S14 Can you model that? Applications of complex systems simulation to explore the past

Iza Romanowska, Stefani Crabtree, Benjamin Davies

The large scale patterns that we commonly detect in the archaeological record are often not a simple sum of individual human interactions. Instead, they are a complex interwoven network of dependencies among individuals, groups, and the environment in which individuals live. Tools such as Agent-based Modelling, System Dynamics Models, Network Analysis and Equation-based Models are instrumental in unravelling some of this network and shedding light on the dynamic processes that occurred in the past.

In this session we invite case studies using computational approaches to understand past societies. This session will showcase the innovative ways archaeologists have used simulation and other model building techniques to understand the interactions between individuals and their social and natural environments. The session will also provide a platform to discuss both the potential and the limitations of computational modelling in archaeology and to highlight the range of possible applications.

S14-01 Agent-based modeling and complexity science: The next step in archaeological theory?

Stefani A Crabtree

Agent-based modeling is on the rise in archaeology; yet how do we decide what questions are appropriate to ask when using this tool? Are all study areas, and indeed all questions, best approached through an agent-based modeling framework? If not, which questions are best answered through this approach? In this paper I place complexity science approaches within the framework of canons of archaeological literature. I then explore which questions are best asked, and answered, through agent-base modeling approaches. Finally I demonstrate how a simple agent-based model of southern France helps clarify standing questions. Finally, I briefly introduce a more complex model to show how agent-based modeling can articulate with both simple theoretical models and complex realistic models. Processual archaeology favored an approach that looked at how variables, such as societies, or levels of hierarchy, or maximal size of community, led to the construction of the archaeological record. Post-processualism, on the other hand, favored exploring the individual experience in the past, which can confuse an understanding of overarching structures. Complexity approaches, however, honor the individual experience by showing how individual decisions do matter, yet allow these individuals to interact to create larger overarching structures. This articulation of the micro-scale to the macro-scale feeds into how to approach archaeology questions with complexity tools. I take a step-by-step approach to showing which questions agent- based modeling can directly examine, and how they can be useful for answering questions that had been posed by processualists and post-processualists alike. I then demonstrate these questions through two models: a simple model of resource trade in southern France, and a complex model of the development of hierarchy in the U.S. Southwest. These two models are on the opposite spectrum from each other in terms of intricacy, yet they succinctly demonstrate how ABM approaches can examine diverse questions.

S14-02 How agent-based models can be used to investigate the evolution of social complexity in the past: A test of circumscription theory in the Valley of Oaxaca

Alice Williams

Complex societies with multiple levels of hierarchy and extended populations of unrelated individuals emerged relatively recently in the human past. How and why these complex societies formed from small-scale groups of people are fundamental questions to ask in archaeology. Attempts to explain this shift have often been verbally argued without explicit

testing. The aim of this research is to test different hypotheses at a regional level by comparing the output from agent-based models with archaeological data. The emergence of increasingly complex social organisation as a beneficial trait at both the individual and group level will be understood within an evolutionary framework. Agent- based models will simulate the actions of individual villages (whether to move or accept a subordinate position) based on the costs and benefits of their situation. It is predicted that increasing the costs of moving (through increasing levels of environmental circumscription) will increase the rate at which hierarchical societies form as a successful strategy. In addition, it is predicted that a model based on real-world environmental data will be comparable with the archaeological record. Archaeological and environmental data from the Valley of Oaxaca in Mexico will be used to test these predictions. The data spans 3,000 years from early small-scale villages to the formation and collapse of the first state-level society in Mesoamerica, and is ideal to investigate changes in social complexity over time. This research shows how agent-based models can be used to link micro- with macro-level processes in the past to understand why some human societies evolved higher levels of social complexity than others.

14-03 Simulating archaeological landscape formation to understand late Holocene population dynamics and mobility in arid Australia

Benjamin Davies, Simon Holdaway, Patricia Fanning

Archaeological interpretation depends on the formation of patterns in the material record, but patterns are not always discernible as the outcomes of a single set of processes. In Australia's desert regions, interpretations of patterning in late Holocene deposits range from intermittent occupation by bands of hypermobile foragers to growing semi-resident populations of complex hunter-gatherers. In particular, archaeologists have focused on the temporal distribution of radiocarbon dates that show trends and gaps consistent with interpretations of population dynamics, periodicity in occupation, and time- dependent preservation. We constructed an exploratory agent-based model around the concept of the palimpsest to evaluate the ability of the coupled processes of cultural and sedimentary deposition and erosion to form these patterns in a surface record of heat-retainer hearths. Initial results suggest that explanations invoking population dynamics or geomorphic processes have the capacity to produce qualitatively similar outcomes. Models are then reconfigured to evaluate a second proxy: optically-stimulated luminescence dates obtained from hearth stones, in order to evaluate the differential influence of these formational processes on these two proxies. The results of the modelling exercises are discussed in relation to patterning observed in the archaeological landscape at Rutherfords Creek, New South Wales, and are used to argue that the record is consistent with neither intermittent occupation or appreciable population growth, but instead indicates regular visitation by groups performing a fairly consistent set of activities during the period of interest. This study demonstrates the suitability of agent-based models for studying archaeological formation, but also how simulations can be used as both ‘tools to think with' and as mechanisms for developing tests of theoretical ideas.

S14-04 Reinforcement learning for decision making in agent-based models

Jean-Marc Montanier, Xavier Rubio-Campillo

Understanding the decision-making processes within past societies is a challenging aspect for archaeological research. In order to validate our understanding of these behaviours, an ideal workflow would be to simulate the behaviours that we imagine are correct. We can then observe, if the imagined behaviours reproduce the evidence collected from the terrain.
ABM has proved to be an efficient approach toward the realisation of this vision. However, many of the phenomenons we wish to study, require the adaptation of the agents to the context they live. For example, it would be interesting to study the behaviors of gatherer

agents in front of changing environments. To face this type of situations, there is a clear need for adaptation abilities. Unfortunately, most of the current behavioural architectures used in ABMs do not let the agent adapt continuously its behaviour so as to fit the environment, thus restricting the modeling possibilities.
Reinforcement learning algorithms have been proposed to address learning problems within multi-agent settings. Once applied to past-societies models, this learning method faces two main challenges: each agent observes only part of the world and the number of states and actions an agent can face is potentially extremely large. Similar challenges have been previously been encountered by researcher applying reinforcement learning methods to multi-robots scenarios. Within this article we aim to present which of the solutions previously developed can be applied to create models of past societies.
Moreover, the use of a UCT architecture has been previously proposed to address the challenge of learning in past-societies models. We will draw a comparison between reinforcement learning and UCT approaches. This comparison will highlight the difficulties each approach is facing, specifically for an application to past-societies models

S14-05 An agent-based approach to weighted decision making in the spatially and temporally variable South African Palaeoscape
Colin D. Wren, Chloe Atwater, Kim Hill, Marco Janssen, Curtis Marean
Even a "simple" human foraging pattern has a large number of moving parts. This requires a complex decision making process to effectively exploit the spatially and temporally variable resources in an environment. Here we present a general framework, based in optimal foraging theory, for agent foragers to make mobility and foraging decisions by weighing expected caloric returns against geographic and social factors, and forecasted future return rates. We evaluate the effectiveness of this and alternative decision making strategies by comparing their caloric returns over the long-term.
During the early Holocene in South Africa, Later Stone Age (LSA) foragers systematically exploited a wide variety of flora and fauna in both terrestrial and inter-tidal environments. We first use a combination of modeling and field-based foraging experiments to rigorously reconstruct the spatially and temporally variable caloric returns of the South African Holocene resource environment. Next we apply our decision making system to this resource environment as a way of gaining greater insight into LSA foraging patterns. Finally, we discuss the implications of our study for the evolution of complex cognition.

S14-06 The versatilist's story of human dispersal: Climate fluctuation, adaptation and the evolution of human uniqueness
Iza Romanowska
The Variability Selection Hypothesis proposed by Potts (1996; 1998) postulates the evolution of behavioural plasticity among early hominins arising during periods of strong environmental fluctuations in the last 6 million years. It argues that the inconsistency in selection regimes caused by the rapid environmental fluctuations produced particularly strong selection pressure on adapting to change rather than any particular set of environmental conditions. This promoted adaptive changes leading to a higher level of behavioural plasticity and the evolution of organisms which can be described as 'versatilists', for example early hominins.
Here, we present an extension of the single locus model by Grove (2011) —the first successful formalisation of the Variability Selection Hypothesis into a mathematical framework. The current implementation aims to assess the implications of the Variability Selection Hypothesis on the agents ability to disperse, a process that is visible in the archaeological record. The model was translated into a stochastic multi-agent simulation to

investigate the dynamics between individuals with different positions and range on the adaptative spectrum (including the 'versatilist' individuals) within a non-homogenous population. The particular focus of this presentation is on the spatial structuring of the migration wave and the question of what characteristics of the original population play a role in its ability to disperse.

S14-07 Dates and dispersions: Examining the spatio–temporal boundaries of the Guaraní expansion into the La Plata basin with Monte Carlo methods
Phil Riris, Fabio Silva
The direction and timing of the Guaraní expansion into the La Plata basin from an Amazonian origin is a matter of no small debate in the study of South American indigenous cultures. The short timeframe of the Guaraní expansion (2000–500 BP) during the late Holocene, as well as the distances involved, are both used to explain it as the result of the migration of significant numbers of people in a classic "wave of advance". The process is further broken down into "pulses" punctuated by periods of relative stasis in which colonization through the valleys of major rivers was halted or slowed. These factors, combined with a broad base of empirical data from decades of research, provide the impetus for refining established chronologies of the Guaraní dispersal.
We use a published database of georeferenced dates to model its spread at the beginning of the Common Era from a presumed entry point until the time of European contact at its known limits at the La Plata delta and Atlantic coast of Brazil. Using regression models and Monte Carlo methods, we examine the dispersal in order to constrain the probable start dates for entry into different zones. Additionally, we investigate the notion that Guaraní groups enveloped large sectors of terrain contiguously as the result of demographic pressures that were interspersed, as noted, with hiatuses of comparatively little movement.
We place our findings in the context of preceding archaeological, ethnographic, and ethnohistorical knowledge on this uniquely South American process of indigenous dispersal. Suggestions for further work to improve the scenarios we present are offered, following the note by Brochado (1984) that in the study of Guaraní archaeology, "computer modelling is probably the only way to achieve refined estimates of population growth" in the La Plata basin.

S14-08 An agent-based modelling approach to a complex problem: Economics and demography of the first farming expansion in the Balkans
Andrea Zanotti, Richard Moussa, Jean-Pierre Bocquet-Appel
How can we see demo-economic processes in the archaeological record? How is the pioneer front of a Neolithic farming society demographically and economically structured? What are the differences in the structure of the population between zones of expansion and zones of increasing density? These questions become especially difficult to answer the farther back in time we study. Here we use an agent-based modelling approach to examine the spread of the first farmers through the Balkans during the Early Neolithic, specifically focusing on the demo-economic impacts of the spread of agro- pastoralism in this region. In this model we combine archaeological records with ethnohistoric and paleodemographic inferences. These are layered on a realistic dataplane built by paleoclimate and soil fertility estimates. Agents interact on this landscape and follow a demographic and economic model in order to simulate the functioning of the Neolithic farming system. Our results provide possible scenarios for the expansion of the first farmers in the Balkans. The agent- based modelling approach permits the exploration of demo-economic structures that are unobservable in archeological record.

S14-09 An agent-based modeling framework for Out of Africa hypotheses
Ericson Hölzchen, Christine Hertler
The "Out of Africa" theory states that the genus Homo originated in Africa and from there dispersed across Eurasia. At least two different dispersal events can be distinguished. On the one hand there were the dispersals of archaic Homo such as Homo ergaster/erectus or even earlier forms which took place around 2 million years ago. We summarize these dispersals under "Out of Africa 1". The dispersals of modern humans took place around 130 thousand years ago. We summarize these dispersals under "Out of Africa 2". The underlying mechanisms for both dispersal events remain under debate. Currently, there are several hypotheses that try to explain these dispersal events with environmental, biological, or cognitive changes, resources and/or competition. There is currently no accepted formal representation of Out of Africa hypotheses which allows testing and comparing them on a quantitative basis. We propose agent-based modeling as an adequate method to explicitly represent Out of Africa hypotheses. An agent-based model consists of agents, an environment and rules of interaction. We apply this structure to model early hominins who interact with a Pleistocene environment. We present an agent-based modeling framework that is based on the most common Out of Africa hypotheses from literature and their associated driving factors. This framework allows the generation of testable and comparable agent-based models of various Out of Africa hypotheses and their subsequent quantification.

Cancelled **S14-10 Testing archaeological narratives of the spread of rice cultivation in Asia**
Fabio Silva
Often in archaeology, narratives are created based on a limited assessment of, or a qualitative take on, the data. This is the case when positing centres of technological or subsistence innovation, which often rely on the, limited and frequently biased, available archaeological evidence. Such approaches are prone to criticism by those who raise concerns that future archaeological finds, in less sampled regions, might completely disprove, or otherwise change, the archaeological story. One example of this is the debate over the origins of rice cultivation in Asia (cf. [1]). There is a need for a framework that can explicitly evaluate the proposed narratives against the wider archaeological record and weigh the evidence in favour of each, while, at the same time, penalise more complex narratives. Such a framework, based on the interface between Information Theory and Likelihood Statistics is here implemented. It is based on the numerical modelling of dispersals and subsequent comparison to the available (dated) archaeological data. Goodness-of-fit is obtained from a quantile regression [2] of the archaeologically inferred age versus a least-cost distance from the putative origin(s). The Fast Marching Method is used to model least-cost distances based on simple geographical features (cf. [3]) and the model's parameters are estimated using a Genetic Algorithm that maximizes the likelihood. Model selection is then conducted using Akaike's Information Criteria (cf. [4]) which allows for a quantification of the weight of evidence in favour of each model/narrative. As a case study, an extensive database of archaeological evidence for rice across Asia, including 400 sites from mainland East Asia, Southeast Asia and South Asia was used to compare several models for the geographical origins of rice cultivation and its subsequent spread. The results indicate that a model with two independent centres of innovation (in the Middle and Lower Yangtze) is supported by the entirety of available archaeobotanical evidence for the presence of cultivated rice in Asia (cf. [1]).
[References]
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S14-11 An agent-based empirical model of collective seasonal hunting

Florencia Del Castillo

This work presents an ethnoarchaeological model of collective seasonal hunting to track the interactions among hunters and guanacos-prey (one of the most abundant and ecologically important mammal species of Patagonian steppe) in a well-known ethnohistorical scenario of Patagonia hinterland. The conceptual model was developed based on ethnographical and historical data from an indigenous society from North Patagonia. We model a place of guanaco hunting named Yamnagoo by the ethnic group gününa këna during XIX century. The data used to design this complex space of hunting, come in part from the description made by European explorers from the XIX century and from ethnographic descriptions of one of the most uninhabited region of South America.
The model was developed to address the interactions between collective hunting organization and the guanaco's capacity to respond and react to it. Therefore, we design a model with collective hunting strategies based on search, stalk, chase, food processing, consume, and prey discard. With the model we experiment with a large number of hunting attacks to quantify how the environmental variables, geographical constrains and communication between hunters, affect density, speed and motion of hunter-agents and guanaco-agents. The aim of the model is analyse and explore how cooperation activities and the role of information transfer in hunting interactions works and how ethnoarchaeological data can be useful to understand social Dynamics in prehistory. The model is validated by comparing the simulation results with archaeological fieldwork and survey.

S14-12 The emergence and process of formation of the La Tène cutlture settlement system in Upper Silesia (Southern Poland and Northern Czech) in the light of the simulation modelling

Jan Zipser

The paper presents findings of research regarding recreation of the processes involved in the taking up of the Upper Silesian area (Southern Poland and Northern Czech) by the La Tène culture settlement, as well as in the formation of its structure, in the context of already existing theories.
Two diffusion simulation models were applied (Probabilistic Model for Residential Growth – also called UNC Model and Intervening Opportunities Model) in relation to the theories regarding the direction of the settlers' influx; the hypothesis referring to the reasons behind the emergence of the presently known settlement pattern; and the interactions between the potential environmental conditions and the detailed course of the settlement system expansion.
The introduction of the two simulation modelling procedures into the research of the La Tène culture settlement in the studied area demonstrated high statistical correlation with the mapped, prehistoric settlement system of the La Tène culture. It also brings respectable basis for interpretation of the settlement processes, not only in the studied case, but presumably also of other prehistoric cultures in different geographical conditions or cultural landscapes.

S14-13 Can you analyse that? Fitting simulations to idealised outcomes for the origins of farming

Elizabeth M Gallagher, Mark G Thomas, Stephen J Shennan

Monte-Carlo simulation is a powerful tool for exploring model behaviour and sharpening intuitions about prehistoric processes. Model-based inference requires empirical data, both to assess relative support for alternative models and to estimate model parameter values. However, inference on prehistoric processes is sometimes challenged by a lack of quantitative and ascertainment bias-free data, and often only general outcomes of past processes are known. In addition, when Monte-Carlo simulation is used to explore model behaviour, this is often done via a fix-all-but-one approach, whereby parameters are set at some default values and then varied one at a time. Such an approach will fail to capture many of the subtleties of parameter interactions.

In this study we examine the origins of agriculture by applying Monte-Carlo simulation to a model first proposed by Bowles and Choi [Bowles S, Choi J-K (2013) Proc Natl Acad Sci USA 110(22):8830–8835]. We vary 11 parameters simultaneously within defined ranges over 12 million simulations to ensure better exploration of parameter space. We also introduce a new method—fitting to idealized outcomes (FIO)—which permits identification of potential parameter interactions. Our FIO approach is analogous to approximate Bayesian computation and allows us to infer the optimum conditions under which farming would evolve, given our model. Our results reveal previously unidentified model behaviours. By setting our 'ideal outcome' as farming being fully established by 9,000 yBP, we show that the key factors for its emergence include farming-friendly property rights (supporting Bowles and Choi's original work), group structuring and size, and conservatism . Furthermore we find that for farming to emerge it is not essential for farming productivity to be greater than that of foraging.

S14-14 Everything seems possible: Exploring the parametric space of a simulated prehistoric scenario

Juan Antonio Barceló, Florencia Del Castillo Bernal

Simulated scenarios allow exploring (by altering the variables) the entire possible range of outcomes for different past behaviors. Therefore, the starting point of the explanation of social systems by means of computer simulation is not the simulation of one particular system but the investigation of the mathematically possible development of specific classes of model systems (pure systems). As these pure systems usually generate a lot more different paths of development than are known from real human history, the automated archaeologist has to limit these possibilities by introducing known social constraints from social reality. The socially interesting question is then why these constraints appeared in reality. Each one of the resulting "simulations" of a historical trajectory of events can be used both to experiment with a theory of historical transition and social change (parameters are manipulated to test for predicted differences) and as a demonstration tool (parameters are manipulated to test for predicted robustness). In this paper we present a way of using experimentally a simulated universal model of a hunter-gatherer past, in which manipulations are allowed for agent- level parameters to test the global implications of behavioral assumptions in the case of small-scale prehistoric societies, but also it is allowed to manipulate global parameters to test a macro theory about the dynamical implications of social behavior assumptions in the case of more complex societies. Different initial parameters are fully explored, and all possible combinations between them (Initial number of households, household size, mean resource on patch, technological efficiency at start-up, mobility, internal change rate). The paper presents how variation in those parameters affect total survival, technology transfer, social interaction, intensity of cooperation, cultural diversity and social polarity.

S14-15 Evolving hominins in HominInSpace—Genetic Algorithms and the search for the perfect Neanderthal

Fulco Scherjon

Genetic Algorithms (GA) are evolutionary computational techniques inspired by natural selection in which individuals participate in a search for optimal results. HominInSpace (HS) is a large scale realistic agent-based modelling and simulation system exploring hominin dispersal through reconstructed landscapes in the deep past. A case study in HS implements Neanderthals moving through North-west Europe where simulated presence is scored against radiometrically dated archaeological sites (checkpoints). Model parameters influence agent behavior and GA are implemented in an automated scan for that specific parameter combination that produces a Neanderthal agent that best matches the archaeology.

The underlying research question for the implementation of HS is the characterization of the effects of the different parameters on hominin behavior in the landscape. 6000 simulations were run with randomly constructed parameter combinations. Statistical analysis (principal components analysis and cluster analysis) are used to determine the influence of each parameter in simulations with high scores. But the total dimensions of the parameter space (23 parameters) is simply too large for an exhaustive parameter sweep guaranteed to find the perfect Neanderthal.

In an effort to optimize that search GA techniques are applied against the set of simulated parameter combinations and their simulation results. Each unique combination of parameter settings is taken as an individual that participates in the automated search. Tournaments are organized to select high potentials, and randomly mixed pairs of successful parents produce hopefully more successful offspring (new combinations). Better scoring individuals are also point mutated on a single parameter to create even more new combinations. Simulation results for the new parameter combinations are added to the pool of individuals that participate in the following tournament rounds. This paper presents the preliminary results and the characterization of some very good Neanderthals.

S14-16 Content or context? Model selection of settlement growth models using entropy maximization

Xaver Rubio-Campillo, Rinse Willet

Entropy maximization is one of the most popular computer models used in archaeology. This family of simulations was designed to explore transport flows in urban and regional geography. The original model was transformed into a high-level methodology designed to explore any scenario where the size of a set of entities is related to spatial interaction. Several archaeological studies applied the methodology to settlement dynamics, thus exploring how geography and interaction could expain the observed size of sites. Recent developments have adapted the framework to the particularities of the field introducing concepts such as uncertainty, decision-making and the study of evolutionary trajectories.

These models characterize settlement growth as a combination of two factors: the intrinsic interest of the location and its relation within the network of settlements. The system is then iterated while updating the importance of each settlement until an equilibrium is reached. The main challenge of the model is to define parameter values for a) the hypothetical intrinsic interest of each site, b) the interaction decay over distance and c) the relative weight of the two components. Beyond the entropy- maximising approach, parameter estimation and comparison between competing hypotheses are two common challenges while evaluating how formal models match evidence under uncertainty.

This work evaluates the plausibility of different entropy-maximising models in the case study of Roman Asia Minor. A hierarchical model integrated the alternate hypotheses and data

uncertainty within the same framework. Parameter estimates and model comparison were then calculated applying Approximate Bayesian Computation. The application of this framework was used to infer new interaction dynamics between the settlements located in this region and improve our understanding of the underlying archaeological record.

POSTER

S14-P1 The origins of agriculture: Mathematical models, cooperation and the rise of social inequality

Elizabeth M Gallagher, Peter J Bentley, Stephen J Shennan, Mark G Thomas

The transition from hunting and gathering to farming was one of the most important events in human history; having major impacts on human demography, evolution, health, culture and technology, and coinciding with a switch from fairly egalitarian to hierarchical societies. The reasons why some societies switched to farming are still debated, with climate stabilization, population pressure and feasting, among others, as popular hypotheses. However, since these processes occurred so long ago and ethnographic studies may not always be comparable to ancient groups, investigating the transition can be difficult without the use of mathematical models.

We have developed a game theoretical agent-based model of social and environmental interactions during the late Pleistocene/early Holocene in order to investigate potential societal impacts of the transition to farming. Our model is used to test various popular hypotheses for the origins of farming (e.g. population and climate pressure). We also investigate the affect of changing levels of cooperation on both the transition to farming and the emergence of social inequality. Our model is conditioned with a proxy for the amount of farming in the Near East (the domestic-to-wild ratio from an archaeobotanical database), and we use a method analogous to approximate Bayesian computation to explore the model's parameter space and interactions in detail.