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Agent-Based Modelling, Archaeology and Paleoenvironment

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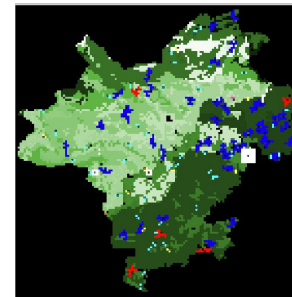
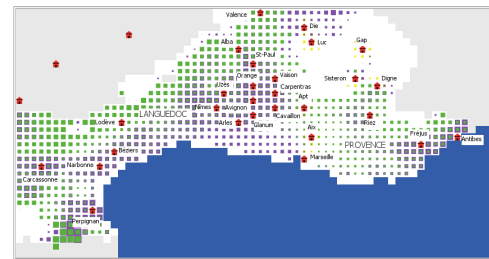
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Agent-Based Modelling, Archaeology and Paleoenvironment:

Assessment and Perspectives for the Study of Past Societies



N. Bernigaud¹, F. Bertoncetto², M.-J. Ouriachi²,
A. Bondeau³, J. Guiot¹

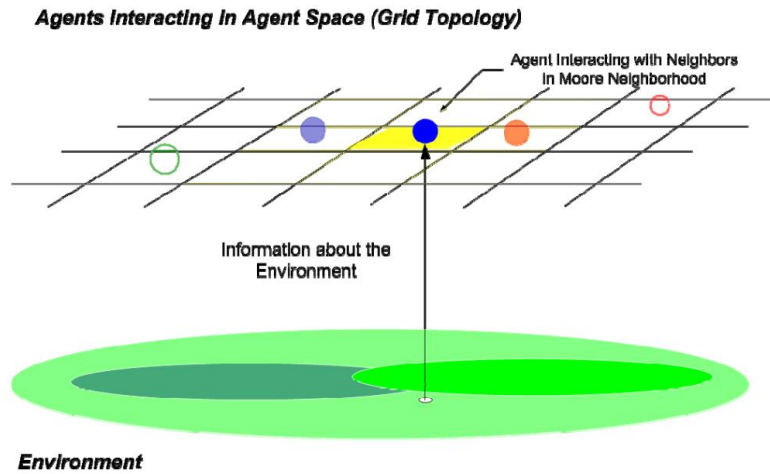
42^e Rencontres Internationales d'Archéologie et d'Histoire de Nice Côte d'Azur, 12-14 octobre 2022

1: CEREGE (Aix-en-Provence), 2: CEPAM (Nice), 3: IMBE (Aix-en-Provence)

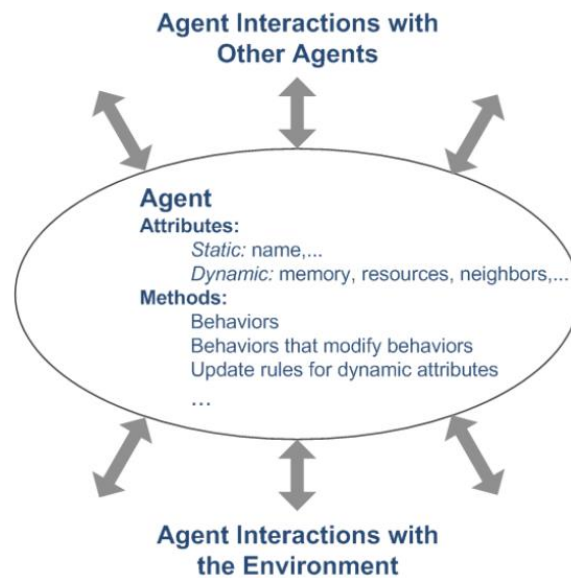
Presentation outline

- I. General principles of ABMs and historiographical overview
- II. Case studies: ModelAnSet, ROMCLIM et FER-AGRI models
- III. Research Assessment and Perspectives for ABMs development

Agent-based modeling (ABM) or Multi-Agent System (MAS): what is this?



General elements of an agent-based model



A typical agent

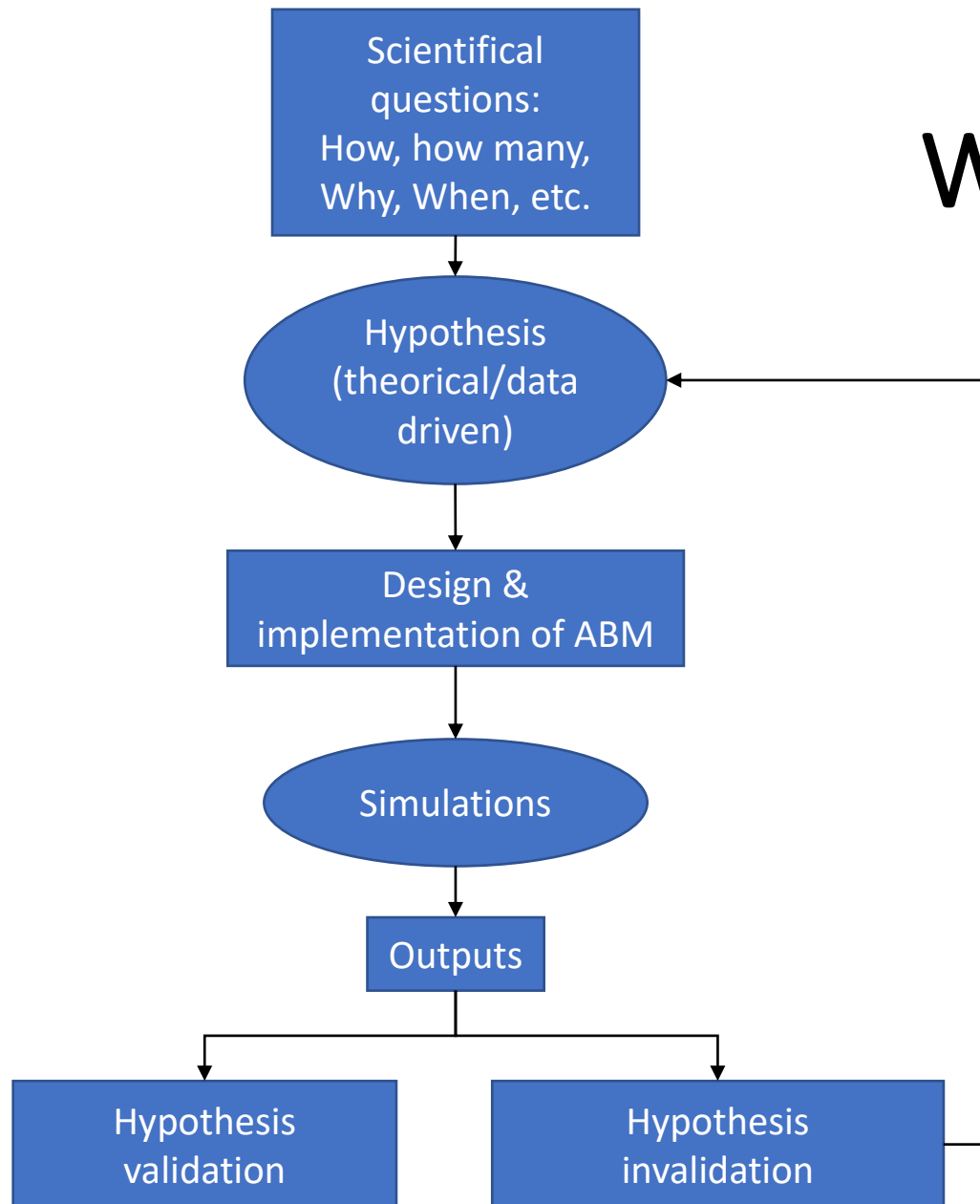
(Figures after Macal and North 2014)

- Software simulating interactions between agents and their environment
- Interactions produce complex phenomena that we are trying to reproduce (or which are 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,...

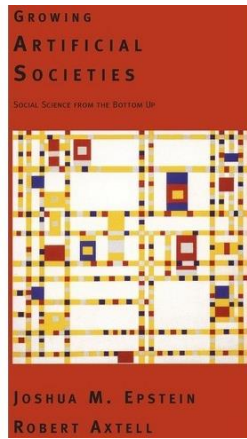
Why using ABM in archaeology ?

ABM: a heuristic tool for testing hypothesis (or a “tool to think”)

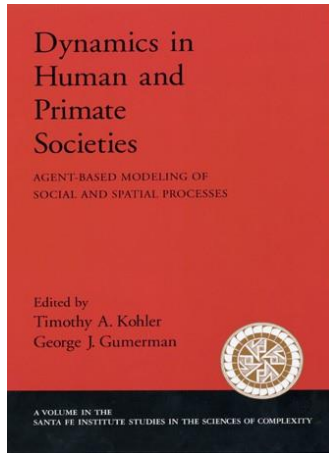
- Understanding the social and environmental causes of changes seen by archaeologists in archaeological records
- Test in ABM theoretical or data driven hypothesis by simulations
- Confronting outputs of the model with archaeological records for validating/invalidating hypotheses
- If all hypotheses are invalidated, try to make a new hypothesis!



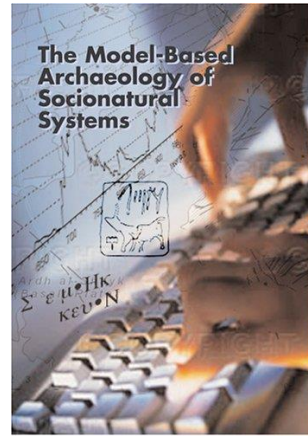
ABM & Archaeology: kick off from USA in the 1990'



Epstein & Axtell 1996



Kohler & Gumerman 2000



Kohler & van der Leeuw 2007

1996

- *Growing Artificial Societies, Social Science from the Bottom Up* (Joshua M. Epstein, Robert Axtell)

2000

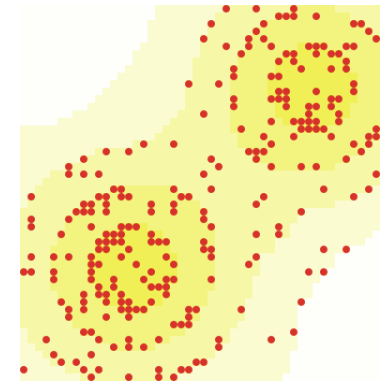
- *Dynamics in Human and Primate Societies, Agent-Based Modeling of Social and Spatial Processes* (Timothy A. Kohler & George J. Gumerman)

2002

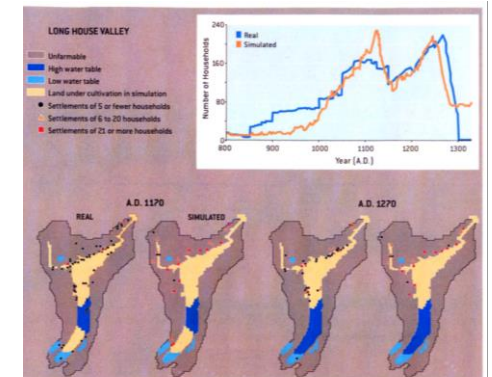
- *Population growth and collapse in a multiagent model of the Kayenta Anasazi in Long House Valley* (Axtell et al. 2002)

2007

- *The Model-Based Archaeology of Socionatural Systems* (Kohler & van der Leeuw 2007)



SUGARSCAPE model
(Epstein & Axtell 1996)



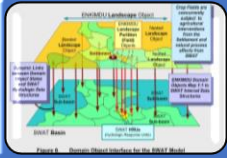
Comparison of Long House Valley simulation results with archaeological evidence.

Artificial Anasazis (AA)
(Axtell et al. 2002)

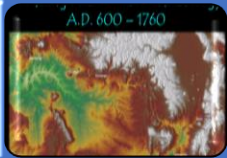
Archaeology & ABMs: socionatural/H.E. perspective



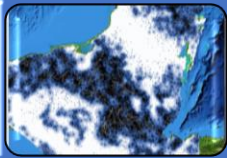
Artificial Anasazi (AA) (Axtell et al. 2002)
<https://ccl.northwestern.edu/netlogo/models/ArtificialAnasazi>



ENKIMDU (Wilkinson et al. 2005)
• Urbanization, Bronze Age Communities, Upper Mesopotamia



The village ecodynamics project (Kohler et al. 2007)
• Modeling Pueblo Historical Ecology
• AD 600-1760



MayaSim (Heckbert 2013)
• Model of the Ancient Maya Social-Ecological System
• Population growth, agricultural production, soil degradation, climate variability, etc.
• <https://www.comses.net/codebases/3063/releases/1.2.0/>



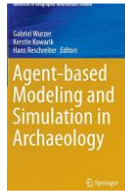
Medland Modeling laboratory (MLL) (Barton et al. 2017)
• Agents: small-holder agropastoral households
• Simulates changes in erosion/deposition, soils & vegetation
• <https://www.comses.net/codebases/4609/releases/1.1.0/>



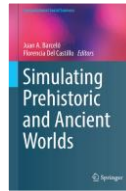
THE INDUS VILLAGE (Angourakis et al. 2022)
Impact of Climate Change on Indus civilization (2500-1900 BC)
• Weather, Land and Crops in the Indus Village Model, A simulation Framework for Crop Dynamics under environmental variability and Climate Change in the Indus Civilisation
• TwoRains project

- Complexity of human-environment dynamics (Human Ecodynamics)
- Understanding interactions between societies and environment as factor of evolutions/transformations
- Identify the internal and external causes of these changes: social, cultural, demographic and environmental factors (climate, erosion, vegetation, etc.)

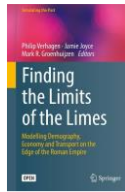
ABM & Archaeology in Europe: awakening since 2010'



Agent-based Modeling and Simulation in Archaeology
(Wurzer, Kowarik, Reschreiter 2015)



Simulating Prehistoric and Ancient Worlds
(Barceló & Del Castilla 2016)



Finding the Limits of the Limes
(Verhagen, Joyce, Groenhuijzen 2019)



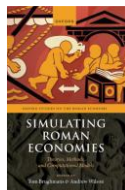
Integrating Qualitative and Social Science Factors in Archaeological Modelling
(Saqalli & Vander Linden 2019)



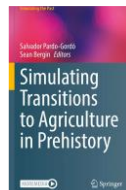
Settling the World, from Prehistory to Metropolis area
(Sanders 2021)



[Agent-based modeling for Archaeology]
(Romanowska, Wren, Crabtree 2021)



Simulating Roman Economies
(Brughmans & Wilson 2022)



Simulating Transitions to Agriculture in Prehistory
(Pardo-Gordo & Bergin 2022)

Computer Applications and Quantitative Methods in Archaeology (CAA)

•2018 « Human History and Digital Future »

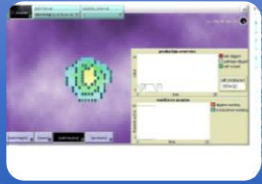
European Association of Archaeologists (EAA)

▪2020 # 415 « From Abacus to Calculus. Computational Approaches to Roman Economy » (I. Romanowska, Ph. Verhagen)

▪2021 # 367 « Agent-Based Modelling of socioecological Systems in Archaeology Towards a New Research Community » (D. Daems)

- **NASSA** (Network for Agent-based modelling in Socio-ecological Systems in Archaeology) (Coord. Dries Daems)
 - Collect and compile ABM code elements
 - Organize them as an openly accessible modelling library

Archaeological ABMs in Europe: some examples



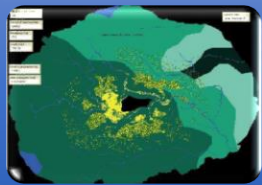
Mining with Agents (Kowarik et al. 2008)

- How mine of salt were exploited in Hallstatt in Bronze Age ?



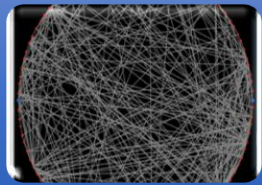
Patagonian Hunter-gatherers (Barceló et al. 2010)

- Emergence of ethnicity & cultural differentiation



“Celtic Oppida” (Cimler et al. 2012,)

- Hypotheses related to agricultural practices around Celtic oppida, Carrying capacity, population growth



MERCURY (Brughmans & Poblome 2015)

- Market Economy and Roman Ceramics Redistribution

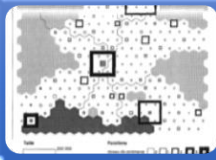


ROMFARM (Joyce 2019, Verhagen 2022)

- Modelling Agricultural Strategies in the Dutch Roman Limes

- **Varied periods:** Prehistory, Bronze Age, Roman period,...
- **Varied topics:** Salt Mining, Agriculture, Social phenomenon, Roman Economy
- Not really a socionatural perspective for most models

Agent-Based Models



SimPop (Guérin-Pace et al. 1993, Pumain et al. 1995)

- Settlement pattern evolution
- Genesis of urban phenomenon in southern France



OBRESOC/ BEAN (Bocquet et al. 2015, Dubouloz et al. 2017, Zanotti 2016)

- Spread of agriculture/LBK culture in Europe in early Neolithic
- [ANR OBRESOC]



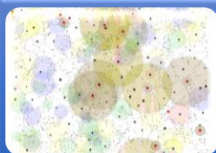
AmphorABM (Crabtree 2016)

- Modeling the Trade of Wine in the Bronze to Iron Age Transition in Southern France
- [ANR TransMonDyn]



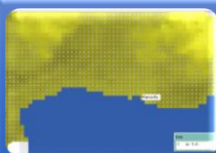
ModelAnSet (Bertoncello et al. 2018)

- Settlement pattern and dynamics during the Roman period in South-Eastern France (impact of social & environmental factors)



SIMFEODAL (Cura 2020, Tannier et al. 2020)

- Concentration of settlement in Middle Age
- [ANR TransMonDyn]



ROMCLIM/FER AGRI (Bernigaud et al. 2022)

- Impact of Climate Change on gaulish and roman societies in southern Gaul
- [RDMed project]

I- General principles, historiographical overview

ABM in France: geographers open the path

Research programs

ANR OBRESOC (2009-2011)

- Trajectoire du Néolithique Rubané
- Coord. J.-P. Bocquet-Appel

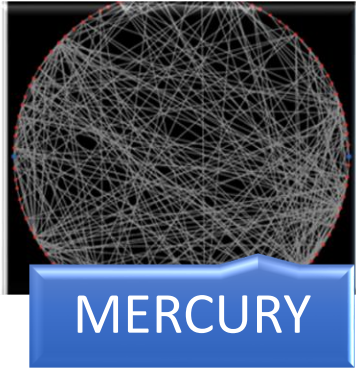
ANR TransMonDyn (2011-2014)

- Modéliser les grandes transitions de l'évolution du peuplement dans l'Ancien et le Nouveau Monde
- Coord. L. Sanders

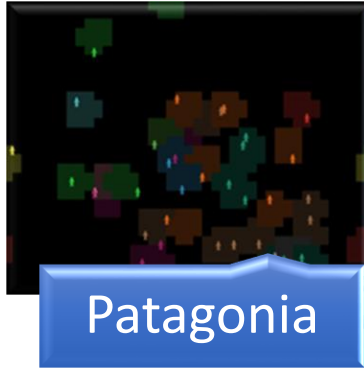
Project A*Midex RDMed (2018-2020)

- Resilience and Adaptation to Droughts and Extreme Climate Events in the Mediterranean
- Coord. J. Guiot

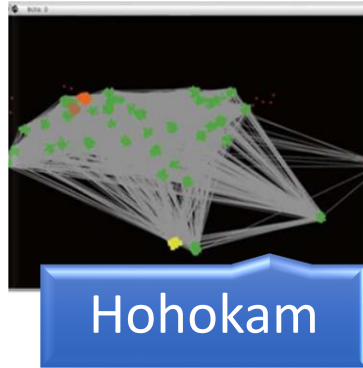
■ Still few models!



MERCURY

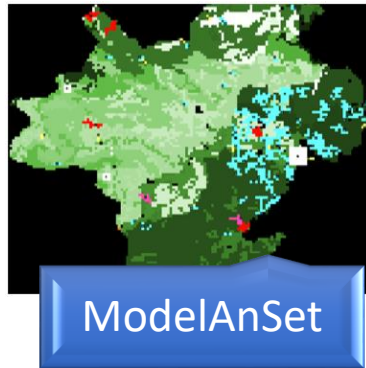


Patagonia

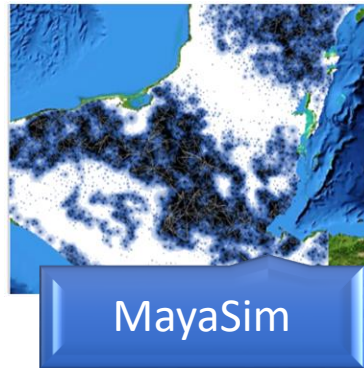


Hohokam

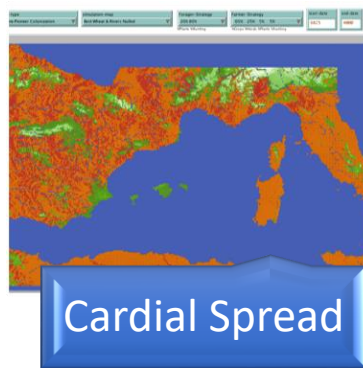
Examples of models without realistic space



ModelAnSet



MayaSim

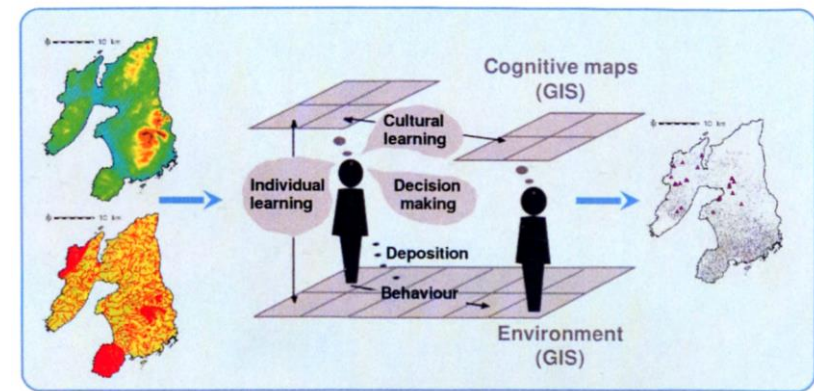


Cardial Spread

Models importing GIS files

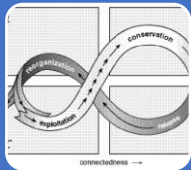
Coupling ABM & GIS

- Incorporating a « realistic » geographic space & environments by importing GIS files (raster, vectors)
- Topography (DEM), hydrology, geology, soils, climate, etc.
- Agents (humans/animals) can have a cognitive knowledge of their environment



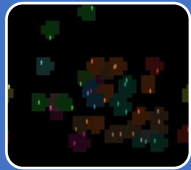
Lake 2000

Main topics for ABMs



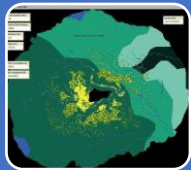
Trajectories of ancient societies (Human Ecodynamics/socionatural approach)

- Societal & Environmental causes [e. g. Artificial Anasazi (AA), ENKIMDU, MayaSim, ModeAnSet, etc.]
- Impact of climate change [e. g. BACO, ROMCLIM, FERAGRI]



Social dynamics (Anthropological & Ethnoarchaeological approach)

- Origin and genesis of social inequality
- Hierarchization of societies
- Ethnogenesis [Prehistoric Patagonia]
- Conflicts



Subsistence strategy & Ressources management (Archaeological/Quantitative approach)

- Prehistoric Hunters-Gatherers [e. g. Central place foraging (CPF)]
- Agricultural systems [e.g. AA, Celtic Oppida, Romfarm, etc.]
- Ressources exploitation & management: salt [Mining with Agents], water [Hohokam water management], etc.



Settlement Pattern genesis (geographical/archaeological approach)

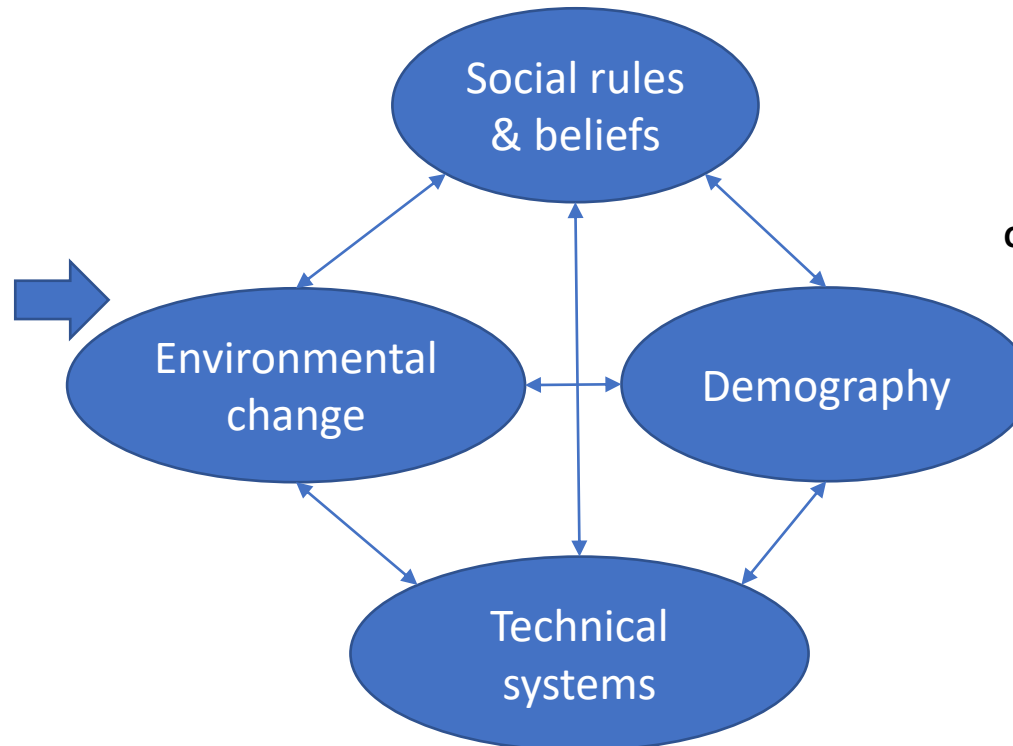
- Genesis of Settlement Pattern [e. g. TravellerSim]
- Genesis of urban phenomenon [e.g. SimPop]
- Concentration of habitat [e. g. SIMFEODAL]



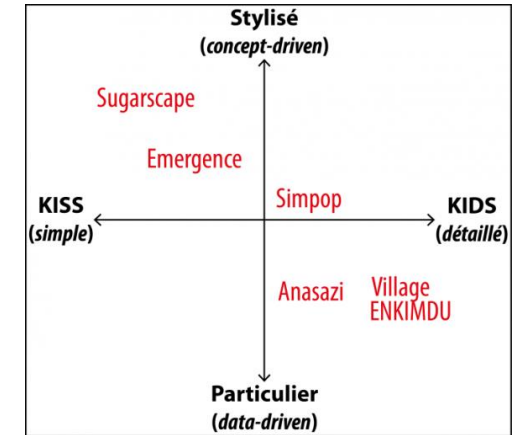
Spreading, circulation & exchanges phenomena (geographical/archaeological/historical approach)

- Populations/archaeological cultures [e. g. OBRESOC/BEAN, CARDIAL SPREAD MODEL]
- Artifacts
- Plagues [e. g. The Antonine Plague]
- Commercial exchanges [e.g. MERCURY]

Main factors modelled



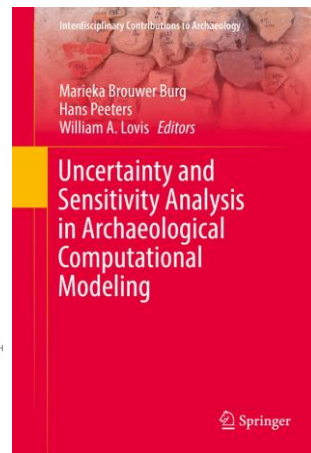
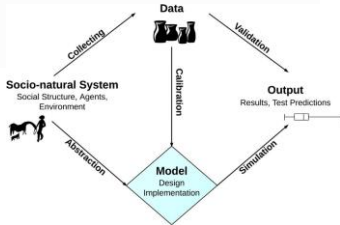
Modelling approaches



Classification (Schmitt & Pumain 2013)

From KISS to KIDS – An ‘Anti-simplistic’ Modelling Approach

Bruce Edmonds & Scott Moss



ABM & Archaeology: main issues & progress

From KISS to KIDS – ‘An Anti-simplistic’ Modelling Approach
(Edmonds & Moss **2004**)

The Complexities of Agent-Based Modeling Output Analysis
(Lee et al. **2015**)

<https://www.jasss.org/18/4/4.html>

Uncertainty and Sensitive Analysis in Computational Modeling
(Brouwer Burg, Peeters, Lovis **2016**)

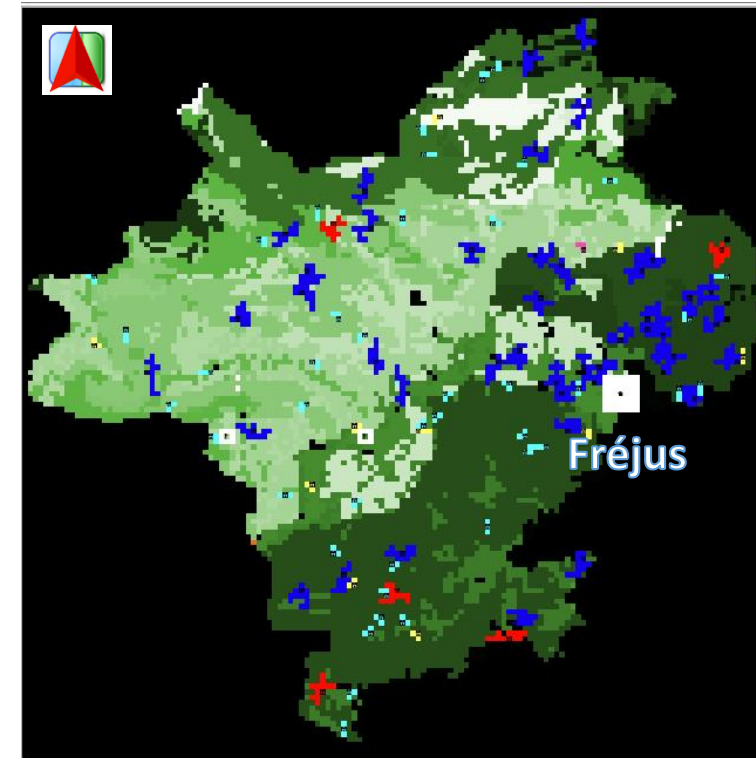
Rethinking the Role of Agent-Based modeling in Archaeology
(Cegielski & Rogers **2016**)

- Building a simple or a complex model? (KISS vs KIDS approach)
 - Opacity of models (« Black boxes »)
 - How evaluate the performance and the outputs of a model?
-
- Protocol « Overview, Design, Details » (ODD)
 - Open Source Repositories:
 - <https://github.com/>
 - <https://www.comses.net/>
 - Sensitive Analysis (SA)

ModelAnSet: a socio-environmental Model

- **ModelAnSet** simulates the processes of creation, growth, abandonment or maintenance of the rural settlements
- **Agents:**
 - 3 types of landowners [**FARMERS**] [**BIG LANDOWNERS**], [**ARISTOCRATS**] with different economic power, social status and behavior
 - 2 types of agricultural settlement [**FARM**] [**VILLA**]
- **Model dynamics:**
 - The profit made by each settlement depends on its environmental context, which is influenced by the climatic conditions, and on the transportation cost to the nearest marketplace
 - According to their economic power and to the profit they derive from each of their settlements, landowners decide to maintain, enlarge, improve or abandon it, or to create a new farm/villa

Explore the respective roles of social & environmental factors in the settlement pattern and dynamics during the Roman period in the roman city of **Forum Julii (Fréjus, Var)**



Settlement pattern

- Forum Julii (Capital of city)
- 1: Aristocratic villa
- 2: Aristocratic farm
- 3: Big Landowner villa
- 4: Big Landowner farm
- 5: Farm



Instanciation of the model: the territory of the Roman colony of *Forum Iulii* (Fréjus, Var, France) (Bertoncello et al. 2018)

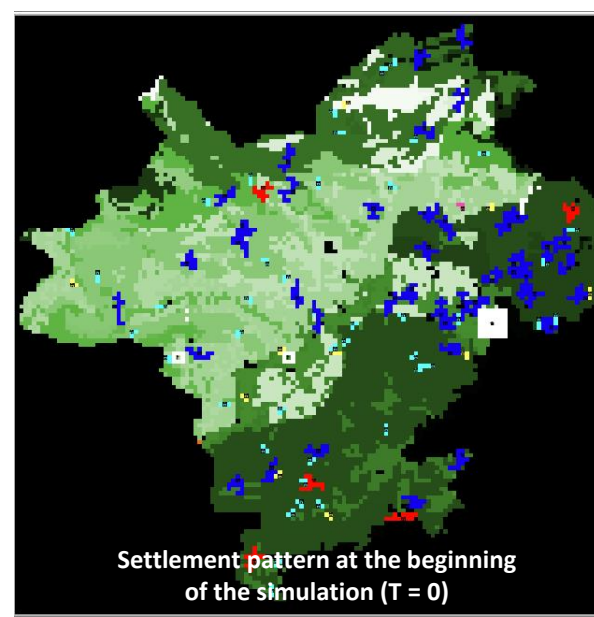
ModelAnSet: a socio-environmental Model

- According to their social status (farmer, big landowner, aristocrat), **landowners have different behaviour (spatial, symbolic) and perceptions** (of land fertility, of the macro-economic context)

⇒ The repeated landowners' decision-making produces a changing macro-level settlement pattern, in terms of number, type and location of the settlements

Needed improvements:

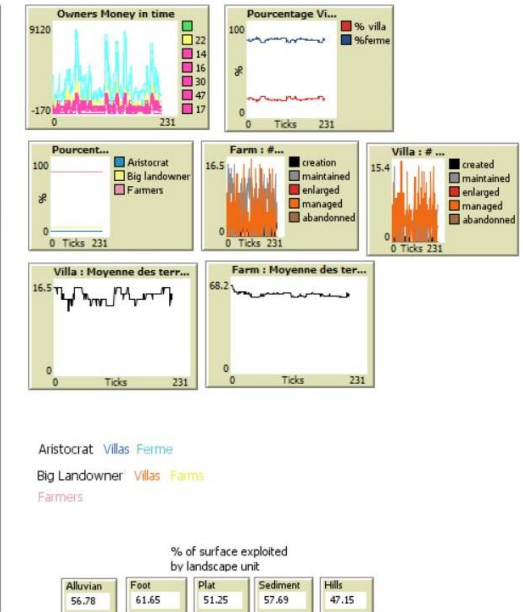
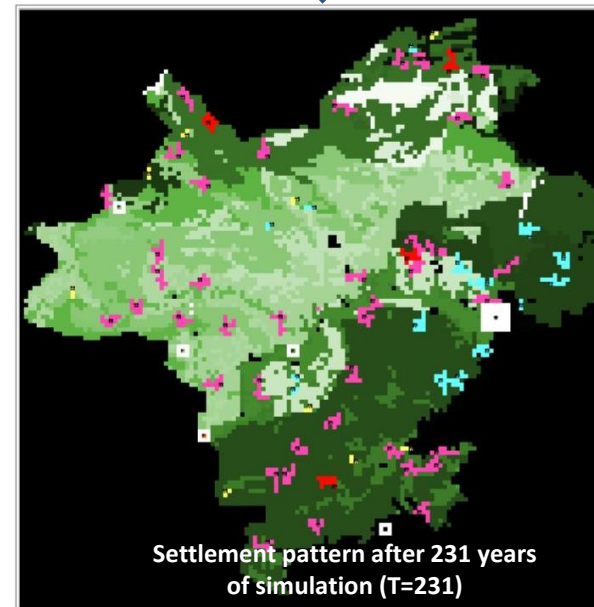
- Introduce “cognitive agents” (vs “reactive agents” acting according to fixed rules) who can diversify their actions according to their beliefs (about themselves and about their environment)
- Refine the calculation of the settlement's profit
- More accurate simulation of the climate impacts on the agricultural yield



II- Case studies

Settlement pattern

- Capital of city
- 1: Aristocratic villa
- 2: Aristocratic farm
- 3: Big Landowner villa
- 4: Big Landowner farm
- 5: Farm

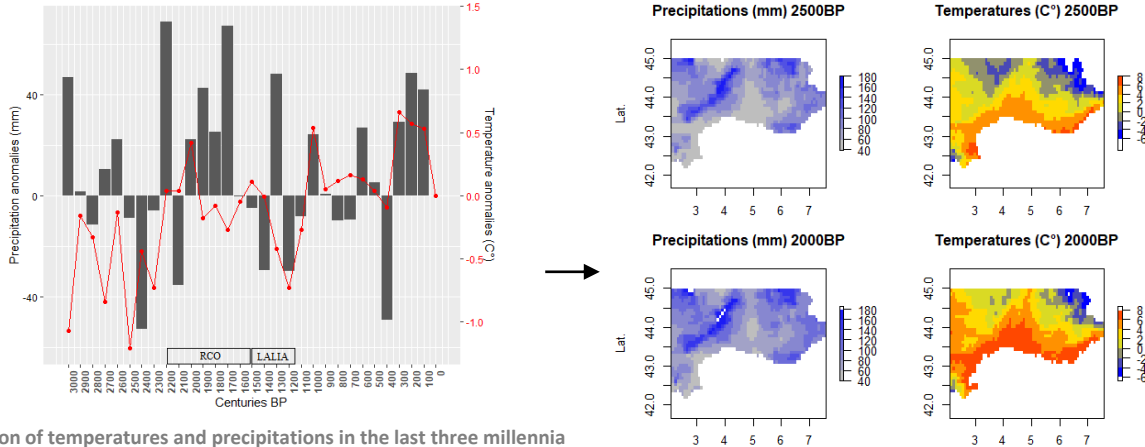


(Bertoncello et al. 2018)

ROMCLIM: a socio-climate Model

- **ROMCLIM** simulates the evolution 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) are calculated by an emulation the agro-ecosystemic model **LUND-POTSDAM-JENA-MANAGED-LAND (LPJML)**
- **Paleoclimatic data** needed by LPJmL are processed for each century between the VIth c BC and the VIIth PC from an actual climate reconstruction (ALADIN) modified with paleoclimatic anomalies (from Guiot & Kaniewski 2015)

Did the Roman Climate Optimum (RCO) boost the economy of the Roman Empire?






Evolution of temperatures and precipitations in the last three millennia (data extracted from Guiot & Kaniewski 2015)

Spatial reconstruction of temperatures and precipitations in southern Gaul in VIth c. BC (2500 BP) and Ist c. BC(2000 BP)

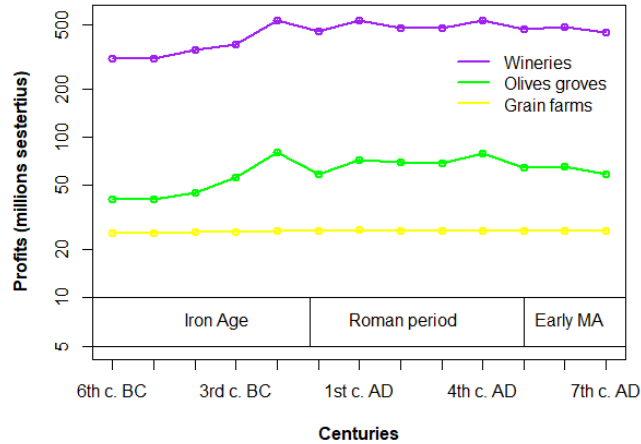
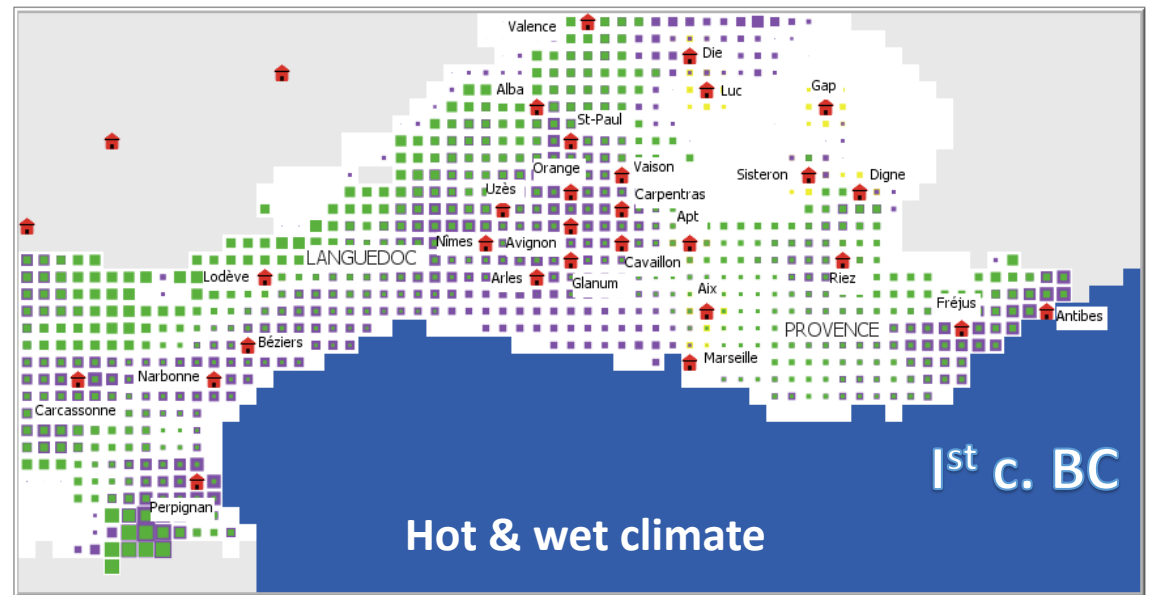
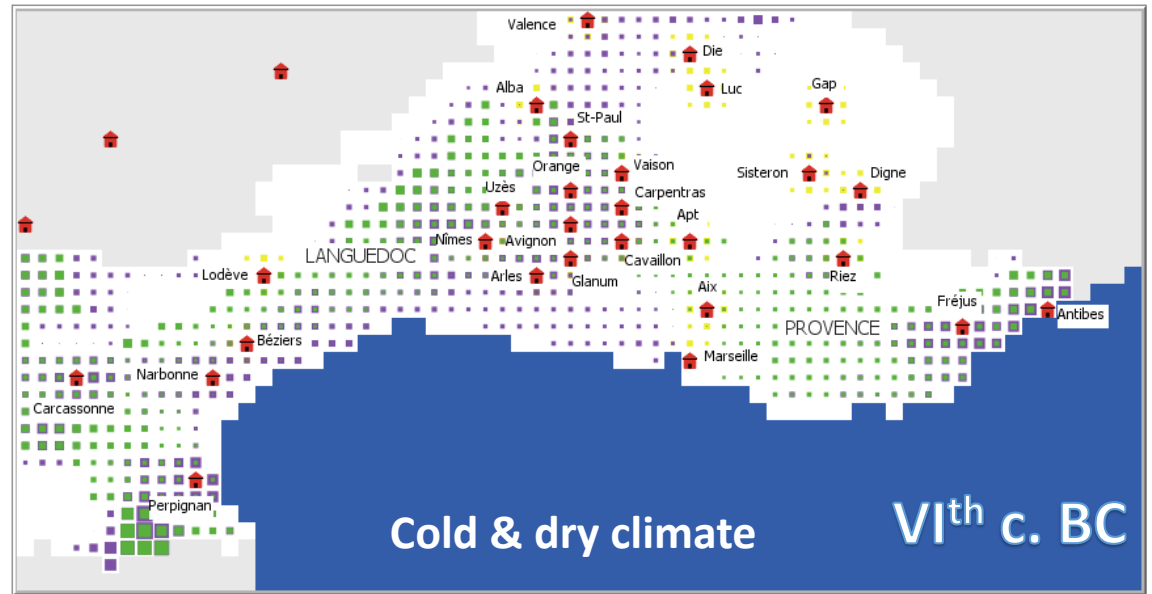
Screenshot of the interface of the ROMCLIM Model

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) (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	

ROMCLIM: main (counterfactuals) results

II- Case studies



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

-  Roman capital of city
-  Benefits of wineries
-  Benefits of olive groves
-  Benefits of wheat farms

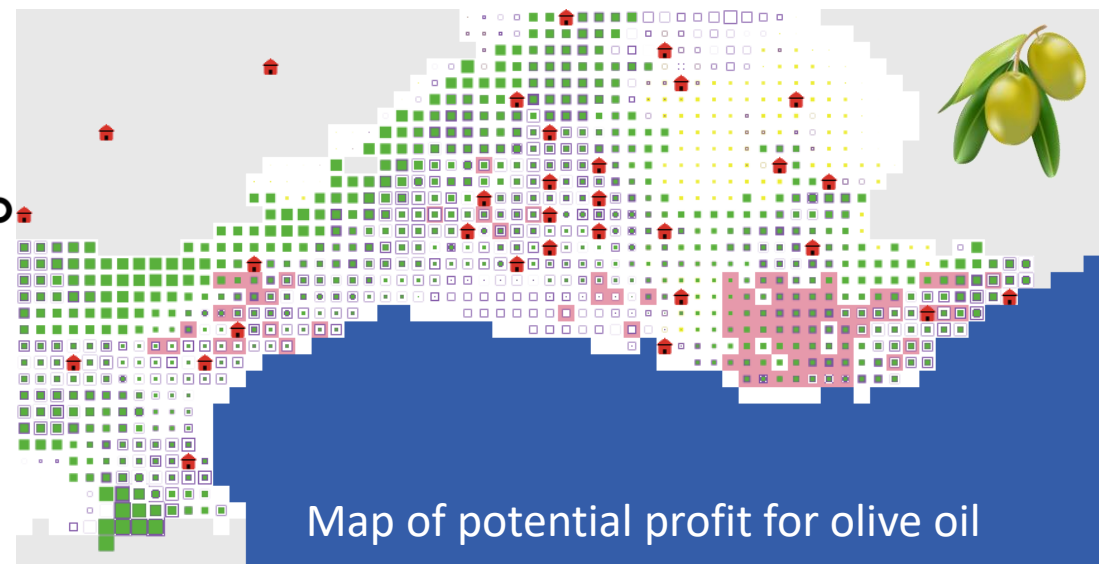
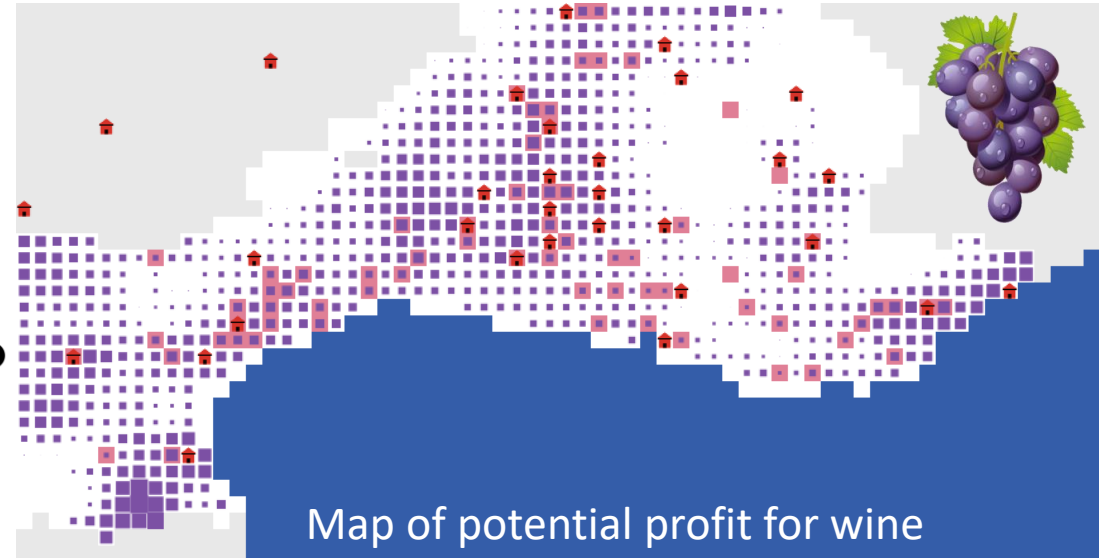
Maps of potential agricultural profit with climate characteristics of the VIth c. BC and the 1st c. BC

- 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

ROMCLIM: predictive model outputs vs archaeological data

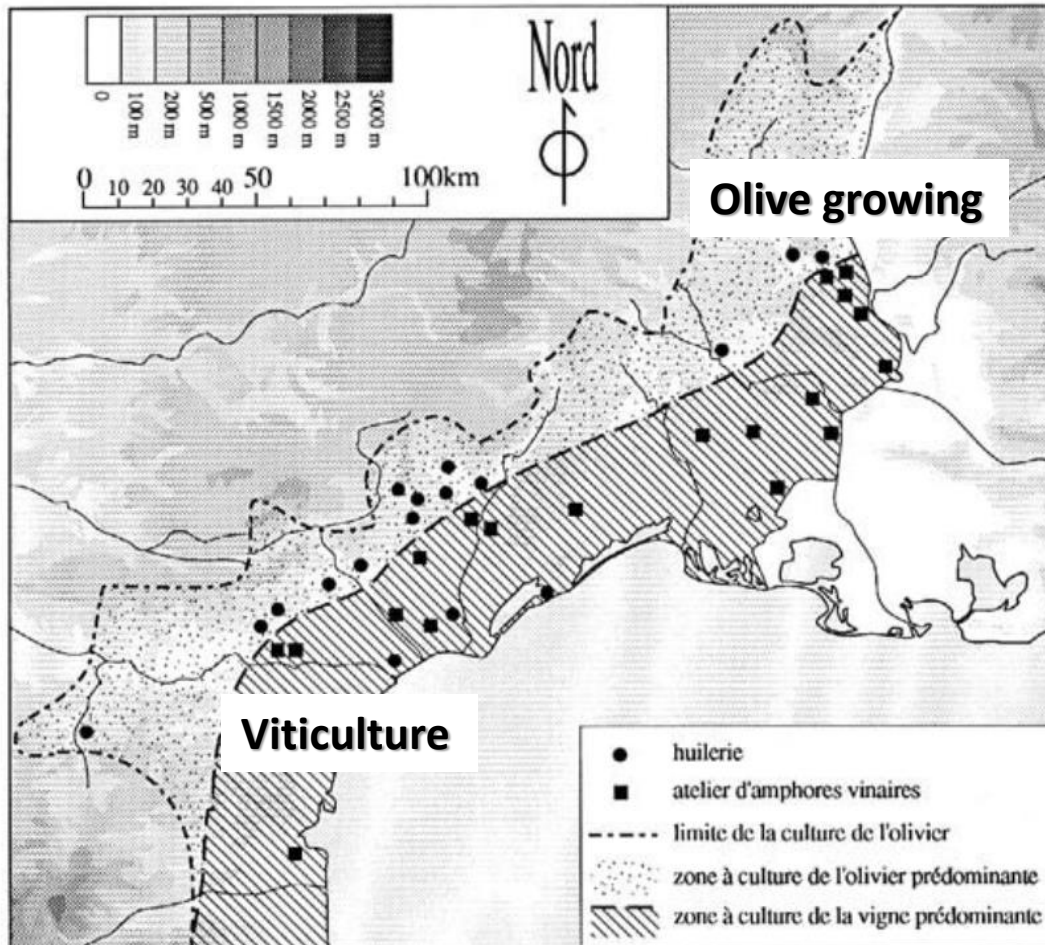
- For winemaking archaeological data for wine roughly match with the area of highest potential profits (Antibes-Fréjus area, middle et lower Rhone valley, languedocian plains)
- For olive oil, main archaeological data are concentrated in Languedoc and mainly in the Var region (thanks to J.-P. Brun works), 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*



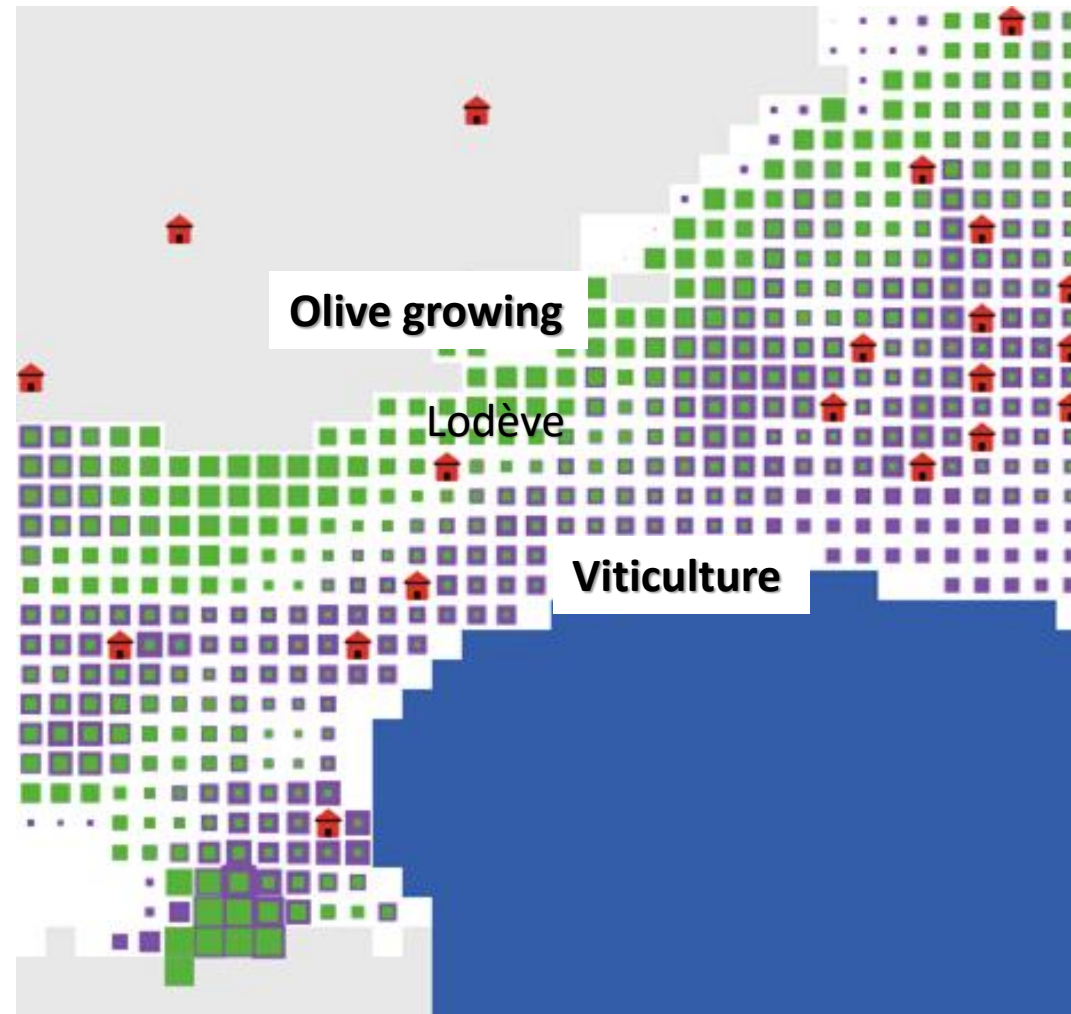
■ Archaeological testimony

Olive growing: model vs archaeological data



- 28: Carte de localisation des installations de pressurages et des ateliers d'amphores vinaires.

After Garcia 1992

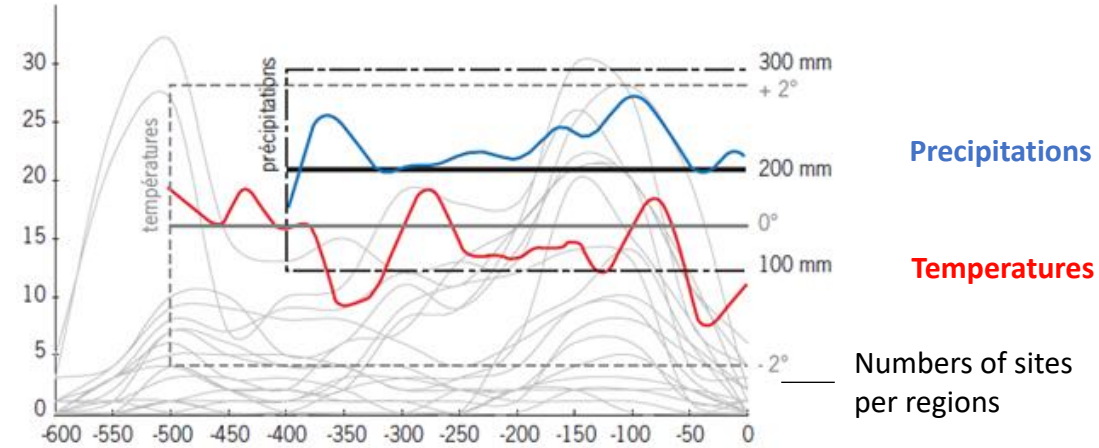


ROMCLIM model

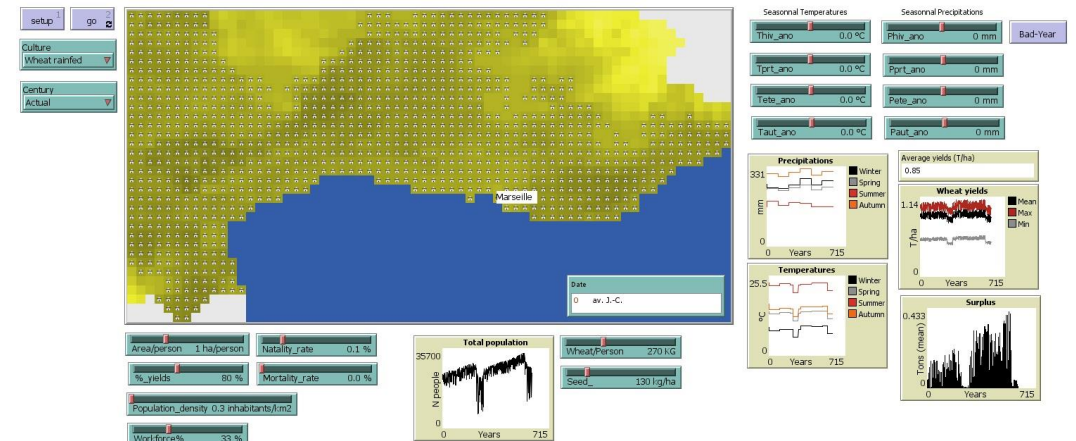
FER-AGRI Model: vulnerability and resilience of Iron Age societies to Climate Change

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

- 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
- 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



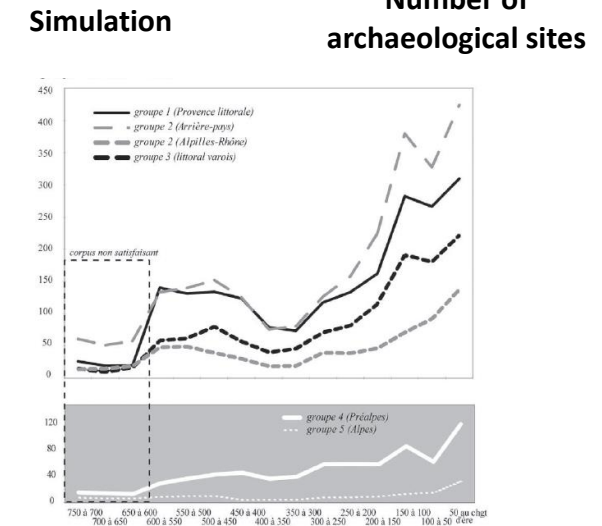
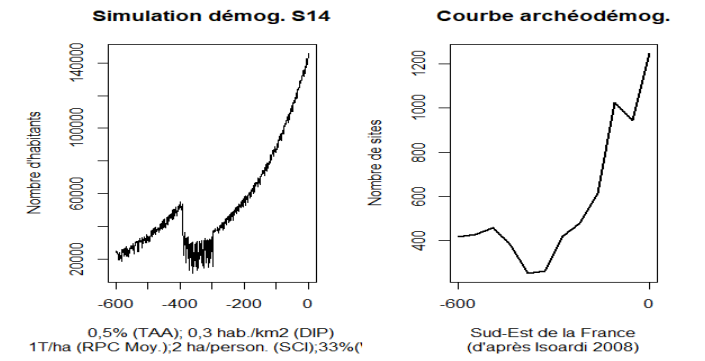
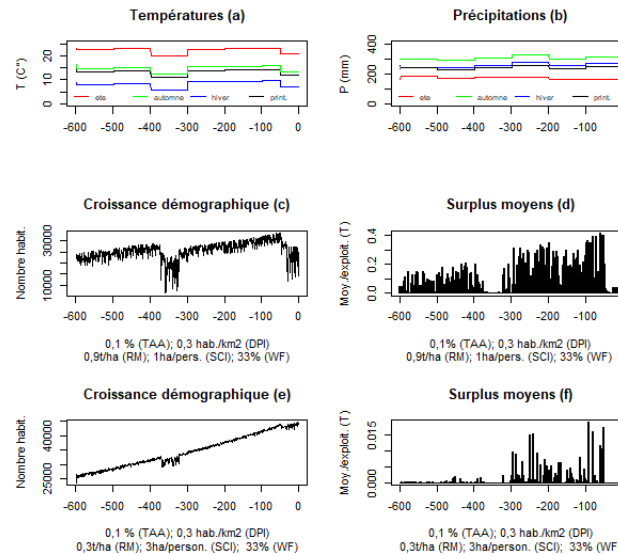
Density of settlement in Northern Gaul in Iron Age and climatic fluctuations (Malrain et al. 2013)



Interface of FER-AGRI Model (Bernigaud et al. in press)

FER-AGRI Model: outputs, results and interpretation

- 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)



-> Assessment of our models

Strengths:

- social modeling for gallo-roman society [ModelAnset]
- climate-agricultural yields reconstructions [ROMCLIM/FER-AGRI]



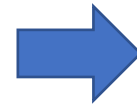
Perspectives:

- Hybridizing the strengths of ModelAnSet & ROMCLIM/FER-AGRI in a socio-environmental perspective

Assessments and Conclusions: ABM: The End of the Beginning?

Global assessment

- Powerful tool for explore hypothesis & rethinking historical narratives
- Use of ABMs grows in Europe, but probably still in a learning & experimental phase in France
- Development of ABMs in France still shy
- Various difficulties entertain methods improvements
- **Heuristic virtues:** test hypotheses & models
- **Integrative power:** stimulates collaborations between communities of archaeologists, environmentalists and computer scientists (cf OBRESOC/RDMed projects)
- Environmental change still few integrated in most models



Global perspectives

- Development for research in landscape archeology (test hypothesis for the causes of fluctuations between cultivated/wooded areas)
- Development for research in the socionatural perspective in the long term & transitions between chronocultural periods
- But necessity of strengthen collaboration with geoscientifics & paleoenvironmentalists (archaeobotany, archaeozoology, geoarcheology,..)