Focus Issue: Is there a global tipping point for planet Earth?

On the origin of planetary-scale tipping points

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Tipping points are recognised in many systems, including ecosystems and elements of the climate system. But can the biosphere as a whole tip and, if so, how? Past global tipping points were rare and occurred in the coupled planetary-scale dynamics of the Earth system, not in the local-scale dynamics of its weakly interacting component ecosystems. Yet, evolutionary innovations have triggered past global transformations, suggesting that tipping point theory needs to go beyond bifurcations and networks to include evolution.

Barnosky et al. [1] recently proposed that human activities could cause a ‘planetary-scale’ ‘tipping point’ in the ‘global ecosystem’. In response, Brook et al. [2] argued persuasively against planetary-scale tipping points in the terrestrial biosphere, despite the existence of local- and regional-scale tipping points. By contrast, Hughes et al. [3] suggest that the biosphere (in a broader sense) has displayed planetary-scale tipping points in the past and may do so again in the future due to human activities. So, who is closer to the truth?

Depending on how a ‘planetary-scale tipping point’ is defined (Box 1), the Earth system has probably passed several during its long past [4]. The ‘Great Oxidation’ of the atmosphere 2.4 billion years ago can be explained by passing a tipping point between two stable states for atmospheric oxygen, involving the formation of the ozone layer [5]. The postulated ‘snowball Earth’ glaciations 720 million and 640 million years ago may have involved sea-ice cover reaching a tipping point at approximately 30° latitude and ‘running away’ to shroud the planet in ice [4]. The key ingredient for such tipping behaviour is strong positive feedback in the dynamics of a system. Given that oxygen is a globally mixed atmospheric gas and sea-ice covers a global ocean, these are both good candidates for truly ‘planetary-scale’ tipping points. However, the key tipping mechanisms are chemical and physical, respectively, rather than biological; therefore, they are only tipping points in the ‘biosphere’ if that is synonymous with the Earth system (Box 1).

It is important to be clear about the distinction between tipping points residing in climate or biogeochemical dynamics and subsequent ecological responses to them. For example, several past extinction events have been linked to oceanic anoxic events [4]. These may have involved a tipping point in which the onset of anoxia on shelf seas triggered phosphorus recycling from sediments, fuelling a runaway spread of anoxia [6]. If so, the consequences for biodiversity were just that, a consequence, rather than an intrinsic part of the tipping mechanism. One candidate [3] for a past tipping point in the terrestrial biosphere involves the switch from gymnosperms to angiosperms [7]. However, given that this transition took millions of years [4], the proposed local tipping point [7] must have been reached at different times in different locations. Hence, the term ‘planetary-scale’ tipping point seems misleading (Box 1).

Tipping points in the terrestrial biosphere tend to be spatially localised [2], although they can stretch to subcontinental scales when vegetation is tightly coupled to atmospheric dynamics [8]. Therefore, the challenge is to explain how they can become planetary in scale. One possibility is globally homogeneous drivers acting on a universal biological or ecological threshold, such that all locations tip synchronously; however, this is unlikely given the heterogeneity of climate change and ecosystems [2]. More interestingly, globally near-synchronous change could arise [2,3] from a ‘tipping cascade’ or ‘domino dynamics’, where tipping one part of the biosphere triggers a response that tips another part and so on. This demands a network view where spatial homogeneity and strong connectivity of nodes could contribute to system-wide tipping [9]. The terrestrial biosphere probably fails to meet either of these conditions [2]. However, domino effects in terrestrial ecosystems may be promoted by connectivity with the climate system [3,8].

The relation between local and global stability in complex systems can be subtle. A recent review [10] of systemic risk provided numerous examples in which network structure and node behaviours interact in non-obvious ways to produce emergent global-scale effects. Hence, the idea of ‘tipping cascades’ in the Earth system [2,3] warrants further research, especially into whether the various tipping elements of the climate system [8] are coupled in a way [11] that could produce ‘domino dynamics’ (Figure 1); or whether homogenising and connecting global human networks of trade and migration [10] could contribute to tipping dynamics.

The rarity of past transformations of the Earth system suggests that a rather special recipe is required to create them [4]. Most of Earth history has involved long intervals of relative stability, dominated by negative feedbacks. However, very recently, positive feedback has started to dominate over negative feedback, producing the saw-tooth oscillatory dynamics of recent glacial-interglacial cycles.
Box 1. Definitional differences

Suess first defined the ‘biosphere’ as the place on the surface of the Earth where life dwells, a concept developed by Vernadsky into something akin to what we now call the ‘Earth system’, including biogeochemical cycles and climate. In ecology, however, the ‘biosphere’ is often used more narrowly to mean the sum total of all ecosystems, just as the ‘biota’ is the sum total of all organisms. None of the studies discussed here give a definition, but our reading is that Brook et al.’s [2] ‘terrestrial biosphere’ is meant as the sum total of all land-based ecosystems, Barnosky et al.’s [1] ‘biosphere’ is the sum total of all ecosystems on the planet, and Hughes et al.’s [3] ‘biosphere’ is really the Earth system, including climate and biogeochemistry. This distinction helps explain how they come to different conclusions.

In popular terms, ‘a tipping point’ is where ‘a small change makes a big difference’ [15] to the state and/or fate of a system. In Earth system science, it is more formally defined [8] as a point at which a small perturbation can cause a qualitative change in the future state of a system. Brook et al. [2] suggest that ‘the change to a new state is typically rapid’, whereas Hughes et al. [3] note that it could unfold slowly relative to human perception; crucially, the timescale is set by the internal dynamics of the system in question. Barnosky et al. [1] liken tipping points to fold bifurcations with hysteresis, but this narrow definition ignores other potential sources of tipping behaviour [8]. Hughes et al. [3] describe a tipping point as ‘a non-linear relationship between a driver… and the [equilibrated] state of the ecosystem’, but a clearly identifiable tipping point will only arise when nonlinearity is strong.

The use of ‘planetary-scale’ tipping point suggests to us and to Brook et al. [2] synchronous or near-synchronous tipping on a global scale. Hughes et al. [3] concede this is ‘very unlikely’ for the terrestrial biosphere, yet they persevere when describing nonsynchronous cascades of smaller-scale tipping points that ultimately add up to global effects. Here, the critical uncertainty is whether the causal coupling between different tipping events is of the sign and strength necessary to produce a global tipping cascade (e.g., Figure 1, main text). The ‘planetary-scale tipping point’ terminology may not be helpful because complex systems, such as the biosphere, often show scale-free distributions of event sizes [14].

in which glacial terminations may (temporarily) involve runaway positive feedback. Thus, the Earth may currently be in a rare state of potential instability [4] (Figure 1).

This adds to concern at the current rate and magnitude of global change. Barnosky et al. [1] describe at length this multiple-dimensional ‘sledgehammer’ and Hughes et al. [3] address what we might do to try and manage it. However, as they clarify [3], the need to live within ‘planetary boundaries’ [12] does not imply the existence of planetary-scale tipping points. Barnosky et al.’s [1] central proposal is that human land use will pass a tipping point that triggers greatly increased biodiversity loss. This is inferred from smaller-scale models of population collapse due to habitat fragmentation. However, it is assumed [1] that projected human population growth will be directly correlated with increased land use, when actual per capita land use has steadily diminished over time [13]. Furthermore, a global ‘fold’ bifurcation is invoked [1] without a clear mechanism, making it pure supposition.

The presence of evolving life in the Earth system brings a source of innovation and, with it, the possibility of a different kind of ‘tipping point’, a rare evolutionary event that ultimately changes the world profoundly from within [4,14]. For example, a novel metabolism that accesses an underutilised source of energy will spread rapidly, and the resulting waste products can perturb the environment and destabilise existing ecosystems. In extreme cases, this can cause mass extinction and a rapid transition to a new steady state [4,14]. When we look back at past ‘revolutions’ of the Earth, such evolutionary innovations are a crucial ingredient; for example, the evolution of oxygenic photosynthesis led ultimately to the Great Oxidation [4,5].
Remarkably, nowhere in the present debate [1–3] is it considered that we may have long since passed such an evolutionary ‘tipping point’ to planetary-scale change. In this case, the ‘small change that makes a big difference’ [15] could perhaps be traced back as far as the origin of natural language [4] in anatomically modern Homo sapiens or, more recently, the invention of the steam engine. The latter facilitated the exploitation of fossil fuels during the Industrial Revolution, improving access to an abundant source of energy with globally disruptive waste products [14].

To summarise, the terrestrial biosphere, in isolation, is not the right place to be looking for a planetary-scale tipping point; one must consider the coupled dynamics of the Earth system as a whole, including evolution. However, regardless of whether it is approaching a global tipping point, we can all agree that the biosphere is in trouble.

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References
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