

Archaeology and Climate Change: New Perspectives of Agent-Based Modelling coupled with LPJmL agroecosystemic model for the Study of relationship between agricultural production and past societies

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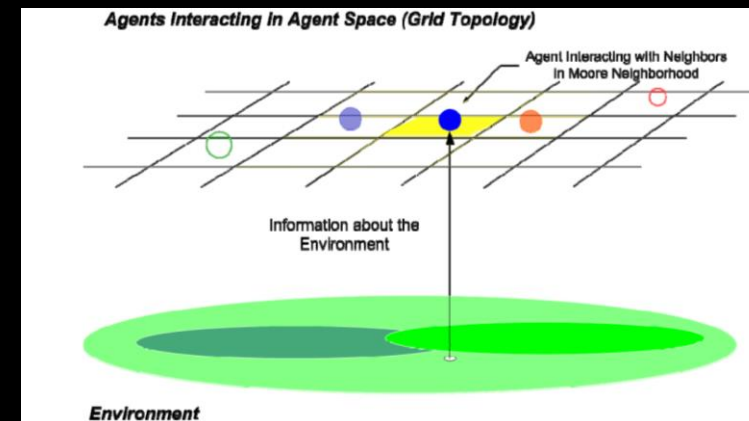
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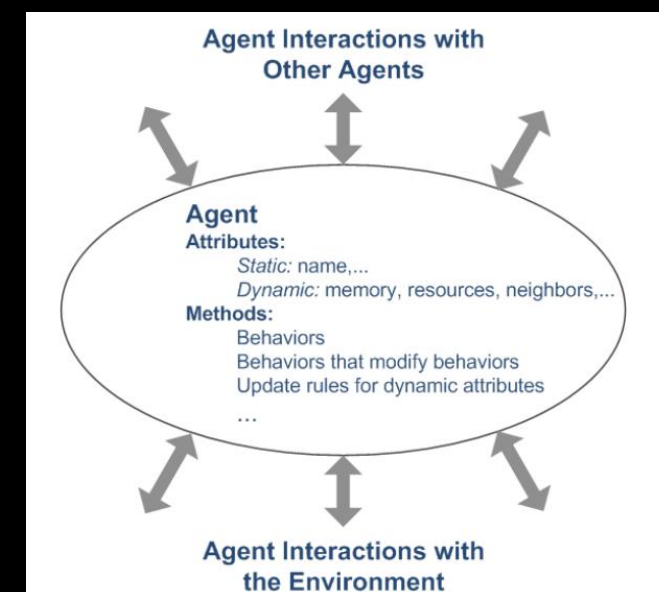
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Agent-based modeling (ABM): what is this?

- Simulating interactions between agents and their environment
- Interactions produce complex phenomena that we are trying to reproduce or unexpected
- More than fifteen computer programs are dedicated to the ABMs (NetLogo, Gama, Repast, Swarm, Mason, etc.)
- Numerous fields of application: Agriculture, Anthropology, Biomedical Research, Crime Analysis, Ecology,...



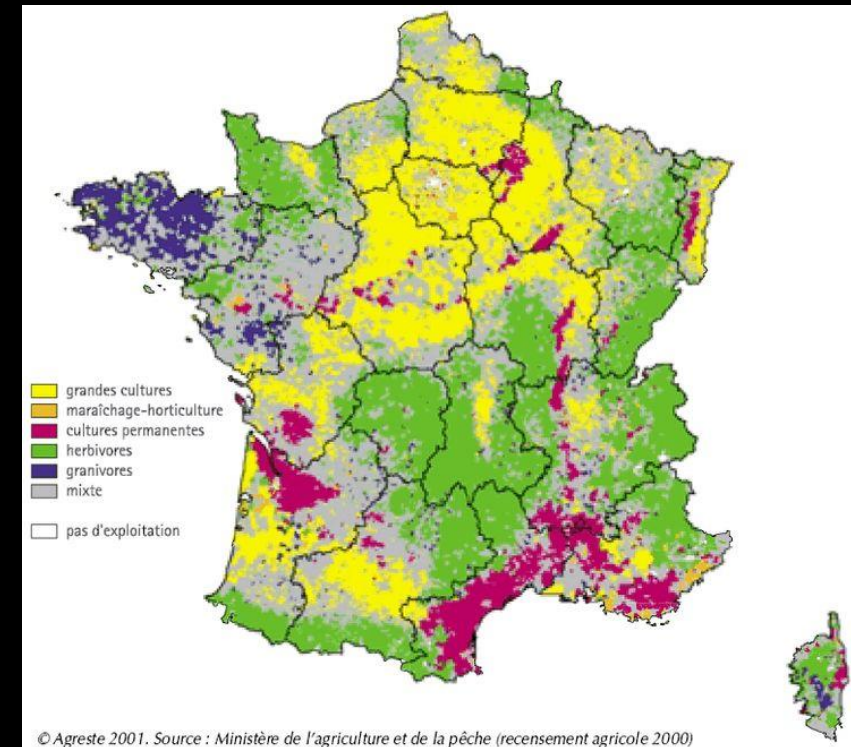
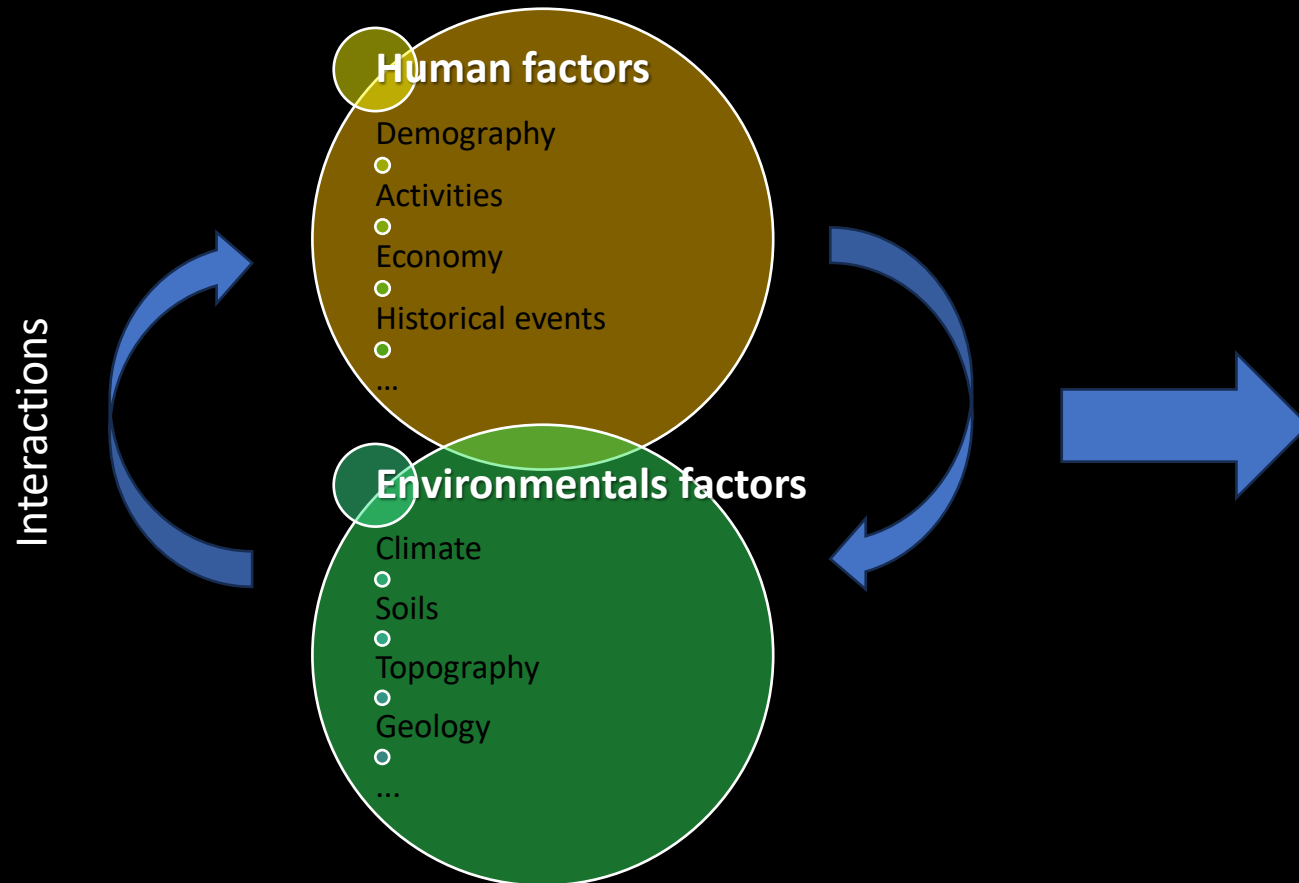
General elements of an agent-based model



A typical agent

(Figures after MACAL and NORTH 2014)

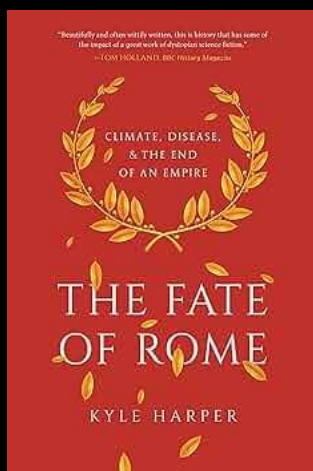
ABM for Landscape archeology: Landscapes as emergent phenomenon of socio- natural interactions



Cultivated landscapes in France today

What was the impact of climate variations on ancient societies and land use?

- Roman Climate Optimum (RCO)/
Optimum Climatique Romain (OCR)
(IInd c. BCE-IInd c. CE)
- Late Antiquity Little Ice Age (LALIA)/
Petit âge glaciaire de l'Antiquité tardive
(VIth-VIIth c. CE)

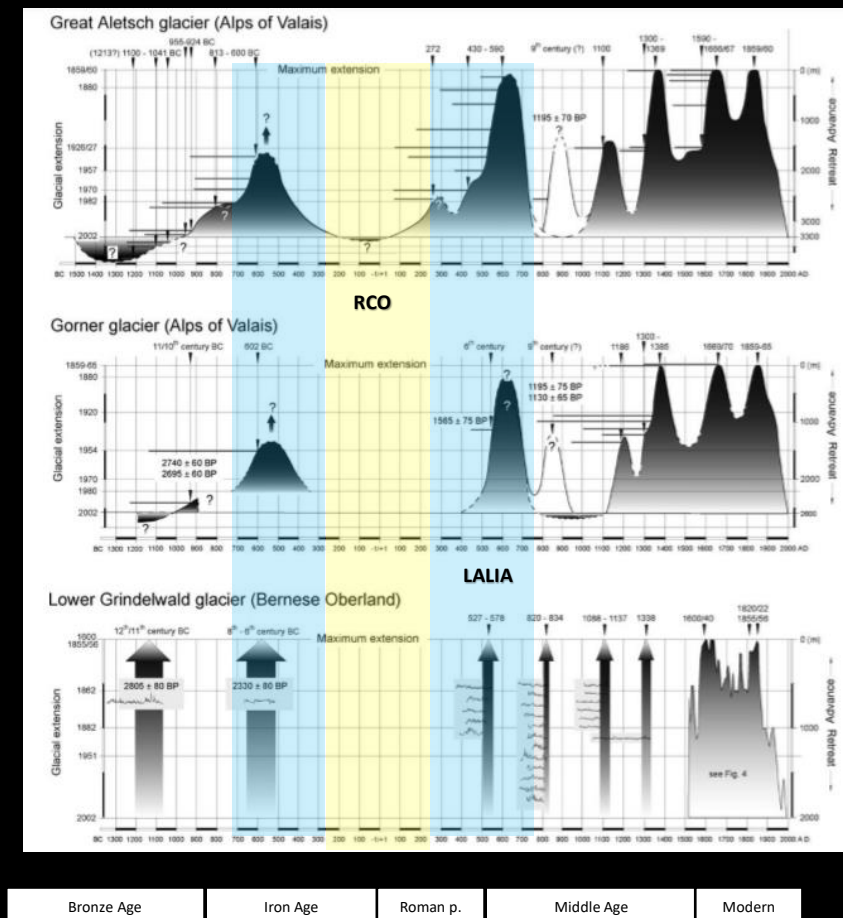


HARPER 2017, p. 52

« The climate of Rome in the empire's halcyon days was a potent incubator of growth. It fueled the agricultural engine of the economy.

The wheat harvest was sensitive to the timing and extent of both temperature and precipitation

Sustained temperature changes on the order of these experienced during the RCO let farmers carve entirely new landscapes of grain... »



Fluctuations in Swiss glaciers
(HOLZHAUSER 2005)

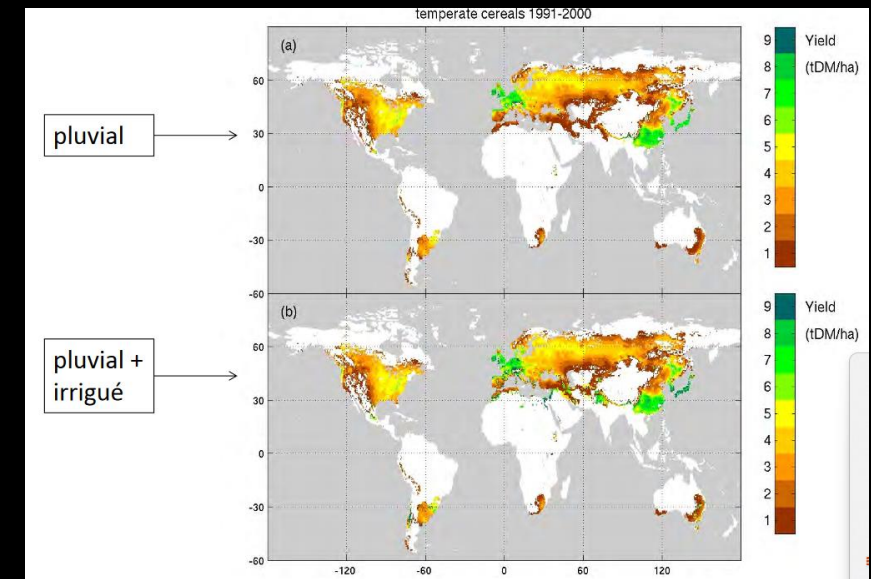
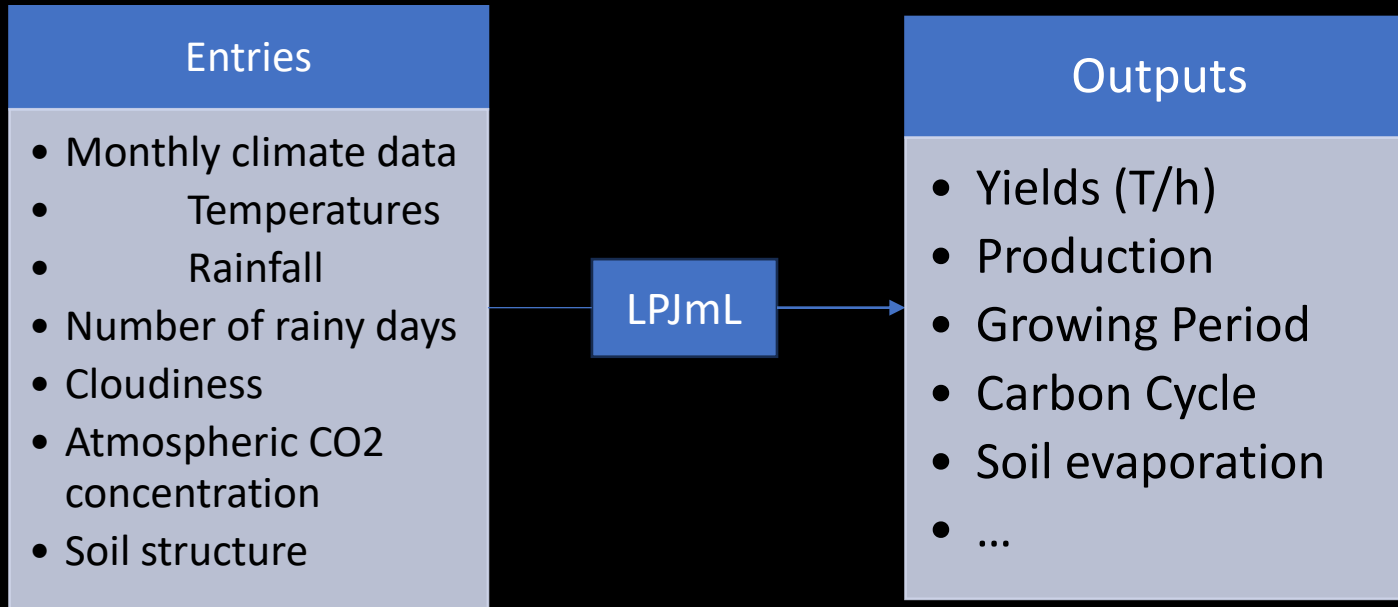
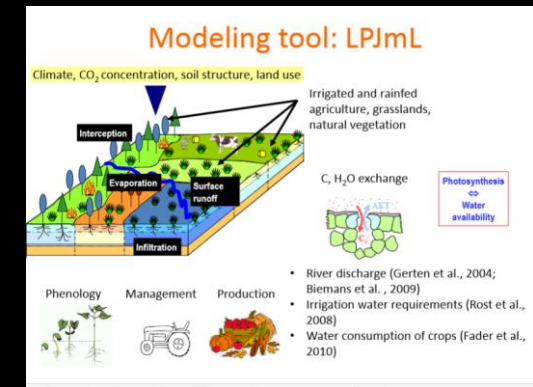
Questions

- Did the RCO really boosted agricultural yields and roman economy during the High Empire ?
- Did LALIA play a role in the end of western roman empire ?
- testing these hypotheses by modelling & simulation

Agro-ecosystem modelling Lund Potsdam Jena managed Land (LPJmL): Principles

Modelling yields of major crops on a global scale based on climate data

- BONDEAU et al. 2007
- FADER et al. 2015



Modelling of world cereal yields (1991-2000) in tons/hectares

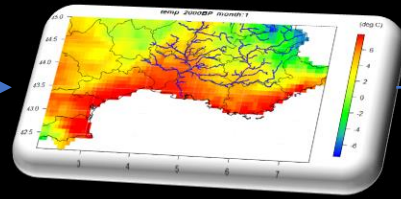
Reconstructing Climates of the Past

II- Modelling yields: LPJmL

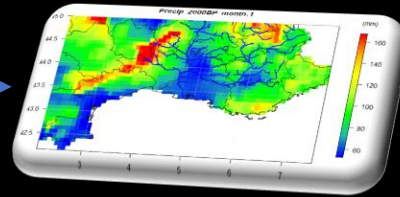
Palaeoclimatic anomalies

GUIOT & KANIEWSKI 2015

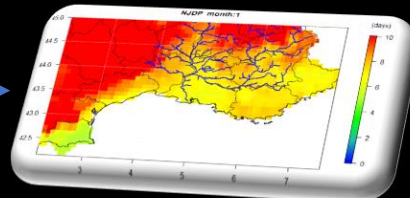
Current Climate Model (ALADIN)



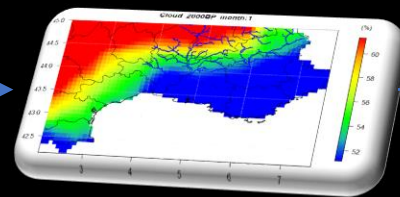
Temperatures



Rainfall



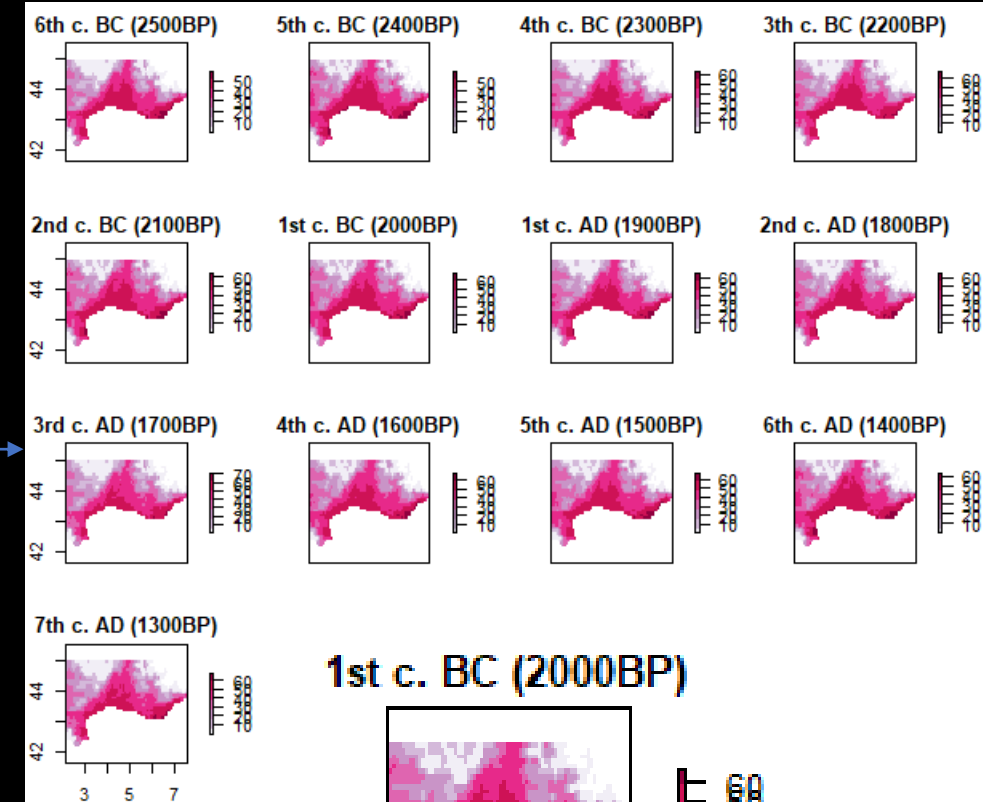
Number of rainy days



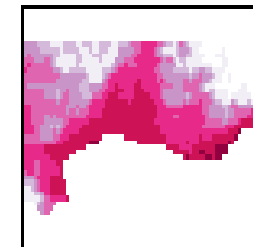
Cloudiness

LPJmL

Potential yields for cereals, wine & olive



1st c. BC (2000BP)



Potential yields for wine in hl/ha



Building an emulator of LPJmL for ABM

Linear equations for potential yields:

-Rainfed cereals (T/ha) (R2=0.63):

$$\begin{aligned}
 PyCer &= 0.3452 + 0.033 \times Thiv + 0.0072 \times Tprt + 0.0467 \times Tete - 0.0523 \\
 &\times Taut + 0.0016 \times Pprt + 0.0004 \times Paut
 \end{aligned}$$

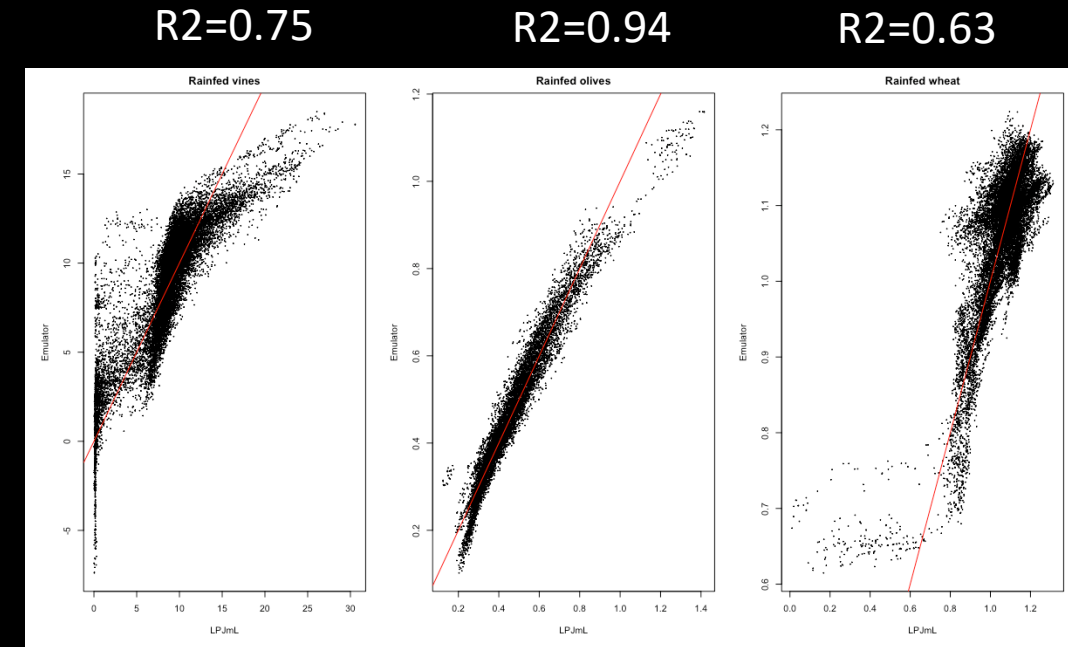
-Rainfed vines (HI/ha) (R2=0.75):

$$\begin{aligned}
 PyVine &= -34.2138 - 2.64 \times Thiv + 2.2907 \times Tprt - 2.4294 \times Tete + 5.3971 \\
 &\times Taut - 0.0033 \times Phiv + 0.04 \times Pprt + 0.0631 \times Pete - 0.0184 \times Paut
 \end{aligned}$$

-Rainfed olive tree (HI/Ha) (R2=0.94):

$$\begin{aligned}
 PyOli &= -0.0553 + 0.053 \times Thiv - 0.0776 \times Tprt - 0.0099 \times Tete + 0.0445 \\
 &\times Taut - 0.00004 \times Phiv + 0.0016 \times Pprt + 0.0026 \times Pete + 0.0005 \\
 &\times Paut
 \end{aligned}$$

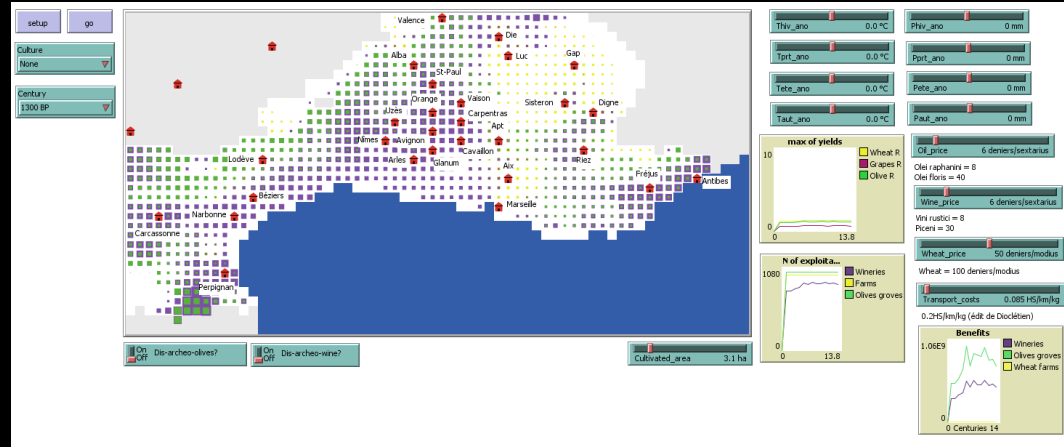
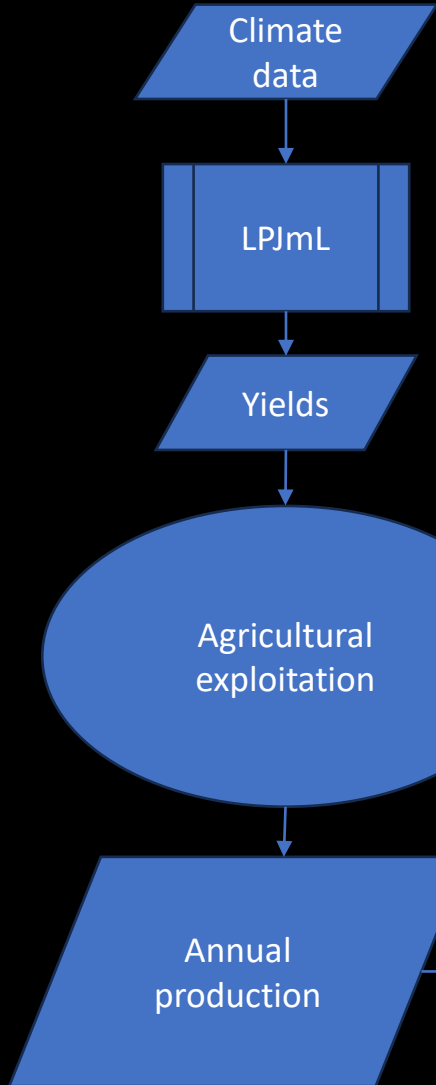
Emulator underestimates the high values of vines and olives and it overestimate the low values of wheat



Work of J. Guiot

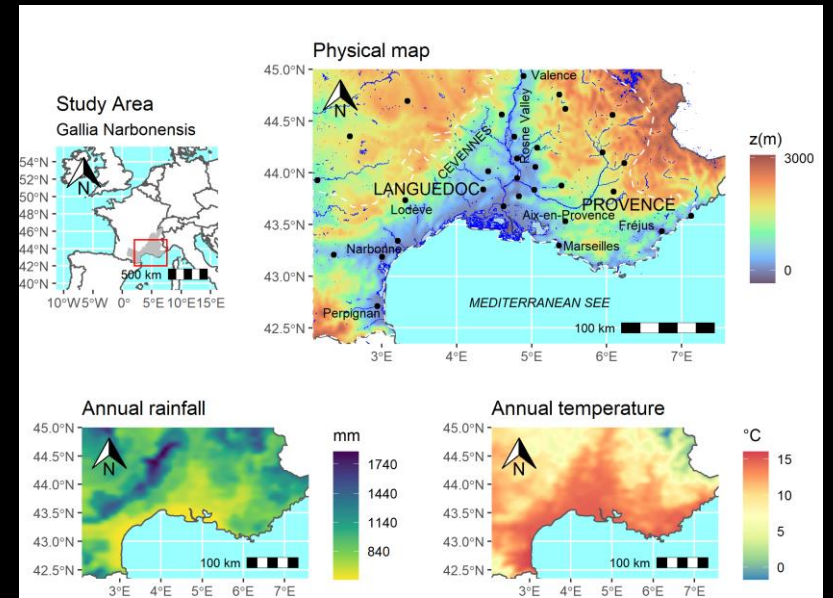
Squared R indicates the proportion of variance of the yield explained by the climate

ROMCLIM: a socio-climate model






Screenshot of the interface of the ROMCLIM model
BERNIGAUD et al. submitted

Output



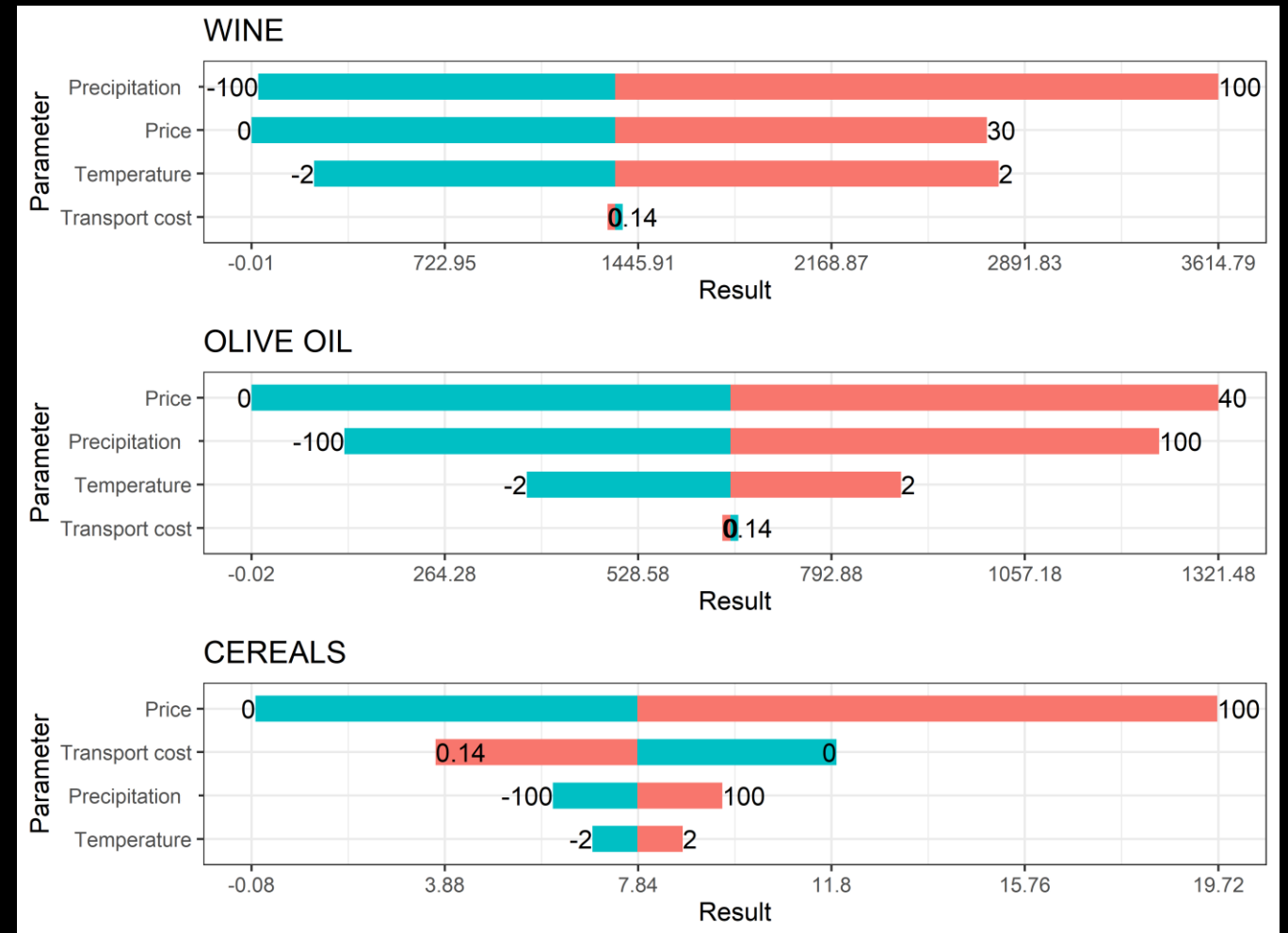
- Simulates the fluctuations of potential profits made by virtual agricultural exploitations (wine, olive and wheat production) in southern Gaul (*Gallia Narbonensis*), according Climate Change
- **Agents:** [WINERIES] [OLIVE GROVES] [CEREAL FARMS] [MAJOR TOWNS] (programmed according to agronomic treatises)
- **Potential yields** (wine, olive, cereals) calculated by an emulation the agro-ecosystemic model **LPJmL**

ROMCLIM: main characteristics of the agents:

Agents :	Wheat farm 	Olive grove 	Winerie 
Number of farmers	6	13	14
Cultivated area	0-2 ha	240 <i>jugera</i> (60 ha) (Caton)	100 <i>jugera</i> (25 ha) (Caton-Columelle)
Yields	Returned by LPJmL emulator calculation/climate		
Harvest	Cultivated area * LPJmL yield		
Price of harvest	0-100 denarius/modius*	0-40 denarius/sextarius**	0-30 denarius/sextarius**
Costs of exploitations	Quantity of grain necessary for feed the family + necessary seed for next year	Number of persons * 140 sesterces/year	140 sesterces/year/slave
Distance to the nearest capital of city	Calculated by the model		
Cost of transports	0-1 sesterce/kg/km * Distance to the nearest capital		
Benefits	Surplus price – costs	Harvest price – costs	
Action	Disappear if annual harvest can't feed the family	Disappear if benefits < 0	

Sensitivity Analysis for ROMCLIM

- OFAT method (One-factor-at-a-time) for weighing the relative importance of economic and climatic factors
- Different types of crops not equally sensitive to climate change
- Precipitation are the most important for wine
- Prices are the most important factor for olive and grain growing
- Climatic factors secondary for cereal cultivation

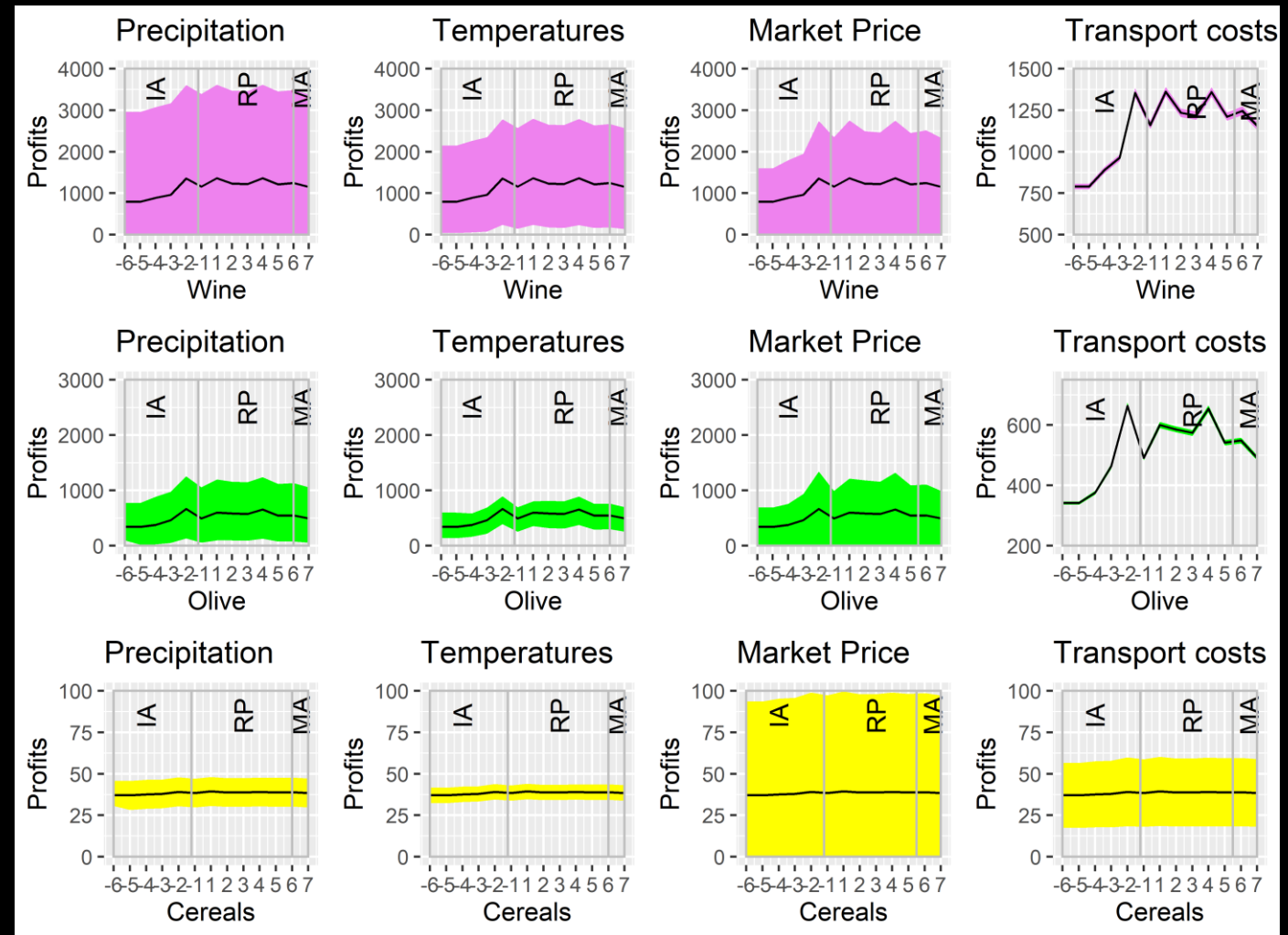


EXAMPLE FOR THE 3RD CENTURY A.D.

BERNIGAUD et al. submitted

ROMCLIM: results

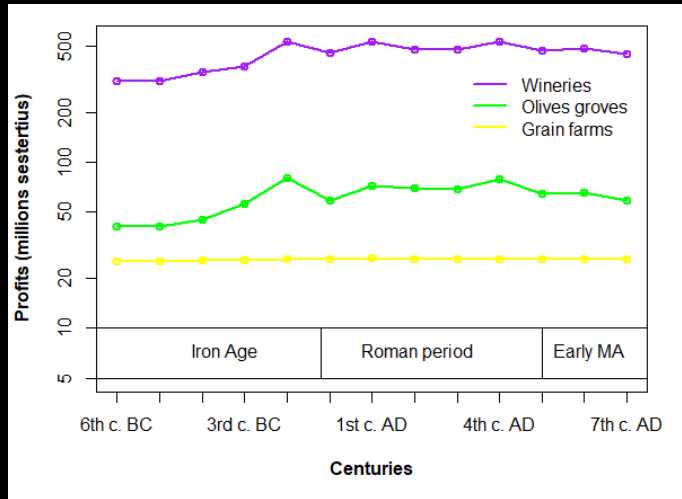
- Strong gradual increase in the potential profitability of viticulture and olive growing during the Iron Age (as a result of the RCO)
- Highest level reached during the Roman period
- Decline during the High Middle Ages (but not dramatic)
- Effect much less pronounced for cereals (flat curves)



Profits (millions of sestertius)

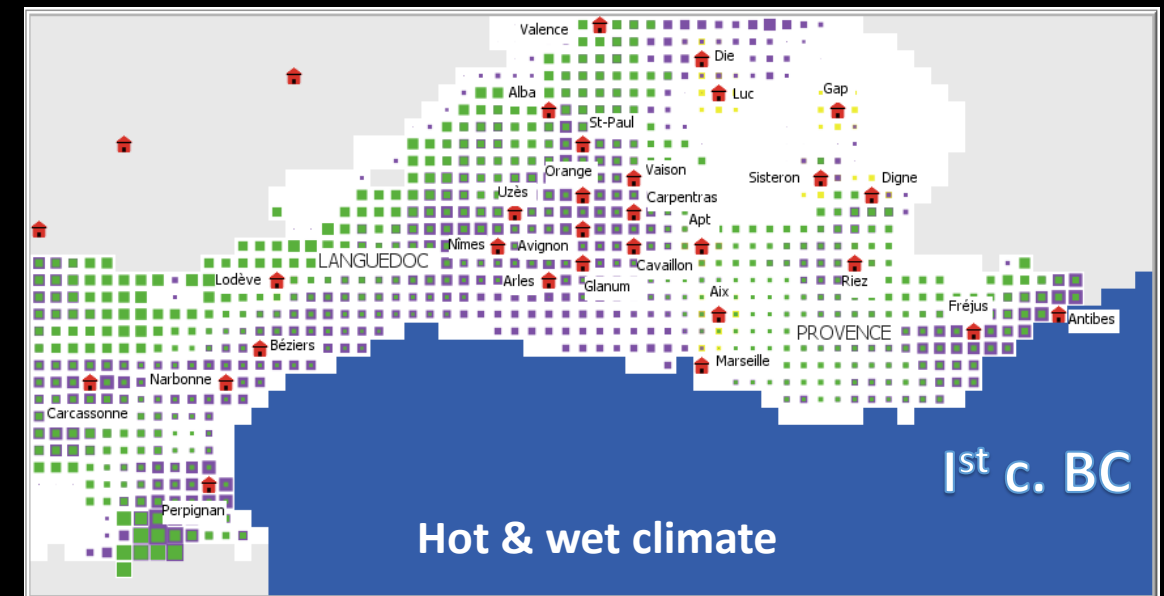
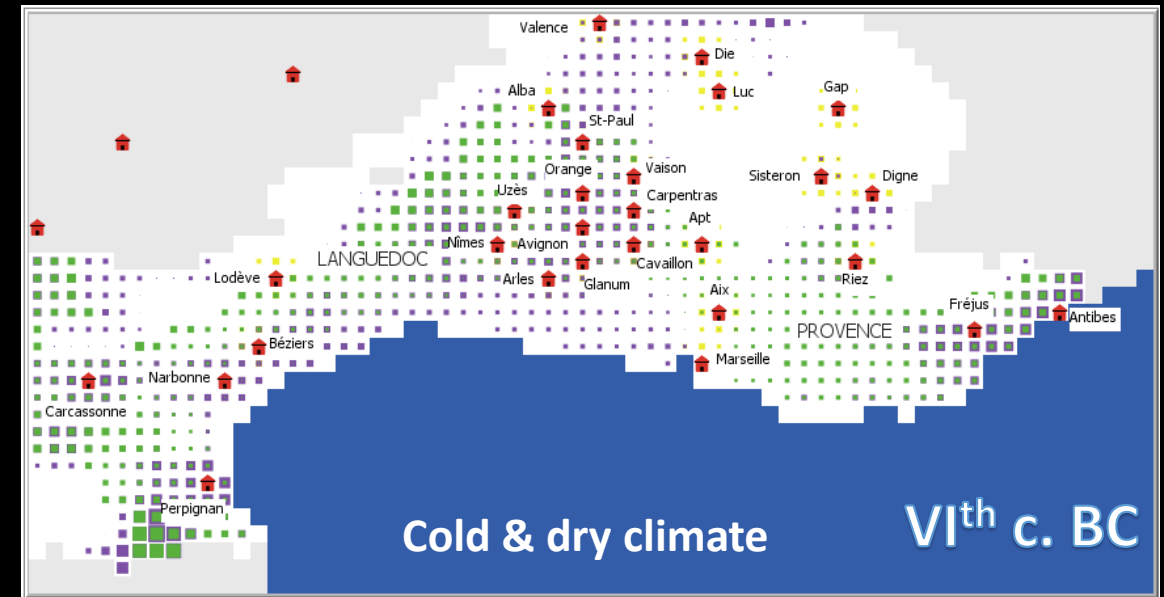
BERNIGAUD et al. submitted

ROMCLIM: results



Evolution of potential profits made by agricultural exploitations (according Climate Change only)

- Strong positive impact of RCO on the potential agricultural profits (peak in the IInd c. BC), slight decrease during Late Antiquity (IVth-VIIth c. AD)
- Maps of potential profits very different according climate characteristics



BERNIGAUD et al. submitted

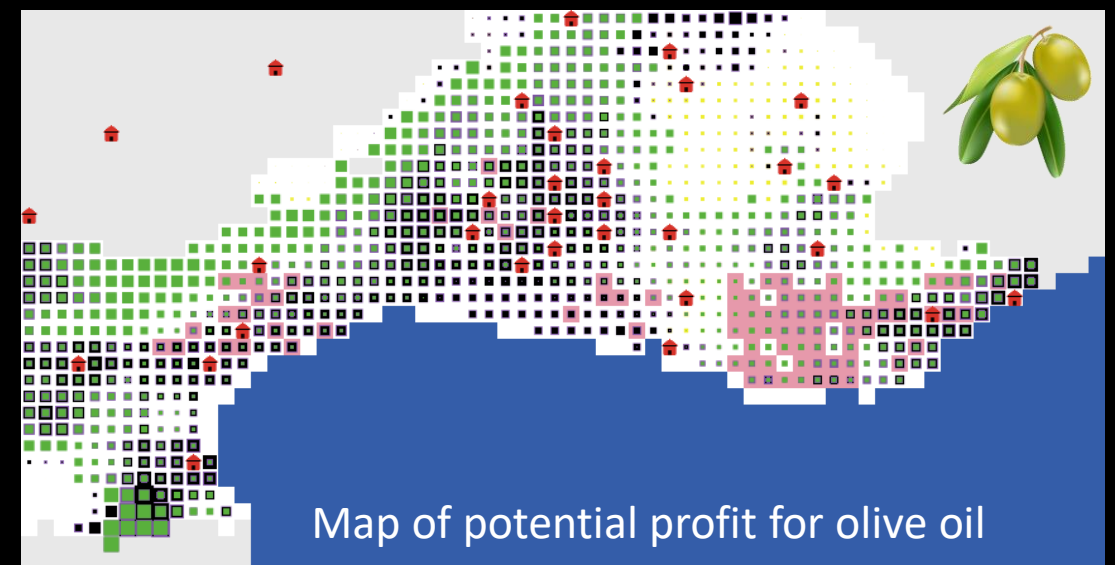
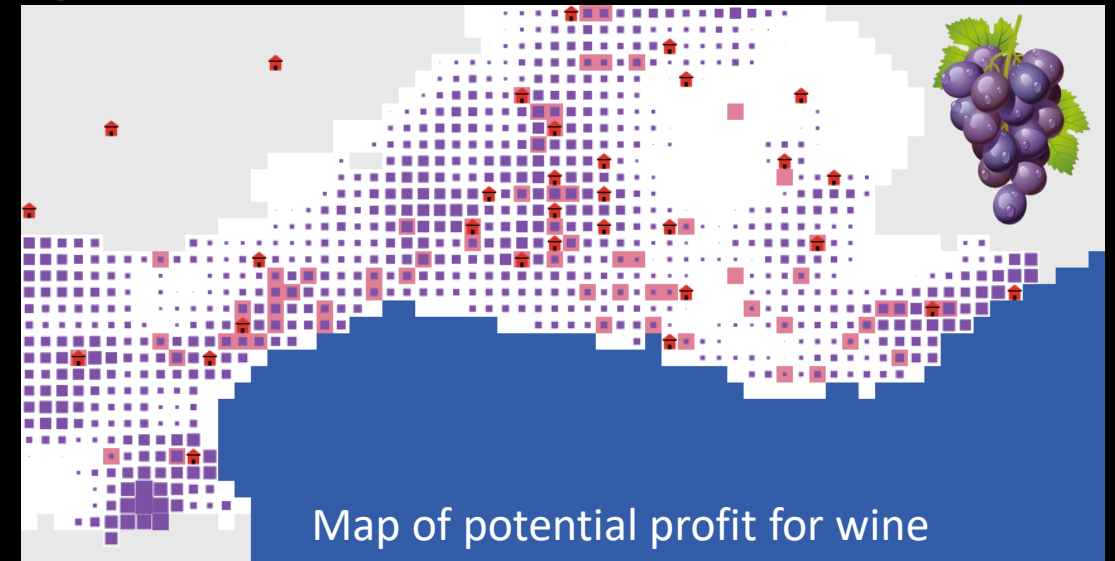
ROMCLIM: outputs vs archeological data

data

- For winemaking archaeological data for wine roughly match with the area of highest potential profits (Antibes-Fréjus area, middle et lower Rhone valley, languedocian plains)
- For olive oil, main archaeological data are concentrated in Languedoc and mainly in the Var region (thanks to J.-P. Brun works), where the potential appears medium. The area with highest potential profits in the languedocian hinterland doesn't match with archaeological data, but researches are not very intensive in this area.

Difficulty to validate the outputs of the model with archaeological data due to their spatial heterogeneity

*-> but model have a stimulating **predictive value** for archaeological research*

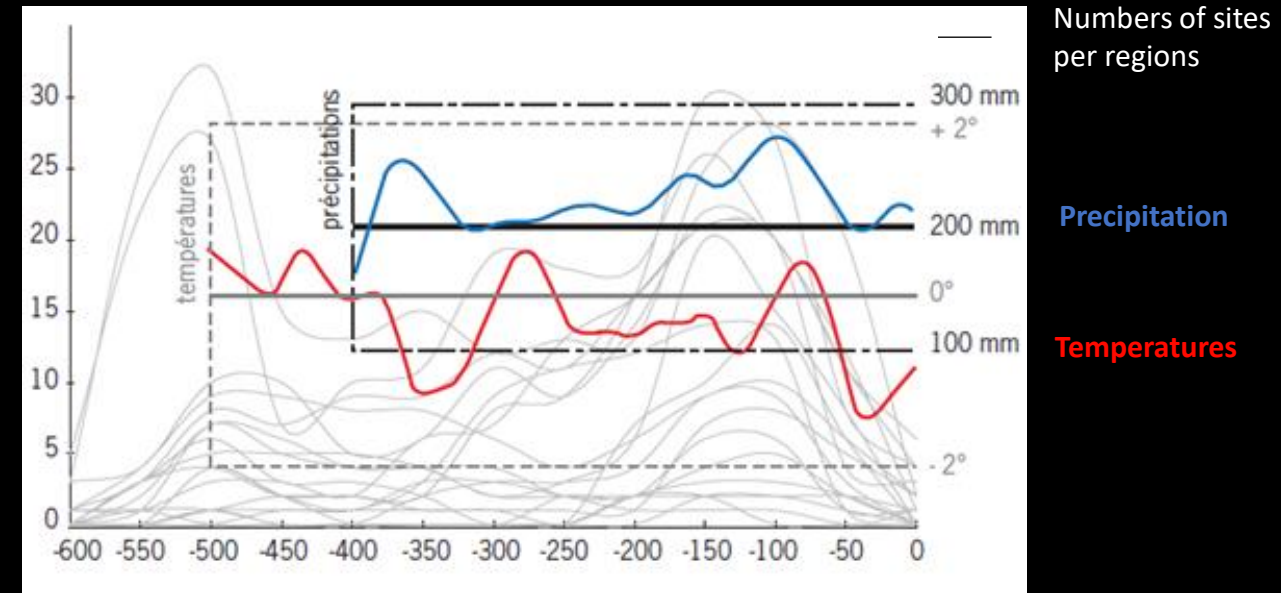


■ Archeological data

FER-AGRI: vulnerability and resilience of Iron Age societies to Climate Change

What was the impact of Climate Change on the Iron Age demography in Gaul between the VIth c. BC and the Ist c. BC ?

A correlation between downshift of temperatures and downshift of archaeological sites ?



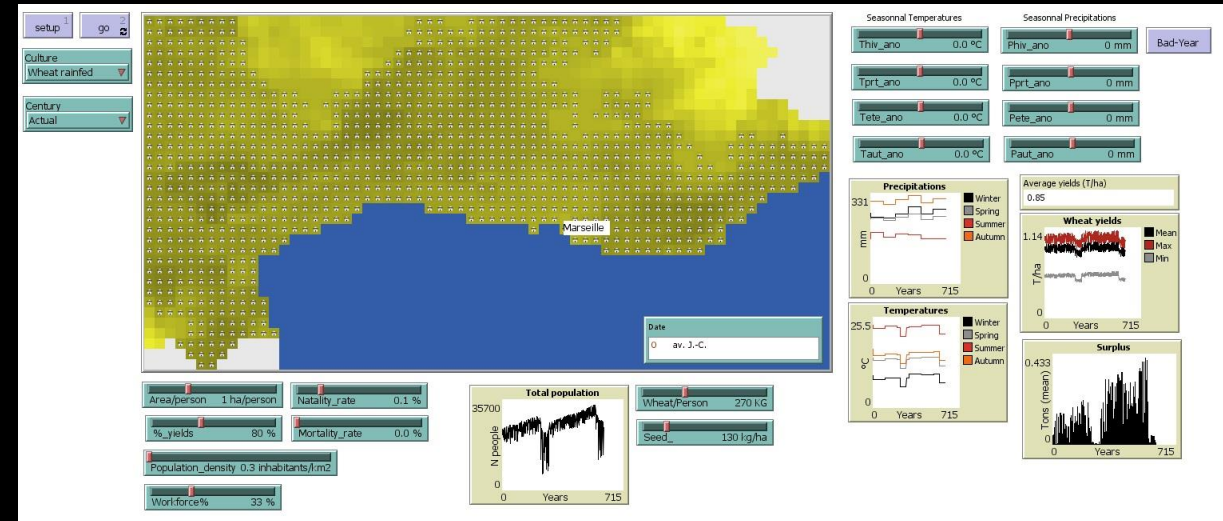
Density of settlement in Northern Gaul in Iron Age and climatic fluctuations (MALRAIN et al. 2013)

Lines in grey represent number of archaeological sites of Iron Age in different regions in northern Gaul

Precipitation and temperature data from BÜNTGEN et al. 2011

FER-AGRI: vulnerability and resilience of Iron Age societies to Climate Change

- Impact of Climate Change on potential cereal production and demographical growth are simulated
 - Cereals yields vary according to paleoclimatic data (LPJmL emulation)
- Population grows each year according to a demographic rate (0,2 – 5 ‰)
 - Agricultural workers (workforce) make a harvest per year for 6 centuries
 - When the harvest and stocks are insufficient in one cell to feed everybody, population disappears



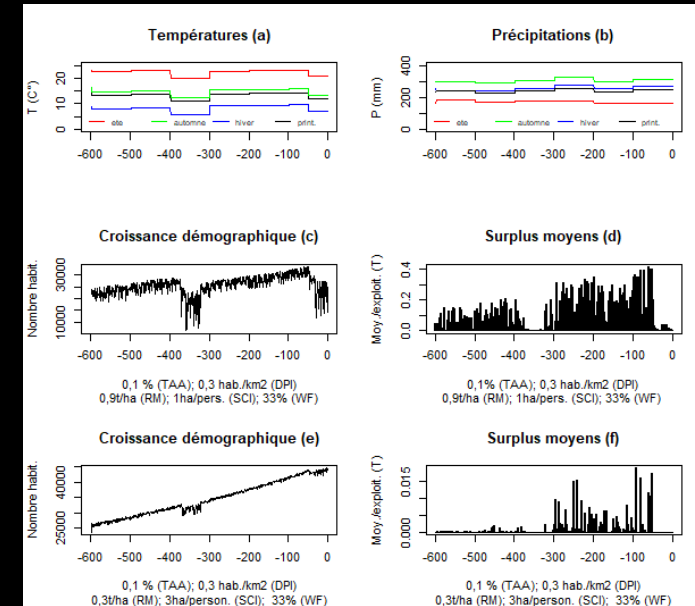
Interface of FER-AGRI Model (BERNIGAUD et al. 2023)

Main parameters:

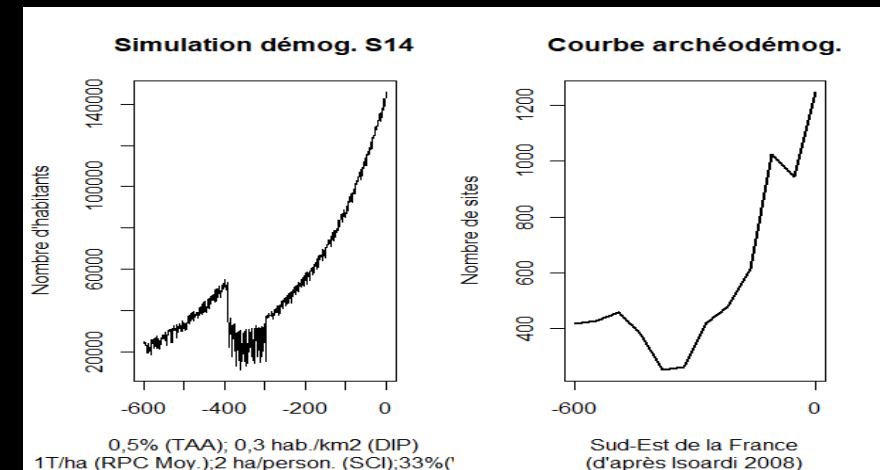
- Cereal yields (kg/ha)
- Rate of natural increase (%)
- Initial population density (inh./km2)
- Harvested area per individual (ha/year)
- Cereal consumption per capita (kg/year)
- Workforce (%)
- Amount of seed used (kg/ha)

FER-AGRI: main results

- Noticeable RCO effect on cereals surplus, but not really on demographical growth
- Cooling of more than -2°C have a negative impact on cereal yields and cause a demographical collapse (system resilient under this threshold)



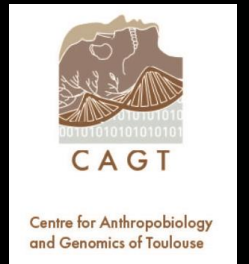
BERNIGAUD et al. 2023



Simulation

Number of archaeological sites

ANR MICA : Modelling Interactions between Climate change and Agriculture in Ancient West



- **Objective:** characterize and model the impact of climate change on agriculture (yields, production) and the choice of crop species and varieties (wine, olive, cereals, etc.)
- **Chronological periods:** Bronze Age – Late Antiquity (1500 BC – 500 AD)
- **Study area:** Mediterranean & Western Europe
- International multidisciplinary team of 50 people : archaeologists, archaeobotanists, geoscientists, environmental modellers, paleogeneticists,...
- Institutions/ Laboratories: ISEM, ASM, Cepam, IMBE, CEREGE, CAGT, Museum National d’Histoire Naturelle,....

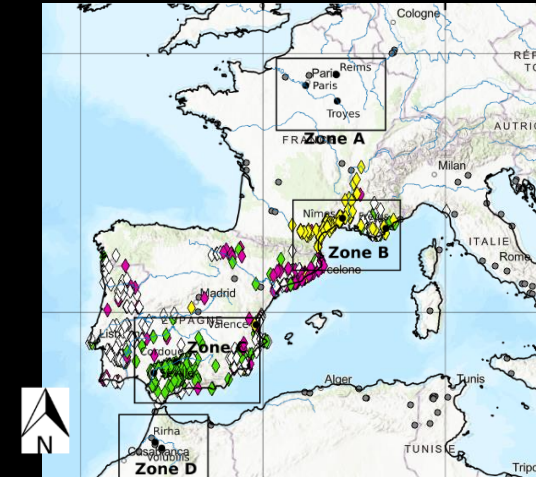


<https://mica.hypotheses.org/>

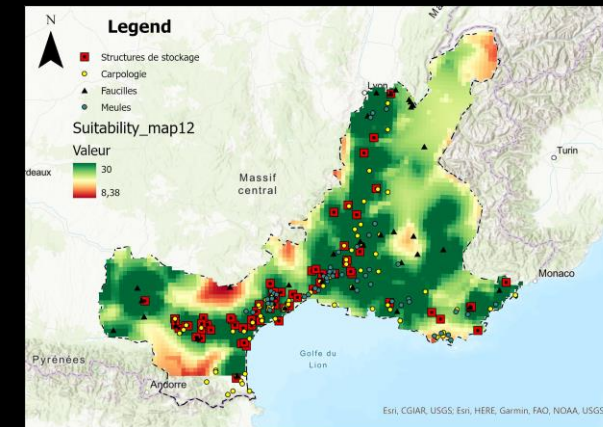
ANR MICA : main objectives & methods



- Identification of cultivated plant species (morphometrics, DNA analyses)
- Yield modelling (LPJmL) for multiple species of cereals
- Collection and mapping archaeological data (grain storage structures, press facilities)
- Production of suitability maps for different crops
- **Development of an ABM to test hypotheses and weigh the role of climatic, socio-economic and cultural factors in the evolution of crop geography at the scale of western mediterranean & western Europe**



GIS mapping in progress of press facilities and grain storage structures (N. Bernigaud)



Suitability map for cereal cultivation in southern Gaul in Roman period (N. Bernigaud)

Thanks

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