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PAPER

A modeling framework for World-Earth system resilience: exploring social inequality and Earth system tipping points

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Abstract

The Anthropocene is characterized by the strengthening of planetary-scale interactions between the biophysical Earth system (ES) and human societies. This increasing social-ecological entanglement poses new challenges for studying possible future World-Earth system (WES) trajectories and World-Earth resilience defined as the capacity of the system to absorb and regenerate from anthropogenic stresses such as greenhouse gas emissions and land-use changes. The WES is currently in a non-equilibrium transitional regime of the early Anthropocene with arguably no plausible possibilities of remaining in Holocene-like conditions while sheltering up to 10 billion humans without risk of undermining the resilience of the ES. We develop a framework within which to conceptualize World-Earth resilience to examine this risk. Because conventional ball-and-cup type notions of resilience are hampered by the rapid and open-ended social, cultural, economic and technological evolution of human societies, we focus on the notion of 'pathway resilience', i.e. the relative number of paths that allow the WES to move from the currently occupied transitional states towards a safe and just operating space in the Anthropocene. We formalize this conceptualization mathematically and provide a foundation to explore how interactions between ES resilience (biophysical processes) and World system (WS) resilience (social processes) impact pathway resilience. Our analysis shows the critical importance of building ES resilience to reach a safe and just operating space. We also illustrate the importance of WS dynamics by showing how perceptions of fairness coupled with regional inequality affects pathway resilience. The framework provides a starting point for the analysis of World-Earth resilience that can be extended to more complex model settings as well as the development of quantitative planetary-scale resilience indicators to guide sustainable development in a stabilized ES.

1. Introduction

Until recently, complex human societies developed during the climatically stable Holocene period in which humans predominantly had to adapt to global dynamics (Lenton and Latour 2018). The Holocene period was remarkably stable, regulated by global feedback processes that emerged over time through the interplay among climatic, geophysical, and biological processes characterized by high resilience—the ability to absorb and recover from perturbations while maintaining systemic features (Past Interglacials Working Group of PAGES 2016). Currently, there is no evidence that modern societies can exist, let alone thrive, in conditions substantially different from the Holocene (Steffen *et al*

2015, 2018). Maintaining Earth in a Holocene-like regime may thus be essential for human survival (Waters *et al* 2016, Rockström *et al* 2021).

During the last five centuries, impacts of increasing human activities through excessive use of natural resources, large-scale destruction of natural habitats, and release of carbon dioxide into the atmosphere threaten the stability of many essential global processes that support Holocene-like conditions. Driven by increasing global populations within the last 50–100 years, from 4 million in 10 000 BCE to 7.2 billion in 2019 (Klein Goldewijk *et al* 2010, UN Pop. Div. 2015), humanity may now be departing the Holocene and entering the Anthropocene. Human societies are now faced with the challenge of maintaining Holocene-like conditions based on limits to how far essential controlling processes can be altered by human activities without risking undermining the stability of the Earth system (ES) (Rockström *et al* 2009) and the stability of global social, economic, and political systems (Raworth 2017, Kemp *et al* 2022).

Addressing this challenge requires an integrated analysis of the interaction between global biophysical systems (the ES) and global social systems (the World system (WS)) to understand the dynamics of the coupled World-Earth system (WES). Given both systems are highly uncertain, the challenge can be cast in terms of building and maintaining World-Earth system resilience (WER). The classic ball-and-cup notion of resilience is based on basins of attraction defined by system structure and the capacity of a system to remain in these basins when impacted by a perturbation to core controlling dynamics (Walker and Meyers 2004). Steffen *et al* (2018) define three such potential ES attractors: the glacial-interglacial cyclical attractor driven by celestial mechanics in the Pleistocene, the 'stabilized' Earth as a continuation of the Holocene, driven not by celestial processes, but predominantly by human activities, and 'Hothouse Earth' also the result of human activities. Although a WS may be possible in the glacial-interglacial limit cycle, long periods of ice cover make this unlikely. Likewise, the environmental conditions in Hothouse Earth may be so severe as to make a WS impossible.

The challenge we face is to characterize the boundaries between such potential attractors and explore mechanisms that enhance or degrade the resilience of the stabilized attractor in which the WER can flourish. Equally important is characterizing the stability landscape controlling transient dynamics on shorter time scales that underlie our capacity to pilot the ES from one long-run attractor to another (i.e. locate feasible trajectories as in figure 2). Feasible trajectories require the dynamic balancing of minimum material flows required to support a just and livable world with their impacts on biophysical processes. Within the planetary boundaries framing, combining the upper biophysical boundary with the lower socio-economic boundary creates an annulus (a 2D doughnut) that defines the safe and just operating space, SJOS (Raworth 2012). This SJOS is the 'stabilized' WES, and the feasible trajectories to it, we seek to characterize via the notion of WER. Because we cannot do experiments to perturb the ES to investigate the effects of transgressing global thresholds, observing when the ES tips into new states and its recovery potential (Steffen *et al* 2011), we must do so *in silico* with modeling experiments. We must also rely on models to investigate how global social and economic systems behave under severe resource scarcity shocks and observe how they respond and reorganize (Bak-Coleman *et al* 2021).

In this paper, we build (section 2) and analyze (section 3) a WES model that merges ideas from ES science and WS theory and captures feedbacks between global biophysical and global social and economic processes that co-determine development pathways and WER. We investigate under what circumstances the WES can transition from one in which isolated regions support low-complexity societies to one in which interconnected regions support high-complexity societies. That is, what are the characteristics of viable transition pathways between these two WES attractors and how sensitive are they to perturbations, acknowledging the possible existence of thresholds when, once crossed, can lead to self-reinforcing feedback processes (e.g. control of the global energy balance) that can lock the planet onto an irreversible, increasingly less human-habitable trajectory for centuries or millennia? In this sense, we are taking a 'pathway diversity' view of resilience (Lade *et al* 2020), focusing on the resilience of transformation pathways toward the SJOS to exogenous shocks.

The goal of our study is neither to innovate new detailed process models nor execute a data-driven modeling exercise focused on assessing the resilience of the present-day WES. Rather, our goal is to develop a conceptual and mathematical modeling framework that is extensible and achieves the right balance between capturing the essential features of a WES, accessibility, tractability, and transparency with appropriate focus on understanding WES resilience in particular. Specifically, current existing ES models are typically too complex, lack transparency, and are difficult to access. Models typically used for resilience analysis, while often more transparent and accessible, are too simple to study WER. Further, the notion of resilience that emerges from these simple models is too limited for the open-ended nature of WES. Thus, there is a research gap defined by the lack of a modeling framework that combines modeling from economics and ES science in a way that enables a richer conceptualization of resilience.

The main contribution of our paper is to introduce such a WES modeling framework with the appropriate level of complexity aimed at qualitatively analyzing WER landscapes to provide a foundation for mathematical definitions and quantification to help fill this gap. We illustrate the potential of the framework by exploring the impact of the interaction of one key socio-economic process, the impact of economic inequality on decarbonization policies, with one key biophysical process in the form of a climate tipping element, i.e. a positive feedback in carbon emissions once a threshold is passed, on WER. This analysis sets the foundation for how WER may be analyzed in a diversity of models with multiple social, economic, and biophysical processes, each potentially exhibiting tipping behavior. We conclude with a discussion of how insights from our WER analysis can be incorporated into the climate change policy discourse for timely action (section 4).

2. Methods and materials

Our focus on the development of a WES model is an attempt to strike a balance between biophysical, social, and economic processes. We envision the WES as a network of polities, each with its own endowment of human, human-made, social, and natural capital (Barfuss *et al* 2017, Geier *et al* 2019) that interact through a global commons. The key premise is that endogenous interactions among nation states is the primary driver of change. That is, polities are not part of a world, but through their interactions, create a WS (Wallerstein 1979, 2004) which then interacts with the ES.

Recent approaches for understanding such dynamics with classic integrated assessment models (IAMs) use a class of simple WES models that are a standard tool for climate policy (van Vuuren *et al* 2016, Mathias *et al* 2020, Keppo *et al* 2021). They typically consist of a low-complexity ES model driven by a neoclassical economic growth model. They may have aggregate ES and WS systems (e.g. Nordhaus 1993) or some spatial decomposition in the ES and some sectoral decomposition in the WS (e.g. Nordhaus and Yang 1996). IAMs typically focus on inter-temporal optimization problems with a time horizon between a few decades and a century to derive investment and/or regulation trajectories that either minimize costs under some global emissions constraint (Nordhaus 1993, Nordhaus and Yang 1996), or that optimize a certain trade-off between these costs and climate-related damages. As such, they cannot be used out of the box to study World-Earth resilience (Barfuss *et al* 2018, Heitzig *et al* 2018).

In principle, their core models, if stripped of the surrounding optimization algorithm, could be used to study the climate and economic subsystems' reactions to perturbations in order to partially assess the persistence form of resilience. However, few IAMs include feedbacks from the Earth subsystem onto the economic subsystem (e.g. the IMAGE model, Alcamo *et al* 1996), or include important nonlinear effects within the Earth subsystem such as positive feedbacks or tipping points, both of which are important on the longer time horizons needed for assessing resilience. Also, IAMs are typically already too complex to provide a deep understanding of the system's behavior. Finally, their detailed assumptions about the economic system might be hard to justify on the slightly longer time scales (at least several centuries) needed to assess resilience. On such timescales, population dynamics are also relevant but hard to model in detail. Finally, if we wish to communicate ideas about WER to a broad audience, the model must be transparent, accessible, and able to be run by individuals without intimate knowledge of the model and in a reasonable amount of time.

For these reasons, i.e. their focus on optimization over decadal time scales, model complexity, lack of strong non-linearities, sectoral rather than social and behavioral focus in economic subsystems, and limited transparency and accessibility, IAMS are not suitable for our purposes (Farmer *et al* 2015, Mathias *et al* 2020). Rather, we utilize the same basic building blocks as in typical IAMS but follow a simpler modeling approach exemplified in Nitzbon *et al* (2017), using a minimal and balanced representation of the most fundamental biophysical and socio-economic dynamics on centennial to millennial time scales. In contrast to Nitzbon *et al* (2017), we introduce a potential threshold for runaway climate change, and two world regions to study the effects of global inequality on the SJOS. To keep the model tractable, we reduce the internal details of both the carbon cycle, economic system, and population dynamics further than (Nitzbon *et al* 2017), so that we are left with only five tractable differential equations that represent well-justifiable approximations of fundamental long-term mechanisms that correspond to well-established basic models from ecology and economics: logistic population growth, capital growth affected by environmental shocks, and environmental pollution and recovery.

We develop and analyze a 2-region WES that enables us to explicitly look at asymmetries in natural infrastructures, initial conditions and path dependencies (idiosyncratic shocks). Such asymmetries generate differences in population dynamics that are shaped by birth-, death-, and migration rates as well as economic investment patterns across regions boosting human well-being but also weakening the global system via climate change through higher emission rates, feeding back on all societies. A 2-region model captures these essential features of a WE system in the coarsest possible way and is thus where we start our analysis. The notion and structure of such a WES is captured in figure 1. Panel A shows the fundamental building blocks. On the bottom is the WS which connects, at a minimum, two polities supported by their respective natural capital endowments through some sort of material or

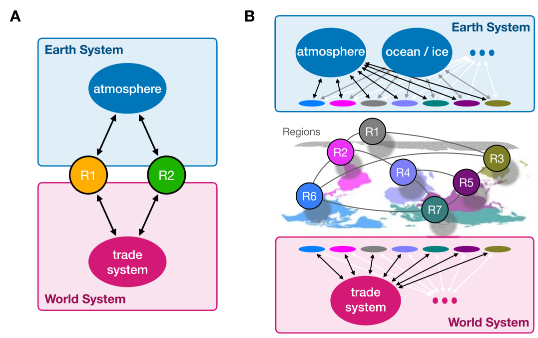

Figure 1. Schematics of World-Earth systems. (A): 2-region system actually modeled. (B): spatial conceptualization of a 6 region (arbitrary, but maps roughly on to our system) including network representation of 6-region W-E system.

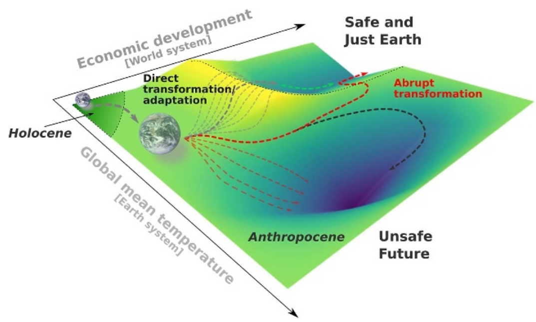

Figure 2. Dynamic landscape for the 'World-Earth System' where social/economic and biophysical features interact. Earth enters the Holocene near the zero economic development axis and has progressed into the Anthropocene. Humanity now faces critical decisions about navigating toward lower or higher global mean temperatures (and how abruptly). Note that this dynamic landscape may or may not contain basins of attraction in the traditional sense, i.e. the Safe and Just Earth 'basin' may be an open-ended valley, thus our emphasis on pathways. See text for further discussion.

information exchange such as the example shown here of trade. The regions (and the polities they support) are connected to the ES through material and energy exchanges through a shared entity of some sort (i.e. a common-pool resource) such as the example shown here of the atmosphere. Panel B illustrates how the simple case we study here can be extended via networks of such building blocks including, for example, human migration, culture exchange, and knowledge exchange in the WS, and oceans, biodiversity loss, and animal migration in the ES. Such networks generate endogenous dynamics underlying WES trajectories like those depicted in figure 2 that are the focus of our resilience analysis. Note that the dynamic landscape depicted in figure 2 shows a traditional 'cup' basin and an open-ended valley to emphasize the open-ended nature of human social and economic development. At the location in state space where the WES is shown, WER depends not on the traditional resilience (size of basin) of the undesirable high temperature, low economic development basin or characteristics of the SJOS valley but, rather, on the curvature of the landscape that determines viable and robust paths by which the WES can reach the SJOS. The ridge depicts a barrier to collective agency that must be overcome through climate action without which the endogenous dynamics will naturally lead to the undesirable basin.

The formal mathematical model combines the same basic building blocks as many IAMS (e.g. DICE) derived from theory and empirical patterns from economic growth, population biology, and ESs science. As mentioned above, our theory for the WS deviates from optimization and, instead, is predicated on WSs Theory (Wallerstein 2004). WS theory revolves around the notion that labor markets do not operate at the local, state, or national scale but, rather, on transnational division of labor and exchange of production based on international trade agreements built on power asymmetries and that create three sets of countries: core, semi-periphery, and periphery. Because capital is allowed to move and seek out cheap labor, this WS tends to devolve, at least historically, to the relatively wealthy core extracting wealth from the less wealthy peripheries. This type of 'inequality regime' (Piketty 2020) is an important determinant of the capacity of WES to transform to SJOS, as we shall see. Our model captures a 'core' i.e. a high-income country (Region 1) and a 'semi-periphery' country, i.e. a lower-income country (Region 2).

The model tracks five state variables: the human population size (billions of individuals) and the level of development of the built environment (capital) in each region, and one variable for the global system, e.g. a global commons such as atmospheric carbon stocks. This leads to the dynamical system

$$dP_j/dt = r_jP_j(1 - P_j/\kappa_j) + M_j \tag{1}$$

$$dK_j/dt = I_j - \delta_jK_j - \sigma_jS_j(G)K_j \tag{2}$$

$$dG/dt = e_1Y_{i1} + e_2Y_{i2} - u(G - G_e) + \theta(G - G_0) \tag{3}$$

for $j \in 1,2$. The term M_j is the net migration into region j. The parameters r_j and κ_j represent the intrinsic growth rate and carrying capacity of the human populations, δ_j the depreciation (entropic decay) of built infrastructure, and σ_j the impact of shocks, $S_j(G)$, related to the global externality G (natural disasters e.g. storm surges, floods, etc related to climate change). The parameters e_1, e_2 and u represent the carbon intensity of industrial production in regions 1 and 2 and the intrinsic assimilation capacity for G (e.g. carbon sequestration by marine and terrestrial systems), respectively. G_e is the carbon concentration toward which the ES will tend within a

Table 1. Parameter definitions, units, and default values. See text for definitions of other parameters that are varied extensively in the analysis.

Symbol	Definition/units	Default value	Source
r_1, r_2	Intrinsic growth rates (1/time)	0.038, 0.042	Fit to historical and projected UN data (UN Pop. Div. 2015)
κ_1, κ_2	carrying capacity (10^9 persons)	1.5, 9.7	Fit to historical and projected UN data (UN Pop. Div. 2015)
δ_i	Entropic decay rates (1/time)	0.05	Standard value used in practice
σ_i	Climate impact factor	0.03	Varied in the analysis
e_i	Emission intensity (hecto ppm/10^{12}\$)	0.0004	(Our World in Data 2021, UN Economic Commission for Europe 2021)
u	Emission uptake rate (1/time)	0.0025	Based on historical estimated uptake of 280 pg over 200 years (Gruber*et al* 2019).
A_1, A_2	Total factor productivity	2.7, 1.7	Historical match of GNP World Bank (2021a).
β_1, β_2	Output elasticity/factor share of labor	0.5, 0.5	Varied in analysis. Historical range 1947–2016: 0.66–0.56 (Giandrea and Sprague 2017).
α_1, α_2	Output elasticity/factor share of capital	0.5, 0.5	Varied in analysis. By assumption, $\alpha_i + \beta_i = 1$ (constant returns to scale).
s_1, s_2	National gross savings rates	0.25, 0.21	Varied in analysis. Rough historical average of around 0.25 (World Bank 2021b).

given climate regime in the absence of anthropogenic forcing, e.g. $G_e = 280$ ppm based on pre-industrial levels. The rate parameter u can be understood as a measure of the global public good provided by the ES to reduce pollution of the global commons. In the analysis, carbon intensity is treated as a parameter in the baseline case, i.e. e_1 and e_2 are fixed. In the decarbonization scenarios, e_1 and e_2 are treated as state variables with simple exponential decay at the (politically determined) decarbonization rate. See the Supplementary Materials for further details. Finally, the function $\theta(G - G_0)$ represents a climate threshold about which we will say more later.

The economic base of each region (GNP) consists of a 'backstop' technology Y_{bj} (e.g. simple agrarian economy) and an 'industrial' technology Y_{ij}. Gross national income (GNI), Y_i, is then GNP plus the net of cross-region trade flows (or international transfers) Tr_{ij}. As industrial technology becomes more productive than the backstop technology, society transitions from the latter to the former thus capturing the idea of 'industrialization' processes. By definition we have

$$Y_1 = \max(Y_{b1}, Y_{i1}) - Tr_{12} + Tr_{21} \tag{4}$$

$$Y_2 = \max(Y_{b2}, Y_{i2}) + Tr_{12} - Tr_{21} \tag{5}$$

where industrial production is modeled with standard Cobb–Douglas technology, i.e. $Y_{ij} = A_j K_j^{\alpha_j} L_j^{\beta_j}$ with L_j and A_j the labor supply and total factor productivity in region j, respectively, and with constant returns to scale ($\alpha_j + \beta_j = 1$). We assume backstop technology is labor intensive, i.e. $Y_{bj} = A_{bj} L_j$.

Next we assume that agents only invest after a minimum subsistence per-capita consumption level, C_m is met and invest a proportion of this 'disposable' income, s_j. This is captured by the expression $I_j = s_j R(Y_{dj})$ where $R(x)$ is the ramp function and $Y_{dj} = Y_j - P_j C_m$ is disposable income. If $Y_{dj} > 0$, $R(Y_{dj}) = Y_{dj}$ and agents invest a proportion of disposable income, $s_j Y_{dj}$. If $Y_{dj} \leqslant 0$, $R(Y_{dj}) = 0$ and investment is zero. Investment should be interpreted broadly to include hard (roads, canals, buildings) and soft (legal systems, information storage and transfer systems) infrastructures. Finally, Tr_{ij} is the trade or transfers from region i to region j. As with investment, trade only occurs after minimum subsistence needs are met—see the supplementary materials for more details.

Table 1 shows the WES parameterization used in our analysis. While this parameterization is empirically-supported by *our* WES, it is important to emphasize that the model with this parameterization approximates the actual WES we inhabit only in a very broad way and is in a sense a placeholder to give the reader relatable context and provide an anchor for model abstractions. What is key is the mode of analysis we present as a foundation for future work on WER. Of critical importance is the fact that the model is easily extensible to any number of regions, WS elements, and ES elements as suggested in figure 1(B). For example, while we focus on a single global tipping element in the sense of Lenton *et al* (2008) in our analysis here, it is straightforward to add other types of regionally or sectorally specific non-linear dynamics and tipping elements (see O'Riordan and Lenton (2013) for an overview of key tipping elements) that may be biophysical (e.g. the

Indian monsoon (Stolbova et al 2016), dieback of the Amazon and boreal forests (Lenton et al 2008, Rasmussen and Birk 2011), food systems (Benton et al 2017, Krishnamurthy et al 2022)), social (e.g. norm shifts (Nyborg et al 2016, Chapin et al 2022, Aschemann-Witzel and Schulze 2023), political (Bers et al 2016, Fesenfeld et al 2022), or economic (Kopp et al 2016) in nature or may involve networks of interacting tipping elements (Klose et al 2020, Wunderling et al 2021, Livina 2023). The framework allows for the systematic study of WER under various assumptions about the presence, absence, or character of these various WES elements.

3. Analysis: transition pathways to SJOS

Our analysis proceeds in two steps. We first (section 3.1) construct a baseline consisting of 600-year scenarios starting from 1900 to illustrate the possible long-run qualitative model behavior and the differential regional impacts of climate change resulting from economic development. In the second step (section 3.2), we generate the paths shown in the conceptual model in figure 2 in an actual formal model realization and analyze how various decarbonization scenarios may influence those paths.

3.1. Representative baseline trajectories

Figure 3 shows three scenarios that represent a 'well-behaved' ES with no critical tipping elements. The six panels show representative trajectories for two regions. The two regions —'high-income countries' (HICs) and 'low-income countries' (LICs)— differ only in their savings rates and total factor productivity. This difference may be due to different cultural contexts (less propensity to save) and organizational capacities (variation in contract creation and enforcement across regions) and roughly matches experiences in the twentieth century. The colored strip represents a hypothetical critical period characterized by high uncertainty through which the WS must find resilient pathways to reach a SJOS. The strip is merely a visual heuristic to orient the reader—it roughly corresponds to 21st century Earth and sets the stage for our discussion of decarbonization scenarios in section 3.2.

The three scenarios differ only in their carbon intensity per unit of GDP. The scenarios begin with the situation in 1900 with the take-off of fossil-fuel-based industrialization and atmospheric CO_2 concentration (ACC) of around 280 ppm. Carbon intensity does not change over the course of the scenarios so they may be seen as business as usual with no policy response. In the low emissions case, ACC reaches around 320 ppm in 2020. There is a soft landing in the future but as the bottom panel shows, development remains significantly unequal. This enables the HICs to reach a high per-capita standard of living (bottom panel, column 1) before it begins to decline due to the impacts of emissions. The atmosphere's assimilation capacity is a common-pool resource that is 'used up' during economic development by HICs at the expense of LICs.

The moderate emissions case roughly maps onto Earth's historical trajectory. In 2020, ACC is around 420, total GDP of HICs is around 35 trillion and LICs is around 55 trillion for a total of around 90 trillion current USD (Our World in Data 2021). In this case, ACC tops out at just under 700 at century's end. This concentration induces significant costs and by the end of the century, world output drops to around 50 trillion and, in the long run, declines to around 30 trillion with HICs and LICs contributing about equally. This masks the per-capita story with the HIC's able to maintain industrial economic structures with 10 times per-capita GNI of LICs. LICs revert back to baseline economic structures (more agrarian-based with an per-capita annual income of around 1000 USD).

Figure 4 shows the trajectory for the moderate emissions case projected in per-capita GNI phase space. The heavy black curve is the business as usual scenario and illustrates three possible attractors. The red, 45° line indicates equal per capita GNI across regions. The dark green region in the lower left is the pre-industrial, baseline technology region where the impact of humans on the ES is minimal (most of the Holocene). The pink regions indicate a degraded ES wherein cumulative emissions associated with industrial production are very high (blue curve, top center panel, figure 3). The limit cycle on the lower left results from the ES pulling carbon out of the atmosphere which reduces economic impacts just enough for a period of mild economic growth which then increases atmospheric carbon again. The blue circle at the maximum development point represents a window of opportunity for decarbonization and/or more balanced growth across regions that corresponds to the colored strip in figure 3. The trajectory ensemble illustrates the notion of pathway resilience. Green paths enable continued development. Salmon-colored paths lead to attractors with unequal development and/or a degraded ES. These paths may be the result of increasingly unequal development that delays or prevents action on decarbonization policies due to political friction generated by inter-regional disagreements (right) or insufficient decarbonization policy in spite of efforts to promote more equitable development across regions (left). WER can then be conceptualized as the 'volume' of the state space containing the green trajectories (SOS) relative to that containing the salmon trajectories and the probability of being knocked out of the SJOS. Key to the notion of pathway resilience is that it emphasizes the complexity of the landscape between attractors rather than characteristics of attractors themselves. We now turn our attention to characterizing these paths.

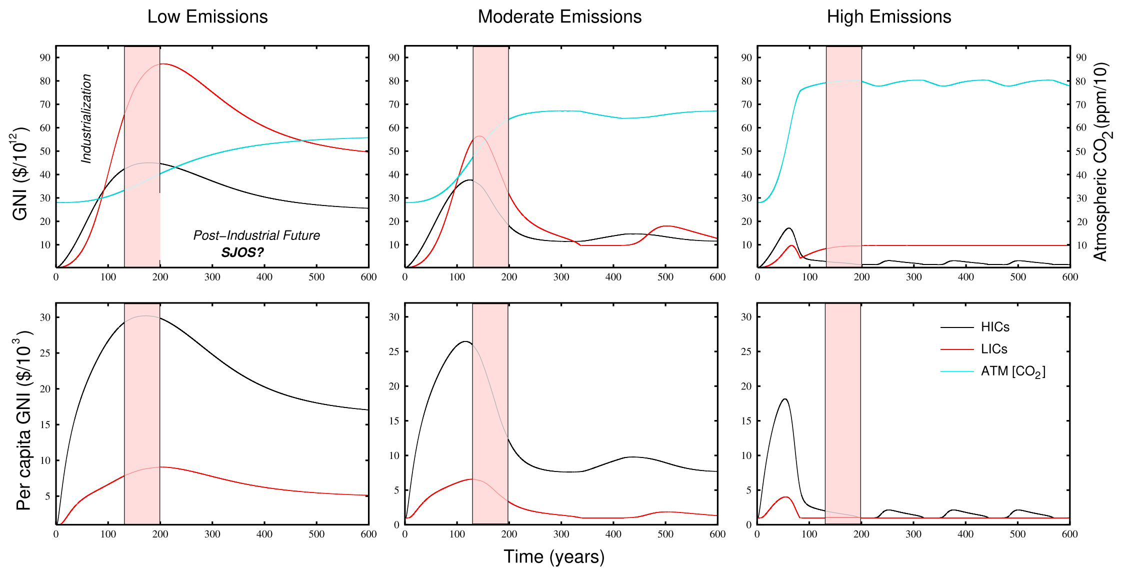

Figure 3. General model behavior for low, moderate (roughly matching historical levels), and high emissions. These are trajectories for a 'friendly' earth systems that responds smoothly to increasing atmospheric carbon. The black and red curves represent the 'higher' and 'lower' income countries. The colored strip represents a veil of uncertainty that separates the last 120 years of industrialization (high fossil fuel use and high pollution) from a post-industrial future through which societies must navigate.

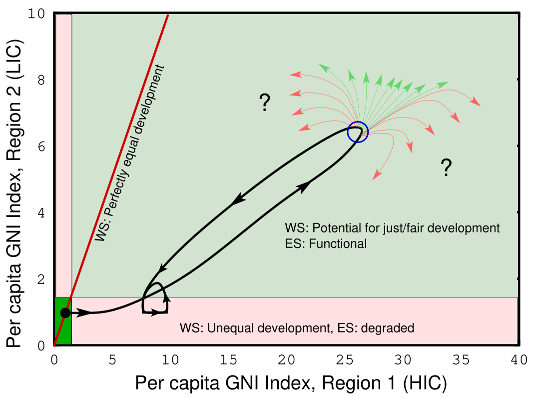

Figure 4. Projection of the moderate emissions trajectory in the two-dimensional space of per capita GNI in higher and lower income counties. This phase space represents in rigorous mathematical terms the methaphorical landscape depicted in figure 2.

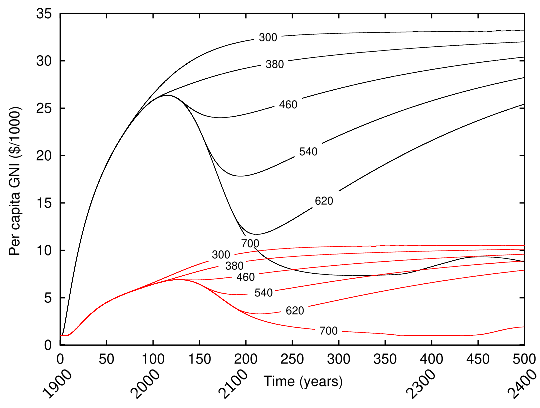

Figure 5. Decarbonization scenarios when there are no tipping points in the Earth system. The black and red curves refer to HIC and LIC respectively. The numbers refer to the atmospheric carbon concentration at which the decarbonization project that reduces carbon concentration by 10% annually begins. Plausible calendar dates for this carbon release process for our WE system are shown at angles on the *x*-axis.

3.2. Decarbonization paths, inequality, and ES thresholds

Figure 5 shows time trajectories of per capita GNI for various decarbonization programs initiated at different ACC levels ranging from 300–700 ppm and proceeding at 10% per year reduction (roughly 90% decarbonization in 20 years and complete decarbonization over 40–50 years). In this case, the ES is 'friendly', i.e. there are no climate thresholds. The main message is that unequal development between regions enables HICs to achieve much higher levels of development than would have been possible had LICs used up more of the (open access) waste assimilation capacity of the environment and, as a result, failure to decarbonize will be more painful for HICs. This historical process underlies the moral incentive for HICs to lead on decarbonization, act early, and assist LICs.

Figure 6(A) shows the projection of the trajectories in figure 5 in per capita GNI space. Note that with no climate tipping elements, the system can always recover from the business-as-usual trajectory (black)—it is simply a matter of how much economic disruption the system experiences. There are two important takeaways from this figure: decarbonization alone reduces inequality (development paths tend closer to the equal GNI development path) and

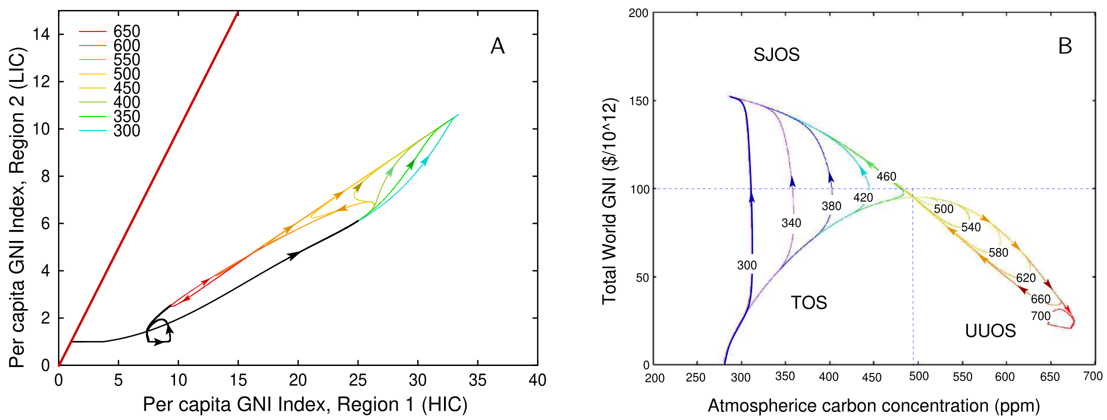

Figure 6. Projection of scenarios in figure 5 in (A) per capita GNI for region 2 versus region 1 in trillions of dollars and (B) total GNI versus atmospheric carbon. Note, the color coding does not match exactly. TOS = transitional operating space, SJOS = safe and just operating space, UUOS = unsafe, unjust operating space. See text for further discussion.

the dividing line between paths that involve some level of economic disruption (turn right and down before turning up and left) is somewhere between 400 and 450 ppm for the historically calibrated parameter set.

Figure 6(B) is the projection of the trajectories in figure 5 in total world GNI-ACC space, i.e. the model representation of the conceptual scenario from figure 2. Notice that in the 'nice' world, the system can enter and remain in the UUOS for some time until decarbonization can pull it out. In this case, again referring to figure 2, the depth of the unsafe basin is determined completely by social factors. The WE system can always be pulled out of this basin by social and economic processes if the WS is resilient enough to act in the face of decreasing levels of wellbeing. In this case, navigating the landscape between the UUOS and SJOS is not necessarily perilous, i.e. pathway resilience is high because the ES resilience is high. This analysis also illustrates why the ball-and-cup visualization breaks down in higher dimensional models–we need to think in terms of bundles of paths.

Figure 7 is the analogue of figure 6 with a climate threshold at 450 ppm. Now there is a stark division between trajectories trapped in the UUOS and those that can reach the SJOS. Those that reach the SJOS initiate decarbonization just under 425 ppm. Policy action must begin 25 ppm before the threshold to compensate for system inertia. The 'ridge' has collapsed to a razor's edge. In this case, the threshold on the global externality creates a basin in the UUOS. It is important to note that tipping elements in the social system could generate this situation as well. In figure 6, the trajectories are distinguished only by *when* decarbonization occurs not *whether* it occurs. It is reasonable to assume that when economic growth and well-being start to decrease globally because of climate damages (e.g. around 490 ppm in figure 6), there may be a point beyond which the appetite for contributing to the public good of decarbonizing goes to zero. This wealth-dependency of contributions to public goods (Heap *et al* 2016) reduces the resilience of the WS to inequality and thus can generate the same type of lock-in effect as loss of resilience in the ES.

As with any even relatively low-dimensional model, there is a large number of parameter choices we could make and with them, a large number of scenarios. For example,

- Can geoengineering remove climate thresholds and thus transform figure 7 into figure 6? In our model, this translates roughly into the next question—i.e. how fast can you draw down atmospheric carbon?
- Where are the potential climate thresholds, if any? For example, if the climate threshold is at 500 ppm, society must start decarbonizing at 10% per year when the ACC is 476 ppm. This is slightly closer to the threshold than with the 450 ppm threshold (24 versus 25 ppm less than the threshold) likely due to the fact that at around 470 ppm, climate damages have begun to bite harder than at 420 ppm so economic inertia will be slightly less, allowing society to act a split second (1 ppm) later. Further, the model results in general do not hinge on the existence of hard thresholds leading to runaway climate change—an issue which remains debated (Armstrong McKay *et al* 2022). We could, for example set G_0 to a very large value acknowledging that there may exist such a threshold in theory, but it will not occur in practice (in the present model parameterization, this condition is $G_0 > 700$ ppm). Additional positive feedbacks of ES dynamics can be captured via the amplifying effect of carbon emissions, e.g. more intense storms, droughts, flooding, etc on society through the functions $S_j(G)$ in equation (3). In this way, the impact of endogenous climate and economic processes on WER can be explored without the assumption of hard climate thresholds.

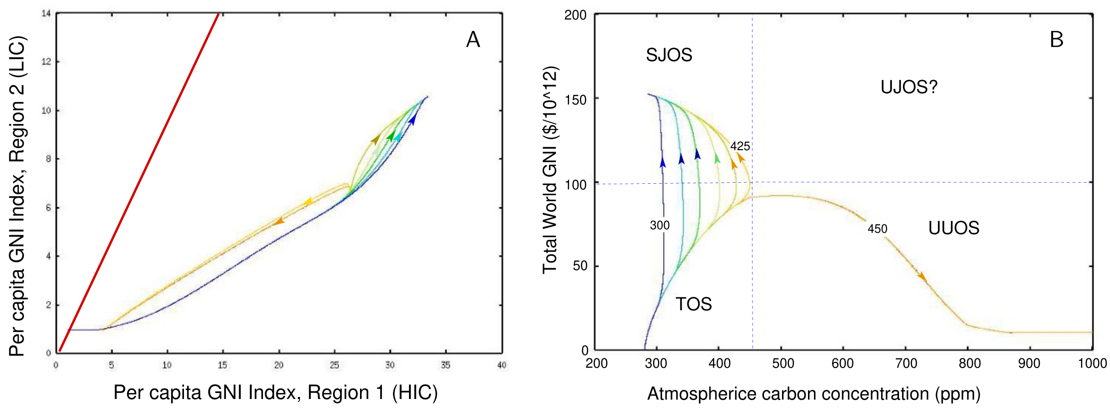

Figure 7. Analogue of figure 6 with a climate threshold at 450 ppm. Per capita GNI is trillions of dollars. (A) Per-capita GNI in region 2 versus region 1. (B) Total GNI versus carbon concentration. As the colors range from blue to yellow orange, the decarbonization threshold ranges from 300 ppm to 450 ppm, respectively. The critical threshold value occurs at approximately 425 ppm. Below 425 ppm, trajectories go to the SJOS. Otherwise they go to the UUOS.

- How might the global externality (G) have regionally differentiated impacts? If, for example, the impact of G on Region 2 is higher than Region 1, the bundle of the trajectories in figures 6 and 7 would rotate clockwise. In the case without a climate threshold, the long run attractor shifts to the right and the limit cycle vanishes. In this unjust outcome, Region 2 can never recover from climate damages even temporarily and Region 1 benefits in that its long run economic output is slightly higher. Region 1 historically contributed more to increasing G thus bearing more responsibility for creating the problem, and Region 2 bears the costs disproportionately.

These issues do not change the basic qualitative dynamics summarized in our analysis—they can shift the trajectories in state space but will not change the underlying topology of the state space. This is why we have emphasized that we are not attempting to capture *the* WE system we live in but, rather *a* WE system that has the same fundamental features as *any* WE system including the one we live in.

What is clear, however, is that less developed countries' (represented as LIC in our model) willingness to decarbonize hinges on inequality and the willingness of rich countries to provide aid. At COP 26, India demanded that rich nations pay 1 trillion USD before it would make a climate pledge (Bloomberg Green 2021, The Straits Times 2021) and demanded that rich countries acknowledge their historic responsibility (The Guardian 2021). Four countries, Brazil, China, India, and South Africa joined forces to tie emission cuts to funding from wealthy countries (The Rio Times 2021). Thus, the question of how economic inequality may affect decarbonization seems potentially more immediate and important than long-debated biophysical details.

Trajectories in figure 7 assume that both HICs and LICs decarbonize starting at the same time and at a rate of 10% per year. The news stories mentioned above suggest this is unlikely. To explore the implications of inequality in our modeled system, we suppose that $re_2 = re_1(1-\lambda_e+\lambda_e \cdot pcGNI_2/pcGNI_1)$ where re_1 is the decarbonization rate of region 1 and $\lambda_e \in [0,1]$ is the weight region 2 (LIC) puts on income inequality in choosing its decarbonization rate. If $\lambda_e = 0$, region 2 matches region 1 in their decarbonization rate (the scenario in figure 7). If $\lambda_e = 1$, region 2 decarbonizes at a proportion of region 1's rate given by the ratio of its per capita GNI to that of region 1. In this modeled scenario with the hypothetical climate threshold at 450 ppm, the threshold to act is at 390 ppm, not 425 ppm. This scenario illustrates the challenges of historical inequality and the social inertia it may generate. For illustrative purposes, consider the modeled scenario in which there is a threshold at 450, decision makers do not account for social inertia, believe the threshold to act is at 425 based on biophysical understanding of inertia in the ES, and the system is at 420 ppm. If inequality matters as news reports suggest, actors in the modeled system would have already missed their opportunity to act or, rather, would have to address social inertia very quickly. Historical inequality is baked into the system. Directly reducing inequality is not an option—this would have required that the HICs transfer 45% of their GDP to LICs ($Tr_{12} = 0.45Y_1$ and $Tr_{21} = 0$ in equations (4) and (5)) from the start of the industrialization process. Given that such enormous historical wealth transfers are untenable, one alternative may focus on reducing perceived unfairness by HICs' strong recognition of historical inequality in the use of a global commons and signaling global solidarity with as much aid as possible directed toward addressing carbon emissions to reduce λ_e.

4. Discussion and conclusions

We have presented a conceptual framework representing WESs as regions connected by a network of WS and ES elements to provide a foundation for studying WER. Based on the conceptual framework, we developed a formal model of a two-region WES connected through perceptions of fairness in the WS and through atmospheric carbon in the ES. While we focused on two regions for clarity of exposition of key ideas, the model is easily extensible to L regions linked through N ES processes and M WS processes for arbitrary L, N, and M. In the model formulation, we have striven for transparency, accessibility, and ease of use so that the conceptual and formal model can serve as a foundation for exploring WER. In this sense, our WES framework, specifically developed to focus on examining WER from a pathwise perspective, is one main contribution of the paper. The second contribution is the mode of analysis we suggest to explore WER in a transparent way.

Our analysis represents a preliminary step in the enormous range of possibilities the framework opens up for analyzing WER. We have chosen to illustrate three key elements of WER: (1) extending the notion of resilience from the traditional basin-of-attraction view to one that more carefully considers the nature of pathways between attractors, (2) the effect of a key element of the ES, potential tipping points, on WER, and (3) the effect of a key element of the WS, inequality, on WER.

Our analysis illustrates why a basin of attraction notion of resilience is not particularly useful in analyzing WER for two reasons: (1) because there may exist very resilient basins that humanity cannot thrive in, and (2) transient pathways to desirable basins may be very difficult to navigate. Thus, we highlight the importance of thinking in terms of pathway resilience, i.e. the relative number of paths that allow us to move from the TOS to the SJOS and avoid falling into the UUOS. We use our WES model to formalize this conceptualization and demonstrate how in a resilient ES (figure 6) pathway resilience depends solely on a WS capable of acting to decarbonize. In a less resilient ES with tipping elements, many paths between the TOS and SJOS vanish (figure 7). This dramatic loss of potential pathway resilience illustrates the value of investing in ES resilience.

Next we use the model to explore how differential regional development impacts the number of viable paths from the TOS to the SJOS. Specifically, prior to the UN Climate Change Conference in Paris, the focus was on 'contraction and convergence'. Based on historical responsibility, HICs recognized that LICs should be allowed to decarbonize more slowly to compensate for economic hardship. However, evidence of the rapid decline of ES resilience at the Paris meeting prompted the realization that 'contraction and convergence' was not tenable. Rather HICs and LICs had to both decarbonize more quickly and at the same rate. The only way to facilitate this was through a compensation scheme whereby HICs provided funds to LICs for decarbonization. The problem, as with all public goods, is under-provision: the Green Climate Fund is likely woefully inadequate for the task. The continued importance of compensation was evident at the Glasgow Climate Meeting (The Rio Times 2021). Our modeling exercise highlights the challenges of addressing historical inequalities and suggests that focusing on enhancing the goodwill of LICs to reduce λ_e is critical. In our real WES, mechanisms to do this would include actions like HICs setting and meeting reasonable contribution levels to the Green Climate Fund.

Our analysis here is just a first step in analyzing WER and much more work needs to be done. First, in the service of clarity, we have neglected some key processes such as migration and technological change. Second, and much more importantly, we analyzed the system *as if* we had perfect information about the system. If this were the case, resilience is a moot point. Direct calculation of the location of basin boundaries would allow us to decide what type of social, technical, or economic transformations are needed to navigate toward a desirable basin and the capacity to do so rests solely in the capacity of the regions in the WS to coordinate and act. However, the reality is that we do not have perfect information about the system, a central fact that future work must address. Our modeling framework and the analysis herein simply sets the foundation for future work on more sophisticated calculations of WER under uncertainty. This will require, for example, extensive Monte Carlo analysis of stochastic versions of our model to characterize pathway resilience in terms of the probability that we may successfully navigate from the TOS to the SJOS. This probability will provide a combined measure of WER including the state of our life support system (ES resilience) and the capacity to act decisively in difficult circumstances (WS resilience).

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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References

Alcamo J, Kreileman G, Bollen J C, van den Born G J, Gerlagh R, Krol M S, Toet A and De Vries H 1996 *Glob. Environ. Change* **6** 261–303
Armstrong McKay D I, Staal A, Abrams J F, Winkelmann R, Sakschewski B, Loriani S, Fetzer I, Cornell S E, Rockström J and Lenton T M 2022 *Science* **377** eabn7950
Aschemann-Witzel J and Schulze M 2023 *Curr. Opin. Food Sci.* **51** 101015
Bak-Coleman J B *et al* 2021 *Proc. Natl Acad. Sci.* **118** e2025764118
Barfuss W, Donges J F, Lade S J and Kurths J 2018 *Nat. Commun.* **9** 1–10
Barfuss W, Donges J F, Wiedermann M and Lucht W 2017 *Earth Syst. Dyn.* **8** 255–64
Benton T, Fairweather D, Graves A, Harris J, Jones A, Lenton T, Norman R, O'Riordan T, Pope E and Tiffin R 2017 *Environmental Tipping Points and Food System Dynamics: Main Report* (The Global Food Security Programme)
Bers C V *et al* 2016 Transformations in governance towards resilient food systems *CCAFS Working Paper No. 190. Copenhagen, Denmark: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)* (available at: www.ccafs.cgiar.org)
Bloomberg Green 2021 *Bloomberg Green (10 November 2021)* (available at: www.bloomberg.com/news/articles/2021-11-10/india-holds-back-on-climate-pledge-until-rich-nations-pay-1-trillion)
Chapin F S III *et al* 2022 *Ambio* **51** 1907–20
Farmer J D, Hepburn C, Mealy P and Teytelboym A 2015 *Environ. Resour. Econ.* **62** 329–57
Fesenfeld L P, Schmid N, Finger R, Mathys A and Schmidt T S 2022 *One Earth* **5** 1100–8
Geier F, Barfuss W, Wiedermann M, Kurths J and Donges J F 2019 *Eur. Phys. J. Spec. Top.* **228** 2357–69
Giandrea M D and Sprague S A 2017 *Monthly Labor Review (February 2017)* (available at: www.bls.gov/-opub/mlr/2017/-article/-estimating-the-us-labor-share.htm)
Gruber N *et al* 2019 *Science* **363** 1193–9
Heap S P H, Ramalingam A and Stoddard B V 2016 *Econ. Lett.* **146** 4–7
Heitzig J, Barfuss W and Donges J F 2018 *Sustainability* **10** 1947
Kemp L *et al* 2022 *Proc. Natl Acad. Sci.* **119** e2108146119
Keppo I *et al* 2021 *Environ. Res. Lett.* **16** 053006
Klein Goldewijk K, Beusen A and Janssen P 2010 *Holocene* **20** 565–73
Klose A K, Karle V, Winkelmann R and Donges J F 2020 *R. Soc. Open Sci.* **7** 200599
Kopp R E, Shwom R L, Wagner G and Yuan J 2016 *Earth's Future* **4** 346–72
Krishnamurthy P K, Fisher J B, Choularton R J and Kareiva P M 2022 *Nat. Sustain.* **5** 956–64
Lade S, Walker B and Haider L 2020 *Ecol. Soc.* **25** 19
Lenton T M and Latour B 2018 *Science* **361** 1066–8
Lenton T, Held H, Kriegler E, Hall J, Lucht W, Rahmstorf S and Schellnhuber H 2008 *Proc. Natl Acad. Sci.* **105** 1786
Livina V N 2023 *Nat. Clim. Change* **13** 15–16
Mathias J-D *et al* 2020 *Earth's Future* **8** e2020EF001573
Nitzbon J, Heitzig J and Parlitz U 2017 *Environ. Res. Lett.* **12** 074020
Nordhaus W D 1993 *Resour. Energy Econ.* **15** 27–50
Nordhaus W D and Yang Z 1996 *Am. Econ. Rev.* **86** 741–65
Nyborg K *et al* 2016 *Science* **354** 42–43
O'Riordan T and Lenton T 2013 *Addressing Tipping Points for a Precarious Future* (Oxford University Press)
Our World in Data 2021 Carbon emission intensity of economies (available at: https://ourworldindata.org/grapher/co2-intensity)
Past Interglacials Working Group of PAGES 2016 *Rev. Geophys.* **54** 162–219
Piketty T 2020 *Capital and Ideology* (Harvard University Press)
Rasmussen K and Birk T 2011 *National Security and Human Health Implications of Climate Change* (Springer) pp 39–48
Raworth K 2017 *Lancet Planet. Health* **1** e48–e49
Raworth K 2012 A safe and just space for humanity: can we live within the doughnut? Oxfam discussion paper (available at: www.google.com/books/edition/A_Safe_and_Just_Space_for_Humanity_Can_w/tSikdAjHPf8C?hl=en&gbpv=1)
Rockström J *et al* 2009 *Nature* **461** 472–5
Rockström J *et al* 2021 *Earth's Future* **9** e2020EF001866
Steffen W *et al* 2011 *Ambio* **40** 739–61
Steffen W *et al* 2015 *Science* **347** 1259855
Steffen W *et al* 2018 *Proc. Natl Acad. Sci.* **115** 8252–9
Stolbova V, Surovyatkina E, Bookhagen B and Kurths J 2016 *Geophys. Res. Lett.* **43** 3982–90
The Guardian 2021 *The Guardian (27 October 2021)* (available at: www.theguardian.com/world/2021/oct/28/not-a-solution-itself-india-questions-net-zero-targets-ahead-of-cop26)
The Rio Times 2021 *The Rio Times (9 November 2021)* (available at: www.riotimesonline.com/-brazil-news/-brazil/-brazil-china-and-india-tie-emissions-cuts-to-funding-from-wealthy-countries/)
The Straits Times 2021 *The Straits Times (10 November 2021)* (available at: www.straitstimes.com/asia/south-asia/india-holds-back-on-climate-pledge-until-rich-nations-pay-us1-trillion)
UN Economic Commission for Europe 2021 Carbon dioxide emissions per unit of GDP, kg of CO_2 per Constant 2010 USD (available at: https://w3.unece.org/SDG/en/Indicator?id=28)
UN Pop. Div. 2015 World population prospects: the 2015 revision *Technical Report United Nations* (Department of Economic and Social Affairs, Population Division)
van Vuuren D P, Lucas P L, Häyhä T, Cornell S E and Stafford-Smith M 2016 *Earth Syst. Dyn.* **7** 267–79
Walker B H and Meyers J A 2004 *Ecol. Soc.* **9** 3
Wallerstein I 1979 *The Capitalist World-Economy* (Cambridge University Press)
Wallerstein I 2004 *World-Systems Analysis* (Duke University Press)
Waters C N *et al* 2016 *Science* **351** aad2622
World Bank 2021a Gross national product (available at: https://data.worldbank.org/indicator/NY.GNP.MKTP.CD)
World Bank 2021b Gross savings (available at: https://data.worldbank.org/indicator/NY.GNS.ICTR.ZS)
Wunderling N, Donges J F, Kurths J and Winkelmann R 2021 *Earth Syst. Dyn.* **12** 601–19