Phil. Trans. R. Soc. B. article template

PHILOSOPHICAL
TRANSACTIONS B

Phil. Trans. R. Soc. B.
doi:10.1098/not yet assigned

Tipping positive change

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Keywords: tipping points, early warning, networks, climate change, ecosystems, Earth system

Main Text

Summary

Tipping points exist in social, ecological and climate systems and those systems are increasingly causally intertwined in the Anthropocene. Climate change and biosphere degradation have advanced to the point where we are already triggering damaging environmental tipping points, and to avoid worse ones ahead will require finding and triggering positive tipping points towards sustainability in coupled social, ecological and technological systems. To help with that I outline how tipping points can occur in continuous dynamical systems and in networks, the causal interactions that can occur between tipping events across different types and scales of system – including the conditions required to trigger tipping cascades, the potential for early warning signals of tipping points, and how they could inform deliberate tipping of positive change. In particular, the same methods that can provide early warning of damaging environmental tipping points can be used to detect when a socio-technical or socio-ecological system is most sensitive to being deliberately tipped in a desirable direction. I provide some example targets for such deliberate tipping of positive change.

Introduction

Tipping points exist in a whole range of complex systems that can exhibit non-linear dynamics, across a range of scales, including individual humans [1], societies [2, 3], ecosystems [4], the climate system [5] and the Earth system [6] (Figure 1). They occur when there is strongly self-amplifying (mathematically positive) feedback within a system such that a small perturbation can trigger a large response from the system, sending it into a qualitatively different future state [7]. Previous work has reviewed tipping points in the climate system [5], in social systems [8], and in social-ecological systems [9, 10], and the regime shifts database [9] catalogues 28 generic types of regime shifts and >300 specific case studies. Here I address how we think about tipping points and could use them to guide action.

The predominant scientific framing of environmental tipping points in climate, ecosystems or the biosphere [7] is an emotionally negative one. We rightly fear abrupt changes away from conditions that humans are adapted to and in which we have flourished – be they social, ecological or climate conditions – because it is challenging to adapt to rapid change and the changes are often for the worst. For example, abrupt deoxygenation of lakes, estuaries, shelf seas, and in the worst case, the global ocean [11]. The great majority of climate tipping points are damaging ones [5] and they may be closer than is often assumed: Parts of the West Antarctic ice sheet appear to already be collapsing because of irreversible retreat of the grounding line [12]. A recent systematic scan of Earth system model projections has detected a cluster of abrupt shifts between 1.5 and 2.0°C of global warming [13], including a collapse of Labrador Sea convection with far flung impacts. Also, tropical coral reefs are projected to be abruptly lost if warming reaches 2.0°C [14]. A global climate tipping point to a hotter state has even been posited [15]. That said, some past Earth system tipping points were for the better in terms of biosphere productivity and ultimately human flourishing [6] – for example, we would not be here without the Great Oxidation ~2.4 billion years ago [16] and the rise of plants >400 million years ago [17], each of which abruptly increased atmospheric oxygen towards present levels.

The cultural framing of tipping points in societies can be emotionally negative or positive [18]. The term 'tipping point' arose from studies of neighbourhood segregation [2, 3] and can apply to violent political revolutions [19] and in the worst case, civilisation collapse [20]. On the other hand, the recognition that little things can sometimes make a big difference can be a reason for hope and source of empowerment that positive change can happen towards a more desirable societal state [18]. Individual human world views change through tipping points rather than incrementally – including beliefs

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about the causes of contemporary climate change [21]. At the level of collective behaviour, game theory, agent-based modelling, experiments and observations all suggest that social norms and behaviour can be tipped from degradation to conservation of a common pool resource – be it localised groundwater [22], or the global climate [23]. At the level of industrial ecology, several past abrupt socio-technical transitions have occurred, and potential future ones towards sustainability have been identified [24]. Recently there have been abrupt shifts in collective awareness and action on environmental issues – including ocean plastics and climate change – facilitated by conventional media (e.g. BBC Blue Planet II) and social media (e.g. #youth4climate), with new political movements rapidly emerging (e.g. Extinction Rebellion).

Clearly the emotional terms 'positive' or 'negative' applied to tipping points depend partly on the beholder as well as the phenomenon, and usually there are a mix of winners and losers. In the Anthropocene the human social world and the Earth system are now thoroughly intertwined, across a whole range of scales. This causal coupling and the resulting feedbacks can produce further tipping points [25], both realised [26] and potential [10]. Here I argue that we can use our knowledge of tipping dynamics both to better risk-manage undesirable tipping points [27, 28] and to help tip positive change [29, 30], and the need for both is clear: Climate change and biosphere degradation have advanced to the point where some damaging tipping points are unavoidable and avoiding others will require finding and triggering positive tipping points towards sustainability. The following sections define tipping points, consider their coupling across systems and scales, their potential for early warning signals, and how that knowledge could be combined to deliberately tip positive change.

Defining tipping points

Following my previous work [5] I restrict 'tipping point' to cases where a small perturbation causes a qualitative change in the future state (or trajectory) of a system. This can come about because the perturbation triggers a change in underling system dynamics, triggering a strong self-amplifying (mathematically positive) feedback that propels the system from one stable state (or mode of operation) to a different one. A similar approach is used to identify entries to the regime shifts database (Figure 1) based on identifying structural changes in feedback systems [9]. This definition does not include all cases of positive feedback, only those that can become sufficiently strong to be self-propelling, and it does not include threshold responses where a perturbation simply exceeds the range of viability of a particular system. Such responses may be important and interesting in their own right, but their underlying dynamics are different.

The best developed mathematical formulation of tipping point dynamics is bifurcation theory, which studies qualitative, structural changes in dynamical systems. Bifurcations can occur in continuous systems described by differential equations and in discrete systems described by maps (e.g. networks). A classic case is the fold (or saddle-node) bifurcation, where under smooth forcing a state loses stability and the corresponding system must transition abruptly into an alternative state. However, there are many other types of bifurcation, and also several other types of tipping [31]. 'Noise-induced' tipping describes situations where a stochastic source of variability (noise) is sufficient to tip a system out of one stable state into another, without any change in underlying drivers [27]. 'Rate-dependent' tipping points are triggered by the forcing of a system exceeding a critical rate (rather than a critical magnitude) [31]. They involve 'excitability', where an abrupt, transient departure from a stable state occurs, without requiring a shift to a new stable state – for example the 'compost bomb instability' where self-propelling breakdown of organic rich soil or compost occurs (sometimes involving combustion) [32].

Tipping points in spatially-extended networks of discrete components are often likened to phase transitions in physics (where matter abruptly changes in state). The nodes of a network can change state abruptly thanks to a process of contagion, whereby one node's state can spread to neighbouring nodes – be it through the spread of a disease vector, or through people copying the behaviour of others they come into contact with (social contagion) with social reinforcement [33]. A different form of tipping point is where the structure of a network (not just the state of the nodes) changes abruptly – in the worst case collapsing altogether. Networks inherently have many dimensions, and this complexity can be represented explicitly with agent-based models – for example, to simulate tipping points between high employment and high unemployment in the economy [34]. Their dimensionality can be reduced down, sometimes to a single control dimension along which a global tipping point can occur [35] – for example, if a critical condition for cascading spread is reached [36]. Plant-pollinator networks, where there are positive feedbacks between plants supporting pollinators and pollinators supporting plants, are another example which can be vulnerable to total collapse [37]. However, in some cases collapses are only partial [37], and the system may only be truly reducible to two dimensions [38]. In general, greater homogeneity, connectivity and nestedness of nodes increases the potential for global tipping of a network [28, 37].

Interactions between tipping events

Tipping points can interact across systems and spatial/temporal scales [39-43]. This links the network and dynamical systems approaches to studying tipping points – for example, individuated dynamical systems can be conceived as linked together in a larger network. Within the Earth system, ecosystems are coupled together, for example through watersheds and through 'precipitationsheds' where rainfall is recycled [44]. More broadly, the global circulation of the atmosphere produces unexpected and sometimes strong causal 'teleconnections' between geographically distant locations [45]. In globalised human systems, international trade can couple material and energy flows in distant locations strongly together [46], and the internet is facilitating instantaneous information exchange between individuals who can reinforce each other's choices.

Cases where tipping one system *increases* the likelihood of tipping another can highlight dangers of escalating damages as well as highlighting opportunities for positive change. Particularly interesting are the subset of cases where tipping one system *causes* the tipping of another, which I call 'domino dynamics' or a 'tipping cascade' (noting that [40] use this terminology less restrictively). This requires strong causal interaction between systems [43], and for domino dynamics to propagate through a network that needs strong network connectivity. Conversely, cases where tipping one system *reduces* the likelihood of tipping another highlight sources of stability and potential barriers to change. Important considerations are the relative scales of the systems in question (Figure 1) and the strength as well as the sign of causal influence between them.

We are used to thinking about changes at larger space and longer time scales impacting systems at smaller space and shorter time scales. In particular, climate change impacts ecosystems and societies. This holds true for tipping points as well: within the regime shifts database, down-scale causal interactions of tipping points are more prevalent than up-scale ones, with Earth system tipping points affecting the likelihood of ecosystem tipping points, particularly aquatic ones [40].

Less common is to think about how changes at smaller scales can interact to produce larger scale change. Yet how could there be large scale tipping without this? Past global tipping points are instructive in this regard [6]. They can involve a truly global variable such as well-mixed atmospheric oxygen being tipped between alternative stable states at the Great Oxidation [16]. Alternatively, they require a tipping cascade between smaller sub-systems that combine to produce a global change. A candidate is the largest mass extinction in the Phanerozoic record ~252 Ma at the Permian-Triassic boundary, which is not adequately explained by a comparably large perturbation (from the magmatic intrusion of the Siberian Traps). Instead, it appears to involve some fundamental instability in the Earth system that links marine anoxia, depletion of the ozone layer and extinction on land and in the ocean [6].

Before the reader starts to panic it should be emphasised that such global tipping cascades cannot be the norm, or we would not be here to reflect on them, because they would have long-since extinguished life [6]. That said, the 'saw-tooth oscillation' pattern of recent glacial-interglacial cycles suggests the Earth system may be unusually unstable at present [6]. On top of that the Neolithic (agricultural) and industrial revolutions and the resulting Anthropocene could be viewed as tipping cascades up spatial scales. The Neolithic revolution involved positive feedbacks between population growth, increased societal complexity (including the first city states) and their aggressive expansion. The industrial revolution involved positive feedbacks between new technologies, capitalism and an expanding labour force [47], and it continues to spread around the world. Now the climatic consequences appear to have tipped the West Antarctic ice sheet into a potentially irreversible retreat [12], raising the question: Could this start a climate tipping cascade [15]?

Expert elicitation suggests slightly more mathematically positive interactions between climate tipping events than negative ones [41], but the positive causal interaction do not appear strong enough to produce a complete tipping cascade [48], and the negative causal interactions reduce its likelihood [42]. In individual cases where tipping one system increases the likelihood of tipping another – for example tipping the Greenland Ice Sheet into meltdown increases the likelihood of collapse of the Atlantic Meridional Overturning Circulation – passing the first tipping point should abruptly increase the incentive to mitigate climate change [48]. Even just the *expectation* of a sufficiently bad tipping point could be enough to tip human social dynamics: Game theory and experiments predict that when the threat of a highly damaging climate tipping point becomes sufficiently certain, social dynamics are tipped from a 'tragedy of the global commons' failure to act collectively to a coordinated effort to pool the necessary societal resources to avert climate change disaster [23]. However, despite evidence of accelerating Greenland ice sheet melt contributing to weakening of the Atlantic overturning circulation [49], there is little sign of such rational collective action. This is an individual as well as a collective failure. However, hope may reside in the potential for tipping points in individual behaviour and consumer preferences – e.g. away from flying and towards plant-based diets – to cascade up scales through social reinforcement of choices (positive feedback) leading to abrupt change in social norms [33] which tip policy change [50].

Early warning signals

For there to be any hope of pre-emptive action to avoid damaging tipping points there must be a way of sensing and forewarning of them. A growing body of work has shown that those tipping points which can be characterised as one-dimensional bifurcations, carry generic early warning signals [5, 28, 51-53]. In particular, as a dynamical system approaches a tipping point it shows increased variability and slower recovery in response to perturbations. This is intimately tied to the changing balance of feedback in the system. For a system to exhibit a recognisable stable state in the first place there must be a preponderance of negative feedback tending to maintain that configuration. But as a tipping point is approached that negative feedback is getting weaker, and strong positive feedback will ultimately take over at the tipping point.

Where repeated known perturbation events have occurred in a system, these can be used to directly measure recovery rates, e.g. recovery of tidal marshes from inundation events [54], or recovery of forest from disturbance [55]. However, in most cases we must rely on continuous monitoring of stochastic variability. Then for early warning signals to be detectable in the statistical behaviour of a system, requires a separation of timescales: the system should be forced slower than its internal timescale (which governs its dynamical behaviour) and it should be monitored faster (more frequently) than its governing internal timescale. Some published studies ignore these basic requirements [56]. The requirements imply that relatively fast and frequently monitored systems – e.g. sea-ice or grasslands – have greater potential to show temporal early warning signals under climate change than slower systems such as tropical forests [57] or ocean circulation [58]. Nevertheless paleo-reconstruction can help [58] and system-specific early warning indicators can be designed [57] for these slower systems.

Spatial early warning signals of tipping points also exist for systems that are causally coupled across space [59, 60], including increasing spatial correlation [61] and increasing spatial variance [62]. This is particularly helpful for systems that have rich spatial data (e.g. from remote sensing) but lack robust long-term and/or high temporal resolution monitoring records, for example vegetation data along rainfall gradients in the Serengeti [63]. A subset of arid, semi-arid, savannah, and peatland ecosystems exhibit periodic spatial patterns [64], quantifiable using feature vectors [65] , which are the result of strong localised feedbacks. Changes in patterning can then provide an early warning signal of tipping point change [64, 65], for example the changing wavelength of vegetation bands in Sudan [66].

For systems that can be characterised as networks, where sufficient spatial and temporal data are available, changes in metrics describing network structure can provide tipping point early warning signals. This has been demonstrated in theory for climate tipping elements, using topological properties such as degree, assortativity, clustering, and centrality [67, 68], and for ecosystems using properties such as nestedness, connectivity, and food web stability [69, 70].

To detect the potential for tipping cascades requires the mapping of larger-scale networks comprising systems prone to tipping, establishing not just the sign of any causal interactions between them [40], but crucially their strength as well [41, 43, 48]. Where tipping points are causally coupled this can affect early warning signals – magnifying or muffling them depending on the nature of the coupling [39]. In the case of a tipping cascade, the leading system (first to tip) shows normal early warning signals and the following system (second to tip) can show extra sensitivity of those indicators [43]. Rate-induced tipping also carries early warning signals [71], whereas noise-induced tipping can occur without warning – however, a probabilistic assessment of the likelihood of its occurrence is feasible [27, 31].

For social systems, tipping points can manifest in material (e.g. population), energy, or information (e.g. price) variables. Corresponding temporal early warning indicators have been found, e.g. for past population collapses from archaeological site ages [72], contemporary electricity grid blackouts from load data [73], or burst of housing bubbles from market data [74]. Generic early warning indicators give mixed results before financial crises [75] but specific indicators such as attempts by traders to gather financial information from the internet increase [76] and network indicators can reveal structural instability [77]. For tipping points in collective behaviour more generally, the content, amount and network structure of activity on social media can provide early warning signals [78].

Deliberate tipping

System instability can provide an opportunity for deliberate system transformation. If a system is detected to be approaching a tipping point (or vulnerable to noise-tipping), then a small perturbation can be deliberately introduced to take it down an alternative path. Statistical early warning methods cannot reveal *how* to intervene to affect the desired change – that also requires process-based knowledge of the system in question – but such knowledge, though imperfect, usually exists, often in the form of process-based models. This approach leverages the inherent self-amplifying (positive) feedback processes in a system prone to tipping to take it in a desired direction. It has several potential applications.

Current approaches to managing (eco)systems prone to tipping points are (understandably) focused on interventions that can avoid undesirable tipping points [79, 80], including the use of process-based models to forecast potential future tipping points and inform interventions to avoid them [81]. However if an ecosystem has already been tipped into a degraded state, early warning indicators may be used to sense when it can be most readily tipped back into a desired state. Or if a common pool resource, such as groundwater, is being unsustainably exploited it can be used to sense when to introduce a new kind of agent behaviour in the system to tip the collective dynamics away from a ‘tragedy of the commons’ [22]. This aligns with the ‘Eco Tipping Points’ project’s efforts to tip social-ecological systems into a desired regime [82]. Early warning methods may also reveal that a system is far from the desired tipping point, indicating that a concerted effort is required to destabilise the incumbent state. That is also useful information because it gives an indication of the resources required for effective intervention.

Candidate targets for deliberate tipping include lake ecosystems where experimental manipulation studies have shown both temporal and spatial early warning signals of a trophic cascade [83, 84] and of abrupt eutrophication [60, 85] and the latter have been successfully used to guide intervention to reverse a cyanobacterial bloom [85]. Historically, large efforts were made to try and reverse shallow lake eutrophication, often unsuccessfully. These efforts could have been more effectively deployed if early warning methods had been available to detect distance from the desired tipping point. Tipping points in human perception of what is (un)desirable can also be crucial to instigating change – a historical example is Cleveland's small 1969 Cuyahoga River fire [86] tipping major (successful) efforts to tip Lake Erie back from a thoroughly degraded state [87].

Coral reefs provide another well-studied candidate for deliberate tipping, back from a degraded, macro-algal dominated state. The response of degraded reefs varies widely [88], again suggesting information on tipping point proximity would be valuable. Indo-Pacific reef recovery can be predicted based on structural complexity, water depth, density of juvenile corals and herbivorous fishes and (low) nutrient loading, but no-fishing reserves had no effect [89]. Sometimes a switch to a degraded ecosystem state does not impair the flow of ecosystem services for humans directly exploiting that ecosystem – for example, fish catches can be maintained or increased after coral bleaching events lead to a macro-algal dominated state [90]. Consequently, those people may resist plans to try and tip the ecosystem back to its original state.

To limit the extent of climate change, there is a widely recognised need to tip accelerated uptake of more sustainable innovations [29, 30] and early warning indicators could be used to inform when to intervene. In the energy sector, the incumbent regime of fossil fuels as backstop energy source is reinforced by subsidies and economic lock-in effects, but an alternative sustainable energy regime could also be stable, and technology transfer and an increasing carbon price could tip the energy transition [91]. Tipping into an alternative 'green growth' economic state (with increased GDP and employment) could be triggered by bold long-term policy targets and supported by a virtuous circle of investment, learning-by-doing and increased growth expectations [92]. There may also be intrinsic socio-technical tipping points, for example, transport-as-a-service provided by autonomously-driven electric vehicles taking over from privately-owned internal combustion engine vehicles [93].

Social tipping that cascades up scales could also play a vital role in positive change and could conceivably be deliberately nudged. For example, to limit climate change the global food system also needs to be rapidly transformed, with dietary change exerting the greatest leverage [94]. Historically there has been a rapid increase in animal protein consumption with income [95], causing non-linear environmental impacts, with production reinforced by subsidies and consumption reinforced by advertising [96]. Conceivably, an alternative, healthier and more sustainable, dietary regime could be stabilised. Tipping a transition could start with changes in individual world views [21] and consumer preferences, encouraged by the advent of plant-based substitutes for meat (e.g. the Impossible Foods burger), with social reinforcement of choices tipping abrupt change in social norms [33] and policy [50].

If we are to respond to early warnings by trying to tip positive changes in societies then that requires a network model of transformative social change, plausibly built on collective intelligence [97] and collaborative innovation [98]. This must recognise the interplay between bottom-up, cascading tipping phenomena and top-down deliberate interventions. It must include short-term payback to the human actors involved in doing things differently, as well as long-term rewards, which could be in love or glory/honour, not (just) money [97].

A necessary caveat is the need to understand and characterise uncertainty in complex, coupled non-linear systems before attempting to deliberately tip them. Historically, some attempts at small perturbations to create a desired state inadvertently tipped a system into an unforeseen negative state – in particular, the introduction of invasive species, such as rabbits to Australia. Conversely some tipping points initially perceived as negative have led to positive outcomes – for example, the 'browning' (drying) of the Sahara in the mid Holocene has been linked to the rise of complex societies [99]. Identifying 'no regrets' interventions would seem wise.

Conclusions

However we respond to tipping points we need to be thinking and acting in a more systemic way. The guarded optimism expressed here can be tempered by past evidence that our ability to use foresight and collectively respond to early warning signals is minimal [26]. Perhaps the best we can hope for is to get quicker at correcting our mistakes [100]. Either way we have a sensing challenge – to monitor coupled complex systems to detect their non-linear dynamics. This is inherently a 'big data' and 'big analysis' challenge. For any given system it needs to be established; which variables to track, where the data comes from, how to analyse it, and the role of models in combination with data to support understanding and offer predictability. Those present important topics for future work.

Acknowledgments

I thank Paul Lussier and the Sackler Forum on Climate Change and Ecosystems for inspiring this piece, the editor Nathalie Seddon and an anonymous referee for valuable feedback, and Bruno Latour, Marten Scheffer and John Schellnhuber for shaping my thinking on tipping points, early warnings and complex systems. This work was supported by NERC (NE/P007880/1) and the Leverhulme Trust (RPG-2018-046).

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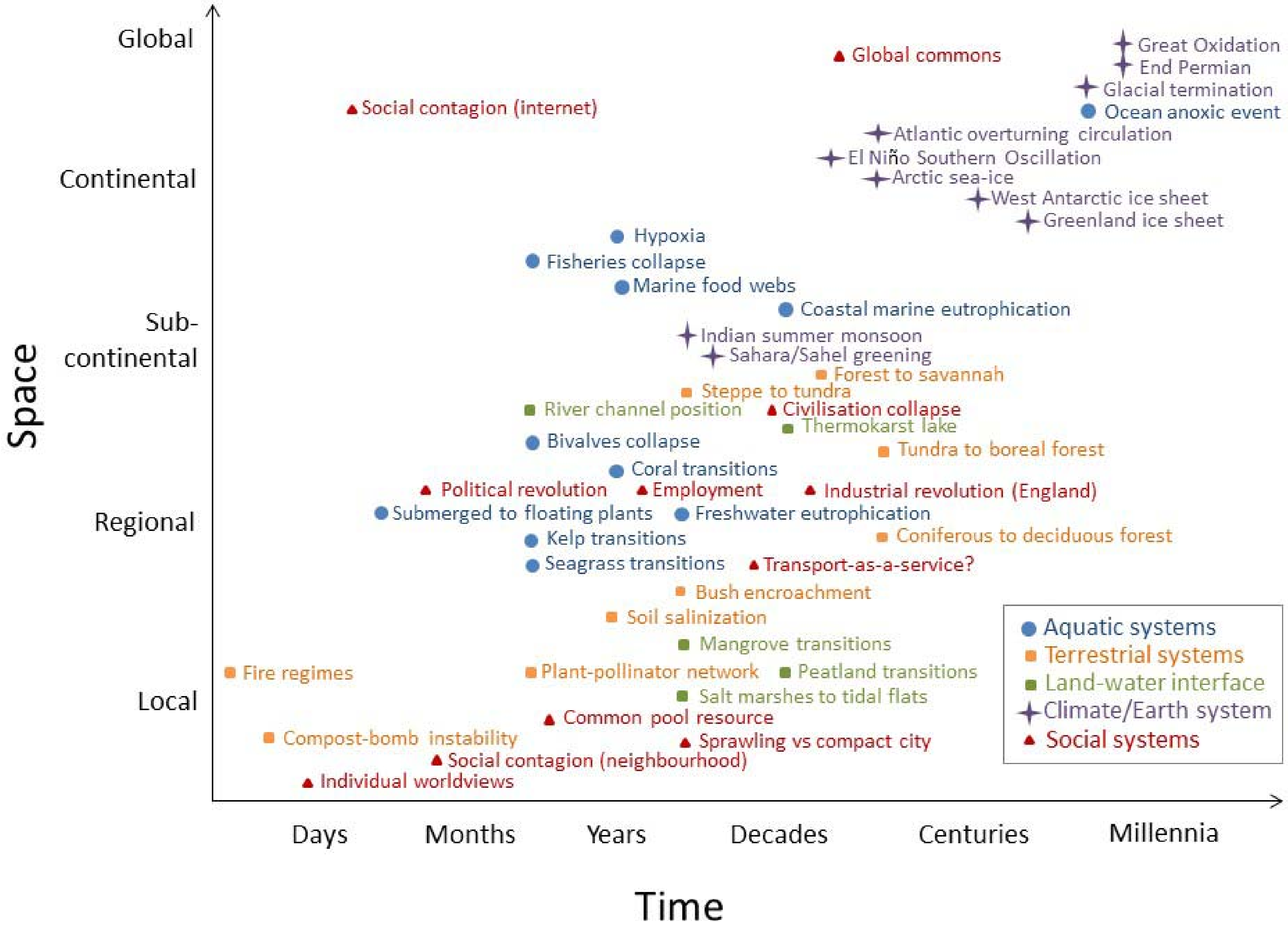
Figure captions

Figure 1: Examples of tipping points across system types and space and time scales – reworked from [9] to include all climate tipping points [5] and additional examples discussed in the present text.


Space
Global
Continental
Sub-continental
Regional
Local
Time
Days
Months
Years
Decades
Centuries
Millennia
Global commons
Great Oxidation
End Permian
Glacial termination
Ocean anoxic event
Social contagion (internet)
Atlantic overturning circulation
El Niño Southern Oscillation
Arctic sea-ice
West Antarctic ice sheet
Greenland ice sheet
Hypoxia
Fisheries collapse
Marine food webs
Coastal marine eutrophication
Indian summer monsoon
Sahara/Sahel greening
Forest to savannah
Steppe to tundra
River channel position
Civilisation collapse
Thermokarst lake
Bivalves collapse
Tundra to boreal forest
Coral transitions
Political revolution
Employment
Industrial revolution (England)
Submerged to floating plants
Freshwater eutrophication
Kelp transitions
Coniferous to deciduous forest
Seagrass transitions
Transport-as-a-service?
Bush encroachment
Soil salinization
Mangrove transitions
Fire regimes
Plant-pollinator network
Peatland transitions
Salt marshes to tidal flats
Common pool resource
Compost-bomb instability
Sprawling vs compact city
Social contagion (neighbourhood)
Individual worldviews
● Aquatic systems
■ Terrestrial systems
■ Land-water interface
✦ Climate/Earth system
▲ Social systems