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Is carrying capacity useful for integrating humans into Earth system models? On the purposes and limits of modelling

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ABSTRACT

There are calls to better incorporate humans into Earth system models. As interdisciplinary research teams are assembled, this has led to interesting discussions about the purposes and limits of such models. In this perspective paper, I draw on a typology of Earth system models to discuss the limits of modelling, and look at how these limits might be affected by incorporating humans. For illustrative purposes, I look at a series of models of human population size as examples of the kinds of models that can be constructed. Two main types of model can be constructed for two different purposes: toy models are intended to elucidate a complex phenomenon and may use a simplified concept like carrying capacity for that purpose; on the other hand, forecast models intended for theory testing may require a more complex concept to better approximate observed reality. Many elements of observed reality are, however, unpredictable. And unlike other aspects of the Earth system, humans have both the capacity and the tendency to deliberately behave unpredictably, meaning that they often behave in ways that are by definition outside of any possible model. This paper therefore helps clarify why the human sciences have not yet produced a more complete model of human behaviour, why such a model might be impossible, and why the unusual unpredictability of human behaviour introduces new limits to Earth system models that incorporate humans.

1. Introduction

There are calls to better incorporate humans into Earth system models (Beckage et al., 2020, 2022; Kempf, 2023; Little et al., 2023; Wang and Grant, 2021). With a wide range of disciplines brought together for this endeavour, in this paper I look at what we might achieve with such models, and what is actually achievable. Of particular interest to interdisciplinary teams tackling this task, this paper considers the epistemic limits to current Earth system models, and extends these limits to consideration of the limits to incorporating human behaviours into these models.

To illustrate this discussion, I focus on models of human population size. Carrying capacity has long been a key concept for expressing the way that human populations are supported by the Earth system. However, for almost as long, the concept has been subject to forceful critique. This leads to the question: Is carrying capacity a useful concept for integrating humans into Earth system models?

In this paper, I begin by setting out various interpretations of the concept of 'carrying capacity' with examples of how they have been used in recent modelling. A main critique of the concept has long been that it is a vast simplification of the many factors affecting populations, and that it is only really possible to estimate carrying capacity for the very simplest of ecological systems such as blowflies in a laboratory setting (Anderson, 2021; Hall, 1988; Puleston and Winterhalder, 2019; Seidl and Tisdell, 1999). This motivates the argument that the relationships between humans and their environments cannot be reduced to such simple concepts, and that complex systems need to be understood more holistically (Delord, 2021; Sayre, 2008).

A defence against these critiques accepts that all models are simplifications, but argues that some models are nonetheless useful. So although carrying capacity is a simplification, there may be some kinds of model in which it is nonetheless useful. I draw on a long recognised distinction between highly idealised 'toy' models used for elucidating our understanding of complex phenomena by reducing them to their simplest form, and more detailed 'forecast' models that capture more of the empirical complexity necessary for hypothesis testing (Cornell et al., 2012; Randall and Wielicki, 1997). This distinction helps us to identify a first set of limits, due to the distinct purposes of elucidation and theory testing. I illustrate this point by looking at two toy models which use the concept of 'carrying capacity' to elucidate rather than test theories

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(Motesharrei et al., 2014; Richerson and Boyd, 1997). I then look at a series of models that explicitly rejects carrying capacity and instead aims to test theories using a more quantitively accurate portrayal of human population dynamics. In short, the concept of carrying capacity still has something to offer to researchers seeking to integrate humans into an Earth system model. But its usefulness depends on the intended purpose of our model, a choice that restricts the use of carrying capacity to models that elucidate, and prevents us using these models to test theories. If we want to produce a toy model that elucidates then carrying capacity might be a useful simplification. But if we want to test theories with a forecast model, then we may need to choose more readily operationalizable concepts, and be prepared to empirically determine the complex relationships between them.

A deeper critique extends from pragmatic concerns about whether the concept of carrying capacity is usable, to critique over whether it is even still coherent. This has led to the development of the concept of 'cultural carrying capacity' which emphasizes that many of the factors which affect human populations are socially determined and include normative considerations. Proponents of 'cultural carrying capacity' suggest that, as a result of the unpredictability of human innovation and biological evolution, a single number for human carrying capacity is essentially meaningless.

I build on this critique of carrying capacity to develop a novel line of argument about the limits of integrating human unpredictability into Earth system models. I extend the logic of Kauffman and colleagues (Kauffman and Roli, 2023), who argue that biological evolution can potentially produce a larger number of complex arrangements of molecules than any model is capable of representing. I apply this same logic to models involving human behaviour. Any Earth system model that incorporates humans must include some assumptions about the actions that humans can take. But the full range of possible actions that humans can take is impossible to define, since humans are capable of novel and unpredictable behaviour. And unlike other aspects of the Earth system, humans can even deliberately do something unexpected. For example, somebody might say 'Let's do something that nobody has thought of doing before' and that action would by definition be impossible to include in a model. Due to this unpredictability, the full range of possible human behaviours cannot be modelled.

I conclude by returning to the example of modelling human populations. Since human behaviour affects population size, it is impossible to model all the factors that affect carrying capacity. This illustrates why the unusual and occasionally deliberate unpredictability of human behaviour represents a fundamental limit to our attempts to incorporate humans into our models.

2. Carrying capacity and its critics

Around the 1840s, the term 'carrying capacity' was first used to describe the payload that ships were designed to carry. By the 1870s the term began to be used to describe how much pack animals could carry. By the 1880s it became used as a measure of how much livestock could be carried by the land, and soon after used to describe rangeland productivity. By the mid-twentieth century the term became used to mean the maximum population of an organism, and around the same time used to express of the maximum population of humans the earth could support (Sayre, 2008).

Though he did not use the term 'carrying capacity', the idea that population growth meets resistance received its best-known mathematical formulation in the logistic equation by Verhulst in 1838:

$$dN/dt = mN - nN^2 \tag{1}$$

where N is the size of the population and m and n are two constants. When $t = \infty$, N tends toward an upper limit. This upper limit is now known as the carrying capacity. In the modern differential expression of the logistic equation, this upper limits is designated K, such that $K = m/n$.

Criticism of the notion of carrying capacity can be traced to as early 1845, and to Verhulst's own memoir. He writes that "the law of population is unknown to us because we ignore the nature of the function that measures the obstacles, whether preventive or destructive, which oppose the indefinite multiplication of the human species" (Delord, 2021). Verhulst recognised that there are many obstacles to population growth, including all the preventive factors that decrease fertility and all the destructive factors that increase mortality. This includes many physical, biological, moral, and political factors that are unknown to us. Given this complexity, the factors affecting population dynamics could not adequately be expressed as simple monocausal resistance to unimpeded growth. Already for its eponymous originator, the Verhulst equation was no more than a heuristic tool (Delord, 2021, p. 90).

The critique, then, is that the concept of carrying capacity fails to capture all the relevant factors that affect a population. One hundred and eighty years later, this criticism persists. In reality, there are so many factors that can influence carrying capacity that even researchers studying nonhuman animals rarely try to parametrize carrying capacity. Where it has been attempted, it has only really been possible to parametrize carrying capacity for the very simplest of ecological systems, such as blowflies in a laboratory setting (Anderson, 2021; Puleston and Winterhalder, 2019; Seidl and Tisdell, 1999). Since carrying capacity is never actually observed in nature, critics point out that there is no empirical support for assuming that it applies to any population outside of a laboratory setting (Hall, 1988; Sayre, 2008, p. 129).

3. In what kinds of model might the concept of carrying capacity still be useful?

So the concept of carrying capacity is such an oversimplification that it is for practical purposes impossible to estimate. Nevertheless, there may be situations in which the reduction of complex relationships into a simple model can still yield useful insights (May 1973, pp. 10–12; Turchin, 2003, pp. 167–196). As statisticians like to remind us: all models are wrong, but some may be useful nonetheless (Box, 1976, p. 792).

To this end, it is useful to define different kinds of model. Since we are interested in the problems of incorporating humans into the Earth system, I draw on a typology of models proposed by Earth system scientists (Cornell et al., 2012, p. 132; Randall and Wielicki, 1997). They define four broad categories of Earth system model, two of which might be good candidates for incorporating humans.

First, elementary models are direct applications of basic physical principles. These typically deal with microscale phenomena such as the properties of cloud droplets or ice crystals, and are usually thwarted by problems of larger size and complexity. There are no elementary models involving humans since such models would indeed by thwarted by the size and complexity of human problems, so I discuss this type of model no further.

Second, forecast models predict the evolution of the Earth system, or some macroscopic part of it. Forecast models can be tested against real data. There are, however, fundamental limits to the deterministic predictability of the Earth system, due to sensitivity to initial conditions. For atmospheric models, the limits of predictability range up to a few weeks at the global scale. One example is the weather forecasts predicting day-to-day variations which have a two-week deterministic limit. Beyond this limit, only system statistics can be predicted, though these can also be described as forecasts. One example is the seasonal weather forecast, which reports the statistics of weather for each time of year, rather than attempting to predict day-to-day variations. Using system statistics, forecast models can also predict longer term climate change where it is driven by predictable changes in external forcing, such as projected greenhouse gas emissions. Since humans produce a lot of greenhouse gas emissions, these are a good candidate for the type of Earth system in which we might incorporate humans.

Third, higher-order closure models (sometimes called statistical models) simulate statistics directly. They are used to solve equations for turbulent flows at a high degree of complexity. Similar to elementary models, higher-order closure models become computationally impractical for problems of larger size and complexity, such as those involving humans, so I discuss this type of model no further.

Fourth, toy models are highly idealised models used to elucidate our understanding of a complex phenomenon in their simplest form. They are not intended to provide quantitatively accurate or physically complete descriptions, and are mainly used as educational tools. For example, a simple carbon cycle model can be used to elucidate the way that plant growth and decomposition may affect atmospheric CO_2 (BioCycle: Denning Research Group - Toy Models, 2024). Toy models typically do not predict the outcome of any measurement and so are rarely useful for testing hypotheses. But for elucidating human-nature relationships, this remains a good candidate for the type of Earth system model into which we might incorporate humans.

Different kinds of models suit different purposes. Toy models prioritise simplicity over realism in order to elucidate. In contrast, forecast models are intended to produce a model state that is consistent with observations of reality, so that they can be used for theory testing. In the context of how to incorporate humans into Earth system models, the model we choose will depend on our purpose for building the model in the first place. Once we know our purpose, we can better decide whether we intend a toy model that elucidates or a forecast model that predicts, and this can clarify what kind of concepts we decide to include in our model.

This returns us to the concept of carrying capacity. As we saw, criticism of the concept derives from the fact that it is a simplification of the complex factors affecting humans population, some of which are unknowable. Nonetheless, if our aim is to simplify our understanding of a complex phenomenon, using a simple concept in a toy model might suit this purpose. In a toy model, the concept of carrying capacity may turn out to be a useful simplification of the complex of factors affecting human population. Indeed, toy models may make a virtue of the way in which carrying capacity reduces population dynamics to an idealised ratio of two parameters, simplifying the complexity of the many factors affecting population. Due to this level of simplification, however, a toy model is unlikely to be useful for hypothesis testing.

A forecast model, in contrast, may be more useful for hypothesis testing. For this, it will need to capture much more of the complex factors that affect human population size. For all but the shortest of timescales, such a model will likely rest on system statistics. Since the concept of carrying capacity cannot be empirically determined outside the laboratory and may be theoretically impossible to determine at all, the concept will be of less use to forecast modellers. As we will see in Section 4, forecast modellers may choose a more readily measurable concept such as maximum observed population size, or set up a procedure for calculating the maximum equilibrium population size from other more readily measurable variables. These empirically determined statistics, though lacking the deterministic predictability of an assumed relationship between variables, will generally be able to capture much more of the complex reality of human-nature relations.

4. Two toy models which use the concept of carrying capacity

Richerson and Boyd sketch a simple toy model to elucidate debates over the future human population of the Earth (Richerson and Boyd, 1997). They use the logistic equation to express the relationship between growth in population and the carrying capacity of the Earth. They suggest that carrying capacity can be derived from a short list of other factors:

$$K = E + bT - cN - dNP + eD \tag{2}$$

where E is the natural environment, T is technology including ‘social technology’ such as institutions, N is population size, P is per capita prosperity, and D is a function of the initial endowment of non-renewables D_0; the constants $b, c, d,$ and e convert the natural units of the variables into population units. Richerson and Boyd’s analysis draws in part upon the well-known I=PAT equation, wherein human impact on the environment is calculated as a function of population, affluence, and technology (Ehrlich and Holdren, 1971).

Richerson and Boyd’s basic model consists of a simple system of two coupled equations specifying the instantaneous change of D (non-renewable) and of T (technology) in terms of the other variables. They extend this with another pair of coupled equations, known as the Lotka-Volterra equations, to model humans in relation to another species, and a final pair of equations to model relations between two subgroups of humans. They conduct an entirely verbal qualitative analysis of this system of equations to elucidate the problem of future population growth. They suggest possible interpretations of their simple model, including the idea that conservative religious subpopulations might outcompete a more secular subpopulation, and that rapid innovation in nitrogen fixation technology might avert a population crash. It is clear that they do not intend their toy model to empirically test theories, merely to produce “robust general analyses that we can understand” in order to “tell us what the empirical task is.”

Similarly, Motesharrei et al. use the concept of carrying capacity in a toy model based on the Lotka-Volterra equations (Motesharrei et al., 2014). They use this toy model to elucidate the collapse or sustainability of a human population disaggregated into subpopulations. Their model has ten parameters relating to each subgroup’s birth and death rate, their incomes and wealth, and resource depletion and regeneration. Like Richerson and Boyd’s model, their parameters are not empirically determined, the model is not intended to closely represent observable reality, and the model runs are not tested against observed empirical data. They interpret their findings both qualitatively and semi-quantitatively, graphing the results of model runs with various representative parameter values and starting values. I reproduce two of their graphs as an example (Fig 2). The graph on the left represents a model run where the population stabilises at a maximum, whereas the graph on the right represents a run where the population irreversibly collapses. The only difference between the two is the level of carrying capacity, which is higher in the sustainable scenario on the left than the collapse scenario on the right. This model can thus be used to elucidate that, if a given ecosystem is able to support different total numbers of humans, then even otherwise identical societies can experience very divergent outcomes.

I have chosen two fairly simple models in this section to illustrate how carrying capacity can be used for the purposes of elucidation. But toy models can also be much more complex. A well-known example is the *Limits to Growth* which used ground breaking computer modelling to track variables including population, food production, resource use, and environmental impact, and which used the concept of carrying capacity to represent the maximum human population of the Earth. Despite the complexity of their model, the authors nevertheless repeatedly emphasized that their modelling scenarios were not predictions but were only intended to illustrate the complex interrelationships within a dynamic system based on “incomplete information and intuition” (Meadows et al., 1972, pp. 43, 92–94, 122, 142). No matter their complexity, toy models are typically useful for the purposes of elucidation, rather than prediction.

5. A series of forecast models that predict population size

Today, the standard methods for demographic forecasting populations do not make use of the concept of ‘carrying capacity’ at all. Indeed, they do not even mention the term, not even to reject it (Mazzuco and Keilman, 2020; Wilson et al., 2022). But in this paper I want to contrast forecast models with the toy models above. So I have chosen to discuss a series of models which use less standard methods to

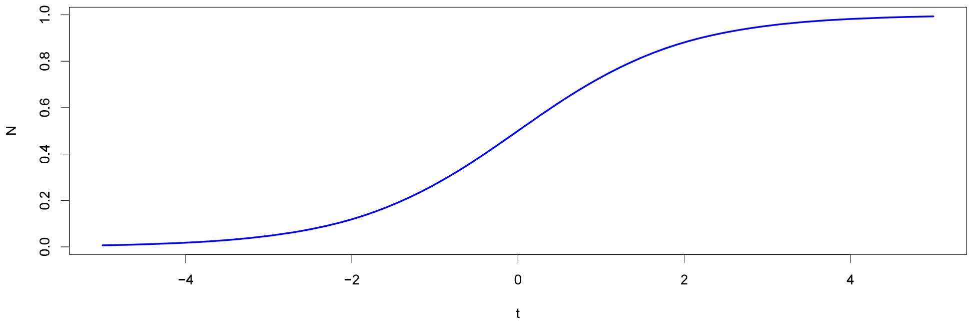

Fig. 1. The standard logistic function.

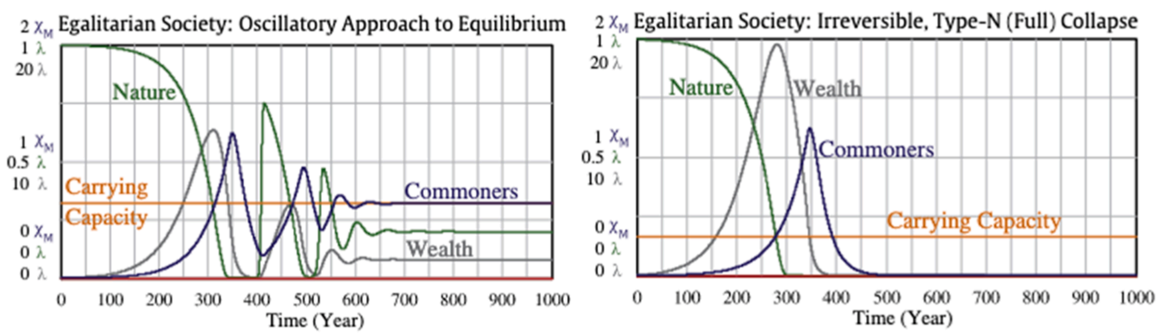

Fig. 2. Left: Oscillatory approach to equilibrium when Elite population (marked in red) equals zero. Final population converges to the carrying capacity, which is lower than its maximum value, XM, in this scenario. Right: Irreversible Type-N collapse (full collapse) when Elite population (marked in red) equals zero. All the state variables collapse to zero in this scenario due to overdepletion. Reproduced from (Motesharrei et al., 2014).

investigate the same kinds of question as the toy models above, and explicitly reject the concept of carrying capacity. For this purpose, I have decided to discuss a series of models that use the 'food-limited demography' approach (Lee et al., 2009; Lee and Tuljapurkar, 2008; Puleston and Tuljapurkar, 2008; Puleston and Winterhalder, 2019; Winterhalder and Puleston, 2018).

In the 'food-limited demography' approach, the equilibrium population size is predicted from variables quantifying agricultural yields, the area of land in cultivation, the number of hours worked, the conversion rate of labour into area cultivated, the age-weighted labour contribution, the age structure of the population, and the per capita calorie requirements according to the age and structure of the populations. As the modellers themselves describe it, the equilibrium population size becomes an output variable in their models, in explicit contrast to the toy models described above where carrying capacity is assumed as an input variable. These 'food-limited demography' models are then used to estimate the population density of real groups in real conditions, such as the 'Opunohu Valley of Mo'orea before European contact (Puleston and Tuljapurkar, 2008).

Interestingly, this series of models challenges the assumption that human population growth in reality necessarily fits a logistic curve. Under the assumptions of the Verhulst logistic equation, a population experiences some degree of population pressure from the moment it grows from zero, for example upon arrival in a new territory. In contrast, the 'food-limited demography' approach predicts instead that resources remain fairly abundant, and predicts that shortages will occur much more suddenly and much later than the Verhulst equation assumes (Fig. 3).

Puleston and Winterhalder use these results to suggest that demographic crises "are not predetermined by an a priori parameter like [carrying capacity], but are emergent from observable properties of vital rates, labor, and the environment of agroecological production" (Puleston and Winterhalder, 2019, p. 321). Toy models reduce complexity for the purpose of elucidating complex problems, but they can always be critiqued for their reductionism. Indeed, through critique of them, toy models may also motivate us to construct our own more holistic models that can capture more of the complexities of life.

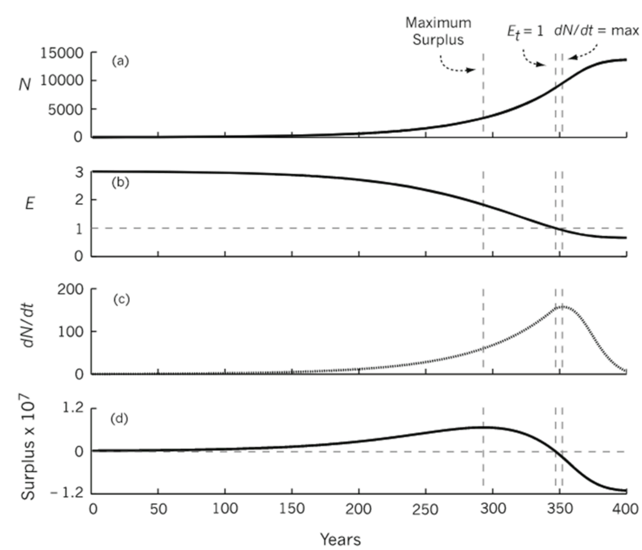

Fig. 3. The space-limited population growth trajectory. The simulation begins with a founding population of $N = 20$ occupying a frontier with 1000 ha of arable land. Panel (a) shows the population growth time series, N; (b) shows the value of the food ratio, E, the variable determining vital rates; (c) shows the instantaneous rate of change in N as a function of time, i.e., whether growth is accelerating or decelerating; and, (d) depicts the capacity of the population to produce a surplus, given constant work effort. Reproduced with slight simplification from (Puleston and Winterhalder, 2019, p. 320).

6. 'Cultural carrying capacity' and the limits to modelling human unpredictability

A deeper critique extends from pragmatic concerns about whether the concept of carrying capacity is usable, to critique over whether it is even still coherent. Since actual populations are affected by so many continually changing factors, the maximum population that any area can support is in reality highly dynamic and uncertain. The concern is that it is no longer coherent to speak of a 'maximum' number since that so-called maximum may change from one period to the next (Sayre, 2008, p. 129).

During the 1980s, the term 'cultural carrying capacity' was coined to refer to the maximum number of deer that could compatibly co-exist with a local human population (Ellingwood and Spignesi, 1986). This introduces the idea that the maximum population size of a given species is not purely a function of the environment but also depends on human preferences. Around the same time, the term 'cultural carrying capacity' also became applied to human populations, and for a similar reason. Whilst 'carrying capacity' expresses the maximum size of human population that could survive on the Earth at a bare subsistence level, the concept of 'cultural carrying capacity' refers to the largest human population that may be supported with a higher quality of life than mere subsistence (Alcott, 2012, p. 112; Hardin, 1986; Seidl and Tisdell, 1999, pp. 403, 405). For example, if humans choose a lifestyle that includes air travel, eating meat, and luxury consumer goods, then their 'cultural carrying capacity' will be significantly lower than the absolute maximum 'carrying capacity' number of humans that could be supported on a subsistence diet alone.

The concept of 'cultural carrying capacity' emphasizes that many of the factors which affect human populations are socially determined (Alcott, 2012; Hardin, 1986, 1988; Seidl and Tisdell, 1999). These factors include human consumption patterns, expected quality of life, and technology. For clarity, proponents of cultural carrying capacity do not intend it merely to replace the concept of carrying capacity with another simple number to plug into our equations. As Seidl and Tisdell put it, they intend the concept of cultural carrying capacity to be a "shift from a positivist-type concept to a normative one. This shift means that there is no longer an objective, single level of carrying capacity (equilibrium population) as in the blowfly experiment" (Seidl and Tisdell, 1999, p. 405). The concept of cultural carrying capacity is normative because it involves decisions about resource consumption and distribution today, as well as consideration of how these decisions impact future generations whose preferences and technologies are unknown to us. This adds further levels of unpredictability and uncertainty. Seidl and Tisdell approvingly quote Arrow et al.: "A single number for human carrying capacity would be meaningless because the consequences of human innovation and biological evolution are inherently unknowable" (Seidl and Tisdell, 1999, p. 405).

The unknowability of human innovation and biological evolution points to an even more fundamental critique of the use of carrying capacity as a modelling concept. Any model must make assumptions about the range of possible model states. In the case of human behaviour, this range must include the actions that humans can undertake. But the range of possible actions that humans may take is impossible to define.

Kauffman and his colleagues put forward a corollary to the assumption that biological evolution is so unpredictable that to list every possible variation is impossible. Their argument is that, as a result, it is physically impossible to construct a model capable of computing every possible variation within the timescale of the universe. Indeed, since the universe is a system that will not pass through every possible system state, the lifetime of the universe is not long enough to produce all the complex arrangements of molecules that are theoretically possible. This means that there are more potential configurations of life, as a complex arrangement of molecules, than the entire universe over its entire lifespan is capable of producing. Any model will necessarily be much smaller and have a much shorter runtime than the universe, and so will be incapable of modelling all the potential configurations that life may have (Kauffman and Roli, 2023). Since human behaviour can change quickly and is even less constrained than biological evolution, it will be even tougher to incorporate human behaviours into our forecast models.

The most unpredictable aspects of human behaviour may be impossible to model altogether. In their discussion of modelling biological evolution, Kauffman and Roli draw a useful analogy with Gödel's first incompleteness theorem which states that, in any consistent axiomatic system whose axioms can be listed, there is a statement that can be neither proved nor disproved within that system (Kauffman and Roli, 2023). To extend this analogy to human behaviour, during any human decision-making process somebody might say 'Let's do something that nobody has thought of doing before'. By definition, the action resulting from such a decision would be impossible to include in any model. So it does not matter how extensive the range of possibilities a model includes, it must fail to capture the full range of possible human decision-making.

In conversation, I know that some colleagues from the Earth sciences had hoped that our efforts might produce models that more or less capture all possible human behaviours across the world and in all possible historical circumstances. Gödel's incompleteness theorems are widely held to show that a complete and consistent set of axioms for all mathematics is impossible. Analogously, the tendency for humans to undertake actions that nobody has thought of doing before suggests a complete and consistent model of human behaviour is impossible. This might help clarify why the human sciences have not yet produced a complete and consistent model of human behaviour – and why it seems unlikely that anyone will ever produce such a model in the future.

6. Conclusion

When incorporating humans into Earth system models, it is worth recognising that there are a diversity of Earth system models that use a diversity of modelling methods. We need to ask ourselves: Into what kinds of Earth system model would we like to incorporate humans? For what purpose? And within which limits?

If we want our model to elucidate otherwise complex relationships, then we might choose a toy model where relationships may helpfully be reduced to fairly simple equations. These may express idealised relationships in terms of simplified concepts such as 'carrying capacity'. On the other hand, if we want our model to test predictions, then we may prefer to construct a forecast model, in which idealised relationships between simplified concepts like carrying capacity may be much less useful. For testing hypotheses, more readily operationalizable concepts may need to be chosen, and the complex relationships between them may need to be determined empirically.

Modelling is a human endeavour, and its future evolution is itself somewhat unpredictable. But there are inherent limitations of modelling when it is applied to any form of life, and especially when applied to humans. Life evolves in unpredictable ways, and humans sometimes take a great many unpredictable decisions in a very short period of time. This renders a complete model of the fundamental laws governing all human behaviour impossible. For those used to modelling more tractable systems, it may come as a surprise that novel limits emerge when incorporating humans into our Earth system models: unlike other aspects of the Earth system, humans have both the ability and the tendency to quite deliberately be unpredictable. Some of our most ambitious modelling goals may therefore be unachievable. But though human unpredictability may frustrate us, we might also be heartened by life's endless capacity to surprise us.

CRediT authorship contribution statement

Tilman Hartley: Conceptualization, Investigation, Methodology, Project administration, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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Data Availability

“All data used is available within the paper itself.”

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