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A ‘Divergence Problem’ of global explanatory models in-between science and humanities

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Large-scale and global explanatory models for past, current, and future human behaviour are currently the focus of all the natural sciences and humanities. But to which extent do such models enable the theoretical and methodological discourse that explains the complexity of human patterns in different geographic and ecological set-ups? Such an effort incorporates principles of geography, ecology, and archaeology, as well as attempts for model parameterisation and adaptation. Building on local behaviour with global implications, this paper explores fundamental parameters of environmental connectivity and ecological functionalities in archaeological and ecological research. As a consequence, I hypothesise a *Divergence Problem* in archaeological and particularly in socio-environmental models—a mismatch between archaeological data complexity, environmental explanatory variables, and simplicity of the resulting model. Theoretically, the adjustment of global models to regional contextualisation can be achieved by introducing a correction coefficient, hereafter referred to as *Glocalization Coefficient*, which could allow for the comparison between regional environmental driving factors and individual human activity spheres.

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Introduction

Models are fundamentals in science, and particularly in archaeology (Clarke 1972; Drost and Vander Linden 2018; Lake 2014). Building on reconstructions of past human behaviour, all interpretations of archaeological records are ultimately models, i.e. simplifications of potential past 'realities', or more meaningfully interpreted as individually perceived life-worlds. Inherent in this concept is, however, that all models are never *real* but abstractions of interconnected variables that best describe an assumption, another variable, or a particular pattern. A simple version of a model that is used for explanatory or predictive purposes is a linear model in which a variable is best predicted by another or a combination of predicting variables. At best, this results in a simple equation that integrates a series of covariates into an explanatory model. Simplicity is the key to maintain physiological sense without overfitting the model with an increasing number of parameters or variables. But these models work well only within a particular spatio-temporal window of operation and in regional or local context. Major problems emerge on the global scale. System interconnectivity, including ecosystem functionality, resource availability, and (planetary) climate systems, increases rapidly with increasing scale of the analyses. And basic geographic factors, such as latitudinal and altitudinal gradients, continental and oceanic climate zones, or interregional connectivity and permeability prevent push-button global model comparability. Consequently, environmental explanatory parameters are unlikely to work similarly in different locations of the earth and can eventually generate feedbacks that further amplify a regionalisation trend of the model. Fitting a larger number of variables to the model in search for more significance of the power of the model only increases complexity but not comprehensiveness of the model.

Increasing model complexity vs. universal power

Complexity is inherent in all socio-ecological systems (SES) (Gallopin et al. 1989), and there is hardly an ecological system that is more complex or less complex than another—in terms of ecologically and socially dynamic conditions (Barton 2014). A parameter that makes a system unique (or different from others), is, for example, sensitivity to significant changes in the controlling parameters, e.g., climatic change, or strong socio-cultural impacts. Temporal variability is of particular importance and quite often, social and ecological subsystems are looked at separately (Fig. 1A).

Most of the time, it is a combination of multiple parameters under the overarching umbrella term climate that accounts for landscape suitability and the subsequent spread and decline of human occupation (Büntgen et al. 2011, 2016; Glaser and Stangl 2004; Weninger et al. 2009). Ultimately, a set of thresholds determine human well-being, and they are primarily controlled by environmental factors. Such location parameters, on the other hand, are regionally controlled and variables that account for suitability in one spot do not necessarily meet the needs of individuals in another. The distance to fresh water can be a limiting factor in semi-arid landscapes, but such a location parameter is relative, considering the strongly seasonal character of rainfall, the high risk of flash floods, or a locally low groundwater table. Consequently, a supraregional model that takes into account a variation of shifting environmental conditions is a combination of multiple local models that demand expert knowledge and high-resolution data analyses to understand the interconnectivity of the immediate ecological feedbacks (Peterson et al. 1998). Ultimately, such a patch-work model dramatically increases in complexity due to the simple fact that ecological functionalities and resource availability that determine niche constructions or ecological habitat development, are strongly interwoven and do not stop at rational (or reasonable) scale definitions, which we would all to readily like to assume for human activity spheres. Hence, very local ecological interactions dissolve into increasingly larger patterns, dominated by overarching control mechanisms that eventually determine global patterns.

Put simply, there is no scale-dependence in what makes a reasonably complex system but rather fuzzy transitions between multiple resource-dependent life-worlds of flora and fauna that enable human action and movement. Changing one pillar of these fundamentals of system complexity can have dramatic effects on all interlinked overarching systems and subsystems due to resource scarcity or over-availability. But these environmental chain reactions and tipping points are hard to predict, which makes it much more difficult to estimate potential response such as human adaptation or temporal collapse to climate variability and even entirely impossible to create a universal standard across scales (Cumming et al. 2013). Model regionalisation can increase the resolution of the input variables and hence the complexity of the interpretation. Universal models with low resolution data structure decrease the interpretation potentials and allow only for very generalised pattern recognition—if at all. The quality of the output is strictly linked to the model complexity. Since every regional context is unique, one model that describes another, based on calibration and prediction is inherently uncertain.

Model parametrization

Searching for general explanations of regional driving forces is difficult. Is there a way to determine model parameters that equally control human behaviour in different landscapes across different scales? What we measure, and what is inherent in a SES, is individual decision making within a particular activity sphere that can be environmentally determined or socio-culturally controlled. Eventually, all records that are used to describe a specific contextualisation of parameters aim to understand human behaviour. Certainly, this is a very anthropocentric position, which builds on the production of landscapes and the creation of activity spheres solely through human perception and movement. In such a system, landscape affordances determine potential interactions with the environment that in turn create socio-environmental relationships between spatio-environmental contexts and an observer (Kempf 2020). On broader scales, however, individual perception of environmental features is very flexible and often shows a temporal component, controlled by traditional narratives of landscapes, long-standing adaptation to climatic variability, and physiological imprints. In a very physical sense, synchronisation of such variables does not entirely explain regionalisation of human patterns (Nakoinz 2021).

Obviously, climatic conditions control ecological development and are prerequisites for human spread (Müller et al. 2011; Racimo et al. 2020). In between these global players, however, we can find multiple subsets of interlinked system dynamics that range from purely environmental parameters, such as potential vegetation to individual or group-specific resource demands and personal needs. These subsets are primarily controlled by human requirements in particular landscapes and in temporal frameworks and are non-static, continuous adaptations to changing environmental and social settings—and hence refer to the complexity of the entire system (Holling 2001; Roe 1998). Different propositions create different demands but the general structure of object/demand or resource/demand or landscape/demand remains always the same. One can argue that objects, resources, and landscapes are synonymous, which even simplifies the model. A potential parametrization of explanatory variables for human

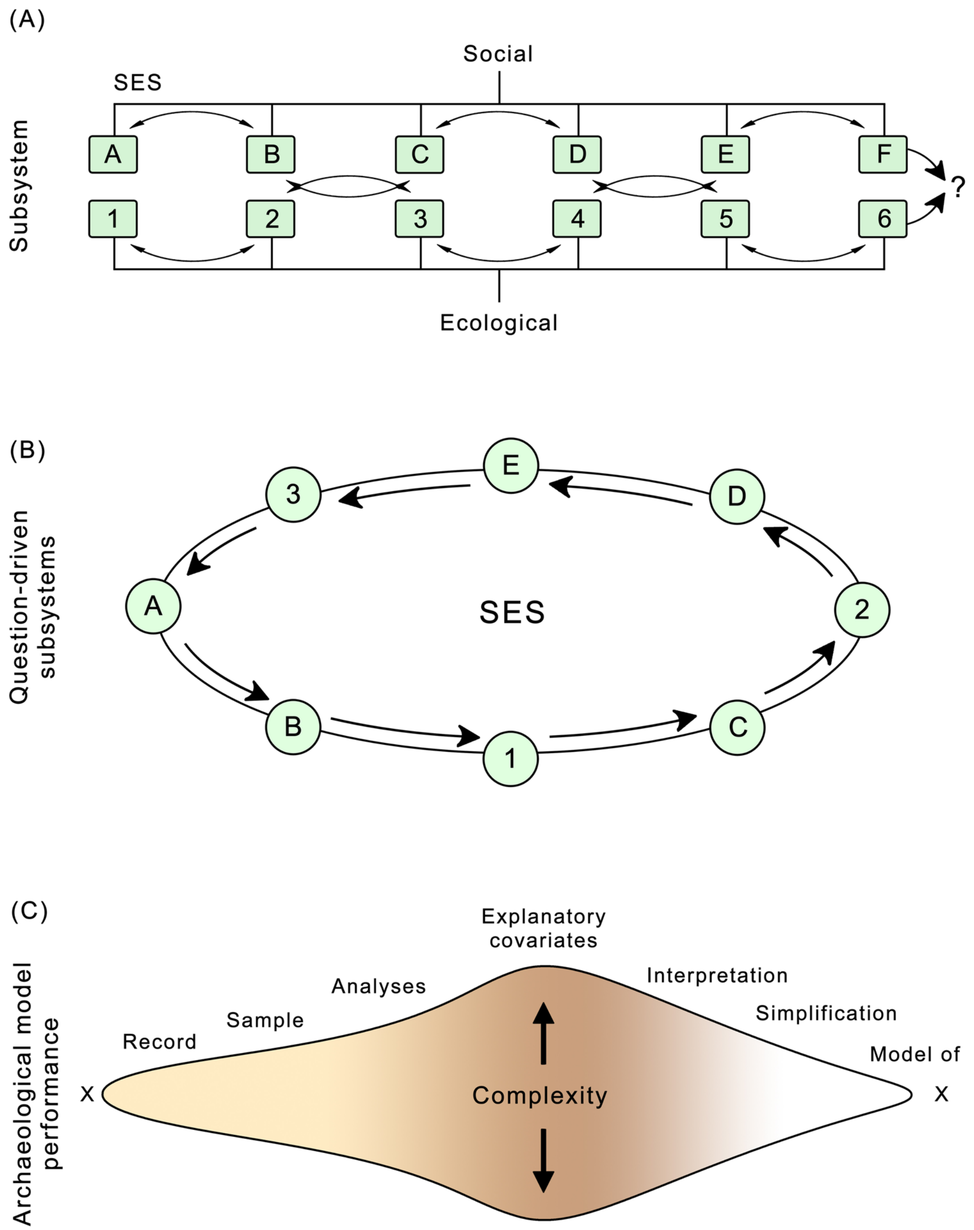

Fig. 1 Three approaches of SES models. A Traditional SES in which social and ecological components are disconnected; **B** question-driven, interacting SES, in which system/model components build on the complexity of the other subsystems (Gallopin et al. 1989); **C** archaeological model, which builds on simple archaeological data, increase in complexity, and simplification during model set-up.

behaviour can thus only be seen in basic human demands, such as hunger, thirst, sleep, inclusivity, security, reproduction, and survival. The search for such a combination of parameters ultimately controls human movement across landscapes and hence is a landscape builder itself. Intentionally, people do not search for fertile soils to grow crops on but for areas to maintain basic needs of everyday life. In doing so, empirical (inductive) knowledge is generated and disseminated that enables a higher level of decision-making in a deductive model of which areas exceed, for example, a certain threshold of required yield. And eventually, these areas are limited, due to the above-mentioned environmental constraints or, which is more likely, due to low carrying capacity in a preliminary state of crop cultivation systems and population growth. Building on these considerations, human movement is then controlled by a decline in availability of resource and habitat patches and the temporally limited loss of ecological functionalities.

In summary, physical environmental prerequisites are hardly possible to parameterise, except general global climatic or topographic constraints. What we can align however, is regional or local adaptation to basic demands and needs within regional activity spheres of individuals. The need to sleep and feed and reproduce is supraregionally exchangeable. Eventually, this can lead to question-driven system subsets that build on each other in search for interlinked socio-environmental feedbacks (Fig. 1B).

A Divergence Problem of socio-environmental models in archaeology?

Recently, I was confronted with the so-called 'Divergence Problem' (DP) in dendroclimatology, which basically refers to the mismatch between modern temperature trends and tree-ring growth parameters since about the late 1960's (Briffa et al. 1998; Büntgen et al. 2022). DP describes the phenomenon that interannual tree-ring variability is predominantly controlled by temperature but long-term trends are not fully explicable by the time series (Büntgen et al. 2022; Esper and Frank 2009). The problem that emerges from such a mismatch is the suitability of one (modern) variable to reconstruct another (past) variable. The divergence probably lies in the increasing complexity of the feedbacks that control ecological development and adaptation. Looking at archaeological data and archaeological models in particular, we can find quite a few similarities between $DP_{climate}$ and $DP_{archaeology}$. In the first place, an archaeological record describes a relatively simple or non-complex issue, basically material left-overs of some kind (Fig. 1C). In a next step, the record gains in complexity, most likely through sampling one site or many sites to create a certain database, which can be material or digital. Then, we try to fit explanatory covariates to the data that best describe an interpretative assumption of how the data could have been arranged within a specific context. That is the peak of complexity, in terms of quantity of the variables and the deductive interpretation that underlies the research environment. Eventually, and due to the fact that archaeology can never describe real circumstances, a strong simplification takes place that reduces the inflated requirements to a simplified model of the initial archaeological record. The archaeological record simply is not sensitive enough to meet the requirements of the accumulated explanatory variables that were chosen in search for the most complex relationship among each other and the record itself. Just like with the $DP_{climate}$, the more complex and overfitted the model, the stronger the $DP_{archaeology}$. This results in a paradox that we ultimately overload the archaeological significance instead of creating simple models of simple circumstances. In a nutshell, the more complex the ecological feedbacks of the explanatory covariates, the simpler the model of the archaeological record and hence less complex its interpretation performance.

Model adaptation and potential

Key question is how to adapt our models to overcome limitations of climate determinism or socio-cultural overfitting. A simple approach or a first attempt would be to move away from scale. With scale, I refer to absolute numbers or context-derived terminologies such as 'local' human activity ranges. Both are based on the same considerations of how fast one can move between A and B and that certainly is an individual disposition and not generally transferable—particularly under a modern perception of physical performance and the window of operation (inherent in computational analysis) (Herzog 2020; Verhagen et al. 2019). Returning to the above-described phenomenon of individual activity spheres, I argue that these are regionally (in a geographic sense) different in extent but equal in terms of providing all necessary supplies within reasonable expenditure of time and energy. Quantification (i.e., adaptation) of the model thus relies on a coefficient that best synchronises geographically different landscapes by latitude and altitude and eventually through a fuzzification of the input parameters. A basic generalisation could be to integrate climate zones, such as the Koeppen/Geiger classification to estimate continental or maritime regimes and to integrate humidity transport into the equation. Movement expenditure is equally adaptive and a generalised and corrected Digital Elevation Model (DEM) can be used to estimate topographic roughness and ultimately landscape permeability, which is the basic assumption of modelling pathways and movement corridors from accumulative cost surfaces where each cell of a raster represents cost to travel through that cell (Conolly and Lake 2014). Finally, a hydrologic system can be estimated on the basis of the DEM and the climate zone to measure (seasonally different) run-off behaviour of large streams, which structure landscapes and enable or prevent movement. Particularly important are long-term climate trends and how to integrate annual or multi-annual variability into the models. Temporal variability can be added by using large-scale climate indices based on tree ring data, such as the Palmer Drought Severity Index (PDSI) (Büntgen et al. 2021; Cook et al. 2015) or pollen data across the Holocene (Mauri et al. 2015). Although the temporal depth is currently limited to the past 2k years, PDSI provides a highly suitable indicator for climate variability on an annual scale (Kempf and Depaermentier 2023). Proxy data from ice cores and speleothems expand the possibility to add geographically local, regional and global climatic signals to potential reconstructions of palaeo-landscape developments (Affolter et al. 2019; Marsh et al. 2018). Physiological indices, such as the PDSI, are useful to estimate environmental suitability for crop production and human occupation because they represent long-term signals of drought or humid periods. A simple linear regression model would include a geographic correction coefficient that can be used to determine a site's complementary region permeability and hence acknowledge for regionally diverse range of resource availability (Kempf and Depaermentier 2023). Using the term *glocalization*, first introduced by Robertson (1995), and later discussed by Bauman (1998), I would like to refer to this correction as *Glocalization Coefficient*, which describes local (or regional) outlooks as embedded into global functionalities.

Outlook

In a rapidly changing world, models are essential parts of current scientific theory of past and future human performance. While we can actively observe today's human behaviour to draw conclusions in an inductive model, all archaeological evidence remains inherently hypothetical and deductive. Model efficacy increases rapidly with increasing sample size but decreases with growing scale of the window of operation. Mosaic ecological feedbacks and nested and interlinked functionalities do not allow for supraregional model comparison with high-resolution spatial and temporal data structure. Eventually, we might compare regionalised human patterns across larger scales solely under the assumption of a set of suitable explanatory covariates that derive from fundamental needs and demands of individuals and groups during particular chronological periods. Simple push-button comparison datasets based on static input variables that aim at explaining the observed patterns, risk underestimating environmental tipping elements and the resilience of the system. Human behaviour is closely connected to local and regional outlooks of the landscape and the socio-cultural manifestations that emerge from them. Because they are spatially and temporally dynamic, a static generalisation of archaeological explanatory models fails to properly describe human activity. We need to let go subjective and random definitions of scale, which prevent the comparison of such individual spheres of activity and rather concentrate on basic needs and demands that individuals put onto their landscapes, for example in terms of resource availability and complementary movement ranges. Such landscape affordances are ultimately controlled by landscape permeability and accessibility, and the integration of basic geographic knowledge and global driving forces enable us to create accumulated time/energy expenditure surfaces from which potential environmental penetration can be derived. Including a *Glocalization Coefficient* from palaeoclimate proxy data would then allow to increase interregional comparison of chronologically and spatially different archaeological models. These however, are subject to a large data bias, most likely generated during the inflated expectations put on the set of explanatory covariates that aim at isolating the signal from the noise. The divergence of the non-complexity or non-sensitivity of the archaeological record and the over-fitted explanatory model expectations risks an over-interpretation of the archaeological evidence. Instead, I would suggest to use simple models that acknowledge for the non-complex nature of the archaeological record.

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Additional information

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