Earth System Economics: a bio-physical approach to the human component of the Earth System

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Abstract. The study of humans has largely been carried out in isolation from the study of the non-human Earth system. This isolation has encouraged the development of incompatible philosphical, aspirational, and methodological approaches that have proven very difficult to integrate with those used for the non-human remainder of the Earth system. Here, an approach is laid out for the scientific study of the global human system that is intended to facilitate seamless integration with non-human processes by striving for a consistent physical basis, for which the name Earth System Economics is proposed. The approach is typified by a foundation on state variables, central among which is the allocation of time amongst available activities by human populations, and an orientation towards considering human experience. A framework is elaborated which parses the Earth system into six classes of state variables, including a neural structure class that underpins many societal features. A working example of the framework is then illustrated with a simple numerical model, considering a global population that is engaged in one of two waking activities: provisioning food, or doing something else. The two activities are differentiated by their motivational factors, outcomes on state variables, and associated subjective experience. While the illustrative model is a gross simplification of reality, the results suggest how neural characteristics and subjective experience can emerge from model dynamics, including transient golden ages. The approach is intended to provide a flexible and widely-applicable strategy for understanding the human-Earth system, appropriate for physically-based assessments of the past and present, as well as long-term model projections that are naturally oriented towards improving human well-being.

1 Introduction

Over the past four decades, Earth system science has developed a rich understanding of interactions between the myriad physical, chemical and biological components of our planet (Steffen et al., 2020). By considering the Earth as a single system, which is itself comprised of a hierarchy of mechanistically-interacting subsystems, Earth system science has facilitated the challenge of thinking across vast scales of space and time, and contextualized global change within the long-term evolution of life (Lenton et al., 2011). In its quest to understand planetary functioning, this new science has succeeded in crossing many disciplinary boundaries, developing entirely new approaches - such as global carbon cycle science (Falkowski et al., 2000) - and, in return, has brought fresh thinking to the previously isolated disciplines from which it was born.

Yet, despite being motivated by the human impacts on the planet, Earth system science has done relatively little to directly incorporate humans themselves (Motesharrei et al., 2014; Donges et al., 2017; Calvin and Bond-Lamberty, 2018). For example, although the seminal textbook by Kump et al. (2004) discusses human impacts on the planet at length, there is no mention of human demographics, societal dynamics, or well-being. Instead, the impacts of the human system are viewed as external forcings on the non-human Earth. This exclusion is particularly clear when considering Earth System Models (ESMs), the numerical flagships of Earth system science. ESMs encapsulate the current understanding of the planet by representing the component systems in a simplified fashion, integrated within a seamless framework and discretized on a global grid. Because all component systems co-exist within the same spatial framework, and because they are based on common foundations of biology, chemistry and physics, the means of exchange between the component systems are obvious, so that they can be integrated as a whole to provide a synoptic global view. But ESMs do not include the global human system within the same common foundations and, as a result, the synoptic perspective of Earth system science typically fails to include its most rapidly changing and disruptive component (Mote et al., 2020). This is not to say there are no efforts in this direction, for example macroeconomic models are frequently run in parallel with ESMs while exchanging information on greenhouse gas emissions and increasingly sophisticated land use changes (Rounsevell et al., 2014), an approach known as Integrated Assessment Modelling. But this approach is targeted primarily toward weighing 21st century climate change impacts vs. greenhouse gas mitigation strategies (Nordhaus and Yang, 1996; Van Vuuren et al., 2007; Anderson, 2019) rather than to provide fundamental insight on the global human system. 'Sectoral' models often resolve geographically-explicit interactions between humans and specific Earth system components, such as the agricultural system (Rosenzweig et al., 2014), or global marine fishery (Galbraith et al., 2017), but the fragmented sectoral approach does not naturally build toward what Voinov and Shugart (2013) call an 'integral' perspective on the human-Earth.

Why has there not been more effort devoted to the human component of Earth system science? I suggest three reasons (though there are certainly more). First, biologically-identical humans have interacted with the Earth system in very different ways when living under different social and technological contexts. For example, a hunter-gatherer society has extremely different per capita impacts on the Earth system than does a 21st-century urbanized society. Thus, assuming a fixed set of functional characteristics for our species - a strategy that works quite well for other organisms within the Earth system - fails to address the most remarkable features of humanity. Second, we care a lot about what humans think and how they feel, which can make scientists hesitate to simplify features of humanity in the way frequently done for other components of the Earth system. Third, there is a vast cultural gulf between natural and social sciences, that is very difficult to bridge due to profoundly incompatible literatures. This gulf has left each culture largely ignorant of the other, a problem that was identified decades ago (Snow, 1959) and continues to persist.

At the root of the natural-social science divide lies the difficulty of linking the essential features of humanity - including knowledge systems, social behaviour and experience - to physical embodiments. This may reflect the historical development of social sciences and humanities, originating as they did when virtually all people believed in an eternal, disembodied soul

(McDonald, 1993). Thus, although many modern social scientists probably do not subscribe to this belief, the underlying conceptual frameworks and approaches remain aligned with its tacit implications, and many core features of social science, such as values, beliefs and norms, continue to depart from non-physical starting points (Bouchaud, 2008). Differences in these non-physical starting points have led, in turn, to a plethora of fields of human study, among which there is little common ground, hampering interdisciplinary progress.

Yet, like all living organisms, humans are physical beings. The biological reality of human bodies embeds us within ecosystems, and links us to biogeochemical cycles through our food production, material fluxes and waste flows (Haberl et al., 2019). The fact that each of us can be only in one place at a time, and engage in a limited number of activities per day, places fundamental physical constraints on our economies (Becker, 1965). In addition, advances in neuroscience now provide rich and compelling evidence that everything that once appeared to be attributable to a disembodied soul is actually formed 'by the meat', i.e. as emergent properties of our brains (Clark, 2015). The intricate network of synapses in each of our heads determines what we think, how we feel, and who we are (LeDoux, 2003). These synapses are continually changing as we go through our daily experiences, at rates that are biologically constrained (Ascoli, 2015). Thus, just as knowledge of the molecular processes occurring within leaves can help to predict aspects of the global terrestrial ecosystem (Stocker et al., 2020), there is good reason to hope that many aspects of humanity, historically considered unquantifiable, can actually be better understood by considering how they emerge from the physical constructs of synaptic networks. Neuroscience still has much to learn about the functioning of the brain, but it holds great promise as a common ground to help unify the fragmented domains of social science (Boyer, 2018).

The lacklustre development of the human component of Earth system science is also evident in its failure to enrich the scientific understanding of humans themselves. This is in contrast to integrative Earth System approaches such as ocean biogeochemistry, which has provided important insights on marine ecology (e.g. (Follows et al., 2007)). Early work under the name of human ecology made significant progress toward modeling hunter-gatherers through their interactions with the environment (e.g. Winterhalder (1993)), providing valuable insights for anthropology and sociology, but these works were not widely seized upon. There have been very few Earth system-scale studies that ask fundamental questions about the physical coupling of humans with the ecosystem (Motesharrei et al., 2014) and even fewer that explore the implications for the quality of human existence. Yet human well-being is of central importance to social science and policy-makers, and could either improve or deteriorate dramatically in future, depending on societal choices (Barrington-Leigh and Galbraith, 2019).

Here a strategy is pursued to provide a seamless integration of human and non-human parts by representing humans on a biophysical foundation. The strategy aims to facilitate new forms of communication, to help connect knowledge at the juncture of natural and social sciences, with the aspiration of providing new insights for both human and non-human systems. The name Earth System Economics (ESE) is proposed for the endeavour, though as discussed below, it differs from mainstream economics in a number of important ways. Section 2 gives a few examples of the types of problems that could be addressed with ESE. Section 3 provides an overview of the key guiding principles that motivate the ESE approach. Section 4 details a high level conceptual framework for the global human system. Section 5 describes a simple numerical model of the global human system, inspired by simple models of the global carbon cycle (e.g. (Sarmiento and Toggweiler, 1984)), as an illustration of how the framework can be operationalized. Section 6 provides analysis and discussion of the model. Section 7 offers concluding comments.

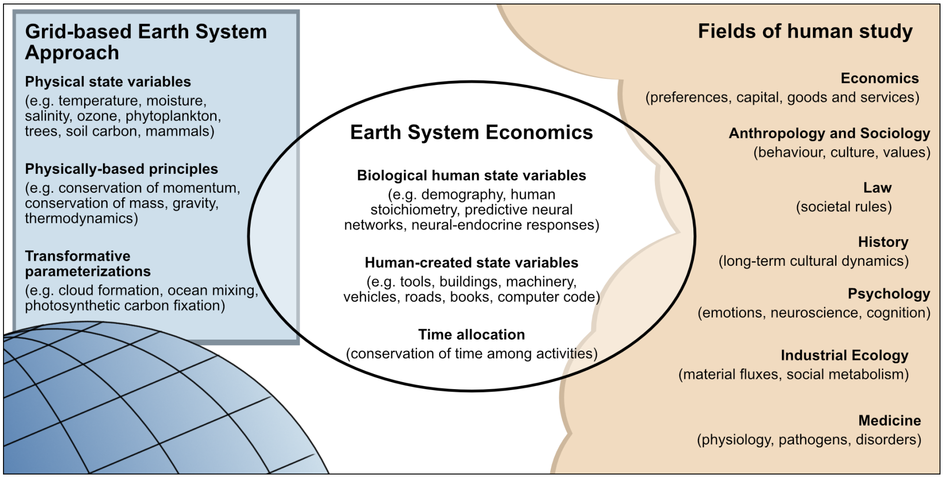

Figure 1. ESE provides a bridge between the Earth system science approach, typified by Earth system models, and the diverse fields of human study.

2 Topics that could be readily addressed with Earth System Economics

As ESE is a new approach, it is difficult to foresee all applications that may arise from its development. Some of the more obvious applications include:

1. Gaining a mechanistic, birds' eye perspective on the spatial and temporal coupling between global material flows and human activities. Essentially, capturing the human system as an integrated part of global material cycles with the ability to resolve high spatial resolution.

2. Testing hypotheses in historical dynamics (Turchin, 2018). In the same way that Earth System models can be used to test hypotheses about past climate changes, ESE models could be applied to test hypotheses about past changes in the human system. For example, what emergent features are required to accurately hindcast the spatial progressions of key societal transitions in history, such as the neolithic transitions, or industrialization?

3. The spatial and temporal dynamics of human interactions with ecosystems and consequences for biodiversity. Tight coupling with physically-based biodiversity models can provide new tools with which to test hypotheses regarding early mass extinctions due to hunter-gatherers, or the controls on future threats to ecosystem stability in a spatially-explicit context.

4. Mechanistic linkages between subjective well-being and the biophysical consequences of societal actions. How could human lived experience vary given different societal pathways and within physical constraints, including coupled Earth System impacts such as climate change and biodiversity loss?

Most of these complex problems have been addressed by other means, especially at local scales, but all remain incompletely resolved. The ESE approach can provide a novel global, integrated view, while prompting new avenues for mechanistic insight. The approach is expected to be more widely applicable than indicated by this short list.

3 Guiding principles of Earth System Economics

In a nutshell, ESE aims to quantify physical aspects of the human-Earth system (state variables), including how the physical state is dynamically altered by human actions (time allocation) and consequences for the nature of human experience. In this section, a few general principles are discussed, as motivation for the framework which follows.

3.1 Striving for physical foundations

Foremost, ESE strives for a grounding in quantifiable, physical terms. Physical variables exhibit persistence over time, and physical processes impose firm limits on possible rates of change, leading to dynamic predictability. Physical variables also lend themselves to strict definitions, which can prevent double-counting, while simultaneously helping to ensure inclusivity. Much of the predictive success of natural sciences lie in their ultimate recourse to physical variables, which provide pathways to diverse insights whether starting from biology, physics or chemistry. For example, the conservation of mass, momentum and energy play essential roles in many branches of Earth system science, from atmospheric circulation to ice sheet motion and sea level rise. Ecosystem and biogeochemical models benefit from the understandings of living processes as molecular interactions writ large.

That said, the aim to ground the human system in physical quantities is not trivial. For some things - population demographics, cars, infrastructure, fossil fuel consumption - it is straightforward. But for many of the most fascinating and important aspects - such as behavioural motivations and subjective experience - the biophysical bases remain vaguely described. Operationally, it will always be necessary to use coarse approximations for these (and other) unresolved or poorly-understood processes, a common strategy in Earth system models, such as the representation of cloud physics with empirical parameterizations. These parameterizations are always unsatisfying, but the fact that they are explicitly recognized as unsatisfactory and can ultimately be replaced by more physically-grounded mechanistic understandings identifies a direction for progress. Resolutely abstract variables, on the other hand, resist connection to complementary scientific insights, and reinforce disciplinary silos. Thus, the important thing is that strengthening the physical foundation is ever present as a central goal of ESE: that long-term progress can be made by improving the physical representation of all aspects of the human system, through improved observations and theoretical development.

3.2 Quantification of activities

The diversity of human endeavours can be overwhelming, and might appear to defy a recourse to conserved quantities in the way that the motion of fluids is linked to momentum and density through the Navier-Stokes equations. However, there is no question that the amount of time available to each human is a strictly-conserved quantity. All humans engage in some form of activity for exactly 24 hours per day. The activities in which a population is engaged determine its impact on the biophysical reality, and also play a major role in determining the subjective experience of its individuals. Thus, activities are employed here as the central feature of ESE.

There does not exist a universal system for classifying activities. Even the activity of a reader of a scientific article can be described in many ways, which may include: reading, working, thinking, learning, sitting, using a screen/computer. The activity may be subjectively enjoyable or unpleasant, depending on the quality of the text and disposition of the reader. The optimal strategy to classifying activities would involve as little subjective interpretation as possible, and be grounded as firmly as possible on physical features, a possibility that could be further developed elsewhere. For the moment, it is sufficient to consider this a difficult and incompletely-resolved problem.

In the absence of a universal lexicon of activities, applicable to all humans at all times, a lexicon must be constructed for a particular purpose. An activity lexicon must identify, as unambiguously as possible, a set of mutually-exclusive activities that together include all possible activities available to the population. Thus, the fractional distribution of time between the activities must sum to exactly one. For example, a simple two-activity lexicon would be sleeping and not-sleeping. To be useful, the lexicon should align activities with the outcomes that motivate them, by considering how they modify state variables.

3.3 Subjective experience

Humans live rich inner lives, and individuals can be either filled with joy or tormented by suffering, depending on what circumstances befall them. Improving the inner life experience of humans has pre-occupied much of society for generations, and remains a central goal of global society, as exemplified by the UN Sustainable Development Goals: eleven of the seventeen goals are oriented towards improving the life experience of humans, while only six are oriented toward maintaining physical health, material welfare and non-human aspects of the planet. Given that subjective experience appears to be the top priority for most of humanity, it is explicitly included as an essential component of the ESE approach.

Despite its importance, the biophysical understanding of subjective experience remains rudimentary (e.g. Alexander et al. (2020)). It will take many years of additional research before quantifications are available to assess human experience that rival, for example, our ability to quantify the concentrations of trace gases in the atmosphere. Nonetheless, the field of subjective wellbeing has made great strides in providing large datasets on how people themselves evaluate their life experiences (Diener et al., 2018). These can be considered along two axes:

1. affect: the momentary emotions felt throughout the day, sometimes assessed by asking a subject whether they felt positive or negative emotions (e.g. laughed, cried, felt angry) over some preceding time interval (Csikszentmihalyi and Larson,

2014), or by asking a candidate to rank the pleasantness (Gershuny and Sullivan, 2019) or unpleasantness (Kahneman and Krueger, 2006) of different activities.

2. cognitive life evaluation and eudaemonia: for the former of these two time-integrated measures, the subject is asked to consider their life as a whole, and evaluate their level of satisfaction with it, usually on a 10-point scale. The results are often correlated reasonably well with affect, and can be predicted to some degree from material and non-material variables (Helliwell et al., 2012; Barrington-Leigh and Galbraith, 2019). The term eudaemonia refers a fulfillment of purpose, and is often oriented towards philosophical goals of what life ought to be, rather than one that is desirable on purely hedonic terms (Ryan and Deci, 2001). Although a major concern of society on historical timescales, often addressed through religion, eudaemonia has been less studied in recent years, with less effort dedicated to developing quantitative indices.

These axes of subjective wellbeing do not capture all that is important to human experience, and the difficulty of comparing assessments between cultures and languages cannot be taken lightly. But it appears likely that the quantitative basis for constructing population-level assessments of life experience will continue to improve as time progresses.

3.4 Drawing on all fields of human-related science

Many disciplines study humans, including the core social sciences of economics, anthropology, sociology and psychology, as well as history, medicine, law, business and education. All of these disciplines can provide useful insights on the global human system. For this reason, ESE aspires to establish common ground that is compatible with aspects of all fields of human study, by explicitly considering the physical foundations that underly them.

So why use the term ‘economics’? In its modern use, this term has become narrowly associated with the distribution of scarce resources, the production and consumption of goods and services by firms and households, and monetary exchanges. However, the origin of the word, from the greek *oikonomia*, referred to managing the home in a rational way in order to benefit its occupants (Leshem, 2016). The root *oiko* is also the basis of ‘ecology’, study of the home. The aim of the current proposal is to provide an additional means for holistic, science-based perspectives to assist in rational decision-making that can improve the management of the wealth of our common home, the Earth system, for the benefit of its inhabitants. Hence, the usage here is consistent with the original greek term. Nonetheless, it should be born in mind that ESE is only very distantly related to mainstream economics.

3.5 Focus on population-level interactions

ESE focuses on humans at the population level as the primary interactive unit. Of course, human behaviours and experiences all actually happen at the individual level. But just as the dynamics of a fluid can be usefully described without resolving the motions of individual molecules within it, population characteristics can be usefully described without resolving individual interactions, and symmetry-breaking can lead to fundamentally different behaviour across scales (Anderson, 1972). What’s more, these population characteristics can show greater predictability when the emergent result depends on well-behaved statistical distributions of individual behaviour, as illustrated by the dynamics of human mobility (Simini et al., 2012; Alessandretti et al., 2020).

Focusing on the population level does not mean that variability within the population must be ignored. Variability can be incorporated as additional information that describes the variability in a parameter, such as a probability distribution function. For example, the distribution of wealth within a population can often be approximated as a power law, for which only a single parameter (the exponent) needs to be defined (Wold and Whittle, 1957).

3.6 Emphasis on the ultimate 'what' and 'why' of activities, rather than the 'how'

A great deal of human study is oriented towards understanding 'how' social activities are coordinated, and the means by which the cooperative activities of many individuals can be optimized. The mechanisms by which this coordination occurs underpin many fascinating aspects of culture, economics, management and law, but are not the target of enquiry here.

Instead, ESE is characterized by a focus on the 'what' and 'why' of human activities. Here, 'what' refers to the final net outcome of an activity, or complex of cooperative activities, in physical terms. The 'why' refers to the ultimate motivations for undertaking the activity, again in relation to the final net outcome in the case of a complex of coordinated activities. For example, the final outcome of creating farming tools, tilling soil, sowing seeds, tending plants, and harvesting crops is to provide food ('what'). The motivation for this is a hunger-driven need for food ('why'). Thus, ESE aims to circumvent the complexity of immediate, individual motivations for component activities (such as whether the work is done for pay, which could itself be motivated for material consumption, which itself could be motivated by a desire to raise social standing) by considering the net outcome of any set of activities as the relevant motivating factor.

3.7 Applicability to any point in time

It could be easier to design a conceptual system exclusively for the present-day, with which we are intimately familiar, than one which works equally well back to medieval times or the late Pleistocene. Yet, if we aspire to consider the distant future, many decades or centuries hence, this ability must be a bare minimum requirement, since presumably the future could hold many revolutionary changes that defy the imagination today. The ESE approach strives to be applicable across the full temporal scope of human existence, enabling hindcasts to test dynamical hypotheses against historical observations as well as to explore hypothetical future projections.

3.8 Focus on emergent consequences of predictable aspects

Most aspects of complex systems, including the human-Earth system, are unpredictable. But within this sea of unpredictability lie islands of predictability. For example, the chaotic processes that determine daily weather can be approximated well enough to provide a very detailed forecast over the next twelve hours, but are almost completely unpredictable on a timescale of one month. Yet, on a coarser scale, seasonal and even decadal climate forecasts are now reasonably good (Smith et al., 2019). Similarly, societal dynamics include a vast variety of interacting, nonlinear processes that are extremely challenging to predict, but within which occur more predictable aspects. Thus, ESE strives to identify the more robust, least unpredictable aspects of the system, seeking insights on the emergent results of their interactions. Societal, cultural and economic characteristics of populations are described through the simplifying lens of how they impact physical variables and time allocation. The roles of the more unpredictable aspects can then be assessed through the quantification of structural and parameter uncertainty, the use of probability distributions, and the direct forcing of tipping points if they are identified through other means.

4 Earth System Economics conceptual framework

Humans have an intellectual ability to foresee the future that is unparalleled amongst other forms of life, and an apparently infinite scope to modify their biophysical surroundings. How could these features possibly be captured in a numerical assessment? To paraphrase George Box, the answer is that it can be done through countless ways, none of which is perfect, but some of which can be useful. And, as written in a discussion of Box's aphorism by Truran (2013), 'it may be necessary to create a model that takes a totally different perspective in order to improve upon currently accepted models.'

Here, a new perspective on the human system is proposed that is consistent with the ESE principles outlined in Section 3, and forms an intuitive and inclusive structure that aligns well with observational data. To be tractable at the global scale, the framework is hierarchical, so that it can be used at a high level of aggregation. The framework is inclusive, encapsulating the entirety of the global human system, while aiming to facilitate the representation of its mechanistic properties. At the same time, the categories are conceptually straightforward to expand into disaggregated detail, with as little ambiguity as possible, and spatial disaggregation should be easy to apply. This proposed framework is intended as a superstructure within which analyses or models could be developed, through further work.

4.1 State variables

The ESE framework is defined by state variables. Each state variable represents some physical aspect of the human-Earth system, living or non-living. Each variable could be measured and quantified over some spatial and temporal domain (at least in theory, even if impractical or impossible to do so with current technology) and is subject to physical constraints.

The highest level grouping of six variable classes, proposed here, is illustrated in Fig. 2 and elaborated below. The five variable classes in the outer ring include everything on the surface of the Earth, and can therefore be thought of as a conceptual superstructure within which more detailed subdivisions can be resolved. The final state variable class, time allocation, is not physically embodied, but is nonetheless subject to the limitation of 24 hours per day, and is unambiguously defined for a population within a given spatial-temporal domain.

Soma. The living ensemble of human bodies and their bio-physical characteristics, including microbiota. The Soma determines the biogeochemical fluxes required to maintain the population, including food and water consumption as well as the production of heat and waste. It also includes properties reflecting the health status of the population (including symbiotic and pathogenic microbes), and physical fitness. Example state variables here could include the total population biomass (kg),

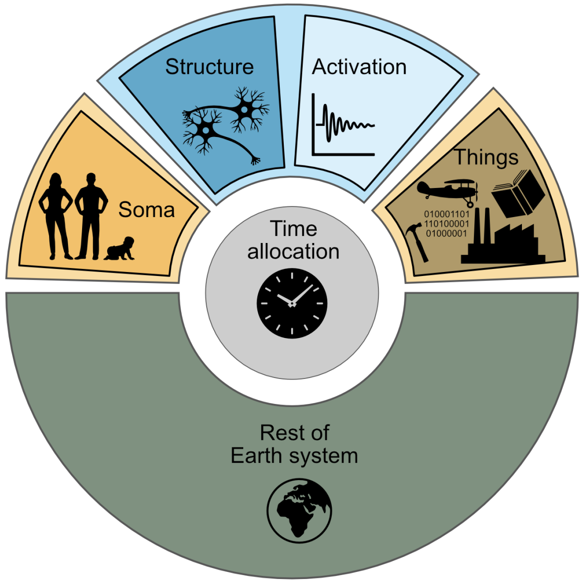

Figure 2. The superstructure of the conceptual framework.

an age-structured population description (number and age), or detailed information on body compositions (e.g. C:N ratio, Fe content).

Neural structure. It is because of the dynamical processes in our brains that we are the dominant species on the planet. Our neurons encode networks that are highly plastic, and this plasticity forms the foundation of our ability to learn (Ascoli, 2015) as well as our responses to stimuli (Lindquist et al., 2012). The biophysical characteristics of our brains lie at the foundation of core societal traits such as knowledge and behaviours, as well as subjective experience (Lindquist et al., 2012; Boyer, 2018). Thus, state variables describing the brains of humans within a population can be used to represent these essential features. One type of state variable could quantify aspects of associative links within the population connectome (the ensemble of all synaptic connections in a population, *sensu* (Sporns et al., 2005)), such as the number of associations encoded by synapses. Other possibilities would be topological descriptions of the neural structure, e.g. degree of diversity of associations within the population, the quality of the predictive capacity of associations, or links with hormonal and emotional responses. Although the processes underlying the formation of new synapses and their selective destructions remain incompletely understood, they are certain to happen at finite, biologically-constrained rates, placing limits on possible rates of learning, and modulating the persistence of behaviour, values and emotional features within a population. Conceptualizing neural structures as real, persistent aspects of the Earth System prompts a novel perspective on the consequences of human time allocation, and points toward the underlying physical basis of how systemic, population-level societal changes can occur.

Neural activation. Existing neural structures are activated by sensory stimulus, and result in what we experience as thoughts, emotions and feelings. The sensory stimulus includes external factors such as the landscape, music, food, mobile phone screens and conversation, as well as interoceptive body status such as hunger and thermal comfort, and in fact both types of sources generally co-occur (Barrett, 2017). This class of state variables represents manifestations of this neural activation. Because the details of the activation itself remain difficult to observe, emergent properties such as subjective well-being measures are most usable at present, though observation technologies are rapidly improving. Neural activation is also conceptually useful, as the pathway by which neural structure is modified.

Things. Humans are clever, but it is not through individual cleverness alone that we have become the dominant species on the planet (Henrich, 2017). Rather, we leverage our ability to think by creating entities with novel properties, constructed through shared knowledge and social coordination, that then amplify our ability to modify the physical environment. This includes the fabrication of tools, the construction of buildings and infrastructure, the making of vehicles and airplanes, the writing of books and computer code. The Things class includes all of these, and is defined as: all non-living entities which are brought into existence as a desired outcome of human activity. As such, the Things class does not include livestock or genetically-modified organisms, nor does it include waste. Instead, these are considered as modifications of the remainder of the Earth system.

Remainder of the Earth system. This includes all living organisms other than humans (including agricultural plants and livestock), the atmosphere, regolith, soil and rock, the ocean and cryosphere. These fall within the traditional domain of Earth System science. Although the variables within this class can all be affected by the human system, and many may be very strongly modified (e.g. cows, grapefruit), they do not require human activity in order to persist and/or are living organisms, thereby differentiating them from Things.

Time allocation. The allocation of time between activities is a complex topic, which has been studied in many branches of social sciences (see (Gershuny and Sullivan, 2019) for a useful overview). In a simple form, the allocation of time can be considered as the emergent outcome of competing motivations, expressed at the population level. Here, a motivation is strictly defined as the reason to undertake an activity (the 'why') that relates to the set of physical outcomes caused directly by the activity (the 'what'). For example, although a cook in a restaurant may be personally working in order to get money, the physical outcome of the action is to produce enjoyable food, and food is therefore the relevant motivating factor. The consequent population-level time allocation, which emerges from the balance of competing motivations, causes changes in state variables including subjective experience according to the context (e.g. the presence of Things, neural structures, climate, etc.). The variables in this class are simply the fraction of time (e.g. hours per day) devoted to each activity by the population.

5 Illustrative model

Next, a simple model is presented that illustrates how the ESE framework could be operationalized in a global model. The model is presented in a '0-dimensional' spatial form, rather than being spatially disagregated, as is common for a proof-of-concept in Earth system modeling (e.g. Wolfe et al. (2016)). The model uses a bare-minimum set of state variables and activities (Fig. 3), and is not intended to yield particularly insightful results, but rather to illustrate how the approach can yield internally-consistent dynamical interactions between state variables. The model structure bears some similarity to simple ecological models that also aim for direct coupling of humans and ecosystems (e.g. Henderson and Loreau (2018)).

5.1 Model overview

The model considers three activities: sleeping, supplying food to the population (*provision*), and doing something else (*other*). The production of the edible food resource E_{food} by living organisms (including agriculture) is given as a fraction ϕ_{edible} of the total Net Primary Production (NPP, in gCd^{-1}); agriculture is not considered dynamically here for simplicity, so ϕ_{edible} is fixed, and the rate at which the existing E_{food} is harvested depends on the fraction of available time spent collecting and providing it to the population, $A_{provision}$. Neural structures evolve over time, but for simplicity this model does not simulate any feedbacks of the neural structures on motivations or technology. Rather, these cultural / social features are held fixed. Also for ease of interpretation, the mass of provisioning Things $T_{provision}$ is held constant in the simulations. This simple illustrative model is not intended to realistically capture any particular period of human history, but to simulate feasible dynamical interactions between the ecosystem, human activities, the modification of synapses, and subjective wellbeing.

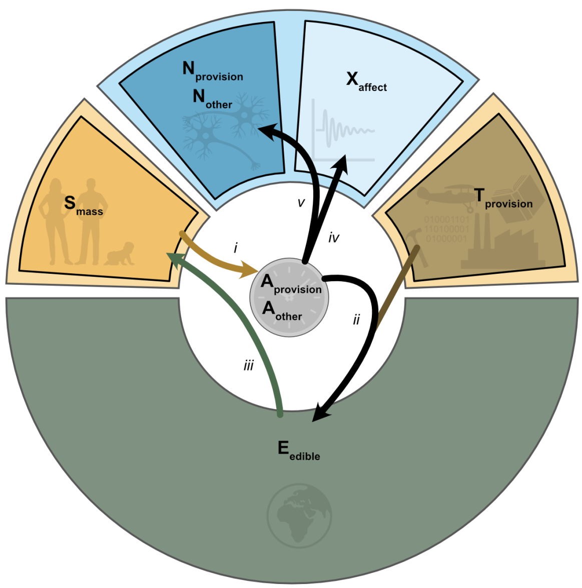

Figure 3. Model architecture, shown within the conceptual framework of Figure 2. Dependencies are shown as arrows: i) $hunger$ influences time allocation, ii) Time allocation to provision, $A_{provision}$ and the availability of provisioning Things $T_{provision}$ influence the per capita extraction rate of edible food E_{edible}, iii) the extraction of E_{edible} supports the metabolism and growth of human biomass S_{mass}, iv) time allocation between activities $A_{provision}$ and A_{other} influences population affect, X_{affect}, v) time allocation influences the population neural structure between $N_{provision}$ and N_{other}.

5.1.1 Discretization

It is envisioned that the most useful application for this framework would be on a global grid, but for ease of illustration the entire planet is represented here as a single entity without any spatial resolution, similar to the seminal model by (Forrester, 1971). The model is discrete in time, and is solved numerically through finite differences from a prescribed initial state using forward time-steps of 1 week.

5.1.2 Variable overview

The model includes six classes of state variables, corresponding to the classes in Fig. 2 and shown in table 1. The simple model here includes human somatic variables, S, neural structure variables, N, thing variables, T, Earth system variables, E, subjective experience X, and activities, A. Subtypes are identified with subscript, e.g. $N_{provision}$. The two activity terms defined in the example here are $A_{provision}$ and A_{other}. Each of these is a compound activity, comprised of many component activities. Parameter values are quantities that are imposed, and do not change dynamically according to the model equations.

5.2 Activities and dynamic time allocation

Each of the time allocation terms A_i is constrained to vary between 0 and $\sum_i A$, where the latter is the total time available for the defined activities. For example, $\sum_i A$ would be less than 1 if essential activities, such as sleeping and eating, were not explicitly defined as activities within **A**. For the illustrative model here, unresolved essential activities are assumed to occupy 40% of the total time, so that $\sum_i A = 0.6$. Following the principle outlined in Section 3.6, each activity is associated with a set of physical outcomes (the ‘what’) and a corresponding motivational factor (the ‘why’).

Motivations are modeled as competing tendencies to alter time allocation between the two available activities, that respond to changes in the corresponding state variables. Each motivation can have a value between 0 and 1, which drives an increase in the fraction of time devoted to the corresponding activity with a strength that is proportional to a response coefficient r. The simple model here considers only two competing motivations. Hunger, the population-level response to food shortage, motivates the activity of providing food, $A_{provision}$. This activity is placed in opposition with a cultural preference to do something other than provide food, associated with the activity A_{other}. To represent saturating responses to an input variable, the Holling type 2 formulation is used, since it provides stability and each usage introduces only one additional parameter (k).

Human behaviour is exceedingly complex, and cannot be predicted from first principles. Thus, the motivational responses to state variables at the population scale are approximated by smooth response functions, dependent on two sets of parameters: the r and k values. Neither of these parameters has a direct equivalence that can be measured precisely, a common occurrence in ecological modelling, and their values are chosen in order to produce reasonable model behaviour. The author is not aware of other models that use this same formulation, but the precise means by which this is achieved are not the focus here. Rather, the goal is simply to simulate internally-consistent dynamical links.

It is emphasized that the r and k parameters are intended to reflect the combined outcomes of individual psychology and societal processes (where societal processes include all cultural, social, political and economic interactions). Although they are held constant in the individual simulations shown here, they would not in reality be static properties of the population, but could in theory be dynamically linked to neural structure state variables. However this would go far beyond the simple scope of the current illustration.

Table 1. Model variables

Variable	Symbol	Units
State Variables		
Human biomass	S_{mass}	kg_{human}
Neural structure, provisioning-activated	$N_{provision}$	$\#$
Neural structure, other-activated	N_{other}	$\#$
Provisioning tools	$T_{provision}$	kg_{tools}
Food biomass	E_{food}	kg
Provisioning activity	$A_{provision}$	$d\,d^{-1}$
Other activity	A_{other}	$d\,d^{-1}$
Affect	X_{affect}	unitless
Parameters		
Net Primary Production	NPP	$kg\,d^{-1}$
Edible fraction	ϕ_{edible}	unitless
Human growth rate	μ	d^{-1}
Human metabolism	ω	d^{-1}
Available time	f_{avail}	$d\,d^{-1}$
Sensitivity to food shortage	k_{hunger}	unitless
Sensitivity to other time shortage	$k_{hankering}$	unitless
Reactivity to hunger	r_{hunger}	unitless
Reactivity to hankering	$r_{hankering}$	unitless
Efficiency of provisioning	$\epsilon_{provision}$	$kg_{human}^{-1} kg_{tools}^{-1} d^{-1}$
Food decay rate	λ	d^{-1}
Synapse formation rate	$\mu^{synapse}$	$\#\,kg_{human}^{-1} d^{-1}$
Synapse destruction rate	$\lambda^{synapse}$	d^{-1}
Affect during provisioning	$\alpha_{provision}$	unitless
Affect during other	α_{other}	unitless

5.2.1 Hunger

Hunger is an essential motivator of time allocation for any animal. Food must be obtained regularly, through actions that are generalized here as $provision$, including all activities required to extract edible organic matter from the environment and distribute it to the population in an edible form. This could include hunting, fishing or farming, as well as any necessary processing and transportation of food. Hunger occurs regularly even in well-nourished individuals within less than a day of eating, and temporary satiation is unlikely to drive a decrease in provisioning activity, therefore hunger is considered here to be ≥ 0. Hunger is given by:

$$m_{provision}^{hunger} = \frac{shortage}{k_{shortage} + shortage} \tag{1}$$

where $shortage$ is the fraction of the population experiencing a food shortage. The value of the half-saturation constant $k_{shortage}$ determines the relative strength with which the population is motivated to respond to a given shortage, with a smaller value responding more strongly to smaller starving fractions and saturating more quickly. $Shortage$ is the fraction of the population that obtains insufficient food to meet metabolic requirements, and is estimated by assuming a normal distribution of individual shortages around the average surplus, where the surplus is defined as the difference between the total food supply and the total food required to support the metabolic needs (ω plus maximum potential growth μ_{max}) of the population.

5.2.2 Hankering

Obtaining food is a primary concern for all animals, but they also tend to spend some fraction of time doing other things. Depending on the species, they might invest time developing burrows or nests, engaging in courtship and mating, or resting in a safe place. Humans, more than any other animal, are characterized by the wide range of activities they engage in other than obtaining food. As the purpose here is to provide a simple illustration, all possible non-provision activities are combined under a single activity, A_{other}. The associated motivation is termed here the $hankering$ for non-provision activities.

It is assumed that the hankering increases in intensity as the time allocated to $A_{provision}$ is increased. This motivation could be construed at an individual level, such as the individual desire to do something more enjoyable, rewarding or relaxing than food provision. It could also occur through social mechanisms, such as cultural norms to engage in rituals or constructing religious buildings, or through economic mechanisms such as a decrease of provision labour wages as food availability is increased. No attempt is made here to represent these mechanisms (i.e. the ‘how’), instead all motivations to do Other things are simply bundled in a non-provision motivation, given by the equation

$$m_{other}^{hankering} = \frac{\sum_i A - A_{provision}}{k_{hankering} + \sum_i A - A_{provision}} \tag{2}$$

where $k_{hankering}$ represents the rate at which the hankering approaches saturation with increasing time spent provisioning.

5.3 Implementation of motivated changes

The model is constructed to place multiple motivations in competition for the available time within the population. As such, the competing motivations exist in tension with each other, and the outcome represents a dynamic balance between them. The motivated change to activity A_i at time t is given by the general form

$$A_i(t)' = A_i(t-1) + r_f m_i^f(t) \tag{3}$$

where m_i^n is the f^{th} motivational factor acting on activity A_i. Note the motivation factor is additional to the previously allocated time, so that an absence of motivation would result in no change in time allocation. The r_f terms reflect the relative strengths of motivations, a cultural feature.

The individual A_i' are then divided by the sum of all A_i' and multiplied by $\sum_i A$, distributing the available time among the possible activities according to their strength of motivation.

5.4 Dynamical changes to state variables

5.4.1 Biomasses

The dynamical change of edible biomass E_{food} is given by

$$\frac{dE_{food}}{dt} = \phi_{edible} NPP - \lambda E_{food} - A_{provision} S_{mass} T_{provision} \epsilon_{provision} E_{food} \tag{4}$$

The fraction of NPP that is converted to edible material, ϕ_{edible}, would vary with many factors including the ecosystem type, climate, and human agency. For example, some ecosystem types may naturally generate a larger fraction of edible plant material (fruit, tubers, seeds, nuts, leaves) and animals (grazing ungulates, birds, fish) than others (Kelly, 2013). Human activity can then modify ϕ_{edible}, increasing it through deliberate modifications including agriculture and aquaculture, or decreasing it by destructively harvesting and over-hunting/fishing. Human activity could also modify NPP, increasing it by changing vegetation to more productive varieties or by fertilizing and irrigating, or decreasing it by causing soil erosion, nutrient loss or other forms of ecological degradation. For simplicity, all of these factors are conceptually bundled within a constant value of ϕ_{edible} as modifications of edible NPP relative to a 'pristine' state (i.e. untouched by humans). For reference, the present-day global annual production of edible material is approximately 0.9 Pg C (the mass of carbon within all edible primary crops, processed crops and animal products) according to the analysis of (Alexander et al., 2017), implying a global ϕ_{edible} of roughly 0.02 for a global NPP of 54 Pg C (Running, 2012).

In the second term, $\lambda(d^{-1})$ represents the consumption of potentially-edible material by all non-human organisms such as other mammals, birds, insects, fungi or bacteria. This non-human consumption is assumed to be first order with respect to E_{food}, for simplicity. The decay constant would be expected to vary with food type and environment, but would generally be on the order of weeks.

The final term is the collection and processing of edible material by humans, up to the point of ingestion, referred to as provision. The term depends on E_{food}, the size of the human population, $S_{mass}(kg_{human})$, the fraction of time allocated to provisioning, $A_{provision}(unitless)$, the mass of provisioning tools available $T_{provision}(kg_{tools})$, and the effectiveness with which the population provisions the existing edible material per unit time and mass of provisioning tools, $\epsilon_{provision}(d^{-1}kg_{human}^{-1}kg_{tools}^{-1})$. The use of linear dependences is sure to be inappropriate, given that there will be an optimum mass of tools per person, optimal resources will be harvested first, and diminishing returns would be expected to lead to a sublinear dependence on $A_{provision}S_{mass}$ (note this is equivalent to labour in the similar Cobb-Douglas production function, which typically has an exponent <1, (Cobb and Douglas, 1928)). This approach could potentially be improved in future.

Next, the human capacity for food ingestion is given by the product of the human population S_{mass} and the sum of the population average biomass-specific metabolic rates ω_{human} and the potential net growth rate μ. Any excess of food provisioned beyond this limit is assumed discarded. An average value of ω_{human} is calculated assuming a per capita energetic requirement of 10 MJ d^{-1} and food energy content of 30 $kJgC^{-1}$ (Alexander et al., 2017). The value of the maximum growth rate μ_{max}, the population growth rate when the rate of food provisioning is non-limiting, influences the transient behavior of the model but not the steady-state outcome, as discussed below. Because μ_{max} is the maximum net growth rate, equal to the birth rate minus the death rate (for constant individual body size), its value reflects both the fertility rates of the population and the mortality due to disease, violent deaths and old age. The fertility rate is dependent on cultural and societal characteristics, while the rate of death depends on cultural and societal characteristics as well as exposure to pathogens. Because the cultural and societal aspects of both fertility and mortality are complex, the model simply considers how the net result decreases below the potential maximum when assuming zero growth among the fraction of the population experiencing a food shortage, so that $\mu = (1 - shortage)\mu_{max}$. Food waste is not treated explicitly, but could be considered as an implicit component of the uncertainty in ω_{human}.

The human biomass then varies as

$$\frac{dS_{mass}}{dt} = min(\mu_{max}, A_{provision}T_{provision}\epsilon_{provision}E_{food}S_{mass} - \omega_{human})) \tag{5}$$

5.4.2 Neural activation

For illustration, one metric of subjective wellbeing is used here: the affect balance associated with different activities. It is assumed that a population-average level of affect α occurs under each activity, as determined by many factors that are not resolved here. Basically, one of the activities is bound to be more enjoyable than the other. Because provisioning generally falls under the category of work, whether or not it is done through the formal economy, it is assumed to incur a lower level of affect. The $other$ activity, although sure to include many sub-activities that are unpleasant, is assumed to incur a higher overall average affect. Note that this analysis ignores any sense of eudaemonia that may result from either activity, and is purely hedonic.

Thus, the instantaneous average affect of the population at time t is given by the time-weighted mean of the activity-specific affects,

$$x_{affect} = \frac{1}{f_{avail}} \sum \alpha_x A_x \tag{6}$$

which can be rewritten for this two-activity model as

$$x_{affect} = \alpha_{other} - (\alpha_{other} - \alpha_{provision})\frac{A_{provision}}{f_{avail}} \tag{7}$$

giving a linear decrease with $A_{provision}$ below a maximum affect α_{other}.

5.4.3 Neural structure

A simple model is used for changes in the neural structure of the population, based on two assumptions. First, that the rate of new synapse formation is constant and randomly distributed within the cortex, and second, that only synapses that are being fired will be strengthened and persist (Ascoli, 2015). (Thus, one does not learn how to play piano by riding a bicycle.) Under these two assumptions, the development of strong synapses, which then become important pathways for future thoughts, are dependent on engagement in relevant activities. In this way, the time allocation to activities contributes to modification of the neural structure.

This basic dynamic is crudely approximated here by

$$\frac{dN_x}{dt} = \mu_x^{synapse} S_{mass} - \lambda^{synapse}(1 - A_x)N_x \tag{8}$$

where N_x is the number of synapses in the population associated with activity x (normalized to the individual-average lifetime synapse production), $\mu_x^{synapse}$ is the biomass-specific growth rate of new synapses that can be activated by activity x, and λ is the synapse-specific rate of synapse destruction.

Thus, the synapses are defined by their associated activity. This does not imply that they are exclusively related to the functional core of the activity, but simply that they are strengthened during the activity. There could also be overlap between the neural structures of different activities due to commonalities, not resolved here.

It is essential that this quantification says nothing about the functional utility of the structural changes. Many of the accumulated synapses may contribute little, or even be deleterious. The processes by which the brain selects and amplifies the functional utility of certain synaptic modifications, while dampening others, remains an important topic of research in neuroscience (Richards and Frankland, 2017). Nonetheless, the fact that synapses are strengthened in response to activation is well-established (Ascoli, 2015) and it is expected that future work can improve on this crude representation.

6 Model analysis and discussion

The transient dynamics of the model can assume many forms depending on the input parameters, which reflects the nonlinear interactions of the cultural aspects (motivational factors) and the human-ecosystem coupling (food provisioning). The following sections describe typical features of the transient behaviour.

6.1 Approach to steady state population

When initialized from a population density well below the steady state value, the human population grows near-exponentially (Fig. 4 a). The food biomass is drawn down (Fig. 4 b), generating decreasing yields for the same effort (Fig. 4 c). Hunger increases in response (Fig. 4 d), which drives a greater $A_{provision}$ (Fig. 4 e). The surplus (difference between the solid and dashed line in Fig. 4 f) gradually shrinks, until after a couple of centuries the surplus reaches the point at which it constrains the growth rate. At this point the population growth rapidly declines to zero and S_{mass} reaches a plateau (Fig. 4 a). The transition

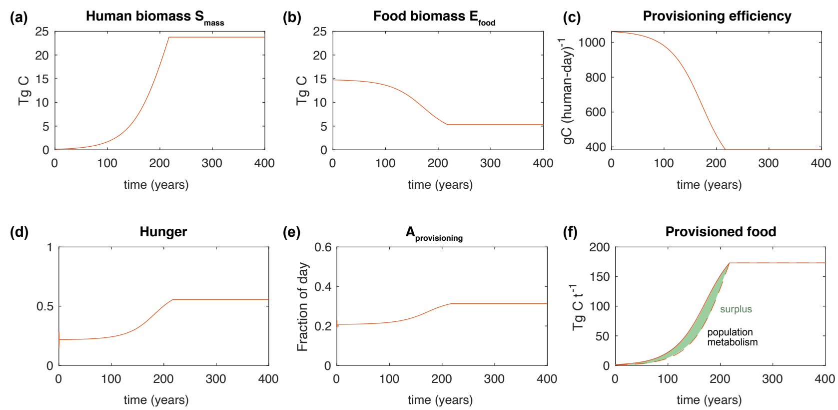

Figure 4. Timeseries of a typical model experiment. In panel f, the dashed line indicates the metabolic cost of maintaining the population (i.e. $\omega_{human} S_{mass}$) and the shaded green area represents the food surplus.

from growth to plateau happens more sharply than under logistic growth because the modeled growth rate remains large even as the food surplus shrinks, and the constraint of food limitation on growth is imposed abruptly. This could be unrealistic for populations that have sufficient foresight to slow their growth rate in advance of food limitation, but is perhaps realistic for populations in which reproductive rates do not decline in response to declining food surpluses.

6.2 Dependence on population size on $r_{hunger}/r_{hankering}$

Figure 5 shows the same experiment shown in Fig. 4, as well as a second experiment in which a single parameter value was changed: $r_{hankering}$ was increased by a factor of 4. This increase reflects a greater motivation within the population to engage in A_{other}, rather than $A_{provision}$. Such a motivation could reflect a desire for leisure, a societal focus on monumental architecture, or a culture of learning - these distinctions are not resolved here.

The higher $r_{hankering}$ (relative to r_{hunger}) results in a smaller population size at steady state (Figure 5 a). This occurs even though the hunger experienced by the population is the same at steady state: the population simply decides to allocate less time to provisioning, because their priority is to engage in other activities. Because they provision less intensively, the food biomass remains more abundant (Figure 5 b), resulting in a greater provisioning efficiency (Figure 5 g). The greater allocation

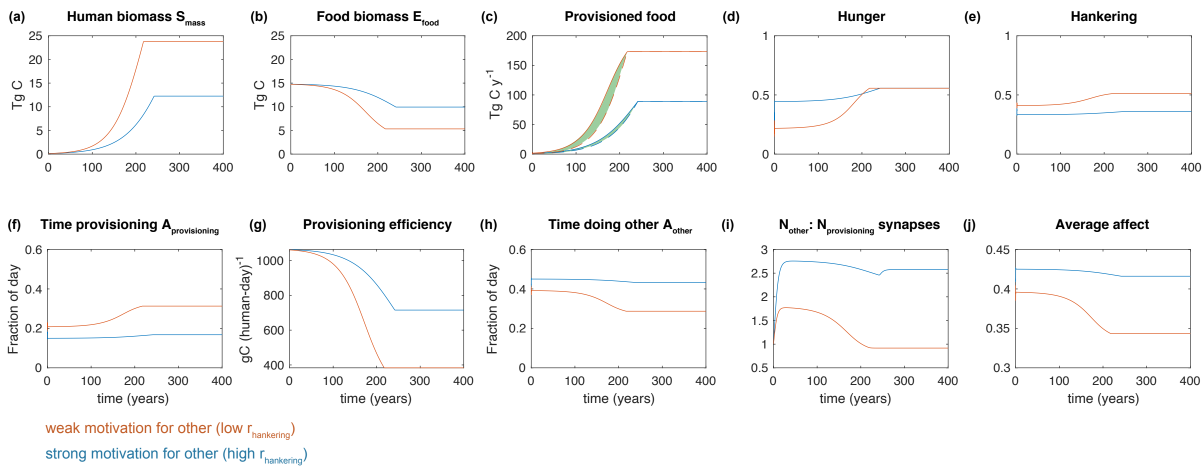

Figure 5. Timeseries of two model experiments with different values of $r_{hankering}$.

of time to other activities results in a large contrast in the neural structure, with N_{other} much greater than $N_{provision}$ in the population with high $r_{hankering}$ (Figure 5 i). Additionally, the steady state affect is greater with high $r_{hankering}$ (Figure 5 j), given the assumption that other activities provide higher affect than provisioning. Thus, the high $r_{hankering}$ experiment produces a smaller population of happier people with a more diverse neural structure.

6.3 Golden ages

Figure 5 illustrates an interesting nonlinear dynamic, particularly pronounced in the food-focused population (low $r_{hankering}$). During the initial population growth phase, A_{other} remains relatively high, since food is abundant and hunger is low. This allows the development of N_{other}, indicating a more diverse neural structure within the population, and supports a high level of affect. However, as food limitation approaches, hunger increases and the low $r_{hankering}$ causes the population activity to shift rapidly to $A_{provision}$. The N_{other} is no longer maintained at the high level, and the affect drops. One could conceive that such a century-timescale transient would be recalled by a society as having passed through a golden age, such as that mythologized in ancient Greece (Baldry, 1952) and frequently echoed throughout history.

This dynamic does not occur under all parameter combinations, and it should be borne in mind that the model is very simple. However, it serves to illustrate a straightforward interaction that would be expected to produce temporary golden ages with abundant food, and the ability to devote abundant time to *other* activities such as learning, producing art and building public works.

7 Conclusions

The global human system can appear overwhelmingly complex, which has contributed to the general hesitance to include it within Earth System science on a common footing with the atmosphere, ocean, terrestrial ecosystem, marine ecosystem and cryosphere. The first part of this paper (sections 2-4) has laid out a simple but inclusive approach, focused on observable, biophysical quantities, intended to provide a scalable global perspective and help build a common footing by bridging the natural-social science gap. The ESE approach simplifies the human system by boiling it down to what humans are doing with their time, and what are the biophysical outcomes of those activities. It is hoped that, by focusing on these key elements, a useful body of work can be developed that will provide a novel vision on humanity's place within the Earth system.

The second part of the paper (sections 5-6) illustrated the ESE approach with a numerical model, of a type that has proven highly useful in carbon cycle science: inclusive, based on a small number of simple principles, and focused on emergent properties. The model dynamically simulates, for the global human population, the partitioning of available time between provisioning food and doing something else, according to motivations that reflect the net outcomes of socially- and culturally-dependent responses to state variables. Although the model ignores many important features (e.g. seasonality, agricultural dynamics, food storage, tools and machinery) and was not comprehensively calibrated with data, it illustrates a hypothetical mechanism for producing golden ages through the coupled interaction of time allocation with ecological feedbacks.

The ESE approach could be greatly advanced through further progress in three key domains in the short term. First, a better understanding of global human activity is required, including improved theoretical foundations and harmonized multinational datasets. Second, a corresponding mapping of human-created Things, that is structurally-consistent with the resolved human activities and their biophysical outcomes. And third, insights on the process-oriented relationships that link activity and context to multiple dimensions of subjective experience. In the longer term, the approach can benefit from an improved set of metrics for neural structures that goes beyond the rudimentary approach used here, and can open the door to realistically quantifying rates of change for key societal characteristics.

The development of a diversity of models that follow the ESE approach (e.g. (Zhu et al., 2020)) as well as related, complementary approaches, is likely to identify new processes, even as they raise new questions. Furthermore, although this paper has focused on the use of ESE for numerical modeling, the framework may prove more useful as a conceptual approach to understanding the global human system in general. With further developments, it is hoped that ESE and allied approaches may help to unite disparate learnings from the social sciences, and to bring them together with natural sciences to answer urgent questions about the functioning of the human-Earth system.

Code availability. All MATLAB code used to run the model and generate figures is available for download from the Zenodo archive at http://doi.org/10.5281/zenodo.4408476.

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