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Agent-Based Modelling, Archaeology and Paleoenvironment:

Assessment and Perspectives for the Study of Past Societies

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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?

- 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,…
I- General principles, historiographical overview

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!
I- General principles, historiographical overview

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

- Growing Artificial Societies, Social Science from the Bottom Up (Joshua M. Epstein, Robert Axtell)
- Dynamics in Human and Primate Societies, Agent-Based Modeling of Social and Spatial Processes (Timothy A. Kohler & George J. Gumerman)
- Population growth and collapse in a multiagent model of the Kayenta Anasazi in Long House Valley (Axtell et al. 2002)
- The Model-Based Archaeology of Socionatural Systems (Kohler & van der Leeuw 2007)

SUGARSCAPE model (Epstein & Axtell 1996)
Artificial Anasazis (AA) (Axtell et al. 2002)
I- General principles, historiographical overview

Archaeology & ABMs: socionatural/H.E. perspective

- 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)
- **Simulating Roman Economies** (Brughmans & Wilson 2022)

- 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

**I- General principles, historiographical overview**

- 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)

European Association of Archaeologists (EAA) - NASSA (Network for Agent-based modelling in Socio-ecological Systems in Archaeology) (Coord. Dries Daems)
- Collect and compile ABM code elements
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- 42e Rencontres Internationales d’Archéologie et d’Histoire de Nice Côte d’Azur, 12-14 octobre 2022
Archaeological ABMs in Europe: some examples

- **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

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

- Still few models!
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
Main topics for ABMs

1. Trajectories of ancient societies (Human Ecodynamics/socionatural approach)
   - Societal & Environmental causes [e.g. Artificial Anasazi (AA), ENKIMDU, MayaSim, ModeArtSet, etc.]
   - Impact of climate change [e.g. BACO, ROMCLIM, FERAGRI]

2. Social dynamics (Anthropological & Ethnoarchaeological approach)
   - Origin and genesis of social inequality
   - Hierarchization of societies
   - Ethnogenesis [Prehistoric Patagonia]
   - Conflicts

3. Subsistence strategy & Resources management (Archaeological/Quantitative approach)
   - Prehistoric Hunters-Gatherers [e.g. Central place foraging (CPF)]
   - Agricultural systems [e.g. AA, Celtic Oppida, Romfarm, etc.]
   - Resources exploitation & management: salt [Mining with Agents], water [Hohokam water management], etc.

4. Settlement Pattern genesis (geographical/archaeological approach)
   - Genesis of Settlement Pattern [e.g. TravelerSim]
   - Genesis of urban phenomenon [e.g. SimPop]
   - Concentration of habitat [e.g. SIMFEODAL]

5. 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

I- General principles, historiographical overview

Modelling approaches

Classification (Schmitt & Pumain 2013)
ABM & Archaeology: main issues & progress

- 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.

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

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).

Instanciation of the model: the territory of the Roman colony of Forum Julii (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

(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-POTS DAM-JENA-MANAGED-LAND (LPJmL)

- **Paleoclimatic data** needed by LPJmL are processed for each century between the VI\(^{th}\) c BC and the VII\(^{th}\) PC from an actual climate reconstruction (ALADIN) modified with paleoclimatic anomalies (from Guiot & Kaniewski 2015)

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**II- Case studies**

*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 VI\(^{th}\) c BC [2500 BP] and I\(^{st}\) c. BC [2000 BP]

- Screenshots of the interface of the ROMCLIM Model

(Bernigaud et al. submitted)
Main characteristics of the agents:

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

- Strong positive impact of RCO on the potential agricultural profits (peak in the II<sup>nd</sup> c. BC), slight decrease during Late Antiquity (IV<sup>th</sup>-VII<sup>th</sup> c. AD)
- Maps of potential profits very different according climate characteristics

![Graph showing potential profits](image1)

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 VI<sup>th</sup> c. BC and the I<sup>st</sup> c. BC
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.

II- Case studies

Map of potential profit for wine

Map of potential profit for olive oil

Archaeological testimony
Olive growing: model vs archaeological data

After Garcia 1992

ROMCLIM model

II- Case studies
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

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

Density of settlement in Northern Gaul in Iron Age and climatic fluctuations (Malrain et al. 2013)
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 chronoculturals periods
- But necessity of strengthen collaboration with geoscientifics & paleoenvironmentalists (archaeobotany, archaeozoology, geoarcheology,..)