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Operationalising Positive Tipping Points towards Global Sustainability

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Operationalising Positive Tipping Points towards Global Sustainability

Abstract

Non-Technical Summary

Transforming towards global sustainability requires a dramatic acceleration of current progress. Hence there is growing interest in finding 'positive tipping points' at which small interventions can trigger self-reinforcing feedbacks that accelerate systemic change. Examples have recently been seen in power generation, personal transport, and lighting. But how to identify positive tipping points that have yet to occur? We synthesise theory and examples to provide initial guidelines for creating enabling conditions, sensing when a system can be positively tipped, who can trigger it, and how they can trigger it. All of us can play a part in triggering positive tipping points.

Technical Summary

Recent work on positive tipping points towards sustainability has focused on social-technological systems and the agency of policymakers to tip change, whilst earlier work identified social-ecological positive feedbacks triggered by diverse actors. We bring these together to consider positive tipping points across social-ecological-technological systems and the potential for multiple actors and interventions to trigger them.

Established theory and examples provide several generic mechanisms for triggering tipping points. From these we identify specific enabling conditions, reinforcing feedbacks, actors, and interventions that can contribute to triggering positive tipping points in the adoption of sustainable behaviours and technologies. Actions that can create enabling conditions for positive tipping include targeting smaller populations, reducing price, improving performance, desirability and accessibility, coordinating complementary technologies, providing relevant information, and altering social network structure. Actions that can trigger positive tipping include social, ecological, and technological innovations, policy interventions, public investment, private investment, broadcasting public information, and behavioural nudges.

Positive tipping points can help counter widespread feelings of disempowerment in the face of global challenges and help unlock 'paralysis by complexity'. A key research agenda is to consider how different agents and interventions can most effectively work together to create system-wide positive tipping points whilst ensuring a just transformation.

Social Media summary

We identify key actors and actions that can enable and trigger positive tipping points towards global sustainability.

Introduction

Tipping points are where small interventions lead to large and long-term consequences for the evolution of a complex system, profoundly altering its mode of operation (Gladwell, 2000; Lenton et al., 2008). Such highly non-linear response is usually hard to reverse, and tipping points can interact across systems, spatial and temporal scales (Lenton, 2020). Crucial to their occurrence is the presence of strongly reinforcing positive feedback within a system, which can amplify a small initial change and turn it into a large consequence.

The recognition of 'bad' tipping points in the climate, ecological, and biogeochemical systems was key to identifying and setting several of the 'planetary boundaries' (Rockström et al., 2009). Recently, evidence that such tipping points may be approaching has underpinned declarations of a climate and ecological emergency (Lenton et al., 2019). This in turn has led to increasingly ambitious targets to tackle climate change and reverse biodiversity decline – notably the target of limiting global warming to 1.5°C. But such targets demand transformative rates of societal change – including a roughly 7% per year continuous decline of greenhouse gas emissions from now on (Otto et al., 2020). Hence, there is a growing consensus that we need to identify and trigger 'positive tipping points' (or 'sensitive intervention points') to accelerate progress to achieve the required, transformative rates of change (Farmer et al., 2019; Jordan et al., 2010; Lenton, 2020; Otto et al., 2020; Sharpe & Lenton, 2021; Tàbara et al., 2018; Totten, 2012; van Ginkel et al., 2020; Westley et al., 2011).

A defining quality of such positive tipping points is that they are intentional. Transformative change can happen in any sufficiently complex adaptive system (Levin, 1998) without anyone willing it to happen. It requires innovations occurring within a system that instigate feedback processes and are subject to some filtering or 'selection' process (Lenton et al., 2021). For example, in Earth history there were several pivotal 'revolutions' long before humans evolved (Lenton & Watson, 2011). Several 'revolutions' in human history also appear unintentional e.g. the Neolithic revolution or the industrial revolution. There may have been human intent at the level of planting seeds or inventing a steam engine, but those innovators did not intend to revolutionise the world. Other large-scale human 'revolutions' are portrayed as intentional, notably the 'green revolution' (driven by a relatively small group of actors intent on radically increasing food production) – but there was still a rich mix of intentional and unintentional change at play. Now that we are explicitly considering collective, intentional transformation towards global sustainability, we are entering arguably unique territory (Lenton & Latour, 2018). As such we need to draw some sort of 'map' to guide the initiation of positive tipping points, and we should be aware that existing 'maps' are likely to have limitations.

The emerging body of work identifying candidate 'positive tipping points' has recently focused on social-technological systems and the agency of policymakers to tip change in the macro-economy (Farmer et al., 2019; Otto et al., 2020; Sharpe & Lenton, 2021). However, earlier work identified multiple social-ecological examples triggered by diverse actors (Marten, 2005). By including ecological change, the opportunities for positive tipping are enriched because ecological systems can have their own tipping dynamics (Scheffer, 2009), and other living things in those systems also have the agency to tip change (Latour & Lenton, 2019). Transformation towards global sustainability must necessarily occur across coupled social-ecological-technological systems, and these may have novel reinforcing feedbacks and tipping points in their coupled dynamics.

Positive tipping points offer hope for accelerating change to avert climate and ecological emergency, but crucial practical questions are how to identify and trigger them. The emerging literature is rather theoretical, speculative, and rarely specific enough to guide actions. Mathematical theory highlights multiple potential tipping mechanisms and associated reinforcing feedbacks (Zeppini et al., 2014), but needs to be translated into specific contexts to guide deliberate tipping. Recent examples of positive tipping points in power generation, personal transport and lighting can provide useful clues to effective action (Kamat et al., 2020; Sharpe & Lenton, 2021). A much larger set of previous social-technical transitions can also provide guidance – even if they were not towards a more sustainable state. That is the foundation of 'Transitions Management' theory (Rotmans et al., 2001) and the associated 'Multi-Level Perspective' (Geels, 2002). It highlights how transformation usually starts in niches before accelerating up an 'S curve' trajectory (and eventually saturating as the new normal). However, in being guided by how change has happened in the past it may foreclose the possibility that change can happen differently (and faster) in the future.

Other established frameworks can help operationalise positive tipping points, in particular systems thinking and Donella Meadows' 'leverage points' framework of places to intervene in a system (Abson et al., 2017; Leventon et al., 2021; Meadows, 1999, 2008; Schlaile et al., 2021). We focus on strengthening reinforcing feedbacks as a key leverage point, but recognise that weakening negative feedbacks exerts comparable leverage, and the most powerful leverage points are those that change the intent of a system (Meadows, 1999, 2008). Meadows' conception of 'intent', derived from cybernetics, does not imply conscious purpose on the part of a system[1] – but trying to instigate positive tipping points is all about putting some conscious 'intent' into social-ecological-technological systems. This needs to be combined with an understanding of complex adaptive systems, but complexity science rarely references leverage points (Holland, 2014). The 'panarchy' framework begins to bring them together, recognising that in a 'reorganisation phase', small (chance) events can have a disproportionate impact in a system, because many system connections were previously broken in a preceding 'release phase' – usually as a result of some crisis (Gunderson & Holling, 2002).

Our aim here is to start to operationalise positive tipping points by synthesising established theory and lessons from past examples, to offer guidance on finding potential future tipping points and associated interventions and actors that could trigger them, and to frame a further research agenda. The paper is structured as follows: Section 2 synthesises existing theory pertinent to identifying positive tipping points. Section 3 draws out a recipe to begin to operationalise the theory – offering some guidelines for those keen to trigger positive tipping points. Section 4 discusses an agenda for further research. Section 5 concludes.

Positive tipping points theory

First, we synthesise relevant existing theory and models of tipping points, relating them to some specific examples. After outlining the challenge, we take a particular mathematical entry point to conceptualising positive tipping points (Figure 1), recalling that "all models are wrong, but some are useful" (Box, 1979) and recognising the limitations of our chosen approach.

Intent and the need for speed

It would appear critical to global sustainability transformations that some human actors are discontent with the current state of a system and have a vision of a desired state they want to transform towards – such as net zero greenhouse gas emissions. They may also have some specific goals they want to achieve to get towards their vision – such as halving greenhouse gas emissions by 2030 and reaching net zero by 2050. Having a vision of an alternative state and associated goals – especially if they are widely and democratically agreed upon – is a potentially powerful motivation for transformative change (Schot & Steinmueller, 2018). But just wanting change to happen is not sufficient to make it happen – that needs practical action guided by a valid model of how transformative change can occur. This must recognise that there are usually other actors with different intents – including those who oppose change – exercising their agency as well.

The 'Transitions Management' literature argues that such systemic change is inherently slow, providing estimates ranging from >20 years for sustainable technology innovations (Gross et al., 2018), to "one generation or more" for a socio-technical paradigm shift (Grin et al., 2010). That sounds like a counsel of despair because sustainability transformation must now happen considerably faster than that. However, in past socio-technical transitions there were things that diverse actors could and did do to accelerate change (Victor et al., 2019). Hence their pace was not predetermined. Looking ahead much work has already been done on multiple fronts towards sustainability transformation – but we still need to trigger it! This brings us to an approach to modelling positive tipping points.

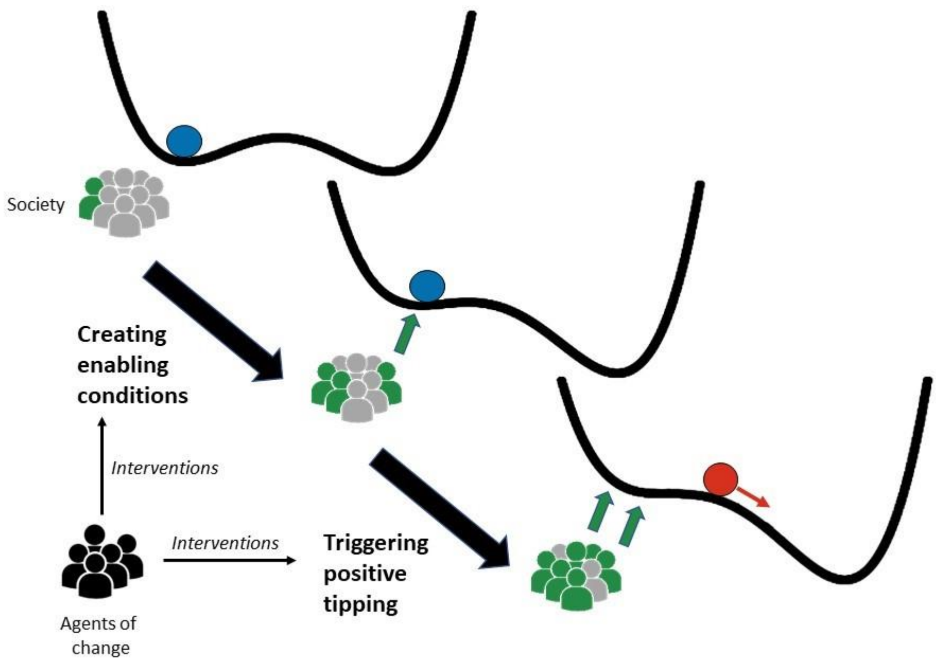

Figure 1: A dynamical systems conceptualisation of positive tipping points.

Dynamical systems approach

At a tipping point, a small perturbation can trigger a large response from a system, sending it into a qualitatively different future state (Figure 1). The notion that a system has alternative dynamically stable states (or 'attractors') and can transition between them means that it contains both negative and positive feedback loops and their relative strength can change. A predominance of negative feedback creates and maintains a dynamically stable state. At a tipping point, positive (reinforcing) feedbacks get sufficiently strong to (temporarily) dominate the dynamics, propelling self-amplifying change between alternative stable states. Thus, any attempt at deliberate tipping needs to seek to trigger strongly reinforcing positive feedback loops – and it may also seek to weaken negative feedbacks that maintain the incumbent state.

A tipping point is a special 'place' or point – we should not expect a system to naturally reside close to one – unless it belongs to a special class of systems that exhibit 'self-organised criticality' (Bak et al., 1987). To bring a system to a tipping point typically requires some *forcing* – i.e. a change in boundary conditions – in a direction that weakens balancing negative feedbacks maintaining the initial state and/or strengthens reinforcing positive feedbacks that amplify change (Meadows, 1999, 2008). Hence there is typically an important phase that precedes the 'triggering' of a positive tipping point: work first needs to be done to create *enabling conditions* (Figure 1). Once nearby, a tipping point may be triggered by a further small change in these boundary conditions or by a small change in a relevant feature of the system. Here we distinguish between *system features* in which a tipping point change may occur, and *control variables* which can bring a system feature to (and past) a corresponding tipping point.

A key challenge in identifying tipping points is thus to identify the critical control variable(s) and features of a particular system. This may seem daunting because there are usually many variables in a complex system. But crucially, the behaviour of a complex system near a tipping point can simplify dramatically such that often just one control variable dominates the behaviour (in mathematics this is the centre manifold theory (Carr, 1982)). That control variable itself may be a mathematical combination of other variables.

Clearly this conceptualisation (Figure 1) is an incomplete representation of complex, co-evolving social-technological-ecological systems. It does not capture their endogenous evolution, and it treats the intentional actions of agents within the system who want to trigger positive change as if they were external forcing factors. But it is meant to be viewed as a partial model of the key dynamics of tipping points, which helps such agents start to formulate interventions.

Existing tipping point models

We now turn to identifying different types of tipping point that can occur in social-technological-ecological systems, their critical control variables, and the reinforcing feedback loops that can propel them (Table 1). There are several models, each capturing different yet overlapping aspects of tipping point dynamics. These models are reasonably well known in their respective academic disciplines, but rarely considered together. We start in the social-technological domain, with models of tipping point dynamics in the 'diffusion' of new norms, behaviours, and technologies through society – elegantly summarised by Zeppini et al. (2014). Then we move to the social-ecological domain.

Table 1: Relevant tipping point models, building on (Zeppini et al., 2014).

Tipping model	Micro-foundations	Key positive feedback(s)	Form of tipping point	Control variables	Key reference(s)	Sustainability examples
Social/behavioural contagion	Imitation, heterogeneous agents	Adoption makes it easier for the next person to adopt	Critical mass	individual adoption threshold distribution, social network structure	(Granovetter, 1978)	Rooftop solar PV, household energy behaviours, EV uptake
Increasing returns	Utility maximisation, homogeneous agents	Technology becomes more attractive the more existing users there are	Critical mass	population size, difference in quality to incumbent technology, strength of increasing returns	(Arthur, 1989)	Solar PV, wind power, lithium-ion batteries
Coordination game (network effect)	Utility maximisation, homogeneous agents	Coordination on a new technology suite gives a superior payoff to an existing technology suite	Critical mass	population size, benefit and cost of new technology, payoff from old technology	(Kandori et al., 1993)	EVs and charging infrastructure
Informational cascades (herding)	Utility maximisation, heterogeneous agents	Adopter expectation based on previous adopter decisions	Critical mass	cost of adoption, probability of future gain, public information	(Bikhchandani et al., 1992)	Organic farming
Percolation	Utility maximisation, heterogeneous agents	Word-of-mouth diffusion depends on neighbours' willingness to adopt	Critical price	cost, number of starting seeds, network connectivity	(Solomon et al., 2000)	?
Co-evolution	Utility maximisation, heterogeneous agents	Payoff depends on choices made by coupled others	Between fitness maxima	number and fitness of components, degree of coupling, governance	(Kauffman & Johnsen, 1991)	?
Ecological	Ecological agents	(many)	(many)	(many)	(Biggs et al., 2018)	Lake recovery
Social-ecological	Utility maximisation, homogenous agents	Social ostracism of non-cooperating resource harvesters	Critical mass & resource level	Resource inflow, effort cost, ostracism strength	(Lade et al., 2013)	Marine protected areas

Critical mass, diffusion of innovations, and social contagion

Several models of innovation diffusion display a tipping point in terms of a **critical mass** of individuals that once reached can tip most (or all) of the population to adopt. The critical mass is a sufficient number of adopters of a new idea, technology or innovation such that the rate of adoption becomes self-sustaining and creates further growth. The concept of a critical mass is central to Diffusion of Innovations theory (Rogers, 1962), which crystallised from studies of the spread of agricultural technologies in the United States in the 1920s and 1930s. It characterises the uptake of innovations as an 'S-curve' and classifies human populations into successive fractions defined in terms of their propensity to adopt innovations (Table 2). New ideas, products or behaviours start with innovators, then early adopters, followed by an early majority, then a late majority, and finally the laggards. Along this trajectory, the products mature, and their functionality improves as a result.

Table 2: Diffusion of Innovation theory classification of populations, following (Rogers, 1962).

Category	Description	% of population
Innovators	are the first to try a new behaviour, product or idea (may even be its creator).	~2.5%
Early adopters	are comfortable with innovations and cognizant that change is often inevitable.	~13.5%
Early majority	must see evidence of the innovation's worth prior to their adoption of it.	~34%
Late majority	are sceptical and more reluctant to embrace change, only adopting an innovation once it becomes the norm in their society.	~34%
Laggards	are bound by tradition and suspicion and dislike change.	~16%

The original mathematical formulation of a critical mass tipping point was in a model of metropolitan segregation (Schelling, 1971)[2]. It was later generalized to a wide range of social phenomena (Granovetter, 1978; Schelling, 1978). The underlying positive feedback of **social contagion** occurs when adoption of a norm or behaviour makes it easier for the next person to adopt it, through imitation (Granovetter, 1978). People are assumed to be heterogeneous with different individual thresholds for adoption of a new norm/behaviour (above which it is beneficial to them), and that threshold depends on how many others have adopted – i.e. people vary in the extent to which they are influenced by others. Adoption does not depend on any qualities of the norm/behaviour. The model can produce cascades within a population, including where one person adopting is sufficient to trigger the whole population to ultimately adopt, but just a small variation in another individual's threshold can prevent this (Granovetter, 1978). Variants of the model consider no preferential influence, or social structure where friends have a higher influence on individual decisions (Granovetter, 1978). The critical mass tipping point for social contagion depends on the distribution of individual thresholds for adoption and on social network structure (Centola et al., 2018). Social contagion underlies accelerating adoption of some sustainable behaviours – for example, the uptake of rooftop solar photovoltaic (PV) systems (Graziano & Gillingham, 2014) and other household energy behaviours (Wolske et al., 2020).

Most of us require a sense of self-efficacy (ability to deal individually with a problem) to adopt pro-environmental behaviour, and a sense of collective efficacy (ability as a group to deal with a problem) can reinforce self-efficacy (Jugert et al., 2016). Values endorsed by our peers can be more important than facts or 'experts' in changing our beliefs and actions. Once a critical mass tipping point is reached, pressure to conform to a collective identity can propel social contagion. Controls on the steepness of the S-curve have been widely studied, e.g. in marketing science, and support social contagion as one mechanism (van den Bulte & Stremersch, 2004). Specifically, greater income inequality, and cultural factors including greater collectivism, power distance, and masculine values can steepen the S-curve[3], meaning change starts later but happens faster once underway (van den Bulte & Stremersch, 2004). However, competing technological standards are more powerful than cultural or economic effects in deterring early adoption but supporting faster change once underway (van den Bulte & Stremersch, 2004). This is consistent with the qualities of norms/behaviours/technologies affecting adoption. This leads to other models with a critical mass tipping point that hinge on different reinforcing feedbacks (Zeppini et al., 2014), to which we now turn.

Increasing returns, coordination, and herding

The positive feedback of **increasing returns** to adoption occurs when a technology becomes more attractive (in quality or price) the more fellow users already use a technology (Arthur, 1989). Several important positive feedbacks can underlie increasing returns, including: **learning by doing** – the more something is done/made, the better it can be done/made (Arrow, 1962); **economies of scale** – the more something is done/made, the more efficiently/cheaply it can be done/made (Bejan et al., 2017), and; **technological reinforcement** – the more something is used, the more technologies emerge that make it more useful. A critical mass of adopters of a new technology can trigger a tipping point where increasing returns and associated adoption becomes self-propelling. That critical mass depends on any difference in quality to the incumbent technology and the strength of increasing returns (Zeppini et al., 2014). Striking examples of increasing returns in sustainable technology uptake are the declining price of renewable energy with increasing deployment (Green, 2019; Kavlak et al., 2018), and of the batteries used in electric vehicles (EVs) (Nykvist & Nilsson, 2015). An increasing returns tipping point can be affected by technology developers, governments supporting them, and consumers acting as the critical mass.

Technological reinforcement can also lead to a distinct critical mass **coordination tipping point**. This can occur thanks to the **network effect** whereby different members of a population must coordinate on a new technology suite to get a superior payoff from it than an existing technology suite. Think of electric vehicles and charging points compared to petrol/diesel cars and refuelling garages. The 'players' in such a 'game' could be technology developers, deployers, or users. The critical mass of coordinators required depends on the benefit and cost of the new technology relative to the payoff for coordinating on an old technology suite (Zeppini et al., 2014). Furthermore, the benefits and costs of a new technology may be subject to positive feedbacks of increasing returns. A coordination tipping point can be affected by firms coordinating, government helping them coordinate, and policy incentives altering the payoffs (e.g. by altering subsidy regimes). Also, if governments coordinate internationally to align their policies in support of the same set of technologies, this strengthens increasing returns.

A different type of critical mass tipping point occurs with **informational cascades** leading to **herding** behaviour (Banerjee, 1992; Bikhchandani et al., 1992). Here positive feedback can occur when each potential adopter of a behaviour forms an expectation (of the payoff) based on the decisions of previous adopters. It can be rational for an individual to behave (e.g. adopt a new technology) based purely on the behaviour of those before them, disregarding their own information. The strength of the positive feedback decreases with adoption. Hence herding cascades can be both initiated by information and stopped by new public information (Bikhchandani et al., 1992). This suggests the creators (e.g. researchers) and broadcasters (e.g. media) of new public information have the agency to change the tipping dynamics. There is evidence of informational cascades in the adoption of organic farming practices (Chatzimichael et al., 2014).

A crucial question is in which fraction of the population is critical mass reached? Clearly it depends on the model and various contextual factors highlighted. It can be just one person (Granovetter, 1978), but typically it is in the range 10-40% of the population, with ~25% being a popular rule of thumb (Centola et al., 2018; Rogers, 1962). Thus, it could lie within the innovators, the early adopters, or the early majority (Table 2). Importantly, early adopters 'help' in developing a solution, buying into the promise, serving as early testers, and providing feedback. In contrast, the early majority typically need evidence of an innovation's worth to adopt. Thus, new behaviour/technology itself changes as it finds more adoption.

Percolation and co-evolution

Other models of social-technological tipping points are not defined in terms of critical mass.

The spread of new norms or behaviours by word-of-mouth recommendation through social networks can lead to a **percolation threshold** if people vary in their willingness to adopt (Solomon et al., 2000). Above a critical level of cost that deters adoption, an innovation can fail to spread from an island of early adopters to the rest of the population (who are never exposed to it). Below that critical cost threshold, which also depends on the number of starting seeds and the network connectivity, an innovation will diffuse throughout a population (Zeppini et al., 2014). Any of us can be starting seeds for the spread of innovation and thus affect the number of those. Network connectivity is itself endogenously evolving with the internet and social media. The critical level of cost can be altered by other reinforcing feedbacks of e.g. increasing returns.

In the development of interdependent technologies there can also be **co-evolution tipping points** between different stable states in the 'fitness landscape' of a suite of coupled technologies. In this model, the fitness of a specific technology depends on the design state of other coupled technologies (Kauffman & Johnsen, 1991; Kauffman & Macready, 1995). For example, the fitness of wind and solar power depends on the design state of energy storage and grid technologies. The model system readily gets locked into local fitness maxima but changes in governance can trigger tipping points to higher fitness maxima. Importantly, neither top-down or more localised governance interventions are universally more effective, outcomes are path-dependent (Zeppini et al., 2014). Co-evolution is of course not limited to the social-technological realm, nor are reinforcing feedbacks.

Tipping mechanisms involving ecology

Ecosystems contain diverse positive feedbacks some of which can get strong enough to generate tipping points, for example in coral reefs, rangelands, and lakes (Scheffer et al., 2001). These are often called 'regime shifts' and there is a database of numerous examples (Biggs et al., 2018). There are also many models of specific ecosystems and their specific tipping points. Most of the literature focuses on bad tipping points triggered by human activities, e.g. lake eutrophication, but positive feedback can always operate in either direction. Positive tipping points towards preferred ecological states have been achieved, e.g. restoring lakes to a clear water state. Notably, however, the positive tipping point for recovery usually requires a much larger change in a critical control variable than what caused the original, bad tipping point. This is because they are different tipping points that bound a region of 'bi-stability' where two alternative states are stable.

There are also social-ecological positive feedbacks – reinforcing interactions between changes in society and ecology (Marten, 2005). For example, marine protected areas rejuvenate fisheries causing people to create additional marine protected areas (Mascia & Mills, 2018). If positive feedback is strong enough this can generate tipping points that are not present in either system alone. For example, a modelled tipping point between avoiding over-exploitation of a common-pool resource (such as fish stocks) through social ostracism of non-complying harvesters, and breakdown of the social norm, collapse of cooperation and over-exploitation of the resource (Lade et al., 2013). Other generic models consider how tipping points in both social and ecological systems that are coupled interact (Mathias et al., 2020).

Finally, there must be positive feedbacks where reinforcing changes in society, technology and ecology are all coupled together. The 'green revolution' would appear to be an example where increasing population, food production, and proliferation of new technologies all fed back to amplify each other. However, there is relatively little literature on social-technological-ecological systems (Ahlborg et al., 2019) and hence a shortage of models of associated tipping points.

Upward-scaling tipping cascades

Sometimes, in interconnected complex systems, the activation of one tipping point can increase the likelihood of triggering another at a larger scale, and so on (Lenton, 2020). Such an 'upward scaling tipping cascade' can progress in time (towards a greater degree of permanence), in space (expanding to affect a larger geographical area), or across system boundaries (e.g. from a product, to an economic sector, to an economy of many sectors) (Sharpe & Lenton, 2021). This can result in very large scale, rapid change (Lenton, 2020; Sharpe & Lenton, 2021).

Current theory and models of upward-scaling tipping cascades are quite abstract and more focused on avoiding damaging cascades (Dekker et al., 2018; Klose et al., 2020). Nevertheless, experience provides some clues as to the type of intervention that can trigger positive cascades. In ecosystems, the reintroduction of a single 'keystone species' can trigger a positive upward-scaling 'trophic cascade' – a famous example being the reintroduction of wolves in Yellowstone national park (Ripple & Beschta, 2012). Several past 'socio-technical transitions' started with disruptive technological innovations in niches that cascaded upwards through tipping points to society-wide change (Smith et al., 2005). The EV revolution appears to be following this pattern: Norway's tipping point to EVs dominating new car sales was initially reversible without the maintaining of policy incentives, but is now becoming irreversible, spreading across Europe and worldwide, and starting to reinforce the transition to renewable energy through availability of cheap battery storage (Sharpe & Lenton, 2021).

Operationalising positive tipping points

Having reviewed available models, we now outline a research agenda to operationalise positive tipping points (Figure 2). Crucial determinants of whether positive tipping can occur are the sensitivity of a system to being tipped, and the leverage of different actors and actions to bring about tipping. First, we draw out some initial guidelines on the enabling conditions for positive tipping points. Second, we consider how the potential for positive tipping can be sensed using models and data. Third, we offer some initial guidelines on who can trigger positive tipping and how.

Identifying enabling conditions for positive tipping points

From the general models (Table 1) and from past examples, we can identify some key enabling conditions that may control positive tipping, depending on the context (Figure 2). Recall the distinction between system features in which a tipping point change may occur, and control variables which may bring a system feature to (and past) a tipping point. The systems features are the 'what' that tips, whilst the control variables help identify the 'how' of tipping. For example, the number of adopters is a system feature, and at a critical mass tipping point one more adopter will trigger a self-propelling cascade of further adoption. But to create enabling conditions, the focus should be on identifying and affecting the control variables (the 'how') that can bring a system to a tipping point. In the example, that is the factors that affect adoption and alter the value of the critical mass.

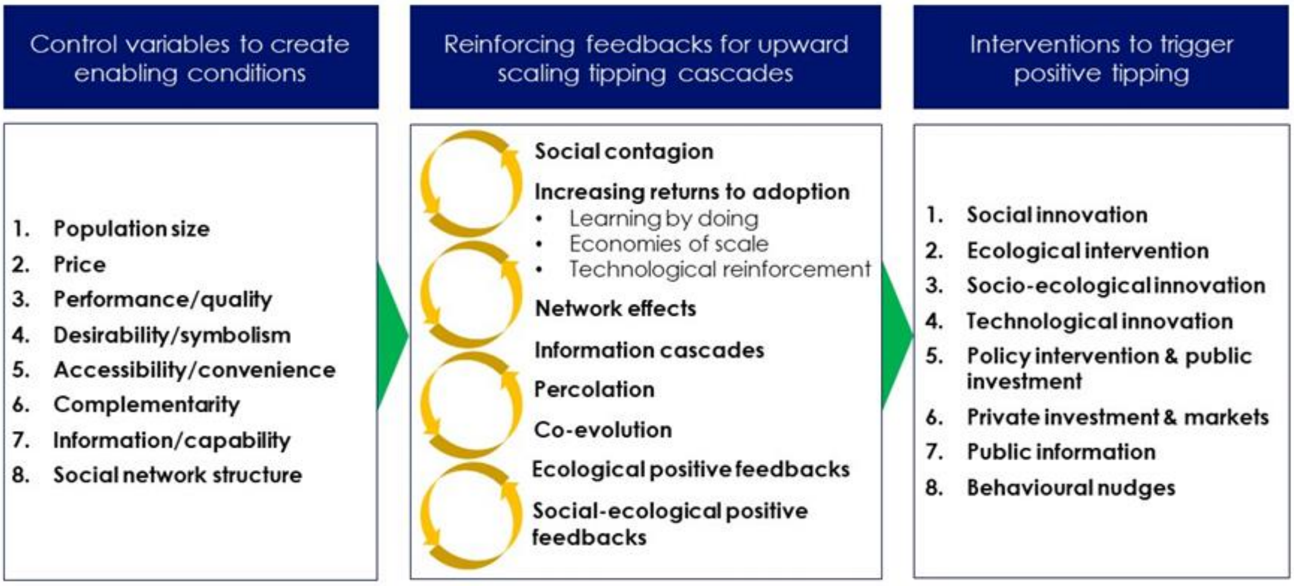

Figure 2: Summary of framework for triggering positive tipping points.

We offer a non-exhaustive list of several familiar things that can be (part of) critical control variables, which if changed in the right direction can enable positive tipping points:

Population size: Where individual thresholds are homogeneous (as in increasing returns and coordination models), more people are needed to reach a critical mass tipping point in a larger population. Conversely, where individual thresholds are heterogeneous (as in social contagion or informational cascades), larger populations can have a greater chance of some small subset group passing a tipping point (Granovetter, 1978). For example, social contagion of rooftop solar PV uptake has been observed to start in sub-populations. This suggests targeting smaller/subset populations as a strategy to enable tipping, for them at least – but it then depends on the existence of an upward-scaling tipping cascade for that to escalate towards global change.

Price: A competitive price signals to consumers the availability of a plausible alternative to an incumbent technology while stimulating demand. A critical price can enable or prevent a percolation tipping point. Equally, critical mass tipping points involving increasing returns and/or coordination can be influenced by price. For example, electric vehicle purchase in Europe appears to exhibit a simple price tipping point – purchase price parity with a petrol/diesel car leads to a non-linear increase in market share (Sharpe & Lenton, 2021) (despite EVs being considerably cheaper to use). Thus, interventions reducing price can help bring a technology alternative to a positive tipping point.

Performance/Quality: When an alternative has equivalent or better quality/performance than an incumbent technology this can attract demand. Difference in quality affects the critical mass at which increasing returns on adoption reaches a tipping point (as does benefit from a new technology in a coordination game). For example, EV access to bus lanes in Norway markedly cut urban school/work commuting times helping propel EV uptake (Figenbaum, 2020). EVs also typically have superior acceleration to ICE vehicles, and differences in range are dwindling rapidly. Another example is accelerating uptake of plant-based meat alternatives – e.g. the Beyond Meat and Impossible burgers – that mimic the taste and texture (quality), and experience (performance) of a beef burger. Thus, interventions that improve quality/performance of an alternative can enable positive tipping.

Desirability/Symbolism: A new alternative needs to be desirable to potential adopters, sometimes irrespective of price or performance. Willingness to adopt is crucial to allowing percolation through a population. There can be strong cultural attachment to an incumbent behaviour that makes it hard to give up. For example, meat consumption is heavily ingrained in tradition in some cultures – e.g. Argentina, France – such that even if plant-based alternatives are cheaper and taste as good, uptake may be resisted. Conversely, sometimes, using a minority technology positively signals being different from the majority and this can overwhelm concerns about being left with a technological orphan of little functional value (van den Bulte & Stremersch, 2004). This can be crucial for early adopters, although the effect clearly weakens if the product takes off. Thus, interventions that make an alternative more desirable can help enable positive tipping.

Accessibility/Convenience: Adoption of a new behaviour or sustainable product benefits from being convenient to access. Agent-based modelling suggests that pro-environmental behaviours are limited by having access to sufficient opportunities for behaving sustainably and emerge systemically as a product of not only infrastructural, social, but also individual factors (Kaaronen & Strelkovskii, 2020). For example, food choices are typically based on convenience and access. Meat is often given preferential shelf space in supermarkets, listed at the top of menus, and provided as default in catering facilities, whereas alternative proteins are often placed in the back of supermarkets, hidden on menus, and only provided on special request. Increasing accessibility can enable positive tipping.

Complementarity: A new suite of strongly reinforcing technologies that are well coordinated can more readily reach a critical mass where they displace an old technology suite. Conversely, a go-alone strategy often fails when complementary innovations by other parties fail to occur. A positive example is the complementary development of the EV market and the charging network in

Norway (Figenbaum, 2020). Coordinating complementary technologies can enable positive tipping.

Information/Capability: Adopters need the right information to use an alternative, or act on a behaviour. Increased exposure to information can enable social contagion (Hodas & Lerman, 2014), and public information can initiate or stop an informational cascade (Bikhchandani et al., 1992). For example, the 'TIST' smallholder tree planting scheme[4] has spread to over 100,000 farmers in 15 years because it was designed to facilitate information sharing in a scalable way, while providing smallholder farmers with the capability to access international voluntary carbon markets. Clearly context defines what information is key, so it is hard to draw out general rules.

Social network structure: Social network structure can affect the tipping points for social contagion, informational cascades, percolation, and co-evolution. For example, greater friendship between people can enable social contagion (Granovetter, 1978). Social network structure can also be altered by changes in information technology, notably social media. For example, the climate protest movements appear to have reached a critical mass partly enabled by social media (Otto et al., 2020). Again, context matters, and it is hard to draw out general rules.

The example of social media highlights that some innovations may change the structure of a system, not just the value of control parameters. By introducing new feedbacks this can alter the existence of tipping points, as well as proximity to them. Technically, this goes beyond the simple dynamical systems approach adopted above, but it is recognised in the leverage points framework.

Sensing the potential for positive tipping

Sensing the potential for positive tipping of some specific system is likely to involve some combination of data and modelling. For the result to translate into action, those intent on triggering positive tipping ideally need to be participants in the sensing activity. This invites the formulation of a general co-design methodology that can be applied to specific cases.

When faced with a specific system and problem, one approach is to bring stakeholders together through workshops and online tools to develop a system map (Stroh, 2015). This involves drawing the interconnections and feedback loops in a system, and for our focus, looking for strong reinforcing feedback loops and the controls on them. This is the start of a model of a specific system. This approach may be complemented by looking for examples of comparable systems elsewhere that have tipped (Sharpe & Lenton, 2021), and trying to draw out general causal patterns.

The next step may be to formalise a mathematical model of a specific system. Where a comparable tipping point has happened elsewhere, one could try and fit a general model (Table 1) to that specific experience and hope it is translatable (Granovetter, 1978). An approach for social contagion is to retrospectively look at the distribution of individual thresholds within a population that has tipped. Having thus calibrated a general model, and accounted for some uncertainty and variability, one can then explore the range of possible outcomes for comparable populations. A complementary approach is to undertake controlled experiments to predict social tipping points of norm change (Andreoni et al., 2021).

Even where a relevant experience of tipping is missing, one may compare a system map with the general models (Table 1) and adopt relevant core mechanism(s) as the basis of a specific model. Such models have been developed to examine specific opportunities for positive tipping. Some operate in an exploratory mode where uncertain parameters are varied over plausible ranges to explore how they affect the outcome. For example, a global model of dietary change that couples psychological theories of behaviour change to their land use consequences reveals the conditions for a self-amplifying shift to sustainable diets (Eker et al., 2019). Or a model that reveals the degree of intervention needed for positive tipping to cooperation over groundwater management in different national contexts (Castilla-Rho et al., 2017). More specific, models have examined, for example, the conditions for a UK tipping point in EV uptake (Shepherd et al., 2012) or city scale reinforcing feedbacks between solar PV power and EVs (Shepero et al., 2018). The challenge is that more detailed models need more data to constrain them and risk overfitting.

We may not understand a complex system well enough to build a specific model of it or have enough data to calibrate a detailed model. However, we can still sense something about the proximity of a system to a tipping point directly from observations of that system because different complex systems approaching tipping points show common *dynamical* behaviour. Specifically, their recovery from perturbations slows down – or in ecologists' terms, they lose *resilience*. This is because the negative feedbacks maintaining stability of an incumbent state are getting weaker before a tipping point is reached where positive feedback takes over (and the system never recovers from perturbation). This 'critical slowing down' behaviour can be detected if a system is subject to known perturbations and we can measure its response, or if a system is subject to continual variability it shows up in changes in the statistical properties describing the system's response – notably, rising temporal autocorrelation and variance (Held & Kleinen, 2004; Lenton et al., 2008; Scheffer et al., 2009).

This approach has been successfully tested on a range of climate and ecological systems, to reveal whether they are heading towards (or away from) a tipping point (Lenton et al., 2008; Scheffer et al., 2009). Rarely is it translated into a statistical forecast of likelihood/ease of crossing a tipping point, but that can be done (Held & Kleinen, 2004). Where the approach needs more testing is in the social realm. Tantalising studies suggest early warning signals before past stock market bubbles (Diks et al., 2018) or electricity grid blackouts (Ren & Watts, 2015). A hypothesis that could be tested by analysing social media data is whether spikes of collective attention on new technologies and associated products, e.g. EVs or alternative proteins, are getting more resilient (i.e. decaying more slowly) over time. Whilst this approach may tell us something about *when* a system is more amenable to being positively tipped, we need understanding of that specific system to tell us anything about *how* to intervene.

Who and how to tip positive change?

What actions, by whom can create different types of positive tipping? There are two phases of action to tip positive change; actions that create enabling conditions that bring a system to a tipping point, and actions that trigger it. The triggering actions, by definition, can be very small right at a tipping point, but variable amounts of effort may be needed to get there.

Who?

We should all feel a sense of agency and autonomy to be part of tipping positive change. Indeed, reinforcing feedbacks can overturn conventional notions of who has power – witness the school strike movement. That said, different actors have differing power to affect change in different contexts. It is hard to resist dividing this into ‘top-down’ and ‘bottom-up’ actors and actions, but that presupposes a questionable model of society. Instead an actor-network view seems apt (Latour, 2005).

Previous studies have catalogued the actors that can be involved in sustainability transitions (Farla et al., 2012), albeit without a specific focus on triggering tipping points. To give a (non-exhaustive) indication: Policymakers and public authorities are a major focus given their role in setting and enacting societal rules. Financial actors have considerable leverage to change the global economy. The third sector (e.g. NGOs) can hold them all to account. Citizens forming social movements can trigger positive tipping points and start upward-scaling tipping cascades. Researchers and technological innovators are the creators of novel alternatives and entrepreneurs can help propel their upscaling. Citizens as consumers are key to their uptake. Firms can actively engage in innovation trajectories and help build an innovation ‘ecosystem’. Public sector organisations can provide a protective environment for innovation niches to develop. Marketing can help tip change in public attitudes. Experts and knowledge institutions can provide authoritative information. The media can help communicate it. The faith sector can help tip hearts and minds.

How?

Tipping points can be triggered by different types of intervention from different actors. Section 3.1 suggested a broadly defined set of actions to create enabling conditions: target smaller populations, reduce price, improve quality/performance, increase desirability, increase accessibility, coordinate complementary technologies, provide relevant information, and alter social network structure. Here we offer a non-exhaustive list of actions to trigger positive tipping, linked to particular actors:

Social innovation: Social disruptors can tip social contagion, for example, protest movements that in turn trigger political change (Kuran, 1989). Notably, what started with the lone protest of Greta Thunberg outside the Swedish parliament became, within 18 months, a worldwide protest movement mobilising millions of people. Political declarations of a climate emergency followed (although the connection to action is questionable). The movement successfully mobilised the ‘new power’ of online crowd-sourcing, radical transparency and leaderless structures (Heimans & Timms, 2019).

Ecological intervention: Human intervention in ecosystems can trigger ecological positive feedback(s) and tipping points in a desired direction – for example, the rapid recovery of a eutrophic lake (Mehner et al., 2008). This approach can co-opt other species of ‘ecosystem engineer’ to do the tipping, for example, introducing blue mussels to recover coastal mud flats (Schotanus et al., 2020). Whilst small in scale, such examples could be emulated worldwide, and positive tipping of coastal mud flats, salt marsh and mangrove ecosystems could sequester significant carbon from the atmosphere.

Social-ecological innovation: Innovations in social-ecological systems can trigger positive feedback(s) in a desired direction (Marten, 2005; Pereira, Drimie, et al., 2020). For example, feeding schoolchildren in Kenya boosted community agroforestry (Borish et al., 2017). Recreation of earthen dams to trap monsoonal rains in Rajasthan, refilled aquifers, supporting dry-season irrigation, successful cash crop production and community rejuvenation[5]. Such innovations have the potential to trigger positive tipping points.

Technological innovation: Technological innovators can create sustainable alternatives and through learning-by-doing improve their quality/performance, desirability, accessibility and price – all of which may take an innovation past a critical mass tipping point. For example, precision fermentation and mycoprotein technology can use plant protein to create products with the same or similar sensory properties as conventional meat. Technology firms can also coordinate to achieve complementarity of interdependent technologies, potentially triggering coordination and co-evolution tipping points.

Policy interventions and public investment: National governments can invest in innovation and R&D, redirect public finance (e.g. subsidies) from incumbents to disruptors, tax unsustainable incumbents, and reconfigure markets and institutions – all of which may help take sustainable innovations past a critical mass tipping point. For example, subsidising renewable energy deployment and introducing a carbon tax specifically on power generation was critical to tipping coal burning out of UK power generation (Sharpe & Lenton, 2021). National governments can also invest in information technologies in a way that makes social network structures more amenable to tipping. Multiple governance levels can help coordinate complementary technologies – potentially triggering coordination and co-evolution tipping points. Regional and local government can target smaller populations more amenable to tipping, for example, cities providing free, accessible EV charging infrastructure.

Private investment and markets: Private sector investments tend to come after government investment as an innovation is starting to take off. They can help propel increasing returns and trigger critical mass tipping points – for example, the rapid expansion and declining price of solar PV (Green, 2019). Withdrawing private finance from unsustainable incumbents, or at least making it harder to access, can also play a critical role.

Public information: Many actors and institutions, including media and government, can generate and spread public information that can trigger social contagion. For example, the BBC 'Blue Planet II' series tipped a persistent change in media coverage and political attention on plastic pollution (Males & Van Aelst, 2021), although there is little evidence it has led to behaviour change (Dunn et al., 2020). The movement from anonymous global food supply chains to food labelling and certification has triggered a shift to alternative food networks (Pereira, Drimie, et al., 2020).

Behavioural nudges: 'Behavioural nudges' – and 'hyper-nudges' using big data (Yeung, 2017) – targeting citizen behaviour through suggestions and positive reinforcement can erode an existing norm and may trigger a social contagion tipping point beyond which a new norm takes hold in society (Brescia, 2019; Sunstein, 2014). For example, smaller plate sizes reduce over-consumption and food loss and waste (Wansink & van Ittersum, 2013), although small levies on single-use plastic shopping bags have had variable effects (Nielsen et al., 2019; Rivers et al., 2017).

Discussion

We have taken a somewhat reductive view of positive tipping points, identifying different models and compiling lists of actors and actions – but these should not be treated as independent if we aim to create transformative change across social-ecological-technological systems. A first application of the framework to food and land system transformations is the subject of a separate report. Looking ahead, a key research agenda is to consider how different agents and interventions can most effectively work together to create system-wide positive tipping points – e.g. through systems entrepreneurship (Schlaile et al., 2021), policy packaging (Fesenfeld et al., 2020), and systems innovation (Hekkert & Negro, 2009). Who and how to work together most effectively can depend on the problem and the phase, and the most effective way to unlock system-wide positive tipping may be to intervene in multiple places simultaneously. Research should also consider how we can recombine what we already have in novel ways to trigger positive tipping (rather than necessarily coming up with new things). Some actors are more attuned to the type of thinking outlined herein than others and may be natural instigators (for example, 'Extinction Rebellion' already applied the principles of critical mass in a designed effort to mobilise public protest). Not all aspects of a desired sustainability transformation may be amenable to positive tipping points and it is part of the research agenda to identify these.

Within this more systemic view, it is vital to consider the political economy of positive tipping points. Any attempt to tip positive change is likely to meet resistance from the incumbent way of doing things. Existing regimes, whether social, technological, or ecological, are stabilised by damping feedbacks that resist change and restore the status quo. This can take many forms, including in the social realm, cultural norms, sunk costs, subsidies, ease of raising finance, and lobbying groups. We have focused on strengthening positive feedbacks but weakening the negative feedbacks that maintain an incumbent state can be just as powerful as a leverage point (Meadows, 1999, 2008). For example, shifting subsidies from fossil fuel extraction to renewable power, and helping workers, communities, and local governments benefit from transformation.

When transformative change takes off, the original incumbent way of doing things must decline – often in an accelerating way propelled by reinforcing feedbacks. There will be losers as well as winners. Hence it is vital to consider whether and how this exacerbates or reduces current inequalities and what social safety nets can help ensure a just transformation (Newell & Mulvaney, 2013; Newell & Simms, 2020; Sovacool, 2021; Winkler, 2020). Good intentions do not necessarily translate into good outcomes. Apparently well-intentioned rapid transformations can turn out to be immensely exploitative for many stakeholders – in the business realm, think of Uber or AirBnB. Thus, part of the research agenda is to consider; how are people going to game the transformation? Who owns the transformation, who has access to it, and who reaps the benefits of it, will be critical to determining the outcome. Public bodies have a huge role to play in value creation – a much bigger one than big business would like us to believe (Mazzucato, 2011). Sadly, public bodies do not generally invest in their own capacities and increasingly outsource everything to companies and consultancies. But when all the knowledge is outside of public bodies who is left in the driver's seat? If it is private institutions without the public good at their heart it could readily lead to negative outcomes.

Given the urgent need for a transformation to global sustainability, not acting is not an option. To help mitigate the risk that well intended positive tipping points pave a road to hell, the 'panarchy' framework emphasises the value of adaptive management as a co-evolutionary process to damp negative outcomes and amplify positive ones (Gunderson & Holling, 2002). Key to this approach is the recognition that we can never fully predict the consequence of intervening in a complex adaptive system, but we can experiment and learn by doing, in 'transformative spaces' (Pereira, Frantzeskaki, et al., 2020) or 'real world laboratories' (Schäpke et al., 2018). This is already occurring widely with cities' experiments to tackle climate change (Castán Broto & Bulkeley, 2013, 2018), where frontrunners have triggered reinforcing feedbacks across networks of cities (Irvine & Bai, 2019). This suggests a systemic strategy to initiate positive tipping points in niches using public investment and policy levers, and thus retain an option to reverse the tipping (if it proves undesirable) by rapidly withdrawing those levers.

Conclusion

Multiple actors have the agency to contribute together to triggering positive tipping points of sustainability transformation. Multiple types of action can trigger them, and multiple reinforcing feedbacks can propel them. Actions that can create enabling conditions for positive tipping include targeting smaller populations, reducing price, improving quality/performance, increasing desirability, increasing accessibility, coordinating complementary technologies, providing relevant information, and altering social network structure. Actions that can trigger positive tipping include social innovation, ecological intervention, social-ecological innovation, technological innovation, policy interventions, public investment, private investment, broadcasting public information, and behavioural nudges. This prototype recipe for triggering positive tipping points can help counter widespread feelings of disempowerment in the face of global challenges and help unlock apparently widespread 'paralysis by complexity'. The proposed initial framework needs testing and refining, especially to create a more systemic recipe for positive tipping. But there is no better way forward than to learn by doing. Continuing to delay action to accelerate a transformation towards global sustainability will only accentuate the need to find and trigger even more dramatic positive tipping points in the future.

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