Agricultural productivity in times of uncertainty: an ecological perspective from resilience to tipping points

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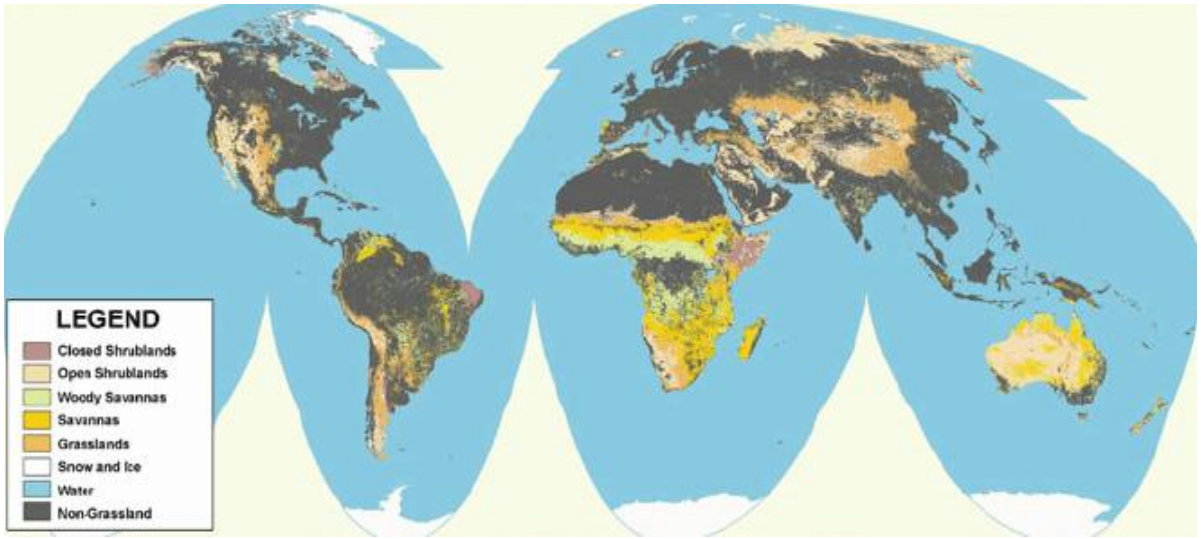
Foto: Álvaro António

The challenges of Pastures

Grasslands

vegetation dominated or co-dominated by graminoids, with varying density of **forbs**, **woody vegetation** and **human intervention**

Blair et al., 2014



Global distribution of grasslands and other ecosystem types dominated by grasses or graminoid vegetation

Pastures

land used permanently (five years or more) for herbaceous forage crops, either cultivated or growing wild (wild prairie or grazing land)

FAO, 2023

distribution of drylands

40% of global land area

+2 billion people

UNCCD, 2017

Pastures and Ecosystem Services

food & feed

carbon sequestration

habitat

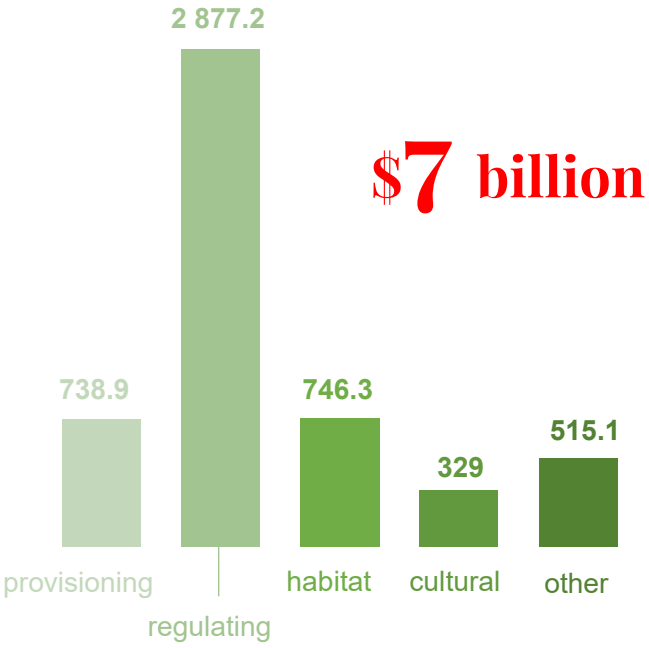
pastures provide several ecosystem services essential to human well-being

control of soil erosion

water flow regulation

pollination

predicted value by type of ecosystem service for Mediterranean grasslands ($ ha^{-1} year $^{-1}$)

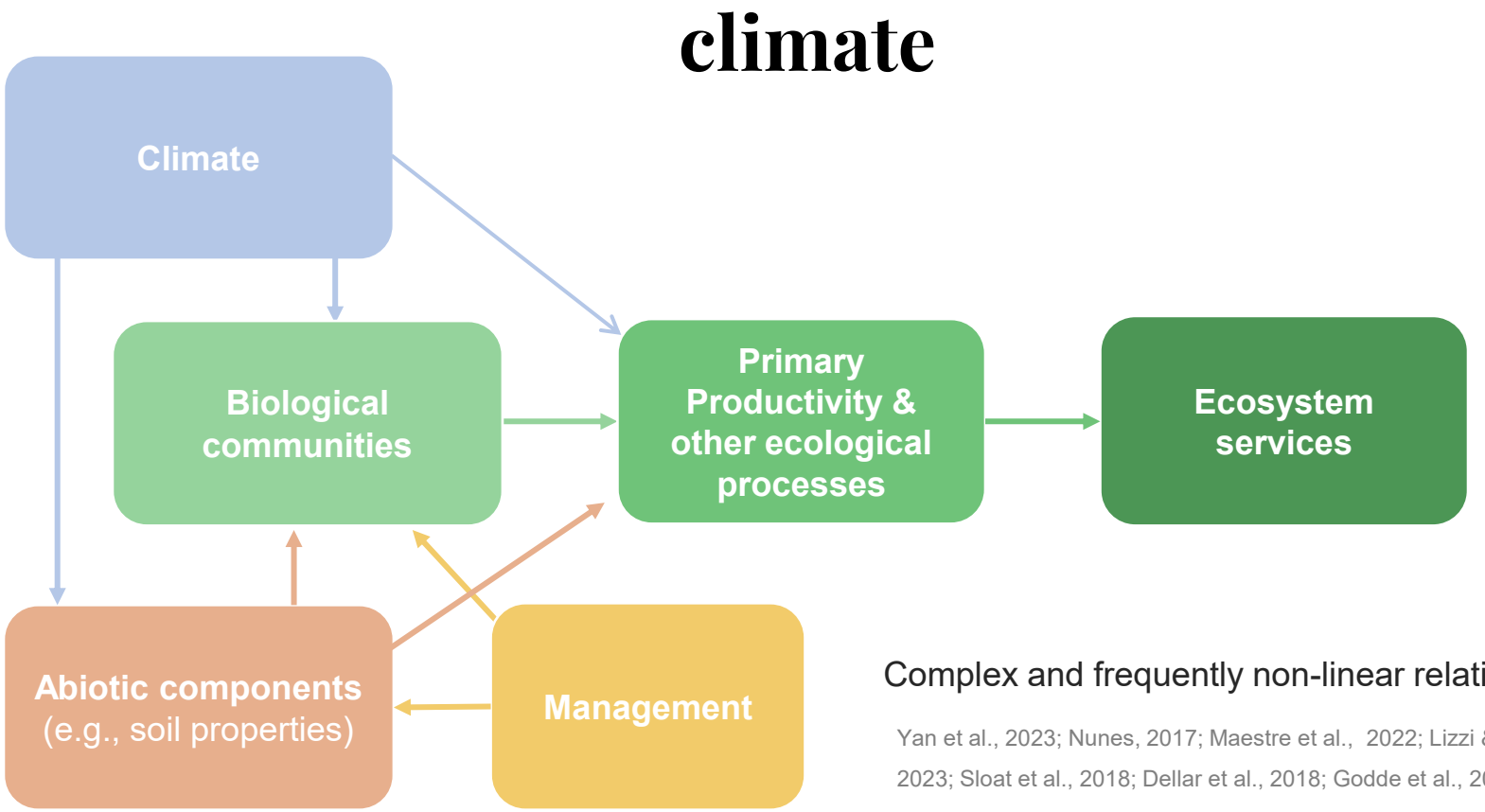


$7 billion year^{-1}

Liu et al., 2021

Determinants of ecosystem functioning and productivity

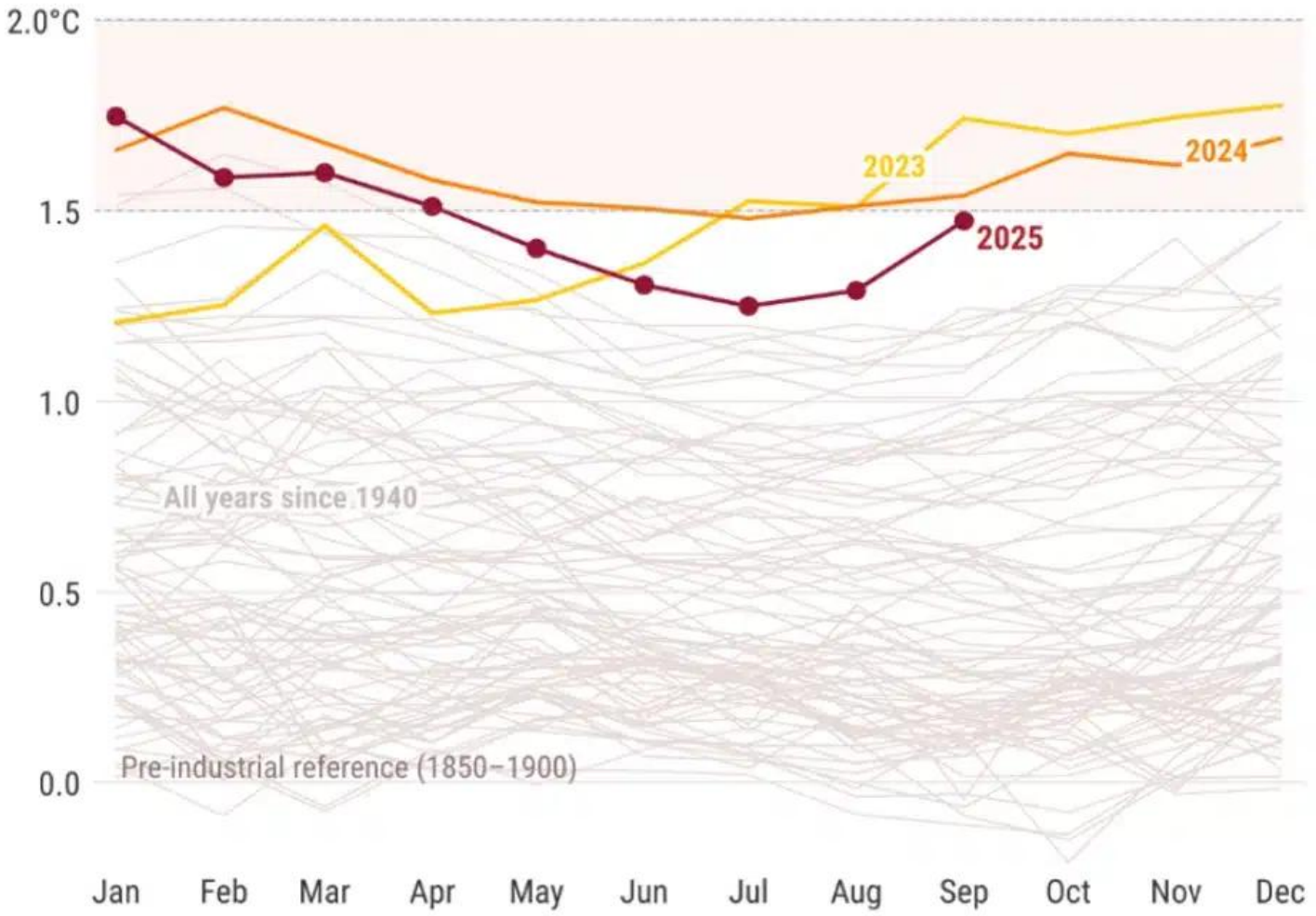
determinants of pasture ecosystem functioning and productivity



Complex and frequently non-linear relationships

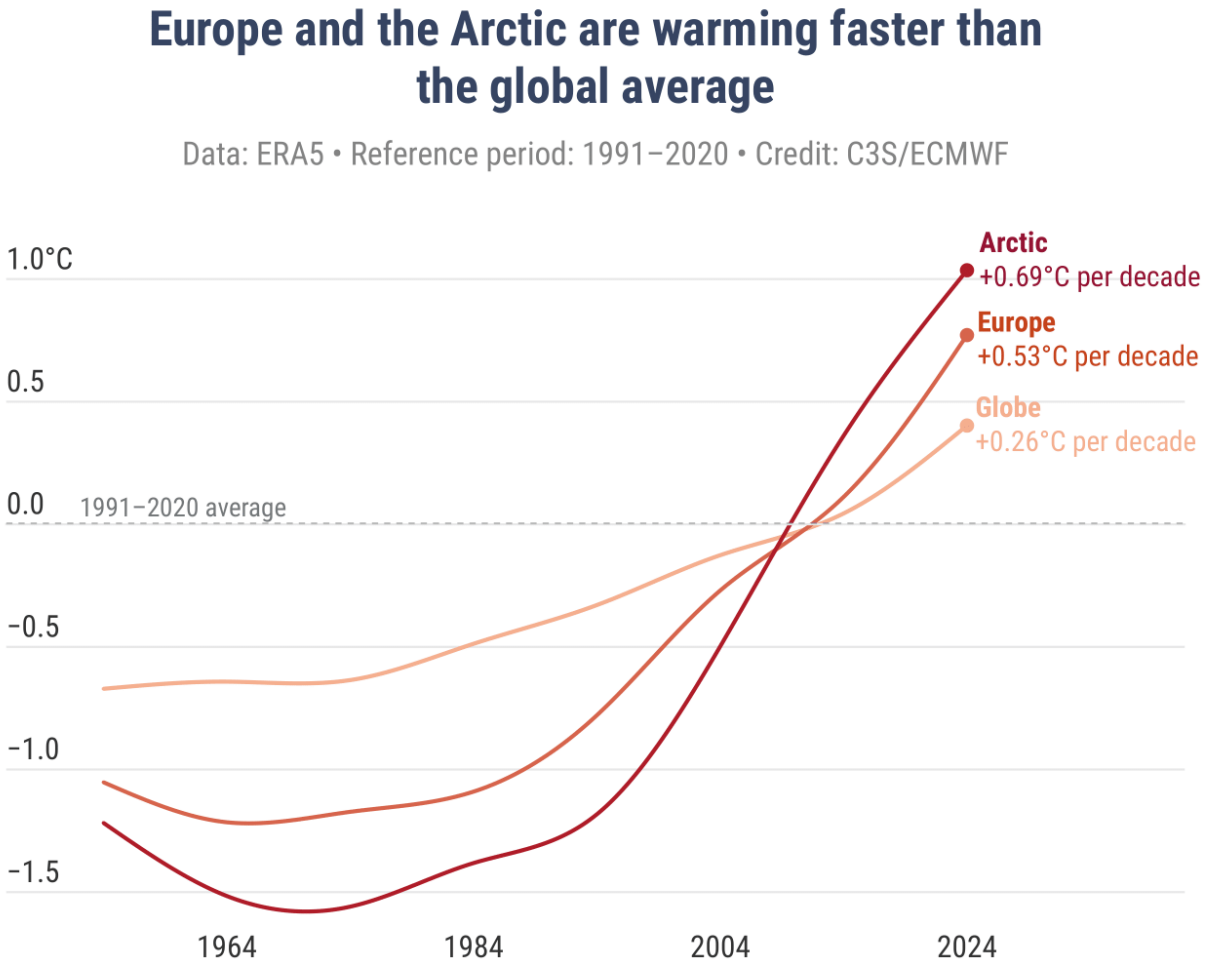
Yan et al., 2023; Nunes, 2017; Maestre et al., 2022; Lizzi & Garbulsky, 2023; Sloat et al., 2018; Dellar et al., 2018; Godde et al., 2019

The challenges of Climate Change



Monthly year-to-date global surface air temperature anomalies relative to 1991-2020 for the ten warmest calendar years on record. The year 2025 is shown with a dark red line. The two warmest calendar years, 2023 (yellow) and 2024 (orange), are also highlighted. Other years are shown in grey. Each data point represents the average anomaly from January to the corresponding month. For example, the value for September 2025 corresponds to the average anomaly from January to September 2025. Data source: ERA5. Credit: C3S/ECMWF.

The challenges of Climate Change



Ten-year average temperature anomalies. Values for Europe and the Arctic are over land only.
Rates of increase per decade are estimates for the last 30 years from 1995 to 2024.

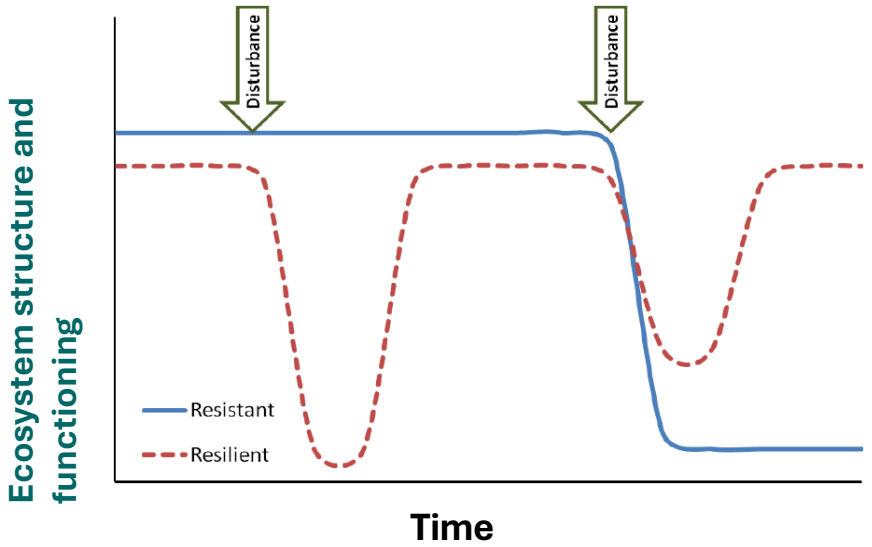
PROGRAMME OF THE EUROPEAN UNION · opernicus · Climate Change Service · IMPLEMENTED BY ECMWF

The stability & resilience of natural ecosystems

Daintree Rainforest
Age: 180 million years
Location: North-east coast of Queensland, Australia
Forest Type: Tropical Rainforest

Amazon Rainforest
Age: over 55 million years
Location: Brazil (60%), Peru (13%), and Colombia (10%)
Forest Type: Moist Broadleaf Tropical Rainforest

Most natural ecosystems are stable since they have self-regulating mechanisms to return to a steady state after most natural disturbances.

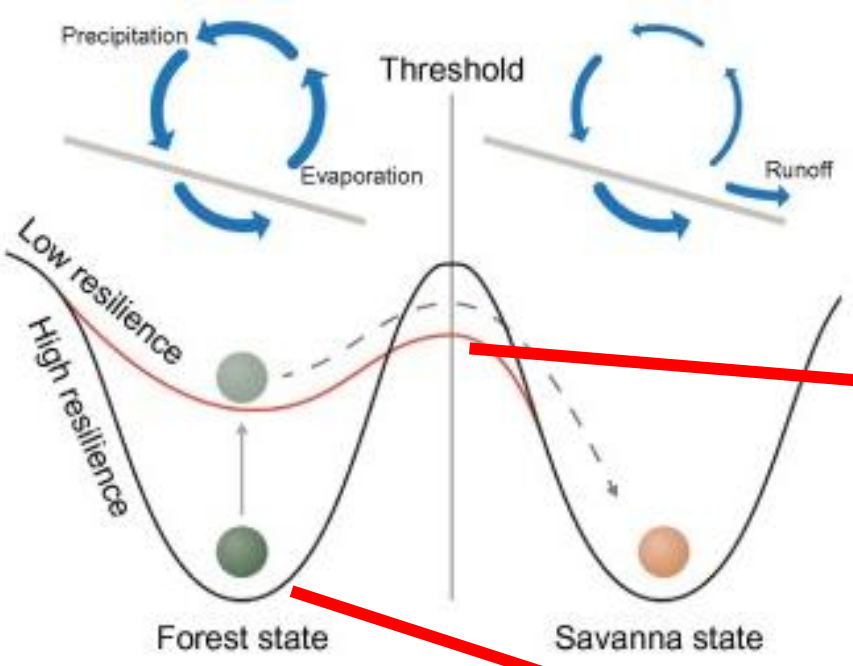


A resilient ecosystem is one that can 'absorb' disturbances and maintain a qualitatively similar state (Holling, 1973, 1996).

1) '**resistance**' is the ability to persist during the disturbance;

2) '**resilience**' is the capacity to recover or 'bounce back' following alleviation of the disturbance.

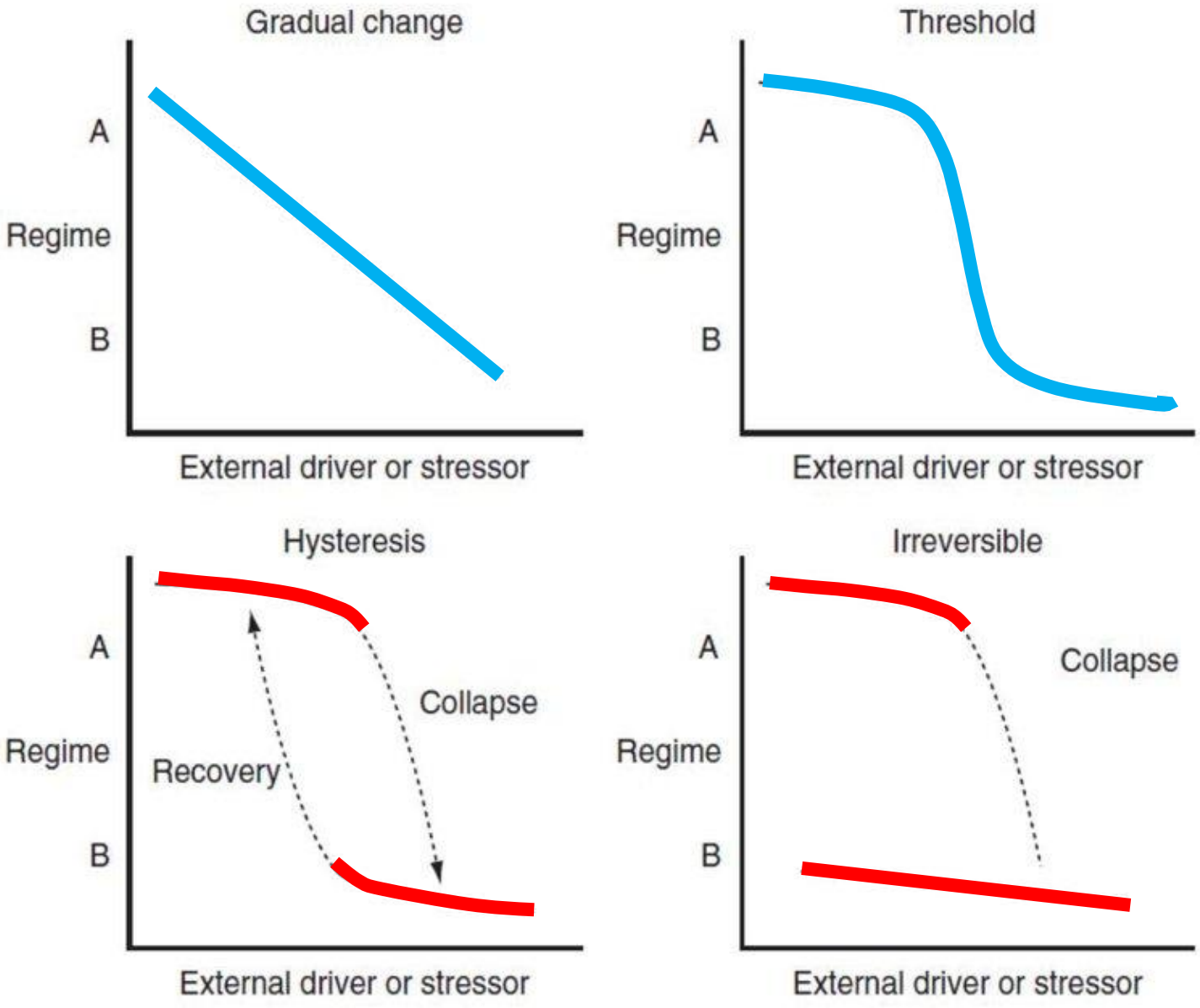
Response in high and low resilience



- Rainforest that is deforested has a lower resilience due to a reduction in moisture recycling and precipitation.
- Below a certain level of precipitation, rainforest can no longer be sustained and collapses to the new stable state of savanna.

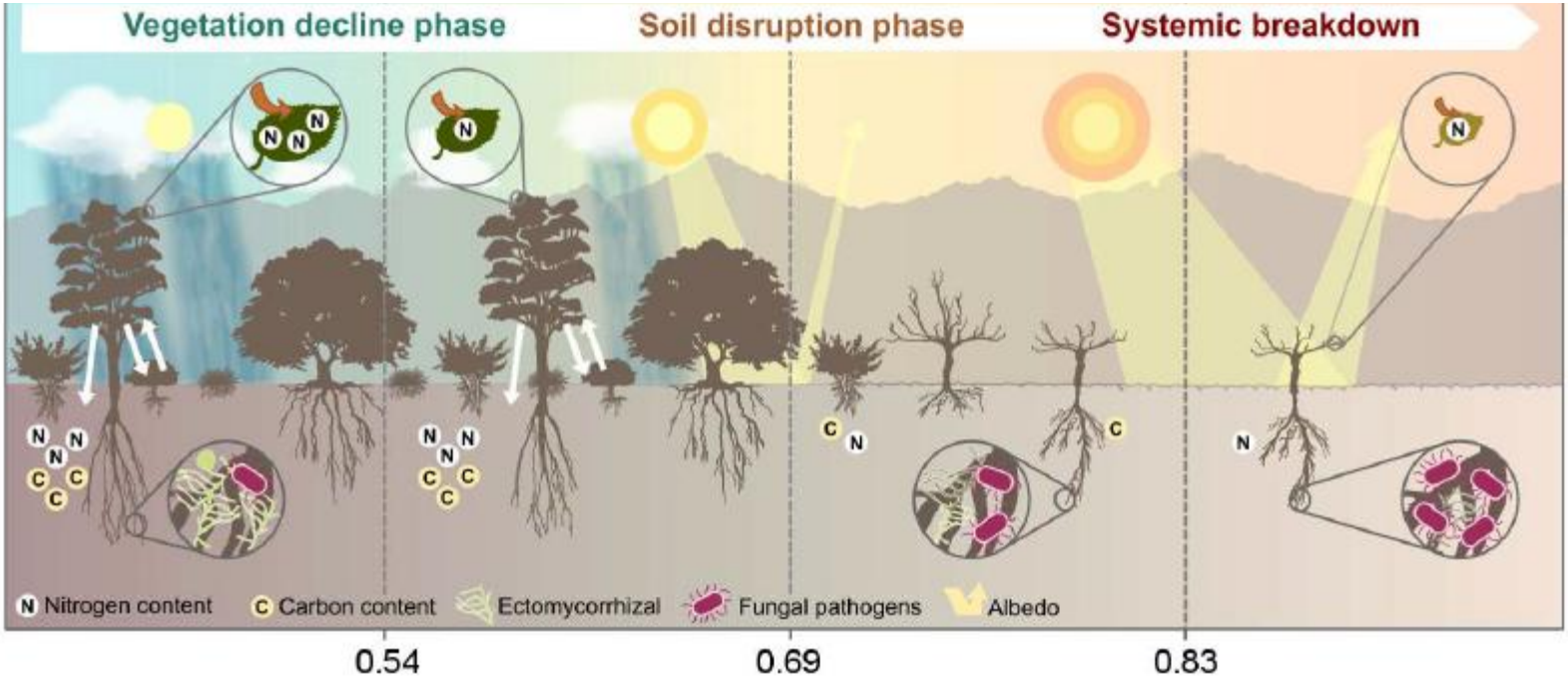
https://doi.org/10.1016/j.hydroa.2018.100009

Types of ecosystem responses to drivers



Nugent, 2013

Tipping points in drylands

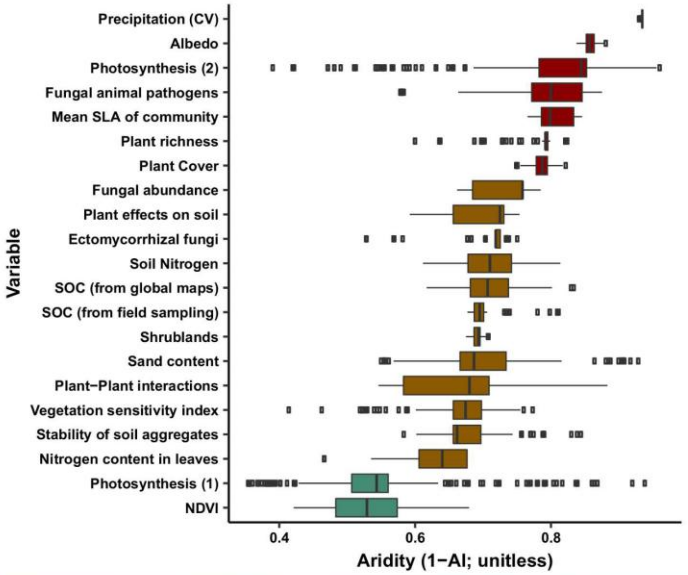


Ecosystem changes associated with the crossing of the 3 phases.

1st threshold 0,55 - decay in vegetation productivity and photosynthetic activity;

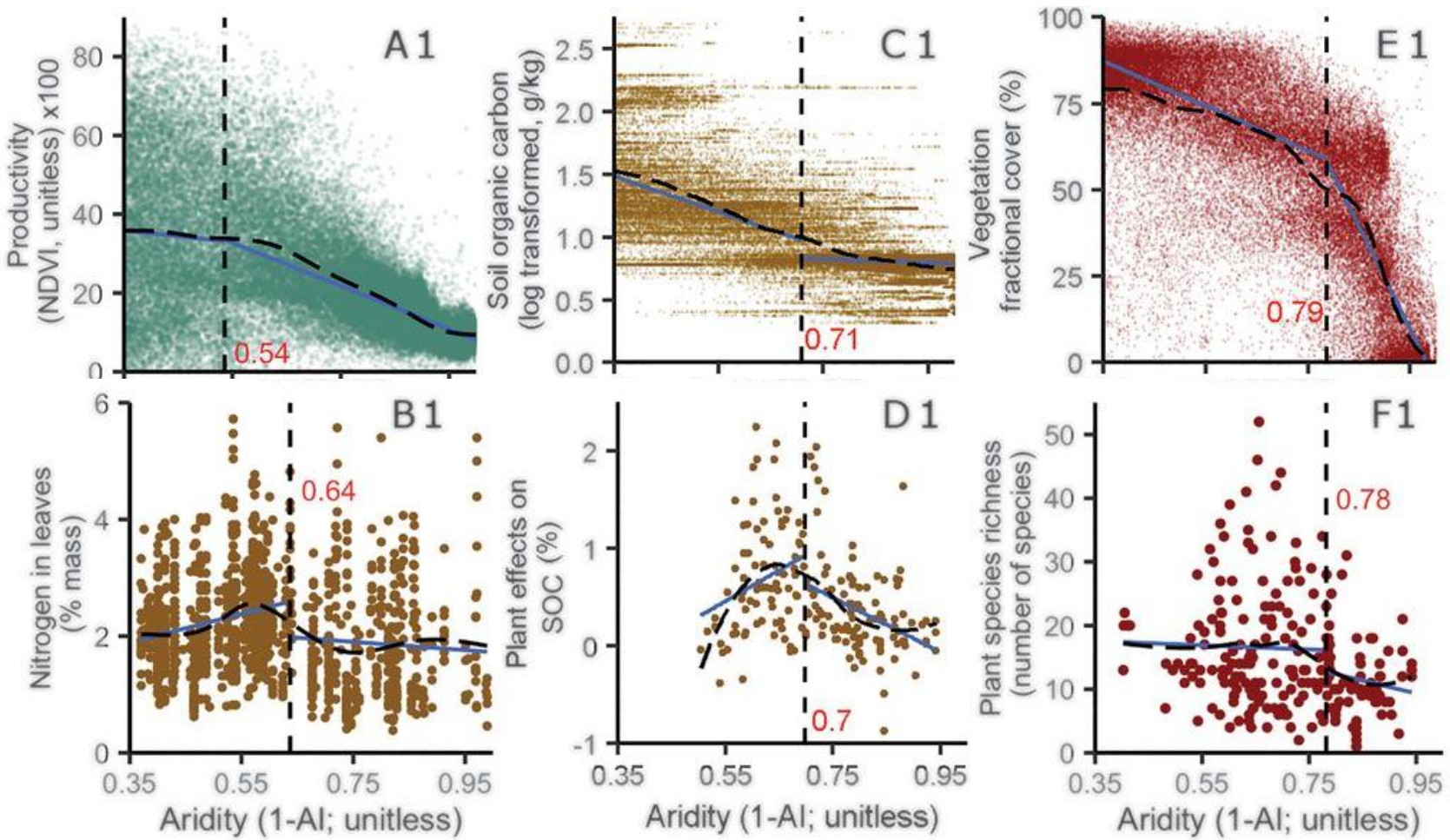
2nd threshold ~ 0.7, declines in soil fertility, plant N content and biotic interactions, drastic compositional changes in plant and soil microbial communities;

3rd threshold ~ 0.8, drastic reductions in plant cover, increases in soil albedo and shifts in leaf traits towards stress-avoidance.



Berdugo et al., 2020

Tipping points in drylands

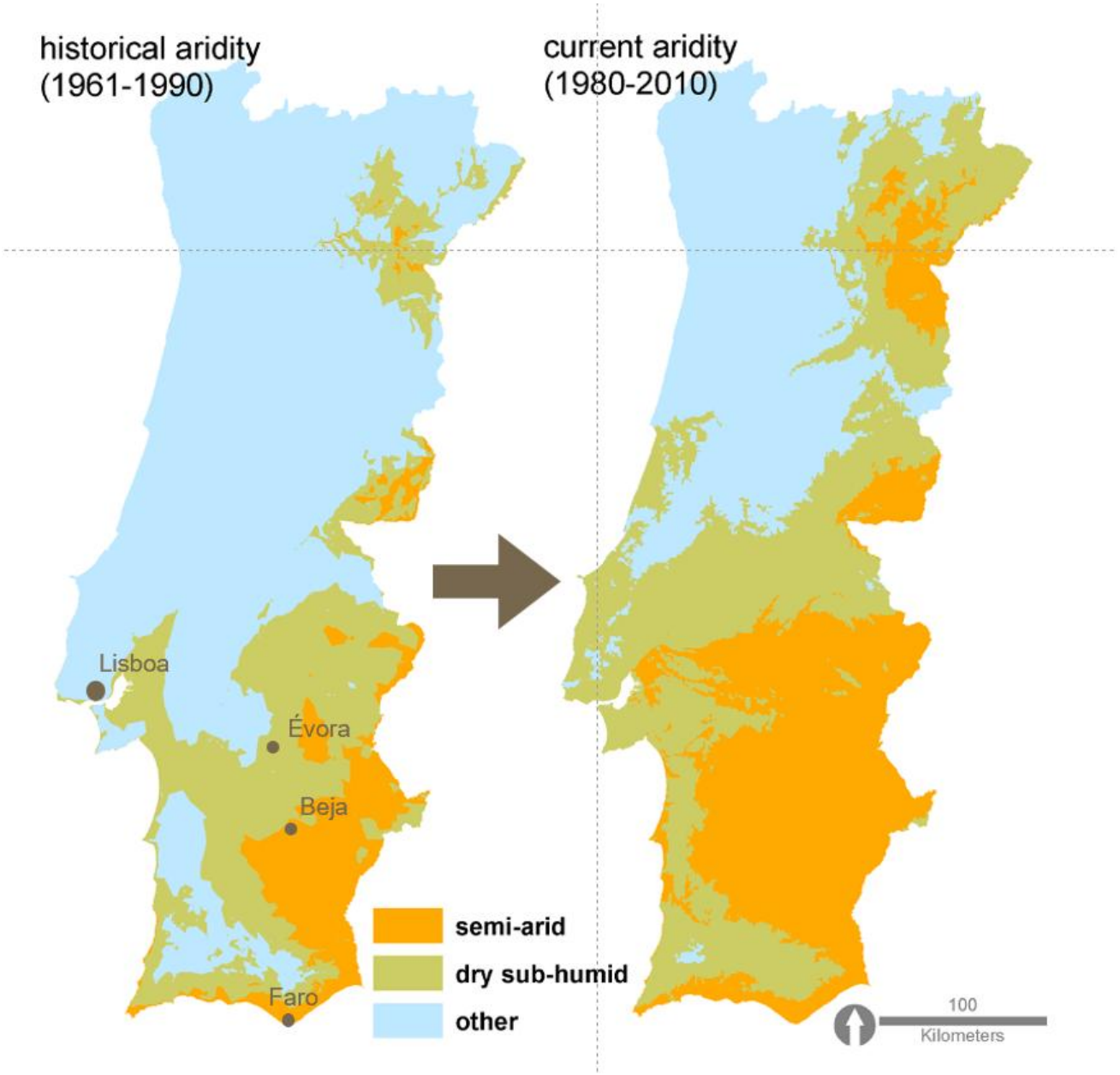


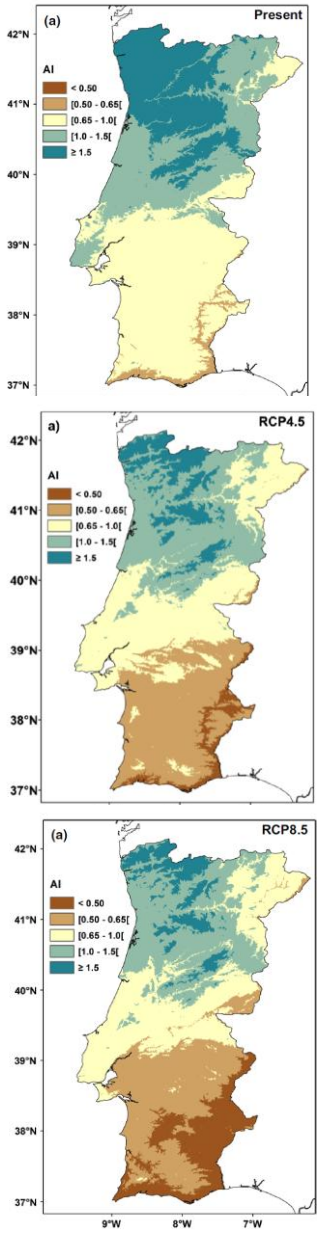
Nonlinear responses of multiple ecosystem attributes to aridity.

NDVI (A), leaf nitrogen content (B), soil organic carbon (C), plant effects on soil organic carbon (D), vegetation cover (E), and plant species richness (F). Black dashed lines and blue solid lines represent the smoothed trend fitted by a generalized additive model (GAM) and the linear fits at both sides of each threshold, respectively. Inset numbers in red and the vertical dashed lines describe the aridity threshold identified.

Berdugo et al., 2020

Index of Aridity in Portugal





Costa et al., 2017

Our question

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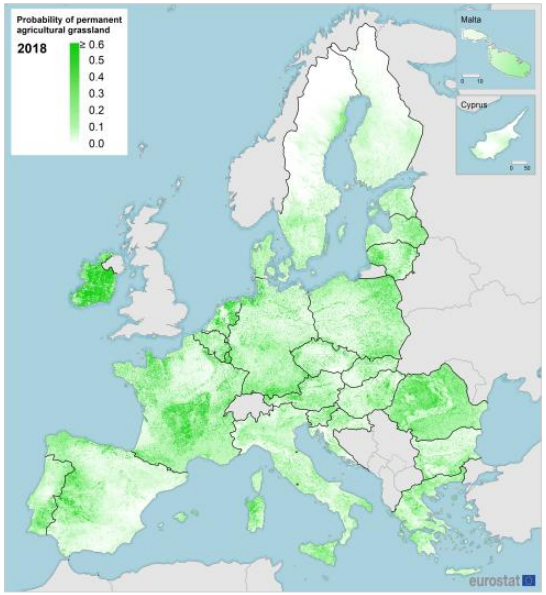
Taking advantage of recent **high-resolution remote sensing** data

Using a **space-for-time** approach

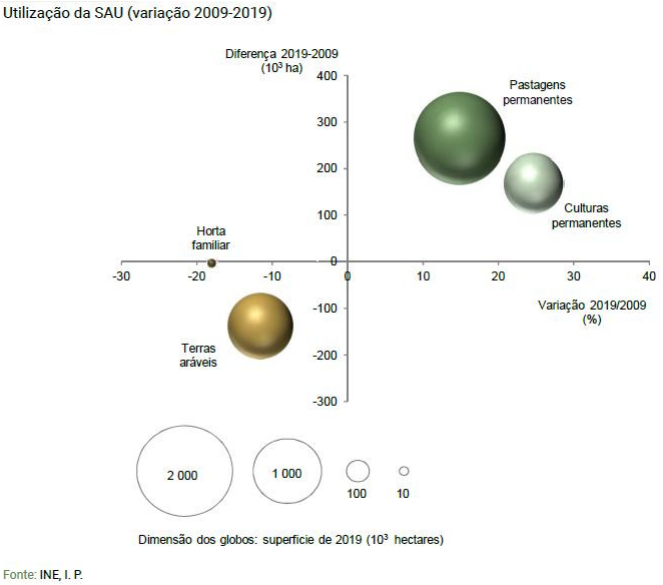
1. **Can we discriminate between pastures along a spatial climate gradient based on differences and similarities in their yearly phenology?**

2. **If so, what environmental factors are driving this zonation?**

Permanent grasslands and pastures in the EU and Portugal



Permanent grasslands and pastures correspond to **13% of the EU**'s area



Fonte: INE, I. P.

Biggest agricultural land cover in Portugal: 51,7% SAU

Unraveling phenology patterns

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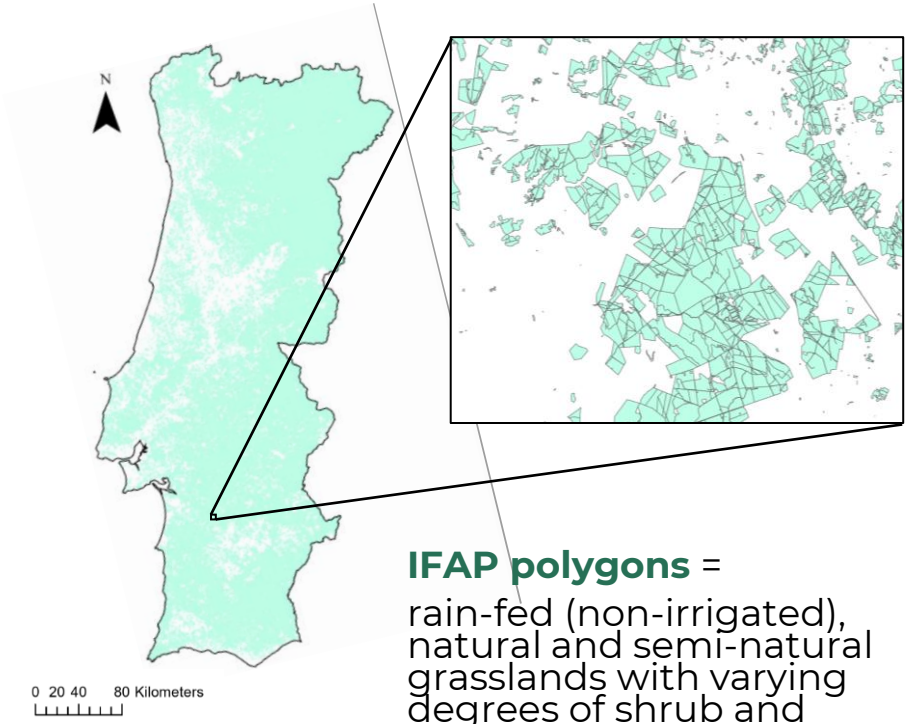
Data: permanent pastures



IFAP polygons = rain-fed (non-irrigated), natural and semi-natural grasslands with varying degrees of shrub and tree cover.

All variables extracted for pasture polygons as **mean values**

3 land-uses :

- "Permanent pastures" (N=342 288);
- "Permanent pastures with shrubs" (N=491 217); and
- "Permanent pastures under the cover of *Quercus* spp." (N=24 142)

Total: 857 647 "farms"

IFAP, 2023
Santo *et al.*, in press

Unraveling phenology patterns

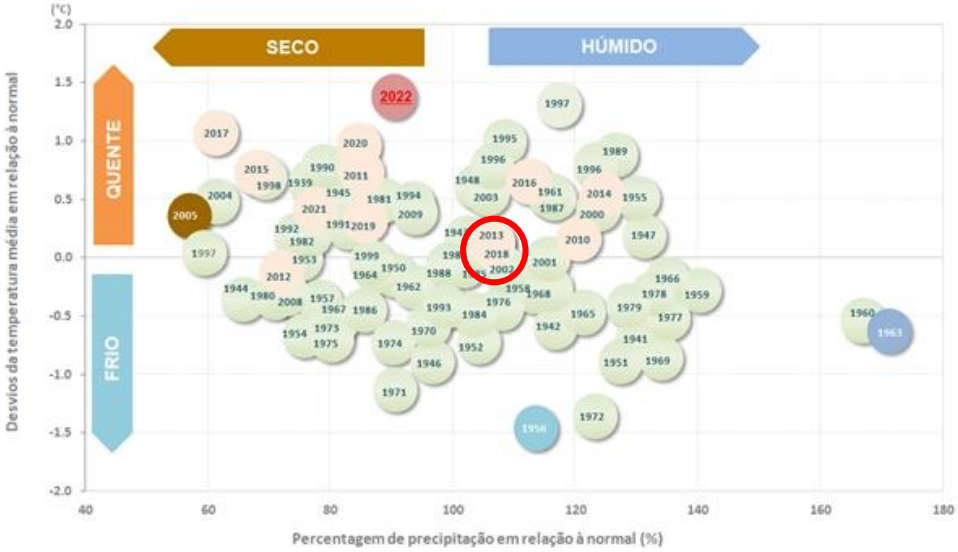
Data: phenology and environment

HR-VPP - high-resolution vegetation phenology parameters from SENTINEL-2

10x10m
5-day revisit time
Plant Phenology Index (PPI) → 13 parameters, 2017 to current time (seasonal productivity, start of the season, length of the season, green-up rate, etc.)

Predictor variables

Topography (elevation, psr, slope)
Bioclimate (temperature, precipitation, aridity, …)
Soil properties (physical and chemical)
Demographics (human population density, …)



High-resolution phenology and productivity

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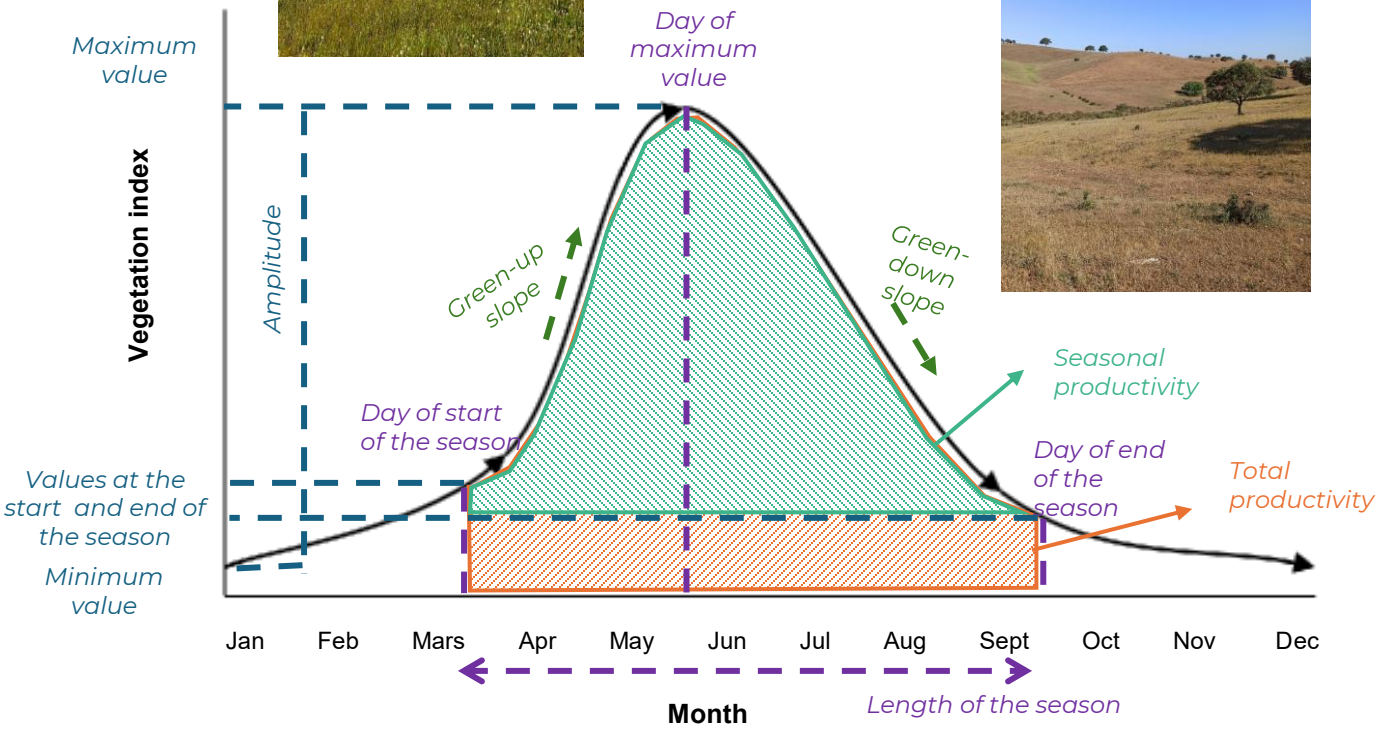
REMOTE SENSING

Spectral **vegetation index** as a proxy of productivity

(e.g., NDVI, EVI, PPI)



Pastures follow a bell-shaped **seasonal growth curve** driven by **inter-** and **intra-annual climate variability**

With impacts on **productivity** and **other ecosystem services** such as carbon storage

Climate change is altering **biological timings** and **functioning**

Santo *et al.*, in press

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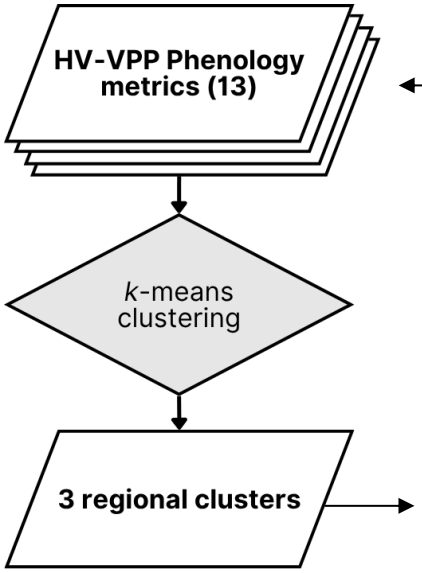
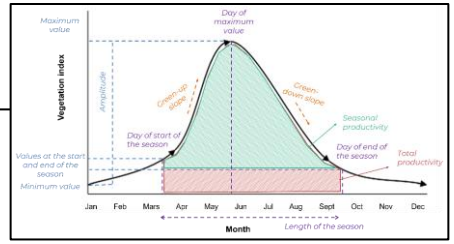
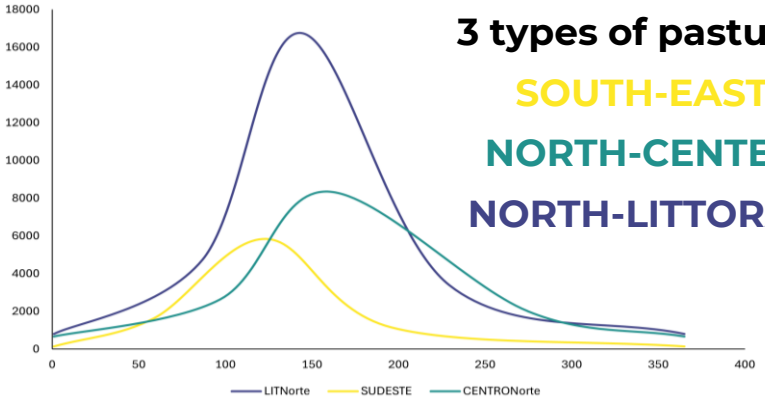
Clustering analysis – *k*-means





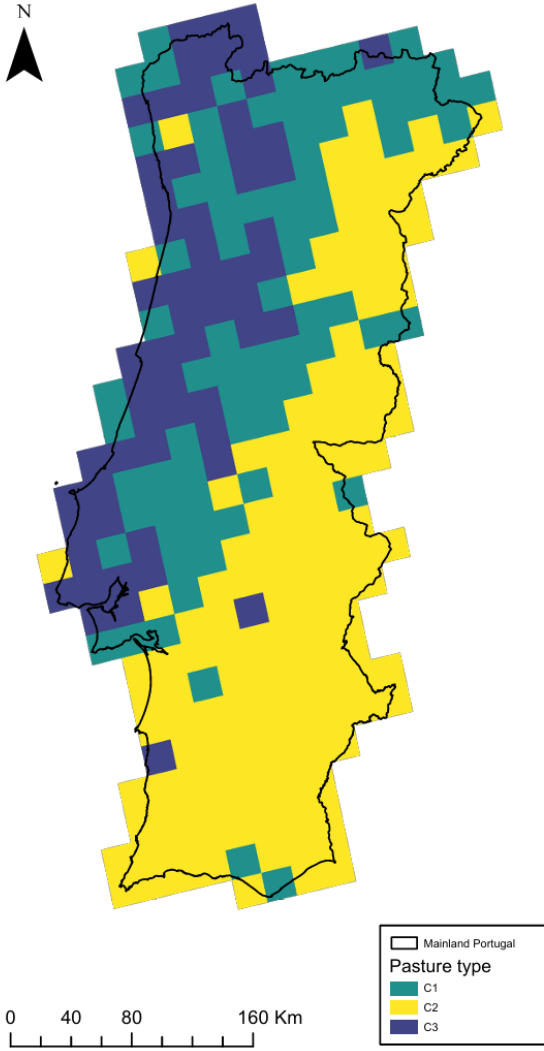


3 types of pastures

SOUTH-EAST

NORTH-CENTER

NORTH-LITTORAL



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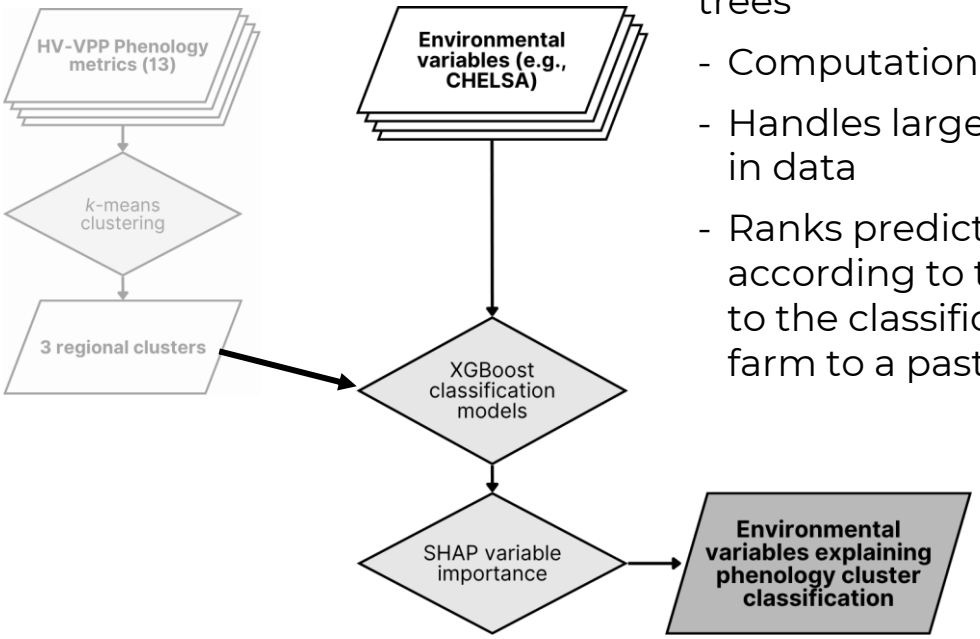
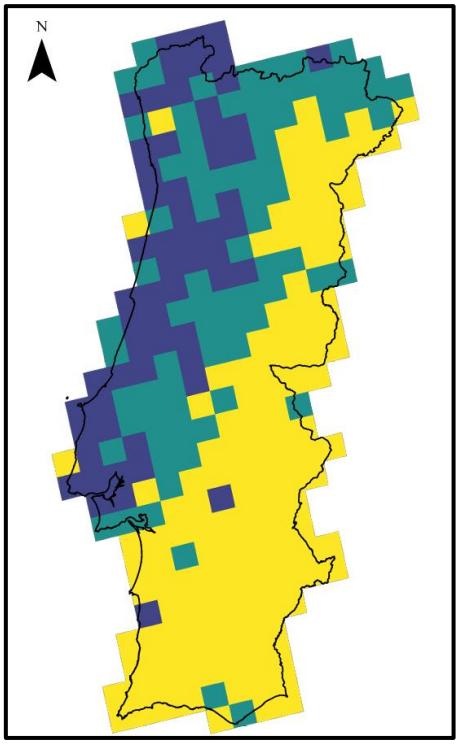
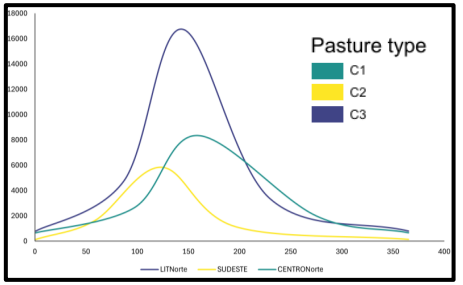
Machine learning model



XGBoost: machine learning algorithm based on decision-trees

- Computationally efficient
- Handles large dimensionality in data
- Ranks predictor variables according to their importance to the classification of each farm to a pasture type





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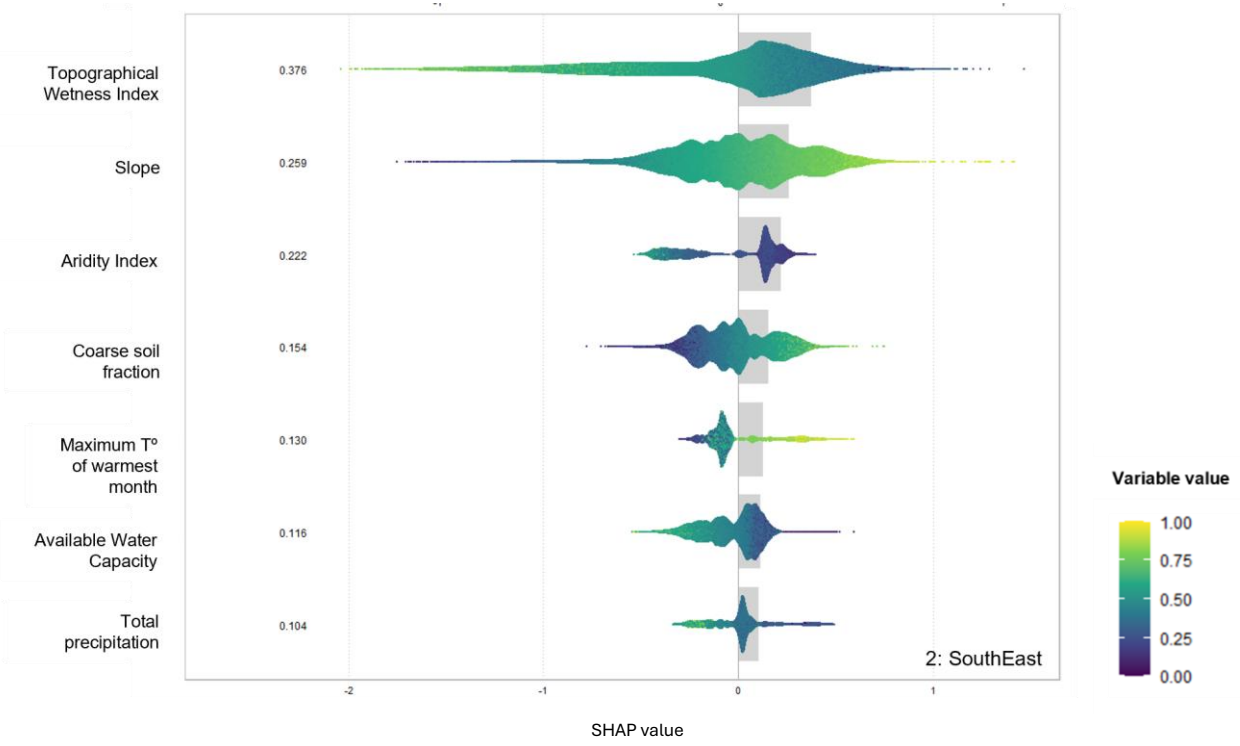
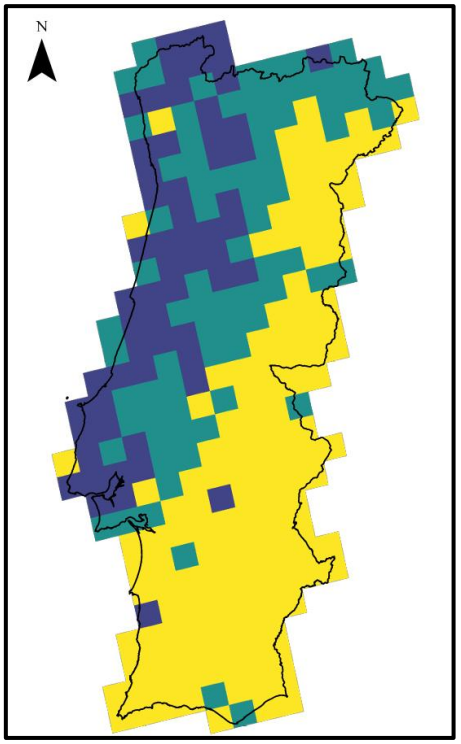
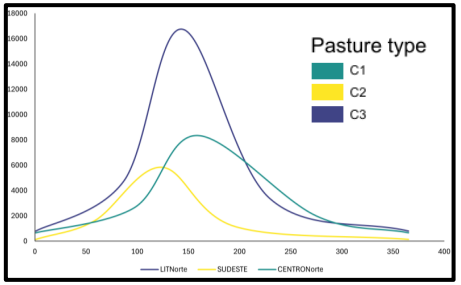
SOUTH-EAST PASTURES







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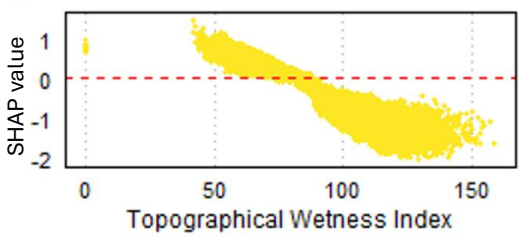
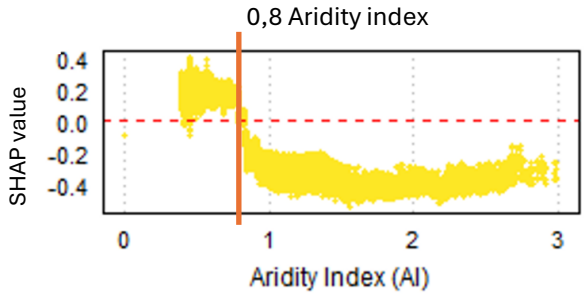
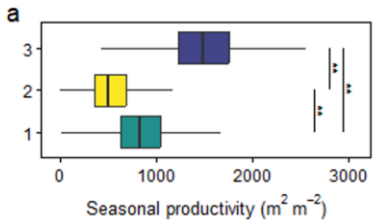
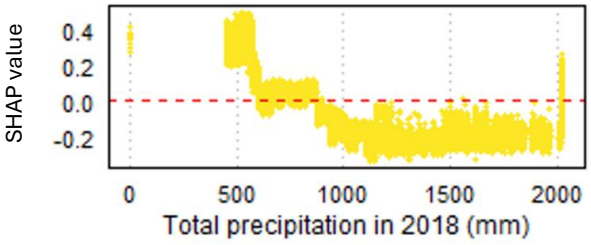
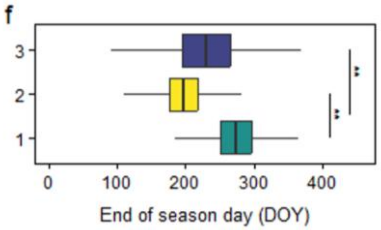
SOUTH-EAST PASTURES

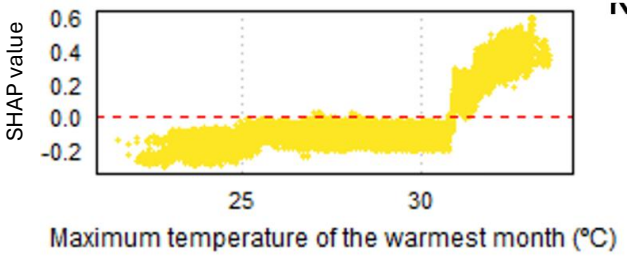


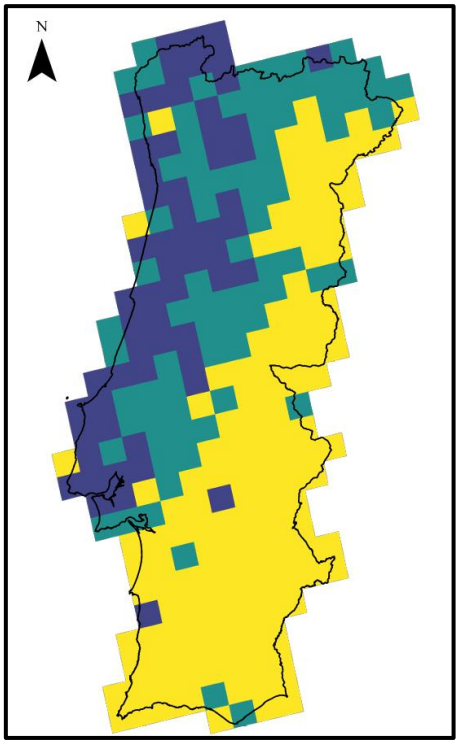


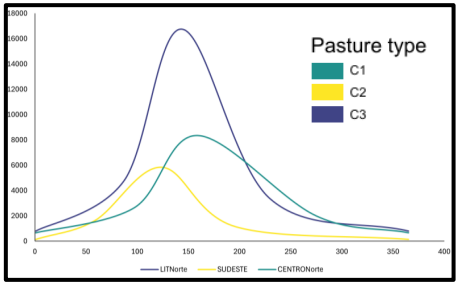












- **Water** is the limiting factor in southern pastures (TWI, aridity index, precipitation), causing the **lower productivity**, **earlier end** to the season and shorter season overall
- Above an **aridity index of 0.8** we are no longer in these pastures, which suggests a **potential tipping point**

Santo *et al.*, in press

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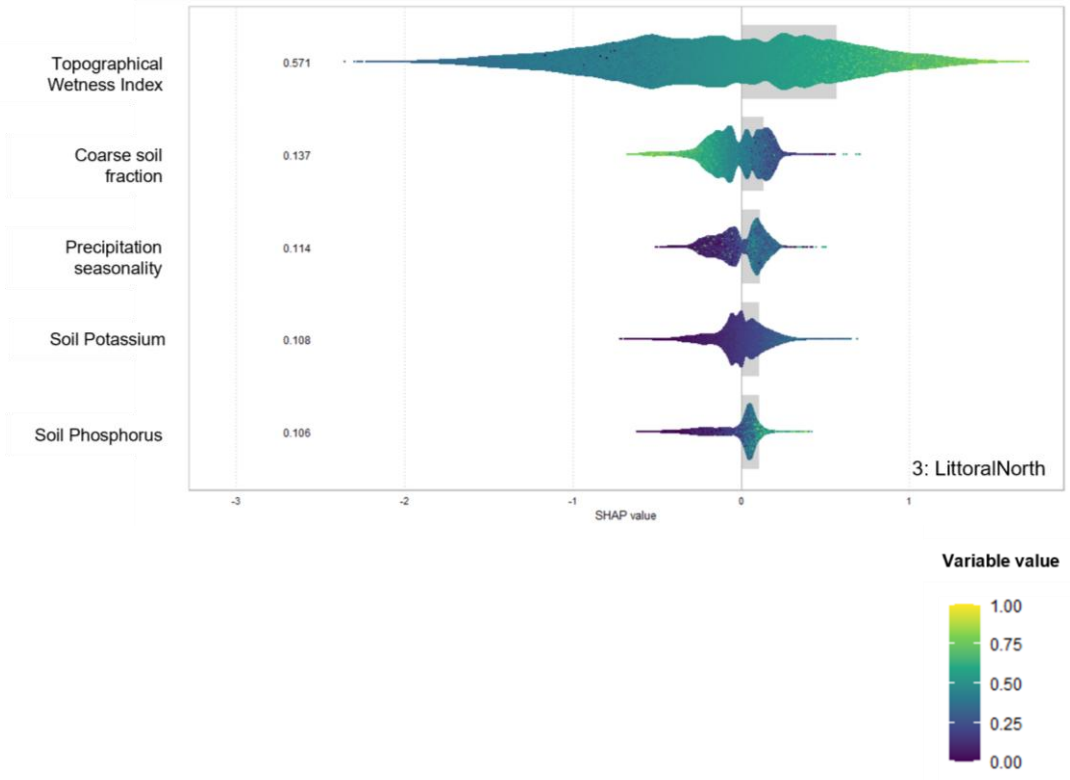
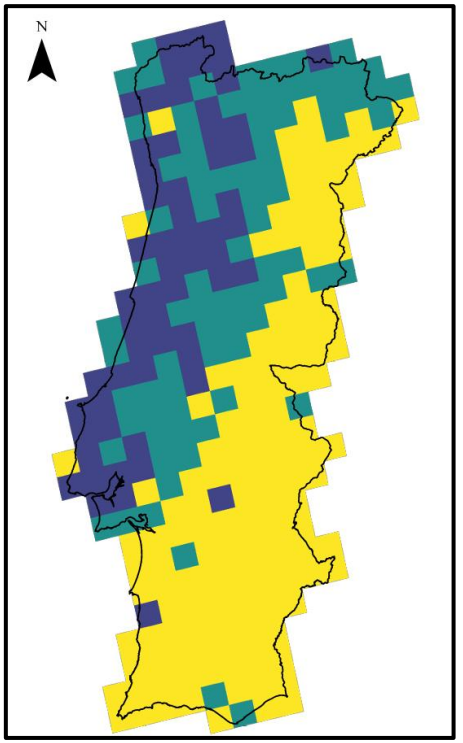
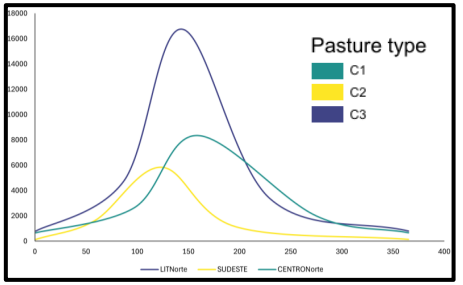
NORTH-LITTORAL PASTURES







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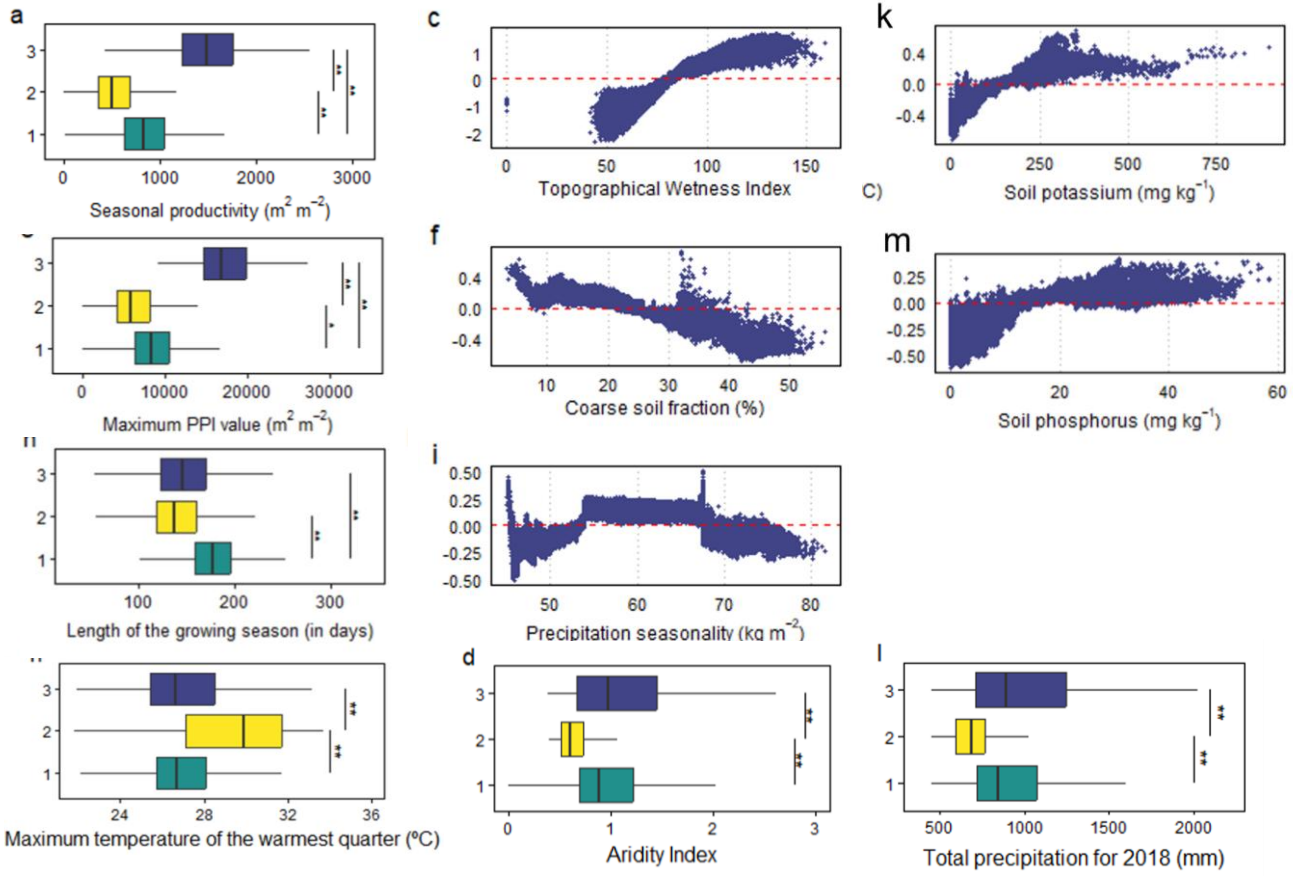
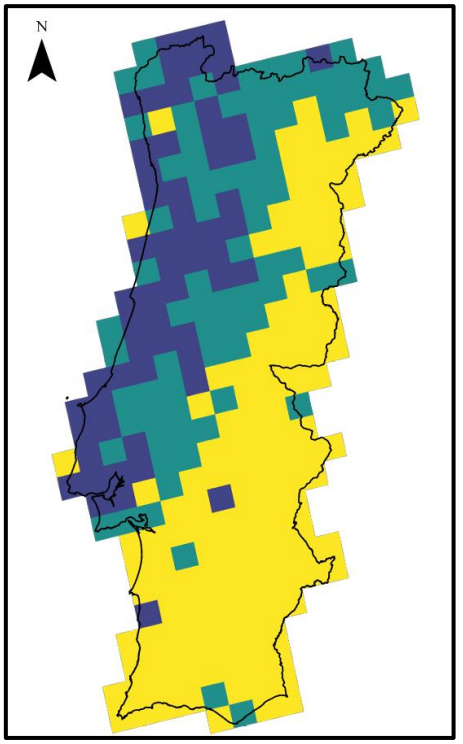
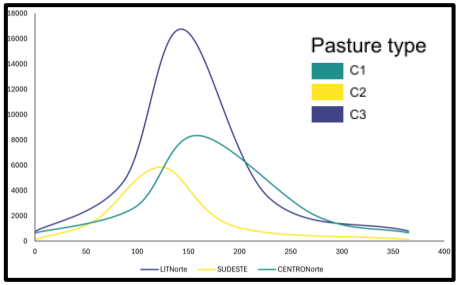
NORTH-LITTORAL PASTURES





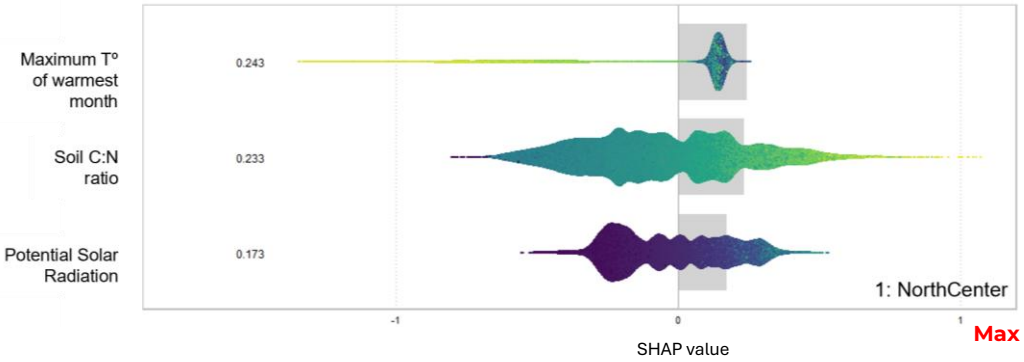


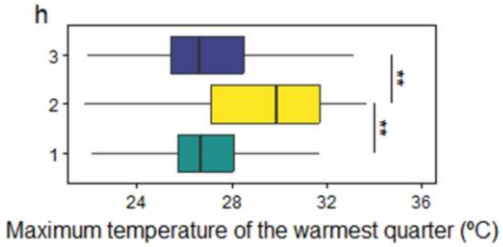
Lower water limitation (higher TWI, lower aridity, lower summer temperatures and higher precipitation) could be driving the higher productivity

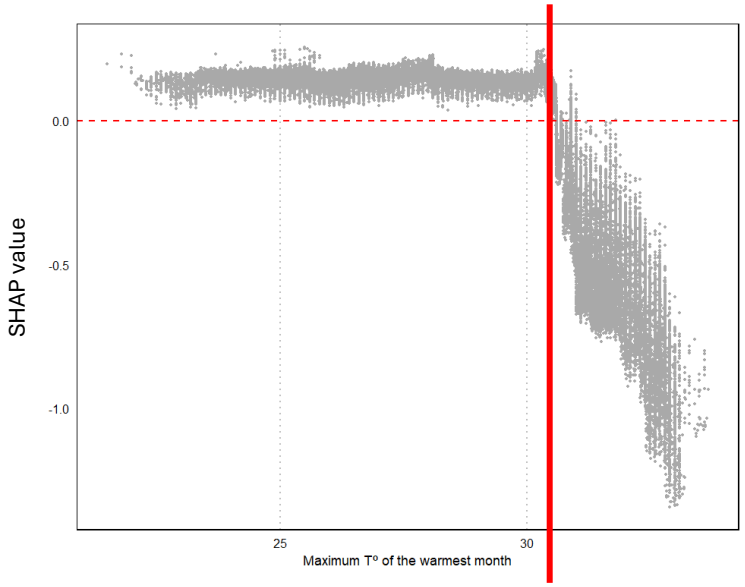
Santo *et al.*, in press

Unraveling phenology patterns

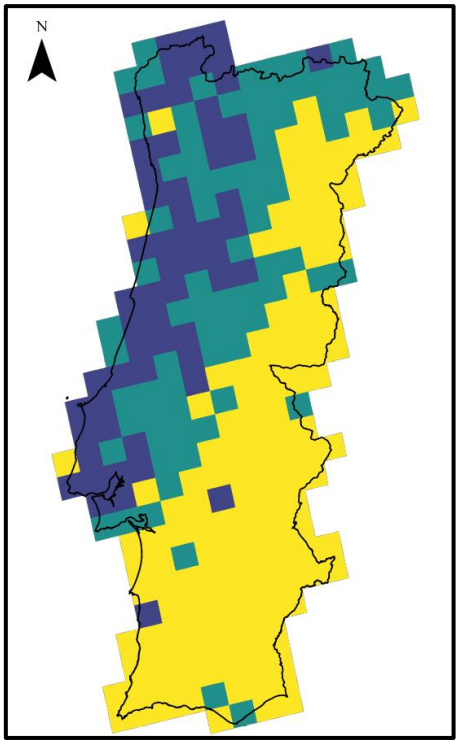
NORTH-CENTER PASTURES

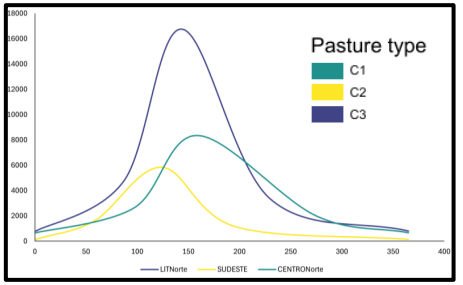






Lower summer temperatures, below **29°C**, should allow vegetation to maintain growth longer and **senesce later**

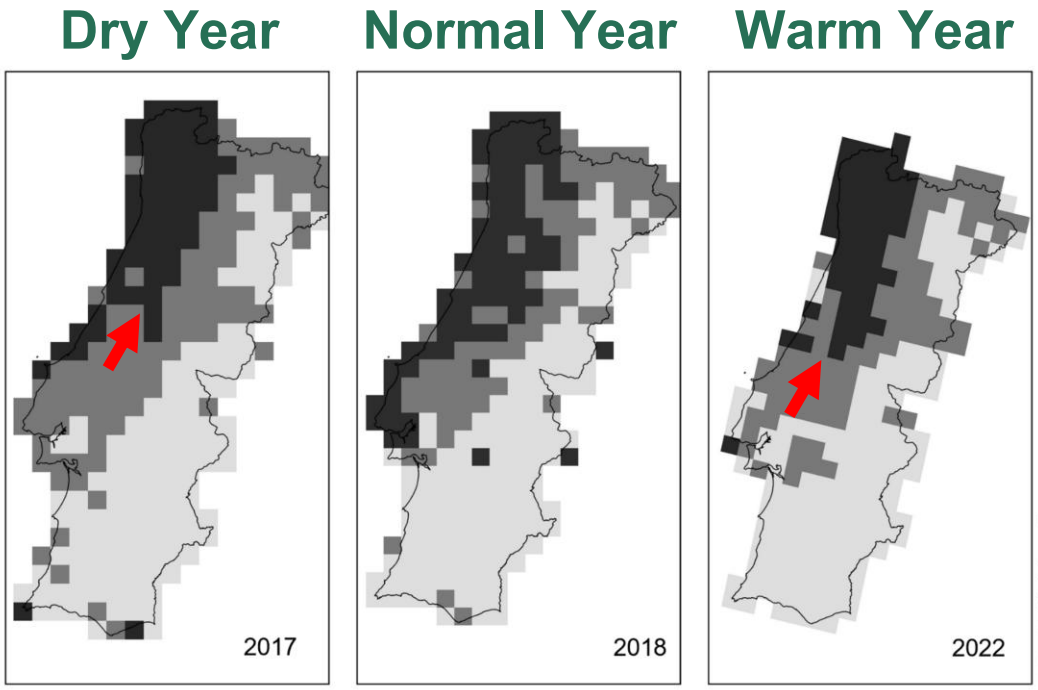




Santo *et al.*, in press

Implications for climate change

Repeating the analyses in **drier (2017)** and **warmer (2022)** years yielded similar results



The darker pasture type contracts in drier and warmer years (red arrow)

Our question

ADAPT FOR GRAZING

Taking advantage of recent **high-resolution remote sensing** data

Using a **space-for-time** approach

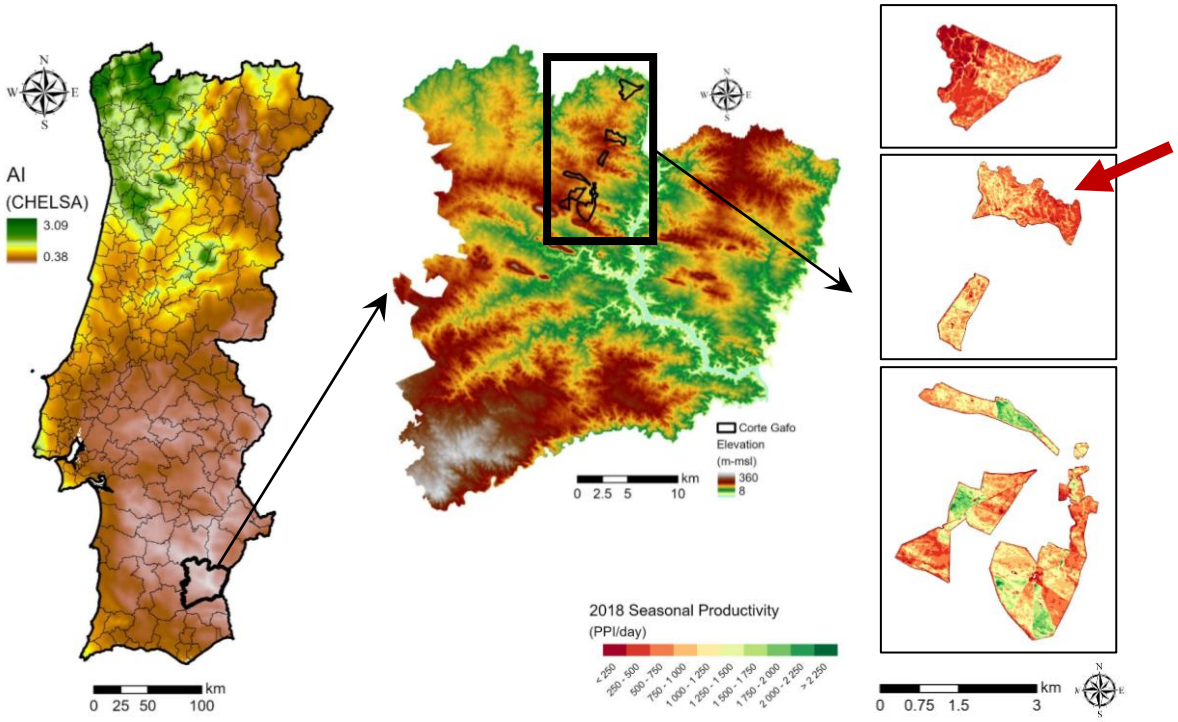
Can we apply this knowledge at the farm scale to allow for precision farming management?

Precision management at the local scale

ADAPT FOR GRAZING

Study area

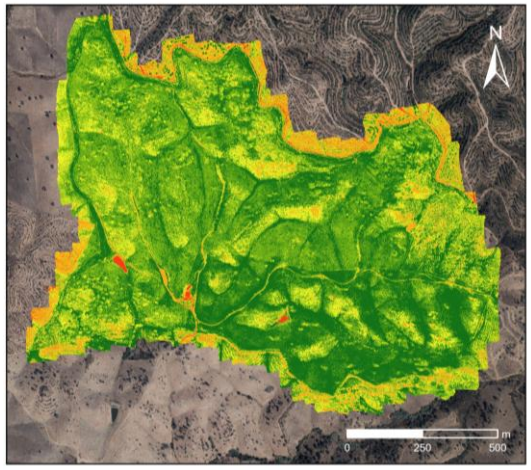
High susceptibility to desertification is one of the drier areas in Portugal

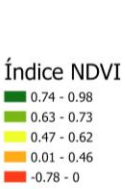


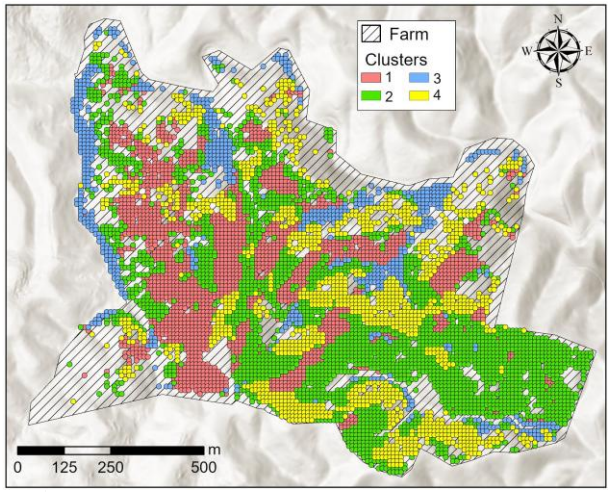
- Low precipitation values (400-650mm)
- High average annual temperature (16-18°C)
- Red-green gradient represents SPROD (seasonal productivity) in 2018 in properties
- Clear productivity variations in adjacent plots indicate the influence of the management (absence of sowing) and characteristics of the places: topography, soil type, etc.

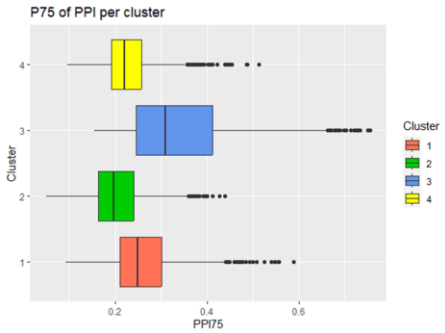
Precision management at the local scale

Spatial Precision







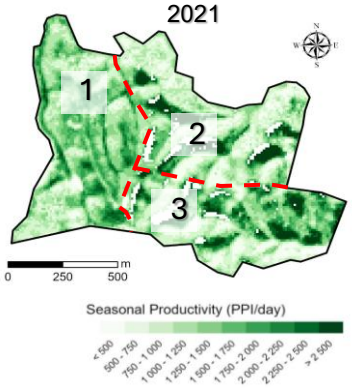


Cluster based on fix local variables: topographic characteristics (elevation, slope, potential solar radiation and topographic moisture index):

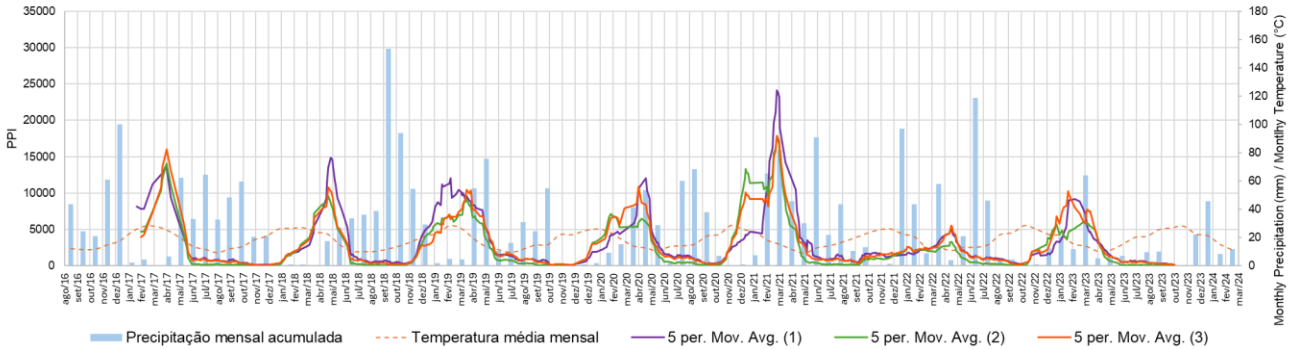
Zone 1: ridge, higher and flatter, with little water and high exposure to solar radiation;
Zone 2: transition zone between ridges and valleys with shade
Zone 3: valleys with high sun exposure and topographic humidity index;
Zone 4: Sloping slopes facing north.

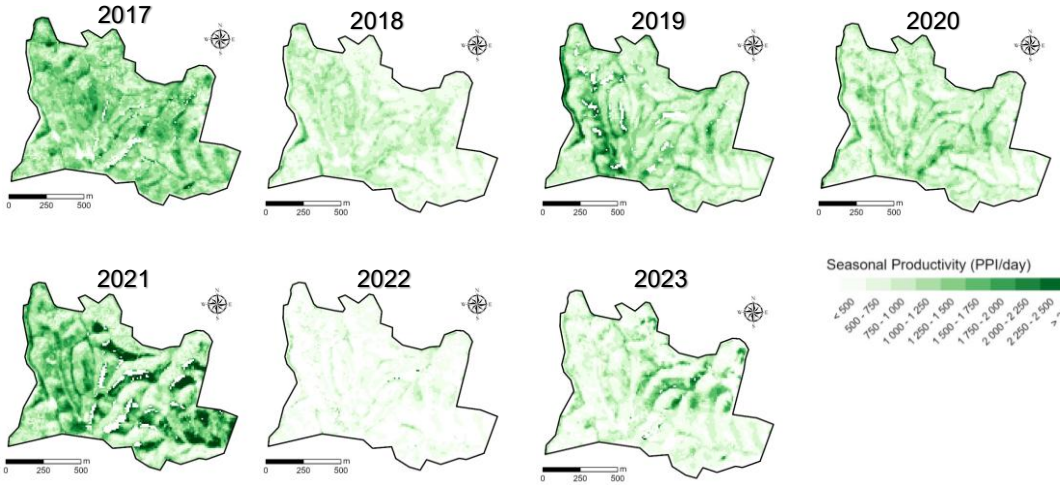
Precision management at the local scale

Temporal Precision



Seasonal productivity over time in spontaneous pastures

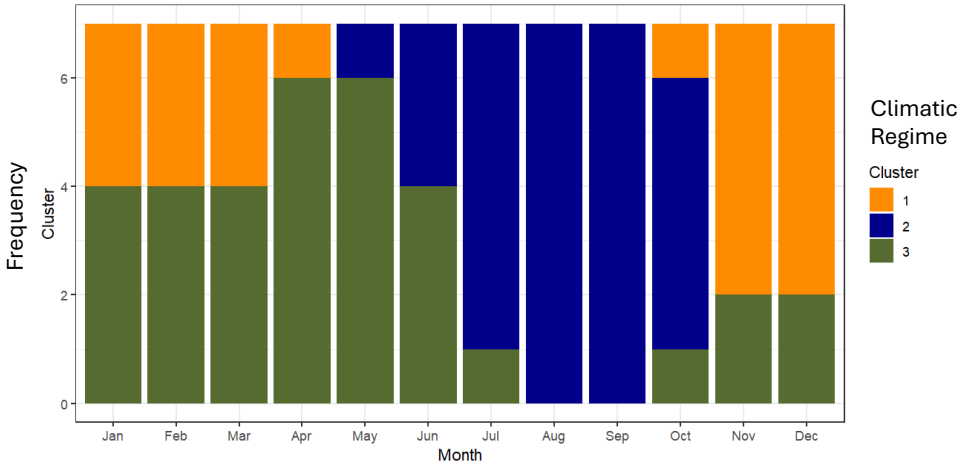




Clear impact of the limiting factor, water availability, on seasonal productivity over time

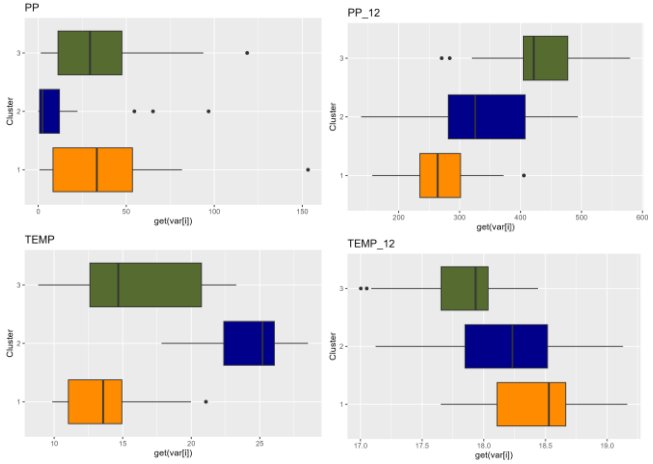
Precision management at the local scale

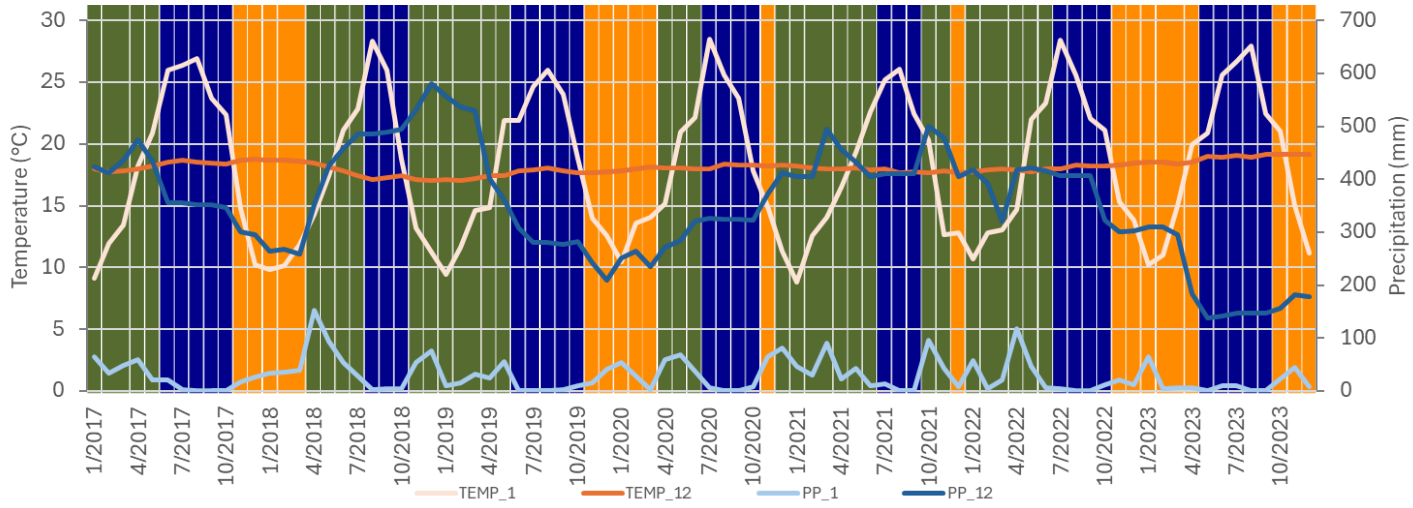
Temporal Precision



Precipitation e Temperature

Short-term → Long-term





Climatic Regimes

2 - Summer
- TEMP ↗
- PP ↘

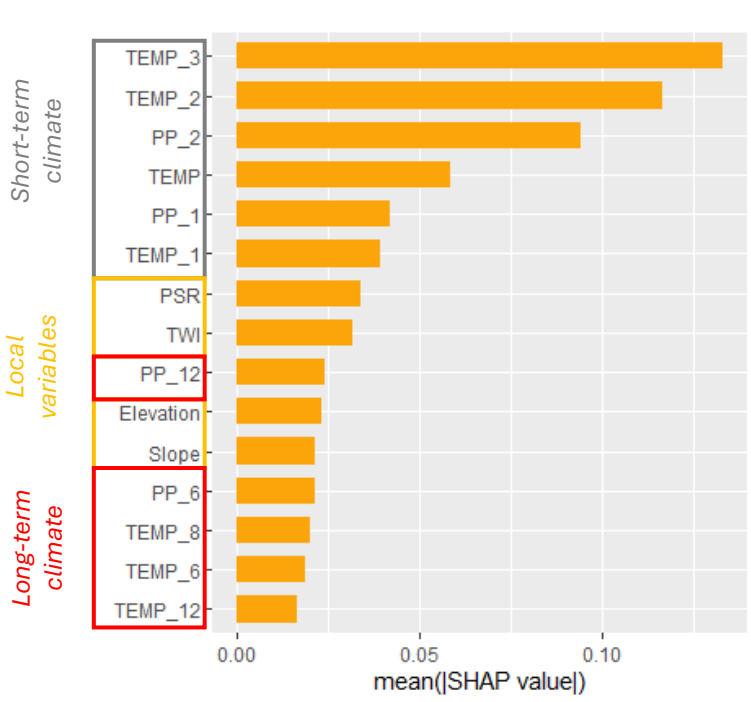
1 - Autumn-Spring
- TEMP ↘
- PP ↘
- Drought legacy

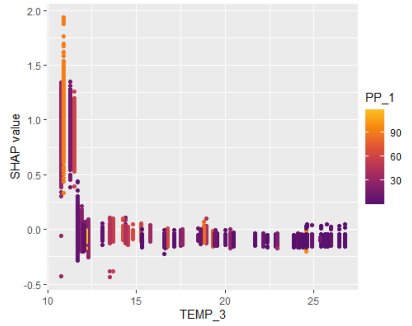
3 - Autumn-Spring
- TEMP ↘
- PP ↗
- Wet legacy

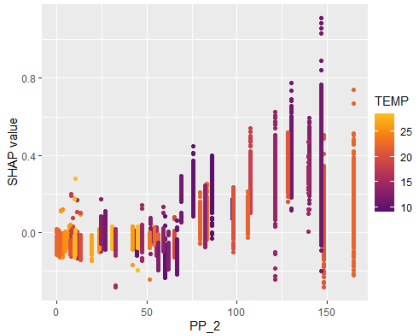
Precision management at the local scale

Temporal and Spatial Precision

Modelling of the monthly productivity







- Sort-term climate
- Topography: microclimate
- Climate legacy

Increased productivity associated with:
The temperature in the last 3 months below 12°;

Rainfall in the last 2 months greater than 70 mm at monthly scale.

Take-home messages

Grazed pastures were organized in three spatially continuous dominant phenological regions along the studied climatic gradient, in response to temperature and water availability filters:

- **Ecological filters** explained close to 70% of pasture types along the gradient, even under a wide range of unknown management conditions

- **One-size-fits-all agricultural policies** are not ideal
- Strategies need to be **tailored according to pasture types** and take into account the different vulnerabilities these are subjected to under climate change

- We can do much better at the farm scale to do **temporal and spatial precision management**

- There is a lot of room to use **ecological knowledge to improve the productivity and delivery of ES to agriculture**