**TITLE - Reconciling global tipping point theories: insight from magnetic experiments**

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**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, 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 behaviour in systems that organise 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 social-economic tipping points.**

**Keywords:** Global tipping points, climate change, abrupt change, fold bifurcation, reaction-diffusion, hysteresis, magnetic experiments, Busse balloon, Barkhausen steps, scale-dependence

**GRAPHICAL ABSTRACT**



**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 recognised by international research groups1,2, international science organisations3, and human security organisations4. In 2023, the United Nations Climate Change Conference COP28 meeting received a major report on tipping points5, that identifies more than twenty-five terrestrial and oceanic elements of the Earth system that are vulnerable to crossing thresholds towards 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 twofold: (i) recent papers outline alternative mathematical models to the classic fold bifurcation that are capable of less abrupt, spatial re-organisation as the natural response to stress6,7; and (ii) 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 ecosystems8,9,10,11,12,13,14.

Scheffer et al’s15 classic tipping point model based on the fold bifurcation (Fig 1a) applies to homogenous 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 modelled with a few coupled partial differentiation equations. The more heterogenous a system is, the less pronounced the change to an alternate state and the less lagged (hysteretic) the recovery appears16. 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 systems17. Rietkerk et al.6 and Bastiaansen et al.7 offer alternative theory based on Turing bifurcations (Fig 1b) that captures the behaviour of heterogenous 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 reorganisation 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.

Sceptical 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 uncommon10. Relatively homogenous 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 alternative state theory11 and may be linearly related to nutrient changes13. Recovery may be more linear than hysteretic8, and clear early warning signals of impending collapse seem to be the exception not the rule9.

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 each other; do they represent quite different sets of systems; or do they represent end members within a continuum of generic system-response behaviour? 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 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 vs. Turing bifurcation). In this way, we could learn much about how different types of system attribute (size, shape, structure) control generic system responses (abrupt, gradual) to different types of applied stress (magnitude, rate, frequency). Such lessons would help inform policy makers tasked with preventing tipping points occurring and, in worst case scenarios, producing strategies for recovery. But 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 behaviour 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 (Fig. 2a-c), ecosystems, such as semi-arid vegetation and peat bogs (Fig. 2d-f) and magnetic materials (Fig 2g-i). 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 works15 offered an accessible conceptual model for threshold-dependent abrupt change in systems by reference to the mathematically defined two-dimensional fold bifurcation with a ball-and-cup analogy (hereafter referred to as the classic model; Fig. 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 towards a new stable state (i.e. move out of the cup). Internally, the tipping point marks the loss of self-stabilising feedback mechanisms in favour of self-reinforcing positive feedback mechanisms with sufficient strength to drive rapid change in the whole system towards a new state or regime (i.e. the ball rolling down a slope to a new cup).

The classic model predicts two further phenomena. 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 hysteresis15. And secondly, 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 signals29. There are also modelled variants of the classic fold bifurcation related to the rate, magnitude and frequency of the applied stress30. Evidence from experimental and modelled ecosystems, and modelled networks, show that increased stress through more drivers31, higher driver rates32 or greater noise31 , and greater heterogeneity in nodal degree33 may bring the tipping point forward substantially. Where systems interact with each other 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 systems34.

The alternative theory based on a reaction-diffusion model (e.g. Turing’s activator-inhibitor principle) involve two substances or two processes that create scale-dependent feedback: short-distance positive feedback and long-distance negative feedback35. A so-called Busse balloon describes the region where multi-stable patterns exist in this alternative bifurcation diagram (Fig. 1b). Patterns in ecosystems, like striped semi-arid vegetation (Fig 2d-f), 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 heterogenous systems. The reaction-diffusion model suggests that these systems respond to lower stresses than needed to transgress a classic tipping point and also questions changing spatial patterns as evidence of approaching tipping points36,37 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, recovery6,7.

**Magnetism and tipping point theory**

The magnetisation 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) can all be used to probe system response18. Well-established theory and measurements, and new magneto-optical observational techniques38 , 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 structures33,,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 behaviours**

The response of ferromagnetic systems to stress may be mapped out as bivariate (M-H) plots (Fig. 1c) of applied magnetic field (H equivalent to stress), and magnetisation (M equivalent to system state), analogous to system bifurcation diagrams. The changes in magnetisation are the result of the minimisation 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 direction18. Magnetic materials absorb the effects of the magnetic field until the nucleation field (Hn) is reached when magnetisation begins to increase or decrease depending on the direction of the field (Fig. 1c). As the field strength increases, magnetisation changes rapidly moving through a critical point, the coercive force (Hc), where 50% of the total magnetic moment has realigned42. Systems with a single domain are referred to as ‘hard’ systems because, once magnetised, they are difficult to demagnetise. They absorb magnetisation (the stress) and remain relatively unaltered until all the magnetisation realigns abruptly. ‘Hard’ systems have relatively high Hc values displaying wide, often ‘square-shaped’, hysteresis loops (c.f. blue curve in Fig. 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 Hc values (Fig. 1c). Note that ‘soft’ behaviour 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 (Fig. 1c). This continuum of behaviour reflects the gradient between Hn and Hc (Fig. 1c) and demonstrates how rates of change may vary greatly within ‘soft’ systems (see Tables 2.2, 2.4 and 2.7 in ref. 43).

Categorisation of ferromagnetic system behaviours 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’ responses17. A third possibility, ‘linear’ change (viewed often in tipping point literature as a warning against simplistic understanding), is also accommodated through paramagnetic and diamagnetic minerals18 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’ analogy15. Thus, well mixed, homogenous systems, like small lakes, are comparable to the single domain case, displaying abrupt ‘hard’ behaviour as they pass a tipping point. In contrast, a spatially complex system, such as semi-arid vegetation, responding to external stress through spatial organisation7 would be a candidate for the multi-domain, ‘soft’ behaviour 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 behaviour. The (de)magnetisation 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 effect44,45 (Fig. 1d). The Barkhausen effect is strongest where the internal structures create a high diversity of viable domain configurations. Repeated demagnetisation of the same thin film suggests a range of Barkhausen step patterns for the same material46.. These observations bear close similarity with the Busse balloon bifurcation model for spatially complex ecosystems6 which also show sequences of steps within a zone of multi-stable parameter space (Fig. 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 (Fig. 3). When used in conjunction with ultra-modern scanning electron microscopy, novel, X-ray based, magnetic tomography techniques47 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. minimising free energy). The similarity extends to distributions of step magnitude described by positively skewed power laws48 that confirm both effects are driven by local positive feedback mechanisms. In ferromagnets, stress above Hn generates positive feedback (such as the exchange energy) which accelerates the re-alignment of domains throughout the crystal with the gradient of the (de)magnetisation curves reaching a maximum at Hc (Fig. 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 Barkhausen48 and Busse6

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 minima18. 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 (Figs. 1a and c) and well-mixed homogenous Earth systems display wide hysteresis loops characteristic of ‘hard’ behaviour.

In a ‘soft’ system, however, remagnetisation behaviour takes place at the scale of each magnetic or ecological domain rather than the system scale. Thus, each domain should be considered as 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 behaviour is observed in a simulation of the Ising model of ferromagnetism39. But 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 (Fig. 1b and 1c), until the whole system reaches a new steady state. As previously noted, ‘soft’ behaviour in ferromagnetic minerals may range widely from the classic ‘soft rounded loop’ behaviour in multidomain minerals to ‘soft square’ behaviour found in modern materials, for example in annealed metallic glasses49. Such materials allow electron spins to re-align rapidly once the magnetic stress reaches a critical level, combining the ease of (de)magnetisation of ‘soft’ systems with the abruptness of change of ‘hard’ systems.

The difference between the two ‘soft’ behaviours broadly reflects the size and number of domains, where fewer, larger domains result in extremely soft, square hysteresis loops50 (Fig. 1c). Thus, we hypothesize that in heterogenous Earth systems, a sequence, or cascade, of local abrupt tipping points represent the means by which the whole system dissipates the stress as ‘soft’ behaviour where the ‘soft’ behaviour 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 (Fig. 1c) indicative of the comparably less energy or work needed to change from, and to return to, the original state.

Laboratory magnetisation 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) magnetisation state. Minor loops occur when the field is either insufficiently large or discontinuous, to realign all the domains, or the field is reversed after Hn 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 studies51 show that reversing the field before the alternate state is reached gives rise to a narrower and shallower hysteretic loop (Fig. 4a), meaning the earlier the reversal, the easier the recovery. This effect has also been linked to slow, rather than fast-responding model ecosystems17, and to modelled global tipping points52 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 behaviours 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 (Fig. 4b). First, the rate of magnetic cycling increases, meaning the magnetic spins realign sooner. Second, the area and width of major hysteresis loops increase53,54 meaning that local domains realign at higher Hn 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 magnetisation 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 domains18. These laboratory-based findings are in accord with computer calculations and modelling experiments of climatic and ecological systems30,31,55 which 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 field18. 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 behavior56,57 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 experiments58,59. Viscous magnetic changes can also arise through random ‘thermal shocks’ that resemble colonisation events (e.g. the reintroduction of key species that went locally extinct) which in-turn can kick-start succession and a return towards the original state60.

**INSIGHT for global tipping points**

Laboratory experiments show that ferromagnets exhibit much of the general system behaviour 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 organise into discrete domains are expected to display, simultaneously, gradual behaviour when viewed at the scale of the whole system but abrupt behaviour at the scale of the local domain. Therefore, large sub-global systems with complex and heterogenous structures will, all other things being equal, collapse in real time as ‘soft’, not ‘hard’ systems6,7. 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 recognise scale-dependence in tipping point behaviour may produce erroneous assessments of the drivers, rates and consequences of global tipping points. It follows that modelled tipping behaviour 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 behaviour where modularity is high40. Thus, simple equation-based models may be a useful guide for anticipating the abrupt behaviour of small, homogenous systems but not necessarily for large, heterogenous systems where incremental or cascading behaviour is more likely. Where models have incorporated spatial dynamics, for example in intermediate complexity modelling of the Atlantic Meridional Overturning Circulation, model outputs indicate ‘softer’ multistable, rather than, ‘harder’ bistable behavior61.

**In the blink of an eye**

Abruptness (in terms of M-H loops or bifurcation graphs) refers to the angle of inflection between Hn and Hc 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 controls62. Laboratory-based magnetic experiments on rate-dependent phenomena confirm modelling experiments30,31,32,55 in suggesting 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 (Fig. 3b): they collapse the system more quickly, though not necessarily more abruptly, and may leave it with a disproportionately higher level of degradation to reverse51. 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 towards the classic model of abrupt responses between alternative system states. But, as we have shown, magnetic experiments underline earlier observations17 that relatively slow forcing in large, heterogenous 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 elements2 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-organisation. Diverse support for this view comes from manipulated ecosystem experiments showing gradual change to gradual increases in CO2 fertilisation64 and evidence that the Earth’s climate system was already shifting before the Great Acceleration of the mid-20th century65. Furthermore, the so-called ‘climate warming hiatus’ 1998-2013 may have been associated with energy redistribution (i.e. spatial reorganization) within the oceans rather than a slowdown in warming66. If verified, 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’s2 definition 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 (Hn) when ‘easy’ reversibility is probable along minor loops and the period of stronger acceleration (around Hc) when reversibility is likely to be hysteretic along major loops. In both ‘hard’ and ‘soft square’ systems, Hn and Hc are essentially coincident. This suggests that tipping point behaviour might usefully be categorised in observations or models by two key factors: the ability to absorb stress (hysteresis loop squareness, Hc/Hn) and the capacity to spatially re-organise readily (hysteresis loop hardness, Hc).

**Managed ecosystems**

A continuum of behaviour between ‘hard’ and ‘soft’ provides a framework for thought experiments about the likely behaviour of managed or engineered systems (e.g. commercial fisheries, canalised 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 freedom6,12, as expressed for example in the numbers of discrete modules, domains, or trophic levels, that will, we hypothesise, 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 which starts with incremental changes when the system is still in a relatively ‘soft’ state. The nutrient-driven degradation of the large lake Erhai in China took place over several decades prior to a final collapse at the turn of the 21st century67, giving weight to the idea that spatially organised systems may display ‘soft’ tipping points at the beginning of the stress period as well as a ‘hard’ collapse towards 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 rather than the actual potential for recovery68. 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 behaviour or not. Therefore, if some global and Earth system tipping points currently display ‘soft’ behaviour it should be anticipated they will exhibit relatively easy reversibility. Nevertheless, many attempts at active ecosystem restoration have shown that recovery is far from easy or unexpectedly slow69. 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. But this need not result in an immediate improvement of system state (Fig. 3) because degradation may continue through local feedback mechanisms until a critical level in the reversal of stress is reached that can trigger domain avalanches towards 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 state70, or the emergence of new feedback mechanisms adapted to the new external stresses63. In these two cases, active reduction of the stress, for example in the case of nutrient-enriched lakes by physically removing upper sediment layers, or a ‘shock’ intervention, for example one-time deep ploughing to break up a compacted subsoil, may be needed to return the system towards 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 down29,71 are less likely to be observed in the time series of ‘soft’ systems because the system response varies across space rather than aggregated in time6,7. Weakly linked domains in simulations of magnetic systems lose resilience and display slowing down in recovery before more strongly linked domains and the overall system are affected39. 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; although, 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 (c.f. Fig. 3). Monitoring the extent and rates of spatial organisation in global ecosystems through changing local vegetation patterns72 may therefore 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 worthwhile73,74,75.

**Positive tipping points**

Triggering tipping points to produce new desirable socio-economic states has recently become a vital topic in the quest to transform social behaviour towards decarbonisation76. 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 social-economic 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 in order to allow consumers to influence each other through their local purchasing options77. As a rule of thumb, early and abrupt change will be aided by manipulating existing systems towards ‘harder’ behaviour. 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, for example, the introduction of beavers to engineer flood controls potentially drive ‘hard impacts’ associated with rapid hydrological, geomorphological, ecological, and societal changes that both enhance flood control and the beaver habitat78.

**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 behaviour 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 representing different scales of system behavior. This implies a need to focus attention on the scale-dependency of system behaviour, 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 behaviour would not only help to identify appropriate descriptors and modelling approaches but also alleviate some of the criticism14 levelled 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 landscapes79. Our analyses also imply that ‘fast’ and ‘slow’ responding systems map well onto ‘hard’ and ‘soft’ behaviors respectively. But 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 modelling 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 heterogenous, 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 Earth’s 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 Sheets2. Yet we might also anticipate other elements with greater capacity to spatially re-organise, for example the Atlantic Meridional Overturning Circulation, to exhibit relatively ‘softer’, stepped and gradual declines61. Such a sequence of global tipping points may already have been observed within the period 130-125 ka BP during the last interglacial period80 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, this would emphasize previous arguments31,34,81 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 threat82.

In sum, when any complex adaptive system shows strong, continuous or cumulative responses to stress it means the system is no longer resilient to that stress. Negative feedback mechanisms are unable to counter the stress, the system has moved across a key threshold and resides outside its safe operating space. This marks the point at which tipping behaviour becomes possible. But, as we show here, whether or not 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 modelling these interactions in specific tipping elements should be a major scientific priority.

**RESOURCE AVAILABILITY**

**Lead contact:** Requests for further information and resources should be directed to and will be fulfilled by the lead contactSimon Willcock ([simon.willcock@rothamsted.ac.uk](mailto:simon.willcock@rothamsted.ac.uk)); Net Zero and Resilient Farming, Rothamsted Research, North Wyke, EX20 2SB, UK.

**Materials availability:** This study did not generate new unique reagents.

**Data and code availability:** There are no data nor code associated with this manuscript.

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**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.

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**FIGURES**

**Figure 1 Alternative modelled representations of tipping point behaviour compared with empirical hysteresis behaviour 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) Normalised ferromagnetic hysteresis curves (M-H) for ‘hard’ (orange), ‘soft rounded’ (purple) and ‘soft square’ (blue) hysteresis behaviour showing nucleation field (+Hn) and coercive force (-Hc) for each behaviour; d) Magnified Busse and Barkhausen steps for slopes (indicated by circles) in 1b and 1c respectively (schematic for Busse, ~108 times magnification for Barkhausen). The two solid arrows show hypothesised similarities between the classic fold bifurcation and ferromagnetic ‘hard’ behaviour, and between the Turing bifurcation and ferromagnetic ‘soft’ behaviour. (Original figure based on refs. 6, 18 and 19).



**Figure 2 Similar structural patterns across different spatial scales: global tipping elements, ecosystems and magnetic materials**. a) Ocean currents. Complex network of currents in NW Atlantic driven by the rotation of the planet20; b) Climate. Open and closed cell cloud formation over the Pacific Ocean produced by Rayleigh-Benard convection cells21; c) Ice sheets. Antarctica’s Larsen C ice shelf showing stress fractures22; d) Arid land. Tiger bush area in Niger with typical patterned vegetation23; e) Permafrost. Tundra polygons produced by freezing and thawing cycles24; f) Peat bog. Striped vegetation patterns in a peat bog within Yuganskiy Nature Reserve, Russia, formed by rows of dwarf Scots pine with intermediate wet Sphagnum glades25; g) Bismuth-iron garnet. Magnetic stripe domains in a thin epitaxial layer of bismuth-iron-garnet imaged by Faraday rotation26; h) Neodymium magnet. Magnetic material NdFeB under a Kerr-microscope showing the magnetic domain structure within microscopic crystal grains27; i) Steel. Magnetic domains and domain walls in electrical steel28. All scales a)-f) approximated from Google Earth. (Photos a) and b) courtesy of the National Snow and Ice Data Center, University of Colorado, Boulder, photo c) courtesy of Nathan Kurtz/NASA Operation Ice Bridge, and photos d),e), and f) under various licenses within the WikiMedia Commons).



**Figure 3 Changes in the microstructure of domain alignment driven by an external field.** Cutaway 3D scanning electron microscope images of magnetic domain structure as observed in a Nd-Fe-B magnet at different external fields (*H*) at different points along the magnetisation (*m*) curve (black dots and line) from positive to negative saturation. The changing colours 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 -2.6T. (Reproduced from Fig. 2c in ref. 47 under a Creative Commons license [http://creativecommons.org/licenses/by/4.0/](https://eur03.safelinks.protection.outlook.com/?url=http%3A%2F%2Fcreativecommons.org%2Flicenses%2Fby%2F4.0%2F&data=05%7C02%7CJ.Dearing%40soton.ac.uk%7C528a4c32dc2a4310337708dc3ce48de1%7C4a5378f929f44d3ebe89669d03ada9d8%7C0%7C0%7C638452199545265476%7CUnknown%7CTWFpbGZsb3d8eyJWIjoiMC4wLjAwMDAiLCJQIjoiV2luMzIiLCJBTiI6Ik1haWwiLCJXVCI6Mn0%3D%7C0%7C%7C%7C&sdata=aYu9Ap1mhQ1trkHU8n%2FbM4TAWInnxdDAPxKrypwhD%2F4%3D&reserved=0)).



**Figure 4 Hysteresis behaviour in a (CoFeB/Pd)4 multilayer film as a function of field magnitude and rate**. a) Major and minor loops of magnetisation (M) plotted as a function of the magnitude of the field (H). The major magnetisation loop (i) shows symmetry between forward and reverse fields indicating complete saturation and alignment of all magnetic domains. Reversing the field application before saturation (-Ms) 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 (triangle symbols) to 6.25 Oe/s (dot symbols) to 62.5 Oe/s (square symbols). The hysteresis loops widen as the field rate increases but the time taken for the magnetisation 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 Fig. 2 and Fig. 5 in ref. 51 under a Creative Commons license [http://creativecommons.org/licenses/by/4.0/](https://eur03.safelinks.protection.outlook.com/?url=http%3A%2F%2Fcreativecommons.org%2Flicenses%2Fby%2F4.0%2F&data=05%7C02%7CJ.Dearing%40soton.ac.uk%7C528a4c32dc2a4310337708dc3ce48de1%7C4a5378f929f44d3ebe89669d03ada9d8%7C0%7C0%7C638452199545265476%7CUnknown%7CTWFpbGZsb3d8eyJWIjoiMC4wLjAwMDAiLCJQIjoiV2luMzIiLCJBTiI6Ik1haWwiLCJXVCI6Mn0%3D%7C0%7C%7C%7C&sdata=aYu9Ap1mhQ1trkHU8n%2FbM4TAWInnxdDAPxKrypwhD%2F4%3D&reserved=0) ).



**TABLES**

**Table 1 Equivalence and similarities between magnetic and large-scale global or ecological systems**. Well-known ecosystem attributes and characteristics41 such as stress, hysteresis and disturbance all have direct magnetic equivalents. Conversely, the major facets of ferromagnets18 such as magnetisation, susceptibility, hysteresis, coercivity and viscosity have counterparts in ecology.

|  |  |  |  |
| --- | --- | --- | --- |
| **Magnetic materials** | **Magnetic symbol and Unit** | **Large-scale global or ecological systems** | **Descriptor or example of ecological process or variable** |
| Time | t (Seconds) | Time | Time scale |
| Magnetisation | 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 | Hn (Tesla) | Threshold point | Point at which structural change starts. |
| Coercive force | Hc (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 (*μ*m) | Discrete self-sustaining zone | Measure of system heterogeneity or patterning (e.g. vegetation mosaic of humid temperate heathlands) |
| Viscosity | δM/δt | 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 | δH/δt | 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 | ΣΔM | Busse balloon steps | Changes in ecosystem structure (e.g. sequence of vegetation patches in dryland ecosystem with lower or higher moisture). |