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Developing Transdisciplinary Approaches to Sustainability Challenges: The Need to Model Socio-Environmental Systems in the *Longue Durée*

Fabio Silva [1,2,*], Fiona Coward [1,2], Kimberley Davies [1,2], Sarah Elliott [1,2], Emma Jenkins [1,2], Adrian C. Newton [1,3], Philip Riris [1,2], Marc Vander Linden [1,2], Jennifer Bates [4], Elena Cantarello [3], Daniel A. Contreras [5], Stefani A. Crabtree [6,7], Enrico R. Crema [8], Mary Edwards [9], Tatiana Filatova [10], Ben Fitzhugh [11], Hannah Fluck [12], Jacob Freeman [13], Kees Klein Goldewijk [14], Marta Krzyzanska [8], Daniel Lawrence [15], Helen Mackay [16], Marco Madella [17,18,19], Shira Yoshi Maezumi [20,21,22], Rob Marchant [23], Sophie Monsarrat [24,25], Kathleen D. Morrison [26,27], Ryan Rabett [28,29], Patrick Roberts [20,30,31], Mehdi Saqalli [32], Rick Stafford [3], Jens-Christian Svenning [24], Nicki J. Whithouse [33] and Alice Williams [34]

1 Institute for the Modelling of Socio-Environmental Transitions, Bournemouth University, Talbot Campus, Poole BH12 5BB, UK
2 Department of Archaeology and Anthropology, Bournemouth University, Talbot Campus, Poole BH12 5BB, UK
3 Department of Life and Environmental Sciences, Bournemouth University, Talbot Campus, Poole BH12 5BB, UK
4 Department of Archaeology and Art History, Seoul National University, Seoul 08826, Korea
5 Department of Anthropology, University of Florida, Gainesville, FL 32603, USA
6 Department of Environment and Society, Utah State University, Logan, UT 84322, USA
7 The Santa Fe Institute, Santa Fe, NM 87501, USA
8 Department of Archaeology, University of Cambridge, Downing Street, Cambridge CB2 3ER, UK
9 School of Geography and Environmental Science, University of Southampton, University Road, Southampton SO17 1BJ, UK
10 Faculty of Technology, Policy and Management, Delft University of Technology, MAS/TPM, 2600 AA Delft, The Netherlands
11 Department of Anthropology, University of Washington, Seattle, WA 98195, USA
12 National Trust–Heelis, Swindon SN2 2NA, UK
13 The Anthropology Program, The Ecology Center, Utah State University, Logan, UT 84321, USA
14 Copernicus Institute of Sustainable Development, Faculty of Geosciences, Utrecht University, 2584 CS Utrecht, The Netherlands
15 Department of Archaeology, Durham University, Durham DH1 3LE, UK
16 Department of Geography, Durham University, Durham DH1 3LE, UK
17 CaSEs Research Group (Culture and Socio-Ecological Dynamics), Department of Humanities, Universitat Pompeu Fabra, 08002 Barcelona, Spain
18 School of Geography, Archaeology and Environmental Studies, The University of the Witwatersrand, Johannesburg WITS 2050, South Africa
19 ICREA, Passeig L. Companys 23, 08010 Barcelona, Spain
20 Department of Archaeology, Max Planck Institute for the Geoanthropology, 07743 Jena, Germany
21 Department of Ecosystem and Landscape Dynamics, Institute for Biodiversity & Ecosystem Dynamics, University of Amsterdam, 1098 XH Amsterdam, The Netherlands
22 Palaeoecology Research Group, Max Planck Institute for Geoanthropology, 07743 Jena, Germany
23 York Institute for Tropical Ecosystems, Department of Environment and Geography, University of York, Heslington YO10 5NG, UK
24 Center for Biodiversity Dynamics in a Changing World (BIOCHANGE), Department of Biology, Aarhus University, DK-8000 Aarhus, Denmark
25 Section for Ecoinformatics and Biodiversity, Department of Biology, Aarhus University, DK-8000 Aarhus, Denmark
26 Department of Anthropology, University of Pennsylvania Museum of Archaeology & Anthropology, Philadelphia, PA 19104, USA
27 Department of Anthropology, University of Pennsylvania, Philadelphia, PA 19104, USA
28 Archaeology & Palaeoecology, School of Natural and Built Environment, Queen's University, Belfast BT7 1NN, UK
29 Institute for Hellenic Culture and the Liberal Arts, The American College of Greece, Aghia Paraskevi, 153 42 Athens, Greece

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[30] School of Social Sciences, University of Queensland, St Lucia, Brisbane, QLD 4072, Australia
[31] isoTROPIC Research Group, Max Planck Institute for Geoanthropology, 07743 Jena, Germany
[32] CNRS GEODE (Geography of Environment) CNRS, Université Toulouse-Jean Jaurès, CEDEX 9, 31058 Toulouse, France
[33] Archaeology, School of Humanities, University of Glasgow, Glasgow G12 8QQ, UK
[34] Nuffield Department of Primary Care Health Sciences, University of Oxford, Oxford OX2 6GG, UK
* Correspondence: fsilva@bournemouth.ac.uk

Abstract: Human beings are an active component of every terrestrial ecosystem on Earth. Although our local impact on the evolution of these ecosystems has been undeniable and extensively documented, it remains unclear precisely how our activities are altering them, in part because ecosystems are dynamic systems structured by complex, non-linear feedback processes and cascading effects. We argue that it is only by studying human–environment interactions over timescales that greatly exceed the lifespan of any individual human (i.e., the deep past or *longue durée*), we can hope to fully understand such processes and their implications. In this article, we identify some of the key challenges faced in integrating long-term datasets with those of other areas of sustainability science, and suggest some useful ways forward. Specifically, we (a) highlight the potential of the historical sciences for sustainability science, (b) stress the need to integrate theoretical frameworks wherein humans are seen as inherently entangled with the environment, and (c) propose formal computational modelling as the ideal platform to overcome the challenges of transdisciplinary work across large, and multiple, geographical and temporal scales. Our goal is to provide a manifesto for an integrated scientific approach to the study of socio-ecological systems over the long term.

Keywords: transdisciplinarity; archaeology; paleoecology; history; prehistory; modelling; *longue durée*

1. Introduction

Humans have been a global species since the late Pleistocene [1]. Since then, we have been an active component of every terrestrial ecosystem on Earth, even those where we do not permanently reside. Although the local impact of humans on the evolution of these ecosystems has been undeniable and extensively documented (e.g., [2]), it remains unclear precisely how our activities are altering them—influencing their character, composition, and distribution—perhaps in part because ecosystems are dynamic systems structured by complex, non-linear feedback processes and cascading effects. While ecosystems can change abruptly and dramatically because of punctuated events such as volcanic eruptions, floods, earthquakes, tsunamis, and other exogenous events, change can also be the outcome of multiple slower processes unfolding over geological and evolutionary timescales (e.g., [3]). Only by studying the deep past of human–environment interactions over timescales that greatly exceed the lifespan of any individual human (i.e., the deep past or *longue durée*), can we hope to fully understand such processes and their implications. An understanding of these interactions is also required to accurately forecast future environmental change, which is vital for informing environmental policies and management interventions (e.g., [4]). The study of human–environment interactions over long temporal scales thus provides a unique set of opportunities for sustainability science that have remained largely untapped.

The recent increase in research on the Anthropocene and related concepts such as anthromes or sociobiomes (e.g., [5–8]) has provided a powerful impetus for re-examining long-term socio-ecological dynamics. The significance of terms such as 'Anthropocene', 'sixth mass extinction', or 'great acceleration', however, like the old 'doomsday clock', lie mostly in their potency for communicating and expressing the anthropic origin and emergency of the environmental threats humanity faces to the public and policymakers. However, within academia, these terms are proving divisive, and we suggest they are, in fact, ultimately counter-productive. For example, too much emphasis has been placed on identifying the start of the Anthropocene (so-called 'early Anthropocene' vs. post-WWII 'great acceleration', e.g., [9]), whereas comparatively little attention is directed towards what we would argue are more important problems, namely understanding the underlying mechanisms regulating the mutual relationships between humans and ecosystems over time. This imbalance requires redress because, as stated above, the analysis of *long-term* dynamics has the potential to provide insights into critical contemporary issues such as the identification of sustainable land-use practices, adaptations to, and mitigations of, climate change, the context of our biodiversity crisis, and the understanding of the dynamics of collapse and recovery of both human societies and ecosystems (e.g., [4,10–12]).

A range of scientific disciplines have provided important insights into past human–environment interactions, including anthropology, archaeology, geography, history, paleoecology, and palaeoclimatology. However, such work is often focused on specific case studies and has infrequently been integrated with broader sustainability science to address modern societal challenges. Two distinct yet complementary approaches need merging. On the one hand, the historical sciences (defined here as all those disciplines which study long-term human and ecological histories and for which contemporary observational data are unavailable) are used to dealing with the *longue durée* (e.g., [13,14]). However, the relative scarcity and patchiness of empirical data and the need for integration of individual case studies to increase spatial coverage are often cited as major challenges (e.g., [15]). On the other hand, contemporary ecologists are more used to addressing present-day issues and often have an abundance of data available, but their data and questions have a limited temporal coverage, often of no more than a few hundred years at best (e.g., [16,17]). Therefore, a more fundamental challenge facing sustainability science right now is the difficulty of integrating different theories, concepts, and data on environmental and social change from the *longue durée* and from more recent studies.

In this paper, we highlight the potential of the historical sciences for sustainability science, identify some of the key challenges faced in integrating long-term datasets with those of other areas of sustainability science, and, crucially, suggest some useful ways forward. Our goal is to provide a manifesto for an integrated scientific approach to the study of socio-ecological systems (SES) over the long term.

2. The Importance of the *Longue Durée*

The first hurdle is to demonstrate the potential of *longue durée* perspectives for sustainability science. This potential has been recognized by a number of researchers throughout the last decade or more, who have suggested that an understanding of human–environment interactions in the past can be of value for understanding such interactions in the contemporary or future world (e.g., [8,10,13,18–23]). Research has confirmed that the past provides a unique repository of examples and case studies for assessing the responses of individual societies to changing climates and environments, which may have important parallels with, and thus offer useful analogies to, present-day communities (e.g., [10,24–26]). Archaeological and palaeoecological research, in particular, has contributed potentially crucial information on human responses to climatic change (e.g., demographic adaptation, migration, dispersal; technological adaptation; and other forms of cultural adaptation such as patterns of interaction, trade/exchange); as well as the influence of humans, for example, on past fire regimes (e.g., cultural burning, fire adaptation, slash and burn cultivation, agroforestry, etc.), and on wider ecosystems (e.g., human-driven extinction; domestication/cultural selection; hydrological change; anthrome formation). It has also informed on complex feedback processes between human activities and environmental change (e.g., biodiversity patterns; health and disease incidence; food webs and food security; soil erosion and land degradation, resource overexploitation; hydrology and aridity) (e.g., [14,27–40]).

However, it must be stressed that even this enormous repository of individual case studies is not in itself sufficient to understand the underlying processes involved. Firstly, the unprecedented scale and rate of change within the current environmental, ecological, and climatic crises means that one is unlikely to find direct analogues of current contexts in the past, whether recent or deep. Secondly, the interconnectivity, inter-dependability, and complexity of modern societies are not necessarily mirrored by past societies. Finally, and more fundamentally, the addition of past analogues to present-day problems does not necessarily contribute significantly to sustainability science. Tackled using pre-existing theories, methods and scales of analysis, such examples simply add to a growing set of 'illustrative' data points, each of which are limited in their temporal and ecological context.

We therefore argue that the role of the historical sciences should not simply be to furnish additional case studies, but to use these as a source of evidence for understanding the core underlying mechanisms of socio-environmental interactions over the *longue durée*. The aim should not merely be to understand why, in the face of environmental change, society *x* collapsed or why society *y* survived, but, instead, to use the *longue durée* to identify and understand the underlying dynamics otherwise hidden by the shorter duration of individual case studies (e.g., [24,41–44]). To this end, past data should be used to create theoretical models to explore current and future human–environment dynamics, for example, by helping establish robust long-term socio-ecological baselines and identifying tipping points, such as suggested by Scheffer [3,45,46]. The eventual goal of such an approach is to understand what combinations and interactions of social and ecological factors lead to adaptation, resilience, phase-shift, or extinction across all human societies and ecosystems with which they are associated. This will allow us to truly understand the dynamics underway in the present, and then use this knowledge to craft *appropriate* future-facing tools, themselves also with long-term solutions in mind.

The development of such a general understanding requires the integration and synthesis of data from case studies drawing from multiple sources and disciplines. Although historical, archaeological, and palaeoecological data inform us about the past and generally exhibit some dimension of temporality, they often result in snapshots that are plagued with sampling biases. The first step should therefore be to transform them into consistent and comparable time-series. This is not a straightforward task, but the examples of exceptional conditions of preservation clearly demonstrate the enormous potential impact of such an exercise (e.g., [46]). From this perspective, the development of new methods, concepts, and tools is imperative and, hopefully, cross-disciplinary transfer of knowledge will play a leading role in this endeavor. The creation and comparison of historical, archaeological, and palaeoecological time-series should not then be a goal in itself, but a first step towards the understanding of the processes that shape SES at vast spatial and temporal scales.

3. The Knotty Problem of Humans

A second issue is how to conceptualize the role of humans in SES. Many of the theoretical frameworks applied to understanding human–environment relationships have converged on a position that considers all components of ecosystems, whether human or 'non-human', in a non-hierarchical way, without separating humans out as exceptional or artificially distinct from their wider environments. Certainly, different elements of the world (plant and animal species, environmental processes and features, etc.) are recognized as having different characteristics and traits, and thus playing different roles in the overall dynamics of ecosystems. Yet, overwhelmingly, humans are seen as inherently entangled with, and not distinct from other aspects of, the environment (e.g., [47,48]). We suggest that such a perspective is fundamental to developing work on SES in the historical sciences. Humans certainly have some unique traits in that we are able to deliberately engineer our ecosystems over temporal and geographical scales unmatched by most other species—even if we cannot—yet?—adequately predict all the consequences (e.g., [49]). However, although we should not downplay the distinctive and catalytic role humans play, neither should we place ourselves at the center of the world. Exactly how much weight is accorded to human activity in any specific context is likely to vary depending on the research question, but we would suggest that de-centering humans is an important step towards enabling a dynamic, transdisciplinary approach that allows for the integration of key theoretical trends across the entirety of the humanities/sciences spectrum (e.g., [50], see Table 1).

Table 1. Key theoretical and/or analytical frameworks of relevance to the study of long-term socio-ecological systems.

Theoretical or Analytical Frameworks	Key Features	Example References
Dynamical systems theory, and associated theories of alternative stable states and Complex Adaptive Systems (CAS)	Strong mathematical basis, originating from physics. Relates to key concepts such as resilience, hysteresis, tipping points, and regime shifts.	[3,51–53]
Dynamics of socio-ecological systems	Involves the application of dynamical systems theory to the analysis of coupled socio-ecological systems.	[54–59]
Planetary boundaries, and concept of Safe Operating Space	Informed by dynamical systems theory, concepts of critical loads, and ecological thresholds. Developed originally for application at the global scale but now being operationalized at the ecosystem scale.	[60,61]
Disturbance theory	An unconsolidated body of theoretical ideas relating to the impacts of disturbance on ecosystems	[62,63]
Driver-Pressure-State-Impact-Response (DPSIR)	A causal framework for describing the interactions between society and the environment, widely used to monitor effectiveness of policy implementation.	[64]
Natural capital and ecosystem services; ecological economics	A framework for considering the benefits provided by ecosystems to people, the flows of which are dependent on the status of natural capital (i.e., ecosystems).	[65,66]
Behavioral ecology; human, behavioral and cultural ecology	Human cultural and physiological adaptation to local environments. Model behavioural interactions between individuals within a population from evolutionary and ecological standpoints. Themes include, but are not limited to, resource competition, mate choice, foraging strategies, etc.	[67–69]
Gene-Culture Coevolution Theory, Niche Construction Theory, Cultural Evolutionary Science; Cultural transmission theory	Model changes in behavior (often in archaeology/anthropology, in material culture) as a result of interplay between genetic, cultural, and ecological inheritance, each with its own distinct mechanism of transmission. Niche construction theory: animals alter their local selective environments to suit their preferences and lead to evolutionary response to other incumbent populations. Dual/triple inheritance: emphasizes coupling of physiological evolution and cultural transmission; alongside individuals' genetic inheritance, animals capable of cultural transmission also gain a 'cultural inheritance' of knowledge transmitted intergenerationally. In some triple-inheritance formulations, the landscape/ecosystem itself and human modifications to it also 'store' knowledge for future generations.	[70–73]
Ethnography/social anthropology/human (and animal) geography	Culture-specific ontologies of human–animal–landscape interactions. Often (particularly among small-scale and forager societies) challenges hierarchization between humans and non-humans and emphasizes an ontology of connectivity and relationality.	[74–81]
Historical Ecology; historical geography	Landscape and ecosystem transformation over time, often influenced by human activity.	[82–88]
Human Cultural/Behavioral anthropology, especially what can broadly be construed as environmental anthropology, e.g., cultural ecology, ecological anthropology, political ecology	Early integrations of ecological systems theory, human ecology and anthropology, emphasizing human interactions with the environment.	[89–92]
(Neo) Evolutionary theory	Genetic variability, mutation, etc., subject to natural selection leads to genotypic and phenotypic change over time.	[93,94]
Physical geography and earth sciences	Physical earth processes and change in physical environments over time (and secondarily their impact on animal communities).	[95]
Biogeography	Ecology at population, community, and ecosystem scales.	[96,97]
Environmental History	Partially documented temporally and geographically specific human behavior, environmental impact, and perceptions	[13,98,99]

One potentially useful perspective on dismantling human exceptionalism comes from approaches across anthropology, geography, history, and related fields documenting how differently other present and past societies conceptualize the relationships between humans, non-humans, and landscapes (e.g., so-called 'new animism' and the 'ontological turn' [78–80]; see also [100]). Empirical work in this area often has a relatively limited temporal depth restricted to the living memory of informants, although some applications demonstrate its potential for documenting and explaining longer-term human-environment relationships and socio-ecological processes (e.g., [85,86,90,101,102]). However, it provides valuable data on how human social organization relates to anhropogenic impact on ecosystems and thus exactly how human agency should be integrated into SES; for example, different family structures, reproductive strategies, and economic and cultural systems will affect the mode and scale of impacts on the environment and potentially the resilience of the society to perturbations in the wider system (e.g., Chayanov ratio: [103], also [104,105]). Such qualitative work may not always lead to specific hypotheses and methods for understanding past socio-ecological systems. Nevertheless, it has potential for informing how researchers might conceptualize such relationships in past (and present) contexts, and it illustrates how such alternate ontologies are integral to the ways in which human communities perceive and interact with ecosystems and their resources. In addition, actively considering Indigenous conceptions and knowledge of the environment is of paramount importance for conservation initiatives and sustainable management (e.g., [106–108]).

4. Transdisciplinary Integration through Computational Modelling

Traditionally, the different components of SES have been studied by distinct disciplines. However, the ongoing climate and biodiversity crisis has provided the impetus to pursue a more holistic vision, in order to understand the critical questions of: (a) how perturbations to one element of this system affect other elements; (b) how the system as a whole, as well as the individual elements, have changed over time; and (c) what kinds of changes are likely to occur in the future. It is thus abundantly clear that we cannot hope to understand the overall SES without cooperation across traditional disciplinary boundaries. This task is universally acknowledged and regularly features in lists of grand challenges and fundamental questions within the fields of archaeology, ecology, and paleoecology (e.g., [14,15,109]). Nevertheless, it remains a daunting challenge.

This endeavor presents a unique set of challenges that go beyond the mere 'borrowing' of data and information across disciplines without necessarily considering the mechanisms that create such information. Each discipline, and indeed often sub-fields within each discipline, comes with its own unique theoretical and methodological paradigms and practices (see Tables 1 and 2). The countless years of compartmentalized, hyper-specialized training and practice that researchers in different fields will have undergone further exacerbates this by brewing uneasiness on the part of practitioners at the prospect of effectively retraining in a different discipline (e.g., [110]). However, we would argue that grasping the corresponding context that gives access to the different paradigms and practices of other disciplines and sub-fields is a *sine qua non* for bridging existing disciplinary gaps.

We contend that a renewed outlook on long-term SES is possible, and that highlighting and building on commonalities across existing theories and practices can lead to new insights for modern sustainability science. However, there are practical barriers to achieving transdisciplinarity in this area, such as: How do we achieve integration of information and perspectives from different disciplines? How do we bring the useful elements of these disciplines together in a way that produces emergent benefits? We propose formal computational modelling as a platform for solving many of these issues. We acknowledge that we are far from the first to highlight the potential of modelling for the study of SES (e.g., [111–115]), and here we draw on some of this work to explore these challenges in more depth, namely: (a) how modelling can be effectively deployed as a transdisciplinary platform; (b) the incommensurability of different data; (c) the question of which scale(s) to work in; and (d) the practicalities of transdisciplinary work in the current academic landscape. In the process, we identify ways in which modelling may help overcome these challenges.

Table 2. Key data types from different fields of relevance to the study of long-term socio-ecological systems.

Discipline/Field	Relevant Data Types (Not Exhaustive)	Notes
Biology, ecology, zoology, ethology, botany	Ecological surveys; ecosystem models; genetic and taxonomic data on population dynamics and adaptive processes and pressures	Can have relatively short time-depth for empirically based, but fine detail possible; longer-term perspectives available
Earth Sciences; physical geography; paleoecology	Core samples; sedimentology; microfossil analysis; geochemistry; radiometric dating; raster and vector geographical data, e.g., survey; LIDAR etc. data; DEMs; geological data; earth systems models; ancient DNA; stable isotopes	Long temporal depth of records; often broad geographical coverage though perhaps at spatial lower resolution
Archaeology	Excavation, survey, and geophysics data; material culture and chronometric distributions in space and time; material evidence of human activity; some models on human–environment interactions; ancient DNA; stable isotopes; faunal and botanical remains	Extends back 3.3 m years though some datasets may be much more recent
History	Census data; quantitative and qualitative description of past SES; evidence of changing human perceptions of environment over time	Variable time depth; may be partial, biased, or simply incorrect; foregrounds humans
Anthropology, human geography	Qualitative and quantitative data on human societies, ideologies, behavior, demography and ecology; cultural transmission and material culture patterning in time and space, including some models	Can be relatively restricted temporally and geographically, though temporal range can extend back hundreds of years (some oral traditions perhaps even further); may be quite culture-specific; often foregrounds humans
Economics	Resource allocation models; capital flow models	Often focused on industrial and post-industrial last two centuries

4.1. Modelling as a Platform

Modelling aims to draw conclusions about the real-world system by studying simpler, indirect representations of it (e.g., [116]). In this sense, modelling is something that humans do constantly: for example, we assess whether a chair will provide stable support for sitting by comparing it with our idealized model(s) of working chair(s) based on experience. Formal modelling systematizes this process into a series of objective standards, such as algebraic formulae, rulesets, or source code. Modelling can be used with a number of goals in mind (Table 3), such as the identification, testing, and prediction of patterns in data (e.g., statistical and spatial modelling, machine learning) or to understand the process that underlies the data being analyzed (e.g., dynamic systems modelling). In a hypothetical modelling exercise, careful specification of the qualities of various cultural and environmental systems can lead to a greater understanding of which feedbacks or dynamics produce observed outcomes under varying circumstances—and which do not, the so-called 'counterfactuals' [117]. Predictions or posterior estimates based on ranges of prior parameter values (drawing on real-world palaeoecological or paleocultural data) can be directly compared to the historical and environmental records to formally assess goodness-of-fit to the real-world systems that generated it (cf. [116,118]).

Because computational modelling is formalized as algebraic equations or programming code, and often outputs graphics and statistics that summarize key results, it acts as a common language that transcends disciplinary boundaries and allows for multidirectional communication of research hypotheses, results, and inferred narratives (e.g., [119]). By acting as a *lingua franca*, modelling offers a way around the limitations of disciplinary jargon and ensuing misunderstandings mentioned above. Additionally, when the principles of open science are followed [120,121], modelling affords a high degree of transparency.

Direct access to the model's formalized dimensions (e.g., its equations and/or source code) permits anyone who learns this language to understand how a given researcher has constructed their model and analysis, which data are being used and how, and what assumptions, trade-offs, and (mis)representations are inherent to the model's formulation. Importantly, this is true regardless of whether the researcher is explicit about, or even aware of, their own biases or mistakes. Which features of the real-world system a modeler elects 'to represent, and which to misrepresent with idealizations' [116] are laid bare, rather than occluded, while open access to the model's equations or source code and their inner workings makes the scholarly endeavor more conducive to transdisciplinary engagement.

Furthermore, the creation of factual and counter-factual narratives in silico can lead to deeper questions about the dynamics of SES. Even if they cannot always be deployed in such a way to allow for a direct comparison of predictions with real-world data, simulations can still be vital for producing—and mediating—shared understandings of the modelled systems. We suggest that it is crucial for incorporating diverse perspectives on and experiences of socio-ecological change over very long timescales, where outcomes are unpredictable at the outset or sensitive to initial conditions. Integrating information that transgresses multiple spatio-temporal scales and disciplines also necessarily means building towards a shared understanding of the limitations and possibilities it encodes, *a priori*. Acting as facilitators of dialogue and reflexive practice within and across fields, models can be useful for communicating across stakeholder and academic communities regarding which mechanisms may be important subjects of future enquiry, or potential targets for intervention [119,122,123]. Thus, model development may also support transdisciplinary and multi-scalar thinking.

Table 3. A non-exhaustive list of modelling approaches relevant for transdisciplinary research into long-term SES with key features, strengths, weaknesses, and references.

Modelling Approach	Key Features	Strengths	Weaknesses	Example References
Statistical Modelling/Data Analysis	Identifies significant patterns in datasets; identifies correlations across different datasets/variables	Variety of algorithms, including bespoke ones; diversity of approaches (e.g., frequentist, Bayesian, likelihood-based); closer to the data; works at multiple scales	Not process driven; mostly identifies correlation, not causation (but see [124])	[125–128]
Machine Learning/Artificial Intelligence	Makes predictions based on a training dataset	Very powerful prediction toolbox, given a large enough training dataset	Inferred causation chain is often hidden (blackbox), hence not always good to understand underlying mechanisms	[129]
Species Distribution Modelling (SDM)	Model habitat suitability in space and potentially over time by correlating occurrence records or physiological data with spatial environmental data.	Numerous algorithms; interactivity; interpolation; receptive to different data	Arbitrary variable selection; human versatility and behavioral plasticity; difficult differentiation between potential and realized niche	[130–134]
Paleoenvironmental reconstruction (PER) and Land-use Modelling	Employs micro- and macrofossils, eDNA, isotopic data, geochemical and molecular proxies to reconstruct climatic and environmental attributes, biomes, land cover and land use over time	Data-driven; potentially multiproxy (pollen, spores, chironomids, beetles, diatoms, biomarkers etc.); low to (sub) annual temporal resolution; physical and biological components of systems; large-scale spatial summaries; evaluation of paleosimulations	Time-consuming and expensive laboratory procedures involved; cost of dating sediments	[135–141]
Agent-based modelling (ABM)	Model agent–agent and agent–environment interaction with algorithmic procedures, which can be probabilistic	Free choice of appropriate scale; highly expandable; captures global patterns from local behavior	Potential complexity; misspecification of interactions; 'begging the question'; computational intensity	[142–146]
Dynamical systems modelling	Typically constructed from linked differential equations	Strong theoretical basis and already applied in a wide range of disciplines	Top-down initialization; formalism; often difficult to testempirically	[3,71,72,147,148]

4.2. Data Challenges

A major obstacle to achieving transdisciplinarity among the vast range of disciplines that can potentially contribute to studying SES is the equally broad variety of data available (see Table 2), subsequent difficulties of integration, and the fundamental issue of the different epistemologies underlying the various datasets. The social, natural, and physical sciences have long-standing traditions of fieldwork, which have independently led to the accumulation of stocks of greatly varying empirical evidence. In practice, scholars from distinct disciplines often have a limited knowledge of what kind of data other disciplines can provide, and how to identify and locate them. The increasing use of dedicated, preferably open-source repositories and licenses, and of the FAIR principles [149], should address some of these issues in the short term. Recent initiatives to raise awareness of the existence and potential of their own forms of evidence are also noteworthy, including the promotion of archaeological records as legacy data for paleoenvironmental research [150], though evidence of systematic successes in crossing disciplinary silos is not yet clear.

More fundamentally, however, transdisciplinary research implies not only participation across disciplines, but also an understanding of the nature and quality of each discipline's data. Data are rarely, if ever, 'raw', but rather processed, transformed, and modelled in one way or another prior to their wider dissemination. Raw data are themselves subject to processes of collection and presentation that are often tacit and implicitly inculcated in new generations through discipline-specific training. As methods develop, the possibility of any one individual understanding all of the assumptions, biases, and idiosyncrasies of different forms of data, even within one's own discipline, let alone across multiple disciplines, becomes nearly impossible—further highlighting the need for transdisciplinary collaboration. Researchers will also need to formalize and share protocols for data manipulation that are often implicit to specific disciplines and fields, in order to maintain awareness of the uncertainties inherent to different datasets and their effective limits and potentials, thereby preventing one from unwittingly reproducing and amplifying data-related noise. Standard protocols and tools for the publishing of source code and modelling results (e.g., [120,151] can potentially be useful here, but their use is currently restricted to more computational disciplines and fields, with researchers from the social sciences and humanities being deterred from using them by lack of familiarity (whether real or perceived) with the skillsets required.

A further complication is that the resolution of the empirical records rarely matches the temporality of the socio-ecological processes involved. For example, the archaeological and palaeoecological records rarely yield results at the temporal scales at which past human agents made decisions, despite the fact that the patterns and processes of interest may have been caused by mechanisms operating at those scales. The reverse is equally true: just because anthropologists have data on human decision-making or discrete behavioral events does not mean that those decisions and events were easily separable from broader historical and environmental processes. In short, it is not always straightforward to identify the relative importance of the long and short term as causal drivers of socio-environmental dynamics. As anyone with first-hand experience in transdisciplinary research can attest, these challenges in integrating complex datasets extend beyond the issue of scale (e.g., [152]), as discussed below.

We argue that the very heterogeneity of past cultural and ecological data is what necessitates formal, transdisciplinary model-building approaches; stating problems in clear probabilistic and/or mathematical terms is the only way to directly account for the sheer variety of different data sources and their inherent issues. Computational modelling makes it possible to analyze and synthesize information from different sources, such as Neotoma [153], SESHAT [154], various continental-scale pollen databases [155–157], ArchaeoGlobe [158], LandCover6k [159], People3k [160], the Paleobiology database (https://paleobiodb.org/ accessed on 1 June 2022), HYDE [161], and the Global Biodiversity Information Facility (https://www.gbif.org/ accessed on 1 June 2022). To account for often wildly varying quality, including but not limited to coverage, resolution, or the various inherent uncertainties of, for example, chronometric, species identification, and cultural data, such computational models can be constructed in such a way as to incorporate insights from a variety of sources and disciplines concurrently.

4.3. The Question of Scale

A second significant challenge to transdisciplinary integration relates to the different spatial and temporal scales involved within and between different fields (e.g., [115,162]). Roughly speaking, one can make a general distinction between fine-grained data on the behavior of individuals or populations over a reduced number of generations (data stemming from anthropology, history, geography, sociology, neoecology) and the considerably longer time scales of earth science, paleoanthropological, and palaeoecological data. However, these distinctions are far from monolithic and, at least in theory, many disciplines embrace multiple temporal and spatial scales. In practice, there is often a lively and at times fractious debate over the appropriateness of temporalities that are viewed as vying for supremacy. In archaeology, for example, there is a long-standing tension between the desire to conduct what are essentially prehistoric ethnographies and the desire to do 'big' history/human ecology, *macro-archaeology* [163,164], or *macro-ecology* [165]. Although archaeologists are arguably at ease working at a (micro-)regional level, it can be said that 'big' (pre)histories have mounted a strong fightback in recent years, fueled by the increasing amounts of digital data and greater processing power, with calls for larger and/or more explicitly comparative studies [99,166,167].

Advocates of theory-driven, as well as of data-driven analyses, tend to overlook the fact that SES are multi-scalar, both temporally and geographically. Recognition of the complexity and the sheer range of variables of relevance to SES immediately entails acknowledging that no one single scale of analysis is sufficient (Figure 1). Some earth-system processes, such as tectonics, may unfold over millennia or eons, whereas catastrophic short-term events, such as mass wasting events or landslides, can cause dramatic environmental changes over the course of days or even hours—their geographical coverage being equally diverse. Biological processes include long-term evolutionary processes, such as speciation, cladogenesis, and extinction, over millennia as well as population cycles operating at much shorter timescales. At the individual level, on the other hand, the relationships between genotypic mutation, selection, evolution, and individual development, growth, acclimatization, reproduction, behavioral strategies, and decisions are enormously complex. Biological processes therefore range from the rapid, highly localized firing of a single neuron to the long-term, and often spatially broad, phylogenetic history of Earth's biota. Even the humanistic disciplines must necessarily grapple with long-term historical and socio-economic processes extending over multiple generations versus individual decision-making—with the two inevitably enmeshed in a complex mutual relationship.

Against this backdrop, we suggest that due to the inherent multi-scalar quality of long-term socio-environmental processes, the search for a 'correct' scale is an analytical and ontological red herring. Emergence of high-level outcomes from low-level processes occurs, by definition, between scales. Thus, we argue that any long-term transdisciplinary view on SES should be explicitly multi-scalar. Indeed, a significant part of the purpose of studying SES is to better understand the interrelationships between these multi-scalar processes and their effects. Smaller-scale analyses provide extensive information on the range of behaviors and tolerances, and hence the resilience of individual agents/components to system perturbation; however, it remains imperative to ensure that researchers can see the 'wood for the trees', moving away from the collection of individual case studies to identify what distinguishes societal and ecological failures from successes. To achieve this, it will require the building of a truly transdisciplinary theory that accommodates and supports the need to tack between large-scale patterns, geographical and/or temporal, and small-scale patterns reflected in intra-site or intra-regional analyses.

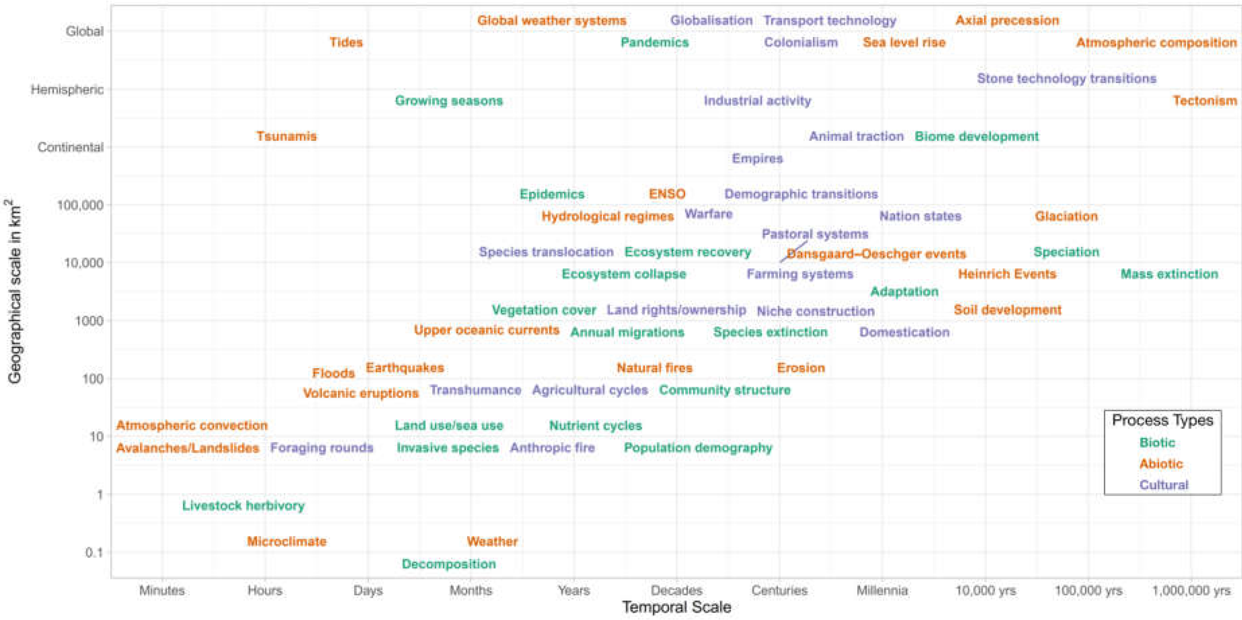

Figure 1. Examples of abiotic (orange), biotic (green), and socio-cultural (purple) processes and their geographical (vertical axis) and temporal scales (horizontal axis).

Instead, much of the attractiveness of SES stems from their transgression of multiple temporal and/or spatial scales concurrently, for which practitioners require computational modelling to fully grasp. In fact, the very premise of simulated-based approaches, such as agent-based modelling or individual-based modelling, is to start with a set of small-scale algorithmic rules to observe medium to large-scale effects [41,112,146,168]. A typical example would be the specification of household-level farming behavior [105,169–171] as an agent-based model to generate system-level patterning in a simulated archaeological [172–175] or environmental [176–179] record. Models are also rarely composed of bottom-up interactions alone; imposition of external drivers of agent behavior are important for understanding the systemic effects of such drivers at lower scales [180]. Modelling offers a way to escape debilitating debates about which scale is the most appropriate and, instead, start exploring the range of scales of interest and feedbacks between them. This shift in emphasis allows archaeological and paleoenvironmental modelers to focus on which tools serve their goals best. Where good information is available on individual-level motivations or behaviors (however an 'individual' is defined) but the functioning of a system is less clear, agent-based models may be a more useful point of departure. In cases when system-level parameters, drivers, or interactions are more readily defined and individual decision-making is less pertinent, algebraic systems modelling may offer a more parsimonious or accessible point of entry [181]. Whether as a collection of algebraic equations in dynamical systems models or as algorithmic rulesets in agent-based models, either set of approaches can be deployed in a multi-scalar capacity to generate predictions about complex socio-environmental systems in deep time.

Other scale-transgressive computational approaches that have made significant methodological strides in recent years but as yet little widespread or systematic use with archaeological and/or paleoenvironmental data, include ecological networks [119,174,176]. Ecological networks are flexible and robust tools for modelling relationships between individuals, species, or assemblages of species across space and in time, in order to understand how they interact, how they differ, and their ecological roles and effects [182]. We anticipate that the ability of ecological networks to handle very complex interactional data, while simultaneously accommodating humans' frequently outsized role in shaping their environments, will appeal to both 'natural' and 'social' scientists working in deep time (e.g., [11]).

5. The (Im)practicalities of Transdisciplinarity

A commitment to transdisciplinarity poses still further challenges, particularly to collaboration between the sciences and the humanities or between qualitative and quantitative approaches. Often a mismatch in expectations and the misunderstanding or assumptions of each other's theoretical perspectives and methodological approaches can hamper attempts at collaboration. One example is the formal incorporation of human agency into broader ecosystems in computational modelling that is, from the perspective of some other theoretical perspectives, often seen as reductionist, overly globalizing, oversimplifying, and incapable of encompassing the complexity of both data and lived experience, in the past and the present. Although this is true to some extent, modelling reflects a commitment not simply to reconstruct and document complexity, but to attempt to understand the deeper processes at work. For some, this is an acceptable trade-off, for others not. The key here is simply to recognize and reiterate that neither approach is inherently *better*, but has different aims which need not be mutually exclusive. Formal, simplified models are not preferable to detailed empirical analysis, but help to knit evidence bases together, whereas empirical analysis is always crucial for ground-truthing and the evaluation of more abstract models. Transdisciplinarity does to some extent require simplification: any transdisciplinary object architecture requires an explicit formalism to translate hypotheses and causalities suggested into rules. In this sense, and if only for practical reasons, simplification is a necessary step.

Such simplifications, however, entail further issues relating to the need to integrate different academic communities of practice: 'shortcuts' or methodological idiosyncrasies and informal but widespread 'hacks' differentiate academic communities, even when using similar data and/or methodological tools, and can hamper communication and genuine transdisciplinary working. Attempts to address this, for instance by formalizing criteria for comparing results beyond a simple juxtaposition of data collections, can be interpreted as overbearing attempts to encroach into other disciplines and consequently met by academic 'boundary policing'. The corollary of this is of course that genuine transdisciplinarity requires a certain amount of trust between disciplines [114]. Not everyone—perhaps no one individual—in the team will genuinely understand at a fundamental level *every* aspect of the project: if they did, there would be no need for collaboration. Instead, multidisciplinary teams must trust their collaborators to be responsible for some aspects of the project in which they lack expertise.

A related point is the need to develop shared terminologies, a seemingly simple yet practically complex task even within disciplines, let alone across them. Concepts that are borrowed and adapted from one discipline are often disassociated from the theoretical and methodological frameworks which underpin them, thus potentially adding confusion to cross-disciplinary dialogue as 'the same' concepts are interpreted and applied in different ways. Such confusion also, of course, persists and is arguably amplified when it occurs between academia and other audiences: notions such as 'ecological baselines', or 'native species', are fashionable amongst policy-makers, but deeply problematic conceptually, and ultimately of limited scientific relevance and application (e.g., [183,184]). For example, terms taken from their original context often evoke dramatic and typically negative images associated with modern and future sustainability, such as 'tipping points', 'collapse', and 'catastrophic shifts'. Such terms carry strongly negative connotations which are not always warranted even from a human-centered perspective: is a phase-shift among human cultures from settled village agriculture to pastoralism genuinely a 'collapse' when de-coupled from western-centered narratives of 'progress'? We suggest that the underlying values and assumptions behind each term should be made explicit by each researcher or publication, thereby allowing for greater transdisciplinary transparency. In addition, a more mature engagement with the theoretical frameworks of the disciplines with which we work will allow for better integration with other sustainability sciences.

Creating a common language and research community implies a reliance not only on good will, but also on an explicating and balancing formalization of counter-powers between research partners. Some methods of terminology and concept co-construction are already used in rural development issues. The method called ARDI (Actors, Resources, Dynamics and then Interactions) is a step-by-step collective work, going through different sessions of identification and connection [185]. This method of formalizing the components of a system has the advantage of integrating the points of view of the different actors and, first of all, of bringing out the divergent meanings in order to create a common vocabulary and perception and by then, a common conceptual model of an issue. It is therefore a deliberately long process which clarifies some elements of affect and power relations inherent in any community, including the academic one and by putting to rest some domination processes (gender, ethnicity, age, institutional and/or financial power). Such method is often disregarded and considered as a waste of time at the outset but creates a form of community of thought around the research question, a community which must be maintained as the research work progresses but constitutes a very strong asset when facing unavoidable conflicts, urgent deadlines, divergences, and practical issues.

However, even where the transdisciplinary spirit is willing, the practicalities of academia may provide additional constraints. A more detailed discussion of some of the logistical and practical barriers to transdisciplinarity are provided in Saqalli and Vander Linden [114]. Key points here are that although research bodies and institutions have over the past couple of decades increasingly favored transdisciplinarity, at least officially, considerable evidence in fact suggests that transdisciplinary proposals are less successful at attracting funding than traditional individual discipline-based ones (e.g., [186]). As our respective disciplines have grown exponentially more complex and specialized, it is becoming increasingly difficult to master, balance, and therefore evaluate a large breadth of methods, questions, and the current state of knowledge, just in one's specific research area, let alone that of a different discipline. One could argue that transdisciplinary research is more difficult to devise, plan, and 'sell' on the part of grant applicants, but also to evaluate on the part of reviewers. As noted above, the simplification inherent in transdisciplinary endeavors may paradoxically make the mooted project more difficult to accept by both/all parties, since it does not conform to the norms of individual disciplines.

Furthermore, one should not minimize the significance of individual disciplines not just in the local intellectual, but also in the administrative landscape. For instance, Rockman and Hritz [187] argue that, in the USA, the lack of an easily identifiable agency responsible for archaeology and cultural heritage hampers the interaction of both fields with other disciplines and their eventual integration within transdisciplinary initiatives. Meanwhile, Saqalli and Vander Linden [114] note that it takes a lot of time and misunderstanding before progressing beyond clichéd understanding of other perspectives, both in the UK and France. Seniority and budget-originated dominations can also have huge impacts on mutual acceptances. The practicalities of communication and cross-referral across UK funding bodies likewise act as a 'drag' on genuinely novel transdisciplinary endeavors, a problem that perhaps does not hamper 'pure' climate scientists or earth scientists in the same way or to the same extent.

6. Concluding Remarks

We have stressed the need for sustainability science to recognize and embrace the true value of the historical sciences and past data to enable a step-change in our understanding of how socio-environmental systems evolved over long temporal and spatial scales. In this process, we have also identified key challenges faced in integrating such long-term datasets across different disciplines. Given the multiplicity of actors and the manifold non-linear causal mechanisms which are involved in socio-environmental systems at a variety of scales, we have proposed the use of computational modelling as a means of integrating and exploring information from a wide range of sources. We also provided some suggestions about how to build on these disciplinary foundations to achieve a more integrated understanding of long-term socio-environmental systems. In doing so, we recognize that no single approach will ever meet all requirements. Rather, our aim here was to highlight some potential ways forward, but not to constrain the innovation and creative thinking that is certainly needed to move forward.

Hopefully, our suggestions will provide an exploratory roadmap for a unified approach to the study of socio-ecological systems, one that does not ignore the *longue durée*, one that is focused not on individual case studies but on developing our understanding of system dynamics across different geographical and temporal scales, and one that relies on computational modelling as the substrate upon which to build this but is still cognizant of the value of qualitative analysis and insights from humanistic disciplines. We contend that such an approach will be essential to tackle the present-day and near-future environmental challenges the world faces.

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