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# Quantification de la production agricole, climat et démographie durant l'Age du Fer en Provence. L'apport de la modélisation agrosystémique et multi-agents

Nicolas Bernigaud, Delphine Isoardi, Alberte Bondeau, Loup Bernard, Eneko Hiriart, Joel Guiot

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Submitted on 7 Feb 2022

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# Quantification de la production agricole, climat et démographie durant l'Age du Fer dans le sud de la Gaule : l'apport de la modélisation agrosystémique et multi-agents

N. Bernigaud, L. Bernard, A. Bondeau,  
D. Isoardi, E. Hiriart, J. Guiot



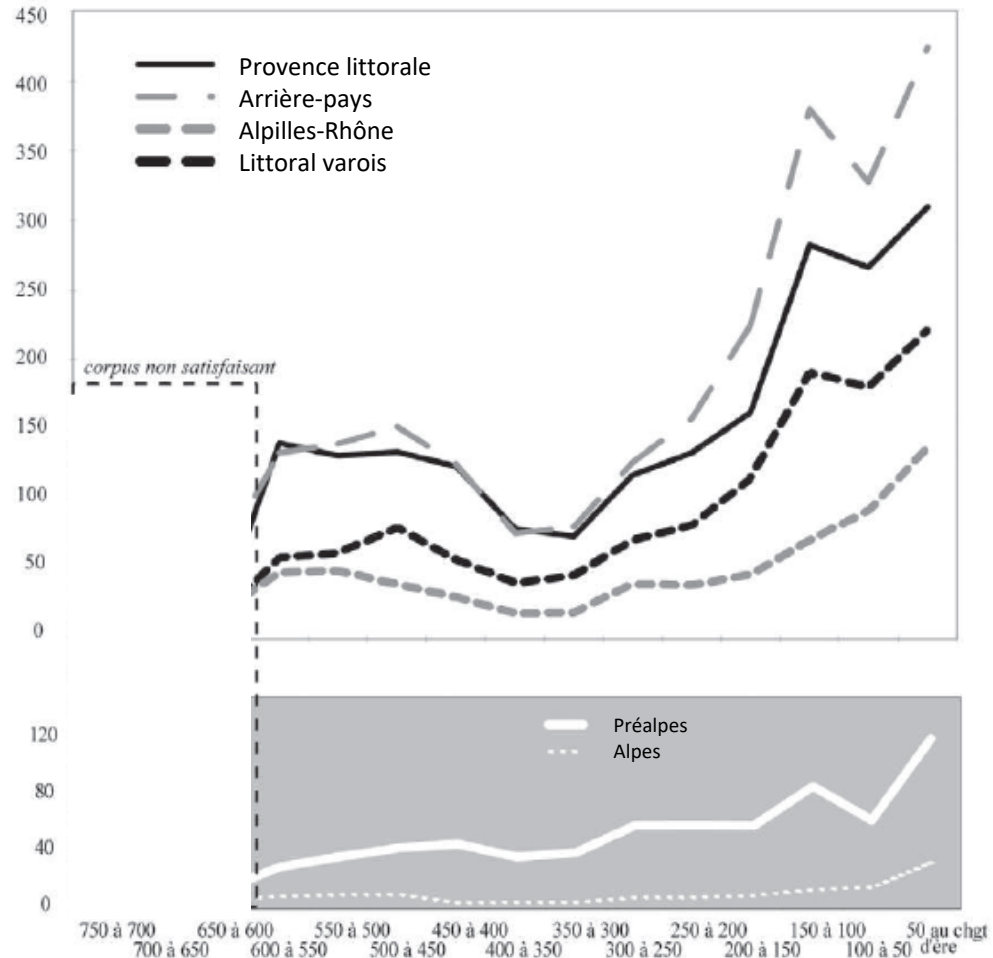
# RDMed project



- **Project title:** Resilience and Adaptation to Droughts and Extreme Climate Events in the Mediterranean: Lessons Learnt from Past on a 1.5°C or more Warmer World
- **Topics:** Mediterranean area, water stress, environmental datasets, socio-ecosystems
- **Concerned disciplinary fields:** climatology, archaeology, history, ecology, economics, geography, agronomy, geosciences
- **Summary:** The goal of the project is to analyze the environmental and socio-economic factors, which have made past Mediterranean societies more or less resilient or capable of adapting to the type of water stress that we are likely to encounter in the 21st century with a world warmer by 1.5°C or more, i.e. the thresholds of the Paris Agreement of December 2015.

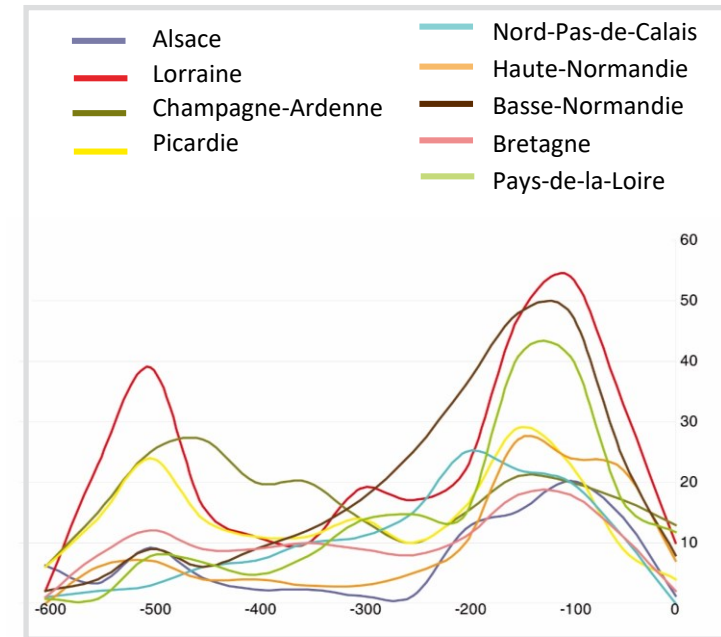
## Quelles dynamiques de peuplement à l'Age du Fer en Gaule ?

### Gaule du sud (Provence)



Modélisations archéodémographiques  
(d'après Isoardi 2008)

### Gaule du nord



Courbes de densité d'occupation par régions dans le nord de la Gaule  
(d'après Malrain et al. 2013)  
Pics d'occupation au VI<sup>e</sup> s. av. J.-C. et vers 150 av. J.-C.

RECHERCHES ARCHÉOLOGIQUES

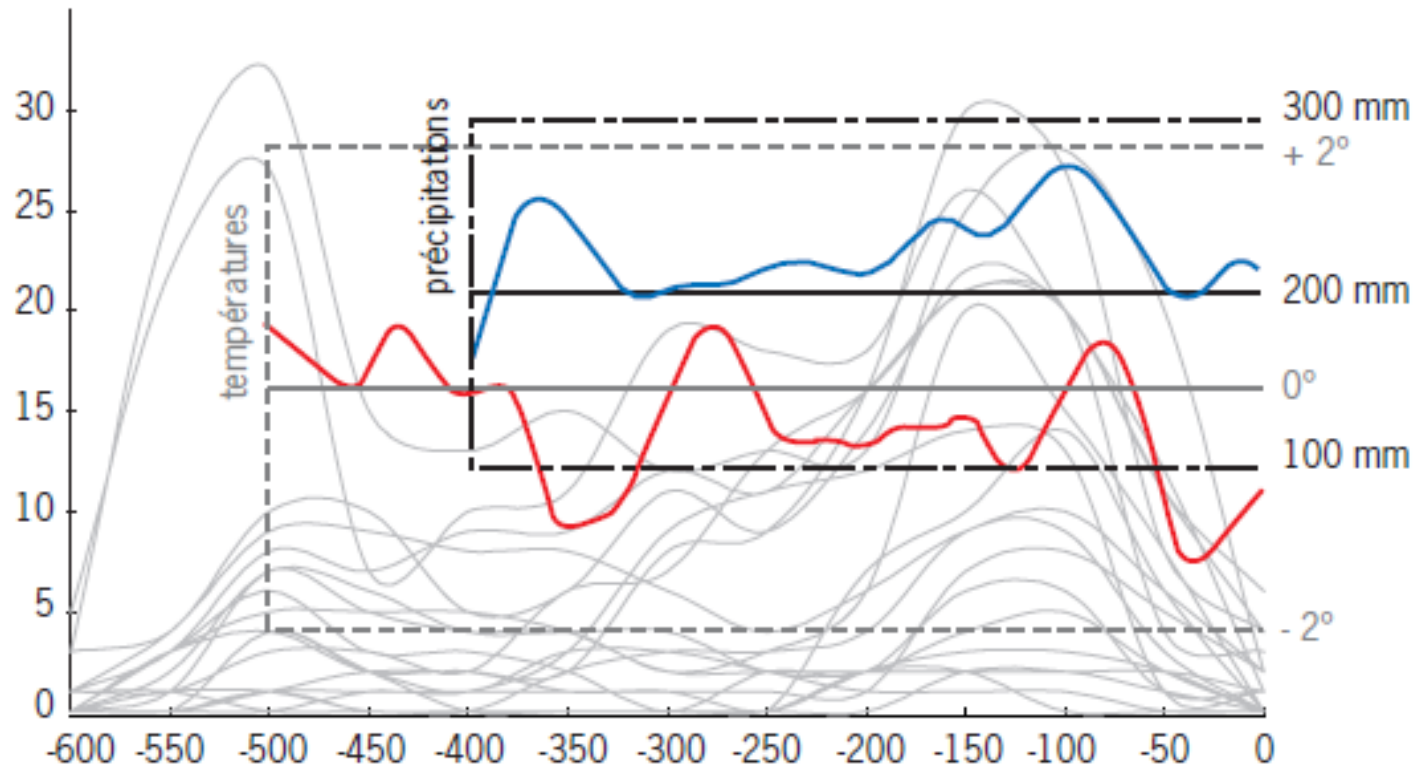
## L'habitat rural du second âge du Fer

Rythmes de création et d'abandon  
au nord de la Loire

sous la direction de François Malrain  
Geertui Blancquaert | Thierry Lorho



CNRS EDITIONS Inrap



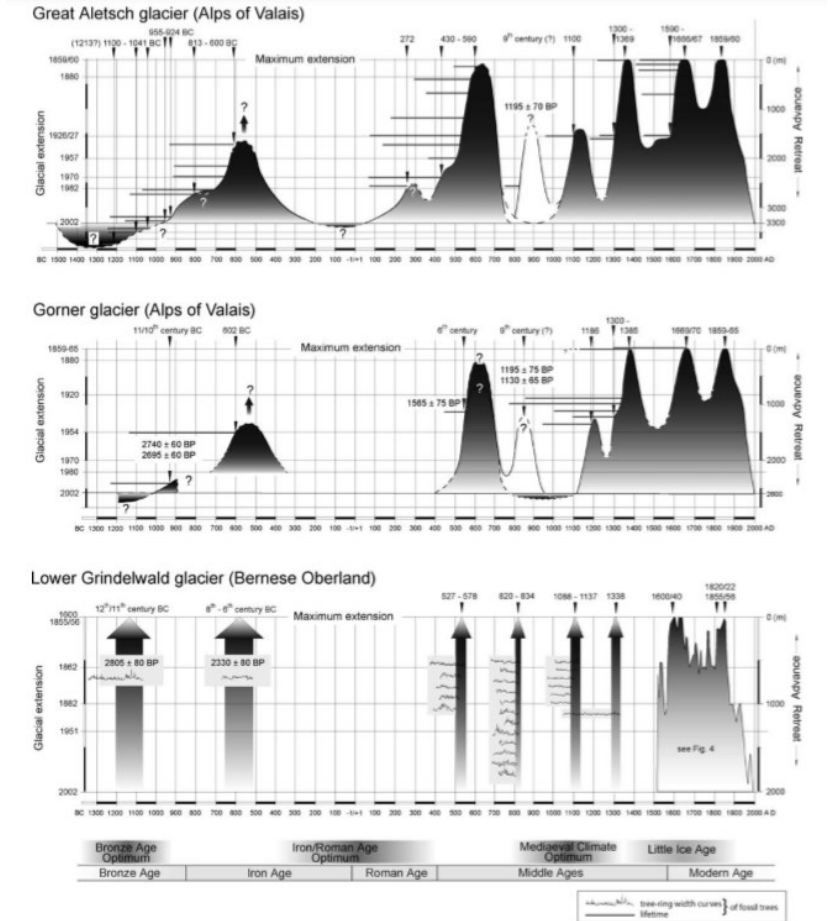
Courbes de variations du nombre d'occupations archéologiques comparée à celle des précipitations et des températures  
(d'après Malrain et al. 2013, source : Büntgen et al. 2011 pour le climat)

## Quel impact des changements climatiques sur la production agricole et la démographie ?

- Recours aux méthodes de modélisation :

-> Modélisation agrosystémique

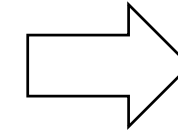
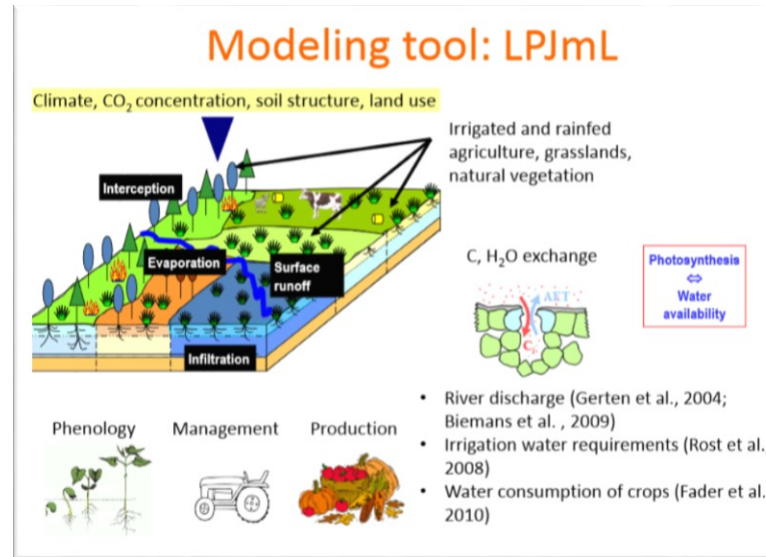
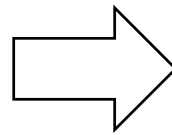
-> Systèmes multi-agents



Fluctuations des glaciers alpins  
(d'après Holzhauser et al. 2005)

## Inputs

- Températures, précipitations, nombre de jours de pluie, nébulosité
- Concentration en CO<sub>2</sub>
- Structure des sols



## Outputs

- Rendements (t/ha, hl/ha), production,
- Cycle du carbone
- Évapotranspiration
- ...

Global Change Biology (2007) 13, 679–706, doi: 10.1111/j.1365-2486.2006.01305.x

### Modelling the role of agriculture for the 20th century global terrestrial carbon balance

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\*Potsdam Institute for Climate Impact Research (PIK), Telegrafenberg, PO Box 601203, D-14412 Potsdam, Germany,

<sup>†</sup>Department of Forest Environment and Resources, DISAFRI, University of Tuscia, I-01100 Viterbo, Italy,

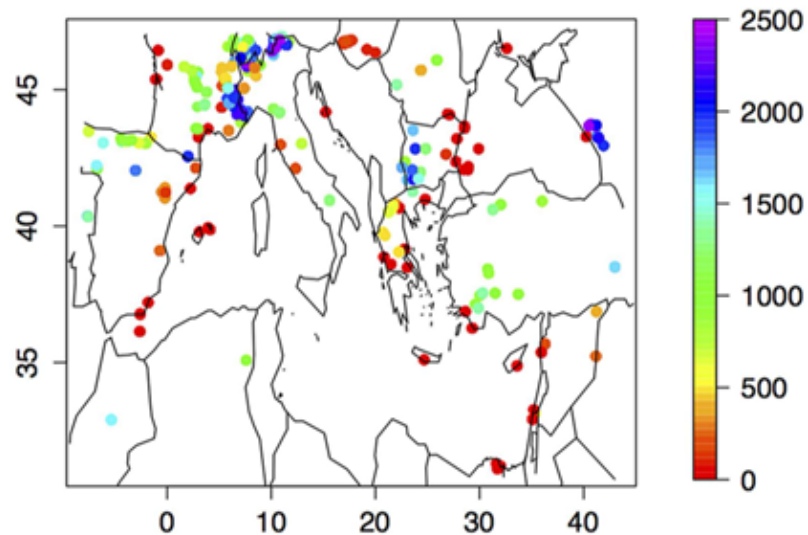
<sup>‡</sup>Department of Physical Geography and Ecosystems Analysis, Geobiosphere Science Centre, Lund University, S-223 62 Lund, Sweden,

<sup>§</sup>International Max Planck Research School on Earth System Modelling, Bundesstr. 53, 20146 Hamburg, Germany

#### Abstract

In order to better assess the role of agriculture within the global climate-vegetation system, we present a model of the managed planetary land surface, Lund-Potsdam-Jena managed Land (LPJmL), which simulates biophysical and biogeochemical processes as well as productivity and yield of the most important crops worldwide, using a concept of crop functional types (CFTs). Based on the LPJ-Dynamic Global Vegetation Model, LPJmL simulates the transient changes in carbon and water cycles due to land use, the specific phenology and seasonal CO<sub>2</sub> fluxes of agricultural-dominated areas, and the production of crops and grazing land. It uses 13 CFTs (11 arable crops and two managed grass types), with

Pollen sites in the Mediterranean region (EPD)



**FIGURE 1 |** Map of the 295 sites used for the reconstruction; the color indicates the elevation of the site.

**ORIGINAL RESEARCH article**

Front. Earth Sci., 18 June 2015 | <https://doi.org/10.3389/feart.2015.00028>

## The Mediterranean Basin and Southern Europe in a warmer world: what can we learn from the past?

 **Joël Guiot**<sup>1\*</sup> and  **David Kaniewski**<sup>2,3</sup>

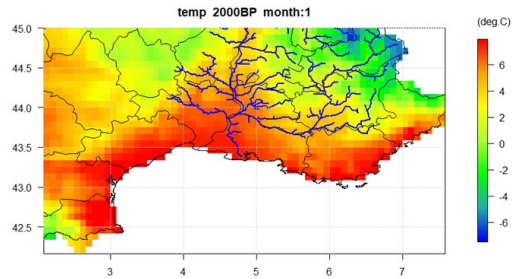
<sup>1</sup>Centre Européen de Recherche et d'Enseignement des Géosciences de l'Environnement UMR 7330 and ECCOREV FR 3098, Centre National de la Recherche Scientifique/Aix-Marseille University, Aix-en-Provence, France

<sup>2</sup>Laboratoire d'Ecologie Fonctionnelle et Environnement, Université Paul Sabatier-Toulouse 3, Toulouse, France

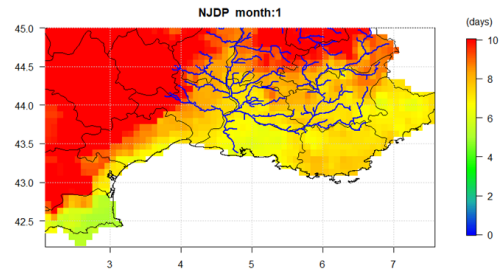
<sup>3</sup>Biology, Health Sciences, Institut Universitaire de France, Paris, France



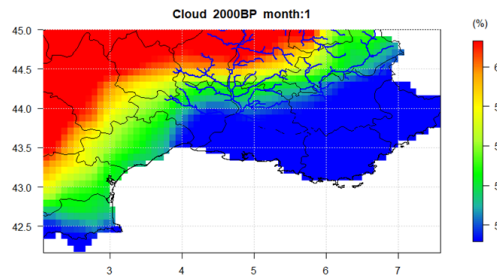
# Using LPJmL for reconstructing agricultural yields of the past



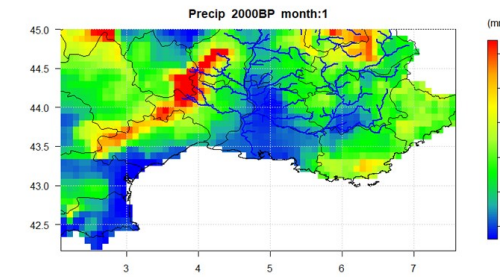
Temperatures



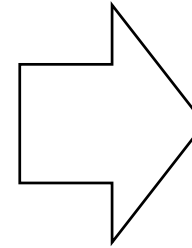
Number rainy days



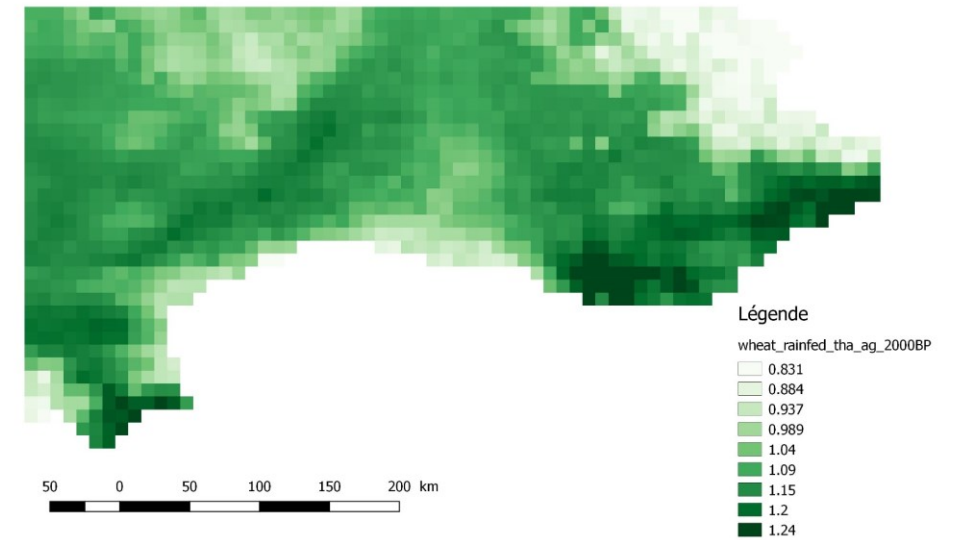
Cloud cover



Precipitations



## Reconstruction of potential yields in 1<sup>st</sup> c. BC



Wheat yield per T/ha (2000 BP)

# Modélisation Lund-Potsdam-Jena managed Land (LPJmL)

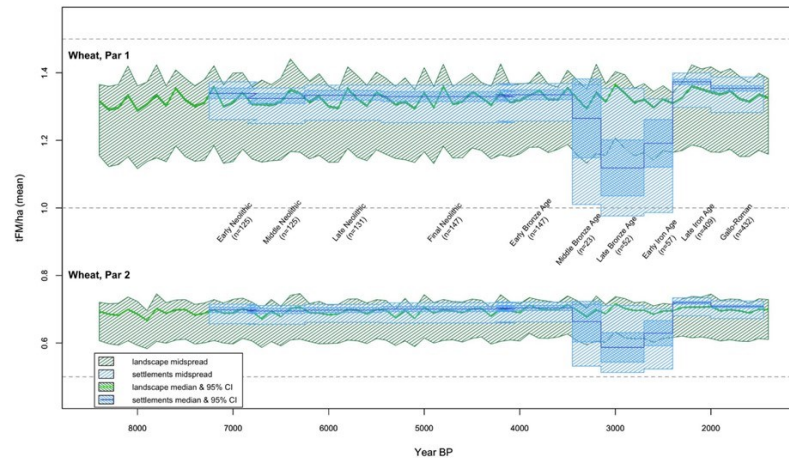
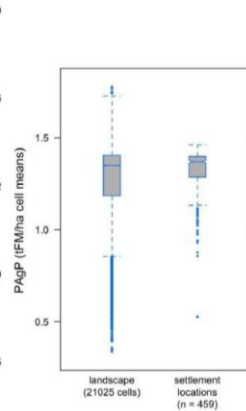
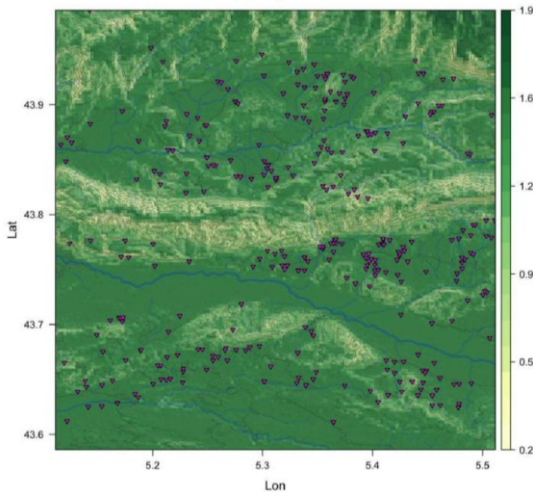


## Adaptation of Mediterranean EcoNOMies of Past to HYdroclimatic changes AMENOPHYS project (2015-2016)



Contreras, Hiriart, Bondeau, Kirman, Guiot, Bernard, Suarez, Van Der Leeuw 2018

mean Potential Agricultural Production (Tfm/ha)  
Occupation & agricultural sites



Quaternary International  
Volume 501, Part B, 20 January 2019, Pages 303-316



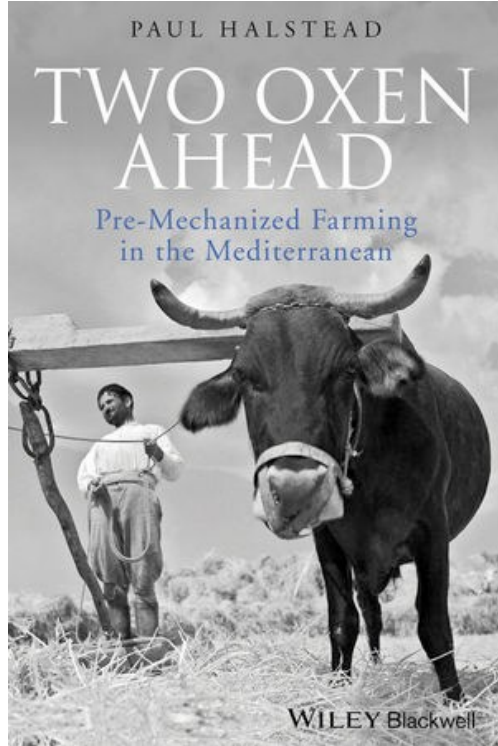
From paleoclimate variables to prehistoric agriculture: Using a process-based agro-ecosystem model to simulate the impacts of Holocene climate change on potential agricultural productivity in Provence, France

Daniel A. Contreras <sup>a, b, c, d, e</sup>, Alberte Bondeau <sup>a</sup>, Joël Guiot <sup>c</sup>, Alan Kirman <sup>d</sup>, Eneko Hiriart <sup>e</sup>, Loup Bernard <sup>f</sup>, Romain Suarez <sup>g</sup>, Marianela Fader <sup>a, h</sup>

Contreras et al. 2019

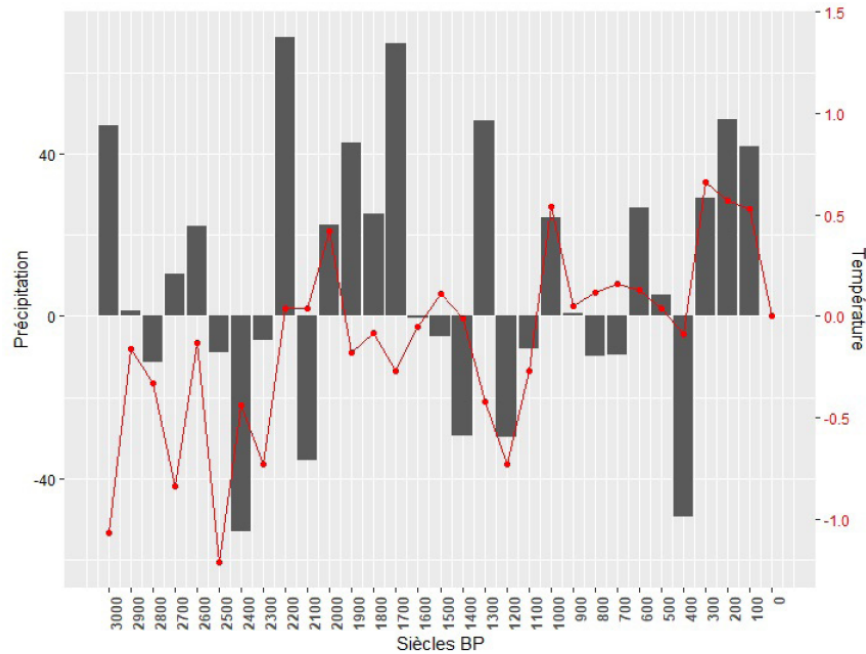
## Mediterranean Farming – estimating pre/proto-historic yields

HALSTEAD, P. 2014. *Two oxen ahead: pre-mechanized farming in the Mediterranean*. John Wiley & Sons.

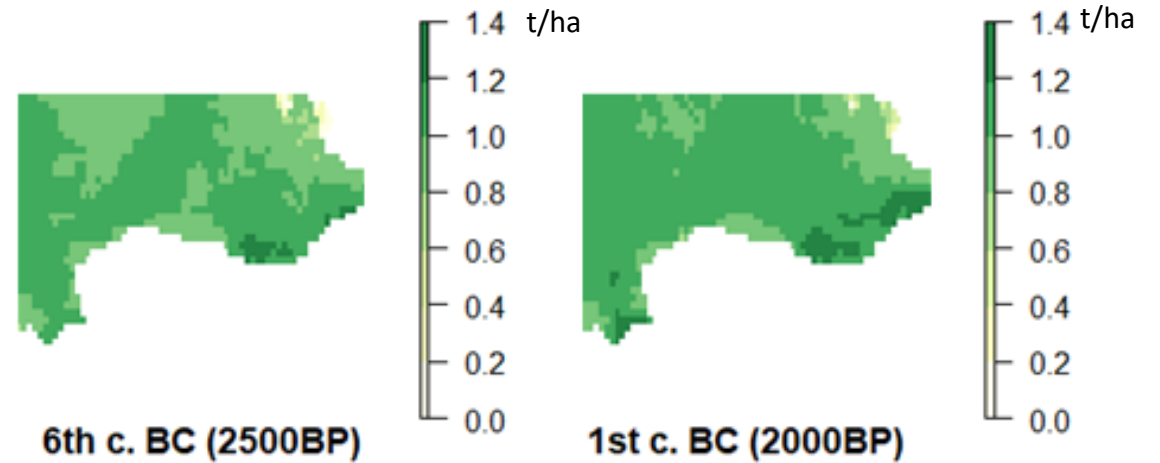


CROP	YIELD ESTIMATE (KG/HA)		SOURCE (P #)	NOTES
	MIN	MAX		
spelt/emmer (dehusked)	1250	2500	239	heavily manured and weeded
emmer (dehusked)	1100	1500	239	lightly manured
einkhorn	500	1250	240	rotated on poor land, unmanured
free-threshing wheat	400	1600 (as high as 7500(!) on freshly-cleared land)	240	depending on fallow, rotation, manuring, and field quality
wheat	250	1900	241	depending on fallow, rotation, manuring, field quality, and weather
barley	410 (rainfed)	1150 (irrigated)	242	manuring varies
winter wheat	630 (rainfed)	1100 (irrigated)	242	manuring varies
cereals generally (estimated range across good and bad years and varying practices)	250	2000	242	

# Centennial variations of WHEAT 's potential yields in t/HA 6<sup>th</sup> c. BC – 1<sup>st</sup> c. BC



Illus. 1 : Écarts par rapport l'actuel des moyennes des températures (en C°) et précipitations (en mm) annuelles par siècle dans le sud de la France (N. Bernigaud à partir des données extraites de Guiot et Kaniewski 2015, point 55).

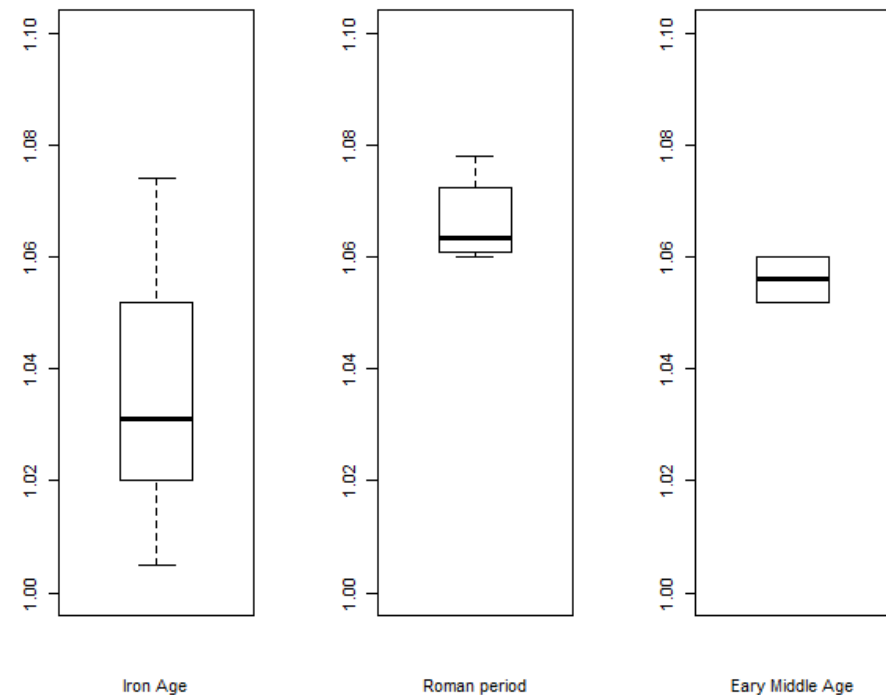
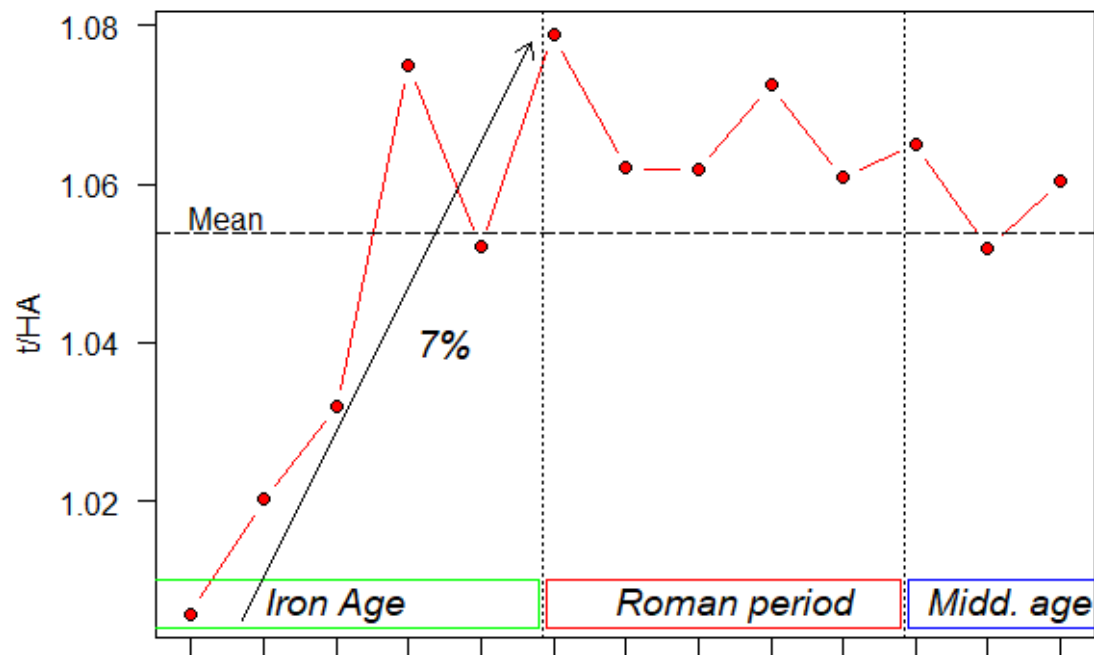


# Centennial variations of WHEAT 's potential yields in t/HA

6<sup>th</sup> c. BC - 7<sup>th</sup> c. AD

- Increase of yields during Iron Age
- Noticeable peak in 3<sup>rd</sup> c. BC
- High yields during Roman period
- Decrease during early Middle age

Centennial average of potential yields of WHEAT in tons/HA



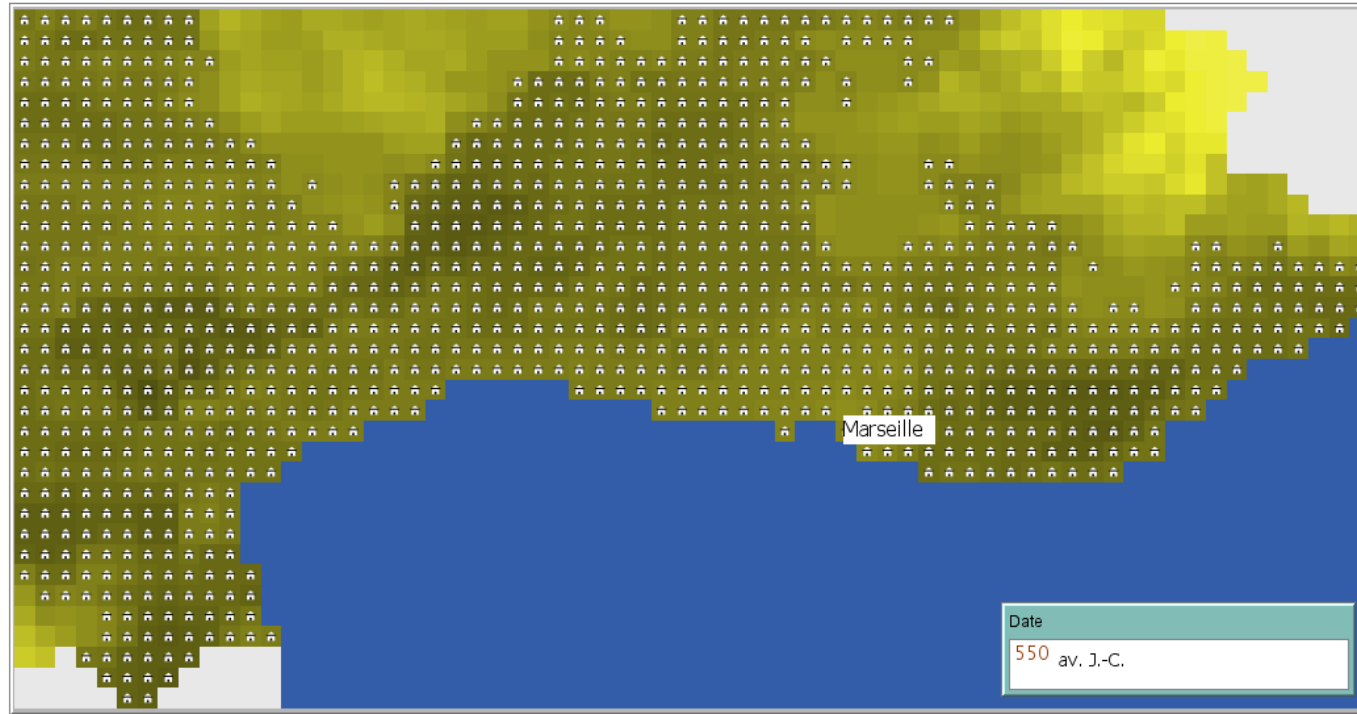
# Agent-based model

# Modèle multi-agents FER-AGRI

2

Culture  
 Wheat rainfed

Century  
 Actual

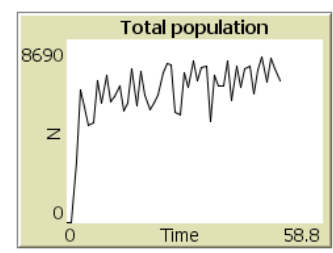


Area/person 0.8 ha/person

Natality\_rate 0.2 %

%\_yields 72 %

Mortality\_rate 0.0 %



Wheat/Person 300 KG

Seasonal Temperatures

Thiv\_ano 0.0 °C

Tprt\_ano 0.0 °C

Tete\_ano 0.0 °C

Taut\_ano 0.0 °C

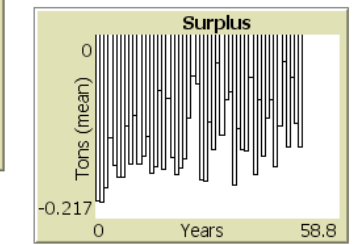
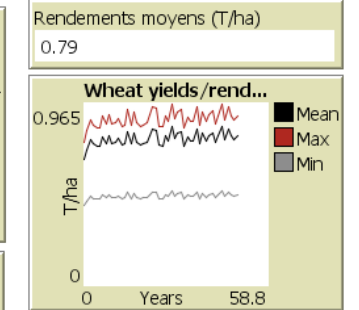
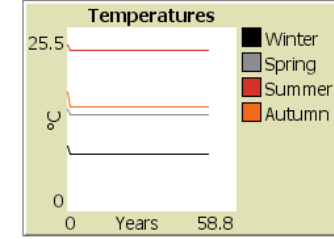
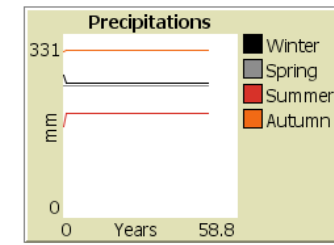
Seasonal Precipitations

Phiv\_ano 1 mm

Pprt\_ano 0 mm

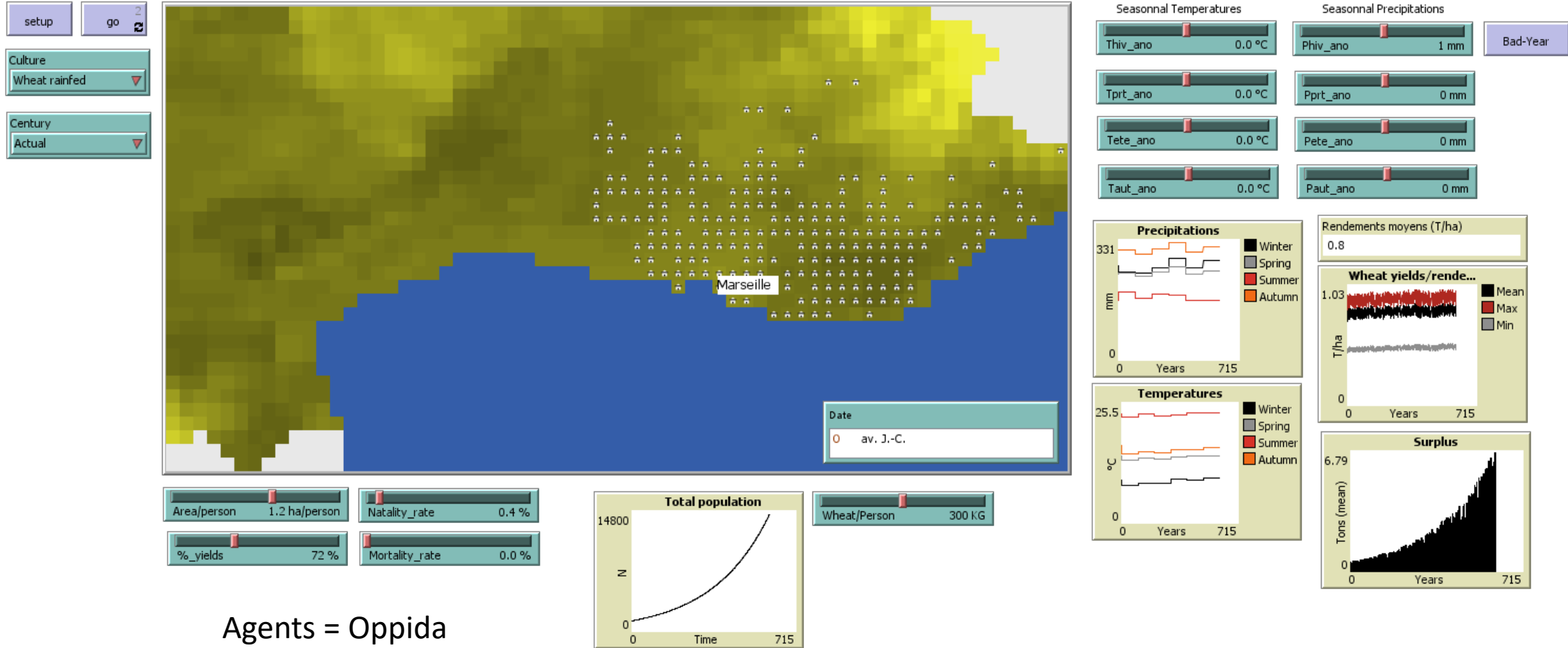
Pete\_ano 0 mm

Paut\_ano 0 mm



# Agent-based model

# Modèle multi-agents FER-AGRI



Agents = Oppida

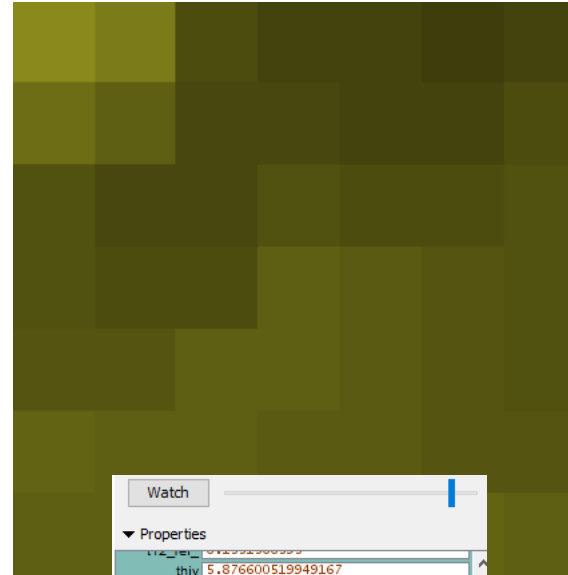
# Fonctionnement de FER-AGRI



## Caractéristiques des exploitations

- Population : 6-50 habitants/exploitation
- Workforce : 1/3 Population
- Nourriture : 200-300 kg/an/personne
- Superficie maximum exploitable/personne : 0,1-2 ha
- Superficie exploitée : Workforce \* Sup. max. exploit./personne
- Production: Superficie exploitée \* rendement (émulation LPJmL)
- Surplus: Récolte annuelle - consommation
- Stock : surplus des 3 dernières années
- Maximum de terres exploitables : rayon de 5 km autour des exploitations

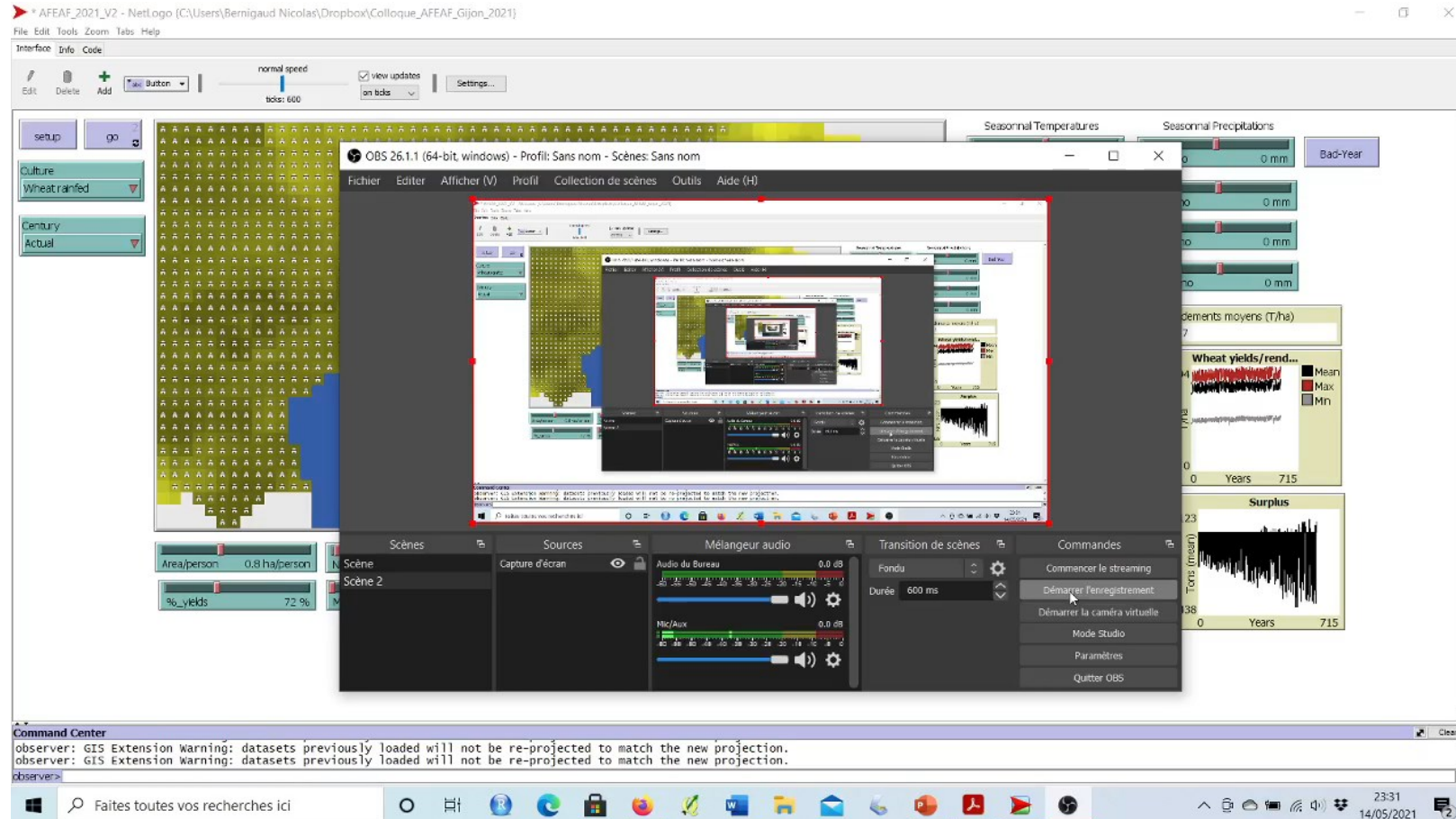
## Patches



Watch	
▼ Properties	
thiv	5.876600519949167
tpri	11.502922230010848
tete	20.744530792929165
taut	13.632039728940043
phiv	346.7258052975247
ppri	219.0145780505273
pete	133.5507937653437
paut	324.053829890577
thiv_var	6.658757704093949
tpri_var	13.03392527000301
tete_var	23.505563082995828
taut_var	15.44642166154583
phiv_var	392.8739276041588
ppri_var	248.16473468838905
pete_var	151.32598750825704
paut_var	367.1843830459476
wr	1.2139676302900493
wr2	0
wr3	0.8740566938088355
gr_2500_	0
gr_2400_	0
gr_2300_	0
gr_2200_	0

- **Exploitations disparaissent si les récoltes et les stocks sont insuffisants pour nourrir les exploitants**
- **Réapparaissent quand le potentiel agricole redevient plus favorable**



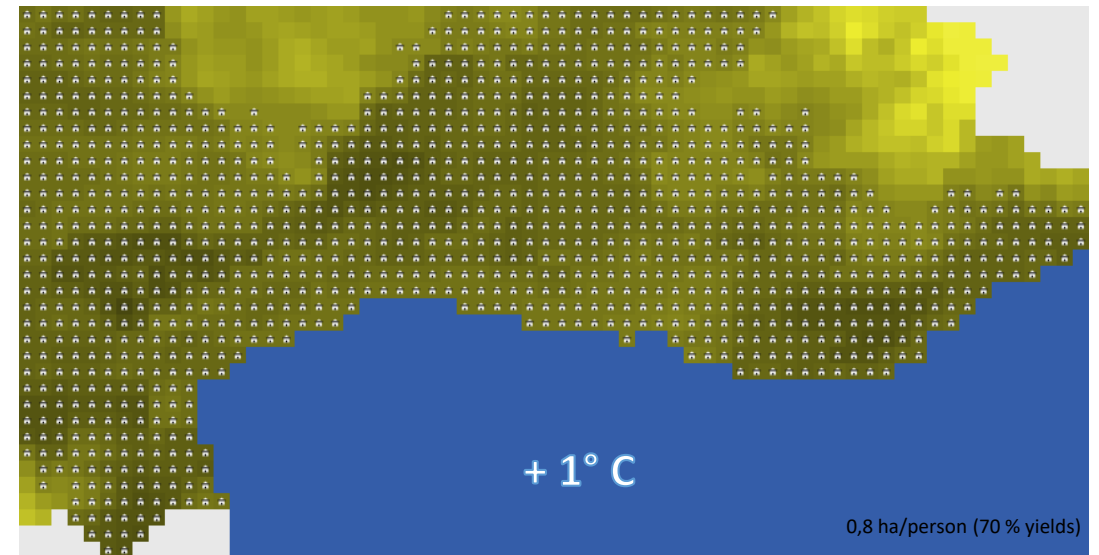
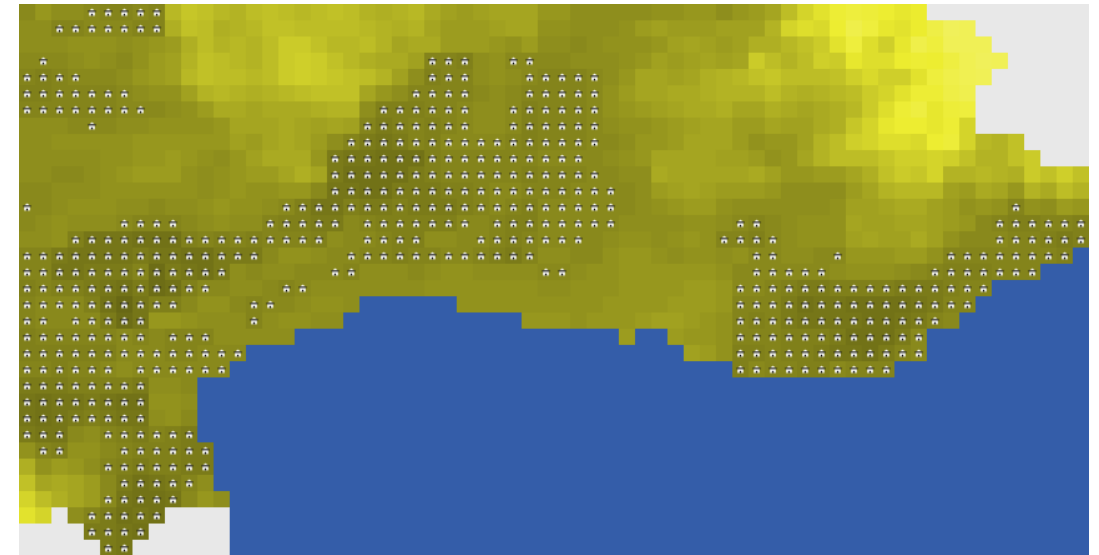


# Quelle sensibilité de la démographie au climat ?



Exploitation

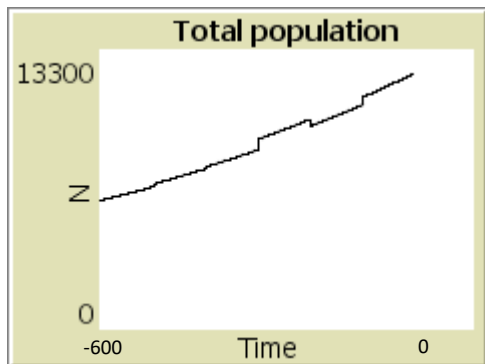
- Variations des rendements et la production de blé plus sensibles aux températures qu'aux précipitations
- Baisse des températures saisonnières = baisse des rendements et de la production (excepté pour les T automnales)



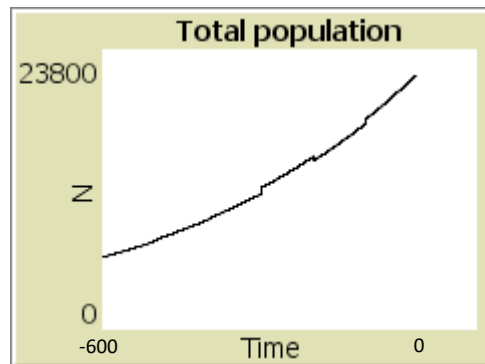
0,8 ha/person (70 % yields)

# Discussion

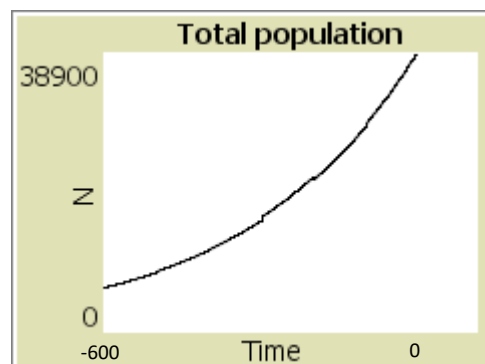
## Ajuster les paramètres grâce aux données archéologiques Quel taux d'accroissement naturel ?



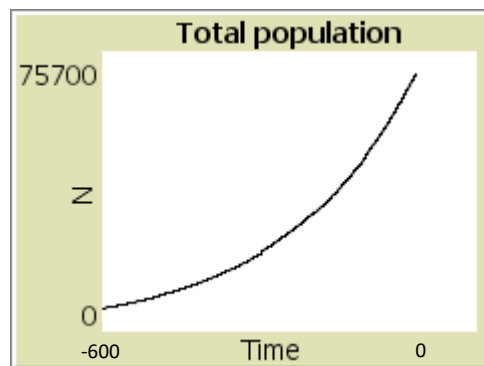
0,1 %



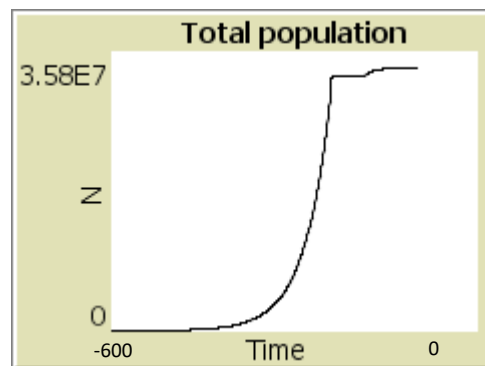
0,2 %



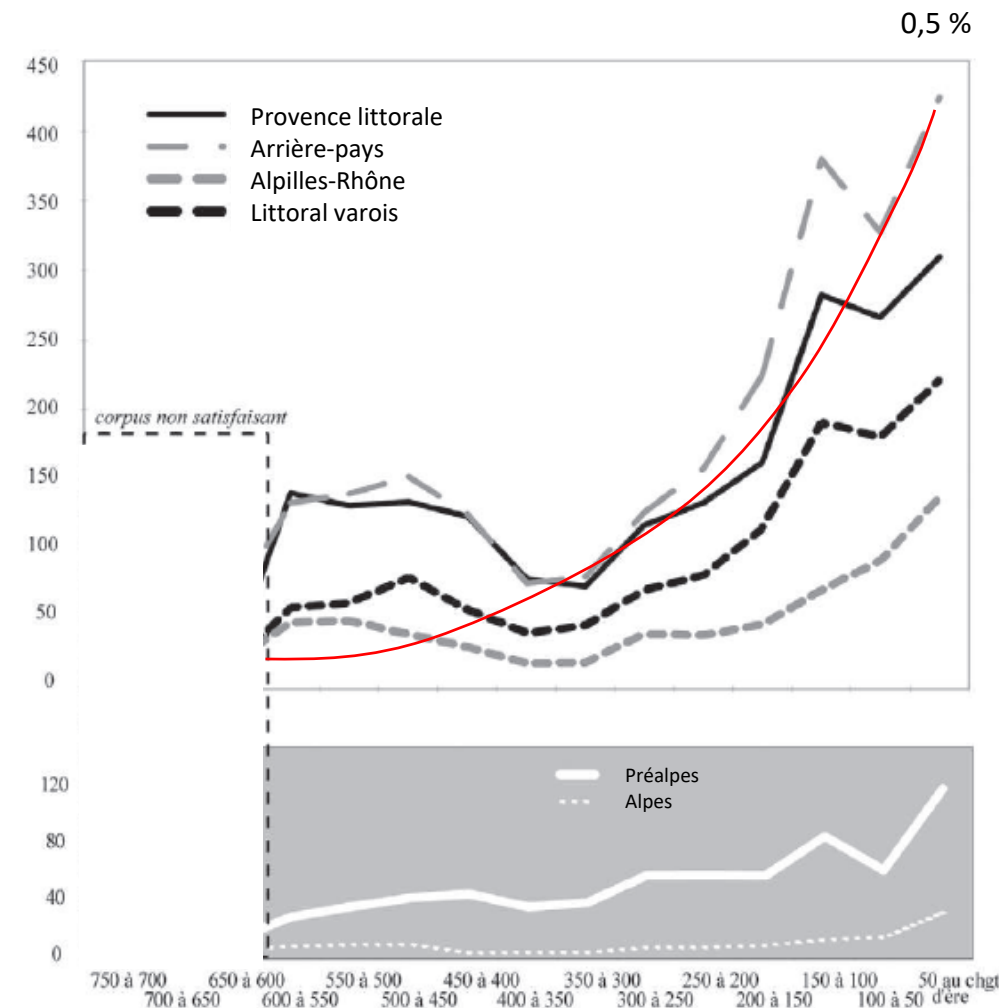
0,3 %



0,5 %

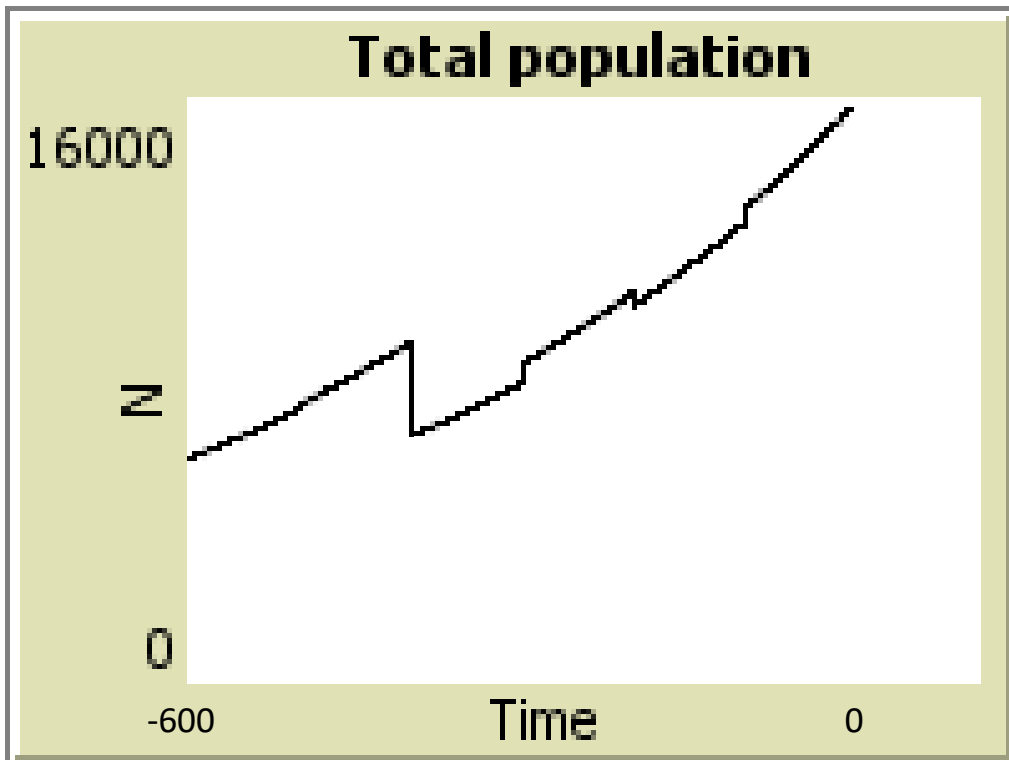


2 %



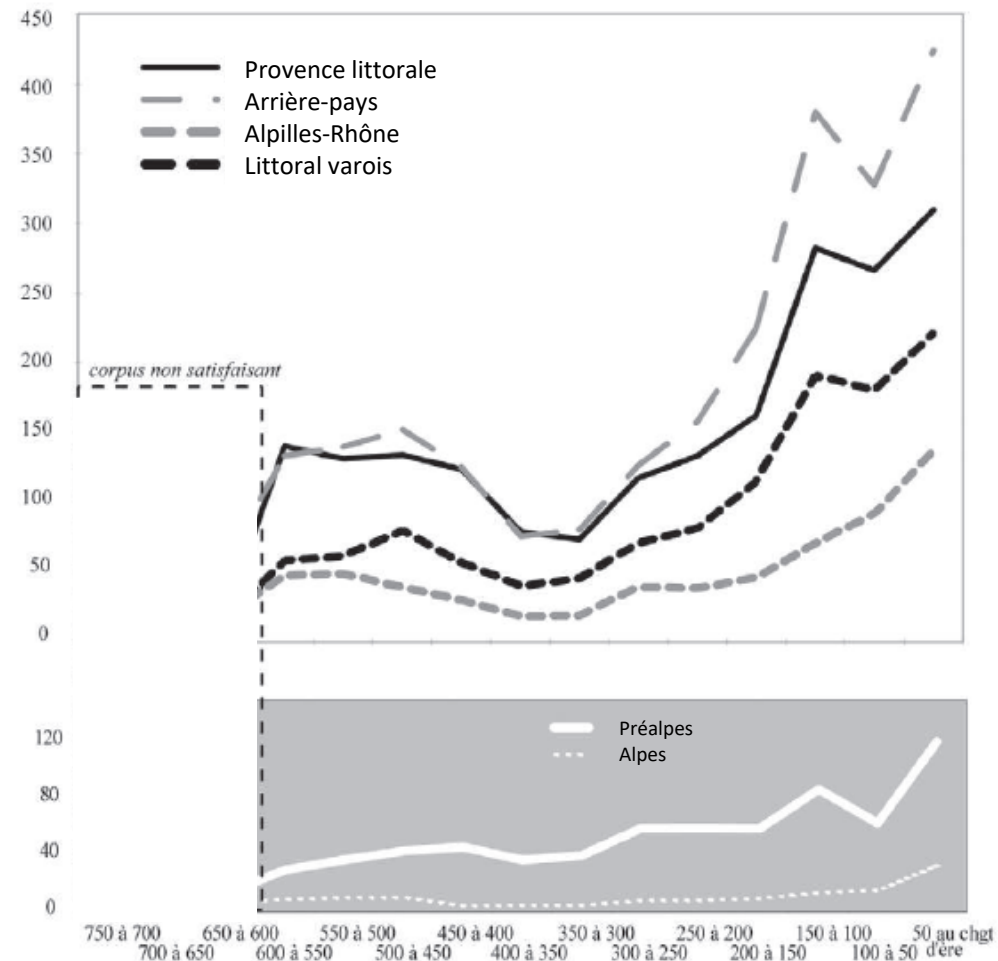
Modélisations archéodémographiques  
(d'après Isoardi 2008)

# Quel impact du climat ?



Avec un rabaissement manuel des T de  
1 °C en 400 av. J.-C.

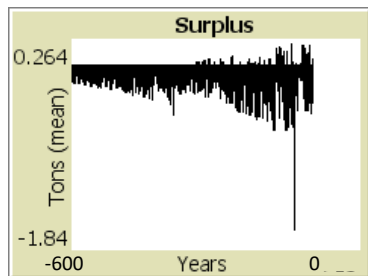
0,2 %



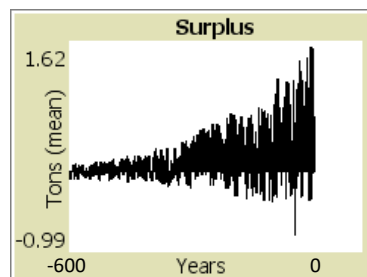
Modélisations archéodémographiques  
(d'après Isoardi 2008)

# Discussion

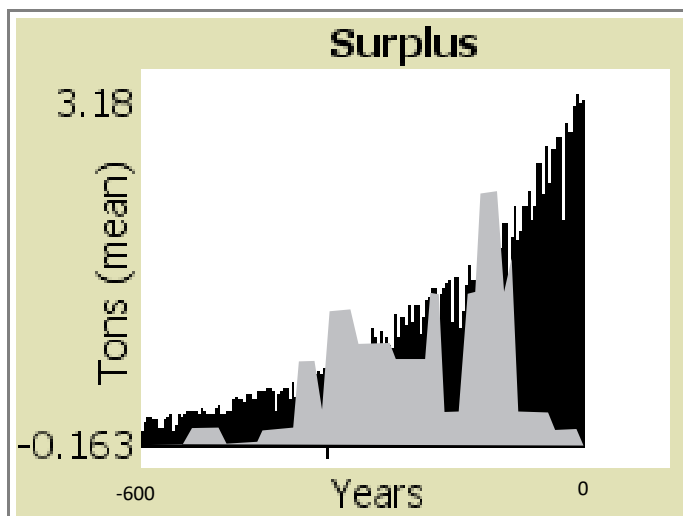
## Surplus agricoles et stockage



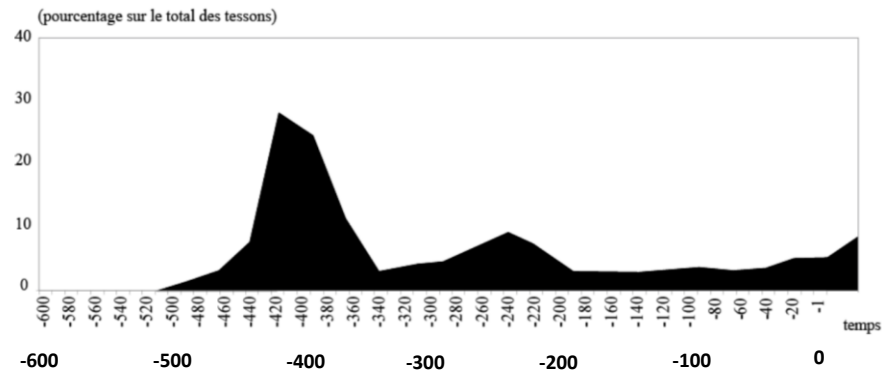
0,8 ha/person



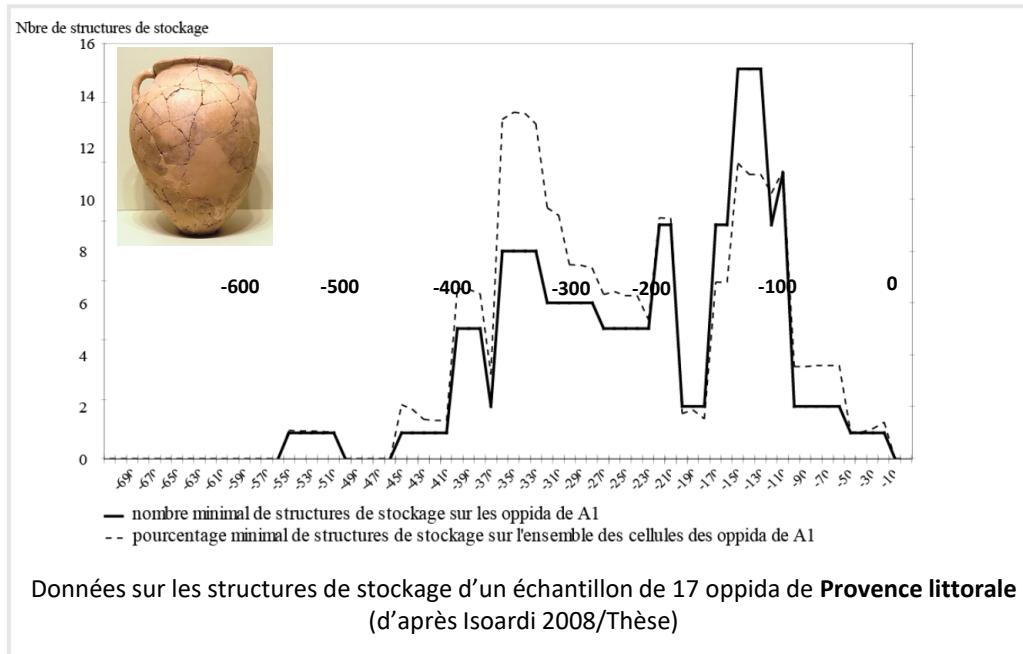
0,9 ha/person



1 ha/person

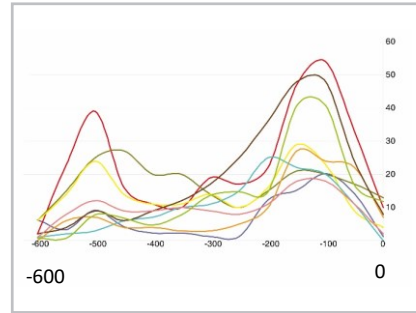
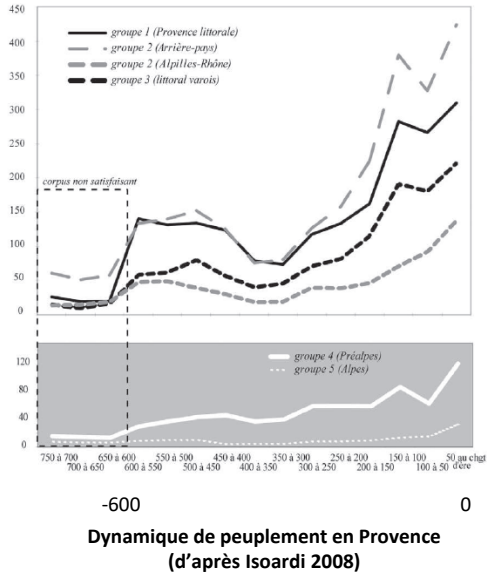


Évolution de la capacité doliare totale en **Languedoc**  
(d'après Garcia 2004)

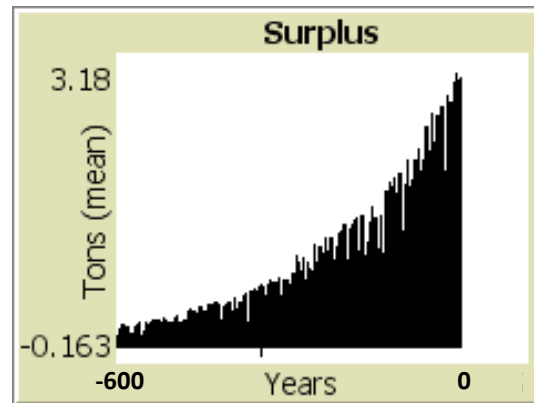
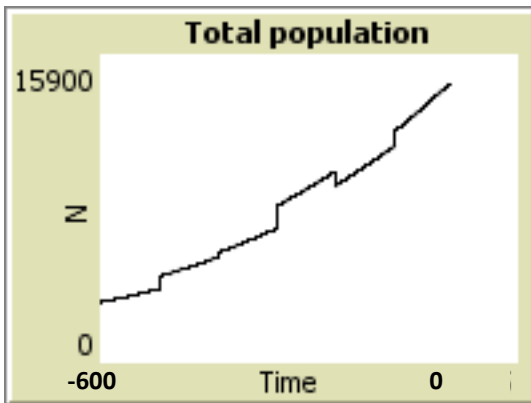


Données sur les structures de stockage d'un échantillon de 17 oppida de **Provence littorale**  
(d'après Isoardi 2008/Thèse)

# CONCLUSION



Dynamique de peuplement dans le nord de la Gaule (d'après Malrain et al. 2013)



- Démographie des populations d'autant plus impactée par les changements climatiques que le taux de croissance est faible
  - Réchauffement climatique + croissance démographique augmente la capacité à dégager des surplus agricoles à partir du III<sup>e</sup> s. av. J.-C.
- > agriculture/démographie moins vulnérable aux aléas climatique
- > facteur favorable à l'émergence des agglomérations urbaines