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Earth System Dynamics
Discussions

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 humans that is intended to facilitate 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 bio-physical state variables, quantification of time allocation amongst available activities at the population level, and an orientation towards measuring human experience. A suitable framework is elaborated, which parses the Earth system into four classes of state variables, including a neural class that would underpin 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. Although the illustrative model is a gross simplification of reality, the results suggest a simple relationship to predict first order changes in the human population size, and how neural characteristics and subjective experience can robustly 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 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). Earth System science is typified by a firmly quantitative perspective, that explicitly considers the spatial distribution of interactive dynamical processes and their evolution over broad timescales. In its quest to understand planetary functioning and global environmental problems, this new science has succeeded in crossing many disciplinary boundaries. In so doing it has developed entirely new approaches - such as global carbon cycle science (Falkowski et al., 2000) - and, in return, brought fresh thinking to the previously isolated disciplines from which it was born.

But despite being motivated by the human impacts on the planet, Earth System science has done relatively little to directly incorporate humans themselves (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. Earth System models, which in many ways provide a unifying lens for Earth system science, tend to either impose human influences as external boundary conditions, or to treat humans in external modules, subject to utterly different assumptions and constraints. Integrated Assessment Models (IAMs), the most common example of the latter, typically solve for an economic general equilibrium once per year in an asynchronously-coupled module with limited or no spatial resolution, and tend to interact with the Earth system model only by feeding it global greenhouse gas emissions and land use forcings (Nordhaus and Yang, 1996; Van Vuuren et al., 2007). '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 build toward what Voinov and Shugart (2013) call an 'integral' perspective on the human-Earth. The Neolithic transition model of Wirtz and Lemmen (2003) and global Paleolithic dispersal model of Timmermann and Friedrich (2016) pioneered simple, generalized approaches to globally-distributed human populations within a spatially-variable environment, but were applied only to specific prehistoric questions. A number of authors have recently detailed the need for alternative approaches to modeling the global human system as an integrated component of the Earth system (Rounsevell et al., 2014; Donges et al., 2017; Müller-Hansen et al., 2017; Calvin and Bond-Lamberty, 2018; Robinson et al., 2018; Anderson, 2019), but few steps have been taken.

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 given 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 essential 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 has persisted for decades (Snow, 1959).

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.

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Yet, like all living organisms, humans are physical beings. The biological reality of human bodies embeds us within ecosystems, links us to biogeochemical cycles, and places fundamental constraints on our economies. 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', (Clark, 2015). The intricate network of synapses in each of our heads, coined a 'connectome' (Sporns et al., 2005), 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 there is no *a priori* reason why knowledge of the biophysical features of brains could not be used to inform even the most unusual aspects of our species (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 (Winterhalder, 1993), providing valuable insights for anthropology and sociology, but these works were not widely seized upon. Instead, more recent efforts in modeling the coupled human-Earth system have gravitated toward the IAM approach of simulating dynamics of greenhouse gas emissions in the late 20th and 21st centuries, given the urgent need to understand the challenge of mitigating climate change. This has led to very few Earth system-scale studies that ask fundamental questions about the physical coupling of humans with the ecosystem (Motesharrei et al., 2014) and its 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 it is argued that an Earth System approach, firmly grounded on a bio-physical foundation within an inclusive, quantitative framework, can provide a powerful and under-exploited perspective on the essential features of humanity. The remainder of this paper outlines and illustrates one strategy toward this end. The name Earth System Economics (ESE) is proposed for the endeavour, with the aspiration of bridging the natural and social sciences to provide new knowledge on both human and natural systems. Section 2 provides an overview of the key principles behind the ESE approach. Section 3 details one appropriate conceptual framework. Section 4 describes an illustrative numerical model of the global human system, inspired by simple models of the global carbon cycle (e.g. Sarmiento and Toggweiler (1984)). Section 5 provides analysis and discussion of the model. Section 6 offers concluding comments.

2 Guiding principles of Earth System Economics

In a nutshell, ESE aims to quantify the physical reality of the human-Earth system (state variables), how the physical state is dynamically altered by human actions (activities) and what the result is on the quality of human life (subjective experience). These are detailed in part 3. First, a few general features are discussed.

2.1 Striving for physical foundations

The aim to ground the human system in physical quantities is not trivial. For some things - population demographics, 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, and much work remains to be carried out before they can be usefully linked to underlying neurological features. 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. The important thing is that strengthening the physical foundation is recognized as a central goal of ESE: that progress can be made by improving the physical representation of all aspects of the human system, through improved observations and theoretical development.

2.2 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.

Classifying activities is not a trivial exercise. 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 also align activities with the outcomes of interest, including the processes that modify the state variables under consideration, and the most distinct activities in terms of subjective experience.

2.3 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. 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 generally fall 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, 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, 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. This can be predicted to some degree from material and non-material variables (Helliwell et al., 2012; Barrington-Leigh and Galbraith, 2019). The closely-related eudaemonia reflects the sense of fulfillment of purpose, which - although a major concern of society on historical timescales, often addressed through philosophy and religion - 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.

2.4 Drawing on all fields of human-related science

Many disciplines study humans, including the core social sciences, as well as medicine, business and education, all of which can provide useful insights on the global human system. 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.

This usage is also well-aligned with how Alfred Marshall (Marshall, 1890) defined economics in an influential textbook, as

> a study of man in the ordinary business of life. It enquires how he gets his income and how he uses it. Thus, it is on the one side, the study of wealth and on the other and more important side, a part of the study of man.

Given that all wealth is provided either directly by the Earth or in combination with the activities of humans, and that an additional goal here is to better understand humans themselves, the term would appear appropriate. However, the approach draws strongly on insights from anthropology, sociology and psychology, and aspires to establish common ground that is compatible with aspects of all fields of human study. In this sense, ESE is only very distantly related to mainstream economics.

2.5 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. 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).

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).

2.6 Applicability to any point in time

It is easier, in many ways, 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.

2.7 Focus on emergent consequences of predictable aspects

Most aspects of complex systems, including the human-Earth system, are unpredictable. For example, nonlinear tipping points could play an extremely important role in the near-future of the human-Earth system (Lenton et al., 2008), but predicting when they might occur is inherently very difficult. Similarly, societal dynamics include a vast variety of interacting, nonlinear processes that can play critical roles, but are poorly understood and therefore extremely challenging to predict. Rather than focusing on the nonlinear processes themselves, ESE is oriented toward the consequences that can be confidently foreseen in terms of biophysical impacts and human activities. Societal, cultural and economic characteristics of populations are therefore described through the simplifying lens of how they impact physical variables and time allocation. Thus, ESE strives to capture the more robust, least unpredictable aspects of the system, seeking insights on the emergent results. The roles of the more unpredictable aspects can then be assessed through the quantification of structural and parameter uncertainty, and the use of probability distributions.

3 Conceptual framework

> What a piece of work is [a hu]man, How noble in reason, how infinite in faculty...In apprehension how like a god.

As expressed by the protagonist of Shakespeare's play *Hamlet*, humans have an intellectual ability to reason and 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? The answer is that it can be done through countless ways, none of which is perfect, but some of which can be useful.

Here, one specific conceptual framework is proposed that is consistent with the ESE principles outlined in Section 2. The framework is intended to provide an intuitive and inclusive breakdown that aligns well with observational data, can be expanded hierarchically, and would be appropriate as a superstructure in which analyses or models could be developed.

3.1 State variables

At the core of the ESE approach are state variables. Each variable represents some concrete physical aspect of the human-Earth system that could be measured and quantified over some spatial and temporal domain (at least in theory, even if impractical to do so), and expressed as a number of some unit. The list of state variables is arbitrary, as there are infinite features of the system that could be described, and one must make a choice as to which to focus on. One useful way to group the state variables, appropriate to the general focus here on integrating human systems with the rest of the Earth system, is illustrated in Fig. 1 as follows:

Somatic. The living ensemble of human bodies and their bio-physical characteristics. This determines the biogeochemical fluxes required to maintain the population, including food consumption and the production of heat and waste. State variables here could include the total population biomass (kg), an age-structured population description (number and age), or detailed information on body compositions (e.g. C:N ratio, Fe content).

Neural. 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 emotional responses to stimuli (Lindquist et al., 2012). Thus, state variables describing the brains of humans within a population are used to address these essential features. One type of state variable could quantify aspects of associative

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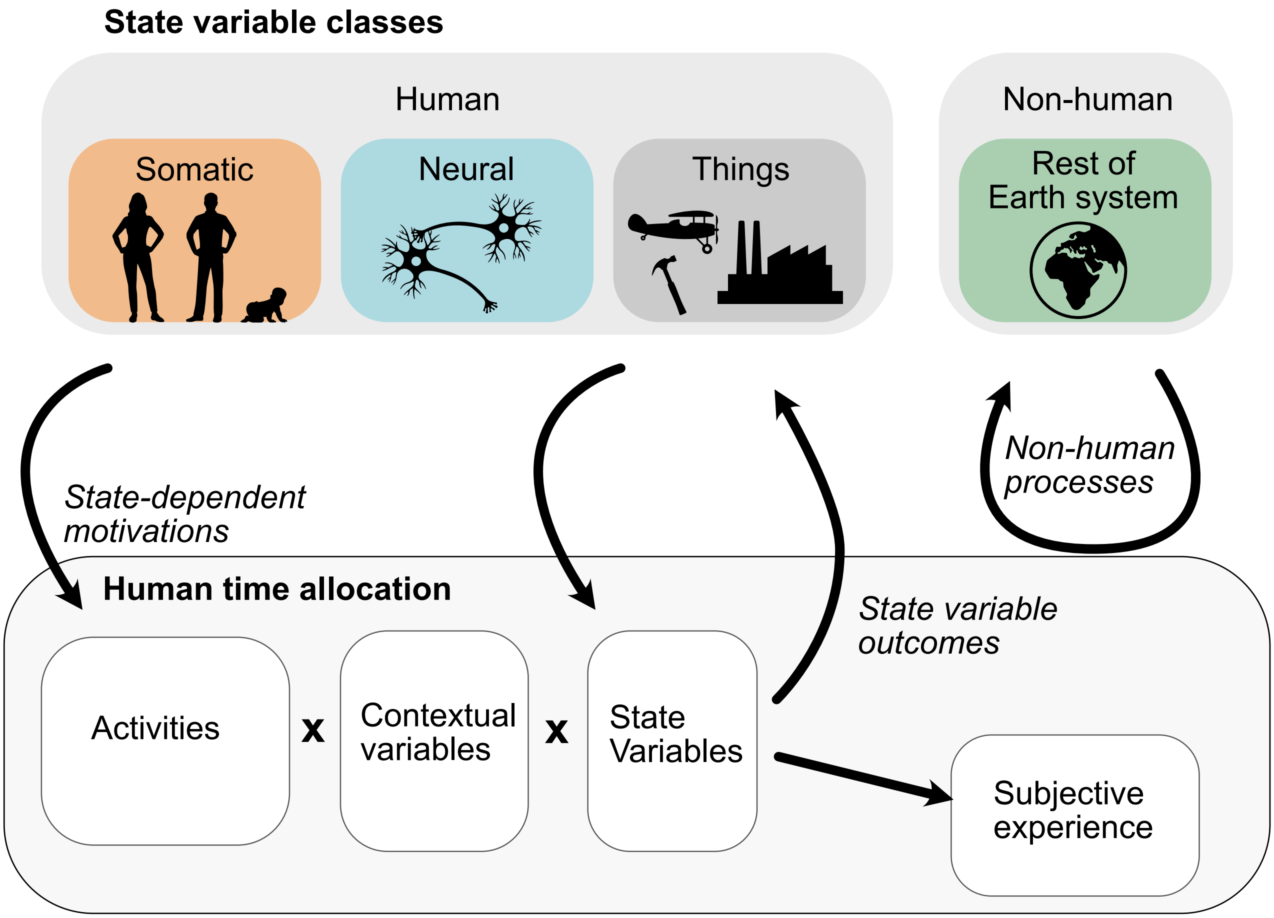

Figure 1. The superstructure of the conceptual framework.

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links within the population connectome (the ensemble of all synaptic connections in a population), such as the number of associations encoded by synapses. Other possibilities would be topological descriptions of the connectome, 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.

Things. We leverage our ability to think by creating entities with novel properties that we then use, amplifying our ability to change the physical environment. This includes the fabrication of tools, the construction of buildings and infrastructure, and the making of vehicles and airplanes. This variable class is defined by the fact that some amount of human activity is required in order for their perpetuation. For lack of a better term, this disparate ensemble of non-living human creations is referred to as Things.

Remainder of the Earth system. This includes all non-human living organisms (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, they do not require human activity in order to persist, thereby differentiating them from Things.

This list of variables includes 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.

3.1.1 Neural characteristics

Neuroscience provides abundant evidence that the biophysical characteristics of our brains lie at the foundation of core societal traits such as knowledge, behaviours and emotions (Lindquist et al., 2012; Boyer, 2018). Given that it is highly unusual to consider neural features as a population characteristic, a few details on how this might be approached are suggested here. The term *connectome*, *sensu* Sporns et al. (2005), will be used to refer to the ensemble of how neurons are configured within all of the humans in a population, with a focus on how neurons are connected at synapses (while acknowledging that the characteristics of neurons and glial cells are also likely to play important roles in connectome functioning).

Each individual has an internal connectome, defined by their own topology of synaptic connections (Seung, 2012). The functional importance of the connectome is that it determines associations that can be activated through thought and experience. A population can be conceived as containing the sum of individual connectomes, themselves loosely connected through interpersonal communication. Thus, one can define a population-level metaconnectome, which reflects the functional assemblage of all connectomes within the population.

A skeptical reader may ask, ‘why bother, given that we have only a vague understanding of how consciousness and behaviour emerge from the connectome?’ The utility of considering the metaconnectome is that, as a bio-physical entity, it is subject to real physical constraints. 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. These biological rates place limits on possible rates of learning, and modulate the persistence of behaviour, values and emotional features within a population. Conceptualizing connectomes as real, persistent aspects of the Earth System prompts a novel perspective on the

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consequences of human time allocation, and points toward the underlying basis of how systemic, population-level societal changes can occur.

3.1.2 Time allocation

The allocation of time between activities in an exceedingly complex topic, which underpins the essence of many branches of social sciences (Gershuny and Sullivan, 2019). In a simple form, the time allocation can be considered as the emergent outcome of competing motivations, each of which acts on individuals, expressed at the population level. Here, motivations are strictly defined in terms of their corresponding state variables (the drivers of motivations) and activities (the outcomes of motivations), which greatly simplifies their application.

Each motivational factor represents a particular set of neurological responses that emerge from human experience. For example, a motivation to work for increased food supplies could result from a perceived shortage of food, a motivation to construct pyramids could be enforced by a neurologically-constructed belief in the afterlife, the motivation to work in the restaurant industry could result from the distribution of monetary incentives through the market. These motivations may be based on rational processes, whereby individuals use information to weigh expected personal outcomes relative to goals. They may result from most individuals following a small number of role models, without conscious consideration or understanding of the outcomes (Henrich, 2017). They may also be impelled by threat of violence, in the case of slaves being forced to work. Regardless of the details, the motivational factors drive a shift in the time devoted to one or more activities, either increasing or decreasing them, subject to the competition for the finite available time. The outcome of this competition will depend both on how strong are the inherent motivations for an activity, and how the motivations respond to time allocations themselves.

The time allocation, which emerges from the balance of competing motivations, then causes changes in state variables and contributes to subjective experience according to the context (e.g. the availability of Things, neural characteristics, climate).

4 Illustrative model

4.1 Model overview

Next, a simple model is presented that illustrates the core concepts of the ESE approach within the conceptual framework outlined in Section 3, using a minimal set of state variables and activities (Fig. 2). The model considers two non-sleep activities: supplying food to the population (*provisioning*), 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 characteristics evolve over time, but for simplicity this model does not simulate any feedbacks of the neural characteristics on motivations or technology. Rather, these cultural / social features are held fixed. The 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.

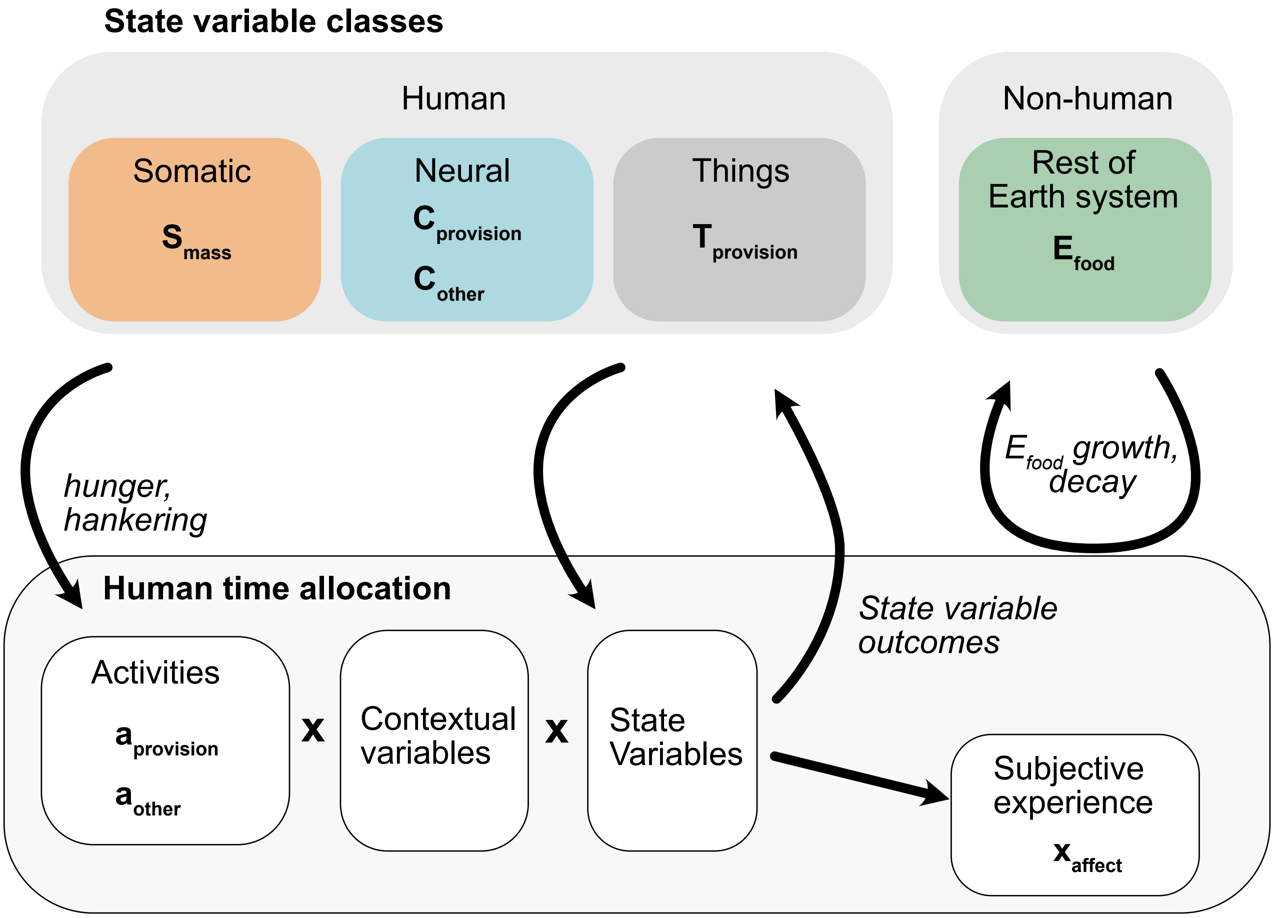

Figure 2. Model architecture, shown within the conceptual framework of Figure 1.

4.1.1 Discretization

280 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. Here a time-step of 1 week is used.

4.1.2 Variable overview

The model includes four types of variables, shown in table 1.

State variables persist from one time step to the next, and quantify persistent aspects of the objective reality that can change according to dynamical equations. State variables belong to multiple classes, each of which is represented by a capital letter. The simple model here includes human somatic variables, S, connectome variables, C, thing variables, T, and Earth system variables, E. Subtypes are identified with subscript, e.g. $C_{provision}$.

The time allocation vector **a** is composed of terms a_i (where i is a type of activity, as defined within the model), each of which is given as a fraction of the total time available (unitless). 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.

Output variables are produced by the model dynamics, but do not feed back on them. Parameter values are quantities that are imposed, and do not change dynamically according to the model equations.

4.2 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 $\sum_i a = 0.6$.

Motivations are modeled as competing tendencies to alter time allocation. Each motivation can have a value between 0 and 1, which motivates an additional time allocation to one or more related activities with a strength that is proportional to a coefficient r. The simple model here considers only two competing motivations. Hunger, the population-level response to individually-experienced food shortage, is associated with 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 parameter (k).

Human behaviour is exceedingly complex, and cannot be predicted from first principles. Here, 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. Thus the values are chosen in order to produce reasonable model behaviour.

It must be 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). Thus, they are not inherent properties of the population, but are dynamic, constantly changing as the fabric of inter-human interactions shifts and evolves. They could therefore also be dynamically linked to connectome state variables, though here they remain prescribed parameters for simplicity.

Table 1. Model variables

Variable	Symbol	Units
State Variables		
Human biomass	S_{mass}	gC
Connectome, provisioning-activated	$C_{provision}$	H
Connectome, other-activated	C_{other}	H
Provisioning tools	$T_{provision}$	g
Food biomass	E_{food}	gC
Activities		
Provisioning food	$a_{provision}$	unitless
Other	a_{other}	unitless
Outputs		
Affect	x_{affect}	unitless
Parameters		
Net Primary Production	NPP	gCd^{-1}
Edible fraction	ϕ_{edible}	unitless
Human growth rate	μ	d^{-1}
Human metabolism	ω	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	$\epsilon_{provision}$	$g^{-1}gC^{-1}d^{-1}$
Food decay rate	λ	d^{-1}
Synapse formation rate	$\mu^{synapse}$	$HgC^{-1}d^{-1}$
Synapse destruction rate	$\lambda^{synapse}$	d^{-1}
Affect during provisioning	$\alpha_{provision}$	unitless
Affect during other	α_{other}	unitless

4.2.1 Hunger

Hunger is an essential motivator of time allocation for any animal. Food must be obtained regularly, through actions that we generalize 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

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processing and transportation of food. Hunger occurs regularly even in well-nourished individuals within a day of eating, therefore it 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, assuming a normal distribution around the average surplus (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).

4.2.2 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 or rewarding 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 the mechanism, 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.

4.3 Implementation of motivated changes

The model is constructed to place multiple motivations in competition for the available time within the population. 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.

4.4 Dynamical changes to state variables

4.4.1 Biomasses

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

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

The fraction of NPP that is converted to edible material, ϕ_{edible} (unitless), 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 global annual production of edible material is approximately 930 Tg C (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, λ 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. Like the consumption by non-humans, this term is assumed to be linear with respect to E_{food}, an approximation. The term also depends on the size of the human population, S_{mass}, the fraction of time allocated to provisioning, $a_{provision}$, the mass of provisioning tools available $T_{provision}$, and the effectiveness with which the population provisions the existing edible material per mass of tools, $\epsilon_{provision}$.

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 $\mu = (1 - shortage)\mu_{max}$.

The human biomass then varies as

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

4.4.2 Connectome

A simple model is used for changes in the population connectome, 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 connectome.

This basic dynamic can be represented by

$$\frac{dC_x}{dt} = \mu_x^{synapse} S_{mass} - \lambda^{synapse}(1 - a_x) C_x \tag{6}$$

where C_x is the number of synapses in the population associated with activity x (in Hebbs, H), $\mu_x^{synapse}$ 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 necessarily mean 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 connectomes of different activities due to commonalities, not resolved here.

It is essential that this quantification says nothing about the functional utility of the connectome 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 hoped that future work can improve the realism of representations such as this.

4.4.3 Subjective experience

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 life satisfaction or 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,

$$x_{affect} = \frac{1}{f_{avail}} \sum \alpha_x a_x \tag{7}$$

which can be rewritten for this two-activity model as

$$x_{affect} = \alpha_{other} - (\alpha_{other} - \alpha_{provision}) \frac{a_{provision}}{f_{avail}} \tag{8}$$

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

5 Model analysis and discussion

5.1 Steady state behaviour

First, a few features of the model are discussed at steady state. These are direct consequences of the model equations, and serve to further characterize the model as well as suggesting insights on the human-Earth system.

5.1.1 Human biomass

At steady state, dS_{mass}/dt and dE_{food}/dt are zero. Rearranging the equations and solving for the human biomass gives

$$S_{mass} = \frac{\phi_{edible} NPP}{\omega_{human}} - \frac{\lambda}{a_{provision} T_{provision} \epsilon_{provision}} \tag{9}$$

The first term can be thought of as the energetic ceiling to the human population. This represents the amount of food energy that is potentially available for digestion, relative to the biomass-specific consumption rate of food energy through human metabolism. The metabolic demand is relatively invariant, and therefore this term will vary predominantly with the food energy supplied to edible material by the ecosystem. If the rate of food energy supply were to double, the contribution of this term to the population would double. Human agency can enter in this term by increasing the edible fraction, ϕ_{edible}, through agriculture, livestock husbandry or other modifications of the ecosystem. Feasibly, ϕ_{edible} could range from very low values, such as 1 in 10,000, to 1 in 10 for intensive agriculture.

The second term can be thought of as the unused potential due to the race to ingest food before it is consumed by a non-human. It reflects the loss of potentially-edible material due to consumption by other animals, bacteria or fungi, the activity of which are encapsulated in the term λ. Humans could reduce λ through unresolved activities such as combatting pests, predators and pathogens, and also through improved means of food preservation and storage. But an important source of variation in this term over human history has arisen from the Things available to aid with provisioning, and the efficiency of the provisioning activity, which appear in the dominator (hereafter abbreviated as $aT\epsilon$).

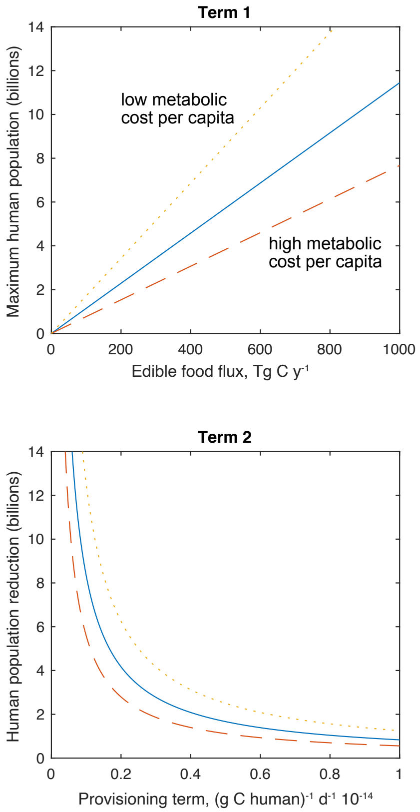

Figure 3. The two terms that determine population size at steady state. The top panel shows the maximum human population that can be sustained by a given flux of edible food, $\phi_{edible}NPP$. The blue line shows a moderate metabolic cost per human, and the dashed lines show low (67%) and high (150%) values relative to the baseline, corresponding to small-bodied/inactive and large-bodied/active populations, respectively. The lower panel shows the loss of potential population due to the failure to capture available food energy, as a function of the food provisioning term $aT\epsilon$ at a constant value of λ.

Fig. 3 shows how the two terms contribute to the human population. Because the equations are written in terms of biomass, the corresponding number of humans depends on the metabolic cost per capita, with a smaller number of humans for large-bodied (e.g. adult, obese) and/or active (high respiration rate) populations. The ceiling of the first term increases linearly with ϕ_{edible}, but the race for food encapsulated by the second term is nonlinear with the product $aT\epsilon$. This means that when $aT\epsilon$ is low, there are large gains to be made by increasing provisioning activity and/or the provisioning tool technology. However these gains only persist while $aT\epsilon$ is small relative to λ. The diminishing returns mean that there is a reasonable time investment to be made in provisioning, dependent on technology and the tendency of the food resource to be consumed by non-humans. Beyond this there is no point investing more time, freeing humans to undertake other activities. The overall result of variation in both terms is shown in Fig. 4.

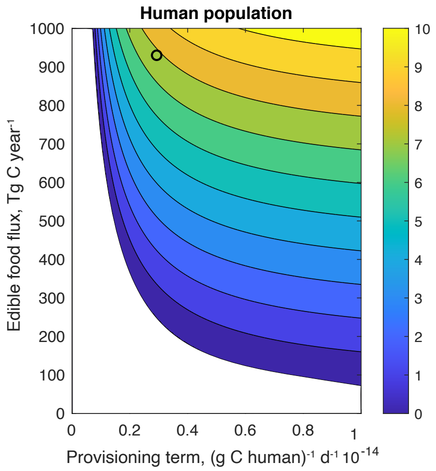

Figure 4. Human population as a function of edible food flux and provisioning term. Coloured contours indicate the steady-state human population that results from the edible food flux and food processing rates. The black circle indicates the approximate present-day food production (Alexander et al., 2017) and global population for comparison.

It should be emphasized that equation 9 is the equilibrium solution to the coupled human-ecological system. It does not imply that the human population is determined by an external carrying capacity, as commonly assumed with a standard logistic model of population growth. Rather, the solution also depends on human cultural, societal and economically-dependent features, as expressed through modification of ϕ_{edible}, the time allocation to provisioning, and the effectiveness of provisioning. Although not developed further here, the possibility of changing ϕ_{edible} through agricultural activity, as well as changes in $T_{provision}$ and $\epsilon_{provision}$ in response to changes in the connectome state variables, could provide interesting avenues of further research.

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5.1.2 Neural outcomes

The current model provides only an extremely simplistic sketch of how neural outcomes might be captured. These results are therefore not intended to be realistic, but rather illustrative of the way in which hypotheses could be developed based on the biophysical reality of how human thought is shaped by activities. The approach could be refined in future to explore feedbacks of neural outcomes on motivations, ϕ_{edible} and $\epsilon_{provision}$.

The connectome equations can be solved, similarly to the biomass equation, to provide the steady state solution

$$\frac{C_{other}}{C_{provision}} = \frac{\mu_{other}}{\mu_{provision}} \frac{a_{other}}{a_{provision}} \tag{10}$$

The first quotient on the right hand side reflects the inherent biological capacity to grow new synapses that can be activated by one of the two activities (assumed here to be equal, $\mu_{other} = \mu_{provision}$). The second quotient is simply the relative apportioning of time between the two activities. This simple formulation ignores many complications, such as the possibility that synapses strengthened through one activity might contribute to the other, possibly via impacts on the modification of the growth rates of new synapses, or global changes in the decay rate.

5.1.3 Subjective experience

The subjective experience calculation performed here is very simple, and not tremendously insightful. However there is one feature worth pointing out: the population-integrated affect, i.e. the population size N multiplied by the affect level, Nx_{affect}. As shown above, the population size can be increased by increasing $a_{provision}$, which would follow from a larger r_{hunger} or lower r_{other}. However, because the provisioning activity was assigned a lower value of affect, this larger population would enjoy a lower level of affect. This implies that there will occur a maximum of the integrated affect, at a population slightly less below that which could be achieved through a greater allocation of time to provisioning.

5.2 Transient simulations

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.

5.2.1 Approach to steady state population

When initialized from a population density well below the steady state value, the human population grows near-exponentially (Fig. 5 a). The food biomass is drawn down (Fig. 5 b), generating decreasing yields for the same effort (Fig. 5 c). Hunger increases in response (Fig. 5 d), which drives a greater $a_{provision}$ (Fig. 5 e). The surplus (difference between the solid and dashed line in Fig. 5 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. 5 a). The

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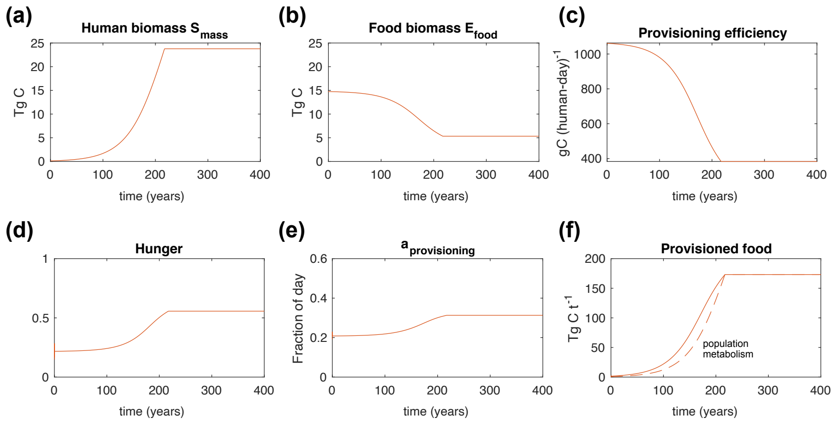

Figure 5. Timeseries of a typical model experiment. In panel f, the dashed line indicates the metabolic cost of maintaining the population (i.e. ωS_{mass}.

transition 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.

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

Figure 6 shows the same experiment shown in Fig. 5, 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 increase of $r_{hankering}$ (relative to r_{hunger}) decreases the population size at steady state (Figure 6 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 in response, because their priority is to engage in other activities. Because they provision less intensively, the food biomass remains more abundant (Figure 6 b), resulting in a greater provisioning efficiency (Figure 6 g). The greater

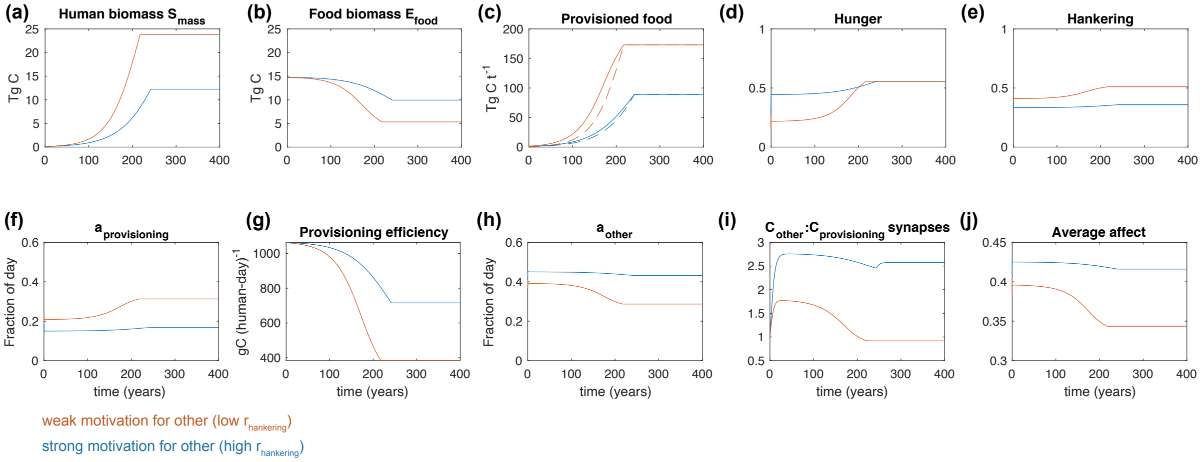

Figure 6. Timeseries of two model experiments with different values of $r_{hankering}$.

allocation of time to other activities results in a large contrast in the connectome, with C_{other} much greater than $C_{provision}$ in the population with strong $r_{hankering}$ (Figure 6 i). Additionally, the steady state affect is higher with strong $r_{hankering}$ (Figure 6 j), given the assumption that other activities provide higher affect than provisioning. Thus, the strong $r_{hankering}$ experiment produces a smaller population of happier people with a more diverse metaconnectome.

5.2.3 Golden ages

Figure 6 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 C_{other}, indicating a more diverse connectome 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 C_{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.

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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 activities such as learning, producing art and building public works.

6 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. This paper has attempted to lay out a simple but inclusive approach, focused on observable, biophysical quantities, intended to help build a common footing by bridging the natural-social science gap. The ESE approach simplifies the human system by boiling it down to three things: what humans are doing with their time, what are the biophysical outcomes of those activities, and what is the nature of their lived experience. 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.

In addition to the proposition for a general ESE approach, this paper has provided a specific conceptual framework that could be used for modeling and analysis over a range of temporal and spatial domains. An important aspect of the framework is its consideration of the neural characteristics within populations as a biophysical state variables. This framework was illustrated 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 socially- and culturally-dependent responses to state variables. Although the model ignores many important features (seasonality, spatial heterogeneity in food resources) and was not comprehensively calibrated with data, it gives a first-order understanding of controls on the human population size and suggests a mechanism for producing golden ages.

The ESE approach could be greatly advanced through further progress in three key domains. First, a better understanding of global human activity is required, including improved theoretical foundations and harmonized multinational datasets. Second, an improved set of metrics for the connectome that goes beyond the rudimentary approach used here, and can open the door to realistically quantifying aspects of knowledge and culture and their rates of change. And third, insights on the process-oriented relationships that link activity and context to multiple dimensions of subjective experience. The development of a diversity of models that follow the ESE approach (e.g. Zhu et al. (2020)) is likely to identify new processes, even as they raise new questions. With these developments, the ESE approach may provide a means to unite disparate learnings from the social sciences, and to bring them together with natural sciences to better understand the functioning of the human-Earth system.

Code availability. All MATLAB code used to run the model and generate figures will be uploaded to the zenodo archive.

Author contributions. EDG is the sole contributor.

Competing interests. The author declares no competing interests.

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