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Ecological Tipping Points: Uncertainties and Policy Approaches

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ABSTRACT

Ecological tipping points have captured policymakers' imaginations for framing local and global environmental change: if an environmental driver becomes too significant, an ecosystem may flip into an alternate state, often with catastrophic and far-reaching consequences. The article first explores the science of ecological tipping points and the uncertainties that limit their validity and value in providing a threshold marking abrupt ecosystem collapse across scales. I then argue that ecological tipping points may be more useful not as a scientific instrument to predict environmental change, but as a gauge of anthropogenic environmental trajectories and a socio-environmental imaginary to mobilise environmental action. Given the complexity and uncertainty of ecological science, I suggest that the science-policy interface of ecological tipping points will benefit from further research in threshold dynamics and ecosystems in transition due to human activity. Furthermore, a pluralistic, deliberative approach to policymaking that brings together different knowledge domains will facilitate adaptive environmental governance to effectively respond to changes in the physical environment and our understandings of it.

SCIENCE ⇒ POLICY

If an environmental driver becomes too significant, an ecosystem may flip into an alternate state, often with catastrophic consequences. However, there is a lack of empirical data on ecosystem collapse and it is difficult to quantify the precise location of tipping points along environmental gradients. Policymakers should adopt a pluralistic approach to ecological knowledge across different scales and consider the level of precaution and trade-offs involved when relying on tipping points in decision-making.

Keywords Ecological Science · Tipping Points · Ecosystems · Environmental Policy

Background

In response to the European Environment Agency's report on Europe falling short of its 2020 biodiversity goals, Stefen Leiner, head of the European Commission Biodiversity Unit cautioned against allowing ecosystem degradation to reach a "tipping point" [1]. Along with the concept of planetary boundaries, tipping points have been central in the science-policy interface of ecological science. In addition to the comprehensive suite of scientific tools to measure, report and set biodiversity targets, policies often rely on tipping points to predict nearly irreversible ecosystem collapse beyond certain thresholds of environmental pressures to guide decision-making and understand trade-offs.

The actual science of ecological tipping points has been contested on several fronts, from the relationships between ecosystem processes to evidence of ecosystem collapse [2, 3]. Recognising the challenges of delivering policy advice with complex socio-environmental systems and scientific uncertainty, this paper examines the science of ecological tipping points and the various knowledge gaps that hinder its applications. As uncertain or misinformed science can have real policy implications, this paper then explores the role of ecological tipping points as a socio-environmental imaginary in policy arenas and realistic pathways to reconcile their uncertainties.

Tipping Points

The term 'tipping point' refers to the inflection point where systems shift radically and potentially irreversibly into a different state, and these points exist at different scales [4]. In bistable or multi-stable systems, which rest at two or more stable states, tipping points constitute the unstable maxima separating the states. Rather than a smooth response proportional to the magnitude of the driver, they are characterised by either 1) non-linearity amplified by runaway conditions, i.e. the internal feedback mechanisms that escalate the initial perturbation, or 2) hysteresis, a dramatic shift into an alternative state (Figure 1). Therefore ecosystem changes are often abrupt, difficult to predict and irreversible, as it is difficult, though not impossible, to restore the ecosystem to its original state by simply reverting to the initial environmental parameters [4, 5].

Historical precedents of tipping points in the biosphere offer cautionary tales of regime shifts when key drivers exceed certain thresholds. During the Great Oxidation Event 2.7 billion years ago, biogeochemical processes increased levels of atmospheric oxygen that led to ozone formation in the troposphere and oxygenic photosynthesis, while feedback mechanisms in nutrient cycling and weathering precipitated a transition from gymnosperm- to angiosperm-dominated ecosystems 100 million years ago [6]. As a result of anthropogenic environmental degradation, Steffen et al. [3, 7] highlight imminent human-driven planetary tipping points that could transform the Earth system into a different biosphere, or a 'hothouse', accelerated by systemic biogeophysical feedbacks.

A range of ecological tipping points with potential extra-regional or global ramifications have already been identified. Simulations of vegetation dynamics under a 3- to 4-degree Celsius warming scenario predict the Amazon rainforest may exhibit a decadal-scale regime shift to drier savannah. This is due to persistent El Niño events, where warmer sea surface temperatures in the Eastern Pacific Ocean cause drier and hotter weather in the Amazon that increases fire frequency [8]. The complex interplay of tree physiology, permafrost and fire can cause large-scale dieback of boreal forests into open woodlands or grasslands [8]. Altered ecosystem structures, functions and dynamics are nested in broader environmental processes and feedbacks – exceeding tipping points in the biosphere can increase the risk of crossing them in other systems. Links were found for 45% of possible system interactions; ecological processes in the biosphere are intertwined with geophysical systems, such as changes in ice cover (e.g. Greenland Ice Sheet and West Antarctic Ice Sheet), monsoon patterns and thermohaline circulation (e.g. Atlantic meridional overturning circulation) with potentially global cascade effects [9].

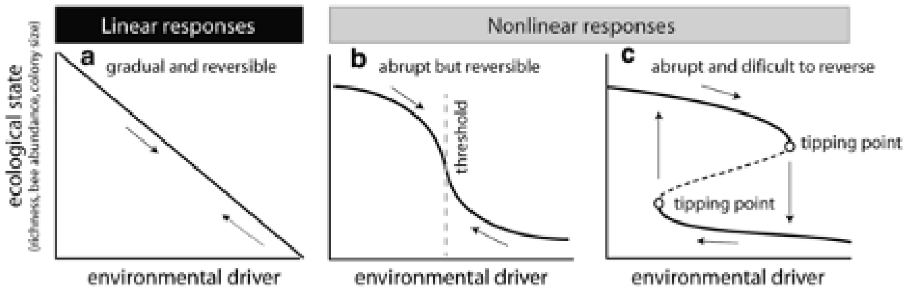

Figure 1: Graphs showing a range of responses to an environmental driver: a) linear decline, b) abrupt but reversible shift at the tipping point, and c) hysteresis in a bistable system. Ecological tipping points fall under b) and c). Reprinted from Latty and Dakos [5].

Uncertainties of Ecological Tipping Points

This section critically examines the knowledge gaps in the science of ecological tipping points at various scales and its central assumption – that subglobal tipping points are compatible with global thresholds across space and time, where the transgression of subglobal ones either escalates to a global tipping point or cumulatively contributes to an aggregate outcome of collapse [7].

Although tipping points can be more easily established at the population and community level, there is insufficient knowledge about processes leading to the ecosystem, regional or planetary scale. Focusing on pollination systems, Latty and Dakos [5] highlight an absence of evidence to confirm tipping points except at the colony level. A 30% loss of European honeybee colony functions as a tipping point that accelerates the reproduction of underperforming precocious bees, further threatening the survival of the colony. At the population and community level, allele effects, genetic diversity loss, environmental and demographic stochasticity can possibly engender extinction cascades [5]. The loss of essential species with high levels of ecological interactions with other species, such as keystone species and ecosystem engineers, has potentially large destabilising effects but it remains unclear how their extinctions can cause regional and global collapse. Furthermore, adaptive ecological responses, such as ‘interaction re-wiring’, where species form new mutualistic interactions to change their tolerance to perturbations in the system, can help to buffer and stabilize ecosystem shifts [10].

The lack of an eco-evolutionary perspective on trait variations and distributions that influence feedbacks maintaining alternative ecosystem states also restricts scientific understanding of the occurrences, timing and abruptness of shifts between states [11]. Phenotypic plasticity (i.e. genotypes exhibiting different phenotypes in different environments) and de novo mutation produce portfolio effects from increased heterogeneity in ecosystem interactions [11]. Yet, while tipping points may be buffered, such feedbacks and adaptive dynamics can also lead to evolutionary suicide, an accelerated tipping point in which population responses compromise its persistence, such as through the directional selection of an undesirable trait [12]. For instance, fishing pressure led to the early maturation of Atlantic cod population with lower reproductive outputs and selected for particular genes, thereby increasing the probability and strength of hysteresis in the ecosystem [13].

Furthermore, the ability of local and regional tipping points to escalate into a planetary tipping point is contingent on the spatial homogeneity and interconnectivity of ecosystem responses [4]. Each ecosystem has its unique biodiversity, biotic interactions and successional dynamics that shape ecosystem functions, such as resource capture, primary production, decomposition to nutrient cycling, and this creates different levels of resilience to change. Not only do ecosystem attributes have to respond similarly across continents and biomes for a cumulative global response, but teleconnections also need to be sufficiently strong to allow localised changes to diffuse across the terrestrial biosphere rapidly enough to create a planetary tipping point response [4]. For instance, the atmospheric circulation of greenhouse gases and oceanic transport of heat that contribute to ecosystem changes between continents must result in a signal that overwhelms background levels [4].

Biospheric responses therefore appear more likely to be gradual, rather than an abrupt tipping point at any level of change. A recent study that conducted 36 meta-analyses of 4,601 field experiments on ecosystem responses to a broad array of environmental drivers supports this line of argument, revealing no widespread existence of alternative states [14]. Instead, ecological changes tend to progressively increase in magnitude and variance as pressure increases. However, the lack of empirical data on ecosystem collapse and the difficulty of quantifying the precise location of tipping points along environmental gradients should not render moot the validity or value of ecosystem tipping points as a concept. Could ecological tipping points exist in certain ecosystem responses and not others? What kinds of environmental gradients should ecologists examine if potential tipping points are shaped by multiple interacting drivers? And how do spatio-temporal heterogeneities, including human interventions, alter system-specific thresholds? [15] From an existential perspective, the definition, measurement and mapping of ecological tipping points rest on highly uncertain scientific foundations.

Policy Implications for Environmental Governance

Over a decade's worth of research on the arbitrariness and indeterminacies of ecological tipping points has not faltered their widespread reference within international platforms, from the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) to the Aichi Biodiversity Targets set by the Convention on Biological Diversity. The concept has been instrumentalised to support human interventions to tip ecosystems to a more desirable state, such as the establishment of a small marine sanctuary in Apo Island of the Philippines that reversed a fishery collapse by triggering positive ecological feedbacks [6]. It is the same perspective that grounds solutions like global reforestation of over 0.9 billion hectares for carbon drawdown [16] and the greening of the Sahara and Sahel by increasing vegetation and soil moisture to weaken the African easterly jet that transports moisture off the continent [6].

The field of restoration ecology provides several encouraging examples of successful smaller-scale interventions that have recreated, initiated or accelerated the recovery of an ecosystem disturbed by anthropogenic factors [17]. Timely restoration can re-establish certain species or improve particular ecosystem functions, such as erosion control and nutrient cycling. For instance, non-indigenous tortoises were introduced as a restoration tool to replace extinct ecosystem engineers on Round Island in Mauritius, which has suffered significant habitat degradation [18]. On the other hand, the South Florida Management District monitored freshwater inputs into the Florida Bay ecosystem to prevent mass seagrass loss that would shift local ecosystem conditions and cause phytoplankton blooms and the collapse of fish populations [19]. However, while restoration is based on a pre-disturbance reference state, it must be recognized that stochastic factors, uncertainties and the inherent dynamism of the ecosystem mean restoration may not lead to reversion to the exact same ecosystem composition and functions as the original state [17].

Tipping points provide an effective socio-environmental imaginary to mobilise public and political support for environmental action. By presenting a common vision of ecological futures beyond a certain threshold, these imaginaries facilitate collective deliberation of the necessary transformational shifts in environmental governance and the appropriate policy responses across different scales [20]. Due to the ecosystem complexities and heterogeneities, ecological tipping points in policies are hindered by a lack of a concrete benchmark, like the highly visible 1.5- and 2-degree Celsius limit in global warming [21]. However, the use of such thresholds risks complacency on the 'safe' side, and fatalism about irrevocable effects on the other [4].

Scientists should continue to regularly revisit the validity of tipping points and policy targets with new biodiversity data or proxy measures, such as the introduction of the Biodiversity Intactness Index to quantify functional diversity [22]. More models should also be built to better account for sticky challenges like time lags and habitat modification for more granular knowledge of threshold dynamics.

As new computational methods become more advanced and available, such as the integration of agent-based modelling into Geographical Information Systems, it is now possible to explore the co-evolution of ecological and socio-economic systems, especially the direct impact of human activity on ecosystem transitions [23]. In fact, up to 80% of ecosystems around the world have undergone some form of human-driven regime shifts at the local or regional scale, creating a biosphere of post-transition, hybrid or novel systems [4].

Given the complexity and uncertainty of ecological science, the science-policy interface of ecological tipping points will benefit from a pluralistic approach that brings together different dimensions of ecological knowledge. IPBES has taken an admirable step towards incorporating indigenous knowledges and values into research and policymaking. Considering the dearth of scientific knowledge on local ecological thresholds outside the Western world, the engagement of local and indigenous communities can bring new insights about ecosystem management, early warning signs of ecosystem changes on-the-ground that statistical measures overlook, and a more explicit account of multi-scalar feedback systems [24].

Using ranges of statistical confidence and negotiating consensus within the scientific community to resolve the uncertain science behind ecological tipping points have shown little promise. Even as the scientific community continues to make inroads, the intricacies of ecological systems will likely never be fully grasped. Uncertainty is then best managed through its joint exploration, a deliberative multi-stakeholder approach to clarify gaps in knowledge and build the capacity for adaptive environmental governance [25]. Tipping points are inherently value-laden and this can facilitate priority setting – for instance, how much precaution should policymakers allow for when using tipping points in decision-making, and what kinds of trade-offs (e.g. social, economic, environmental) are at stake when shifting thresholds in policies? Such an approach promotes trust in decision-making, and importantly, responsive and reflexive governance structures that are in constant dialogue with a range of experts, from scientists to local environmental stewards [25].

Conclusion

In conclusion, ecological tipping points may never be fully applied as a scientific instrument in the policy arena, but they serve as an immensely informative device to model, forecast and predict ecosystem changes with known and unknown environmental drivers. At the same time, as a socio-environmental imaginary, it provides a normative function of illustrating links between environmental degradation across scales and the ecosystem services that directly affect human welfare. Science-policy platforms tackling ecological change will do well to leverage the expertise and experience of different communities to realise the potential behind the uncertain science of ecological tipping points.

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