SYNTHESIS REPORT

Environmental tipping points and food system dynamics: Main Report

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 main report is accompanied by an executive summary report, Environmental tipping points and food system dynamics: Executive Summary. 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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Contents

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.

Introduction

What is this report about?

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 move biophysical systems into a new stable state and a new way of functioning, often 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. However, these thresholds may be difficult to predict, and, because of the complexity of human-environment interactions, difficult to mitigate or adapt to due to their unpredictability, scale and magnitude. Despite this, there is significant need to understand and manage any tipping point and the associated environmental change as this could have profound effects for global food security, especially as the global population grows and food demand increases. It is therefore critical to understand how food systems are impacted by environmental tipping points and what options exist to mitigate these risks at global to local levels.

This report considers whether tipping points, if passed, might affect the food system, through changing prices, social transformations, and availability, thereby undermining progress towards food security. We suggest that the potential consequences of passing tipping points is not receiving the attention it needs perhaps because (a) the science is uncertain and they seem too "unlikely", or because the hazard seems regionally localised, so the risk to the global food system is judged to be low. We explore these issues and highlight the growing evidence for the existence of tipping points. Given the global interconnectivity of climate, and the associated global-scale risks associated with climate change, coupled with the increasing connectivity of the global food system, tipping points may present a real risk to global food security. We then explore potential solutions to reduce the hazards identified through market- and policy-based mechanisms.

For whom is this 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. This report emerged from an inter-disciplinary and inter-sectoral working group, and part of our aim is to encourage disparate academic as well as policy and business communities to appreciate the interplay between the non-linear dynamics of biophysical systems and the socio-economic systems that underpin societal health and well-being.

Food systems and shocks

The term "food system" encompasses the entirety of the production, transport, manufacturing, retailing, consumption, and waste of food, and their impacts on nutrition, health and well-being and the environment (Fig 1). For most countries in the world, the food

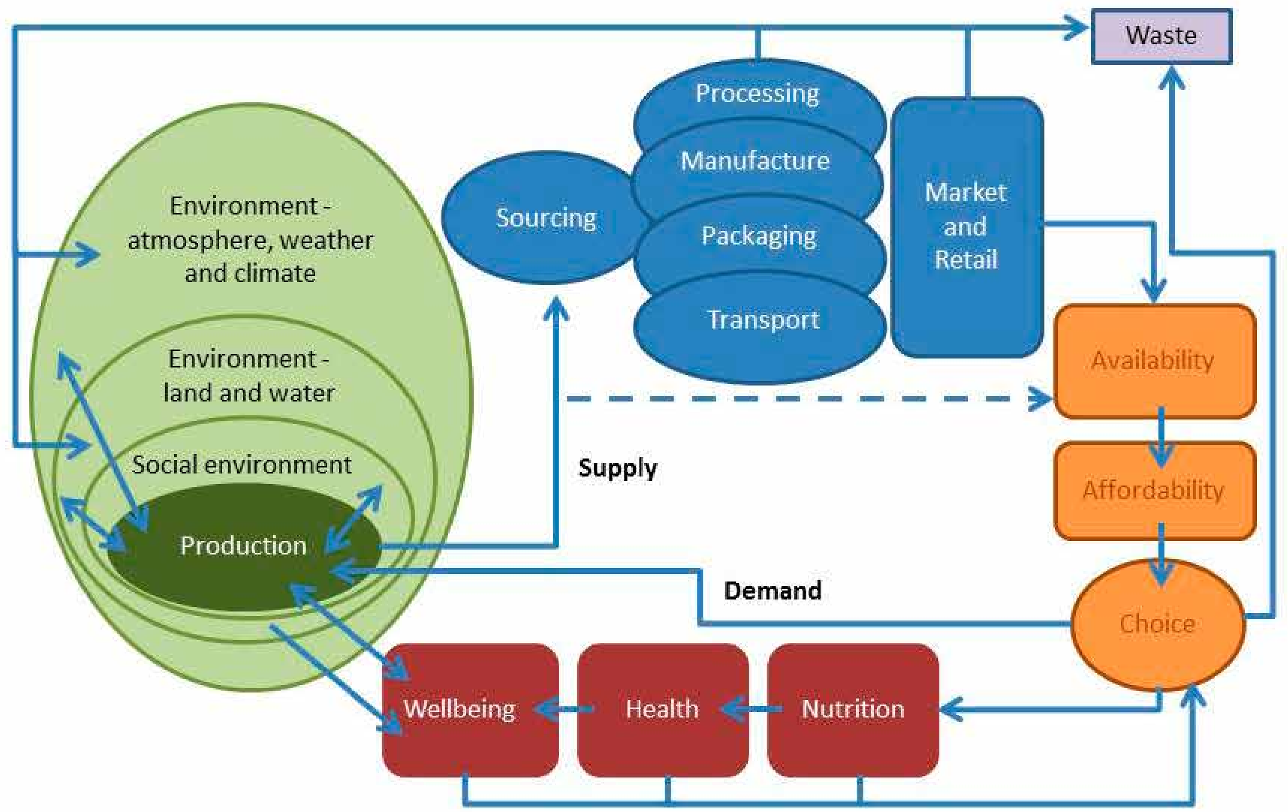


Figure 1. A representation of "the food system".

system is highly complex. For example, the UK imports food from 168 countries (about 85 % of the world's countries) (Defra, 2012), and in total, over half of the UK's food-and-feed requirements are met from imports. If the total area required to grow crops for the UK food system is estimated, over two-thirds of our land footprint is overseas (de Ruiter *et al*., 2016).

Whilst there is a very large diversity of produce from agriculture, there is a concentration of production into a relatively small handful of commodity crops. Over 85 % of the world's calories come from wheat, rice , maize, sugar, barley, soy, palm, and potato (Cassidy *et al*., 2013), which are geographically concentrated in a small number of regions (Foley et al., 2011). The concentration of commodity crops into a relatively few, highly productive, regions leads to international trade networks that are growing in complexity as volumes of trade increase (Fig 2) (Puma *et al*., 2015).

The food system today, therefore, is highly global and increasingly complex (Puma et al., 2015). As food production requires land, water, labour, and infrastructure (MacDonald et al., 2015), a perturbation to any of these can affect the network of trade and, depending on a range of interaction factors (policy, stock-to-use ratios, severity of perturbation, poverty and vulnerability), can propagate through the system and ultimately change prices over the world. Whilst price changes can be beneficial in signalling the need for compensatory changes in production, price changes that markedly amplify the price signal can have negative local and global consequences, particularly affecting poor people and also the environment through increasing agricultural production more than is required[1] (Puma *et al*., 2015; Tamea *et al*., 2016).

A globalised trading system is often seen as beneficial. Each country can produce what they excel at, exploiting their own comparative advantages, export any surplus, and use that revenue to import what they do not produce. It also increases the resilience of the whole system to small perturbations: a loss in one region can be compensated for by a surplus in another delivered through the market. Local food security[2] depends on a complementary interaction between local and international production but crucially with the market operating efficiently. However, as was seen with the food price spikes last decade, it is possible for the market to amplify supply-side worries (through a range of mechanisms) which can lead to significant and untoward outcomes as rapid price rises may act as a risk multiplier. This may lead to reduced availability of food, especially for global and local poor, and potentially to increasing hunger or food poverty and their associated problems. Rapidly rising prices can also destabilise fragile national economies. Reliance on global markets can thus carry a systemic risk (Centeno et al., 2015; Puma *et al*., 2015). The risk of such market failure may well be proportional to the size of any initial supply shortfall.

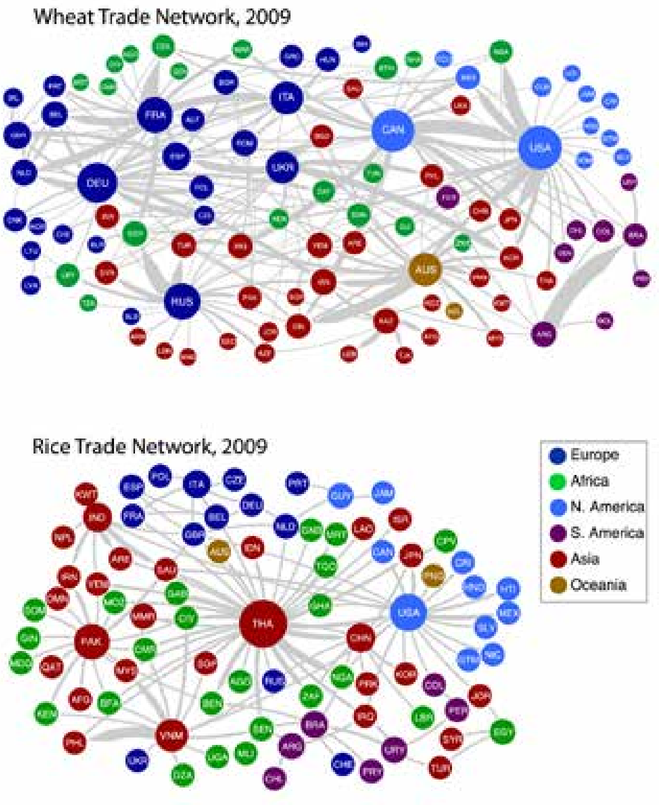


Figure 2. Representations of the international trade networks for wheat (top) and rice (bottom). From Puma et al. 2015.

Markets are supposedly designed to enable demand and supply to reach equilibrium via changing prices. The responsiveness of price is thus important in signalling the need to increase or reduce production. However, when events interact (e.g. a perturbation, low stocks, and geo-political instability) it is possible for markets to over amplify the demand-supply imbalance and not reach equilibrium. Given the systemic risk associated with the amplification of price spikes it is important to consider the food system's resilience to perturbations wherever and whenever they happen: will a perturbation, especially a large-scale one, create market failure as well as induce further social inequality?

In recent years, there has been consideration of the role of weather in creating perturbations to the food system[3]. An extreme weather event may create a production shock, but, all things being equal, it will be temporary. Another form of perturbation can occur that may have permanent impacts: when a critical point – a tipping point - is passed. These are the focus of this paper: if there is a risk of a major, difficult-to-reverse perturbation, to the food system, how should we respond?

1 http://www.foodsecurity.ac.uk/assets/pdfs/extreme-weather-resilience-of-global-food-system.pdf
2 Broadly, access to safe, affordable nutritious food for a healthy life, for all and at all times
3 http://www.foodsecurity.ac.uk/assets/pdfs/extreme-weather-resilience-of-global-food-system.pdf

Part 1: Setting out the issues

Resilience and tipping points: a primer.

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 farmers can plan their operations because they understand this variability. However, imagine if, over time, agricultural intensification has gradually reduced some property 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, 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 . It would be a "tipping point" or "critical transition" creating a step-change in system function.

The state of a system can be assessed by some important functional variables. These include agricultural yields for farming, or food prices, or availability for food systems. A resilient system is one where these functional variables may vary, but essentially, they remain within "normal" bounds. A farmer can cope with year-to-year variability in yields in terms of a few percent, or a consumer with variability in prices of a similar magnitude. Resilient systems (see glossary) are those that are stable in the sense that they are robust to perturbations (moving relatively little for a given perturbation), and/or quick to return to a pre-perturbation functional state. Non-resilient systems are those that, once perturbed, take a long time to, or even never, return to the pre-perturbed state. The key characteristic of a tipping point is that there is a transition to a "new normal" that is not easy to reverse. The alternative state is perversely resilient. If a lake is gradually enriched it may suddenly switch from clean water to turbid (see below). 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. When an incremental driver (e.g. nutrients, atmospheric CO^2, soil carbon, fishing intensity) creates a forward tip at a different level than the reverse backwards tip, it is termed hysteresis (see glossary). Some tipping points lead to a state of true irreversibility – such as when a species goes extinct. Hence, tipping points can be conceived as going from one resilient state to another, and that alternative stable state may not be desirable.

Within an agricultural system, we are interested in its function: producing yield. This arises from a combination of input variables (seed, soil, nutrients, climate, and management). In dynamic systems theory, the current state of a system can be described by the position of a ball to represent how it currently "functions" (e.g. the yield at a given time). Imagine the ball on a surface with lots of dips and humps. Mathematically, this surface is defined by combinations of variables; for example, in an agricultural scenario these variables may be soil quality and climate. Perturbations to the system (such as unusual weather) provide knocks to the ball, which will randomly move it away from its resting position. If the surface is not flat, the ball will end up in a dip, and small perturbations will not provide enough of a kick to move it out of the dip, so, on average, it stays in the same place: it is locally stable (Fig 3). In other words, certain combinations of variables make agricultural functioning stable (e.g. good soils in fertile plains are likely to be high yielding over time, mountain tops with poor soils are likely to be permanently low yielding) and others may make agriculture unstable (e.g. shifting monsoon belts).

Resilience: how does a system respond to a perturbation?

The resilience of the system – how stable it is - depends on the shape of the dip: all things being equal, a steeper sided dip requires more of a kick to move the ball, and it will return to being motionless at the bottom faster than a shallow sided dip (Fig 3A vs 3B). If there are multiple stable states (Fig 3C), the lip between adjacent dips represents a tipping point: a small perturbation will move the ball up the side of the dip, but it will roll back (Fig 3C first black arrow in inset graph). If the perturbation pushes the ball over the lip it will roll into the next cup, and it will undergo a critical transition between alternative stable states (Scheffer *et al*., 2012).

The world is changing all the time, so the static cartoons in Fig 3 are inadequate. Environmental or social change will lead to changes in the shape of the surface, and thus the system's resilience. As a cup disappears, under some gradual environmental change, the system gets more unstable, and even small perturbations can lead to the crossing of a tipping point (Figure 4).

Agricultural yields arise from the intersection of management with natural systems. Agriculture can tip from a stable, resilient and economical state to an uneconomical one in multiple ways. For example, through environmental change (such as climate change

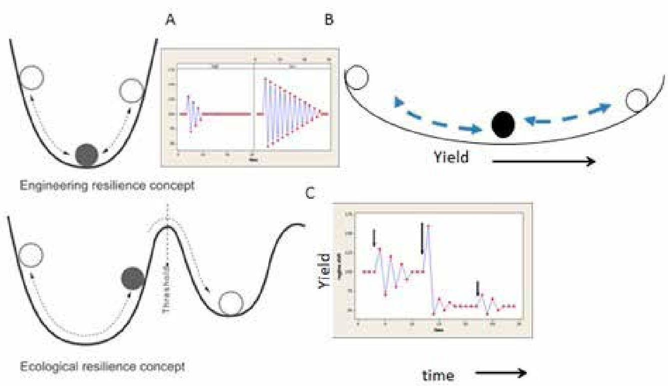


Figure 3. Cartoons illustrating the concept of resilience. The state of the system is the "ball" and the shape of the cup describes its resilience to a perturbation. A) high resilience, (B) low resilience, (C) a sufficiently large perturbation can push the cup over a threshold – a tipping point – into a new stable state.

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

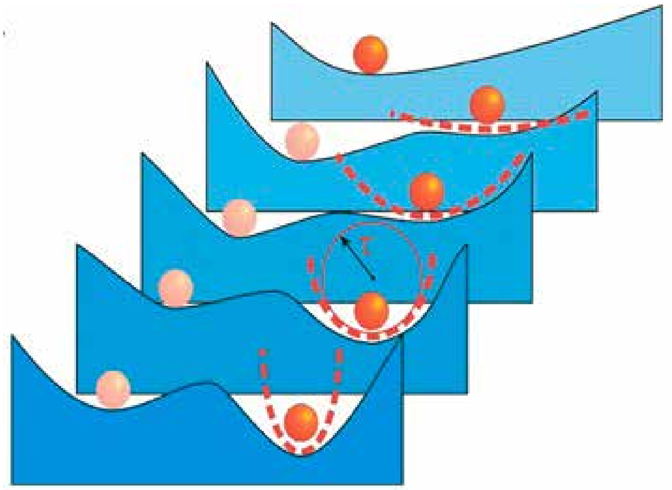
 

Fig. 4a. The stability of the system may change over time or depend on a driving variable. Here, a driving variable (e.g. nutrient levels in a lake) changes smoothly from bottom to top, and as it does, the basin of attraction (the cup) changes shape. Initially, the ball is in the right hand basin and is very resilient (the time taken for the system to return to equilibrium is proportional to tau, the radius of the basin). As the nutrient levels increase, the current state becomes less resilient until there is a sudden change and the ball rolls into the left-hand cup. SOURCE: (Lenton et al., 2008), ©National Academy of Sciences, U.S.A. In this example, the right hand cup is the natural state with clear water, and the left hand cup is the nutrient-rich state with algal blooms making the water turbid and reducing the natural biodiversity. This critical transition can be experimentally induced, as shown in Fig 4b, where nutrients have been added below the curtain dividing the lake (http://sevenhillslake.com/technical.html).

reducing agricultural suitability), sudden natural events (e.g. soil loss) or even socio-technological change (e.g. if pesticides are banned, or when labour is lost, or the market for a given product disappears, perhaps because it can be produced more cheaply somewhere else).

For those interested in food system resilience, tipping points are important for three reasons. First, the world is changing through changing climate and environmental transformation. Global intensification results in greater yields coming from the same land, and potentially at the same time, widespread degradation of soil and biodiversity. In essence, there is potential for these driving variables to be changing the shape of the cups (Fig 4a). Second, 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. Larger perturbations increase the likelihood of knocking the ball out of the basin of attraction (Fig 3). Thirdly, as there was an excess of land, water and resources ("biophysical redundancy") in the past, these could buffer countries against global perturbations to food supplies. This has been reducing in recent decades on a global basis (Marianela *et al*., 2016). Nowadays, countries rely on global trade in agricultural produce for their own food systems to function (Puma *et al*., 2015). Whilst this is highly beneficial in spreading risk, it creates a systemic risk in wider geographic exposure to risks. If every country were isolated and self-sufficient, only local risks matter. If every country is connected by trade, and through labour movements, a large enough perturbation in one place, especially if price signals are over-amplified, could create impacts across the world. A new dust bowl event, affecting long-term yields in a breadbasket region, could have consequences for us all.

Are tipping points really worth worrying about?

To date, most consideration of agri-food system sustainability and resilience is based on "linear thinking". This 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 exemplify a non-linear world; it is possible incrementally to drive a system – perhaps through increasingly intense farming – to a zone that suddenly switches from one state to another, from which it is difficult to recover.

In the literature there are many examples of tipping points (also called regime shifts) between stable states in environmental and socio-environmental systems (Walker and Meyers, 2004) (Beisner *et al*., 2003; Scheffer and Carpenter, 2003), including agro-ecological systems. We collate some of these in Appendix A –they include events like the mid-West Dustbowl, desertification through over-grazing, forest clearing driving local climate change and causing a "switch" from forest to grassland, and shifts in climate that cause the collapse of agriculture and societies.

The examples of tipping points have typically occurred at relatively small scales, especially with respect to terrestrial ecological systems (Brook *et al*., 2013). This is often taken to imply that tipping points are unlikely to be important at a global scale. For example, Brook *et al* (2013) say, "Although there is convincing evidence that human drivers can cause regime shifts at local and regional scales, the increasingly invoked concept of planetary scale tipping points

in the terrestrial biosphere remains unconfirmed. By evaluating potential mechanisms and drivers, we conclude that spatial heterogeneity in drivers and responses, and lack of strong continental interconnectivity, probably induce relatively smooth changes at the global scale, without an expectation of marked tipping patterns."

However, the atmosphere and climate system has potential to create "strong continental connectivity" and create tipping points with planetary-scale impacts (Hughes *et al*., 2013; Lenton and Williams, 2013), through changes in the ocean and atmospheric circulation creating changes in global weather. Another example might be the gradual warming and acidification of the oceans that may create a collapse of coral reef ecosystems across the tropics over the next decades. Furthermore, our globalised world (Hughes *et al*., 2013) has the potential to create global connectivity through the movement of goods, technologies, people or practices. For example, 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 soil degradation with the potential for sudden loss of soil function across multiple areas.

Agriculture and fisheries are an intimate interplay between socio-economic and environmental systems, so a tip in an environmental system may have significant consequences for the socio-economic system that utilises it. In addition, socio-economic systems are often highly complex and have multiple feed-back links, direct and indirect, that can create non-linear dynamics and sudden switches in behaviour (such as the collapse of the Soviet Union (Patrick *et al*., 2011)). It is an open question for research about whether the interaction of biological and socio-economic systems will amplify or damp each other's tipping points.

However, given the importance of food systems for the stability of socio-economic systems more broadly, the degree to which environmental tipping points may drive changes in the food system is perhaps particularly important to consider. While the global system may be resilient to small-scale shocks arising from changes in agricultural production at a local scale, the spatial inter-connectedness that arises through trade and geopolitical relationships makes each individual country potentially more exposed to larger cascading risks (Puma *et al*., 2015; Jessica *et al*., 2016; Philippe *et al*., 2016).

Key questions

Whilst there is a huge literature on sustainability in agri-food systems, and a growing literature on resilience, there is little consideration of the potential for critical transitions to affect food production and food systems. Part of this comes from a lack of knowledge of the potential for tipping points to exist, and at what scale, and whether crossing them is likely. For example, a common scientific result is to observe that biodiversity or an ecosystem service ("soil health", or equitable climate) is in decline. From this, many people extrapolate linearly from the current state to the zero state many years ahead, and then infer that a linear rate of decline requires no urgent action. Instead, the key question should be whether the decline in service is moving the system closer to a non-linear threshold, beyond which the functionality will suddenly decline.

To assess the relevance of tipping points to food systems necessitates addressing the following questions:

- Would passing tipping point(s) influence important aspects of the food system (e.g. prices)?[5]
- If so how would this happen?
- How can we avoid this, and ensure the market is aware of such tipping points and has appropriate mechanisms with which to respond?

To begin to address these questions, we explore a set of case study scenarios for tipping points. These include an example of one past (collapse of a fishery), two that may currently be happening (soil salinization, aridification) and two plausible ones that could happen (a dustbowl and a big climatic shift); the plausible ones we explore in some detail in terms of thinking about mitigation and/or adaptation strategies.

We do not aim to be alarmist and sketch yet another version of the "apocalyptic tragedy" narrative (Foust and O'Shannon Murphy, 2009). We want to examine the implications of known biophysical phenomena for the socio-economic system that we each rely on daily. A recent review of the results of the family of climate models used by the Intergovernmental Panel on Climate Change (IPCC) community, shows a significant number of occasions, under future emissions scenarios, 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)?

It is possible to understand the future impacts of currently unsustainable behaviour and act to prevent the apocalyptic future. In essence, this is the positive outcome of the "ozone hole" story. Following identification of the ozone hole and the consequences of its growth, research indicated its cause was chlorofluorocarbon (CFCs) compounds (Crutzen and Arnold, 1986). From this came the Montreal Protocol and the banning of >100 industrial chemicals (Andersen, 2015), resulting in significant emissions reductions and signs of recovery of ozone (Swanson and Mason, 2003; de Laat *et al*., 2015). The counterfactual to this is what would be the situation now if the scientific warnings had gone unheeded?

5 The focus of this document is from environment to food systems, and there are equally valid questions about how socio-economic tipping points might feed onto the environment. Another question which we don't address is "when does increasingly integrated and open trading introduce new tipping points by increasing the complexity of a nation's food system?".

Case studies – real and plausible – of tipping points affecting the food system

In this section, we aim to examine five case studies of existing or plausible bio-physical tipping points that have or may have significant implications for local, regional or global food production. Each case study presents a scenario/description of the change in the environment and then addresses the question: what were or would be the consequences for the food system?

Example 1. Collapse of exploited populations: Newfoundland cod as an example

The northern Atlantic cod (*Gadus morhua*) fishery off southern Labrador and to the northern Grand Bank of Newfoundland was once the largest cod fishery in the world. Its collapse "was a social and economic disaster for the region" (Myers and Cadigan, 1995) – an example of where an environmental tipping point drove a step-wise change in the socio-economic system. The rise, decline and fall of the fishery is illustrated in Fig 5. There were two major eras in recent decades (Hamilton *et al*., 2004): when stocks were abundant and when they collapsed. In the former, industrialisation of fishing occurred when open boats using lines switched to trawling (in the late 1960s) leading to a boom time with high returns, and further investment in dragnets, which increased fish bycatch. From the late 1980s, stocks collapsed, forcing societal change. The 1994 moratorium meant that 400 fish plant workers lost their jobs. In 2003, the cod fishery closed down. Increasing dependence on government assistance meant many young people left the area for education or employment. Stocks are now beginning to recover, and are currently about 20% the size of the late 1980s (Rose and Rowe, 2015). It will take another decade or more of recovery before the fishery can be re-opened – a 40 year hiatus, much longer than initially expected.

Overfishing was the primary cause of a decline of fish stocks. However, climatic conditions also had a role (Drinkwater, 2002), with cold conditions reducing growth rates and recruitment of adult fish for a decade. Furthermore, size-selected mortality (the largest, most fecund, fish are preferentially caught) suppressed recruitment when the fishing industry relied on recruitment rates to restore fish populations. Population models, and some circumstantial evidence from other population collapses in cod fisheries (De Roos and Persson, 2002; Gårdmark *et al*., 2015), suggest the non-recovery was partly due to the existence of an alternative stable state. When cod are common, the adults eat prey species, which would otherwise compete with the young cod for food. When adult cod become rare, the prey species become more common, increasing competition for young cod, reducing their ability to survive and grow, suppressing the population growth rate.

From an industry perspective, the decline of cod stocks from their peak led to impacts on other parts of the marine ecosystem. Initially, fishing efforts switched to other fish species (e.g. redfish, Greenland halibut), but when these stocks declined (Hamilton *et al.* 2004), fishing effort switched to invertebrates (e.g. northern shrimp, American lobster and snow crab). However, fewer licences were issued than had been available for cod fishing, as not all areas were suitable for crustacean fisheries. The ability of fishers to adapt depended on geography, their ability to invest, and also licensing/quota rules.

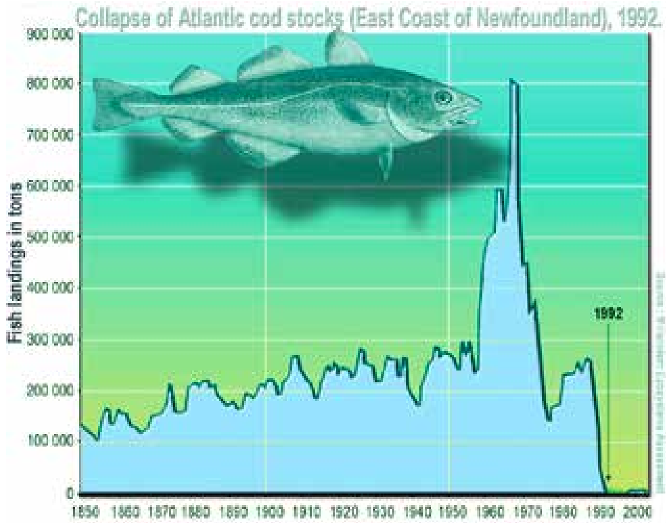


Figure 5. The rise and fall of the Newfoundland cod fishery. Illustration by Lamiot, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=10648302.

The economic impacts of the collapse were felt beyond the region. The FAO's capture fish price index rose by 20-40%[6]. This fishery collapse also highlighted the necessity to further ensure sustainable fisheries management, and inspired the development of the *Marine Stewardship Council* in 1997 to set global standards for sustainable fishing.

The socio-economic system acted in a number of ways to mitigate the impact of historical over-fishing, and potentially allow the stock to return from the "low equilibrium" to "high equilibrium" state. At the time of the collapse, the reduction in employment in the sector meant that overfishing would not continue. The likelihood of there being a lag in employment growth following a recovery in stocks means that the recovery is more effective. The increase in the market price also means that the demand for fish is reduced. In addition to the market impacts, the closure of the fishery coupled with other regulatory interventions from the marine stewardship council have also contributed.

6 see http://www.fao.org/in-action/globefish/fishery-information/resource-detail/en/c/338601/

Example 2. A tipping point in progress? Salinization of the Mekong Delta

The Mekong Delta, also known as Vietnam's rice bowl, accounts for more than half of Vietnam's rice and fruit production, 90% of its rice exports, 60% of its fishery exports and is home to 20 million people. Originating on the Tibetan Plateau and flowing through a number of countries before meeting the South China Sea in Vietnam, water levels in the Delta commonly drop during the dry season, allowing some temporary saltwater intrusion from the South China Sea before freshwater levels are bolstered when the rains come.

Soils with too much salt in them become infertile; "salting the earth" was a Near East custom to signify the permanent destruction of an enemy society in ancient times[7]. Climate change is creating the potential for a significant tipping point through rapid salinization of the soils. This arises through two routes. First, as drought intensity increases, groundwater levels fall, allowing for greater saltwater intrusion from the sea. Secondly, as sea levels rise, the likelihood of salt-water inundation, as well as intrusion, increases. A sea-level rise of one metre is expected to submerge 40% of the delta, potentially rendering a great deal of agricultural land non-viable. The risk of catastrophic salinization is further enhanced by anthropogenic changes; damage to the region has also been brought about by infrastructure change, introduction of canals, dikes and dams as well as new water management and land use techniques. These negatively affect water levels (increasing extraction pressure downstream) and sediment movement (reducing silt deposition and thus making the delta more vulnerable to sea-level rise).

The potential loss of soil functionality through salinization is exemplified by the 2015-16 "mega-drought" associated with the El Niño, leading to the lowest water levels in the lower Mekong since records began – down 30% to 50% compared to average levels. Lack of freshwater has allowed for greater and more prolonged saltwater intrusion – in April 2016, salt levels of four parts per thousand reached 50 kilometres inland, while groundwater was found to be tainted in rice paddies as far as 90 kilometres inland. As a result, 159,000 hectares of rice paddy has already been lost, with an estimated 500,000 hectares still likely to be damaged (10% of the nation's arable land, and perhaps the most fertile). This loss to agriculture due to salinization and drought has the potential to threaten food security in Vietnam as well as impact international markets for key Vietnamese crops, such as rice, cassava, maize, coffee, and cashew nuts. It may also threaten the livelihoods of the 20% of the Vietnamese population who depend on agriculture on the delta[8].

Example 3: A tipping point in progress: Drought in California.

Another tipping point that may already be in progress is the drying of southwestern North America and the attendant consequences for regional food production, especially in California.

Droughts have been a recurring feature of California's climate. Significant droughts occurred in 1929-1934, 1976-1977, and 1987-1992. This century, there was a less severe drought in 2007-2009. However, since 2012, California has faced a drought of extreme proportions, with record-high temperatures and record-low levels of snowpack and precipitation[9]. Climate observations and modelling suggests that the SW N America region (including parts of Mexico) is undergoing a transition to a more arid state, which may mimic past regional 'mega-droughts' in the paleo-record (e.g. those linked to the collapse of early civilisations) or even exceed them (Cook *et al*., 2015; Diffenbaugh *et al*., 2015) (Fig 6).

Agriculture is a key industry in California, accounting for about 2% of the state's economy. In the US, it is the leading producer (in terms of income), and produces more than 12% of US farm gate receipts. In 2014, California's 76,400 farms had a gross income of $54 billion[10]. The state of California is a major exporter (exporting $22bn by value, more than 14% of the US's agricultural exports). California's top 10 export destinations are (in order) European Union ($3.7bn in 2014), Canada, China/Hong Kong, Japan, Mexico, Korea, India, United Arab

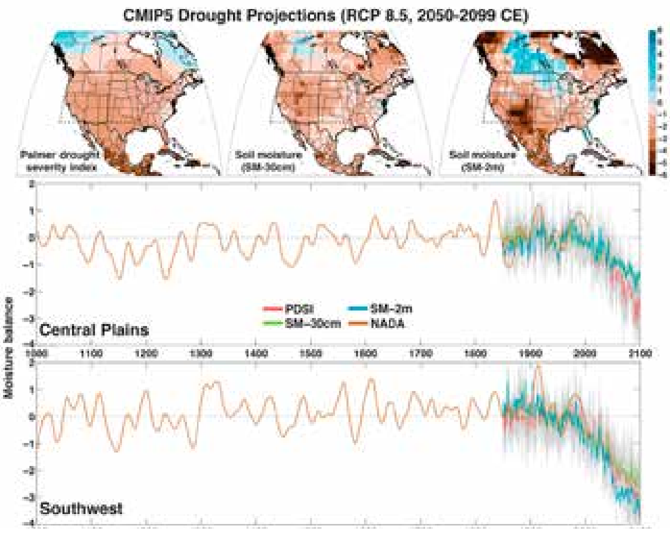


Figure 6. Predictions of drought in Central and SW US up to 2100. Top panel drought maps for 2050-99. The predicted soil moisture balance time series over 1100 years for Central Plains (Middle panel) and SW US (bottom) shows development of unprecedented drought. From Cook et al (2015)

7 E.g. "And Abimelech fought against the city all that day; and he took the city, and slew the people that was therein, and beat down the city, and sowed it with salt." King James' Bible Judges 9:45.
8 https://news.mongabay.com/2016/10/will-climate-change-sink-the-mekong-delta/
9 http://www.californiadrought.org/drought/background/
10 https://www.cdfa.ca.gov/statistics/PDFs/2015Report.pdf

Emirates, Turkey, and Vietnam. California is the US's sole exporter of many commodities including table grapes, raisins, dried plums, kiwifruit, dates, olives and olive oil, figs, almonds, walnuts, pistachios, garlic, and artichokes. In terms of size of the agricultural economy, California is placed 5-9th (depending on the metric) in the global list, above countries like the UK, Canada and Germany[11].

Drought clearly acts as a constraint to agricultural production. Estimates of the cost of drought in 2015 suggest a $2.7bn fall in revenue, with 21,000 job losses (Howitt *et al*., 2014). In 2014, over 400,000 acres, about 6 percent of cropland, was left unused because of the drought[12]. In times of drought, reliance on water extracted from underground increases (as surface water becomes more scarce), rising from 40% of water used in non-drought years, to 65% in drought years. High levels of abstraction exceed the recharge rates, and as a consequence land subsidence in some areas can be very severe (up to 94cm in the period 2006-2010, and up to nearly 4cm a month in 2014[13]). Whilst subsidence can itself cause significant costs (e.g. to roads, canals, flood risk), it reflects collapse of the aquifer and its water storage ability.

The tipping point from a stable, equitable, agriculture-friendly historical climate regime to the current drought exemplifying the "new normal" will have significant impacts both on local production and perhaps on global food systems (given the global reliance on almonds and pistachios, grapes and raisins, and wine). From a water-use perspective, the greatest volume of water used for irrigation is for forage (including alfalfa), underpinning livestock production (dairy in particular): forage uses some 4 times more water than almond and pistachio combined[14]. In addition, in recent years, and taking advantage of cheap shipping, the export of alfalfa from California has grown significantly, to the extent that in essence, a drought-prone state is currently "exporting 100bn gallons of water to China"[15]. It is unlikely that changes in irrigation efficiency will materially affect water requirements (Ward and Pulido-Velazquez, 2008). Hence, to make water usage sustainable within a long-term water-limited system implies significant changes in production area or crop type. This clearly has the potential to be both economically harmful and potentially sudden.

The geographical extent of aridification (Fig 6) extends beyond California. In Mexico, some 18% of people work in agriculture. An increasing lack of water, as well as intensifying heat, is likely to significantly impact on their production and farming practices (such as constraining double cropping). It may also lead to increased migration[16].

Example 4. A plausible local tipping point: soils and an East Anglian dustbowl.

There is a potential tipping point in East Anglia with the degradation and loss of peat soils, creating conditions where widespread soil erosion may occur.

The East Anglian fenland peats cover a total area of 132,000 ha in the East of England. In Cambridgeshire, 70% of land is Grade 1 or 2, compared to the average for England of 18%[17], and it is under intensive cultivation of high value field vegetable and horticultural crops. Peat was originally formed in waterlogged conditions, prior to the fenland drainage that started in the 17th Century.

Only 16% of the peat stock recorded in 1850 in the fens now remains; within this area, there are about 33,500 ha of remaining deep peats. Recent predictions suggest that peat cover – depending on climate scenario – will be gone within decades (Fig 7; from Graves and Morris, 2013; Oats, 2002).

The loss of peat leads to a reduction in soil organic matter (SOM) and soil biodiversity caused by intensive cultivation has long-term detrimental effects on crop yield and susceptibility to erosion (Panagos *et al*., 2015; Rickson *et al*., 2015). Continued intensive agriculture leads to change in the in soil community from one dominated by fungi and earthworms binding soil aggregates together, to one dominated by more ephemeral species, such as bacteria, leading to the degradation of soil structure (Rillig and Mummey, 2006; Blankinship *et al*., 2016). In addition to increasing resilience to erosion, high carbon soils with good structure can hold more moisture and be more drought-resistant (Bhattacharyya *et al*., 2016). During a long drought, any loss of structure is exacerbated and the organic soils become friable and so erosion risks – to both wind and rain - increases. The Fenland of East Anglia is one of the areas identified at highest risk of losing soil by wind erosion – greater than a 1 in 20 chance of exceeding 4 t ha^{-1} y^{-1}, especially during drought (Kibblewhite *et al*., 2014).

We consider a plausible scenario to be an unprecedented drought. Had it not rained in late spring 2012, breaking the prolonged drought of 2010-2012, this might represent such a scenario, coupled with loss of field crops (creating bare land during the summer), or a drought extending into winter when soils are typically bare. Under these conditions, any strong winds can drive erosion. In Kansas, wind erosion during the over-winter drought in 1995/6, lead to soil loss of 65 t ha^{-1}. The highest rates of soil erosion recorded are 445 t ha^{-1} (Montgomery, 2007), from a report published in 1950 on erosion in Western Iowa. The US Dustbowl of the 1930s was an environmental and economic disaster, in high-erosion areas, over 75% of topsoil

11 Measure of Californian Agriculture (2009). http://aic.ucdavis.edu/publications/moca/moca_current/moca09/moca09chapter5.pdf
12 https://www.washingtonpost.com/blogs/govbeat/wp/2015/04/03/agriculture-is-80-percent-of-water-use-in-california-why-arent-farmers-being-forced-to-cut-back/
13 http://water.ca.gov/groundwater/docs/NASA_REPORT.pdf
14 http://www.arb.ca.gov/fuels/lcfs/workgroups/lcfssustain/hanson.pdf
15 http://www.bbc.co.uk/news/magazine-26124989
16 http://archive.alleghenyfront.org/story/climate-change-forces-mexican-farmers-migrate.html
17 https://www.scambs.gov.uk/sites/default/files/documents/13_NS%20Phase%201%20ES%20Agriculture_and_soil.pdf

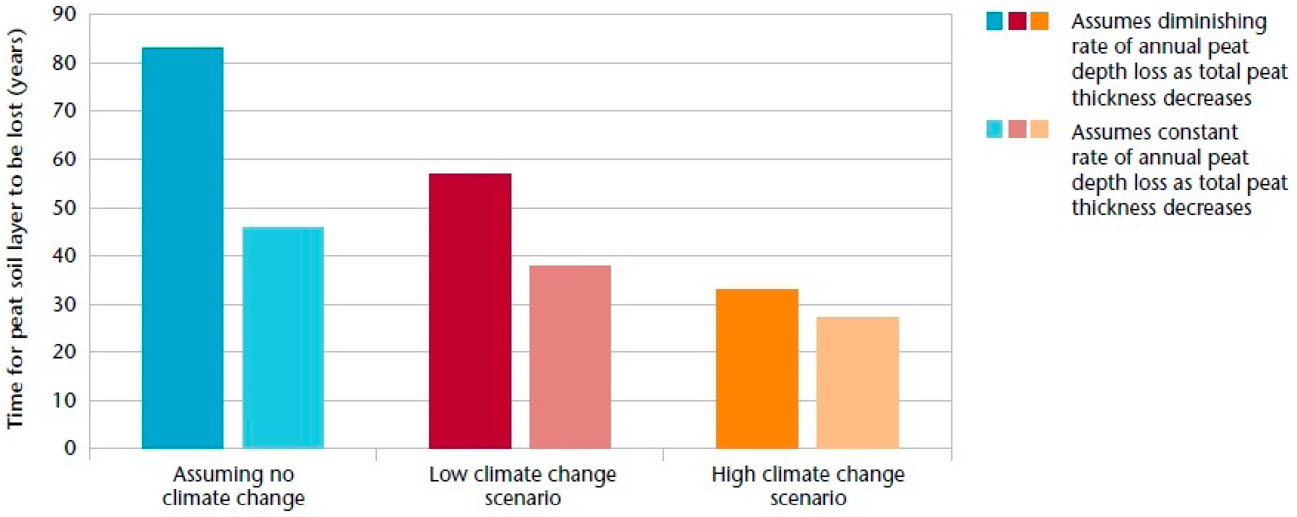


Fig 7. Estimated time in years for peat layer to be lost in East Anglia, The analysis presented in the Adaptation Sub-Committee (2013) draws on data developed by Graves and Morris (2013). The analysis assume an initial depth of 86 cm in 2012. The dark bars assumes a diminishing rate of peat loss with peat depth reduction and the lighter bars assume a constant rate of loss with peat depth reduction. The effect of climate change on peat loss is based on a no climate change scenario, a low emissions scenario and a high emissions scenario as presented by the UKCP09. The analysis draws on data that suggests that CO_2 emissions from peat increase by 30% for every one degree rise in temperature.

was lost in successive years, severely – and to this day – reducing land values (Hornbeck, 2009).

The Fenland area is more fertile and used for higher value crops (like root vegetables) than much of the rest of England. Loss of fertility would reduce the ability to produce home-grown vegetables (East Anglia, accounts for about 29% of Great Britain's area planted for potatoes[18]). Any loss of fertility would have economic impacts beyond farm revenues. The Cambridgeshire district of Fenland has twice the national average of businesses in agriculture[19] (over 12% of all business in the area are agricultural) which accounts for significant employment of poorly qualified and seasonal workers (where other employment opportunities are limited). In addition, suspended soil particles in a "dust storm" can have significant impacts on human health, traffic, business and domestic costs (through disrupted transport and cleaning requirements): a dust storm in New South Wales in September 2013 was estimated to have a total economic cost of A$300m (Tozer and Leys, 2013).

Whilst this "plausible scenario" is chosen as a "local example" of a tipping point resulting in a step-wise change in agricultural yields, it is connected in two ways to the global system. First, drought is made more likely due to climate change. Second, the drivers of climate change and agricultural intensification both arise from growing global demand. High value agricultural land is degrading in the UK and elsewhere in Europe. If a drought is spatially widespread, then a significant wind-erosion event in the UK might be replicated on the continent. Thus loss of production for the entire food system may extend beyond local losses and may result in even more ephemeral employment conditions for migrant labourers.

Example 5. A plausible large-scale climatic tipping point: collapse of the Atlantic overturning circulation

A potential future climate tipping point is a collapse of the Atlantic Meridional Overturning Circulation (AMOC). This Atlantic branch of the global ocean's 'conveyor belt' (thermohaline) circulation transports a large flux of heat northwards across the equator and on to the NE Atlantic region including Europe. Climate observations already show a 'cold spot' in the North Atlantic – the only place globally that is not warming – linked to an observed weakening of the AMOC. Models project further weakening of the AMOC as climate change continues, including a potential shut-off of deep convection in the Labrador Sea region to the west of Greenland; and, in more extreme scenarios, a complete collapse of the overturning circulation. Whilst in current models the latter requires sustained greenhouse gas emissions, there is some evidence that the models may be biased towards being too stable when compared to observations.

Although there is little certainty as to whether the AMOC is likely to slow or stop in the foreseeable future, its strength has weakened considerably since the 1970s (Rahmstorf *et al.*, 2015), and particularly in the last decade or so. It is therefore a plausible albeit "low probability-high impact event" for forthcoming decades. It would also be very difficult to reverse (carrying hysteresis). Were there to be significant change in the AMOC, it would happen over an uncertain timescale – from a decade to many decades.

As the "Gulf Stream" is drawn towards NW Europe by the overturning circulation, it is not surprising that AMOC collapse would reduce the temperate maritime nature of our climate in NW Europe, and

18 http://potatoes.ahdb.org.uk/sites/default/files/publication_upload/GB%20Potatoes%202015-2016.pdf
19 http://cambridgeshireinsight.org.uk/file/1061/download

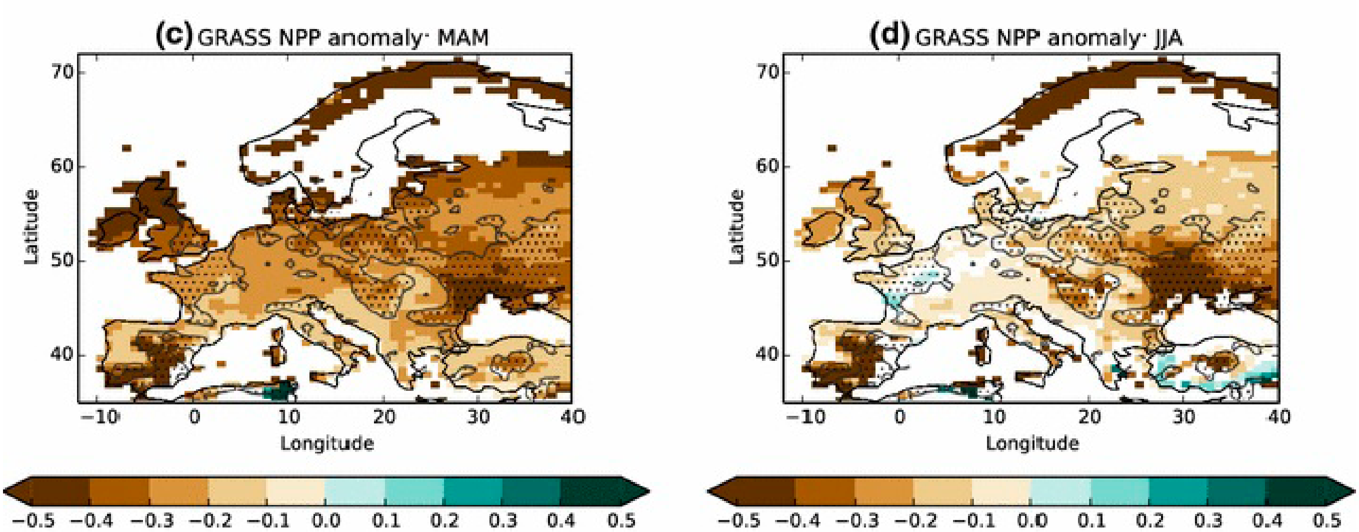


Figure 8. The Spring (C) and Summer (D) change in productivity of grasses (as a proxy for crops) if the AMOC slowed down significantly. (from Jackson et al, 2015 @ Crown Copyright, Met Office).

provide some degree of similarity to similar latitudes in NE North America (e.g. Labrador). In other words, the key impacts of AMOC collapse would include a marked increase in seasonality of European climate with harsher winters (even in a globally warmer world) and a strengthening of the winter storm track across the UK and western Europe, together with hotter, drier and less windy summers. Simulations of AMOC collapse in the Hadley Centre climate model show a marked reduction in net primary productivity across Europe which would translate into a significant loss of crop yields (Jackson *et al.*, 2015).

Jackson *et al.*'s state-of-the-art model study simulated the slowing of the AMOC to about a third of its current strength. Their principal results, which they consider robust, include:

- Widespread cooling throughout the North Atlantic and northern hemisphere in general, with cooling in Europe of several degrees.
- Much greater sea ice coverage in the North Atlantic.
- Less precipitation and evaporation in the northern hemisphere mid-latitudes. Across Europe, summer precipitation generally decreases; however, there is an increase in precipitation around the Mediterranean. In winter, precipitation generally decreases, but with a greater proportion as snow, leading to an increase in duration of snow-cover.
- Strengthening of the North Atlantic storm tracks, with a greater penetration of storms over land in Europe (leading to localised increases in winter precipitation associated with storms)
- Reduction in productivity of vegetation associated with changes in temperature, seasonality and water availability.

Further afield, AMOC collapse would cause a southward shift to the inter-tropical convergence zone causing potentially abrupt weakening of the Indian summer monsoon and for example, loss of irrigated rice, increased desertification in sub-Saharan Africa due to abrupt shift in the West African Monsoon, and drying over much of Brazil and Central America. Whilst the AMOC may collapse over a relatively long timescale, shifts in the monsoon systems could be more abrupt (Chang *et al.*, 2008).

Some of the impacts on food production are clear: loss of significant European crop and grassland production (Fig 8), perhaps as much as a third, extending across to Russia. In addition, significant losses of rice production in India, changes in rainfall in Sub-Saharan Africa, and drying in Central S America, and the corresponding losses in productivity in soya and sugar. Were this to happen rapidly, this would cause unprecedented losses in global production. Recent estimates suggest that a 1-in-200 year extreme event, equates to a loss of about 10% of the world's production of the major commodity crops[20]. Historical shortfalls in calorie production, much less than the magnitude that may occur with a sudden AMOC collapse, have led to price spikes, famine, civil disorder and social breakdown. Early warning to allow mitigation and/or adaptation is key to minimising the global disruption this might cause.

20 http://www.foodsecurity.ac.uk/assets/pdfs/extreme-weather-resilience-of-global-food-system.pdf

Part II: Understanding and managing risks

Risk management and tipping points

Risks are typically managed under a simple framework (such as Figure 9). The risk is the combination of the probability of the hazard occurring (i.e. the tipping point being crossed) and its consequence[21]. However, this simple business framework may be difficult to apply, especially when there is great uncertainty about the probability. This uncertainty can arise from imperfect understanding of the process – poor estimates of maximum sustainable yield in Northern cod (Hutchings, 1996), to unwillingness to credit the evidence, such as climate change denial (Dunlap, 2013). Nonetheless, from an institutional perspective (whether a country or a business), crossing a tipping point may primarily be a "hazard risk", but with impact on all the major classes of risk identified in the Institute of Risk Management framework (Figure 9).

So, what knowledge is needed to understand the "tipping point" risk? Firstly, there is a need to recognise that the function relied on by a business or country (e.g. food production, food availability, food price) may show "tipping point" behaviour, where a step change in function can occur in response to an incremental change in a variable, or an unprecedented perturbation. This requires us to acknowledge that we live in a non-linear world, where an incremental change can have a big effect. Acknowledging the potential of large and unprecedented changes is perhaps the most important initial step. Is it possible for the rains to change? Is it possible for the soils suddenly to lose functionality? Is it possible for climate to switch?

If tipping points are acknowledged as possibilities, our suggestion is that we need to think through four further points for understanding the impact on food systems (Figure 10):

1. Where is the system now relative to the tipping point?
2. What is the likelihood, trajectory and rate of approach to the tipping point?
3. What is the cost of passing the tipping point?
4. What alternative trajectories are available (such as through changing farming systems, crops, emissions or demand for food)? What are the direct and indirect costs associated with different trajectories? How long do we have the option to move between trajectories? When do those options close down?

In short: 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.

If we have these elements of knowledge, the market, in combination with policy has potential to price in the costs of crossing the tipping point and the losses caused (including need for adaptation), or can price in positive actions to ensure the trajectory towards the threshold is avoided. Without better understanding of where we are relative to a threshold, institutional actors (state or non-state) tend to resort to putting their short-term interests first; with better knowledge of the threshold, actors are more likely to co-operate to bring about collective action (Barrett and Dannenberg, 2012).

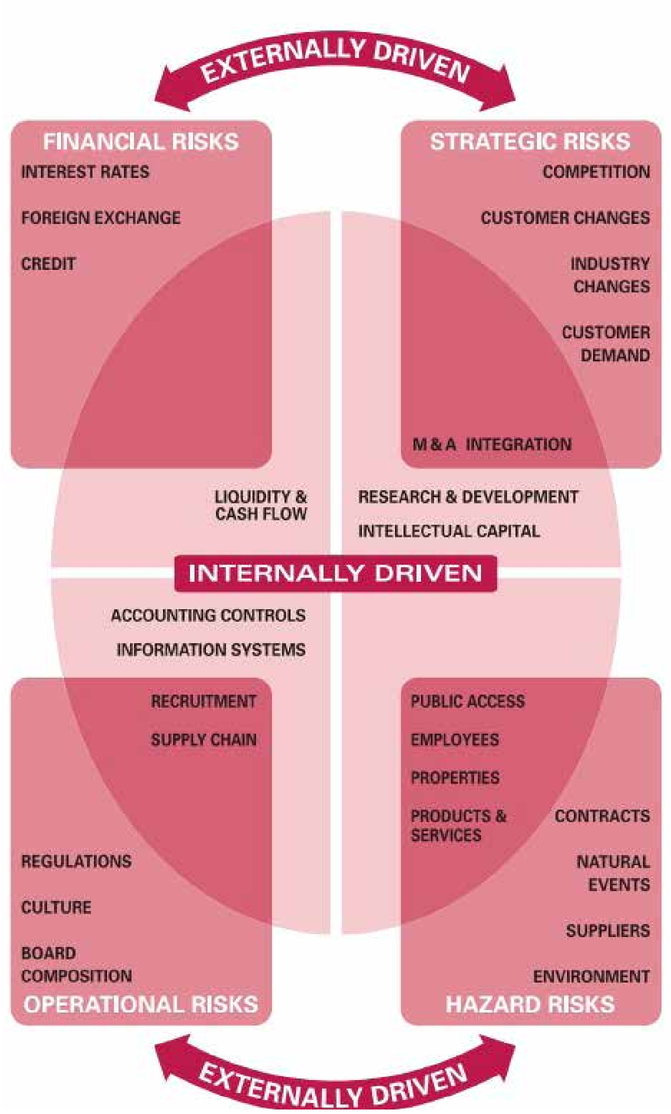


Figure 9 from https://www.theirm.org/media/886059/ARMS_2002_IRM.pdf

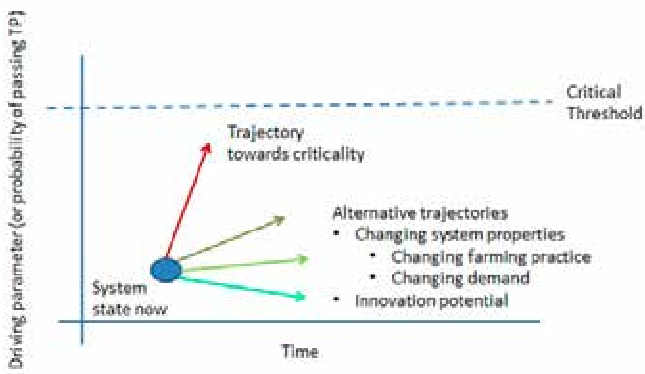


Figure 10. The "Existence, Threat, Trajectory, Alternatives" framework for thinking about critical thresholds.

21 https://www.theirm.org/media/886059/ARMS_2002_IRM.pdf

Forecasting the proximity to a tipping point

If action by the market or policy requires knowing the trajectory towards a threshold or tipping point, it suggests we need early-warning indicators that signal our closeness to a threshold with sufficient time to act. Broadly, there are two kinds of indicators. The behaviour of many complex systems is known to change as they approach a tipping point. Typically, before a tip the way the system interacts with random events (like weather, generically termed "noise") changes. Away from a tipping point, noise may simply create "normal variability" in the functionally important variables. 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). As well as increasing, the variability of the system may change its properties usually "slowing down" in frequency – 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). Increasing volatility – as well as creating negative impacts in its own right – can therefore signal the nearness of a critical transition.

Given that environmental variability affecting 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 – in terms of the system being perturbed enough to move from one stable state to another (Fig 3c) – 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 diagnostic dynamical signals of the proximity to a tipping point, there are biophysical measurements that can indicate the change in a system that is likely to be detrimental. Often used proxies include, for example, decreasing soil carbon or soil depth, decreasing abundance or biodiversity of pollinator communities, or increasing nutrient quantity of water bodies. However, whilst such variables may say something in general about the state of the system, they do not indicate the existence of, or closeness to, a boundary. Such state variable therefore do not necessarily prompt action.

Forecasting needs to be accurate to prompt action

The existence of early warning indicators is a necessary part of mitigating or adapting to the tipping point. However, there is a significant constraint in that the value of information in such signals is crucially dependent on their accuracy (or their perceived accuracy). An interesting study, using game-theory (Barrett and Dannenberg, 2012), suggests that uncertainty about when a critical threshold is passed leads to lack of consensus on action for avoiding dangerous climate change. We can illustrate why this is with respect to a simple experiment.

Table 1	Event occurs	Event does not occur
Plan	Cost-1	Cost-2
Do not plan	Cost-3	Cost-4

Using decision theory, we can quantify the value or utility of forecast information by combining knowledge about our ability to forecast an adverse event, with an understanding of the costs and losses associated with the occurrence of that event, subject to different planning strategies (Lindley, 1985). In this approach, costs and losses are characterised using a 2x2 matrix whose elements are calculated on the basis that there are two outcomes (the adverse event either occurs or not) and two decisions (to plan for the adverse event or not). As shown in Table 1, potentially different costs or losses are associated with each of the four possible event/decision combinations.

The adverse event occurs with probability P, known as the base rate. Accordingly, the probability that the event does not occur, is 1-P. The costs and/or losses associated with the different events are denoted by the Cost values, and are determined by the decision to plan or not plan.

In the absence of any information other than the probability, P, of the event occurring, the optimal decision is the one that minimises the expected costs/losses. Consequently, depending on the specific values in the matrix and P, the decision maker should always plan or always not plan. This case represents the baseline losses against which other forecasts are measured. For example, in the limit that it is possible to predict the occurrence of the adverse event with 100% accuracy, we would always be able to select the appropriate decision that minimises the losses. This example of perfect forecast information defines the maximum value of a forecast relative to the baseline. More generally, forecasts are never 100% accurate and, therefore, only provide "partial information" (this is particularly true in the cases we are discussing: uncertainty in both "if" and "when"). This information can still be of use, but its expected utility or value is determined by a combination of the forecast accuracy and the decision-maker's cost-loss matrix. In particular, for a given cost-loss matrix, a forecast which correctly predicts the occurrence of the event more often, has greater value. Notably, however, the forecast only attains value, relative to the baseline, above a certain level of accuracy which depends on the cost-loss matrix. Figure 11 compares the value of a forecast as a function of its accuracy for two sets of Costs (i.e. values in Table 1).

This simple approach re-emphasises that when a decision is costly, a forecast will be valued only if it is perceived to be trust-worthy. For repeated events, models can be developed iteratively and "earn" trust (e.g. the improving skill of weather forecasting). For one-off events, this is problematic since their performance at capturing tipping points cannot be fully assessed.

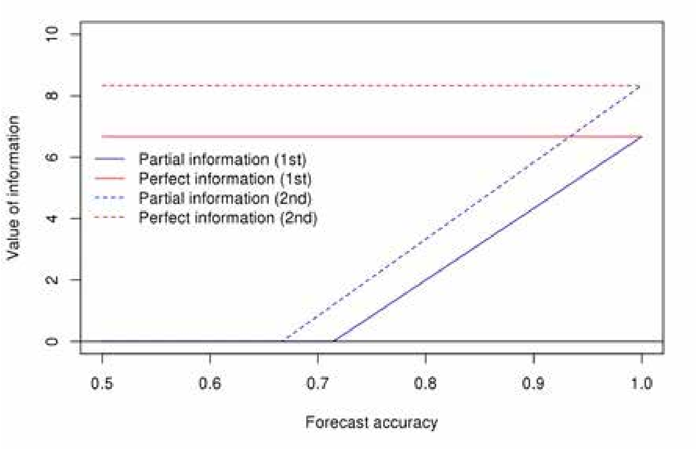


Figure 11: value of forecast information as a function of forecast "accuracy" for two different cost-loss matrices. Here, forecast accuracy is quantified using either the definitions of hit rate or proportion correct, which range from 0-1. Below an accuracy of ~0.7 the forecast offers no value above the baseline. Above this threshold, the value increases linearly up to the maximum theoretical value as the accuracy tends to 1 (i.e. 100%).

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

The ETTA framework (Figure 10) suggests that once a potential tipping point's existence has been established and the trajectory towards it has been verified as a threat, then it is necessary to assess the costs and 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 ensure sustainability. This could be through pricing the damages of 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[22].

If the information is trusted and transparently available, 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. However, there may be requirements for public policy levers to ensure that the market responds appropriately (whether these are regulatory or incentivising public investments looking for innovative solutions from research). In addition, consumers ultimately are 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 increase future prices, along with other indirect effects, such as geo-political destabilisation), consumers may be more willing to accept changing prices (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 (i.e. "conversation science").

As discussed above, the value of a prediction about crossing a tipping point depends on its accuracy, in particular the accuracy about when an event will happen rather than what will happen if a critical threshold is crossed (Barrett and Dannenberg, 2012). This uncertainty allows actors (from individuals to governments) to defer the cost/responsibility because the event might not happen within their career or administration. This, of course, leads to the challenge of coordinating actions to avoid conscientious actors bearing the costs, while less conscientious actors get the benefits. However, the evidence for a tipping point is likely to become stronger the closer it gets. Given the multiple decades it takes for research to turn into adopted innovation, and often similar timescales for institutional innovation and infra-structural development, there is a conundrum in creating the impetus for markets to work to stimulate mitigation; by the time the evidence is strong enough, perhaps there is insufficient time to change[23]. In addition, there is a particular challenge in assessing the likely impact of crossing such a tipping point as predicting the ability of any future society to adapt to such a change is even more difficult than predicting the physical tipping point itself. Identifying the discount rates that should be used in assessing the future costs of such tipping points requires significant further research and any policy recommendations based on particular discount rates should be treated with care.

Finally, in determining actions in response to tipping points, it is clearly crucial to consider fully the potential for unintended consequences. Recognising the need to build resilience or mitigating the approach to a critical threshold may affect other aspects of "sustainability" or create further lock-in to the current trajectory. For example, if building resilience in Europe reduces productivity, and if demand did not change, this may cause price signals to intensify production elsewhere in the world, with the potential for negative consequences, such as undermining soil structure. This may therefore shift the risk of crossing a tipping point geographically, without significantly reducing exposure to market shocks.

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

22 E.g https://www.gov.uk/government/publications/carbon-valuation-in-uk-policy-appraisal-a-revised-approach
23 This is similar to the climate change debate about "avoiding dangerous climate change": 2 degrees Celsius as a limit was first mooted in 1975 and has been discussed up to COP21 in Paris where it was acknowledged in the aim of not exceeding 1.5 degrees. However, there is now little time to avoid exceeding the target (https://www.carbonbrief.org/two-degrees-the-history-of-climate-changes-speed-limit).

What would we do differently: case study scenarios

Case study 1: "The East Anglian dustbowl"

Existence of tipping point: As outlined above, intensification creates substitution of carbon-based, organic, nutrients with synthetic ones; leads to loss of soil biodiversity; loss of structure; and increased erosion risk. At the same time, drought risk is changing as the climate changes. Erosion risk can be >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) that removes large amounts of soil (and impinges upon agricultural productivity, which may lead to a downgrading of land classification and associated change in cropping patterns – such as switching from root vegetables to wheat). This would have significant impacts on the local agricultural economy (and its requirement for labour), both in the short and long-term. The local costs would not only affect those individual landowners whose farming practices have degraded the soils. Eroded soils are transported across the surface, if they are heavy, including by bouncing (so called saltation), or suspended in the air (the lighter particles). Transport of these 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, not suspended, can be deposited against fences (blocking roads) or in watercourses, creating siltation and blocking drains, and affecting flood risk.

Whilst it is likely that in absolute terms a local event like an East Anglian dustbowl would affect a small amount of global production, we nonetheless note that one of the amplifying factors for the 2007/8 global food price spike was reduced yields, negligible on a global scale, from reduced Australian wheat production. Therefore, under some circumstances local production shortfalls in a limited area can interact with other factors (e.g. stock-to-use ratios, transport risks, weather elsewhere, geo-politics) to impact globally.

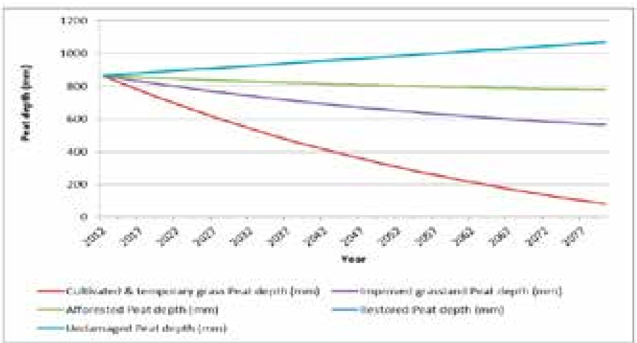
Trajectory: Soils are losing carbon, microbial biodiversity and thus structure and thus resilience; at the same time climate is changing making droughts more likely. Soils are much more fragile than previously, and droughts are increasing in frequency; currently the system is somewhere near but not on the threshold. Climate change is reducing the distance to the threshold by making drought and crop failure more likely and this is compounded by current, intensive, farming practices. Although it would require new research to characterise the risk of an East Anglian Dustbowl, new policy pressure to 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). Assuming a no climate change scenario (Box Error! Reference source not found.), the continued arable intensive scenario resulted in the most rapid loss of peat. The rate of loss was reduced under the improved grassland and afforestation scenarios, and peat depth increased under the restored peat scenario, with the result that there was an increase in the peat stock.

Costs of alternative trajectories: The market and non-market costs of these scenarios up to 2080 were also assessed by Graves and Morris (2013), using a cost benefit analysis model that assumed discount rates of 3.5% up to 2052 and 3% beyond that. They did not model the potential costs of significant erosion. 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, making continued agricultural production the preferable land use for a farmer.

However, when the non-market externality of these scenarios in terms of the associated carbon loss was aggregated with these financial benefits, it was found under continued arable production scenario, that the present value of future agricultural income (£14,500 ha-1) was greatly in deficit to the cost of carbon emissions associated with that agricultural income stream (£47,000 ha-1). This resulted in a negative net present value of £33,000 ha-1. Furthermore, climate change increased the speed of peat degradation, decreasing the present value benefit from agriculture and increasing the present value costs of the soil carbon losses.

The present value benefits for the peat restoration and peat conservation options on the other hand, whilst lower in terms of agricultural income, were found to be a vastly preferable use of fenland peats when the cost of carbon emissions were also included. The net present value of the aggregated net agricultural benefit and soil carbon emission in the peatland restoration scenario was £10,500 ha-1 due to the sequestration of carbon in the peat as the peat stock increased. Peatland conservation



Box figure 1: Peat depth change under different land use scenarios assuming no climate change (from: Graves and Morris 2013).

using extensive grassland management was also assumed to result in peat formation, providing a positive present value of £12,500 ha-1. The semi-intensive grassland use on the other hand also resulted in a much higher soil carbon emission cost then agricultural income benefit, and resulted in a negative present value of £17,000 ha-1.

Whilst this "dust bowl" 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 externality 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.

However, additional issues will need to be considered 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 affected by such interventions, is also highly political given the dependence on foreign labour for some farming practices. Another political dimension occurs considering how land management can affect water quality, water availability and flood risks in urban centres downstream, and how to balance the risks across different communities.

Case study 2: Collapse of AMOC

Existence of tipping point: As outlined above, models suggest increasing greenhouse gas emissions increase the probability that the North Atlantic overturning circulation (AMOC) will weaken or switch off. This may happen over a timescale as short as a few years, and, whilst unlikely, it could happen over the next decades. Although it is a climate example, some of the key impacts of AMOC collapse would be on global food systems. If we could predict AMOC collapse, its impacts on the food system would be a prime motivator for action – therefore we think it is reasonable to address here; how could or should we respond? Applying the ETTA framework to AMOC collapse we know that a potential tipping point exists, we are uncertain about its likelihood, but we know that likelihood increases with the magnitude of climate change (Kriegler *et al.*, 2009) and potentially also with the rate of climate change (Stocker and Schmittner, 1997).

Threat from the tipping point: Regarding the threat from AMOC collapse, the physical climate impacts have been outlined above and span (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 relatively rapid, global decline in productivity of the order of tens of percent, which could be unprecedented (given that a 10% loss of global calories has been suggested to be a 1-in-200 year return time event). Unprecedented global losses in production are likely to lead to unprecedented policy and market responses, leading to price rises significantly greater than have ever been seen. Looking across the whole economy, William Nordhaus has suggested that AMOC collapse could cause a 25-30% reduction in global GDP (akin to the Great Depression but permanent), but no one really knows what this figure is (Nordhaus and Boyer, 2000). Suffice to say, 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 currently increasing. Existing expert elicitation (Kriegler *et al.*, 2009) suggest 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. Therefore, on the centennial timescale, if there is no decisive action to limit global GHG emissions, AMOC collapse

24 The probability given here is not the annual probability of occurrence (which is what is more commonly used in risk assessments), rather the risk of it occurring over the time period. A 10% risk of AMOC collapse prior to 2200 might mean, of course, that it happens this decade, just as it may rain today even if the forecast chance is 10%.
25 http://www.fabians.org.uk/wp-content/uploads/2015/10/Hungry-for-Change-web-27.10.pdf

should not be seen as a "high impact-low probability" event; it should be viewed as a "high impact-high probability" event[24].

Alternatives to BAU: There are alternative trajectories with different outcomes, attendant costs and benefits. According to the same expert elicitation (Kriegler *et al*., 2009), if global warming were limited to around 3 degrees Celsius, the probability of AMOC collapse by 2200 drops to less-likely-than-not, approximately 20%, and if it is limited to less than 2 degrees Celsius, it drops to approximately 10% or less. These scenarios amount to different rates of decarbonising the global economy (with attendant costs) to get to net zero (or even net negative) global GHG emissions. For stabilisation at 3 degrees Celsius, GHG emissions need to cease around the end of this century, for stabilisation at 2 degrees Celsius they need to cease soon after mid-century and be followed by global-scale carbon dioxide removal (CDR) from the atmosphere (and for 1.5 degrees Celsius, they need to cease by mid-century and be followed by even-more-massive CDR). Such pathways are, of course, the subject of intense international negotiation and national action following the Paris Agreement.

Whilst the larger part of such mitigation efforts concerns non-agricultural parts of the global economy, the agri-food system accounts for about a third of global GHG emissions, including some of the hardest to mitigate (e.g. N2O emissions). Furthermore the greatest economic potential for CDR lies in alternative land-use systems notably 'biomass energy with carbon capture and storage' (BECCS), which themselves may impinge on food production (such as through requiring significant land and water resources). 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, and it contains its own non-linearities that could play a key role in determining the outcome. Notably, 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).

To follow low warming trajectories, and minimise the likelihood of AMOC collapse, will require markets today to recognise a relatively high social cost of carbon, well above that currently used in US Federal policy (Cai *et al*., 2015; Lontzek *et al*., 2015), which would require solid evidence that the benefits of avoiding the tipping point exceed the costs, all discounted. Were this to happen, it is likely to need carbon pricing on food to reflect the true cost of the externalities caused by food. This would incentivise changing demand away from carbon-intensive production and diets towards a low carbon lifestyle. However, such "TruCost" food could have undesirable consequences for the poor. Recognising this dilemma, the Fabian Society Commission Hungry for Change (2015)[25] concluded, "there must be a new focus on improving incomes rather than keeping prices artificially low" (page 21). Collective anxiety about crossing a tipping point might also lead richer consumers to help coordinate a global shift towards less carbon-intensive diets (Barrett and Dannenberg, 2012), changing social norms around meat-eating and reaping the associated benefits for personal health.

If action is too late or insufficient to avoid AMOC collapse, then the costs become those of adapting to its consequences. If this is retrospective action once 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 global poor, especially in import-dependent sub-Sharan African countries, with significant impacts on the local poor in every country. This would clearly represent more than a market failure for it transgresses sustainable development goals. It occurs because the externalities in this scenario are not marginal, and strongly suggesting that policy intervention is also needed in the case of AMOC collapse (just as it is needed to avoid AMOC collapse).

Such policy intervention could be in advance of AMOC collapse occurring (even it were unavoidable) and take the form of 'pre-emptive adaptation' investment to deal with changes in food availability. In general, the prospect of an approaching tipping point should lead to precautionary investments to help smooth

consumption (van der Ploeg and de Zeeuw, 2014). The question is then approaching the AMOC collapse what form could that investment take? The accumulation of food stocks is a very expensive option and one that would only ever be effective in the very short term. Nevertheless, until recently, China maintained stocks equivalent to 70% of annual consumption, partly because of the historical occurrence of major droughts and famines associated with millions of excess deaths (e.g. 1876-79, 1928-30, 1942-43, 1959-61), and partly to protect rural incomes. Accumulating capital and infrastructure that enables new agricultural opportunities to be exploited rapidly in the event of AMOC collapse would seem a more long-term effective approach. This is predicated on the natural science understanding that there will be climate change winners as well as climate change losers in an AMOC collapse scenario – including increased yield potential in some regions. It will also likely require global coordination and associate mechanisms for redistributing capital.

As, and when, increasing evidence for the likelihood of AMOC collapse is gathered, the finance community will 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 starts to be 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. Markets could respond by trying to re-value investments based on the new outcomes and attempt to price-in avoiding AMOC. However, the market imperfections and lack of timeliness that exists may make this very difficult and could lead to several markets crashes and re-alignments until market sentiment settles on what it considers to be the most likely outcome.

The transfer of risk to the insurance and reinsurance markets can be a very efficient method of transferring potential risk to capital markets, however there is limited potential to transfer all risk to markets. Insurers typically provide cover for relatively short time scales, with reinsurance programmes constantly changing and adapting to emerging risks and market competition. Insurers are able to react relatively quickly following large losses, and if the risk is perceived to be too great (or too frequent) then cover can be reduced, policy holder risk retention increased, or cover withdrawn completely. Should this be the case then risk will be pushed back onto the policy holder, governments, or society as a whole. Insurance seeks to price risk as efficiently as possible, but as most insurers underwrite for a profit some residual risk will remain. Some products can reduce the cost of risk to very low levels (parametric insurance products for example) but they tend to deal with only a handful of perils, so should be used carefully. Ultimately, insurance and risk management can positively influence sustainable behaviour by society, but may not be able to effectively respond to long term changes in risk or sharp corrections in risk profile.

Conclusions

- Tipping points in environmental systems do occur. 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 are likely to have profound local effects.
- Such tipping points matter for the food system. Extreme events – like widespread droughts -in the natural environment have been demonstrated to perturb food markets, and have contributed to food price spikes (in combination with other factors like export restrictions). Crossing an environmental tipping point has potential to contribute to market effects in a similar way, but with the "perturbation" being long-lived or even permanent.
- Furthermore, 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 damp each other's tipping points. The present paradigm that trade is typically beneficial is based on assumption that an open trading system will dampen shocks, which is certainly true for small shocks. 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. Greater research is needed to improve understanding of these risks.
- Early warning indicators of an approach to a tipping point can be increasing frequency of "extremes" (as the system " flickers" close to the critical threshold) prior to the permanent change to a "new normal". Even "local" tipping points (such as those associated with the creation of a dustbowl or a fisheries collapse) can contribute to supply shortfalls and potential for price spikes. Global scale tipping points like AMOC could change supply in an unprecedented way.
- The value of predictions crucially depends on their accuracy, and the trust placed in them. Establishing an evidence base supporting predictions that are trusted takes time (as shown from climate change mitigation negotiations). This time requirement may lock us in to the situation that we accept the evidence that something is likely to happen when the event is close-to-happening, reducing our ability to mitigate and increasing our requirement to adapt.
- If predictions about time horizons are trusted, and if the pathway to mitigate crossing the tipping point are understood (e.g. whether from avoiding over-fishing, or improving "soil health" or de-carbonising the economy) – and if public policies do not distort market responses - an environmental tipping point could lead to smooth market response and fewer price spikes in food.
- But often the market doesn't 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. There is a risk of a stand-off in market-policy interaction: the market expects government to carry the risks, and so does not cover them; whereas the government expects the market to work well.
- It may be possible to undertake a cost-benefit analysis in some depth. 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 frequently be the case that the actions taken are not those predicted by a cost-benefit analysis.
- Nonetheless, wider consideration of the risks posed by tipping points might inform individuals and market actors and help prompt mitigating actions. As the UK's Climate Change Risk Assessment Report (2012) report concludes: "[A] risk-based approach, and planning properly for the long term for a range of futures, is a big challenge. Tackling that challenge successfully will allow us to protect and enhance our economy, society and environment both now and for future generations."
- There are at least three reasons that underpin people's willingness to make behavioural changes (e.g. to change food preferences to mitigate the environmental costs of production). Firstly if the risk is local and/or observable, secondly if it is likely to occur in a short timescale, and finally if their actions have direct impact on the risk. For example, with cod fisheries it is clear that it is overfishing that caused the collapse, the impact was directly on the livelihood of the fishers and the reduction in fish available to

catch was observable year on year. In this case both consumers and fishers find it relatively easy to understand what the issue is and to see how their behaviour change could have impact. However, with an issue such as the slowing or collapse of the AMOC, the event is unlikely to happen in an urgent timeframe, it is not immediately evident that it is happening, and it is not clear how an individual could improve things. The lead would need to come from policy or markets.

- If a tipping point is inevitable, even if we are able to predict it accurately and make contingency plans then there is still likely to be a transient period where there is a large amount of variability in the system which will make the food availability unpredictable. This is where food storage might become more cost effective in the medium term to smooth over those variations.
- There is no "zero sum game" (where there are no overall losers) in the handling of tipping points in the food system. Many people depend on non-sustainable food production regimes on the land and seas and coasts where tipping points are almost inevitable. To take them away from their currently viable livelihoods without well prepared plans for their safeguard could result in great injustice and possible political instability to say nothing of food insecurity. To address tipping points in any food system requires great sensitivity to risk based assessments and large amounts of carefully managed local participation by means which are demonstrably inclusive and interactive. In this setting adherence to sustainable development goals with all of their important interconnections, provides a valuable guide.
- Our discussions outlined here define a wider research agenda.
    - Whilst there is good evidence that alternative states can exist, both in environmental and socio-economic systems, and critical transitions can occur between them, there is little understanding about how environmental and socio-economic systems may respond to each other's potential tips.
    - For environmental systems, we need better knowledge of both whether tipping points are likely, as well as the magnitude of their effects and their geospatial coherence: if something happens to European soils, are similar drivers likely to create impacts in other locations?
    - We need better understanding of how the proximity of tipping points can be predicted. These include both proxies based on the underlying systemic state (e.g. how does soil carbon inform the likelihood of strong erosive events? Or how is a decline in biodiversity likely to inform collapse of pollination services?) and also dynamic "early warning" indicators
    - Given that it is easier to forecast impending doom than to act on the prediction, we need a more nuanced understanding of decision making under risk and uncertainty. This includes understanding better the optimal control of risks (i.e. minimising both risk and cost of control).

Glossary

Diagrams may help. Outline definition(s) and link concepts

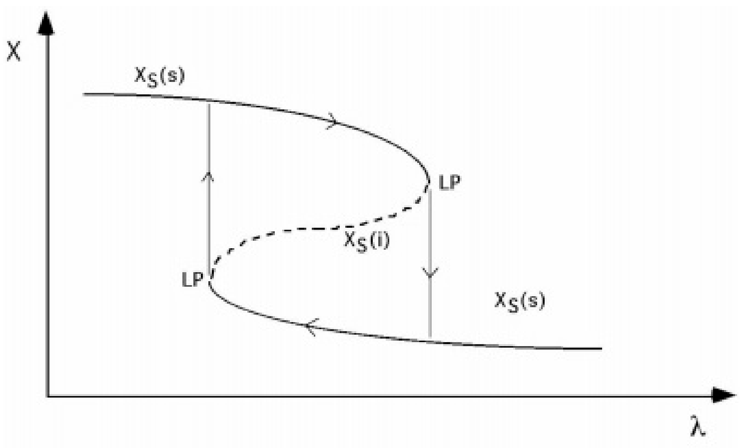
- **Hysteresis** – hysteresis occurs when the incremental increases lead to the switch between states, but then incremental decreases do not immediately (or perhaps ever) take you back to the original state (see figure).

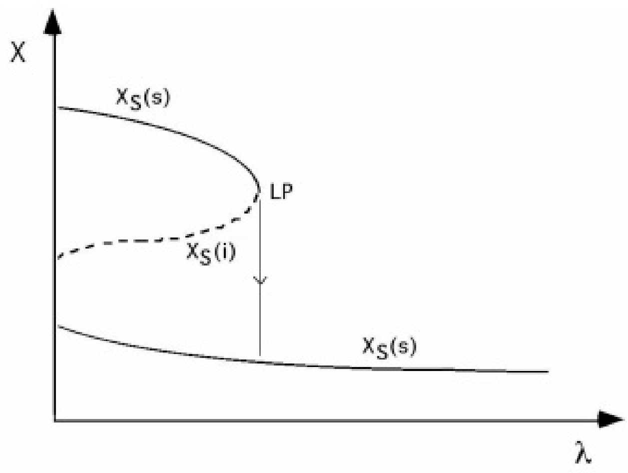
- **Resilience** (engineering and ecological) – Two conceptual definitions of resilience are widely used in systems science, generally referred to as ecological resilience and engineering resilience. Ecological resilience is based on the concept of (Holling, 1973) and has been defined as the capacity of a system to tolerate disturbance without changing to an alternative configuration, and is therefore important for maintaining desired ecosystem functions (e.g. (Myers-Smith *et al*., 2012)). In contrast, engineering resilience is based on the concept of (Pimm, 1984) who defined resilience as the time taken for a system to return to its pre-disturbed, stable "state". Thus engineering resilience is a measure of the dynamics of the system in the region of a stable equilibrium. These definitions, however, are in a state of flux in the current literature (e.g. (Desjardins *et al*., 2015; Xu *et al*., 2015)).

- **Resistance** – in contrast to resilient systems, resistant systems remain rigid and unyielding in response to increasing frequency and magnitude of disturbance, until they reach a point where they shatter – in other words, they are "brittle", like a pane of glass. This might be because the system behaviour is "locked-in" to specific ways of working.

- **Tipping point** – Tipping points occur when a system moves from one stable state to another, where a stable state is one that is resilient to small perturbations. Several types of tipping point have been identified from a mathematical point of view. These include (i) 'noise-induced tipping' from one basin of attraction to another (as per Figure 3), (ii) 'bifurcation-tipping' as per Figure 4 where a basin of attraction disappears, and (iii) 'rate-induced tipping' where a critical rate of forcing causes an abrupt change. Within these categories one can make further distinctions, for example within (ii) bifurcation tipping can encompass shifts between alternative fixed point ("equilibrium") attractors ("critical transitions") and also transitions between e.g. a stable fixed point and a limit cycle (persistent oscillation), or vice versa. The former is more likely to be irreversible, in the sense of hysteresis (see below). In the real world one must also consider a different kind of irreversibility – that of species extinctions.

- **Value of information** – quantitative assessment of monetary value associated with knowledge, advice or data provided to a given decision-maker, based on the user-specific costs and losses associated with different outcomes, decisions, and a judgement of the accuracy of the information.





Figures: For our example, λ is the gradually changing driving variable e.g. farming intensification, x is, for example, soil quality. In the left hand graph, starting on the left hand side and following the arrows, as intensification is increased then the soil quality slowly decreases until the point LP when it drops significantly to another state. If the intensification is then decreased we cannot immediately jump back up to the original state, we have to decrease the intensification much more before the system recovers back to its original state. In the right hand graph it is not possible to recover because intensification cannot be reduced enough to allow the system to recover. Both graphs show hysteresis (graphs taken from http://homepages.ulb.ac.be/~dgonze/TEACHING/nonlinear.pdf)

Appendix A – examples of tipping points

Many of these examples originally derived from (Walker and Meyers, 2004)[26].

- **The Dustbowl.** In the US mid-west in the 1930s, what was, for the time, apparently stable and productive agricultural production was perturbed by drought. Failure of crops, and thus farm enterprises, left land bare leading to significant soil erosion (over 20m ha of land lost up to 10cm of soil) which intensified the drought through surface-climate feedbacks (Donald, 2004; Cook et al., 2009; Fraser, 2013). Loss of functionality from erosion led to very long-term impacts on productivity and land value (Hornbeck, 2009).
- **Desertification through over-grazing.** In the southern Sahel*, rapid increase in the populations of people and livestock has resulted in overgrazing from the 1950s onwards, prior to which the local population was sustained by a stable agricultural system. Constant intensive grazing destroyed the rootstock of palatable perennial shrubs, giving way to short-lived, shallow rooted annuals. Subsequently, the annuals were grazed out, leaving a landscape of bare soil and shallow rooted unpalatable shrubs. Much of the topsoil, along with its nutrients, was blown or washed away, leaving bare rock. Silt, which settled in drainage areas, baked hard after rain. Roots could not penetrate this hard layer and no germination could occur. The grasslands have been replaced by desert (Sinclair and Fryxell, 1985). In a similar way, over-grazing in Australia's rangelands has led, in places, to permanent vegetation changes*. Heavy grazing of the perennial grasses leaves the soil exposed. A soil crust forms, water infiltration decreases and soil erosion increases, with an associated loss of nutrients. The germination of perennial seeds decreases, further reducing vegetative biomass (Fernandez et al., 2002), leading to a stable low-vegetation state.
- **Salinization*.** Salt typically accumulates in groundwater (Rengasamy, 2006), and in arid zones, the water table is often deep and very saline. Changes in vegetation (e.g. removal of deep-rooted trees to make way for agriculture) can reduce evapotranspiration and bring the water table upwards. If the soil is inundated (e.g. irrigation, seasonal rainfall) salts can be brought upwards by capillary action. This can lead to degradation in soil function if the concentrations are sufficient to impede plant growth. Two potential thresholds are covered in this example. First the threshold of the loss of sufficient deep-rooted perennials to raise the water table; second the amount of salt brought into the root zone. A historical example of salinization is the Sumerians in ancient Mesopotamia (Southern Iraq today) who first had to switch from wheat to more salt tolerant barley and lost yield in so doing, and then lost the ability to grow barley leading to civilisation collapse (Artzy and Hillel, 1988).
- **Forest-savannah hysteresis.** There is a significant body of evidence that there can be a tipping point between two stable ecosystems: forests and savannahs/grasslands. Both evapotranspiration-rainfall feedbacks (Da Silveira Lobo Sternberg, 2001), and fire feedbacks (Hirota et al., 2011; Murphy and Bowman, 2012) are important. Forests tend to stimulate more rainfall through enhancing convection, due to their low albedo relative to other land-use types, and returning vast quantities of moisture to the atmosphere, through evapotranspiration. For example, air that has passed over tropical forests can produce twice as much rainfall as air that has not (Spracklen et al., 2012). If forest cover is reduced, positive feedbacks may reduce rainfall and hasten the transition to savannah. Forests also tend to suppress fires whereas grasslands 'encourage' fires and have numerous fire-adapted traits – producing a positive feedback. In pre-historical times, fire was the likely cause of the tip from forest to grassland (Hirota et al., 2011; Murphy and Bowman, 2012). In historical times, clearance of forest for agriculture has been identified as the main cause for fire. Indeed, there is some evidence that deforestation around the Mediterranean, initiated largely during the Roman Empire, has contributed to the drying of regional climate (Reale and Shukla, 2000). Deforestation is also, in some cases, also linked to desertification through reduced precipitation and soil loss, following storms (Millán et al., 2005) . In addition to these impacts, changes in forest cover in tropical regions can alter convection patterns, stimulating rainfall on the crop/forest boundary (Garcia-Carreras and Parker, 2011). Hence, anthropogenic deforestation can initially stimulate rainfall on the new cropland, but after a certain point, can also reduce rainfall to the detriment of both forest regeneration and productive agriculture.
- **Over-fishing and trophic change.** Rock lobsters are an important fishery in South Africa*. Rock lobsters are active predators and scavengers that, although preferring to feed on mussels, will eat many different animals including whelks (predatory snails). In areas where lobsters are abundant, they appear to operate as keystone predators, regulating their prey at relatively sparse densities, thereby allowing the establishment of other species such as seaweeds. Under these conditions, whelks cannot become numerous enough to mass-attack and kill lobsters. If lobsters are removed from an area, for example because of over-fishing or hypoxia-events, the whelks become common, and, in turn, suppress lobster populations – a case of predator-prey reversal.

*26 Some have been collected into a database: Resilience Alliance and Santa Fe Institute. 2004. Thresholds and alternate states in ecological and social-ecological systems. Resilience Alliance. (Online.) URL: http://www.resalliance.org/thresholds-db. We take many examples from this database, and lightly edit their summary descriptions. These examples are acknowledged by the symbol *.*

- **Shifts in climate leading to change in yields.** The regionalisation of the Mayan agricultural system provided a buffer against fluctuating productivity with climate variability*. It included a diversity of agricultural production systems, from high altitude to coastal plains. This allowed “spatial buffering”; if production was low for one product from one place, it could be compensated for by abundant production in other areas. The population of the region increased to as many as three million people, with high densities in the political centres. Farmers not only had to provide food for the growing population, but also had to support the costs of an elite hierarchy, investment in large construction, hydraulic and agricultural infrastructure, and the administration of growing regional domains. As the population increased, the marginal returns deteriorated. Regionalisation expanded and agricultural domains became homogenised. For example, the lowlands had little diversity and the clearing of large areas of rainforest would have reduced that diversity still further. Society was already under stress at the beginning of the 9th century when there was an abrupt shift to more arid conditions for approximately 200 years (800-1000 A.D.), an event that occurred several times during the late Holocene, altering ocean circulation and terrestrial climate (Hodell et al., 1995). On uniformly low yields, the Maya could not feed its dense population, let alone continue to pay for other societal costs. Groups with little food would raid neighbouring groups to make up for their deficit. Population pressure, warfare and socio-political complexity were systematically linked. The collapse was swift, over a few decades, with population numbers falling from approximately three million people down to 450,000 people. The larger centres such as Tikal may have lost up to 90% of their population. This example shows a shift decline in both the ecological system (agricultural productivity) and the social system (human occupation) (Tainter Joseph, 1988).

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