One Earth

CellPress OPEN ACCESS

Perspective

Reconciling global tipping point theories: Insight from magnetic experiments

John A. Dearing,[1,*] Roy Thompson,[2] Kirsty Tooke,[3] and Simon Willcock[3,4,*]
[1]School of Geography and Environmental Science, University of Southampton, Southampton SO17 1BJ, UK
[2]School of GeoSciences, Edinburgh University, Edinburgh EH9 3JW, UK
[3]Net Zero and Resilient Farming, Rothamsted Research, North Wyke EX20 2SB, UK
[4]School of Environmental and Natural Sciences, Bangor University, Bangor LL57 2DG, UK
*Correspondence: j.dearing@soton.ac.uk (J.A.D.), simon.willcock@rothamsted.ac.uk (S.W.)
https://doi.org/10.1016/j.oneear.2025.101358

SUMMARY

Driven by a combination of global warming and unsustainable resource management, global tipping elements represent existential threats to Earth's systems and communities. However, the tipping point theory is still developing. Here, we reconcile alternative theories through a comparison of mathematical tipping point models and empirical experiments on micromagnet systems. We show how discontinuous change in spatially complex ecosystem models and multidomain magnetic materials represents common generic stress-response behavior in systems that organize spatially when placed under stress. Such systems show "soft," incremental rather than "hard," abrupt change and may represent the majority of ecological, landscape, and social-ecological systems. The findings emphasize how the classic fold bifurcation model should be restricted to describing simple systems. We explore the effects of stress magnitude and rate on soft and hard systems and draw insight for global tipping elements: scale dependence, abrupt versus incremental change, reversibility, early warning signals, and positive socioeconomic tipping points.

INTRODUCTION

For many, the tipping point has become the prescient warning of widespread systemic collapse, a term now part of the contemporary discourse around abrupt and unexpected change in climate, ecological, social, and economic systems. Climate tipping elements are especially recognized by international research groups,[1,2] international science organizations,[3] and human security organizations.[4] In 2023, the United Nations Climate Change Conference COP28 meeting received a major report on tipping points[5] that identifies more than 25 terrestrial and oceanic elements of the Earth system that are vulnerable to crossing thresholds toward new steady states. Driven by a combination of global warming and unsustainable resource management, these elements are viewed as representing existential threats to humanity. However, in our opinion, some reporting fails to provide an appropriately nuanced assessment of the uncertainty in translating tipping point theory to real-world situations. The reasons for holding this view are 2-fold: (1) recent papers outline alternative mathematical models to the classic fold bifurcation that are capable of less abrupt, spatial re-organization as the natural response to stress[6,7] and (2) an increasing number of publications pointing to a lack of empirical evidence for tipping points or critical transitions in large databases and time series for real-world ecosystems.[8–14]

The classic tipping point model based on the fold bifurcation (Figure 1A) of Scheffer et al.[15] applies to homogeneous systems that can generate sufficient positive feedback to cause a self-accelerating shift in the whole system. These are exemplified by well-mixed shallow lakes susceptible to critical transitions from clear to turbid water quality that may be modeled with a few coupled partial differentiation equations. The more heterogeneous a system is, the less pronounced the change to an alternate state and the less lagged (hysteretic) the recovery appears.[16] Systems vary in the speed at which they respond to stress, and slow-responding systems may exhibit incremental rather than abrupt changes even in threshold-dependent and hysteretic systems.[17] Rietkerk et al.[6] and Bastiaansen et al.[7] offer an alternative theory based on Turing bifurcations (Figure 1B) that captures the behavior of heterogeneous systems. They propose that the response following threshold-dependent change may be more gradual, in a series of incremental steps, because of three-dimensional spatial reorganization leading to different system segments existing in stable co-existence. In this way, a real complex system may effectively avoid abrupt change to a new state.

Skeptical voices draw upon different lines of empirical evidence to argue that tipping points are not easily observed in real ecosystems, a view seemingly at odds with much of the discourse around global systems. For example, reviews of large ecological databases suggest that threshold-dependent changes are uncommon.[10] Relatively homogeneous systems, like lakes, for which the classic model should apply, do not always appear to respond rapidly to an external stress. Long-term patterns in lake water quality are not easily explained by

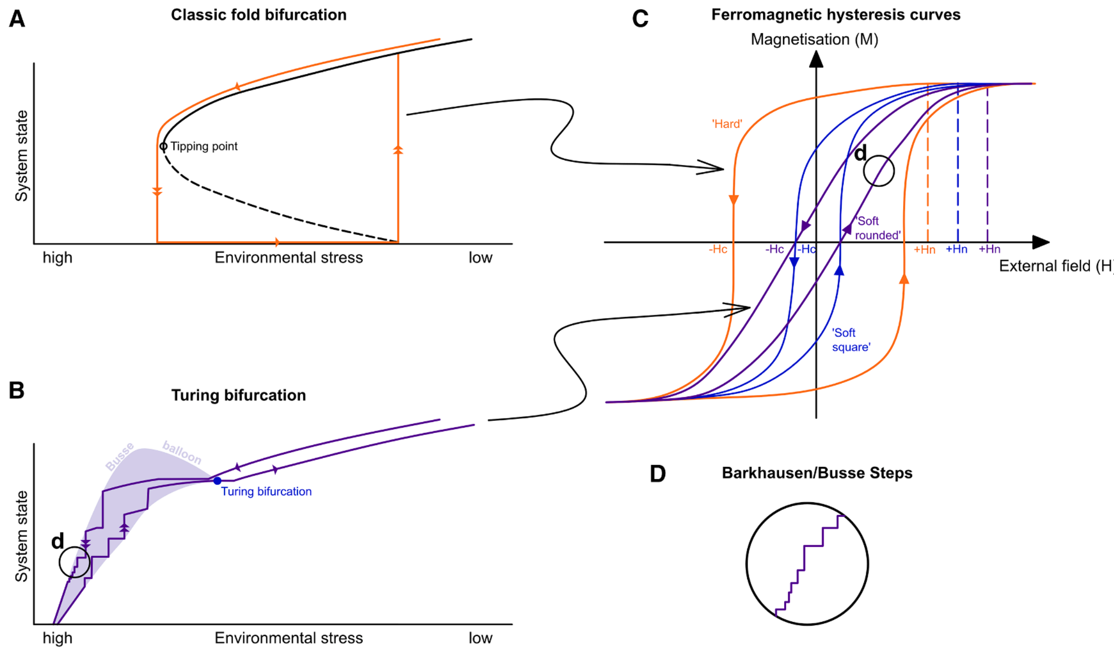

Figure 1. Alternative modeled representations of tipping point behavior compared with empirical hysteresis behavior in ferromagnets
(A) Classic fold bifurcation model showing tipping point.
(B) Turing bifurcation at lower stress levels than the classic tipping point showing the parameter space (shaded), where patterns are dynamically stable, known as a Busse balloon.
(C) Normalized ferromagnetic hysteresis curves (M-H) for hard (orange), soft rounded (purple), and soft square (blue) hysteresis behavior showing nucleation field ($+H_n$) and coercive force ($-H_c$) for each behavior.
(D) Magnified Busse and Barkhausen steps for slopes (indicated by circles) in (B) and (C), respectively (schematic for Busse, ~108× magnification for Barkhausen).
The two solid arrows show hypothesized similarities between the classic fold bifurcation and ferromagnetic hard behavior and between the Turing bifurcation and ferromagnetic soft behavior.[6,18,19]

alternative state theory[11] and may be linearly related to nutrient changes.[13] Recovery may be more linear than hysteretic,[8] and clear early warning signals of impending collapse seem to be the exception not the rule.[9]

These tensions between models and empirical evidence indicate that tipping point theory is still developing. This means that the potential threats posed by global tipping elements to humanity contrast with the uncertainty faced by policymakers in determining how to anticipate and mitigate the threats. Thus, the central question for researchers is how we should consider these contrasting observations, models, and theories. Do they contradict one another, do they represent quite different sets of systems, or do they represent end members within a continuum of generic system-response behavior? What determines whether a system is a slow or fast responder to stress? Do the difficulties in monitoring large-scale global systems mean that we are over-reliant upon mathematical models to inform us about tipping points?

One approach to resolve this issue would be to conduct experiments on real systems that allow testing of alternative mathematical models (i.e., classic fold versus Turing bifurcation). In this way, we could learn much about how different types of system attributes (size, shape, structure) control generic system responses (abrupt, gradual) to different types of applied stress (magnitude, rate, frequency). Such lessons would help inform policymakers tasked with preventing tipping points from occurring and, in worst-case scenarios, producing strategies for recovery. However, such an approach is impossible for putative global tipping elements at regional and global scales.

Therefore, in this perspective, we explore one candidate for this type of experimental test: laboratory measurements of ferromagnetic and ferrimagnetic minerals and synthetic materials such as garnet films (all hereafter referred to as ferromagnets). Under controlled and repeatable conditions, it is possible to observe a wide range of generic system behavior that we contend may be applied to global tipping elements. Similar dynamic patterns may be observed across global-scale physical phenomena, such as in the ocean currents, cloud formation, and ice sheets (Figures 2A–2C); ecosystems, such as semi-arid vegetation and peat bogs (Figures 2D–2F); and magnetic materials (Figures 2G–2I). It is through the empirical study of the effects of stress on patterns in these microscale systems that we attempt to test and reconcile alternative tipping point theories, drawing insight for strategic environmental management.

ALTERNATIVE TIPPING POINT MODELS

Early works[15] offered an accessible conceptual model for threshold-dependent abrupt change in systems by reference

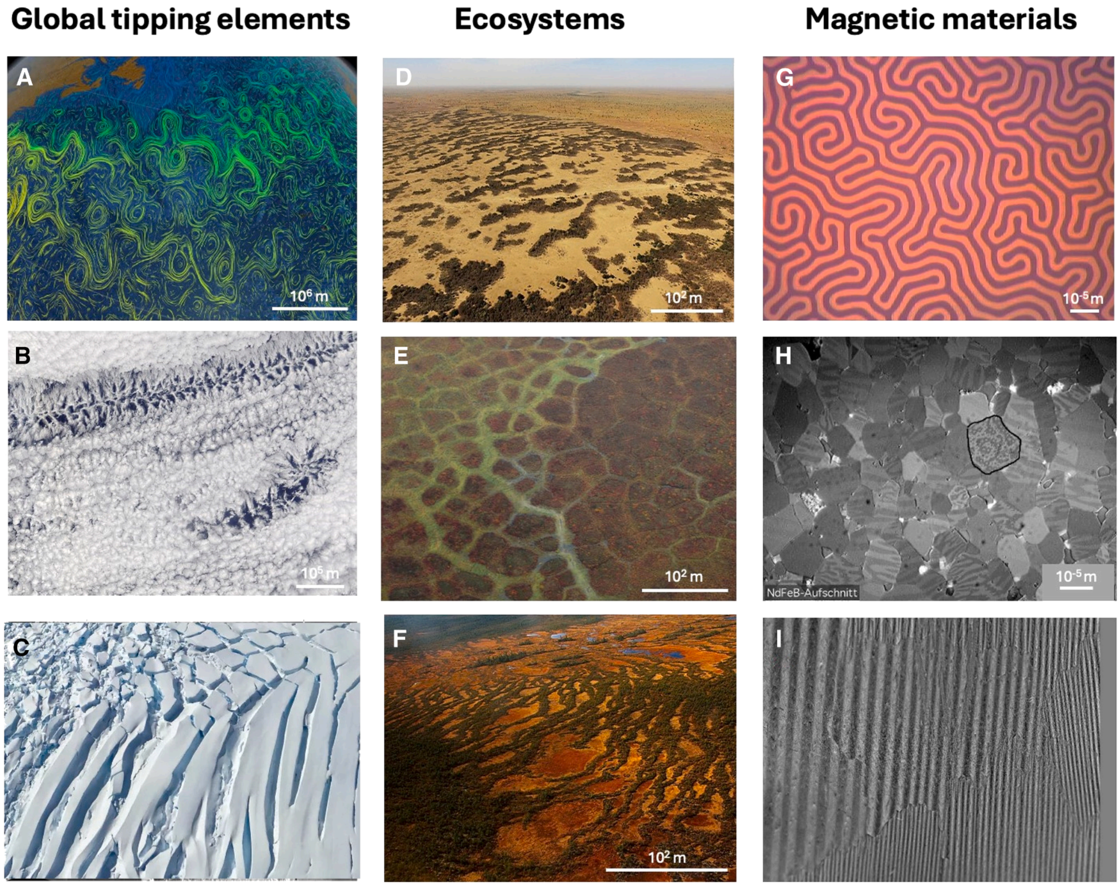

Figure 2. Similar structural patterns across different spatial scales: Global tipping elements, ecosystems, and magnetic materials
(A) Ocean currents. Complex network of currents in the northwestern Atlantic Ocean driven by the rotation of the planet.[20]
(B) Climate. Open- and closed-cell cloud formation over the Pacific Ocean produced by Rayleigh-Bénard convection cells.[21]
(C) Ice sheets. Antarctica's Larsen C ice shelf showing stress fractures.[22]
(D) Arid land. Tiger bush area in Niger with typical patterned vegetation.[23]
(E) Permafrost. Tundra polygons produced by freezing and thawing cycles.[24]
(F) Peat bog. Striped vegetation patterns in a peat bog within Yuganskiy Nature Reserve, Russia, formed by rows of dwarf Scotch pine with intermediate wet Sphagnum glades.[25]
(G) Bismuth-iron garnet. Magnetic stripe domains in a thin epitaxial layer of bismuth-iron-garnet imaged by Faraday rotation.[26]
(H) Neodymium magnet. Magnetic material NdFeB under a Kerr microscope showing the magnetic domain structure within microscopic crystal grains.[27]
(I) Steel. Magnetic domains and domain walls in electrical steel.[28]
Scales (A, B, D, E, and F) are approximated from Google Earth. Photographs (A) and (B) courtesy of the National Snow and Ice Data Center, University of Colorado, Boulder. Photograph (C) courtesy of Nathan Kurtz/NASA Operation Ice Bridge. Photographs (D)–(F) under various licenses within WikiMedia Commons.

to the mathematically defined two-dimensional fold bifurcation with a ball-and-cup analogy (hereafter referred to as the classic model; Figure 1A). In a stable state, a system (i.e., the ball) absorbs stress without showing significant external change (i.e., a ball sits within a deep cup). As resilience is lost to increasing stress (i.e., the cup becomes shallower), the system becomes increasingly vulnerable to reaching a tipping point where it can shift toward a new stable state (i.e., move out of the cup). Internally, the tipping point marks the loss of self-stabilizing feedback mechanisms in favor of self-reinforcing positive feedback mechanisms with sufficient strength to drive rapid change in the whole system toward a new state or regime (i.e., the ball rolling down a slope to a new cup).

The classic model predicts two further phenomena. First, once the system reaches a new state or equilibrium with the external environment, simple reversal of the system is challenging. The fold bifurcation shows that a system requires the level of stress for recovery to involve a larger effort than the level that was needed to precipitate the tipping point in the first place, so-called hysteresis.[15] Second, increasingly slower responses to stress as a system loses resilience may produce predictable changes in time series, such as increased autocorrelation and variance, that may foretell a tipping point: so-called early warning signals.[29] There are also modeled variants of the classic fold bifurcation related to the rate, magnitude, and frequency of the applied stress.[30] Evidence from experimental and modeled ecosystems and modeled networks shows that increased stress through more drivers,[31] higher driver rates[32] or greater noise,[31] and greater heterogeneity in nodal degree[33] may bring the tipping point forward substantially. Where systems interact with one another there is the further danger that one tipping element becomes a new and significant stress on another system creating a collapsing domino or cascading effect across systems.[34]

The alternative theory based on a reaction-diffusion model (e.g., Turing's activator-inhibitor principle) involves two substances or two processes that create scale-dependent feedback: short-distance positive feedback and long-distance negative feedback.[35] A so-called Busse balloon describes the region where multi-stable patterns exist in this alternative bifurcation diagram (Figure 1B). Patterns in ecosystems, like striped semi-arid vegetation (Figures 2D–2F), are thus explained as the combined effects of short-range modification of the environment coupled to long-range competition for resources. The reaction-diffusion model provides an alternative perspective on how systems may shift from one steady state to another, particularly for heterogeneous systems. The reaction-diffusion model suggests that these systems respond to lower stresses than are needed to transgress a classic tipping point and also questions changing spatial patterns as evidence of approaching tipping points[36,37] because an observed change in spatial pattern may simply represent a multi-stable state system moving gradually from one slightly different state to another as it adapts to stress. In this alternative to the classic model, change by small steps is also the means of recovery. Unlike the classic theory, reversal of the stress may lead to relatively direct responses with weak hysteretic, rather than lagged or strongly hysteretic, recovery.[6,7]

MAGNETISM AND TIPPING POINT THEORY

The magnetization or magnetic polarity of ferromagnetics (equivalent to the system state in the classic model) is easily manipulated under laboratory conditions. External magnetic fields (equivalent to the external driver and stress in the classic model) or temperature (equivalent to random shocks or noise) or elapsed time (equivalent to forcing rate) all can be used to probe system response.[18] Well-established theory and measurements, and new magneto-optical observational techniques,[38] allow internal structures to be monitored as the ferromagnet is cycled between alternate states. The Ising model of ferromagnetism has been used to simulate critical transitions under different system structures,[33,39,40] but here we focus on an empirical comparison of ferromagnets with larger-scale global and ecological systems. Such a comparison reveals many similarities and equivalences that help provide a framework to unify current tipping point theories (Table 1).

Hard and soft behaviors

The response of ferromagnetic systems to stress may be mapped out as bivariate (M-H) plots (Figure 1C) of applied magnetic field (H equivalent to stress), and magnetization (M equivalent to system state), analogous to system bifurcation diagrams. The changes in magnetization are the result of the minimization of the total energy in the system contributed by the magnitude of the external field, mineral composition, imperfections and inhomogeneities, crystal shape, size, and orientation. The most important physical element, in lowering the total energy, is the magnetic domain, a zone within the material where magnetic spins align in the same direction.[18] Magnetic materials absorb the effects of the magnetic field until the nucleation field (H_n) is reached when magnetization begins to increase or decrease depending on the direction of the field (Figure 1C). As the field strength increases, magnetization changes rapidly moving through a critical point, the coercive force (H_c), where 50% of the total magnetic moment has realigned.[42] Systems with a single domain are referred to as "hard" systems because, once magnetized, they are difficult to demagnetize. They absorb magnetization (the stress) and remain relatively unaltered until all the magnetization realigns abruptly. Hard systems have relatively high H_c values, displaying wide, often square-shaped, hysteresis loops (cf. blue curve in Figure 1C). In contrast, multi-domain or "soft" systems respond to small increases in stress as realignment takes place domain by domain. Consequently, they display narrower hysteresis loops with relatively lower H_c values (Figure 1C). Note that 'soft behavior can exhibit a variety of loop shapes. These range from upright soft square loops through the classic soft rounded sigmoidal shaped loop to flat, thin parallelogram shaped loops at the other extreme (Figure 1C). This continuum of behavior reflects the gradient between H_n and H_c (Figure 1C) and demonstrates how rates of change may vary greatly within soft systems (see tables 2.2, 2.4, and 2.7 in McLyman[43]).

Categorization of ferromagnetic system behaviors on a spectrum from hard to soft resonates with global tipping point literature that describes system change as abrupt/strongly hysteretic or step/weakly hysteretic[6] and as fast or slow responses.[17] A third possibility, linear change (viewed often in tipping point literature as a warning against simplistic understanding), is also accommodated through paramagnetic and diamagnetic minerals[18] whose simpler structures allow for direct and reversible relationships between M and H. Interrogating the similarities further (Table 1), we can surmise that ferromagnetic domains are comparable to discrete zones or patches within spatially complex ecosystems (e.g., arid land patterns) that have reached a minimum energy state or local equilibrium, as in the cup-and-ball analogy.[15] Thus, well-mixed, homogeneous systems, like small lakes, are comparable to the single-domain case, displaying abrupt hard behavior as they pass a tipping point. In contrast, a spatially complex system, such as semi-arid vegetation, responding to external stress through spatial organization[7] would be a candidate for the multi-domain, soft behavior case.

Busse and Barkhausen steps

Magnetic support for the reaction-diffusion model comes from well-established theory for the internal structural processes that lead to soft magnetic behavior. The (de)magnetization process in soft systems, equivalent to the (reversal) application of stress in an ecosystem, is not normally smooth because a domain may struggle to align with the applied field until it experiences a higher applied field (more energy). This results in stepwise and discontinuous magnetic domain wall movement known as the Barkhausen effect[44,45] (Figure 1D). The Barkhausen effect is strongest where the internal structures create a high diversity of viable domain configurations. Repeated demagnetization of the same thin film suggests a range of Barkhausen step patterns for the same material.[46] These observations bear close similarity to the Busse balloon bifurcation model for spatially complex ecosystems,[6] which also show sequences of steps within a zone of

Table 1. Equivalence and similarities between magnetic and large-scale global or ecological systems

Magnetic materials	Magnetic symbol and unit	Large-scale global or ecological systems	Descriptor or example of ecological process or variable
Time	t (s)	time	timescale
Magnetization	M (A/m)	response	transformed attribute (e.g., lower or higher biodiversity, primary production, resilience)
External field	H (Tesla)	stress or forcing	transforming process (e.g., climate change, nutrient loading)
Nucleation field	H_n (Tesla)	threshold point	point at which structural change starts
Coercive force	H_c (Tesla)	system tipping point	point at which structural change may be self-accelerating (e.g., critical phosphorus level in aquatic system)
Magnetic domain	region of aligned magnetic spins; dimensions (μm)	discrete self-sustaining zone	measure of system heterogeneity or patterning (e.g., vegetation mosaic of humid temperate heathlands)
Viscosity	$\delta M/\delta t$	elasticity	the speed with which a system returns to its previous state (e.g., succession following deforestation)
Hysteresis	energy loss (M-H) on cycling once around a major M-H loop	hysteresis	dependence of system state on its history, causing the existence of alternative, stable (non-transitory) regimes under the same external conditions and lagged recovery following regime shift (e.g., recovery of vegetation following drought)
Sweep rate	$\delta H/\delta t$	stress rate	rate at which stress level increases (or decreases) over time (e.g., rate of global warming or nutrient supply)
Temperature fluctuation	ΔT (Kelvin)	disturbance	variations in natural ambient conditions (e.g., extreme temperature, species immigration, disease)
Barkhausen noise	$\Sigma\Delta M$	Busse balloon steps	changes in ecosystem structure (e.g., sequence of vegetation patches in dryland ecosystem with lower or higher moisture)

Well-known ecosystem attributes and characteristics[41] such as stress, hysteresis, and disturbance have direct magnetic equivalents. Conversely, the major facets of ferromagnets[18] such as magnetization, susceptibility, hysteresis, coercivity, and viscosity have counterparts in ecology.

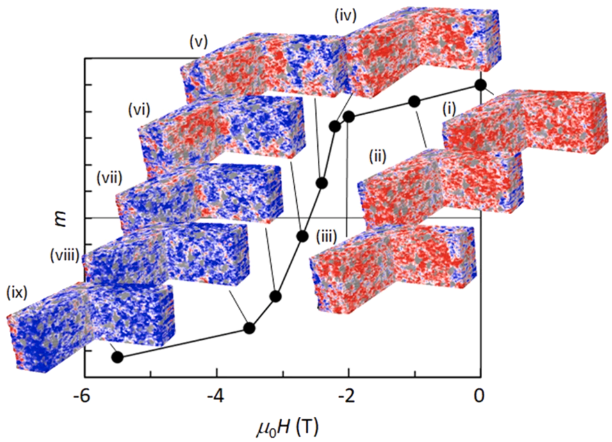

Figure 3. Changes in the microstructure of domain alignment driven by an external field

Cutaway three-dimensional scanning electron microscope images of magnetic domain structure as observed in an NdFeB magnet at different external fields (*H*) at different points along the magnetization (*m*) curve (black dots and line) from positive to negative saturation. The changing colors show the switch from predominantly normal alignment (red, phases i–iii) to predominantly reversed alignment (blue, phases vii–ix). The coercive force is passed between phases v and vi as the reverse field sweeps through −2.6 T.

Reproduced from Takeuchi et al.[47] with permission (http://creativecommons.org/licenses/by/4.0/).

multi-stable parameter space (Figure 1B) as individual ecosystem domains are forced from one local equilibrium state (the cup) to another. Moreover, the realignment of magnetic domains in multidomain materials as the external magnetic field is changed is now observable (Figure 3). When used in conjunction with ultra-modern scanning electron microscopy, novel, X-ray based, magnetic tomography techniques[47] allow the changing magnetic domain patterns to be mapped out in detail.

In energetic terms, both Barkhausen and Busse effects describe similar phenomena: local spatial zones adjusting to changes in global external energies (e.g., magnetic field, temperature) by overcoming local attractors so that the whole system reaches a lower energy state (i.e., minimizing free energy). The similarity extends to distributions of step magnitude described by positively skewed power laws[48] that confirm both effects are driven by local positive feedback mechanisms. In ferromagnets, stress above H_n generates positive feedback (e.g., exchange energy) which accelerates the re-alignment of domains throughout the crystal with the gradient of the (de)magnetization curves reaching a maximum at H_c (Figure 1C). Hence, the coercive force may be considered the equivalent of the point at which change becomes self-perpetuating. Despite the markedly different time scales between the Barkhausen[48] and Busse[6] effects, the similarity between the two phenomena strongly points to the importance of primary, global at-distance drivers coupled to secondary, local feedback mechanisms (associated with small-scale spatial inhomogeneities) in determining the hysteresis dynamics of complex systems at widely different spatial scales.

Hysteresis

Recycling a ferromagnet back to its original state by reversing the external magnetic field is comparable to recovering an ecological system by reversing the external stress. Hysteresis, or a lag, occurs because the newly aligned system requires relatively more energy to reverse its direction. In ferromagnets, defects, impurities, dislocations, and grain boundaries create negative feedback processes that pin the domains in local energy minima.[18] Moving out of a local energy minimum is therefore invariably a hard response requiring the accumulation of significant energy to overcome the resilience created by net negative feedback. This explains why both single-domain ferromagnets (Figures 1A and 1C) and well-mixed homogeneous Earth systems display wide hysteresis loops characteristic of hard behavior.

In a soft system, however, remagnetization behavior takes place at the scale of each magnetic or ecological domain rather than the system scale. Thus, each domain should be considered a local energy minimum with its own sensitivity to a reversed stress. Some highly sensitive local domains will tip very quickly as the stress begins to strengthen but with little effect on the whole system. Other domains will absorb relatively large amounts of stress before tipping. Such behavior is observed in a simulation of the Ising model of ferromagnetism.[39] As the external field or stress increases, new or stronger positive feedback will cause more domain interactions with an increasing number and size of domain or sub-system collapses, exemplified by the cascading sequences in Busse balloons and Barkhausen avalanches (Figures 1B and 1C), until the whole system reaches a new steady state. As previously noted, soft behavior in ferromagnetic minerals may range widely from the classic soft rounded loop behavior in multidomain minerals to soft square behavior found in modern materials (e.g., in annealed metallic glasses).[49] Such materials allow electron spins to re-align rapidly once the magnetic stress reaches a critical level, combining the ease of (de)magnetization of soft systems with the abruptness of change of hard systems.

The difference between the two soft behaviors broadly reflects the size and number of domains, where fewer, larger domains result in extremely soft, square hysteresis loops[50] (Figure 1C). Thus, we hypothesize that in heterogeneous Earth systems, a sequence, or cascade, of local abrupt tipping points represent the means by which the whole system dissipates the stress as soft behavior where the soft behavior may range from incremental to abrupt. A key point is that multidomain ferromagnets and, by analogy, spatially complex global systems alike will display narrow hysteresis loops (Figure 1C) indicative of the comparably less energy or work needed to change from and to return to the original state.

Laboratory magnetization experiments distinguish between saturating (major loop) and non-saturating (minor loop) hysteresis. Major loops occur where the maximum external applied field is sufficiently large and continuous to rotate (tip) all the magnetic spins within all the local domains into the alternative (reversed) magnetization state. Minor loops occur when the field is either insufficiently large or discontinuous, to realign all the domains, or the field is reversed after H_n but before the alternate reversed state is reached across the whole mineral. This is analogous to reversing a stress in an environmental system after a critical threshold has been crossed but before the alternate state is reached. Some studies[51] show that reversing the field before the alternate state is reached gives rise to a narrower and shallower hysteretic loop (Figure 4A), meaning the earlier the

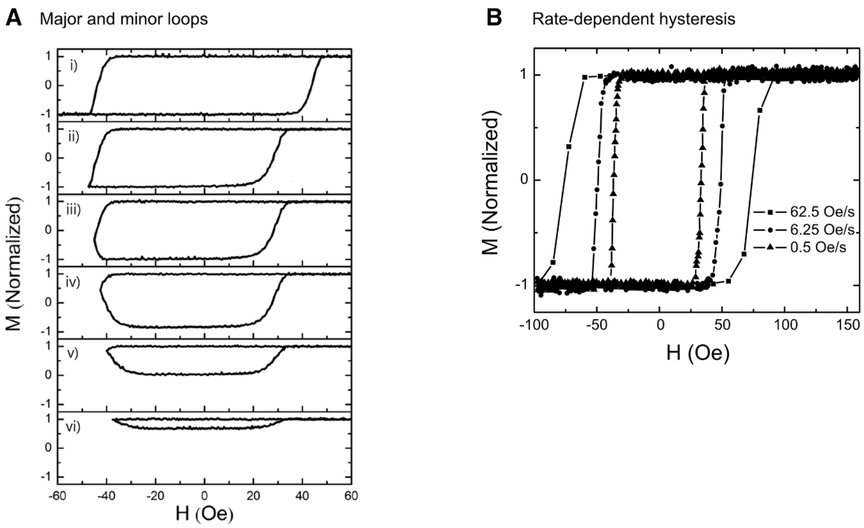

Figure 4. Hysteresis behavior in a $(CoFeB/Pd)_4$ multilayer film as a function of field magnitude and rate

(A) Major and minor loops of magnetization (M) plotted as a function of the magnitude of the field (H). The major magnetization loop (i) shows symmetry between forward and reverse fields indicating complete saturation and alignment of all magnetic domains. Reversing the field application before saturation ($-M_s$) is reached (ii–vi) produces narrower and shallower minor loops.

(B) Rate-dependent hysteresis in a major loop as the rate of change of the external field (H) increases from 0.5 Oe/s (triangles) to 6.25 Oe/s (dots) to 62.5 Oe/s (squares). The hysteresis loops widen as the field rate increases, but the time taken for the magnetization curve to reach −1 (i.e., totally reversed) shortens as indicated by the declining number of equal-time steps shown by the numbers of data symbols. Reproduced from Quach et al.[51] with permission (http://creativecommons.org/licenses/by/4.0/).

reversal, the easier the recovery. This effect has also been linked to slow- rather than fast-responding model ecosystems[17] and to modeled global tipping points[52] where thresholds may be temporarily exceeded without a total collapse. Combining these different observations suggests that slow responding real systems may simply represent spatially complex soft systems, which respond early and continuously to long-term external forcings.

Stress rates

The behaviors of magnetic and climate tipping elements are clearly affected by rates of applied stress. Ramping up the rate at which the external magnetic field is applied has two major effects (Figure 4B). First, the rate of magnetic cycling increases, meaning the magnetic spins realign sooner. Second, the area and width of major hysteresis loops increase,[53,54] meaning that local domains realign at higher H_n values. Higher rates of applied stress therefore make systems tip earlier and tend to make soft systems harder.[51] The dependence of the width of hysteresis loops or magnetic hardness on the frequency of the applied field physically arises because the thermal activation of the magnetization, which facilitates the magnetization to overcome local energy barriers, is time dependent. Slower rates of applied stress give the system more time to relax to lower energies and more time for temperature fluctuations to reconfigure the magnetic domains.[18] These laboratory-based findings are in accord with computer calculations and modeling experiments of climatic and ecological systems[30,31,55] that show how rapid forcing (e.g., increasing global warming rate) causes tipping to occur sooner than with slower forcing and require a stronger (more elevated) level of stress to return the system to its original state.

Slow relaxation of magnetization, known as magnetic viscosity, may take place in the absence of change in an external field.[18] This relaxation or recovery in the presence of natural thermal variability alone resembles the emergence of complex systems, for example, through ecological succession in a stationary climate. Viscous magnetic behavior[56,57] has parallels with well-known elastic ecological processes such as where r-selected species recover significantly faster than k-selected species following a disturbance. Such bounce backs are widely encountered in ecosystems as long-term plant succession, such as observed in the long-term Rothamsted Wilderness experiments.[58,59] Viscous magnetic changes can also arise through random thermal shocks that resemble colonization events (e.g., the reintroduction of key species that went locally extinct) which in turn can kick-start succession and a return to the original state.[60]

INSIGHT FOR GLOBAL TIPPING POINTS

Laboratory experiments show that ferromagnets exhibit much of the general system behavior predicted by tipping point models. Building on the fact that experiments are more feasible to conduct on magnetic than ecological/global systems, we are able to draw out some important implications for global tipping points.

Scale dependence

Climate and ecological tipping elements with the capacity to spatially organize into discrete domains are expected to display simultaneously gradual behavior when viewed at the scale of the whole system and abrupt behavior at the scale of the local domain. Therefore, large sub-global systems with complex and heterogeneous structures will, all other things being equal, collapse in real time as soft, not hard systems.[6,7] Such upheavals do not exclude abrupt change, as with soft square loops, but indicate that some complex Earth systems are expected to change under stress relatively easily and may also recover relatively easily. Thus, failure to recognize scale dependence in tipping point behavior may produce erroneous assessments of the drivers, rates, and consequences of global tipping points. It follows that modeled tipping behavior will in part reflect the accuracy with which the models simulate the appropriate scale of internal interactions. Network models manipulated to simulate varying types of nodal connections show that mean-field or aggregate approximations may lead to inaccurate transitional behavior where modularity is high.[40] Thus, simple equation-based models may be a useful guide for anticipating the abrupt behavior of small, homogeneous systems but not necessarily for large, heterogeneous systems where incremental or cascading behavior is more likely. Where models have incorporated spatial dynamics, for example, in intermediate complexity modeling of the Atlantic meridional overturning circulation, model outputs indicate softer multistable rather than harder bistable behavior.[61]

In the blink of an eye

Abruptness (in terms of M-H loops or bifurcation graphs) refers to the angle of inflection between H_n and H_c measured per unit stress—in other words, whether the system trajectory changes abruptly along a steep gradient or incrementally along a gradual gradient. However, this definition alone does not provide information about the speed or duration of the transition to an alternative state. In strategic management terms, the rapidity and duration of a transition per unit time are arguably more important than abruptness (per unit stress). Real collapse times remain uncertain, but there is evidence that system size and stress rates are important controls.[62] Laboratory-based magnetic experiments on rate-dependent phenomena confirm modeling experiments[30–32,55] in suggesting that rapid forcing (e.g., increasing global warming rate) causes tipping to occur earlier and sooner than with slower forcing because the damping feedback is not able to act fast enough to counter the applied stress. Magnetic experiments confirm that high forcing rates are doubly bad for a real system (Figure 3B): they collapse the system more quickly, although not necessarily more abruptly, and may leave it with a disproportionately higher level of degradation to reverse.[51] Despite the likelihood that the tipping point may occur at a higher stress level (e.g., at a higher temperature), this does not represent a beneficial trade-off because recovery will require greater effort.

"Boiling frogs"

The global tipping points literature leans toward the classic model of abrupt responses between alternative system states. However, as we have shown, magnetic experiments underline earlier observations[17] that relatively slow forcing in large, heterogeneous systems can trigger incremental change long before rapid change is observed. Notwithstanding the fact that incremental change may mean a long-term self-sustaining cascade of change, there remains the risk that we overstate the catastrophic nature of future change and downplay the significance of relatively slow degradation that may already be happening at the present: the well-known "boiling frog" metaphor. In this respect, the gradual degradation that we observe in some contemporary Earth system elements[2] may demonstrate that crucial "warming thresholds" have already been passed: system resilience has been lost, but the response has been gradual, in human timescale terms, through re-organization. Diverse support for this view comes from manipulated ecosystem experiments showing gradual change to gradual increases in CO_2 fertilization[63] and evidence that the Earth's climate system was already shifting before the "Great Acceleration" of the mid-20th century.[64] Furthermore, the "climate warming hiatus" of 1998–2013 may have been associated with energy redistribution (i.e., spatial reorganization) within the oceans rather than a slowdown in warming.[65] If verified, then this would mean that it may be too late to detect early warning signals in some tipping elements.

Major or minor?

A key challenge for real systems is to identify the point when the potential safety of a minor loop is lost prior to the irreversibility that strengthens as stress is increased and the major loop is approached. Determination of such safety parameters in global systems might allow more nuanced definitions of tipping points. For example, Armstrong McKay et al.[2] notes that tipping points occur "when change in part of the climate system becomes (i) self-perpetuating beyond (ii) a warming threshold as a result of asymmetry in the relevant feedbacks" (p. 1) could be extended to include both the period of weak self-perpetuation following the start of structural change (H_n) when "easy" reversibility is probable along minor loops and the period of stronger acceleration (around H_c) when reversibility is likely to be hysteretic along major loops. In both hard and soft square systems, H_n and H_c are essentially coincident. This suggests that tipping point behavior might usefully be categorized in observations or models by two key factors: the ability to absorb stress (hysteresis loop squareness, H_c/H_n) and the capacity to spatially re-organize readily (hysteresis loop hardness, H_c).

Managed ecosystems

A continuum of behavior between hard and soft provides a framework for thought experiments about the likely behavior of managed or engineered systems (e.g., commercial fisheries, canalized rivers, or agroecosystems) in contrast to natural systems and global tipping elements (e.g., Greenland ice, permafrost). In network terms, engineering a system normally reduces system complexity, effectively reducing the degrees of freedom,[6,12] as expressed, for example, in the numbers of discrete modules, domains, or trophic levels, that will, we hypothesize, tend to make the system harder. As an example, an intensive agroecosystem is expected to show harder responses to an external stress (e.g., drought) than the original spatially complex ecosystem, with more abrupt collapse. It also follows that as managed systems approach a degraded state there is greater likelihood for a final hard collapse as the system approaches single-domain status. This final phase will be the most rapid change observed in a stepped sequence that starts with incremental changes when the system is still in a relatively soft state. The nutrient-driven degradation of the large Erhai Lake in China took place over several decades prior to a final collapse at the turn of the 21st century,[66] giving weight to the idea that spatially organized systems may display soft tipping points at the beginning of the stress period as well as a hard collapse toward the end as the stress accumulates.

Active recovery

There is a tendency to refer to the difficulties of recovering a collapsed system in terms of irreversibility. However, the term irreversibility is not always well defined and may reflect more the practical challenge of recovery than the actual potential for recovery.[67] More formally, and by analogy with magnetic materials, the costs (e.g., energy, effort, information, money) required to recover a collapsed system largely depend on whether it displays strongly lagged, hysteretic behavior or not. Therefore, if some global and Earth system tipping points currently display soft behavior, then it should be anticipated that they will exhibit relatively easy reversibility. Nevertheless, many attempts at active ecosystem restoration have shown that recovery is far from easy or unexpectedly slow.[68] One reason may be an unrealistic expectation of how much stress reversal is needed to halt degradation, even before recovery is observed. As discussed above, avoiding total collapse is possible with early reversals of the stress, for example, as achieved by initiating the equivalent of a minor magnetic loop. This need not result in an immediate improvement of system state (Figure 3), however, because degradation may continue through local feedback mechanisms until a critical level in the reversal of stress is reached that can trigger domain avalanches toward recovery. Recovery that is relatively easy in energetic terms might still require substantial time before changes in system state are observed.

Passive recovery

In contrast to active restoration, many attempts at local ecosystem restoration, such as natural re-wilding or management of effluent discharge into a eutrophic lake, involve passive recovery through the cessation of stress, rather than the direct reversal of stress. Analogous to magnetic viscosity, passive recovery in ecosystems may simply require the passage of time for ambient energy to generate local positive feedback mechanisms and structural changes that drive local recovery, over relatively long timescales, in a reversed Busse trajectory. However, passive recovery alone may be insufficient to overcome the strength of feedback processes that maintain internal structures within the new steady state,[69] or the emergence of new feedback mechanisms adapted to the new external stresses.[70] In these two cases, active reduction of the stress (e.g., in the case of nutrient-enriched lakes by physically removing upper sediment layers) or a shock intervention (e.g., one-time deep ploughing to break up a compacted subsoil) may be needed to return the system to its original state. This suggests that complete recovery of any hysteretic system, even when the main stress has been removed or reduced to its original level, may require additional active intervention.

Early warning signals

Classic early warning signals based on critical slowing down[29,71] are less likely to be observed in the time series of soft systems because the system response varies across space rather than aggregated in time.[6,7] Weakly linked domains in simulations of magnetic systems lose resilience and display a slowing down in recovery before more strongly linked domains and the overall system are affected.[39] For Earth tipping elements, this problem is exacerbated by the spatial scale of observation, which is frequently inadequate to make analyses at the appropriate domain scale; conversely, in ecology, the necessary temporal resolution is often lacking. Therefore, identifying the scale of Earth and ecological elements (domains) will be a key procedural advance, although pinpointing the scale may be challenging as the required size of elements is expected to change through clustering as systems degrade (cf. Figure 3). Monitoring the extent and rates of spatial organization in global ecosystems through changing local vegetation patterns[72] may be a profitable approach if the analysis can identify the appropriate scale of observation. Seeking less scale-dependent approaches that interrogate systems for significant structural changes that reflect loss of resilience may also be worthwhile.[73–75]

Positive tipping points

Triggering tipping points to produce new desirable socioeconomic states has recently become a vital topic in the quest to transform social behavior toward decarbonization.[76] The insight here confirms that creating the conditions for a tipping point in a soft system requires large-scale global changes that allow local positive feedback mechanisms to develop. In developing and enabling new socioeconomic tipping cascades, a key element is to ensure that global and local changes are appropriately coupled. In the case of helping consumers switch from fossil fuel to electric cars, both the global pricing of vehicles and the availability of charging points need to be changed at complementary rates to allow consumers to influence one another through their local purchasing options.[77] As a rule of thumb, early and abrupt change will be aided by manipulating existing systems toward harder behavior. This may mean simplifying the complexity of the current state, speeding the process of change, or providing a kick-start through, for example, reducing bureaucracy and greater investment. In conservation ecology, the introduction of beavers to engineer flood controls can drive hard impacts associated with rapid hydrological, geomorphological, ecological, and societal changes that enhance both flood control and the beaver habitat.[78]

OUTLOOK

In this perspective, our central thesis is that although the stability of climate and ecological systems when influenced by external (often human produced) pressures or dynamics is multifaceted and shows extensive variety, there are, nevertheless, many equivalences and similarities with the behavior of magnetic materials. This leads to a need for more nuanced messages around future changes in global systems.

In answer to our original questions, we have shown that studies of ferromagnets under controlled laboratory conditions can provide insight into the generic energetics of tipping point behavior that helps reconcile contrasting observations, models, and theories. Our analysis suggests that classic and reaction-diffusion models are not so much contradictory as they represent different scales of system behavior. This implies a need to focus attention on the scale dependency of system behavior and away from solely the implications of simple bifurcation models. In theory, hard and soft types of behavior may represent end members of system behavior, but further research is needed to apply the spectrum of behaviors to the scale of global and regional tipping elements that, outwardly at least, fundamentally vary in their dominant mechanisms of change. At the highest order, we might expect ecosystems to be inherently softer than physical systems, but in reality, we have no simple means to compare, for example, the Amazon and the Atlantic meridional overturning circulation in terms of their adaptive capacities. Classifying tipping elements according to their potential generic behavior would not only help to identify appropriate descriptors and modeling approaches but also alleviate some of the criticism[14] leveled at the undiscerning application of the tipping point concept. Equally, we need to discriminate between different degrees of softness in global systems that are inherently heterogeneous. Magnetic experiments consider structural heterogeneities linked to the domain form and patterns caused by underlying mineral conditions (e.g., geochemistry), but the challenge is to translate heterogeneity-driven responses to other systems—for example, environmental landscapes.[79] Our analyses also imply that fast- and slow-responding systems map well onto hard and soft behaviors, respectively. This does not remove the challenge of defining future rates of time to tip and time to reach a new state in absolute terms, a critical quest in the current environmental crisis. Finally, our insights do not lessen the need for mathematical modeling and simulation studies, but caution is needed in deducing tipping point behavior. Many models may be applicable to a certain scale, or range of scales, of system behavior that may not be matched to the fundamental scale at which tipping point behavior, as observed in the whole system, operates.

We can use these insights to briefly speculate about the future. Expanding out across time and space, we might envisage a Busse balloon curve for the whole, complex, highly heterogeneous, Earth system that describes a soft response to global warming. As global temperatures rise, we would expect the number of local tipping points crossed in temperature-sensitive elements to multiply even while only gradual changes are observed at larger scales. Each stage in Earths long-term degradation would be represented by one of many interacting regional tipping elements or domains. Perhaps the first relatively hard steps have already been observed in the cryosphere dynamics of the west Antarctica and Greenland ice sheets.[2] We might also anticipate other elements with greater capacity to spatially re-organize (e.g., the Atlantic meridional overturning circulation) to exhibit relatively softer, stepped, and gradual declines.[61] Such a sequence of global tipping points may already have been observed within the period 130 to 125 ka before present during the last interglacial period,[80] when each tipping element may have acted as a separate domain, forced by the same global warming driver, but with interacting positive feedback loops. If so, then this would emphasize previous arguments[31,34,81] that modern global warming may strengthen interactions and hence accelerate other tipping elements in an ever-enlarging vortex of degradation. Such a worst-case vision highlights the dangers of uncontrollable positive feedback mechanisms and the need to view all observed and predicted threshold-dependent change as an existential threat.[82]

In summary, when any complex adaptive system shows strong, continuous, or cumulative responses to stress, it means the system is no longer resilient against that stress. Negative feedback mechanisms are unable to counter the stress, the system has moved across a key threshold, and it resides outside its safe operating space. This marks the point at which tipping behavior becomes possible. However, as we show here, whether the system eventually reaches a new steady state through one abrupt step, a series of steps, gradual change, or some hybrid of these will depend upon the subsequent interaction of stress and system attributes in space and time. Understanding and modeling these interactions in specific tipping elements should be a major scientific priority.

ACKNOWLEDGMENTS

The authors acknowledge helpful and constructive comments from three anonymous reviewers and comments on the first draft of the manuscript from Dr. Zoë Thomas, Prof. Ke Zhang, and Dr. Joan Zimmerman. J.A.D. and S.W. acknowledge funding from the United Kingdom's Natural Environment Research Council via the Recovery Pathways for Lake Ecosystems project (NE/X014150/1). K.T. and S.W. were funded by the United Kingdom's Biotechnology and Biological Sciences Research Council via BBS/E/RH/230004B through the Resilient Farming Futures project (BB/X010961/1).

AUTHOR CONTRIBUTIONS

J.A.D. conceived the idea for the paper. J.A.D., R.T., and S.W. developed the idea further and, with K.T., wrote and illustrated the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

1. Lenton, T.M., Held, H., Kriegler, E., Hall, J.W., Lucht, W., Rahmstorf, S., and Schellnhuber, H.J. (2008). Tipping elements in the Earth's climate system. Proc. Natl. Acad. Sci. USA *105*, 1786–1793.
2. 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). Exceeding 1.5°C global warming could trigger multiple climate tipping points. Science *377*, eabn7950. https://doi.org/10.1126/science.abn79.
3. IPCC (2021). Intergovernmental Panel on Climate Change (IPCC). Climate Change 2021: The Physical Science Basis. Working Group 1 Contribution to the IPCC Sixth Assessment Report. https://www.ipcc.ch/report/ar6/wg1/.
4. UNU-EHS (2023). UNU-EHS Interconnected Disaster Risks 2023: Risk Tipping Points (United Nations University).
5. Lenton, T. M., Armstrong McKay, D.I., Loriani, S., Abrams, J.F., Lade, S.J., Donges, J.F., Milkoreit, M., Powell, T., Smith, S.R., Zimm, C., et al., (Eds). (2023). The Global Tipping Points Report 2023. University of Exeter. https://global-tipping-points.org.
6. Rietkerk, M., Bastiaansen, R., Banerjee, S., van de Koppel, J., Baudena, M., and Doelman, A. (2021). Evasion of tipping in complex systems through spatial pattern formation. Science *374*, eabj0359.
7. Bastiaansen, R., Dijkstra, H.A., and von der Heydt, A.S. (2022). Fragmented tipping in a spatially heterogeneous world. Environ. Res. Lett. *17*, 045006.
8. Capon, S.J., Lynch, A.J.J., Bond, N., Chessman, B.C., Davis, J., Davidson, N., Finlayson, M., Gell, P.A., Hohnberg, D., Humphrey, C., et al. (2015). Regime shifts, thresholds and multiple stable states in freshwater ecosystems; a critical appraisal of the evidence. Sci. Total Environ. *534*, 122–130.
9. Spears, B.M., Futter, M.N., Jeppesen, E., Huser, B.J., Ives, S., Davidson, T.A., Adrian, R., Angeler, D.G., Burthe, S.J., Carvalho, L., et al. (2017). Ecological resilience in lakes and the conjunction fallacy. Nat. Ecol. Evol. *1*, 1616–1624.
10. Hillebrand, H., Donohue, I., Harpole, W.S., Hodapp, D., Kucera, M., Lewandowska, A.M., Merder, J., Montoya, J.M., and Freund, J.A. (2020). Thresholds for ecological responses to global change do not emerge from empirical data. Nat. Ecol. Evol. *4*, 1502–1509.
11. Davidson, T.A., Sayer, C.D., Jeppesen, E., Søndergaard, M., Lauridsen, T. L., Johansson, L.S., Baker, A., and Graeber, D. (2023). Bimodality and alternative equilibria do not help explain long-term patterns in shallow lake chlorophyll-a. Nat. Commun. *14*, 398.
12. Blom, A., Ylla Arbós, C., Chowdhury, M.K., Doelman, A., Rietkerk, M., and Schielen, R.M.J. (2024). Indications of ongoing noise-tipping of a bifurcating river system. Geophys. Res. Lett. *51*, e2024GL111846. https://doi.org/10.1029/2024GL111846.
13. Graeber, D., McCarthy, M.J., Shatwell, T., Borchardt, D., Jeppesen, E., Søndergaard, M., Lauridsen, T.L., and Davidson, T.A. (2024). Consistent stoichiometric long-term relationships between nutrients and chlorophyll-a across shallow lakes. Nat. Commun. *15*, 809.
14. Kopp, R.E., Gilmore, E.A., Shwom, R.L., Adams, H., Adler, C., Oppenheimer, M., Patwardhan, A., Russill, C., Schmidt, D.N., and York, R.

(2025). Tipping points' confuse and can distract from urgent climate action. Nat. Clim. Chang. *15*, 29–36.

15. Scheffer, M., Carpenter, S., Foley, J.A., Folke, C., and Walker, B. (2001). Catastrophic shifts in ecosystems. Nature *413*, 591–596.
16. Scheffer, M. (2009). Critical Transitions in Nature and Society (Princeton University Press).
17. Hughes, T.P., Linares, C., Dakos, V., van de Leemput, I.A., and van Nes, E. H. (2013). Living dangerously on borrowed time during slow, unrecognized regime shifts. Trends Ecol. Evol. *28*, 149–155.
18. Thompson, R., and Oldfield, F. (1986). Environmental Magnetism (Allen & Unwin).
19. Wikipedia. Random Barkhausen jumps on the magnetisation curve of a ferromagnetic material. https://en.m.wikipedia.org/wiki/File:Barkhausen_jumps.svg.
20. (2023). Earth's oceans are filled with complex network of currents driven by the rotation of the planet. NASA/Goddard Space Flight Center Scientific Visualization Studio. https://maritime-executive.com/editorials/new-satellite-data-will-reveal-hidden-details-of-ocean-currents.
21. NASA Earth Observatory (2016). Open- and Closed-Cells over the Pacific. https://earthobservatory.nasa.gov/images/87456/open-and-closed-cells-over-the-pacific.
22. National Snow and Ice Data Center. Aerial view of the calving front of Larsen C on the Antarctic Peninsula. https://nsidc.org/learn/parts-cryosphere/ice-sheets/why-ice-sheets-matter.
23. van Zeijst, V. (2020). Aerial view of a tiger bush area in Niger. https://commons.wikimedia.org/wiki/File:Niger,_tiger_bush_(1).jpg.
24. U.S. National Park Service (2020). Polygons - a sign of continous underground permafrost. https://commons.wikimedia.org/wiki/File:Vibrant_geometry_(9906168084).jpg.
25. Bulyonkova, T. (2012). Aerial view of a peatbog in the Yuganskiy nature reserve. https://commons.wikimedia.org/wiki/File:Peatbog_(Yugansky_Nature_Reserve_-_aerial).jpg.
26. Gualtieri, D.M. (2011). Magnetic stripe domains. https://commons.wikimedia.org/wiki/File:Magnetic_stripe_domains.jpg.
27. Gorchy. NdFeB-Domains. (2005). https://commons.wikimedia.org/wiki/File:NdFeB-Domains.jpg.
28. Matesy (2012). Magnetic domains of grain oriented silicon or electrical steel. https://commons.wikimedia.org/wiki/File:Magnetic_domains_of_grain_oriented_silicon_or_electrical_steel.png.
29. Scheffer, M., Bascompte, J., Brock, W.A., Brovkin, V., Carpenter, S.R., Dakos, V., Held, H., van Nes, E.H., Rietkerk, M., and Sugihara, G. (2009). Early-warning signals for critical transitions. Nature *461*, 53–59.
30. Ashwin, P., Wieczorek, S., Vitolo, R., and Cox, P. (2012). Tipping points in open systems: bifurcation, noise-induced and rate-dependent examples in the climate system. Phil. Trans. R. Soc. A *370*, 1166–1184.
31. Willcock, S., Cooper, G.S., Addy, J., and Dearing, J.A. (2023). Earlier collapse of Anthropocene ecosystems driven by multiple faster and noisier drivers. Nat. Sustain. *6*, 1331–1342.
32. Siteur, K., Eppinga, M.B., Doelman, A., Siero, E., and Rietkerk, M. (2016). Ecosystems off track: rate-induced critical transitions in ecological models. Oikos *125*, 1689–1699.
33. Reisinger, D., Adam, R., Kogler, M.L., Füllsack, M., and Jäger, G. (2022). Critical transitions in degree mixed networks: A discovery of forbidden tipping regions in networked spin systems. PLoS One *17*, e0277347.
34. Rocha, J.C., Peterson, G., Bodin, Ö., and Levin, S. (2018). Cascading regime shifts within and across scales. Science *362*, 1379–1383.
35. Rietkerk, M., and van de Koppel, J. (2008). Regular pattern formation in real ecosystems. Trends Ecol. Evol. *23*, 169–175.
36. Van Nes, E.H., and Scheffer, M. (2005). Implications of spatial heterogeneity for catastrophic regime shifts in ecosystems. Ecology *86*, 1797–1807.
37. Butitta, V.L., Carpenter, S.R., Loken, L.C., Pace, M.L., and Stanley, E.H. (2017). Spatial early warning signals in a lake manipulation. Ecosphere *8*, e01941.
38. V. Franco and B. Dodrill, eds. (2021). Magnetic Measurement Techniques for Materials Characterization (Springer).
39. Füllsack, M., Reisinger, D., Adam, R., Kapeller, M., and Jäger, G. (2023). Predicting critical transitions in assortative spin-shifting networks. PLoS One *18*, e0275183. https://doi.org/10.1371/journal.pone.0275183.
40. Reisinger, D., Adam, R., Tschofenig, F., Füllsack, M., and Jäger, G. (2023). Modular tipping points: How local network structure impacts critical transitions in networked spin systems. PLoS One *18*, e0292935. https://doi.org/10.1371/journal.pone.0292935.
41. Grimm, V., and Wissel, C. (1997). Babel, or the ecological stability discussions: an inventory and analysis of terminology and a guide for avoiding confusion. Oecologia *109*, 323–334.
42. Pitoňák, M., Neslušan, M., Minárik, Čapek, J., Zgútová, K., Jurkovič, M., and Kalina, T. (2021). Investigation of magnetic anisotropy and Barkhausen noise asymmetry resulting from uniaxial plastic deformation of steel S235. Appl. Sci. *11*, 3600.
43. McLyman, C.W.T. (2004). Transformer and Inductor Design Handbook (CRC Press)).
44. Barkhausen, H. (1919). Zwei mit Hilfe der neuen Verstarker entdeckte Erscheinugen. Physik Z. *20*, 401–403.
45. Bush, H.D., and Tebble, R.S. (1948). The Barkhausen Effect. Proc. Phys. Soc. *60*, 370–381.
46. Kim, D.-H., Choe, S.-B., and Shin, S.-C. (2003). Direct observation of Barkhausen avalanche in Co thin films. Phys. Rev. Lett. *90*, 087203.
47. Takeuchi, M., Suzuki, M., Kobayashi, S., Kotani, Y., Nakamura, T., Kikuchi, N., Bolyachkin, A., Sepehri-Amin, H., Ohkubo, T., Hono, K., et al. (2022). Real picture of magnetic domain dynamics along the magnetic hysteresis curve inside an advanced permanent magnet. NPG Asia Mater. *14*, 70.
48. Mueller, B.Y., Baral, A., Vollmar, S., Cinchetti, M., Aeschlimann, M., Schneider, H.C., and Rethfeld, B. (2013). Feedback effect during ultrafast demagnetization dynamics in ferromagnets. Phys. Rev. Lett. *111*, 167204.
49. Patel, S. K., Swain, B. K., Behera, A., and Mohapatra, S. S., (2020). Metallic glasses: a revolution in material science. Metallic Glasses (IntechOpen). https://www.intechopen.com/chapters/70175.
50. Di, S., Zhou, J., Cai, M., Cui, J., Li, X., Shen, B., Ke, H., and Wang, Q. (2023). Improved ductility of annealed Fe-based metallic glass with good soft magnetic property by cryogenic thermal cycling. J. Alloys Compd. *960*, 170686.
51. Quach, D.-T., Pham, D.-T., Ngo, D.-T., Phan, T.-L., Park, S.-Y., Lee, S.-H., and Kim, D.-H. (2018). Minor hysteresis patterns with a rounded/sharpened reversing behavior in ferromagnetic multilayer. Sci. Rep. *8*, 4461.
52. Ritchie, P.D.L., Clarke, J.J., Cox, P.M., and Huntingford, C. (2021). Overshooting tipping point thresholds in a changing climate. Nature *592*, 517–523.
53. Lyberatos, A. (1999). Magnetic viscosity and the field rate dependence of the magnetization. J. Magn. Magn Mater. *202*, 239–250.
54. Vértesy, G., and Magni, A. (2003). Frequency dependence of coercive properties. J. Magn. Magn Mater. *265*, 7–12.
55. An, S.-I., Kim, H.-J., and Kim, S.-K. (2021). Rate-dependent hysteresis of the Atlantic Meridional Overturning Circulation system and its asymmetric loop. Geophys. Res. Lett. *48*, e2020GL090132.
56. Street, R., and Woolley, J.C. (1949). A study of magnetic viscosity. Proc. Phys. Soc. *62*, 562–572.
57. Nagata, T., Fisher, R.M., and Schwerer, F.C. (1972). Lunar rock magnetism. Moon *4*, 160–186.
58. Perryman, S. (2015). Geescroft wilderness accumulation of organic carbon. Electronic Rothamsted Archive, Rothamsted Research. https://doi.org/10.23637/KeyRefOAGEWoc.
59. Perryman, S., (2015). Broadbalk Wilderness accumulation of organic carbon. Electronic Rothamsted Archive, Rothamsted Research. https://doi.org/10.23637/KeyRefOABKWoc.
60. MacArthur, R.H., and Wilson, E.O. (2001). The Theory of Island Biogeography, *1* (Princeton University Press).
61. Lohmann, J., Dijkstra, H.A., Jochum, M., Lucarini, V., and Ditlevsen, P.D. (2024). Multistability and intermediate tipping of the Atlantic Ocean circulation. Sci. Adv. *10*, eadi4253.
62. Cooper, G.S., Willcock, S., and Dearing, J.A. (2020). Regime shifts occur disproportionately faster in larger ecosystems. Nat. Commun. *11*, 1175.
63. Klironomos, J.N., Allen, M.F., Rillig, M.C., Piotrowski, J., Makvandi-Nejad, S., Wolfe, B.E., and Powell, J.R. (2005). Abrupt rise in atmospheric CO2 overestimates community response in a model plant–soil system. Nature *433*, 621–624.
64. Turney, C., and Fogwill, C. (2021). The implications of the recently recognized mid-20th century shift in the Earth system. The Anthropocene Review *9*, 403–410.
65. Yan, X.-H., Boyer, T., Trenberth, K., Karl, T.R., Xie, S.-P., Nieves, V., Tung, K.K., and Roemmich, D. (2016). The global warming hiatus: slowdown or redistribution? Earths Future *4*, 472–482.
66. Wang, R., Dearing, J.A., Langdon, P.G., Zhang, E., Yang, X., Dakos, V., and Scheffer, M. (2012). Flickering gives early warning signals of a critical transition to a eutrophic lake state. Nature *492*, 419–422.
67. Buhr, L., Lenzi, D.S., Pols, A.J.K., Brunner, C.E., Fischer, A., Staal, A., Hofbauer, B.P., and Bovenkerk, B. (2024). The concepts of irreversibility and

reversibility in research on anthropogenic environmental changes. PNAS Nexus *4*, 577. https://doi.org/10.1093/pnasnexus/pgaf036.

68. Jones, H.P., Jones, P.C., Barbier, E.B., Blackburn, R.C., Rey Benayas, J. M., Holl, K.D., McCrackin, M., Meli, P., Montoya, D., and Mateos, D.M. (2018). Restoration and repair of Earth's damaged ecosystems. Proc. Biol. Sci. *285*, 20172577.
69. Wang, R., Dearing, J.A., and Langdon, P.G. (2022). Critical transitions in lake ecosystem state may be driven by coupled feedback mechanisms: A case study from Lake Erhai. China. Water *14*, 85.
70. Chaparro-Pedraza, P.C. (2021). Fast environmental change and eco-evolutionary feedbacks can drive regime shifts in ecosystems before tipping points are crossed. Proc. Biol. Sci. *288*, 20211192.
71. Lenton, T.M., Livina, V.N., Dakos, V., van Nes, E.H., and Scheffer, M. (2012). Early warning of climate tipping points from critical slowing down: comparing methods to improve robustness. Philos. Trans. A Math. Phys. Eng. Sci. *370*, 1185–1204.
72. Boulton, C.A., Lenton, T.M., and Boers, N. (2022). Pronounced loss of Amazon rainforest resilience since the early 2000s. Nat. Clim. Chang. *12*, 271–278.
73. Doncaster, C.P., Alonso Chávez, V., Viguier, C., Wang, R., Zhang, E., Dong, X., Dearing, J.A., Langdon, P.G., and Dyke, J.G. (2016). Early warning of critical transitions in biodiversity from compositional disorder. Ecology *97*, 3079–3090.
74. Wang, R., Dearing, J.A., Doncaster, C.P., Yang, X., Zhang, E., Langdon, P. G., Yang, H., Dong, X., Hu, Z., Xu, M., et al. (2019). Network parameters quantify loss of community structure in human-impacted lake ecosystems. Glob. Chang. Biol. *25*, 3871–3882.
75. Mayfield, R.J., Langdon, P.G., Doncaster, C.P., Dearing, J.A., Wang, R., Nazarova, L.B., Medeiros, A.S., and Brooks, S.J. (2020). Metrics of structural change as indicators of chironomid community stability in high latitude lakes. Quat. Sci. Rev. *249*, 106594.
76. Sharpe, S., and Lenton, T.M. (2021). Upward-scaling tipping cascades to meet climate goals: plausible grounds for hope. Clim. Policy *21*, 421–433.
77. Mercure, J.-F., Lam, A., Buxton, J., Boulton, C., and Lenton, T. (2024). Evidence if a cascading positive tipping point towards electric vehicles. Preprint at Research Square. https://doi.org/10.21203/rs.3.rs-3979270/v1.
78. Brazier, R.E., Puttock, A., Graham, H.A., Auster, R.E., Davies, K.H., and Brown, C.M.L. (2021). Beaver: Nature's ecosystem engineers. WIREs. Water *8*, e1494.
79. Zwaan, A., Staal, A., Beest, M.t., and Rietkerk, M. (2024). Widespread forest-savanna coexistence but limited bistability at a landscape scale in Central Africa. Environ. Res. Lett. *19*, 124035.
80. Thomas, Z.A., Jones, R.T., Turney, C.S.M., Golledge, N., Fogwill, C., Bradshaw, C.J.A., Menviel, L., McKay, N.P., Bird, M., Palmer, J., et al. (2020). Tipping elements and amplified polar warming during the Last Interglacial. Quat. Sci. Rev. *233*, 106222.
81. Wunderling, N., Donges, J.F., Kurths, J., and Winkelmann, R. (2021). Interacting tipping elements increase risk of climate domino effects under global warming. Earth Syst. Dynam. *12*, 601–619.
82. Kareiva, P., and Carranza, V. (2018). Existential risk due to ecosystem collapse: Nature strikes back. Futures *102*, 39–50.