SYNTHESIS REPORT

Environmental tipping points and food system dynamics: Executive Summary

Global Food Security

Sustainable, healthy food for all

This report originates from an inter-disciplinary and inter-sectoral working group of academics and industry experts tasked with examining environmental tipping points and how they interact with food system dynamics. The working group was led by the UK's Global Food Security programme.

This executive summary report has been produced to complement the full report, Environmental tipping points and food system dynamics: Main Report. This report is for stakeholders in the food system that have an interest in risk management. This includes the agri-food industries, as well as investors and (re-)insurance, and academic and policy communities.

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Key findings

- Environmental tipping points occur when there are step changes in the way the biophysical world works – whether loss of soil fertility, collapse of a fishing stock, or sudden changes in weather patterns, such as those that caused the grasslands in North Africa to become deserts, 6000 years ago. These non-linear shifts arise following a critical degree of change, resulting from either many small cumulative changes or one large shock, "tipping" the system over a threshold and into a new stable state. Entering an alternative stable state is associated with a change to system function, usually being difficult to reverse or "tip" back into the original state. Increasingly we recognise that human-environment interactions are affecting the likelihood that critical thresholds for tipping points will be crossed, leading to step-changes in the provision of environmental goods and services, and impacting upon food security.
- This report provides evidence that tipping points in environmental systems do occur and that they could have significant effects on food security. Agri-food systems rely on the maintenance of function of a wide range of supporting systems (soil, water, climate, as well as biodiversity-related services like pollination and natural pest suppression); sudden changes in function associated with tipping points in climate, weather, soil health or biodiversity may have profound effects, at least at some scale.
- Extreme events – such as widespread droughts - in the natural environment have been shown to perturb our globally interconnected food markets, and have contributed to food price spikes (in combination with other factors such as export restrictions). Crossing an environmental tipping point has the potential to contribute to market effects in a similar way, but with the perturbation being long-lived or even permanent. Even "local" tipping points (for example the possibility of a dustbowl in East Anglia or a fisheries collapse) can contribute to supply shortfalls and have potential to prompt food price spikes. Global scale tipping points such as collapse of the Atlantic Meridional Overturning Circulation could permanently change supply in an unprecedented way, through harsher winters and a strengthening of the winter storm track across the UK and Western Europe, together with hotter, drier and less windy summers.
- Economic systems are like natural systems in having feedback loops, non-linear behaviour and tipping points. We do not currently know enough about the interaction of biological and socio-economic systems to know whether they will amplify or dampen each other's tipping points. The present paradigm that trade is typically beneficial is based on the assumption that an open trading system will dampen shocks, and this is true for small shocks. But as potential shocks - from evolving weather and potential tipping points - increase in magnitude, frequency and longevity, the confidence with which this assumption is made may be tested. More research is needed to better understand the risks.
- One potential early warning indicator of an approaching tipping point is increasing volatility, as behaviour of the system "flickers" close to tipping and prior to a permanent change to a "new normal". More research is needed to be able to characterise and anticipate the reaching of critical thresholds in ways that are trusted enough to prompt action.
- If predictions about critical thresholds and when we might cross them are trusted, the pathways to mitigate crossing the tipping point are understood (for example, avoiding over-fishing, or improving soil health or de-carbonising the economy), and public policies do not distort market responses, then an environmental tipping point could lead to a smooth market response and no price spikes in food.
- However, the market does not often work to "perfectly price" and governments do intervene in ways that distort market responses (such as reducing exports during a food price spike). There is a clear need for the potential risks of crossing tipping points to be understood more widely, and for consideration of potential actions to mitigate and adapt to these.
- It may be possible to undertake an in-depth cost-benefit analysis. This might inform whether adapting to a "new normal" or mitigating the tipping point in advance of crossing it is economically preferable. However, many of the options are deeply political, or geo-political, in nature and it may be that the actions taken are not those predicted by a cost-benefit analysis.

Summary

The term “food system” encompasses the entirety of the production, transport, manufacturing, retailing, consumption, and waste of food, as well as their collective impacts on nutrition, health and well-being, the environment and, ultimately, global food security. Most countries’ food systems are highly complex, reflecting the interplay between locally produced and imported food, serviced by increasingly complex globalised trade networks. If the market works, a shortfall in production – such as created by extreme weather - creates a price signal that helps the global system respond by increasing production and buffering the shortfall. However, depending on a range of interacting factors (policy interventions, stock-to-use ratios, severity of perturbation), this price signal can be amplified and create a global price spike that will have negative impacts on the local and global poor, far away from where the shock originated. Reliance on global markets carries a systemic risk to perturbations wherever they may arise (Centeno et al., 2015; Puma et al., 2015). The risk of such market malfunction may well be proportional to the size of any initial supply shortfall.

An extreme weather event may create a production shock, but, all things being equal, it will be temporary as the system returns to its pre-disturbance functioning. A resilient system is one where functional variables may vary, but essentially, they remain within “normal” bounds. However, under some circumstances, the system may not return to how it previously worked.

Environmental tipping points occur when there are step changes in the way the world works, such as through loss of soil, as happened in the 1930s US Dust Bowl, collapse of a fishing stock, or sudden changes in weather patterns. Tipping points may be precipitated by a gradually changing driver – for example, CO2 levels, nutrient enrichment, biodiversity loss – passing a critical threshold which causes the transition from one system state to another and a sudden change in the provision of environmental goods and services. This switch to a “new normal”, the alternative stable state, is difficult to reverse. For example, if a lake is gradually enriched by agricultural pollution, it may suddenly change from clean water to turbid. In this case, a small reduction in nutrients will reduce the nutrient load to below the “forward critical threshold” but will not change the water back to clear. The “backward critical threshold” requires that nutrients have to be reduced to very low levels before the system can “tip back” to the clean state.

Near a critical threshold, tipping points can be provoked by perturbations that the system would otherwise be resilient to.

We typically think of the world as linear; “linear thinking” can be characterised as (a) “small, incremental changes have small incremental effects” and (b) “it is as easy to move backwards and restore system functioning as it is to move forwards and reduce system functioning”. Tipping points are an example of the consequences of living in a non-linear world; it is possible incrementally to drive a system – perhaps through increasingly intensive farming - that suddenly switches from one state to another, from which it is difficult to recover. Currently, the existence of, and proximity to, tipping points is difficult to predict, and, because of the complexity of human-environment interactions and the potential scale and magnitude of effects, difficult to mitigate or adapt to.

Are tipping points really worth worrying about?

In the literature there are many examples of tipping points (also called regime shifts) between stable states in environmental and socio-environmental systems (Beisner et al., 2003; Scheffer and Carpenter, 2003; Walker and Meyers, 2004). They include events like the mid-West Dustbowl, desertification through over-grazing, over use of ground water in irrigation, forest clearing driving local climate change and causing a “switch” from forest to grassland, and regional collapse of agriculture through shifts in climate, leading to socio-economic collapse.

Most examples of tipping points have impacted only at a regional or local scale. However, future tipping points may have increasingly global impacts for two reasons. Firstly, climate is a global system, and perturbations to normal functioning (such as the El Niño) can have very widespread consequences; for example, increasing greenhouse gases in the atmosphere has the potential to create tipping points (Hughes *et al*., 2013; Lenton and Williams, 2013). Likewise, the gradual warming and acidification of the oceans could lead to a global collapse in coral reef ecosystems. Secondly, our world is increasingly interconnected through movement of people, trade and technologies (Hughes et al., 2013), for example, facilitating the spread of a pathogen attacking a common crop plant (such as UG99) (Singh *et al*., 2011); or intensification of agricultural production worldwide causing widespread and simultaneous soil degradation.

Considering the risks for food systems

For food system resilience, tipping point risks are growing in importance because:

- The world is shifting through climate and environmental change. Global intensification results in greater yields coming from the same land, and at the same time, widespread degradation of soil and biodiversity. This may be driving the system towards critical thresholds. Similarly, increasing greenhouse gas emissions may risk climate tipping points.
- The world’s weather is changing and what was once extreme weather is becoming more common. This means there is potential for environmental perturbations to the agri-food system to become larger.

- In the past, an excess of land, water and resources ("biophysical redundancy") could buffer countries against global perturbations to their food supplies. This is no longer necessarily the case. Furthermore, if trade interconnects every country, a large enough perturbation in one place, could lead to the over-amplification of price signals with impacts across the world. A new dust bowl event, affecting long-term yields in a breadbasket region, could have consequences for us all.

Such tipping points are not flights of fancy. A recent review of the outputs of the family of climate models run under future emissions scenarios by the Intergovernmental Panel on Climate Change (IPCC) community, shows a significant number of occasions of abrupt and non-linear changes in climate and weather systems (Drijfhout et al., 2015). Were such a sudden change in weather patterns to occur, how would our food system respond? If we can predict such an event happening decades in advance, could the market respond to prevent it, or at least lessen its impacts, and what help would be needed from policy? How can we avoid an environmental tipping point leading to a step-change in an important food-system variable (such as price or availability)?

There is evidence that tipping points exist, and we therefore use a set of case study scenarios to unpack how they may relate to food system functioning. Our case studies include:

- an example of a historical event (collapse of the Newfoundland cod fishery),
- two events that may currently be happening (soil salinization in the Mekong delta, aridification in California), and
- two plausible events that could happen in future (a dustbowl in East Anglia and a big climatic shift occurring with the loss of the North Atlantic's overturning circulation)

For each, we discuss whether crossing the critical threshold would affect important aspects of the food system (for example creating food price spikes, or the undermining a region's agricultural economy), and the ways this could be avoided. In particular, we consider if the market could become aware of such tipping points and if it would have appropriate mechanisms with which to respond. The plausible examples we explore in some detail in terms of thinking about mitigation and/or adaptation strategies (Box 1, 2). Whilst Box 1 explores the potential for a localised dust-bowl, Box 2 explores the consequences of a climatic tipping point that would have very widespread and severe consequences.

Risk management and tipping points

Acknowledging the potential of large and unprecedented changes is perhaps the most important, and initial, step in thinking about, and managing, the risks from non-linear events such as tipping points. Is it possible for the rains to change? Is it possible for soils suddenly to lose functionality? Is it possible for climate to switch? Is a new disease likely to emerge? What happens if pollinator populations suddenly collapse?

We have developed a framework for thinking about managing tipping point risks (Fig 1). Does the threshold Exist? What is the Threat? What is the Trajectory towards the threshold? What are the Alternatives? We term this the "ETTA" framework, and it can be articulated through the following sequence of questions:

1. Does a tipping point exist for the system in focus? In other words, is it possible that gradual change – in connectivity, degradation, emissions, biodiversity loss or exposure to changing weather – can lead to sudden changes in function?
2. If so, where is the system now relative to the tipping point?
3. What is the trajectory and rate of approach to the tipping point?

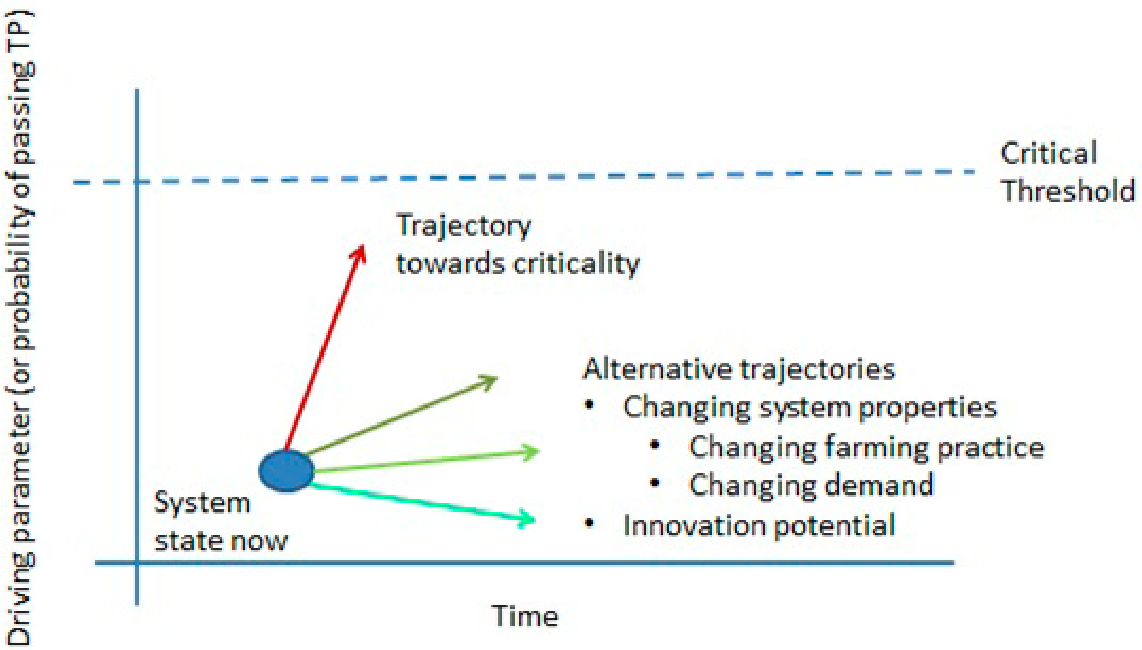

Figure 1. The "Existence, Threat, Trajectory, Alternatives" framework for thinking about critical thresholds.

4. What is the cost of passing the tipping point?
5. What alternative trajectories are available (such as through changing farming systems or emissions or trade)? What are the direct and indirect costs associated with different trajectories? How long do we have to move between trajectories? When do those options close down?

If we have these elements of knowledge, the market, in combination with policy has the potential to price in the costs of crossing the tipping point and the losses caused (including the need for adaptation), or alternatively it can price in positive actions to ensure the trajectory towards the threshold is avoided.

Forecasting the proximity to a tipping point

The behaviour of many complex systems is known to change as they approach a tipping point. Typically, the way the system interacts with random events (such as weather), generically termed "noise", changes as it approaches a tipping point. Away from a tipping point, noise may simply create "normal variability" in the functionally of important variables; but, as the system approaches the tipping point, the volatility of the system may increase, consistently or intermittently (so called "flickering") (Greenman and Benton, 2003; Scheffer *et al*., 2012; Wang *et al*., 2012). The variability of the system, as well as generally increasing, may change its properties, usually by "slowing down" – so instead of varying above and below the average from time step to time step, the system spends more time on one side or other of the average (Lenton, 2011; Scheffer *et al*., 2012). Therefore, increasing volatility – as well as creating negative impacts in its own right – can signal the nearness of a critical transition.

Given that environmental variability, which affects many aspects of the agri-food system, is also likely to increase due to climate change's impact on weather, the risk of a tipping point being passed also increases. Actively tracking the environmental variability affecting a system and the volatility of the system's response may be increasingly important for diagnosing tipping point risks.

In addition to signals arising from the systems' dynamical behaviour, biophysical measurements can indicate detrimental changes in a system e.g. decreasing soil carbon or soil depth, decreasing abundance in biodiversity of pollinator communities, increasing nutrient quantity of water bodies. However, they do not indicate the existence of, or closeness to, a boundary. Such state variables therefore do not necessarily prompt action.

Model-based predictions of tipping points are possible, but when a decision is costly, a forecast will be valued only if it is perceived to be trust-worthy. If a model is predicting repeated events, the model can be developed iteratively and "earn" trust (e.g. the skill of weather forecasting is constantly being improved as it is tested daily). However, for prediction of single, high-impact events, this clearly presents an issue since a model's performance at predicting tipping points cannot be fully assessed until the event happens (or not).

If we know we are heading for a tipping point, what might we do differently?

If we know – or suspect – that we are heading towards a tipping point, the ETTA framework (above, Fig 1) suggests it is necessary to assess the costs, benefits and potential of doing things differently. If there are no feasible alternative trajectories, then efforts can be made to adapt to the likely change in function through the market pricing in the costs of adaptation (e.g. through insurance, or designing in resilience into the socio-economic system). If alternatives are available, policy and market actors have the potential to stimulate a switch from "business as usual (BAU)" to "business unusual" in order to avoid passing the tipping point. This could be through pricing the damages created on unmitigated pathways or pricing the adaptation costs to avoid an outcome. Whilst these are theoretically similar, there may be good reason to base valuations on mitigation cost[1].

Given trusted and transparently available information, the market may partly respond, though the extent to which this occurs will depend on the extent to which externalities are present. If externalities are prevalent, as they typically are in the case of environmental concerns, then information alone is not sufficient. Public policy levers may be needed to ensure that the market responds appropriately (whether these are regulatory or incentivising public investments looking for innovative solutions from research). In addition, consumers are ultimately a determining force in the functioning of the food system. Whilst consumers may be price-sensitive, if low prices inflate the chance of a tipping point (which may in turn increase future prices, along with other indirect effects, such as geo-political destabilisation), consumers may become more willing to accept changing prices if these act to prevent the tipping point occurring (Bailey et al., 2014). Thus, an important route for stimulating and supporting market change is through dialogue with the public about how their individual actions can help: "conversation science".

It is likely that all three areas will be needed if the externalities are large: engagement of citizens and consumers, market responses and policy interventions.

To unpack "what might we do differently" a little more concretely, we take two plausible future tipping points and discuss application of the ETTA framework (see Boxes 1 and 2).

1 E.g. https://www.gov.uk/government/publications/carbon-valuation-in-uk-policy-appraisal-a-revised-approach

What would we do differently: case study scenarios

BOX 1: Case study 1– A potential East Anglian dustbowl as a local example.

Existence of tipping point: Intensification of agriculture has significant impacts on soil: creating substitution of carbon-based, organic, nutrients with synthetic ones; loss of biodiversity; loss of structure; and increased erosion risk. At the same time, drought risk is changing as the climate changes. Erosion risk can be over 6000 times greater in drought conditions than non-drought conditions.

Threat from the tipping point: A worst case scenario would be a significant erosion event (or sequence of events) removing large amounts of soil (reducing agricultural productivity, land values and causing change in cropping– such as switching from root vegetables to wheat). This would affect the local agricultural economy (and its labour needs), both in the short and long-term. As well as farmers, who have degraded the soils, suffering a cost, the transport of soil off the farm imposes costs on others. Dust suspended in the air-column may have significant short-term economic impacts (including on health and transport). Larger soil particles can be deposited against fences (blocking roads) or in watercourses, creating siltation, blocking drains, and impacting flood risk.

Trajectory: Increasing agricultural intensification, coupled with climate change, puts us on a trajectory towards greater erosion risk through drought and loss of soil structure. Although it would require new research to quantify the risk of an East Anglian Dustbowl, policy pressure to further intensify production without mitigating loss of soil condition would almost certainly accelerate the trajectory.

Alternatives to BAU: Alternative trajectories are immediately available. Graves and Morris (2013) developed a model to estimate the rate of loss of peat and carbon for a range of climate change and land use scenarios (continued intensive arable, degraded arable, conservation grassland, and peatland restoration). They did not consider the sudden costs imposed by a dustbowl event. Nonetheless, from a farmer's financial perspective, the income stream associated with continued agricultural production scenario was much more profitable than that associated with peat conservation or peat restoration scenarios. However, when the non-market externality of continued degradation of soil carbon was factored into farm incomes, the continued arable production scenario created the largest net loss. The present value benefits for the peat restoration and peat conservation options, whilst lower in terms of agricultural income, were associated with the greatest total value when the cost of carbon emissions were also included. Whilst this "dustbowl" is a plausible scenario, quantifying the risks needs research. Given a sufficiently strong evidence-base, there could be explicit and public agreement of the need to manage the fenland soils for the long term. This could be incentivised via a number of potential market and policy routes, for example:

- Through agri-environment schemes to compensate farmers for the lost income arising through alternative soil management.
- For land and business valuations, including insurance, to reflect unsustainable management through changing prices or investment opportunities
- Government could create a Pigovian tax –which taxes an action that creates an external cost to the same as the cost of the externality - to dis-incentivise unsustainable soil management.
- For there to be clearer signals from the (re)insurance markets on likely timescales until insurance becomes unaffordable/ unavailable (where the risk in any given year that the tipping point will be breached becomes too high for an insurance product to operate).
- Through addressing the "Principal-Agent problem" in short-term leases. This occurs when a tenant, on a short lease, is not interested in the value of the land, only the revenue extractable from it. The land agent is interested in maximising the income for the landowner, which, through self-interest, may not fully price in the cost of maintaining the soil carbon stocks. Addressing this might require prescriptions within tenancy about good stewardship.

Of course, many issues exist beyond pure cost-benefit analysis that may impact the decisions taken above and the exact solutions implemented. For example, the social aspect of reclaiming land or changing its function is highly political. Farm labour, which could be adversely impacted by such interventions, is also highly political given the dependence on foreign labour for some farming practices.

BOX 2: Case study 2 – A climatic tipping point: collapse of Atlantic Meridional Overturning Circulation

Existence of tipping point: A potential future climate tipping point is the collapse of the Atlantic Meridional Overturning Circulation (AMOC). This branch of the global ocean's 'conveyor belt' circulation transports heat from the tropics northeast towards Europe. The only place globally that is not warming is a "cold spot" in the NW Atlantic, linked to an observed weakening of the AMOC. As climate change continues, models project further weakening of the AMOC, including a potential shut-off of deep convection in the Labrador Sea, and, in more extreme scenarios, a complete collapse of the overturning circulation. This could occur over a timescale as short as a decade. Some of the key impacts of AMOC collapse would be on global food systems, and their impacts would be a significant reason for action.

Threat from the tipping point: The physical climate impacts would affect (at least) Europe, Central and South America, Sub-Saharan Africa, and India. Potential impacts on the global food system include a reduction in EU yields of approximately 30%, 10% of losses in rice yields in India, reduction in soya and sugar production in Latin America, and eliminating the potential to produce food in large parts of the Sahel. This would amount to a potentially rapid, global decline in productivity of the order of tens of percent, which would have no historical analogue. Unprecedented global losses in production are likely to lead to unprecedented policy and market responses, leading to price spikes significantly greater than have been seen. Looking across the whole economy, AMOC collapse could cause a 25-30% reduction in global GDP (akin to the Great Depression but permanent) (Nordhaus and Boyer, 2000). The prospect of an order of 10% irreversible reduction in global GDP is sufficient to radically change the outcome of cost-benefit analyses (Cai et al., 2015; Lontzek et al., 2015).

Trajectory: Global GHG emissions are increasing and current trajectories are on-course for around 4 degrees of global warming by the end of this century (and more warming thereafter), so the risk of AMOC collapse is increasing for the near future. The probability of an AMOC collapse by 2200 is about as likely-as-not (i.e. approximately 50%) if we continue on our present (high warming) trajectory (Kriegler et al., 2009), and, of course, while less likely, but it could start over the next few years. On the centennial timescale, if there is no decisive action to limit global GHG emissions, AMOC collapse is not a "high impact-low probability" event, it is a "high impact-high probability" event.

Alternatives to BAU: There are alternative trajectories with different outcomes, attendant costs and benefits. For example, if global warming is limited to less than 2 degrees Celsius, the risk of AMOC collapse by 2200 drops to approximately 10% or less. The agri-food system accounts for about a third of global GHG emissions, so low-carbon approaches here could support this alternative trajectory.

The agri-food system accounts for about a third of global GHG emissions, so low-carbon approaches here could support an alternative trajectory. Furthermore, achieving a low-carbon

trajectory (and avoid AMOC collapse) may require significant land and water resources for 'biomass energy with carbon capture and storage' (BECCS), reducing resources for agriculture. Thus, the global agri-food system has a key role to play in determining whether AMOC collapse occurs, as well as suffering key impacts if it does occur. Reducing carbon-intensive food in diets has considerable potential leverage in reducing GHG emissions (Bajzelj et al., 2014; Hedenus et al., 2014; Bryngelsson et al., 2016). This may need carbon pricing on food to reflect the true cost of the externalities caused by food.

If action is too late or insufficient to avoid AMOC collapse, then the costs become those of adapting to its consequences. If adaptation does not occur until wide-scale losses are occurring then the market response will lead to price being a rationing mechanism. The impact would therefore be greatest on the poor: the global poor, especially in import-dependent sub-Saharan African countries, and the local poor in every country. This would clearly represent a market failure.

In general, the prospect of an approaching tipping point should lead to precautionary investment to help mitigate and smooth over the step-change (van der Ploeg and de Zeeuw, 2014). What these should be is open to question: for example, global stock piles of food may help mitigate production impacts, but would be very expensive.

As, and when, increasing evidence for the likelihood of AMOC collapse is gathered, the finance community should start to build in the downside risks of such an event into its evidence base. There is likely to be a tipping point in the finance sector when this risk is perceived as real. Particularly for AMOC collapse where the risk is a significant loss of global GDP, the risks to investment and the normal functioning of financial markets are so large that this tipping point in the socio-economic system is likely to be significant, at least in the short-term.

What are tipping points?

A "tipping point" or "critical transition" occurs when a particular system experiences a shift from one stable state to another, thereby altering its function. In order to make this shift, a critical degree of change, either resulting from many small cumulative changes or one large shock, is necessary to "tip" the system over a threshold and into its new state. Such shifts are often described as "step-changes" as they deviate from the linear way we might usually expect a system to behave - small, incremental changes having small incremental effects. An example of linear behaviour is gradual soil degradation over time; an example of a step-change (tipping point) is a sudden substantive loss of soil function, for example the US dustbowl.

A system is resilient if it can withstand a great deal of change, or a large shock, and still remain in its original state. Resilience is determined by the different variables within the system; for example, in an agricultural scenario, these variables may be soil quality and climate, with high quality soil and an advantageous climate making crop yields more resilient to any potential shocks.

Once a tipping point has been crossed it is typically difficult to revert the system back to the original state, requiring a similar critical change to be applied in the opposite direction before a reversal may be possible. While a system moving into a new state is not inherently a bad thing, tipping points occurring in biophysical systems have the potential to significantly change how humans interact with that system. For example, environmental tipping points have the potential to bring about step-changes in the provision of environmental goods and services, which in turn could have profound effects for global food production. It is therefore critical to understand how food systems are impacted by environmental tipping points, especially as the global population grows and food demand increases.

To put this in context, imagine a farmer's field, growing a single crop. Over the years, intensification of farming has led to increases in yields, with weather typically driving variation around this trend, but, on average, yield variation is manageable relative to what is expected. The system is quite resilient, and the farmer can plan their operations because they understand this variability. However, imagine if, over time, agricultural intensification has gradually broken down the structure of the soil making it less stable to weather; and, at the same time, climate change is causing an increase in extreme rainfall events. Under these circumstances the resilience of the system has been compromised, and it is possible to imagine an intense rainfall event capable of washing soil away to the extent that yields are permanently affected. This would be a prolonged change as it might take decades or hundreds of years to replenish the soil[2]. This would be a "tipping point" or "critical transition" creating a step-change in system function.

2 Land prices in 1930s "Dustbowl" counties remain depressed to this day.

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