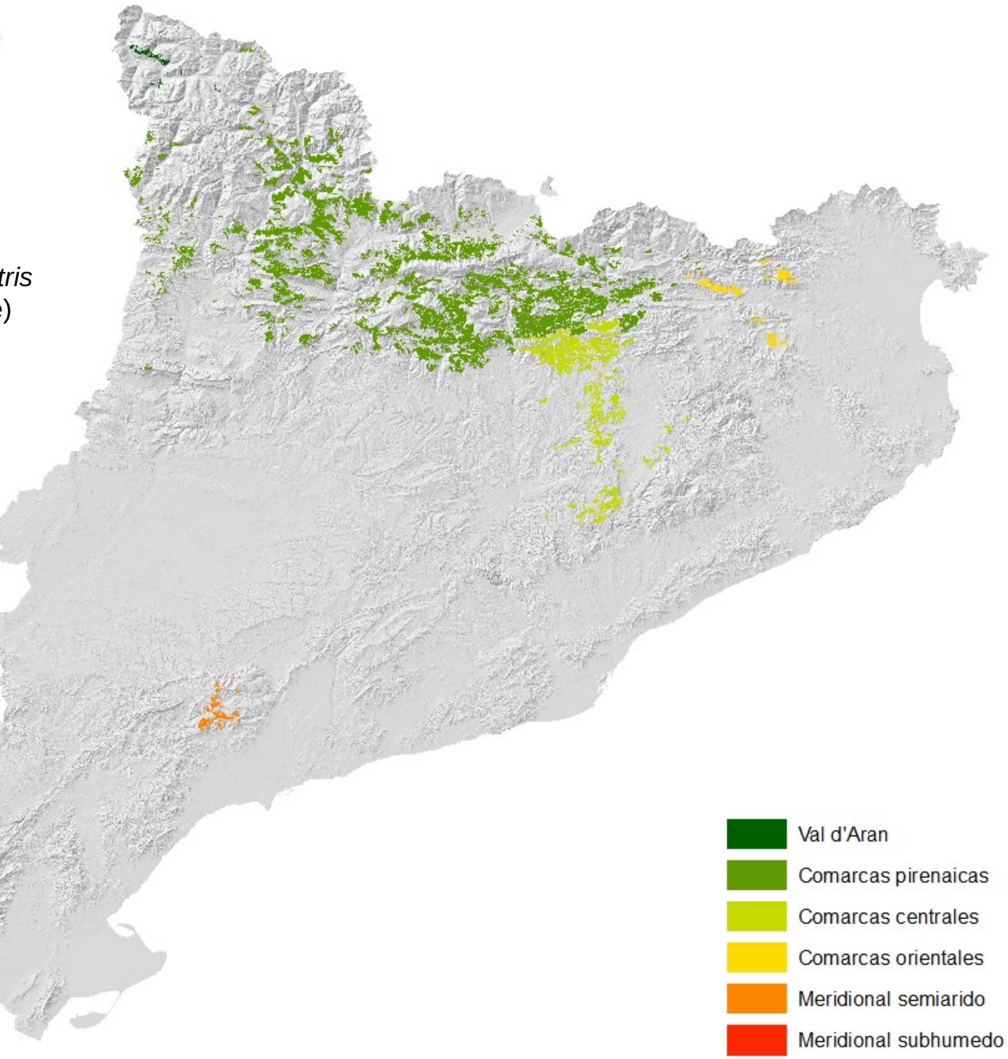


03

Applications of water balance models

Forest and water resource management

Pinus sylvestris
(Scots pine)



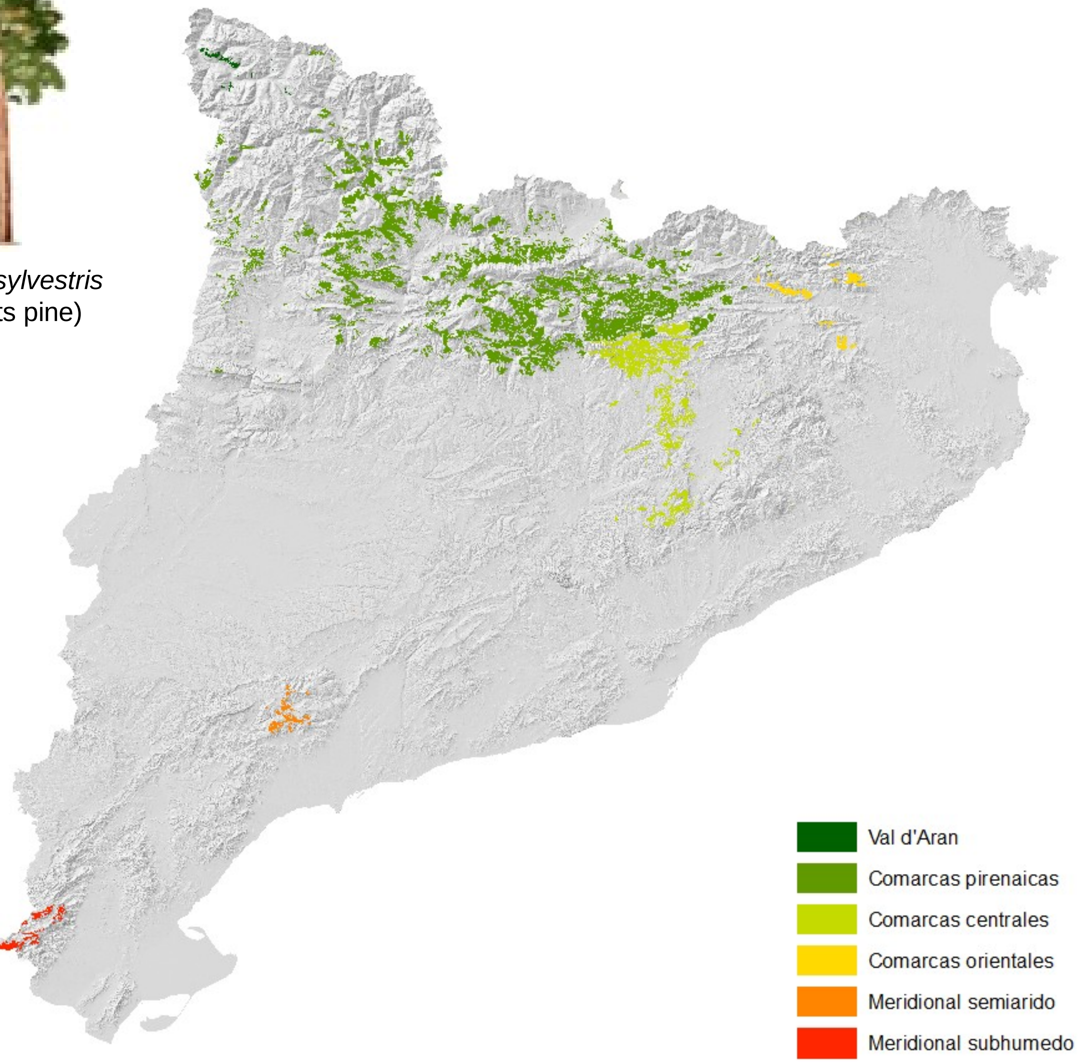
M. Beltrán

T. Valor

S. Martín

[Ameztegui et al. (2017). Ecol. Mod., 356, 141-150.]

Pinus sylvestris
(Scots pine)



Humid Site

Temp	8.7
Precip	828

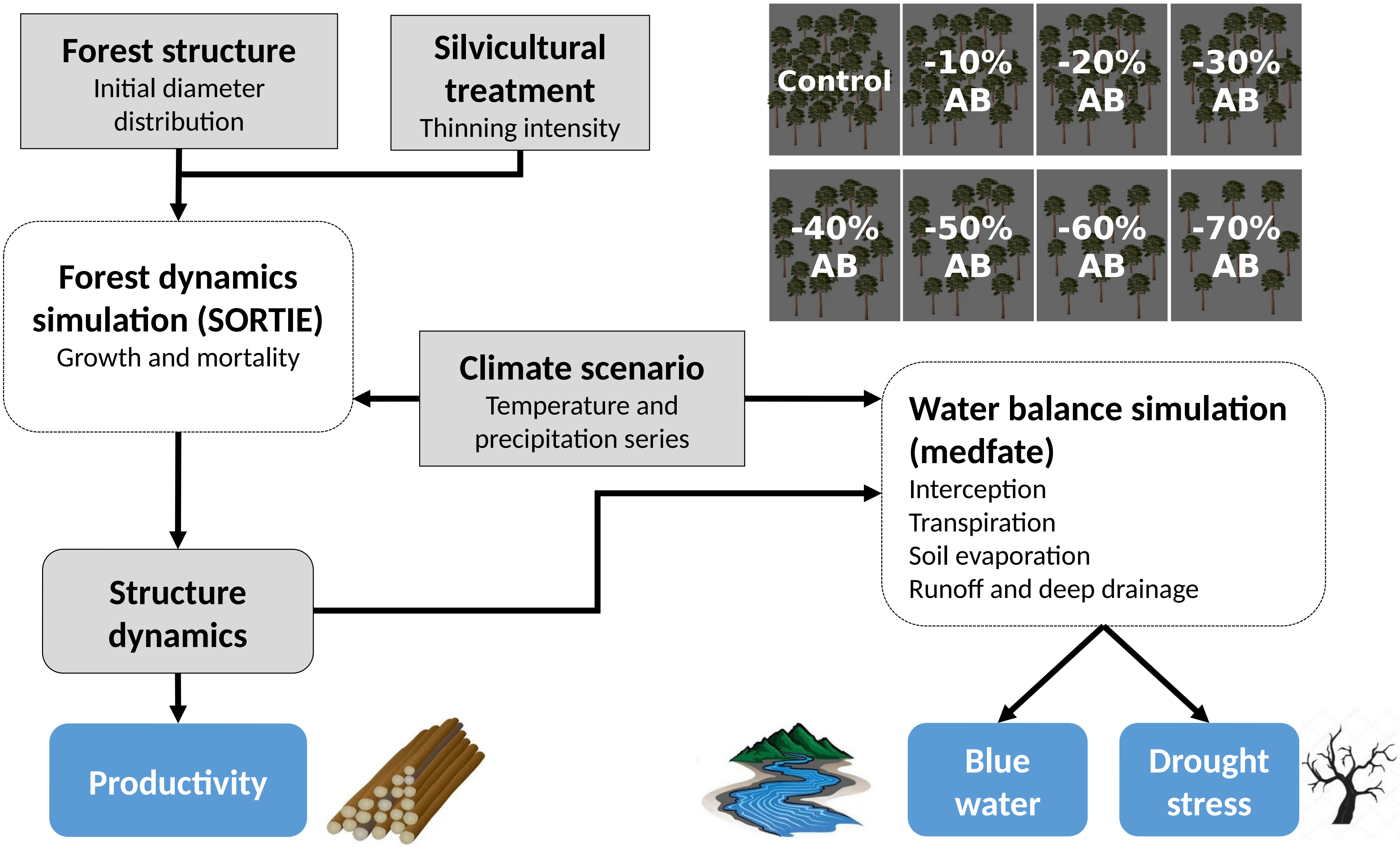
Mesic Site

Temp	12.0
Precip	714.3

Xeric Site

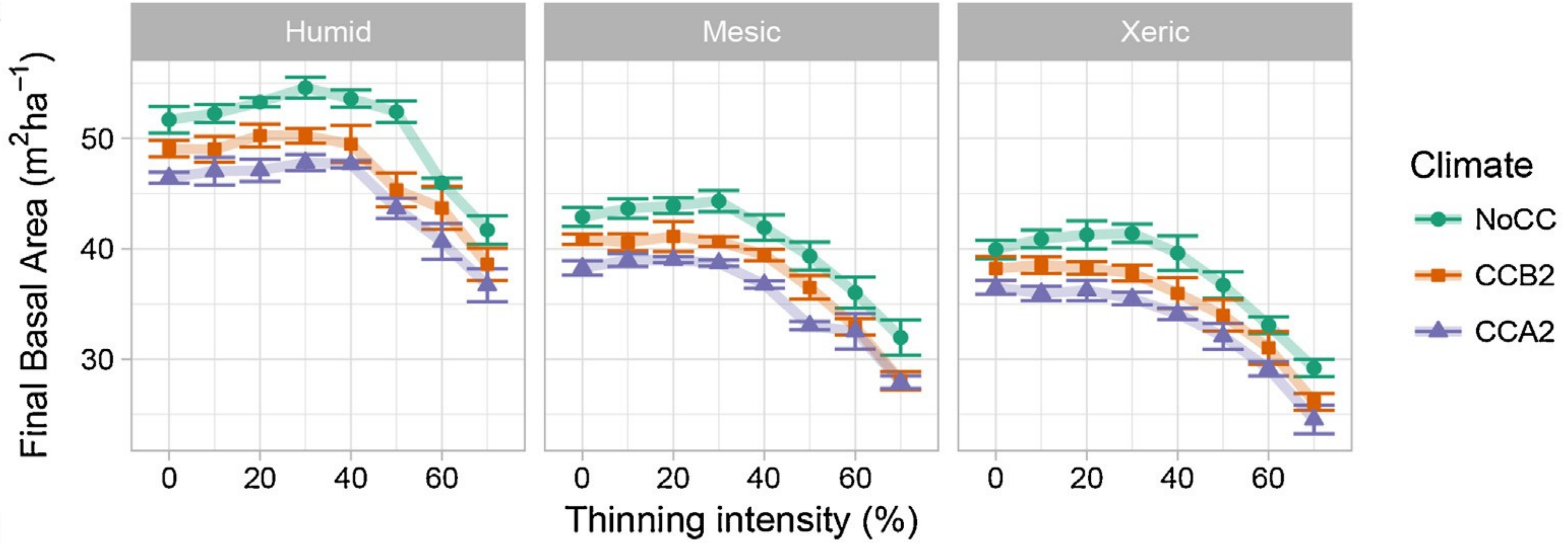
Temp	12.5
Precip	564.3

Ameztegui et al. (2017). Ecol. Mod., 356, 141-150.



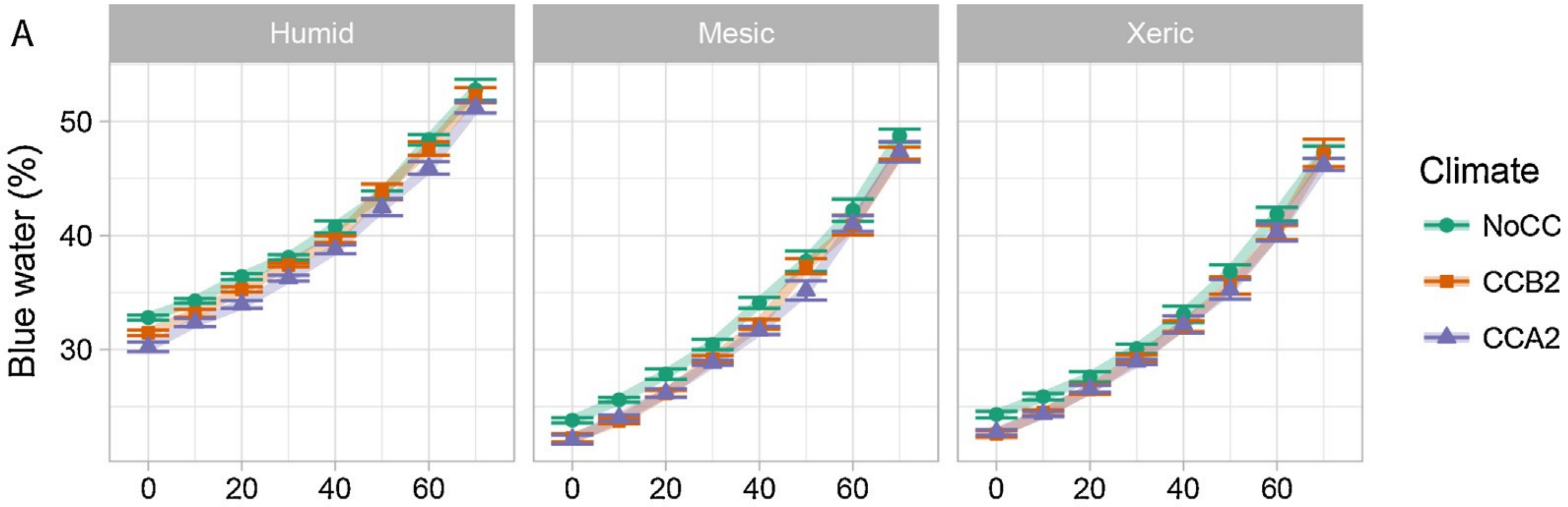
Ameztegui et al. (2017). Ecol. Mod., 356, 141-150.

Effect of thinning on final basal area



Ameztegui et al. (2017). Ecol. Mod., 356, 141-150.

Effect of thinning on blue water



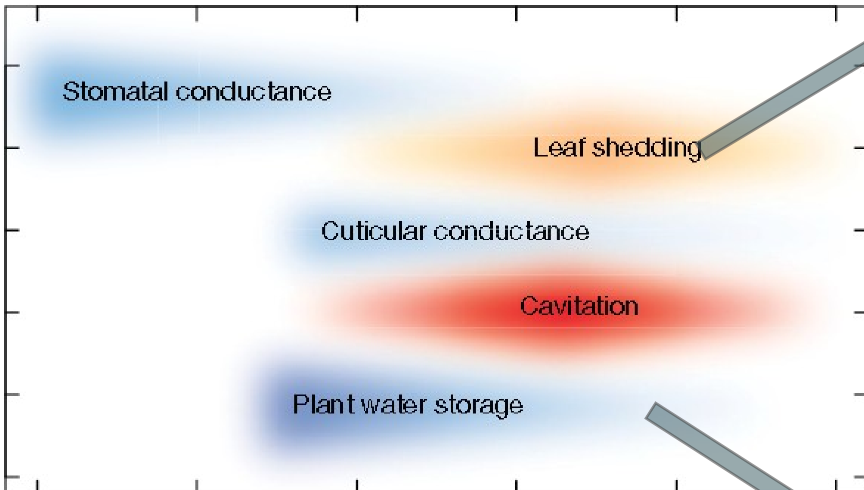
Ameztegui et al. (2017). Ecol. Mod., 356, 141-150.

03

Applications of water balance models

Forest drought monitoring

Forest drought and wildfire risk



+ Dead fuel loading

+ Wildfire risk

– Live fuel moisture content (LFMC)

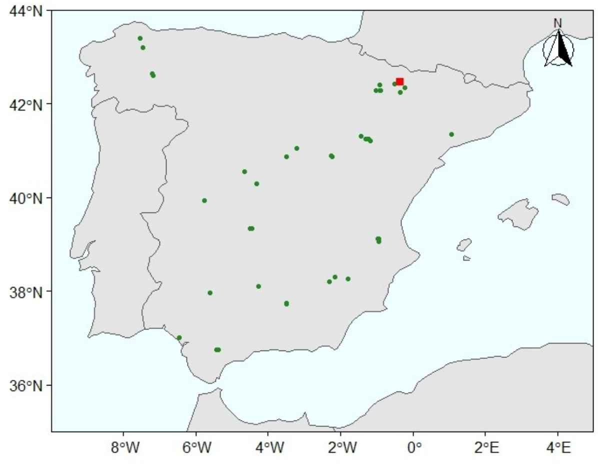
Drought type	Focus	Assessment
Meteorological drought	Decreased precipitation	Climatic indices (PSDI, SPI, SPEI)
Agricultural drought ***Forest* drought**	**Decreased soil moisture and plant water status**	Soil probes Remote sensing (NDWI, SMOS) **Computed soil moisture**
Hydrological drought	Decreased streamflow	Total water deficit index Surface water supply index
Groundwater drought	Decreased groundwater levels	
Socio-economic drought	Failure to meet societal demand for water	

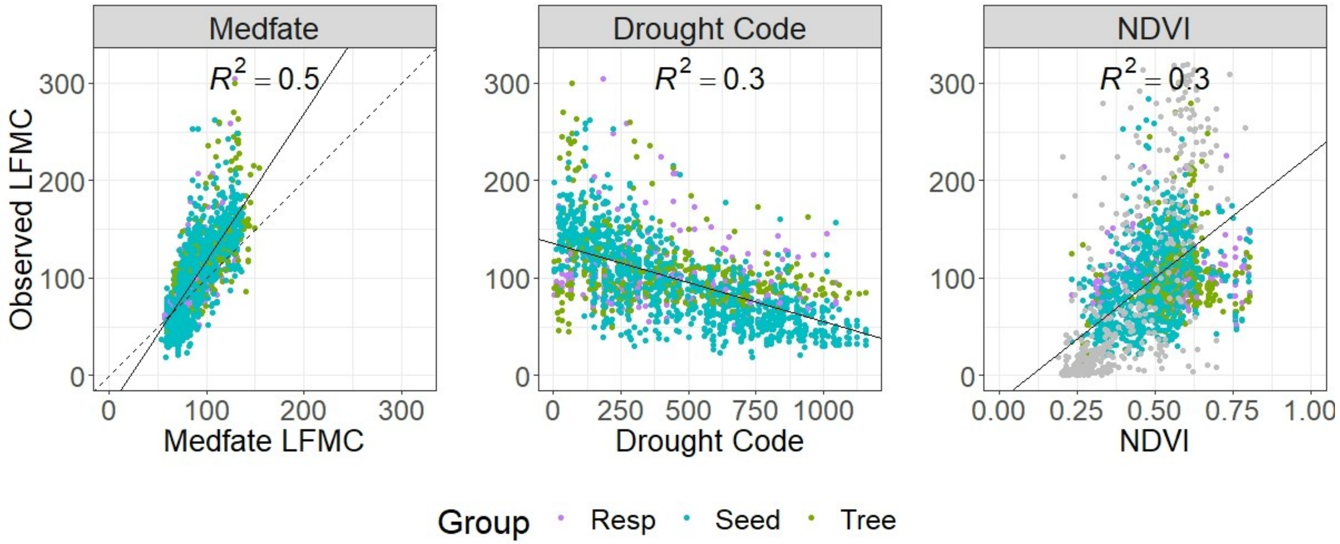
Mishra & Singh (2010). J. Hydrol., 391, 202–216.

Estimation of Live Fuel Moisture Content (LFMC)
By Rodrigo Balaguer Romano (PhD. student UNED)

1. LFMC derived from soil water balance model
2. Climate index calculation (Drought Code)
3. Remote sensing index (NDVI)

Yebra et al. (2019). Sci. Data, 6, 155.



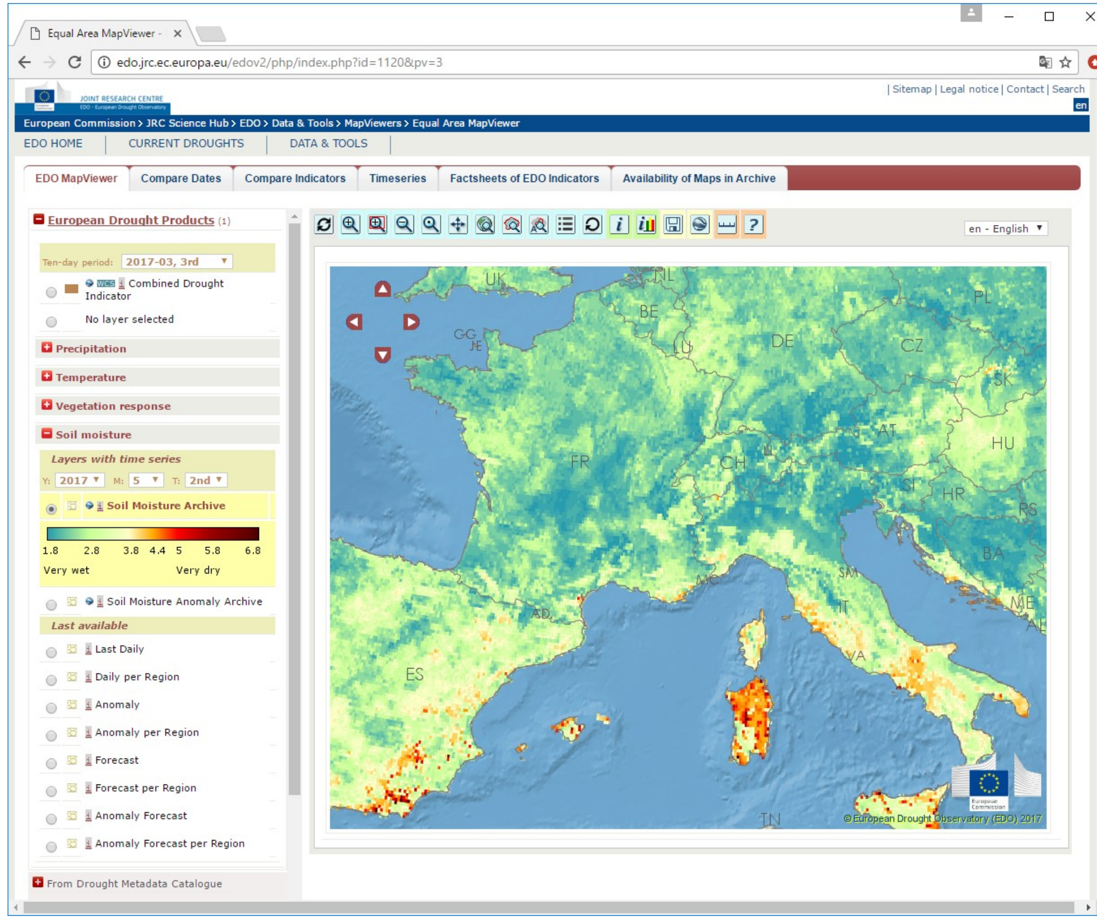


Balaguer-Romano et al. (2022) Agr. For. Met. 323

Agricultural drought monitoring at European level

Combined drought indicator

Standardized Precipitation Index (SPI-3)
Anomalies of soil moisture (LISFLOOD/5km).
Anomalies of fPAR (Remote sensing)



Sepulcre-Canto et al. (2012). Nat. Hazards Earth Syst. Sci., 12, 3519-3531.

03 Applications – Forest drought monitoring

CREAF

Forest structure and composition

Soil properties

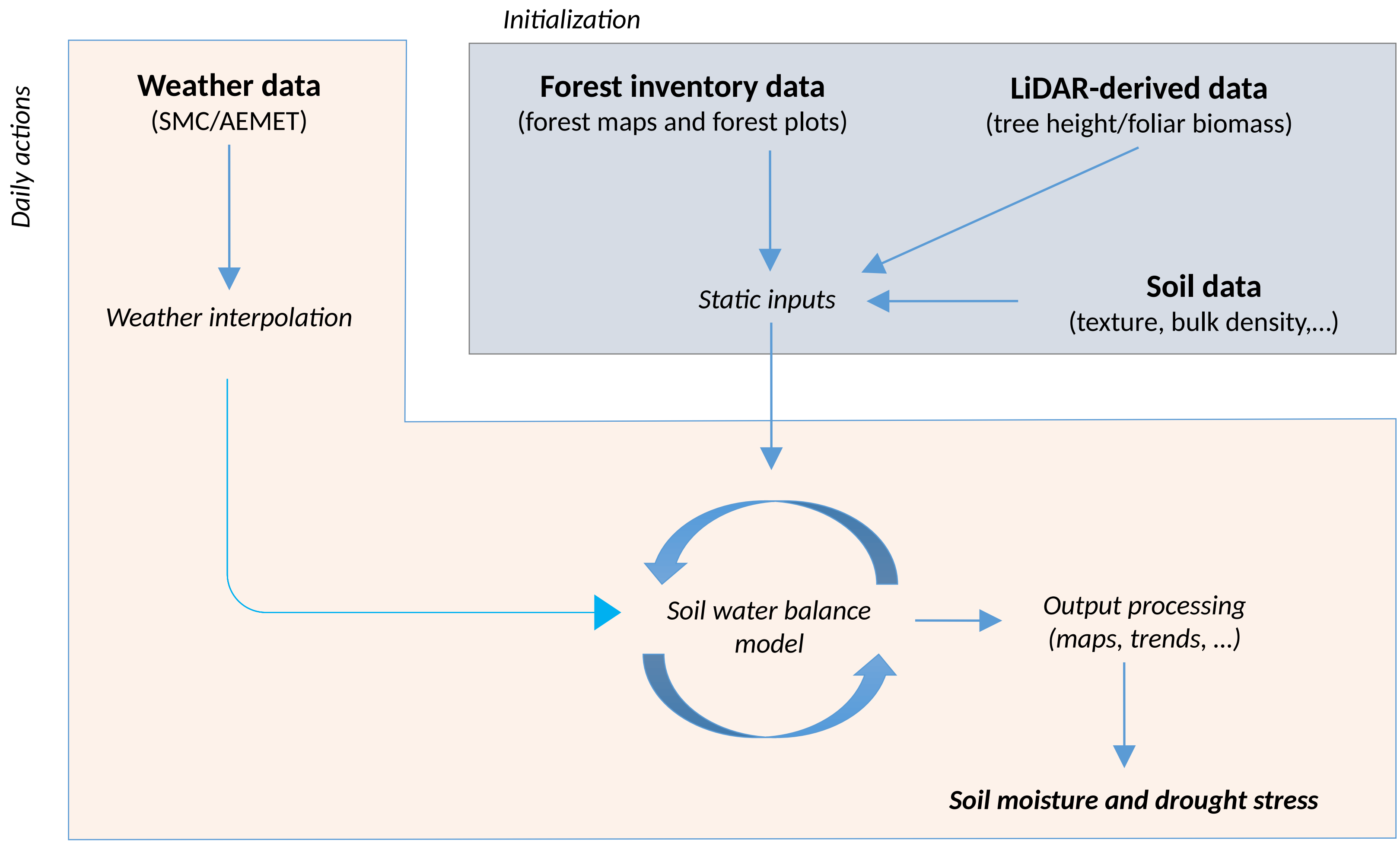
SoilGrids
A system for automated global soil mapping
www.soilgrids.org
ISRIC
World Soil Information

Climate forcing (daily series)

AEMet
Agencia Estatal de Meteorología

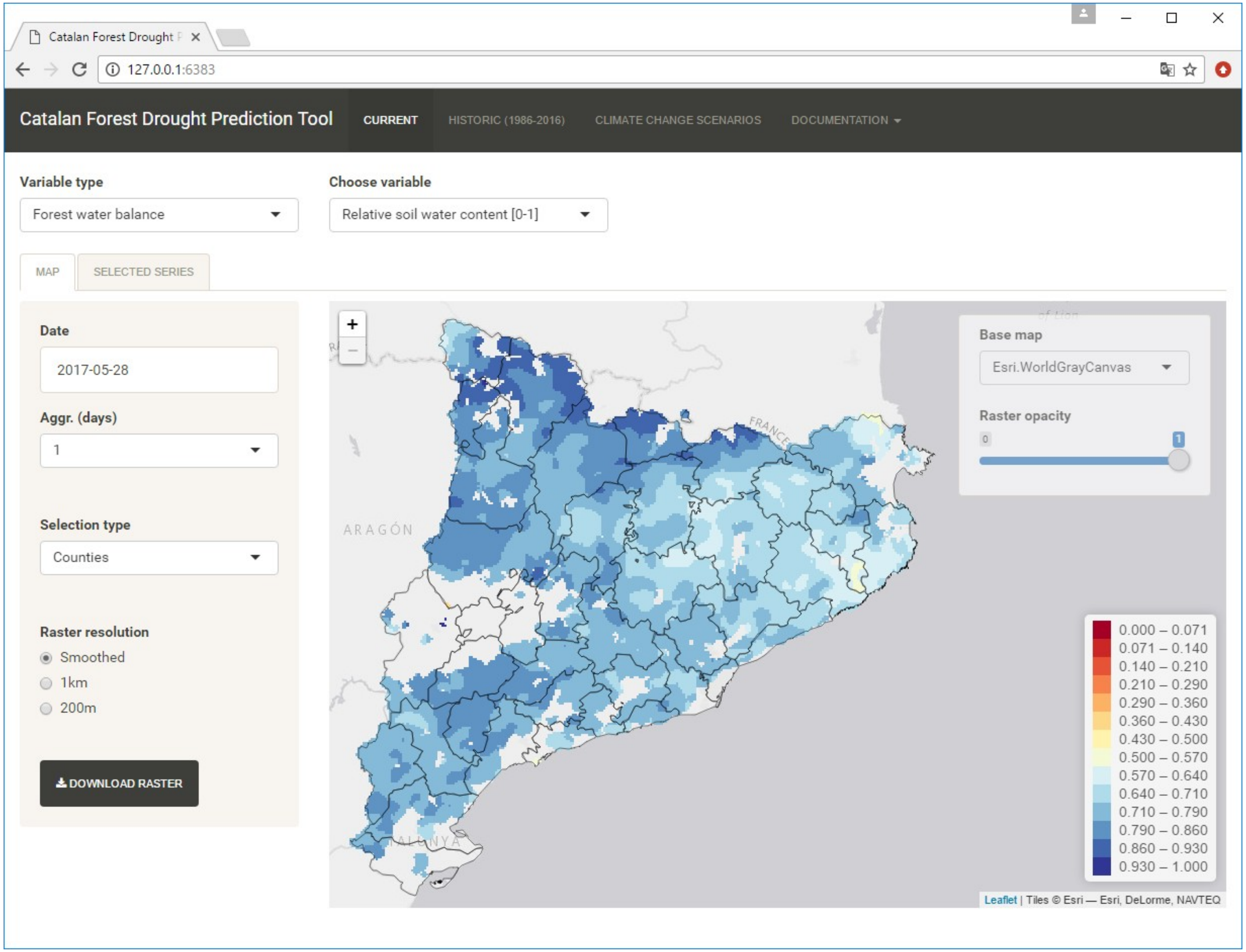
meteo.cat
Servei Meteorològic de Catalunya

CatDrought - Architecture

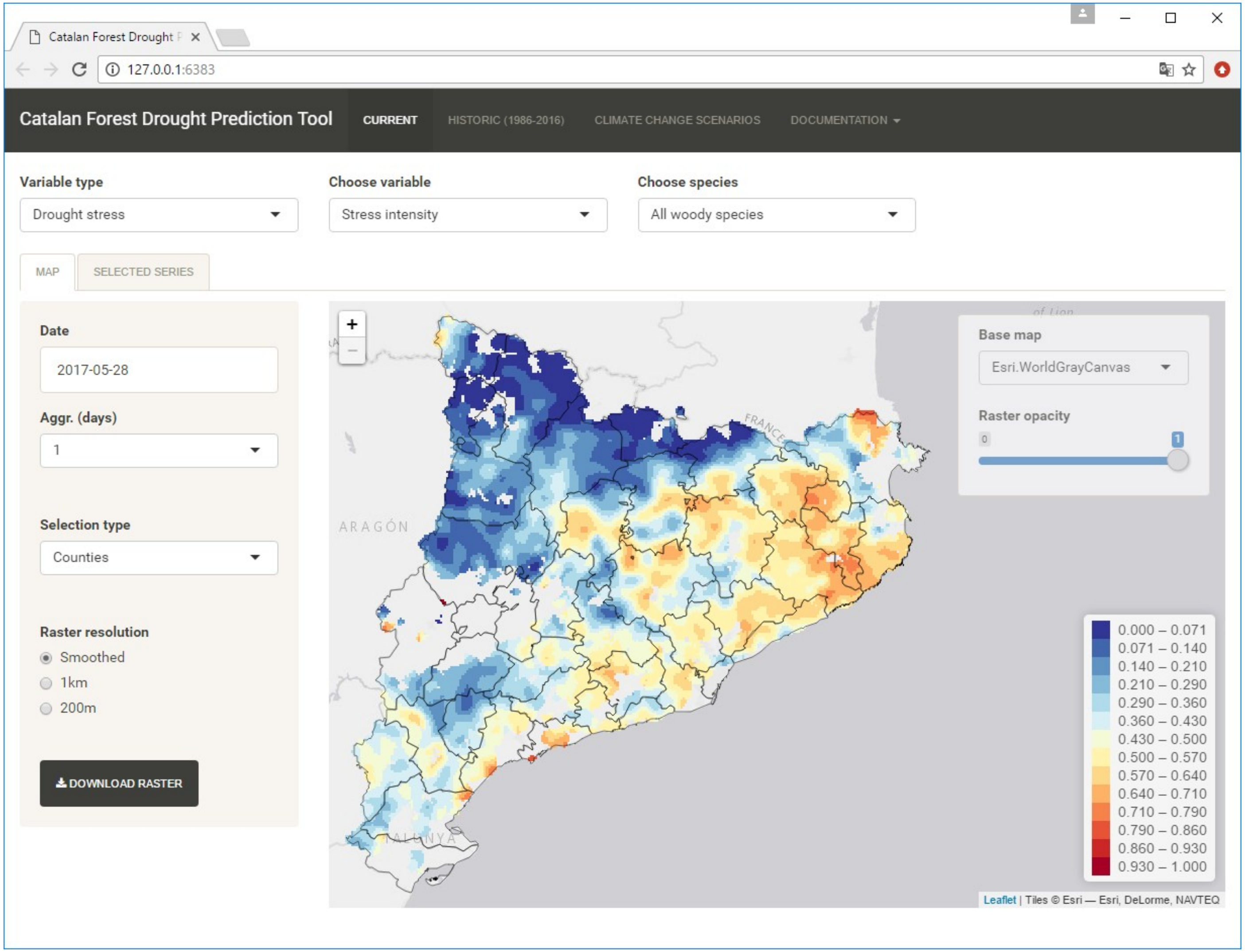


03 Applications – Forest drought monitoring

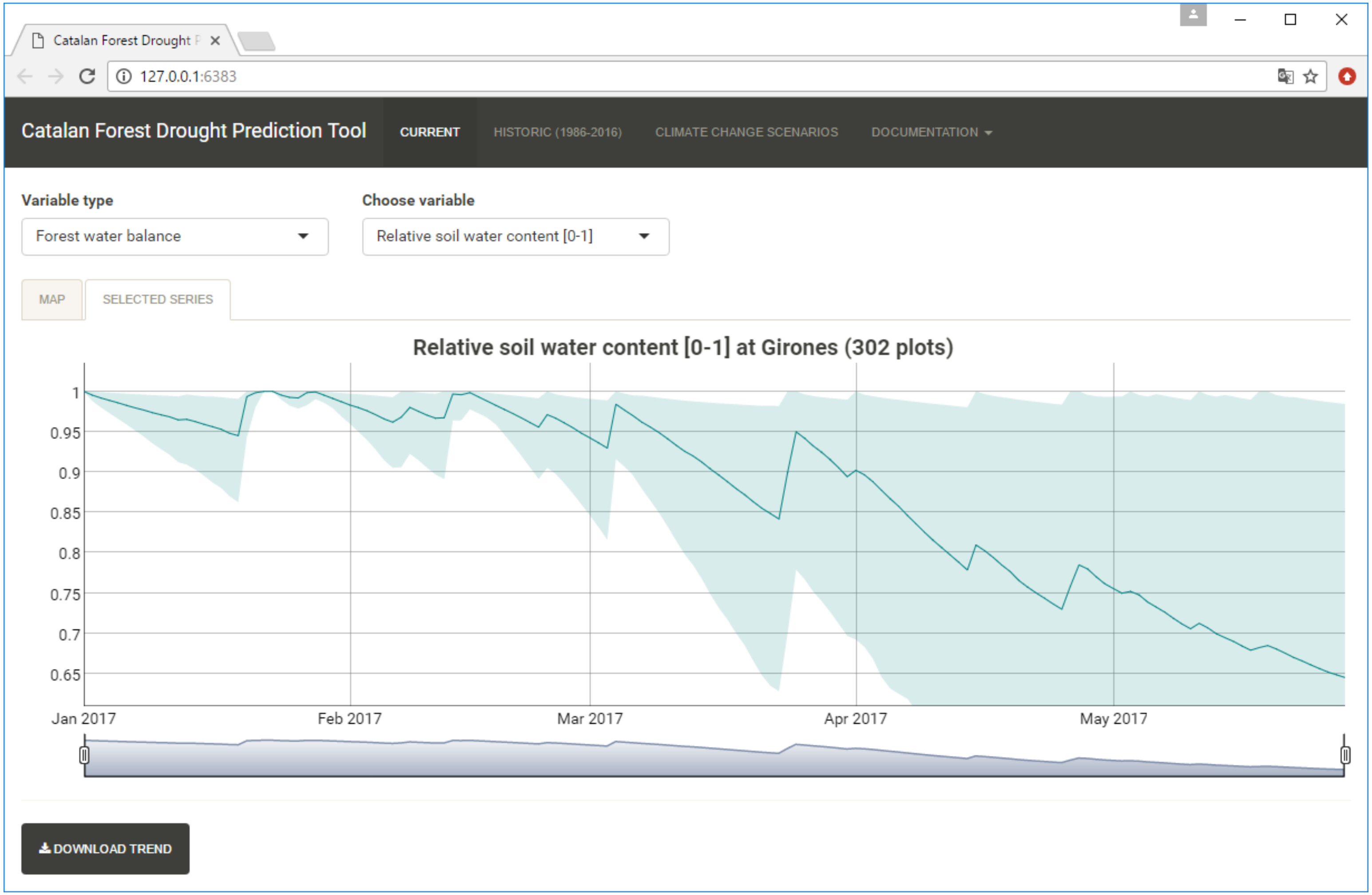
CatDrought - Soil moisture map



CatDrought - Stress intensity map



CatDrought - Soil moisture dynamics



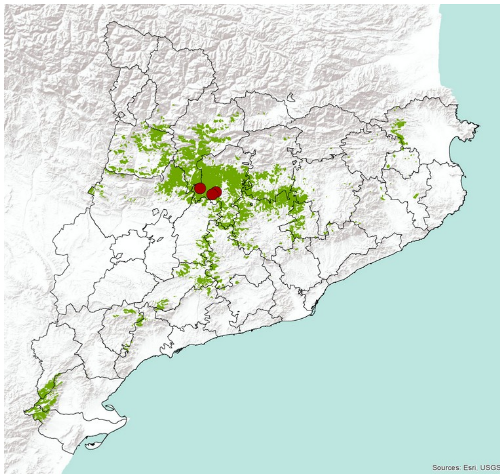
03

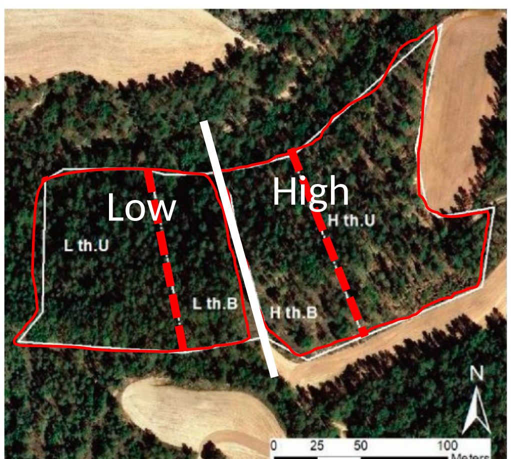
Applications of water balance models

Effect of understory management on drought stress

By Lena Vilà Vilardell
(Ph.D. Student at CTFC)

How does understory growth affect forest vulnerability to drought?





Treatment layout

Thinning intensity

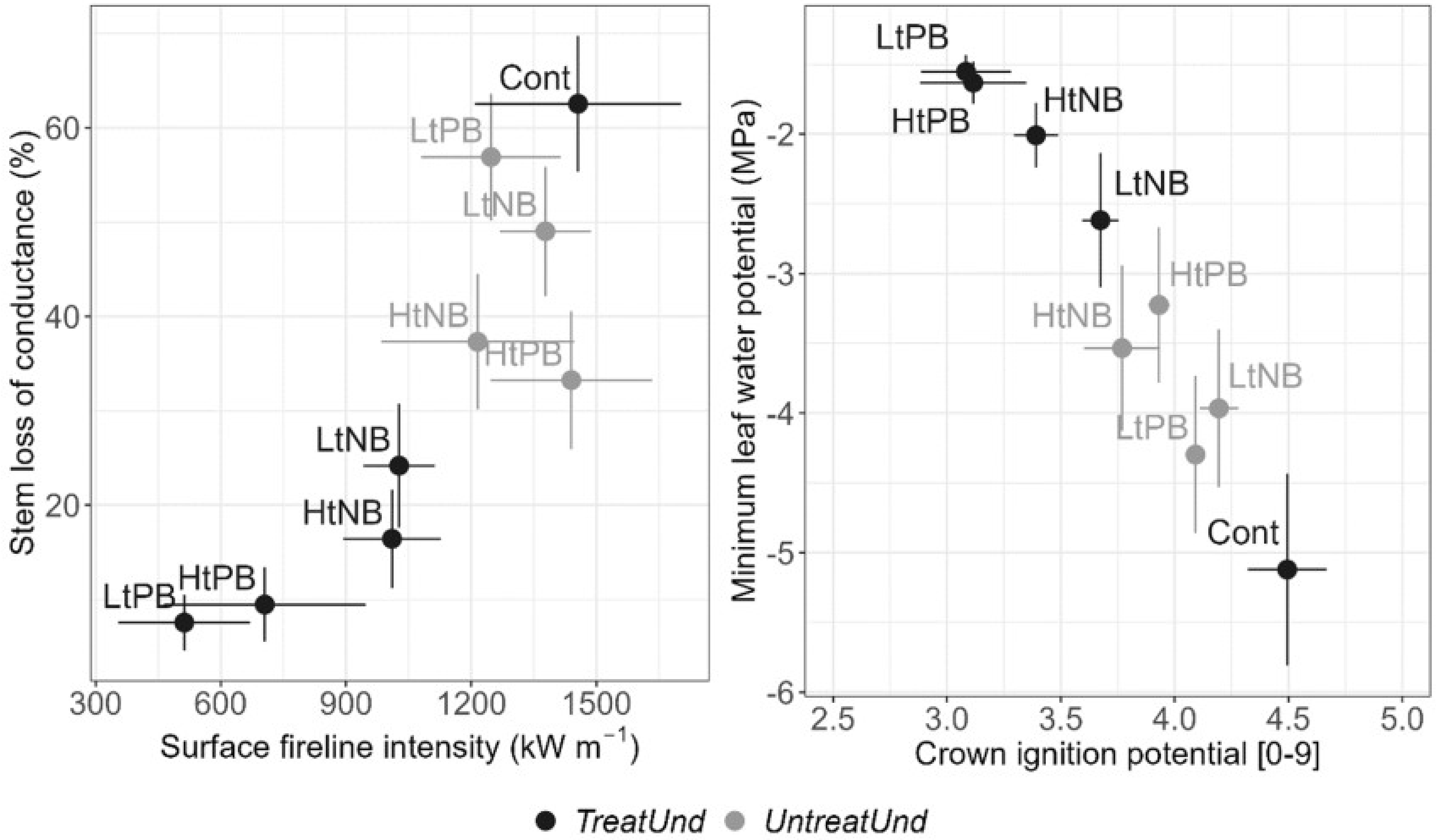
Understory and debris management

Control	High ↓ 40% BA	Low ↓ 10% BA
Burning	HtPB	LtPB
Mechanical	HtNB	LtNB

Vilà-Vilardell et al. (2023) For. Ecol. Man.

Thinning intensity		Control	High		Low	
Understory treatment			Mechanical	Burning	Mechanical	Burning
Basal area	m2/ha	35	24	21	31	32
Canopy cover	%	76	60	48	73	71
Shrub cover	%	100	43	30	56	31
Shrub load	t/ha	18	4.4	3.6	5.5	2.8
Overstory LAI	m2/m2	1.9	1.2	1	1.7	1.8
Understory LAI	m2/m2	1.5	1	0.6	0.8	0.3

Vilà-Vilardell et al. (2023) For. Ecol. Man.



Vilà-Vilardell et al. (2023) For. Ecol. Man.

03

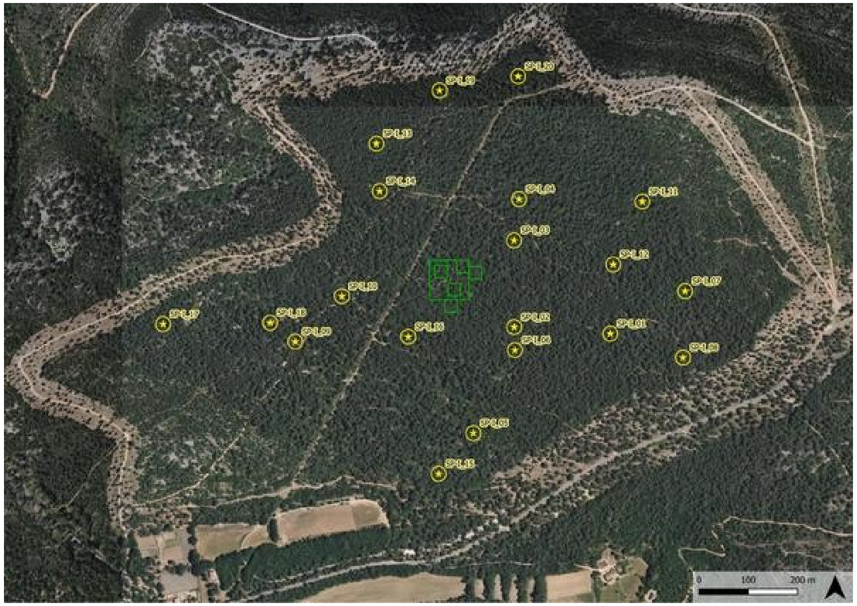
Applications of water balance models

Detailed stand-scale water balance

Location: 15km east from Marseille (FR)

Forest type: Mixed holm oak (*Quercus ilex*) Alepo pine (*Pinus halepensis*) forest

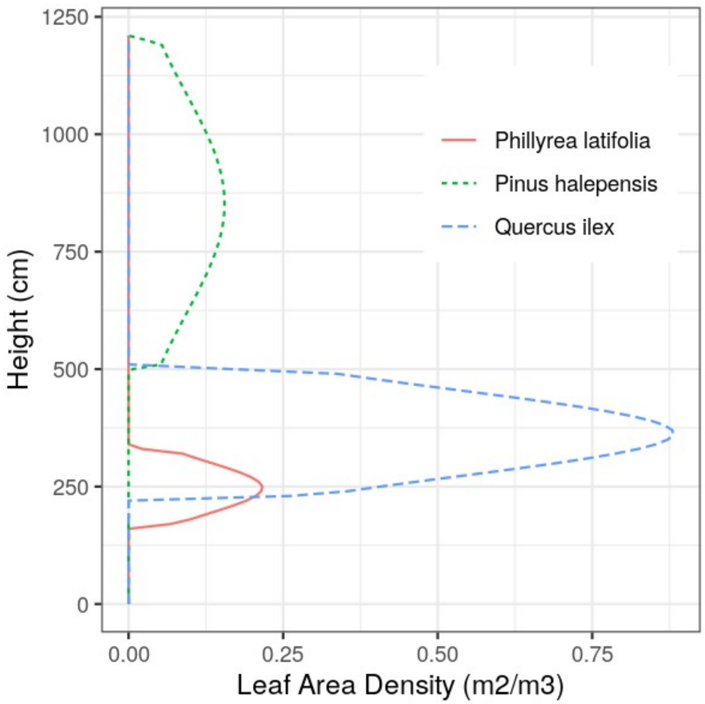
Monitored since 2007 by URFM (Unité de Recherche des Forets Méditérraneens) at INRAE (Avignon)



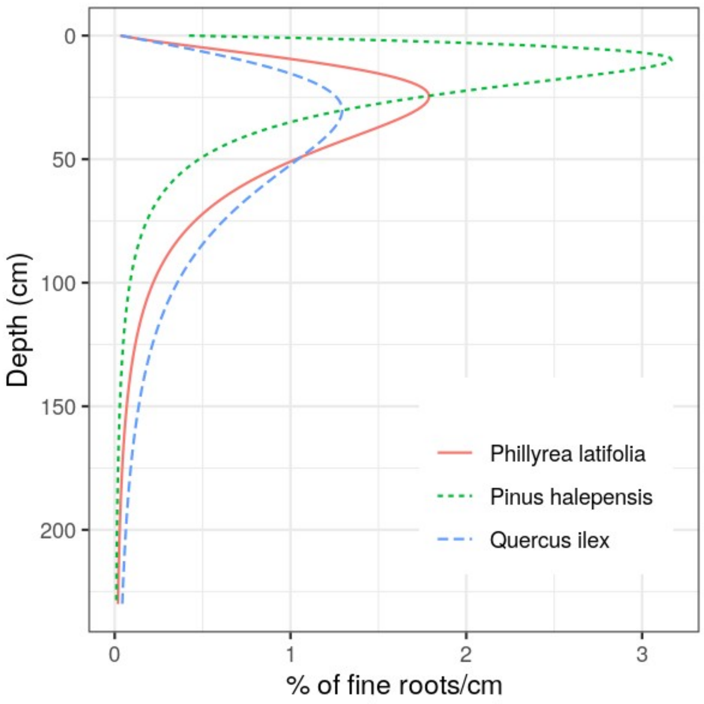
Simulation results using MEDFATE model (https://emf-creaf.github.io/medfate/)

Three species (plant cohorts): holm oak (*Quercus ilex*), Alepo pine (*Pinus halepensis*) and green olive tree (*Phillyrea latifolia*)

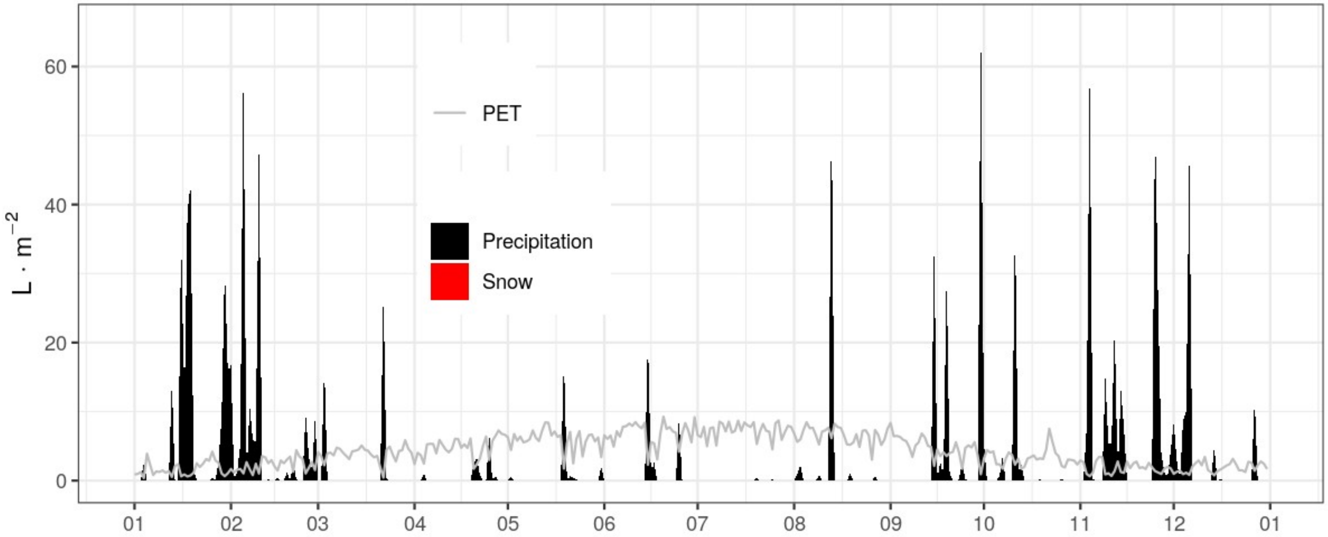
Leaf area distribution



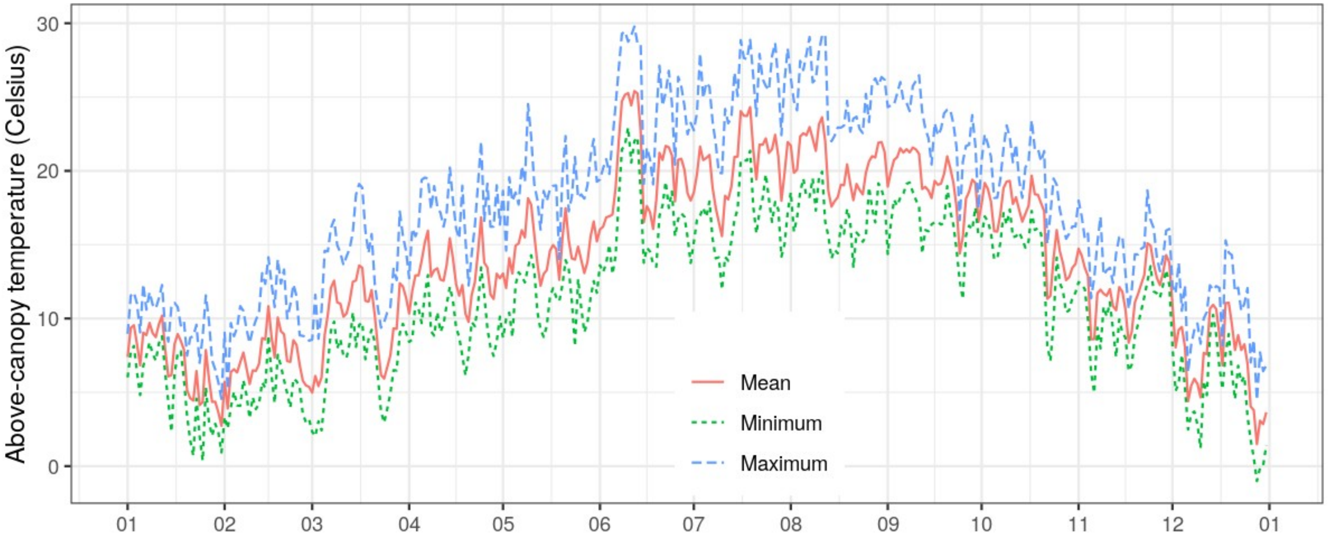
Fine root distribution



Precipitation and PET



Temperature

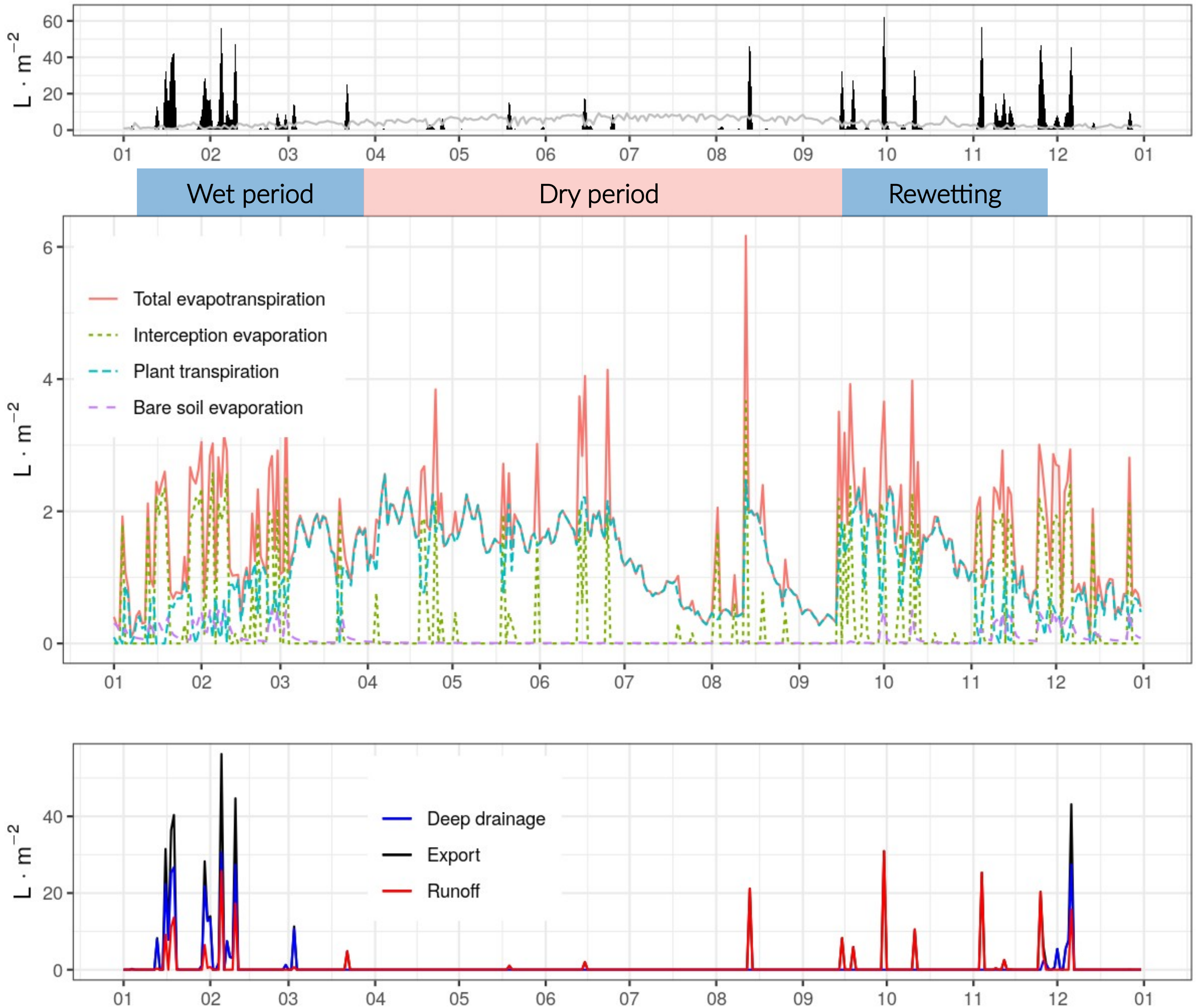


03 Applications – Detailed stand-scale water balance

Weather

Water balance components (I)

Water balance components (II)



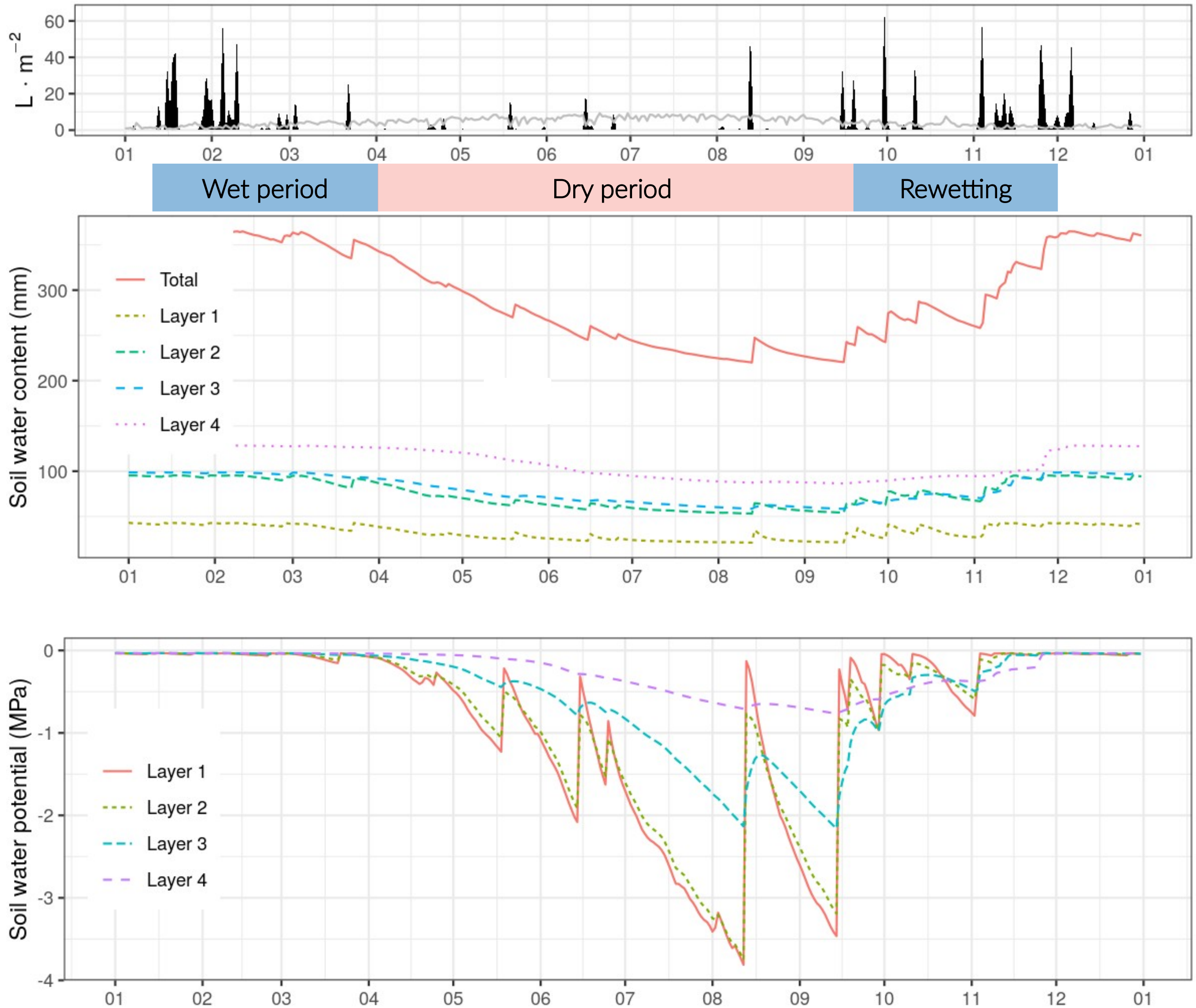
03 Applications – Detailed stand-scale water balance

CREAF

Weather

Soil water content

Soil water potential
(matric forces)

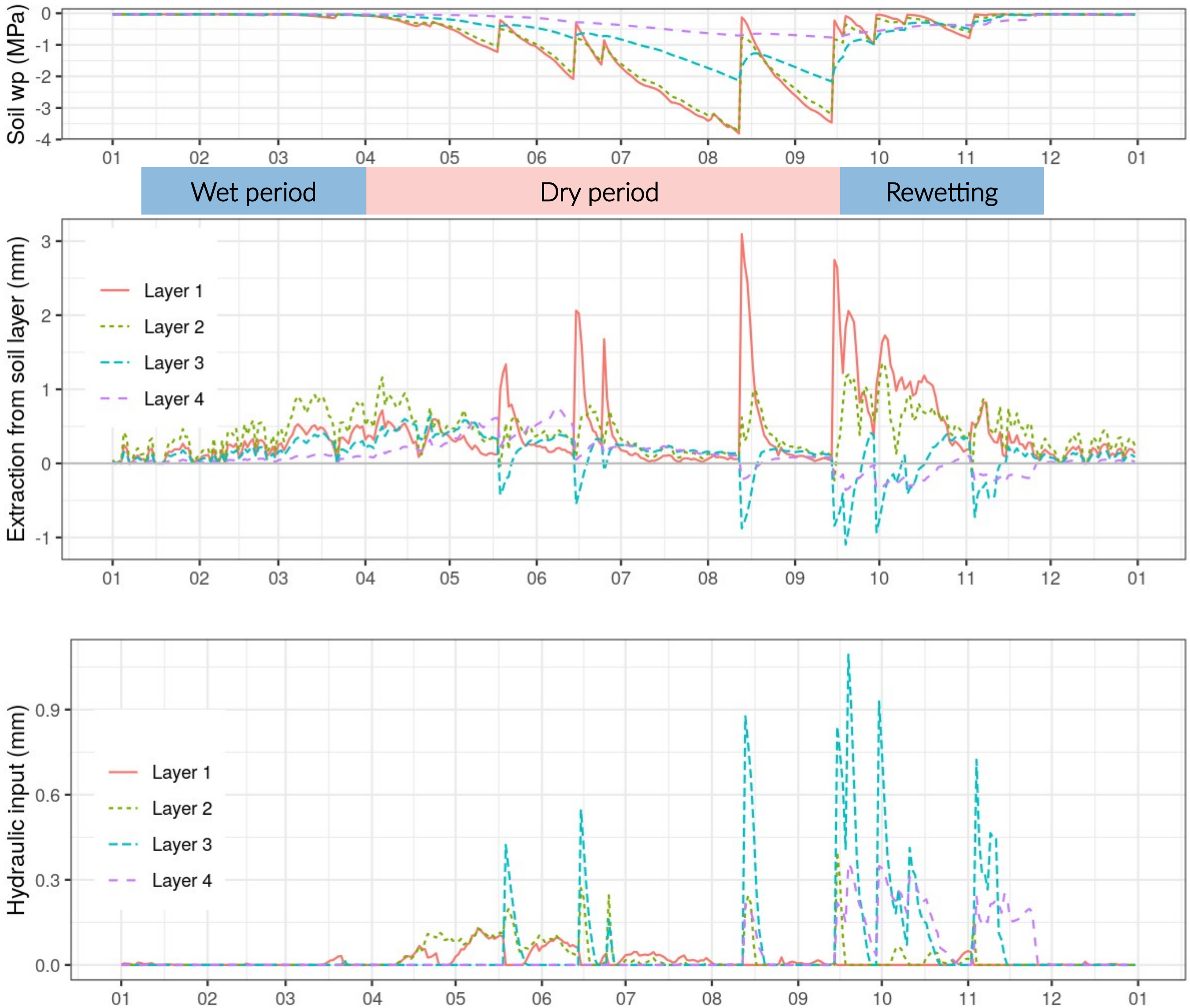


CREAF

Soil water potential

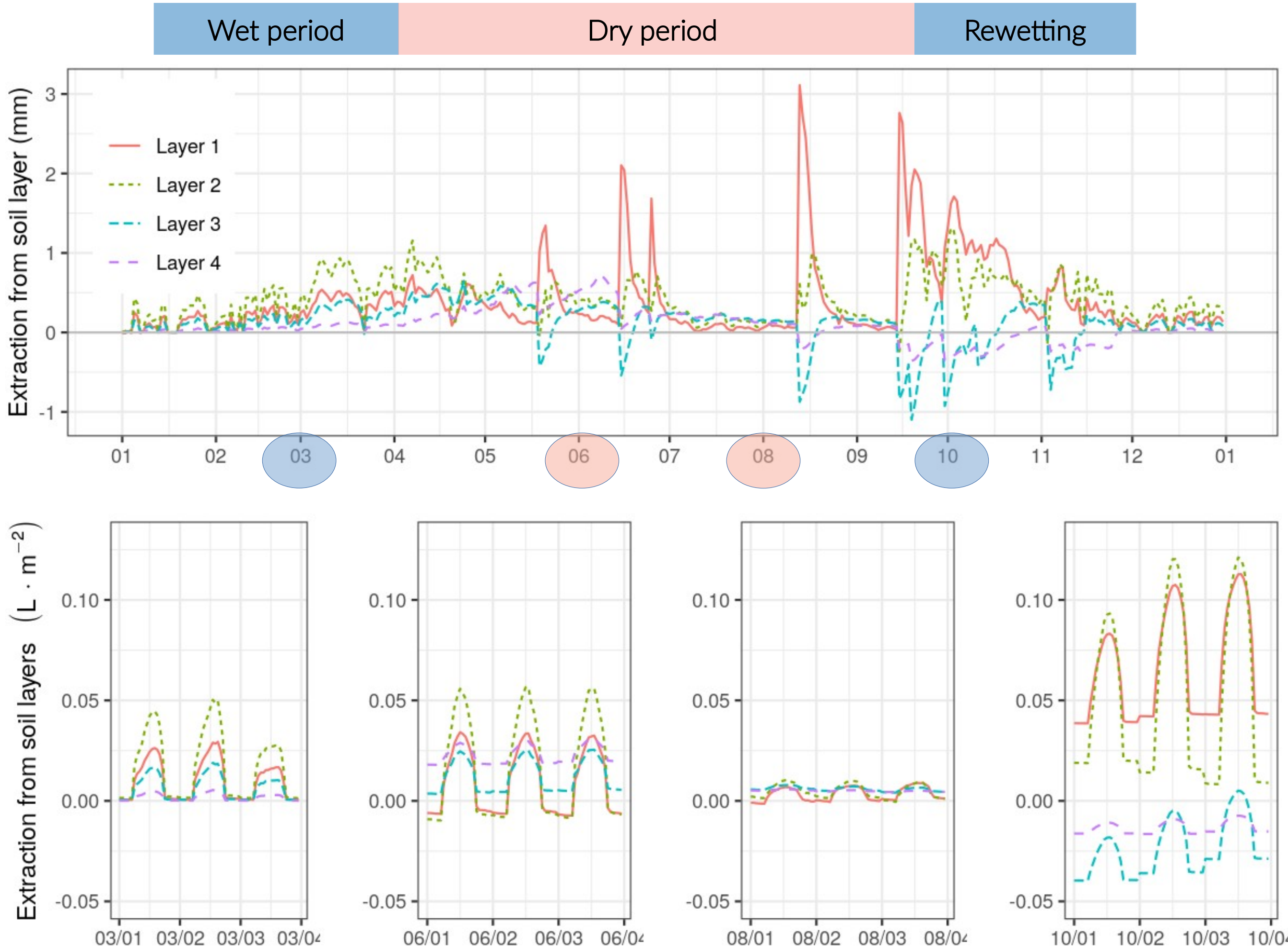
Water net uptake (or release)

Water input from other layers



Water uptake (daily)

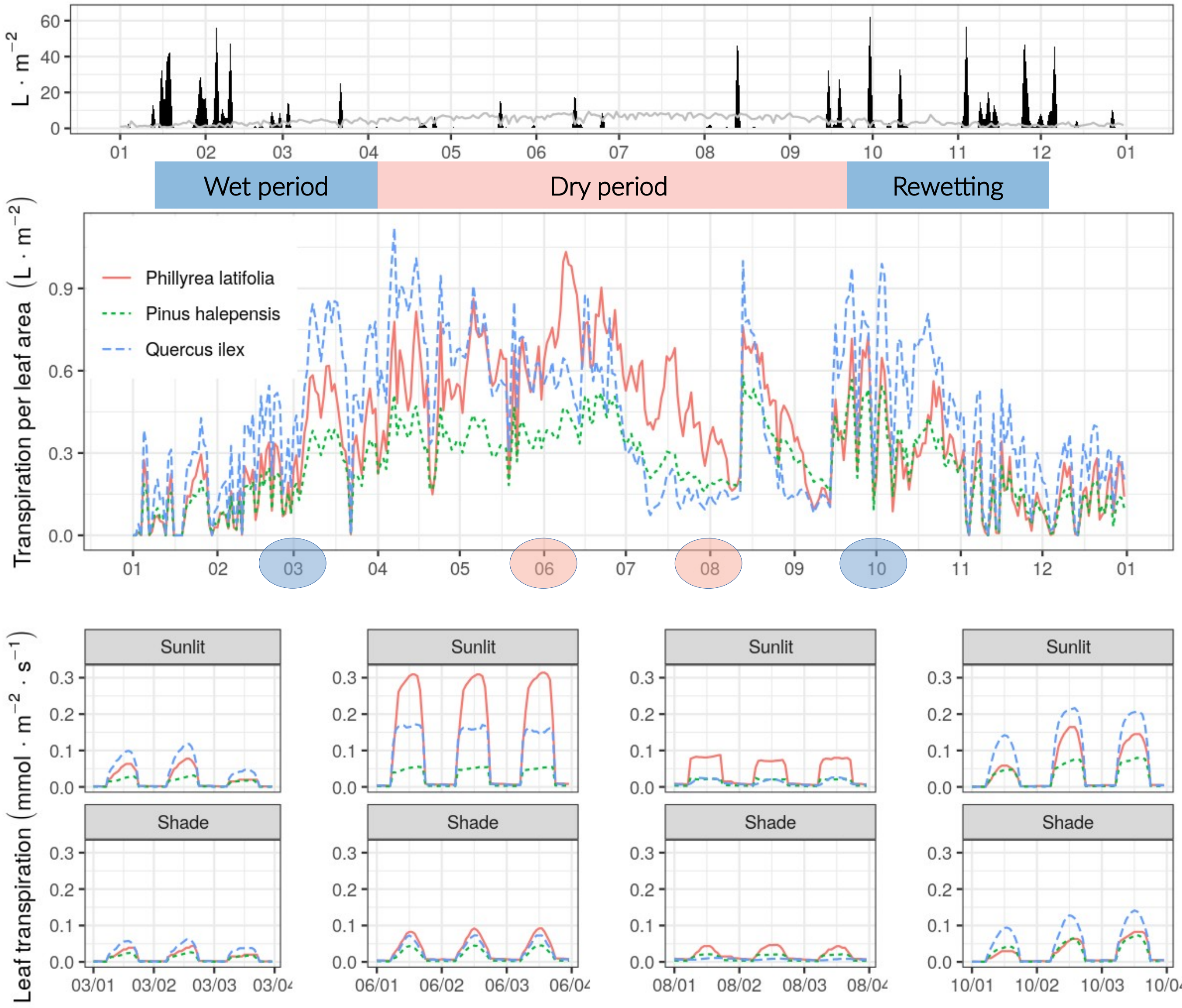
Water uptake (subdaily)



Weather

Transpiration (daily)

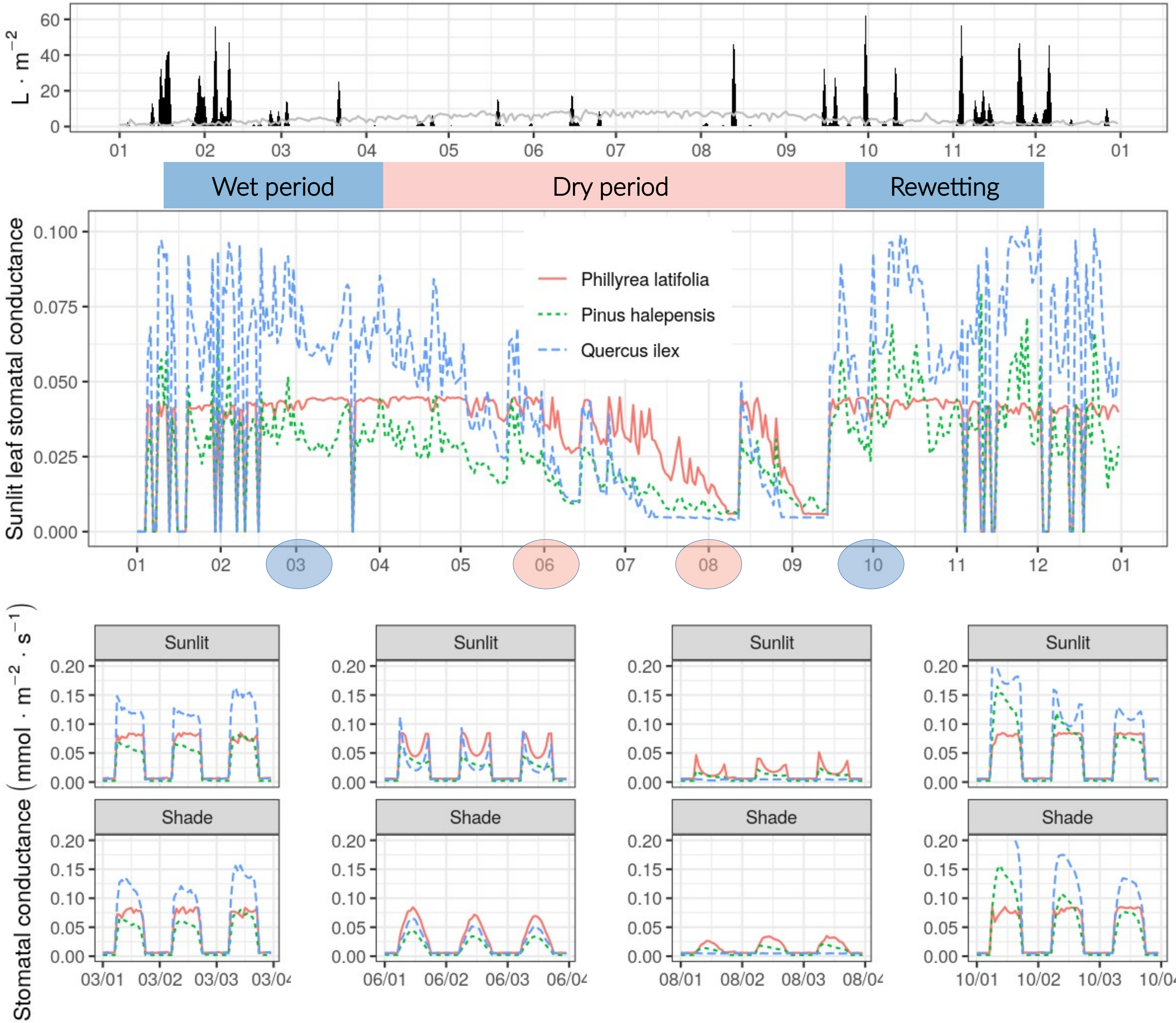
Transpiration (subdaily)



Weather

Stomatal conductance (daily)

Stomatal conductance (subdaily)

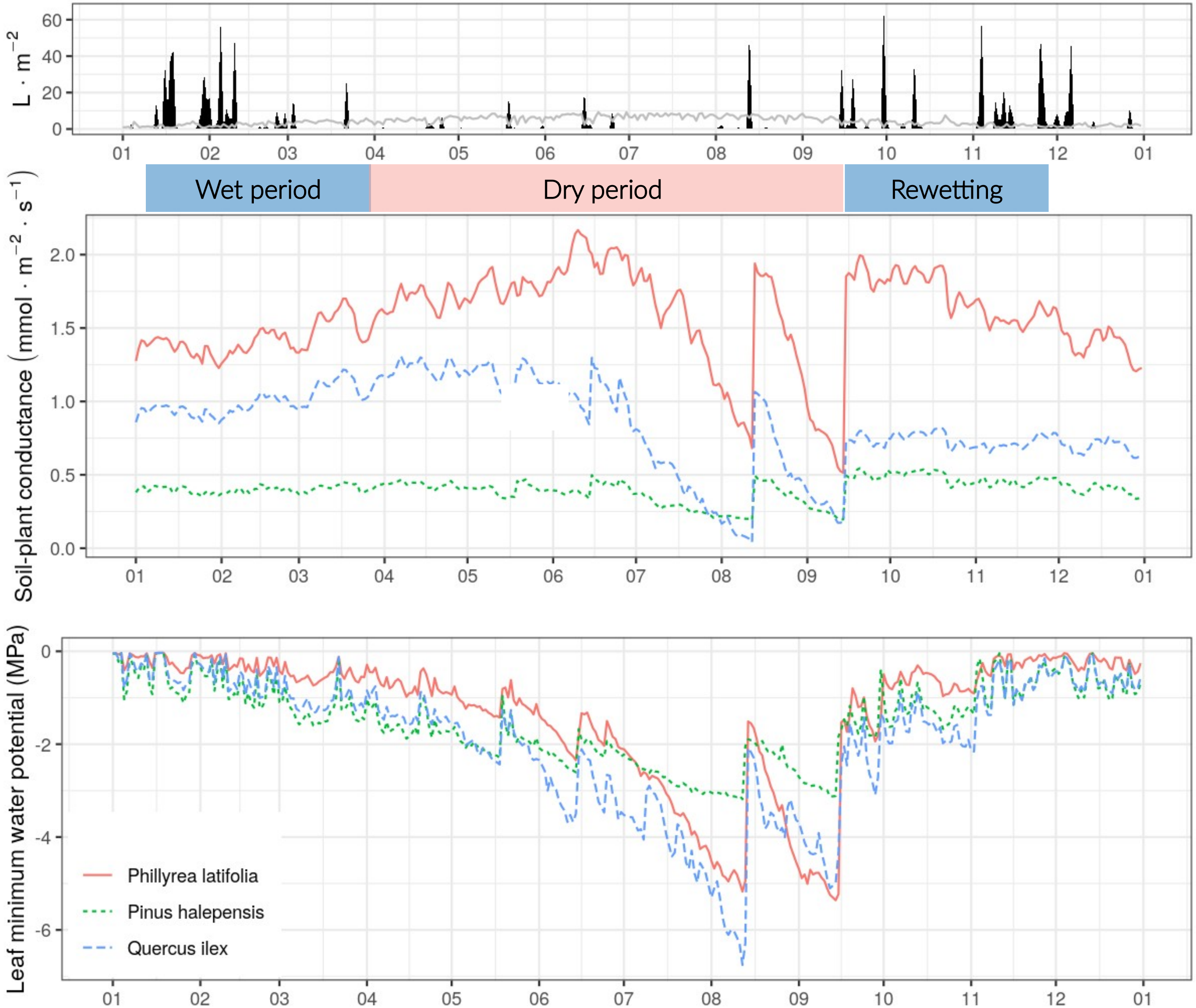


03 Applications – Detailed stand-scale water balance

Weather

Soil-plant hydraulic conductance

Leaf water status



Thanks!

Collaborators

- Jordi Martínez Vilalta (CREAF/UAB)
- Maurizio Mencuccini (ICREA/CREAF)
- Nicolas Martin StPaul (INRA)
- Pilar Llorens (IDAEA-CSIC)
- Victor Granda (CREAF)
- Antoine Cabon (CTFC/CREAF)
- Rafa Poyatos (CREAF/UAB)
- Lluís Coll (CTFC/UdL)
- Aitor Ameztegui (UdL)
- Pere Casals (CTFC)
- Mario Beltrán (CTFC)
- Lena Vilà (CTFC)
- Rodrigo Balaguer (UNED)
- Daniel Nadal-Sala (UB)
- Santiago Sabaté (UB)
- Xavier Morin (CEFE)

Forest water balance modelling and applications

Miquel De Cáceres (EMF-CREAF)
miquelcaceres@gmail.com